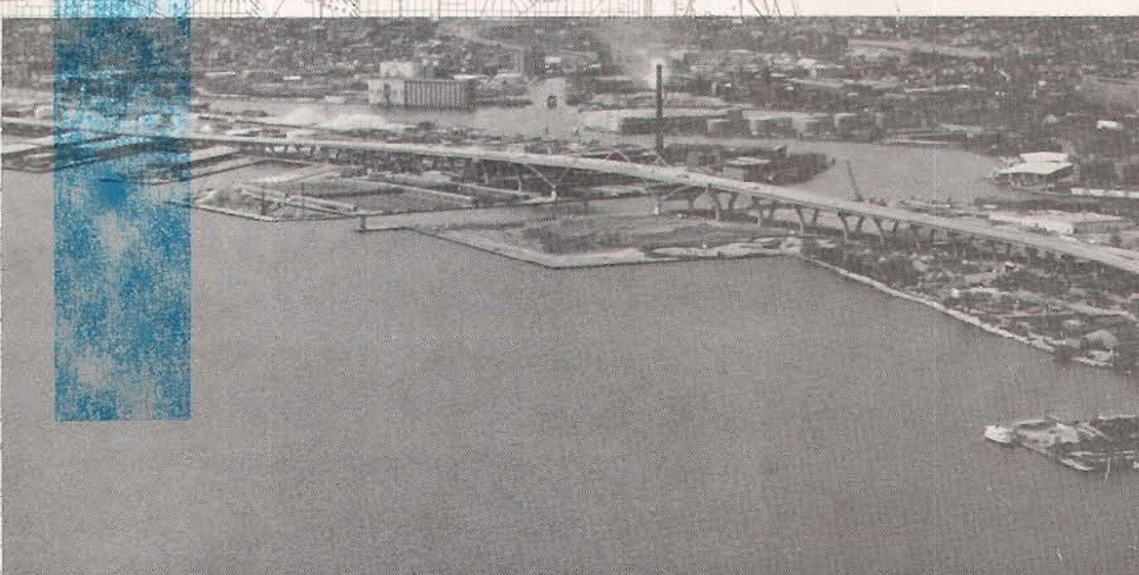
PLANNING REPORT NO. 37

A WATER RESOURCES MANAGEMENT PLAN FOR THE MILWAUKEE HARBOR ESTUARY



volume one

INVENTORY FINDINGS

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A WATER RESOURCES MANAGEMENT PLAN FOR THE MILWAUKEE HARBOR ESTUARY

Volume One

INVENTORY FINDINGS

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March 1987

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STATEMENT OF THE CHAIRMAN

The Southeastern Wisconsin Regional Planning Commission, in 1982, undertook a comprehensive study of the water pollution, flooding, storm damage, and dredging problems of the Milwaukee Harbor estuary area. This study was conducted in response to a long-standing formal request from the Common Council of the City of Milwaukee, a request reenforced by the U. S. Environmental Protection Agency and Wisconsin Department of Natural Resources. The primary objective of this study was to develop a workable plan for the abatement of water pollution within the Milwaukee Harbor estuary so as to meet established water use objectives in a cost-effective manner and thereby further the protection and wise use of the natural resource base. More specifically, the study was intended to develop a plan to abate water pollution from combined sewer overflows, including a determination of the level of protection to be provided by such abatement, and from other point sources of pollution and from nonpoint sources; to recommend any instream measures, including the removal of polluted sediments, that might be needed to help achieve established water use objectives; to abate damage caused by flooding and by storm wave action; to facilitate the continued maintenance of navigation for deep draft commercial vessels by recommending means for the environmentally safe disposal of polluted dredged material; to prevent deterioration of the estuary shoreline; and to maximize the utilization of the estuary as a prime urban recreational area.

The findings and recommendations of this study are presented in a two-volume planning report. This, the first volume, presents a summary of the findings of the extensive inventories conducted to provide a factual basis for the plan preparation. The inventories were carefully designed to describe the pertinent man-made and natural resource base of the drainage area tributary to the Milwaukee Harbor estuary; describe the complex hydrologic and hydraulic characteristics of the estuary area; identify and define the water resource problems of the estuary; and identify the sources of water pollution. In addition, the inventories were designed to assist in the formulation and application of a set of mathematical simulation models and other analytical procedures to be used in alternative plan design, test, and evaluation. The study included the most intensive water resource monitoring efforts ever conducted for the estuary, including massive sediment and water quality sampling programs, surface- and groundwater level and flow monitoring programs, and extensive plankton sampling, algal productivity, faunal toxicity, and fish habitat surveys during both wet and dry weather conditions. These inventories provided the data required for a thorough understanding of this complex estuarine system and facilitated reliable analyses of water quality and sediment conditions, and of the potential effects of alternative means of water quality management on those conditions.

The second volume of this report identifies and sets forth water resource management objectives, alternative means for meeting those objectives, and the best means available from among these alternatives, together with effective means for their implementation. Careful review and study of the entire report by responsible public officials and concerned citizens is urged, for the findings and recommendations of the Milwaukee Harbor estuary program may be expected to have far-reaching impacts on the sound development and redevelopment of the central business district of the City of Milwaukee and on the overall quality of life within the greater Milwaukee area.

Respectfully submitted,

Anthony F. Balestrieri
Chairman

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Chapter I

INTRODUCTION

The inner and outer harbors of the City of Milwaukee, formed by the confluence of the Kinnickinnic, Menomonee, and Milwaukee Rivers with Lake Michigan, represent a valuable natural resource, forming an important part of the transportation system of the greater Milwaukee area, and contributing significantly to the economic base as well as natural beauty of that area. Historically, it was the confluence of these three rivers with a natural bay on Lake Michigan that provided for and encouraged the development of early settlements in this portion of Wisconsin.

The growth of Milwaukee from an early trading village to the major metropolitan center it is today may be attributed in large measure to the development of its transportation facilities, most notably, the development of harbor facilities for handling waterborne commerce in the mid- to late-1800's. With the steadily progressing urbanization and industrialization of the lands along the major waterways forming the Milwaukee Harbor, however, the waters of that harbor became increasingly polluted. Pollution of these waters has now become so severe as to significantly impair the recreational uses and aesthetic qualities of the estuary in the downtown Milwaukee area. The severely polluted conditions of the Milwaukee Harbor constitute a threat to necessary and desirable forms of water uses in the near-shore zone of Lake Michigan and of the inner and outer harbors. These conditions may also threaten certain aspects of the fishery of Lake Michigan itself in the vicinity of the Milwaukee area, and may adversely affect land use development and redevelopment in the areas bordering the estuary.

Other problems regarding the Milwaukee Harbor such as flooding in the estuary, harbor maintenance and the ultimate disposition of dredged spoils, and storm damage prevention and shoreline protection must also be addressed in a comprehensive study of this important estuarial environment. Accordingly, the Milwaukee Harbor estuary planning program was designed to identify the nature and extent of the water pollution, flooding, dredging, storm damage, and shoreline protection problems within the estuary; to evaluate the effectiveness of alternative water pollution and flood damage abatement measures, alternative dredging and spoils disposal practices, and alternative storm damage prevention and shoreline protection techniques; and to recommend a comprehensive set of specific actions devised so as to ensure the enhancement and preservation of the estuary environment as a significant resource in a highly urbanized setting.

Since the Milwaukee Harbor estuary planning program is an integral part of the overall work program of the Southeastern Wisconsin Regional Planning Commission, an understanding of the need for and objectives of regional planning, and of the manner in which these objectives are being met in southeastern Wisconsin, is necessary for a proper understanding and appreciation of the findings and recommendations of the estuary planning program.

NEED FOR REGIONAL PLANNING

Regional planning has become increasingly accepted as a necessary governmental function in most of the large urban areas of the United States. This tendency reflects growing awareness that certain pressing problems of physical and economic development and of environmental deterioration transcend the geographic limits, as well as the fiscal capabilities, of local units of government and require the cooperation of all units and agencies of government concerned for sound resolution.

The term "region," as used in this context, applies to an area larger than a county but smaller than a state, united by economic interests and geography and by common problems brought about by areawide urbanization. A regional approach is essential to the sound planning and development of highway and transit, sewerage and water supply, and park systems. A regional approach is also necessary to the sound resolution of such problems as flooding, air and water pollution, the deterioration or destruction of the natural resource base, and rapidly changing land use.

Federal, state, county, municipal, and private interests all are vitally affected by such areawide problems and by proposed solutions to these problems. It appears neither desirable nor possible for any one level or agency of government to impose the decisions required to solve these areawide problems. Instead, such decisions must come from a consensus among the various levels and agencies of government and private interests concerned, based on a common interest in the welfare of the entire Region. Regional planning is imperative for promoting such a consensus and the necessary cooperation between urban and rural; local, state, and federal; and private and public interests.

THE REGIONAL PLANNING COMMISSION

The Southeastern Wisconsin Regional Planning Commission (SEWRPC) represents an attempt to provide the necessary areawide planning services for one of the large urbanizing regions of the United States. The Commission was created in August 1960, under the provisions of Section 66.945 of the Wisconsin Statutes, to serve and assist the local, state, and federal units of government in planning for the orderly and economic development of southeastern Wisconsin. The role of the Commission is entirely advisory, and participation by local units of government in the work of the Commission is on a voluntary, cooperative basis. The Commission itself is composed of 21 citizen members, three from each county within the Region, who serve without pay.

The powers, duties, and functions of the Commission and the qualifications of the Commissioners are set forth in state enabling legislation. The Commission is authorized to employ experts and a staff as necessary for the execution of its responsibilities. Basic funds necessary to support Commission operations are provided by the member counties, the budget being apportioned among the seven counties on the basis of relative equalized assessed valuation. The Commission is authorized to request and accept aid in any form from all levels and agencies of government for the purpose of accomplishing its objectives and is authorized to deal directly with the state and federal governments for this purpose. The organizational structure of the Commission and its relationship to the constituent units and agencies of government comprising or operating within the Region are shown in Figure 1.

THE REGIONAL PLANNING CONCEPT IN SOUTHEASTERN WISCONSIN

Regional planning as conceived by the Commission is not a substitute for, but a supplement to, local, state, and federal planning efforts. Its objective is to aid the various levels and units of government in finding solutions to areawide developmental and environmental problems which cannot be properly resolved within the framework of a single municipality or a single county. As such, regional planning has three principal functions:

1. Inventory—the collection, analysis, and dissemination of basic planning and engineering data on a uniform, areawide basis so that, using such data, the various levels and agencies of government and private investors operating within the Region can better make decisions concerning community development.

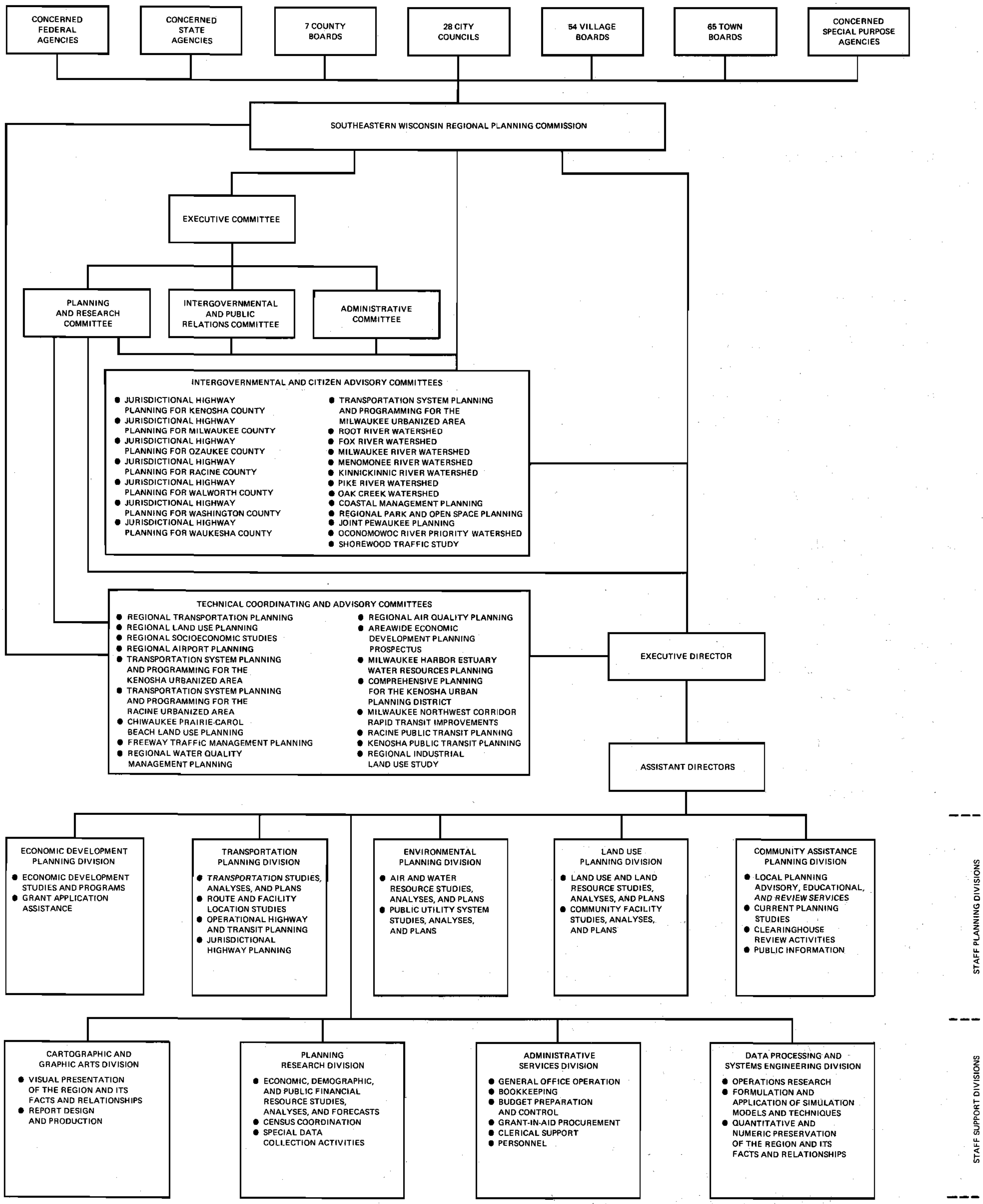
2. Plan Design—the preparation of a framework of long-range plans for the physical development of the Region, these plans being limited to those functional elements having areawide significance. To this end, the Commission is charged by law with the function and duty of "making and adopting a master plan for the physical development of the Region." The permissible scope and content of this plan, as outlined in the enabling legislation, extend to all phases of regional development, implicitly emphasizing, however, the preparation of alternative spatial designs for the use of land and for the supporting transportation and utility facilities.

3. Plan Implementation—the provision of a center for the coordination of the many planning and plan implementation activities carried on by the various levels and agencies of government operating within the Region. To this end, all of the Commission work programs are intended to be carried out within the context of a continuing planning program which provides for the periodic reevaluation of the plans produced, as well as for the extension of planning information and advice necessary to convert the plans into action programs at the local, regional, state, and federal levels.

The work of the Commission, therefore, is visualized as a continuing planning process, providing outputs of value to the making of development decisions by public and private agencies, and to the preparation of plans and plan implementation programs at the local, state, and federal levels of government. The work of the Commission emphasizes close cooperation between the government agencies and private enterprises responsible for the

Figure 1

SEWRPC ORGANIZATIONAL STRUCTURE: 1984



Source: SEWRPC.

development and maintenance of land uses within the Region and for the design, construction, operation, and maintenance of the supporting public works facilities. All of the Commission work programs are intended to be carried out within the context of a continuing planning program which provides for the periodic reevaluation of the plans produced, as well as for the extension of planning information and advice necessary to convert the plans into action programs at the local, regional, state, and federal levels.

THE REGION

The Southeastern Wisconsin Planning Region, as shown on Map 1, is composed of Kenosha, Milwaukee, Ozaukee, Racine, Walworth, Washington, and Waukesha Counties in southeastern Wisconsin. Exclusive of Lake Michigan, these seven counties have a total area of 2,689 square miles, and together comprise about 5 percent of the total area of the State of Wisconsin. About 37 percent of the state population (1980) resides within these seven counties, which contain three of the eight and one-half standard metropolitan statistical areas in the State. The Region contains approximately 37 percent of all the tangible wealth in the State of Wisconsin as measured by equalized valuation, and represents the greatest wealth-producing area of the State, with about 39 percent of the state labor force employed within the Region. The seven-county Region contains 154 local units of government, exclusive of school and other special-purpose districts, and encompasses all or parts of 11 natural watersheds.

Geographically the Region is located in a relatively good position for continued, long-term growth and development. It is bounded on the east by Lake Michigan, which provides an ample supply of fresh water for both domestic and industrial use as well as being a recreational attraction and an integral part of the major international transportation network. It is bounded on the south by the large northeastern Illinois metropolitan region and on the west and north by the fertile agricultural lands and desirable recreational areas of the rest of the State of Wisconsin. As shown on Map 2, many of the most important industrial areas and heaviest population concentrations in the Midwest lie within a 250-mile radius of the Region, and more than 32 million people reside within this radius.

COMMISSION WORK PROGRAMS

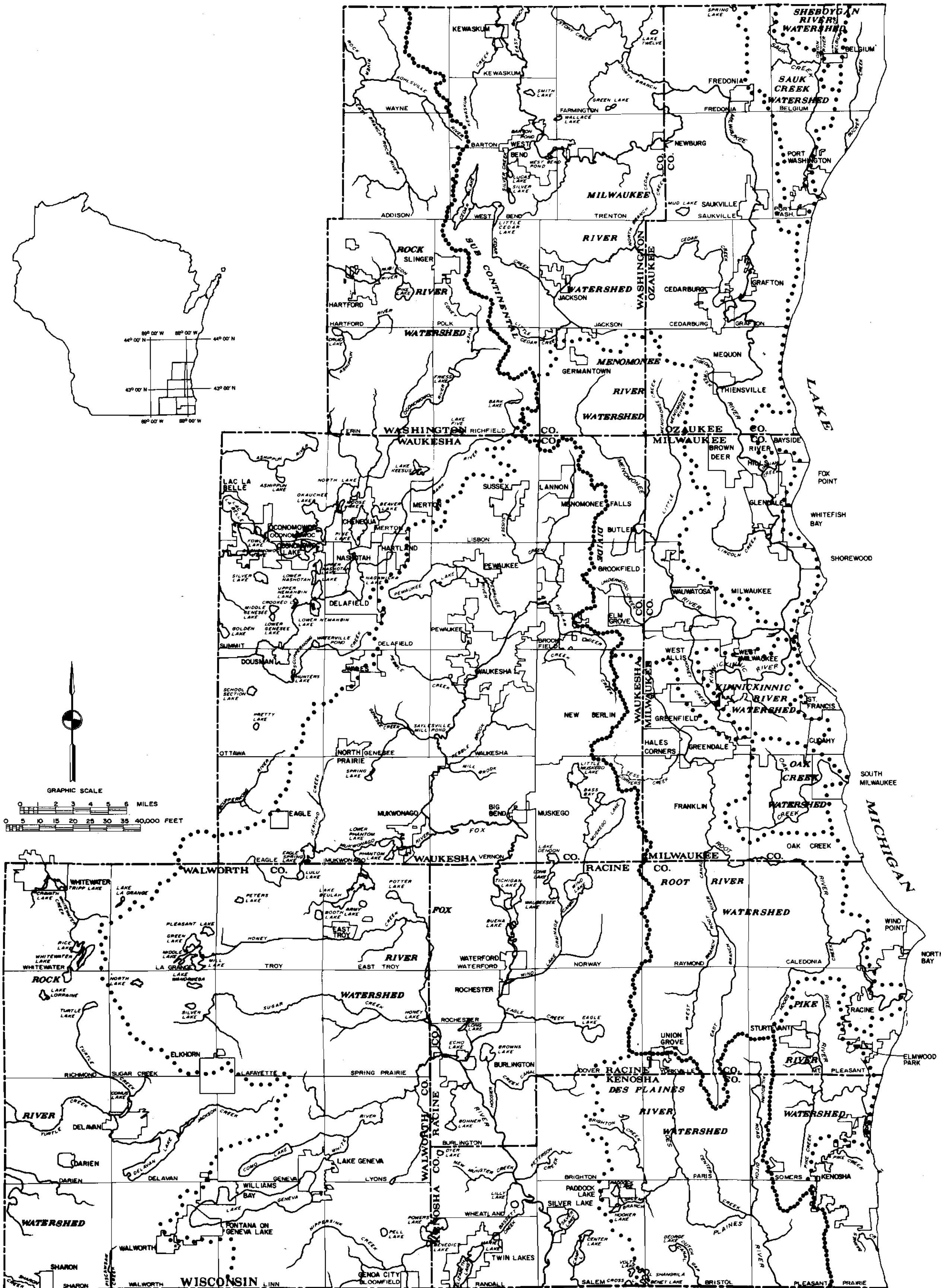
The Milwaukee Harbor estuary planning program was conducted within the context of, and has been fully coordinated with, the Commission's ongoing comprehensive planning program for southeastern Wisconsin. It is appropriate to review briefly here selected aspects of the Commission's past and current work programs inasmuch as some of the data obtained and some analytic techniques developed under those programs were used in the Milwaukee Harbor estuary planning program. Furthermore, recommendations contained within the Milwaukee Harbor estuary plan are based in part on, and are coordinated with, land use and other recommendations emanating from other Commission planning programs.

Regional Land Use and Transportation Planning Program

The Commission, in cooperation with its constituent county and local units of government and the affected state and federal agencies of government, has engaged since 1963 in a continuing regional land use and transportation planning program. Included in this continuing planning effort is the collection of current, definitive data on changing public attitudes and values relating to land use, housing, and transportation; on the amount and spatial location of population and economic activity; on land use development and the factors affecting such development; on the public utility base; on the underlying and sustaining natural resource base, including definitive information on soils, wetlands, woodlands, wildlife habitat areas, surface waters and associated shorelands and floodlands, groundwater recharge areas, and areas having scientific and cultural value; on automobile and truck availability; on trip generation and distribution; on mode of transportation utilized; on local land use and transportation plans; and on plan implementation actions. These data collection efforts provide information useful to sewerage, water supply, flood control, and park and open space planning and to air and water pollution control planning, as well as to land use and transportation system planning. The major inventory findings and plan recommendations are documented in SEWRPC Planning Report No. 25, A Land Use Plan and a Transportation Plan for Southeastern Wisconsin: 2000, Volume One, Inventory Findings, and Volume Two, Alternative and Recommended Plans.

Map 1

SOUTHEASTERN WISCONSIN REGION

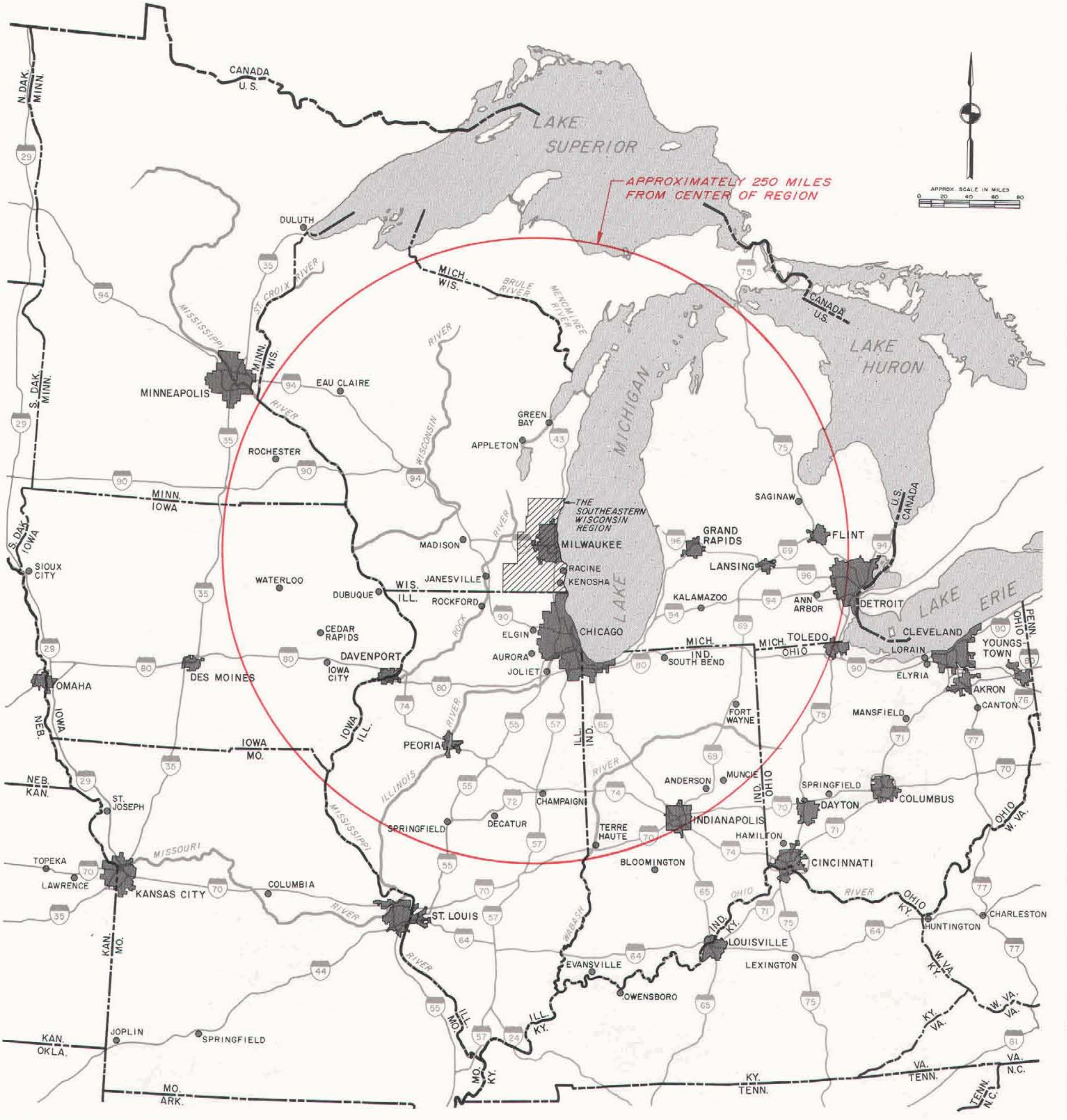


The seven-county Southeastern Wisconsin Region encompasses a total area of 2,689 square miles, or about 5 percent of the total area of the State of Wisconsin, but contains about 37 percent of the total population of the State (1980). The Region also contains approximately 37 percent of all the tangible wealth in the State, as measured by equalized valuation, and represents the greatest wealth-producing area of the State, with about 39 percent of the state labor force being employed within the Region.

Source: SEWRPC.

Map 2

THE REGIONAL SETTING IN THE MIDWEST



Many of the most important industrial areas and largest population and employment concentrations in the Midwest are located within 250 miles of the Southeastern Wisconsin Region. More than 32 million people, or more than one-seventh of the entire population of the United States, live within the 250-mile radius.

Source: SEWRPC.

Comprehensive Watershed Studies

The regional planning program very early recognized the significance of existing water-related resource problems, including flooding and water pollution. The natural watershed was selected by the Commission as the basic water and water-related resource planning unit, and comprehensive watershed plans have been completed for the Root, Fox, Menomonee, Milwaukee, Kinnickinnic, Pike River, and Oak Creek watersheds within the Region.

The basic purpose of watershed planning programs, as developed within the context of the overall regional planning program, is to provide long-range plans for the development of flood control and water pollution abatement facilities, and thereby to provide for the coordination of local, state, and federal water resource management programs within the Region and its watersheds. Specifically, the objectives of the watershed planning programs include: the abatement of flood damage; the protection of floodways and floodplains from incompatible development; the abatement of water pollution and the protection of water supply; the preservation of land for park and related open space; the preservation of woodlands, wetlands, wildlife habitat, and prime agricultural lands; and the promotion of wise and judicious use of the limited land and water resources of the Region. In addition, the watershed plans serve to refine and detail the regional land use plan, particularly in the riverine areas, and help achieve a more complete integration of land and water resource planning. Because of the importance of the Milwaukee, Menomonee, and Kinnickinnic River watersheds as tributary areas to the Milwaukee Harbor estuary, the findings and recommendations of the watershed planning programs for those watersheds are presented below.

The Milwaukee River Watershed Study: The Milwaukee River watershed study was the third comprehensive watershed planning program undertaken by the Commission. The study was initiated in October 1967 and was completed in October 1971. The findings and recommendations of this planning effort are documented in SEWRPC Planning Report No. 13, A Comprehensive Plan for the Milwaukee River Watershed, Volume One, Inventory Findings and Forecasts, and Volume Two, Alternative Plans and Recommended Plan. The plan for the Milwaukee River watershed contains recommendations for the abatement of the flooding, water quality, water supply, recreation, and related land and natural resource conservation problems of this important watershed. The study also produced special lake use reports for selected major lakes within the watershed. Of particular importance to the Milwaukee Harbor estuary study are the recommendations in the Milwaukee River watershed study for the abatement of water pollution from combined sewer overflows, recommendations which were essentially reaffirmed after many years of intensive, detailed and costly planning by the Milwaukee Metropolitan Sewerage Commission.

The comprehensive Milwaukee River watershed plan is comprised of five major elements: a land use plan element, a flood control element, a stream water pollution abatement plan element, a lake water pollution plan element, and a water supply plan element. The land use plan element recommends the implementation of the adopted regional land use plan and, more specifically, the regulation of land use development in accordance with the plan over the entire watershed through the exercise of local land use controls. The land use plan element also recommends the public acquisition of all remaining undeveloped environmental corridors in urban areas of the watershed, and the acquisition of sufficient additional park and open space area to meet future demand for such land use. The flood control plan element is essentially nonstructural, consisting of the land use development proposals contained in the land use plan element particularly as such proposals affect the riverine areas of the Milwaukee River watershed. The principal components of the flood control plan are recommendations for the prevention of new construction in floodways; for the gradual, voluntary removal of structures rendered nonconforming uses in the urban floodways; for the floodproofing of all structures located between the 10-year and 100-year recurrence flood hazard lines; and for the continuation of a long-established stream gaging program.

The stream water pollution abatement element contains recommendations for both the lower and upper portions of the Milwaukee River watershed. For the lower portion of the watershed the plan recommends the completion of a sanitary sewer relief program to eliminate the 117 sanitary sewer overflow devices discharging raw sewage to the Milwaukee River and its tributaries; the connection to the Milwaukee metropolitan sewerage system of those industrial outfalls discharging wastewater, other than noncontact cooling water and selected wastewater discharges amenable to treatment by the industry, directly to the surface water system of the watershed; and the construction of a combination deep tunnel-mined storage/flow-through treatment system to collect, convey, and treat all combined sewer overflows from the 112 combined sewer overflow devices located throughout the 17,200-acre combined sewer service area in Milwaukee County. For the upper portion of the watershed the plan recommends the provision of secondary waste treatment and post-chlorination and, in certain cases, tertiary or advanced waste treatment at existing sewage treatment facilities within the watershed; the abandonment of the Thiensville sewage treatment facility and subsequent connection to the Milwaukee metropolitan sewerage system; the institution of voluntary agricultural land use management practices; and the continued operation of a water quality monitoring program throughout the watershed.

The lake water pollution abatement plan element recommends the provision of sanitary sewer service at nine lakes in the Milwaukee River watershed; the control of nuisance algae blooms as necessary at eight lakes in the watershed; machine harvesting of aquatic weed growth as necessary at 13 lakes in the watershed; and the establishment of a long-term soil and water conservation program to control pollution from agricultural runoff. This plan element also recommends the installation of sanitary sewerage systems to eliminate potential health hazards in the lakes as a result of inadequate or malfunctioning individual, onsite, soil absorption sewage disposal systems.

The water supply plan element contains recommendations concerning well location and spacing necessary to achieve proper utilization of the deep sandstone aquifer and the shallow sand and gravel and dolomite aquifers in the watershed. This plan element further recommends the establishment of public water supply systems in four villages within the watershed, and the creation of a municipal water supply system, drawing on Lake Michigan, to serve the Villages of Bayside and River Hills in Milwaukee County and the City of Mequon and the Village of Thiensville in Ozaukee County.

The Milwaukee River watershed study was formally adopted by the Commission in March 1972. The Wisconsin Natural Resources Board approved the plan in July 1972, and in August 1972 certified the plan to the U. S. Environmental Protection Agency (EPA). The EPA formally approved the plan in March 1973. Thus, the Milwaukee River watershed plan provided an approved basin plan for use by state and federal agencies in support of the review and award of federal grants-in-aid for sewerage and water quality control facility construction.

<u>The Menomonee River Watershed Study:</u> The Menomonee River watershed study was the fourth comprehensive watershed planning program undertaken by the Commission. The study was initiated in February 1972 and was completed in October 1976. The findings and recommendations of this planning effort are documented in SEWRPC Planning Report No. 26, <u>A Comprehensive Plan for the Menomonee River Watershed</u>, Volume One, <u>Inventory Findings and Forecasts</u>, and Volume Two, <u>Alternative Plans and Recommended Plan</u>. Like the Milwaukee River watershed plan, the Menomonee River watershed plan set forth recommendations for the abatement of the flooding, water pollution, recreation, and related land and natural resource conservation problems of this important basin. The Menomonee River watershed study, however, was the first such study to be conducted by the Commission for a watershed which is extensively urbanized and which is expected to become almost entirely urbanized in the near future.

The comprehensive Menomonee River watershed plan is comprised of three major elements: a land use plan element, a floodland management plan element, and a water quality management plan element. The land use plan element includes recommendations for the continued implementation of the adopted regional land use plan, the protection of the existing 14.7 square miles of net primary environmental corridors in the watershed, the public acquisition of an additional 6.3 square miles of primary environmental corridors, and the maintenance of 5.2 square miles of existing outdoor recreation and open space lands. The land use plan element also recommends the development of a scenic drive-recreational trail system along the Menomonee River.

The recommended floodland management plan element consists of both structural and nonstructural measures. Among the structural measures are recommendations for the construction of a detention reservoir, the channelization of certain stream reaches, floodproofing of existing structures and the acquisition and removal of other existing structures in the floodplain, and the design of all new or replacement river crossings in accordance with the plan and so as not to significantly increase flood flows or stages. Among the nonstructural measures are recommendations for the implementation of the land use plan element, the establishment of a program for cleaning both stream channels and bridge and culvert waterway openings, and the maintenance of a basic stream gaging network.

The water quality management plan element recommends the abandonment of four municipal sewage treatment plants in the Menomonee River watershed, the provision of sanitary sewer service to approximately 12 square miles of existing unsewered urban development within the watershed, and the implementation of agricultural land management practices to effect a significant reduction in pollutant runoff from approximately 36 square miles of crop and pastureland in the watershed. This plan element also recommends the elimination of certain industrial discharges to the Menomonee River and its tributaries, and the elimination of approximately 140 sanitary sewerage system flow relief devices discharging raw sewage directly to the surface waters within the watershed during periods of wet weather. This plan element envisions that the recommendations in the Milwaukee River watershed report for the collection, conveyance, and treatment of combined sewer overflows will be refined by ongoing detailed facility planning being conducted by the Milwaukee-Metropolitan Sewerage Commissions.

The Kinnickinnic River Watershed Study: The Kinnickinnic River watershed study was the fifth comprehensive watershed planning program to be carried out by the Commission. The study was initiated in July 1972 and was completed in December 1978. The findings and recommendations of this planning effort are documented in the single-volume SEWRPC Planning Report No. 32, A Comprehensive Plan for the Kinnickinnic River Watershed. Like the Milwaukee River and Menomonee River watershed plans, the Kinnickinnic River watershed plan set forth recommendations for the abatement of the flooding, water pollution, recreation, and related land and natural resource conservation problems of this important basin. The Kinnickinnic River watershed plan was the second such study conducted by the Commission for a heavily urbanized basin.

The comprehensive Kinnickinnic River watershed plan is comprised of three elements: a land use plan element, a floodland management plan element, and a water quality management plan element. The land use plan element recommends the implementation of the adopted regional land use plan, the maintenance and preservation of approximately 325 acres of existing net primary environmental corridors within the watershed and the protection of about 232 acres of the Lake Michigan shoreline primary environmental corridor on the eastern edge of the watershed, and the development of a four-mile segment of a recreational corridor passing across the eastern end of the watershed.

The recommended floodland management plan element consists of both structural and nonstructural measures. Among the structural measures are recommendations for the construction of detention reservoirs, the channelization of certain stream reaches, floodproofing of existing structures and the acquisition and removal of other existing structures in the floodplain, and the design of all new or replacement river crossings in accordance with the plan and so as not to significantly increase flood flows or stages. Among the nonstructural measures are recommendations for the implementation of the land use plan element, the establishment of a program for cleaning both stream channels and bridge and culvert waterway openings, and the maintenance of a basic stream gaging network.

The water quality management plan element recommends the elimination of approximately 29 sanitary sewerage system flow relief devices discharging directly to the Kinnickinnic River and its tributaries, the elimination of industrial discharges to the Kinnickinnic River and its tributaries, and the abatement of pollution from the 23 known combined sewer outfalls in the lower reaches of the Kinnickinnic River watershed. This plan element also recommends a reduction of approximately 25 percent in nonpoint source pollution through the implementation of measures designed to control additional sources of toxic and hazardous substances.

Areawide Water Quality Management Planning Program

In July 1979 the Commission completed an areawide water quality management planning program that has important implications for the Milwaukee Harbor estuary study. The areawide water quality management planning program updated and refined previous water quality plan elements such as the regional sanitary sewerage system plan and earlier comprehensive watershed plans. At the same time, this planning program extended those water quality plan elements to the portions of the Region not then having watershed plans, and updated all the plan recommendations to the plan design year 2000.

The areawide water quality management plan consists of the following five major elements: 1) an element addressing land use; 2) an element addressing the elimination of pollution from point sources; 3) an element addressing the elimination of pollution from nonpoint sources; 4) an element addressing the handling, recycling, and disposal of sewage sludge; and 5) an element addressing water quality monitoring. The plan includes the designation of wastewater treatment and water quality management agencies. The findings and recommendations of the areawide water quality management plan are set forth in SEWRPC Planning Report No. 29, A Regional Wastewater Sludge Management Plan for Southeastern Wisconsin, and SEWRPC Planning Report No. 30, A Regional Water Quality Management Plan for Southeastern Wisconsin: 2000. This plan was adopted by the Commission on July 12, 1979, and by the Wisconsin Department of Natural Resources on July 25, 1979. The Governor approved and certified the plan to the U. S. Environmental Protection Agency on December 3, 1979.

The adopted regional water quality management plan for southeastern Wisconsin consists of five major plan elements: a land use plan element, a point source pollution abatement plan element, a nonpoint source pollution abatement plan element, a sludge management plan element, and a water quality monitoring plan element. The land use element is the adopted regional land use plan. This plan proposes that urban development be encouraged to occur only in areas that can be readily served by centralized sewerage, water supply, and public transit facilities; that are covered by soils suitable for urban use; and that are not subject to special hazards such as flooding or severe erosion. The plan also proposes that the primary environmental corridors of the Region be preserved in essentially natural, open uses; that prime agricultural lands be maintained in agricultural use; and that the development of subdivisions served by septic tanks and private wells with lot sizes smaller than five acres per dwelling unit be discouraged. This plan element recognizes that the type, intensity, and distribution of rural and urban land uses will determine to a large degree the quality of the surface waters of southeastern Wisconsin.

The point source pollution abatement plan element includes recommendations on the location and extent of sanitary sewer service areas; the location, type, and capacity of sewage treatment facilities and the level of treatment required to meet the recommended water use objectives; the location, configuration, and size of trunk sewers; the abatement of pollution from separate and combined sewer overflows; and the abatement of pollution from industrial waste discharges.

The nonpoint source pollution abatement plan element includes recommendations concerning diffuse sources of water pollution. Diffuse sources include runoff from such urban sources as residential, commercial, industrial, transportation, and recreational land uses, construction activities, and onsite septic tank sewage disposal systems; and from such rural sources as runoff from cropland, pasture, and woodland, atmospheric contributions, and livestock wastes. Recommended controls include a septic tank system management program; a construction erosion control program; improved timing and efficiency of street sweeping, leaf collection, and catch basin cleaning; a livestock waste control program; better management of fertilizer and pesticide application; contour plowing; and conservation tillage. This plan element also recommends that the practices indicated as needed for nonpoint source pollution control be refined and detailed by local level planning.

The sludge management plan element recommends specific processes for each individual major public sewage treatment facility in the Region. Among the recommended sludge management processes are disposal by incineration, land application, fertilizer production, and disposal in landfills. This plan element envisions that the recommendations for each sewage treatment plant will be refined by detailed local studies.

The water quality monitoring plan element sets forth recommendations for the establishment of a sound water quality monitoring program within the Region to determine the extent to which the recommended water use objectives and supporting water quality standards are being met over time. It is recommended that the water quality monitoring program be designed so as to serve the needs of both the Commission as an areawide water quality management planning agency and the Wisconsin Department of Natural Resources as a regulatory agency.

Other Regional and Subregional Work Programs

Additional regional planning programs undertaken by the Commission, all directed toward the preparation of major elements of a comprehensive plan for the physical development of the Region, include, among others: a regional sanitary sewerage system planning program, completed in 1974; a regional airport system planning program, completed in 1976; a regional park, outdoor recreation, and related open space study, completed in 1977; and a regional air quality attainment and maintenance planning program, completed in 1980. All of these plan elements provide data useful to and have implications for the harbor estuary study.

THE MILWAUKEE METROPOLITAN SEWERAGE DISTRICT WATER POLLUTION ABATEMENT PROGRAM

The Milwaukee Metropolitan Sewerage District (MMSD) is a special-purpose unit of government directed by an appointed commission. Geographically, the Milwaukee Metropolitan Sewerage District, as shown on Map 3, includes all of Milwaukee County except the City of South Milwaukee[1]. In addition, sewage conveyance and treatment services are provided by contract to portions of Ozaukee, Racine, Washington, and Waukesha Counties. The primary responsibility of the MMSD is to provide for adequate collection and transmission of domestic, industrial, and other sanitary sewage to and into an areawide trunk and intercepting sewer system, and the subsequent proper treatment of the sewage before discharge to Lake Michigan. The District, which exists pursuant to the provisions of Section 66.88 of the Wisconsin Statutes (Chapter 282, Laws of 1982), has a number of important responsibilities in the area of water resources management.

In order to comply with the requirements of the federal Clean Water Act of 1977 and subsequent court orders and decisions, the MMSD has defined a series of interrelated projects which, although many actually consist of deferred maintenance, are collectively referred to as the Milwaukee water pollution abatement program. The principal elements of this program are:

- A sewer system evaluation survey and subsequent rehabilitation of the sewer system in order to reduce the introduction of excessive levels of clear water from both inflow and infiltration.
- The provision of relief sewers in order to correct wet weather bypassing of the existing separate sanitary sewer system.
- The abatement of combined sewer overflows.
- The rehabilitation and expansion of the Jones Island sewage treatment plant and the improvement and expansion of the South Shore sewage treatment plant.
- The provision of storage facilities to contain peak flow in excess of the capacity of the sewage treatment plants.
- The development of improved methods to process, use, and dispose of waste solids through a solids management program.
- The extension of trunk sewers to serve other communities in the MMSD planning area and thereby reduce septic system failures and eliminate small and inadequate wastewater treatment facilities in such communities.

The MMSD water pollution abatement program shares many significant and interrelated goals with the comprehensive Milwaukee Harbor estuary planning program. As such, both planning programs should be closely coordinated through all phases of development.

The Milwaukee Metropolitan Sewerage District water pollution abatement program includes recommendations to alleviate the pollutant discharges from separate sewer system overflows and provides for the reduction in discharges from the combined sewer system. Overflows from the separate sewer system are planned to be essentially eliminated, while the discharge from the combined sewer system is to be abated. Preliminary plans envision limiting combined sewer overflows to one or two times per year, a so-called six-month to one-year recurrence interval level of protection. The MMSD pollution abatement program has left some questions regarding water quality improvement within the estuary to be answered by this Milwaukee Harbor estuary study. These questions include the level of protection needed for the abatement of pollution from combined sewer overflow, and the need for related measures such as sediment removal to achieve the water use objectives and supporting standards established for the estuary. The water use objectives and supporting standards for the estuary are also to be reevaluated.

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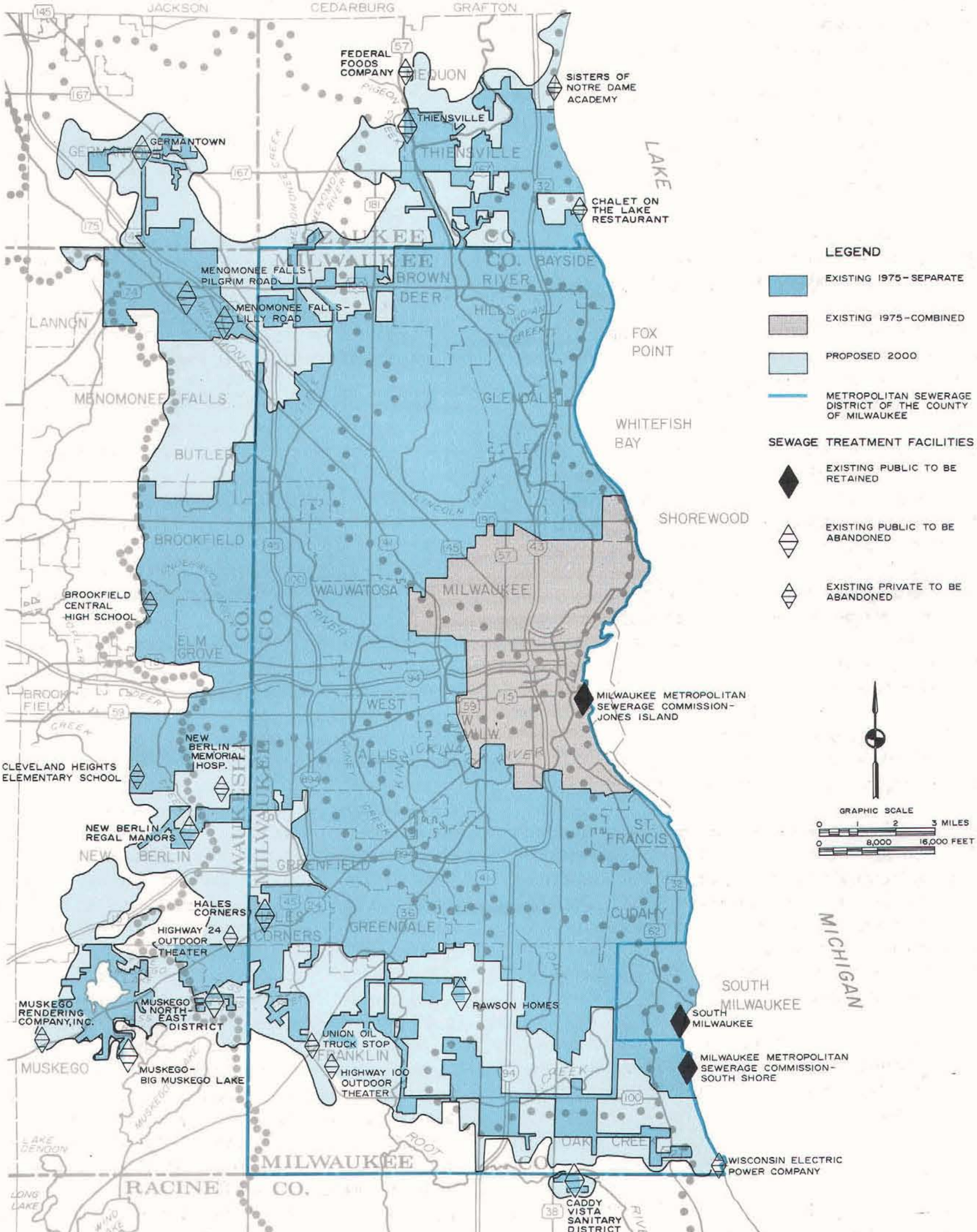
[1] *During 1984, steps were taken by the District to remove certain lands in the southern portions of the cities of Franklin and Oak Creek from the District since those areas were not planned to be provided with sewer service within a ten-year planning period.*

Map 3

MILWAUKEE METROPOLITAN SEWERAGE DISTRICT AND PLANNED CONTRACT SERVICE AREA



The Kinnickinnic, Menomonee, and Milwaukee River watersheds encompass a total area of about 832 square miles, exluding that portion of each watershed lying within the estuary direct drainage area, and contain a combined total of nearly 410 miles of perennial streams. The Commission has completed and adopted comprehensive studies for each of these three watersheds for those stream reaches lying upstream of the Milwaukee Harbor estuary. In 1984, the boundaries of the Milwaukee Metropolitan Sewerage District, which had historically included all of Milwaukee County except the City of South Milwaukee, were adjusted to delete areas in the Southern portion of the Cities of Franklin and Oak Creek which are not expected to be provided with sewer service within a 10-year planning period.

Source: SEWRPC.

With regard to the level of protection from combined sewer overflows needed to meet the water use objectives and supporting standards, it should be noted that the level required may be more or less than envisioned in the preliminary plans. However, if the level of protection is less than that presently planned, the system as now being designed probably will not be changed since the size of the storage component required will then be controlled by needs to store flows from the separate sewer system. Should the level of protection be greater than now planned, the additional storage capacity or other measures will be added to the system following an evaluation of the alternative means of achieving the increased protection in the most cost-effective manner.

THE MILWAUKEE HARBOR ESTUARY PLANNING PROGRAM

In July 1973, the Common Council of the City of Milwaukee formally adopted a resolution requesting the Southeastern Wisconsin Regional Planning Commission to undertake a comprehensive study of the Milwaukee Harbor estuary upon completion of the Kinnickinnic, Menomonee, and Milwaukee River comprehensive watershed studies. This action was taken by the Common Council in an effort to seek ultimate resolution of the serious water pollution problems experienced in the Milwaukee Harbor estuary. The last of the prerequisite watershed studies—that for the Kinnickinnic River watershed—was completed in mid-1978. At that time the Commission was ready to turn its attention to the requested study of the Milwaukee Harbor estuary.

Meanwhile, in July 1977 the Commission's Technical Advisory Committee on Areawide Wastewater Treatment and Water Quality Management Planning recommended that the requested study of the Milwaukee Harbor estuary be expanded to include all six estuaries within the Region, together with that portion of the Region which drains directly to Lake Michigan. The Commission accordingly asked its Technical and Citizens Advisory Committee on Coastal Management in Southeastern Wisconsin, a committee comprised of 29 public officials and citizen leaders from throughout the coastal area of the Region, to assist its staff in the preparation of a prospectus for the requested study. That Committee identified and described five serious water resource-related problems existing within the estuaries of the Region and the watershed tributary thereto, and six serious water resource-related problems existing within the drainage area directly tributary to Lake Michigan. The former include water pollution, flooding and flood damage, harbor dredging and maintenance, public access and recreational needs, and changing land use. The latter include water pollution, bluff failure and shoreline erosion, flooding and flood damage, deterioration and destruction of the natural resource base, public access and recreational needs, and changing land use.

In August 1978, the Commission's Planning and Research Committee approved conceptually the estuary and direct drainage area subwatershed studies as proposed in the draft prospectus. Because of concerns over the attendant costs expressed by representatives of the county boards involved, however, this Committee directed that two separate, scaled-down studies—a Milwaukee Harbor estuary subwatershed study and a shoreline erosion study—be developed as alternatives to the more comprehensive studies initially set forth in the draft prospectus. The prospectus, setting forth the major work elements and attendant costs for both these alternatives, was endorsed by the Commission in September 1978, published, and, in accordance with the advisory role of the Commission, transmitted to the governmental agencies concerned for their consideration and action.

In March 1979, the Common Council of the City of Milwaukee acknowledged receipt of the prospectus and reaffirmed the City's interest in the conduct of a study to resolve the water quality problems of the Milwaukee Harbor estuary. In March 1980, the Wisconsin Department of Natural Resources (DNR) submitted a federal assistance pre-application for a proposed demonstration project entitled "Demonstration of the Resident Pollutant Impact on Milwaukee Harbor Estuary Water Quality." In light of the concerns expressed by the City of Milwaukee and the importance of the Milwaukee Harbor as a major source and location of pollution on Lake Michigan, and in view of the need to better understand the water quality effects of alternative water quality management measures in the watersheds draining to the Milwaukee Harbor estuary, the U. S. Environmental Protection Agency in June 1980 requested the Regional Planning Commission to prepare a study design for a water resources planning and management program for the Milwaukee Harbor estuary. Pursuant to this request, the Commission established the Ad Hoc Technical Task Force for the

Milwaukee Harbor Estuary Study Design, a Committee comprised of 16 public officials, academicians, and citizen leaders, to guide the preparation of the study design. Work on the study design for the Milwaukee Harbor estuary planning program was initiated in July 1980 and completed in September 1981.

In order to accomplish the financing of the study as outlined in the study design, the Milwaukee Metropolitan Sewerage District filed a grant application with the EPA seeking funds under Section 201 of the Clean Water Act of 1977. The MMSD subsequently entered into a contract with the Regional Planning Commission whereby the Commission agreed to undertake the work program detailed in the study design utilizing funds made available through the agreement between the EPA and the MMSD. The Commission also entered into a contract with the U. S. Geological Survey (USGS) wherein the USGS agreed to provide matching funds and services for specific work elements detailed in the study design. Work on the study, as set forth in the study design, began in February 1982.

Need for the Study

As set forth in the prospectus, five major considerations dictated the need for the Milwaukee Harbor estuary study:

1. Measured water pollutant concentrations in the Milwaukee Harbor estuary have been found to be in excess of the water quality standards established by the Wisconsin Department of Natural Resources. Specifically, dissolved oxygen levels, fecal coliform counts, and nutrient concentrations are the water quality indicators which most frequently violate the established standards. Toxic and hazardous substances, such as heavy metals, pesticides, and polychlorinated biphenyls (PCB's), may also violate recommended standards in the Milwaukee Harbor estuary. Turbid water due to high sediment content, oil slicks, unsightly algae mats, and floating debris all attest to the degraded water quality conditions in the Milwaukee Harbor estuary.

2. Flooding has been an increasing problem along the tributary rivers which flow into the Milwaukee Harbor estuary and has resulted from the failure to recognize and understand the relationship between uses of land in and adjacent to the natural floodplains of the rivers and the behavior of the river systems. As the land continues to be developed, covering more porous land surface with impermeable roads, sidewalks, and buildings, the tendency for flooding increases. Many of the upper reaches of the Milwaukee Harbor estuary have been modified to provide an increased hydraulic capacity in response to flood problems. Because urban development and redevelopment continue to occur, however, not only in the watershed directly tributary to the harbor estuary but in the larger tributary watershed areas as well, such actions are but temporary means to reduce and prevent flooding. The long-term abatement of any potential flooding problems within the Milwaukee Harbor estuary can be resolved only within the context of a comprehensive planning program which addresses the interrelationship between potential flooding problems and land uses in the entire estuary watershed.

3. Because the Milwaukee Harbor is situated at the confluence of the Kinnickinnic, Menomonee, and Milwaukee Rivers with Lake Michigan, sediment and polluted material, which the rivers acquire before they flow into the estuary, tend to accumulate on the harbor bottom along with polluted sediments from separate and combined sewer overflows discharged directly into the estuary. Dredging of the harbor floor is thus periodically required to remove this accumulation of sediment. Without this dredging, commercial ships cannot carry full cargo loads because of the shallower waters which must be negotiated. Prior to 1970, the majority of dredged spoils from the Milwaukee Harbor were dumped offshore in the open waters of Lake Michigan. In that year, however, the Wisconsin Department of Natural Resources prohibited the further disposal of polluted spoils in state waters, citing the need for further evaluation of the environmental impacts of dredging and the disposition of spoils on navigation, fish and other aquatic life, water pollution, and the general public interest. Polluted dredged spoils must now be placed within confined disposal facilities. Results of analyses performed on sediment samples collected in the Milwaukee Harbor indicated that all of the samples were polluted. Because confined

disposal facilities represent only a temporary solution to the disposition of polluted spoils, and since maintenance dredging and new work dredging may be expected to increase in the next few years, the development of alternative disposal techniques for polluted dredged materials is an integral part of a comprehensive estuary planning program.

4. The demand for access to Lake Michigan for recreational purposes has been growing and may be expected to continue to grow as the Milwaukee Harbor estuary and tributary areas become increasingly urbanized and as a growing number of people desire to spend some of their recreational time using Lake Michigan. There are three major water-based activities—swimming, boating, and fishing—which require not only suitable water quality, but also land adjacent to the water for access. Existing water quality conditions and the configurations of the existing bulkhead lines and dock walls generally preclude the use of the Milwaukee Harbor estuary for such water contact sports as swimming. The demand for recreational boating on Lake Michigan waters within the Southeastern Wisconsin Region has been forecast to more than double by the year 2000. This increase may be expected to exert great pressures on the existing public access areas to Lake Michigan, particularly in the highly urbanized Milwaukee Harbor estuary. The demand for public access facilities, including improved recreational boat-launching sites and marina slips, can best be addressed in the context of a comprehensive estuary planning program. Moreover, such a planning program can best determine how the Milwaukee Harbor estuary can contribute toward the demand for sport fishing. This estuary does not presently meet, to any significant degree, the existing demand for sport fishing since the fishery resources are quite limited as a result of unfavorable habitat conditions imposed by water pollution and channel modifications. A comprehensive water resources management plan for the Milwaukee Harbor estuary, therefore, is needed to provide for the maximum utilization of this estuarial environment in order to meet the existing and anticipated demand for water-related recreational activities such as boating and sport fishing.

5. Severe storms over Lake Michigan have caused anchorage and navigation problems, as well as shoreline protection problems, in the outer harbor. Storm damage in the Milwaukee Harbor has been caused in part by waves associated with wind set-up and wave reflection, strong oscillating currents associated with harbor surge, and wind-blown spray from breaking waves. Piers and pleasure craft in the McKinley Marina have been damaged periodically by wave action. The strong oscillating currents and standing waves in commercial slips in the outer harbor periodically make mooring conditions unsafe and have even caused the sinking of a ship, the bulk cargo carrier E. M. Ford, in 1979. A severe storm in 1973, with wave heights of up to 13 feet, washed out the revetment protecting the Summerfest grounds, and damaged pierside buildings and the Jones Island wastewater treatment plant. A comprehensive planning program for the Milwaukee Harbor estuary would provide the best means for addressing the problems of storm damage and shoreline protection in the outer harbor area.

Study Objectives

The primary objective of the Milwaukee Harbor estuary study is to develop a sound and workable plan for the abatement of water pollution within the Milwaukee Harbor estuary so as to meet established water use objectives and supporting water quality standards in a cost-effective manner, and so as to further the protection and wise use of the natural resource base. Attendant to this primary objective is the need, as already noted, to determine the degree to which combined sewer overflow should be diverted to temporary storage facilities in order to provide a specifically defined level of protection against the occurrence of such overflows and the attendant pollution of the Milwaukee Harbor Estuary. The secondary objective of the estuary study is the development of measures to abate damage caused by flooding; to provide for the navigation of deep draft commercial vessels through a maintenance dredging program which ensures the environmentally safe disposal of polluted spoils; to ameliorate damage in the harbor area caused by storm and wave action, and to prevent deterioration of the shoreline within the estuary; and to maximize the utilization of the estuary as a prime urban recreational area. To be effective, the plan must be amenable to cooperative adoption and joint implementation by all levels and agencies of government concerned. It must be capable of functioning as a practical guide to decision-making concerning water resource development within the estuary so that, through such implementation, the major water resource and water-related resource problems within the estuary may be abated and the full development potential of the estuary realized.

More specifically, the objective of this planning program is to prepare a plan which will assist in:

1. The control of public and private point and nonpoint sources of water pollution to ameliorate pollutant loadings to the estuary.

2. The identification and *mitigation* of flood problems within the estuary.

3. The implementation of harbor maintenance dredging activities, and the environmentally safe disposal of polluted spoils, for both water quality enhancement and commercial navigation purposes.

4. The implementation of control measures designed to abate storm damage problems in the Milwaukee Harbor, including shoreline protection measures, in order to ensure safe navigation and anchorage facilities.

5. The maximum utilization of the Milwaukee Harbor estuary as a prime urban recreational area, particularly for boating and sport fishing activities.

Staff, Cooperating Agency, Consultant, and Committee Structure

The basic organizational structure for the Milwaukee Harbor estuary planning program is outlined in Figure 2. As the agency responsible for comprehensive regional planning in southeastern Wisconsin, and as the formally designated areawide water quality management planning agency for southeastern Wisconsin, the Southeastern Wisconsin Regional Planning Commission accepted primary responsibility for the conduct of the Milwaukee Harbor estuary planning program. Commission staff work under this program was centered in the Environmental Planning Division and supplemented primarily by work performed by the Land Use, Planning Research, and Data Processing Divisions.

As indicated in Figure 2, the Commission staff responsibilities in the Milwaukee Harbor estuary planning program include: the organization of the study; the development of objectives and standards; the collation and review of meteorologic, hydrologic, water quality, biological, storm damage, and sedimentation and dredging data and studies; the collation of inventories of water resources management institutions and sources of pollution; the preparation of forecasts of change and development in the estuary and tributary watersheds; concurrent water quality management efforts; plan design, test, and evaluation; and final report writing.

Figure 2 also indicates the cooperative functions of the agencies actively participating in the Milwaukee Harbor estuary planning program. The U. S. Geological Survey had principal responsibility for streamflow monitoring, surface water quality monitoring during designated storm events, suspended sediment monitoring, groundwater quality sampling and monitoring, water level monitoring within the inner and outer harbors, and a hydraulic modeling effort for the inner harbor.

The Milwaukee Metropolitan Sewerage District had principal responsibility for surface water quality monitoring of the estuary and its tributary rivers, and of the Jones Island wastewater effluent; laboratory analyses of water quality samples collected by MMSD and the USGS; meteorological data collection in the study area; and, most importantly, bottom sediment sampling and associated laboratory analyses.

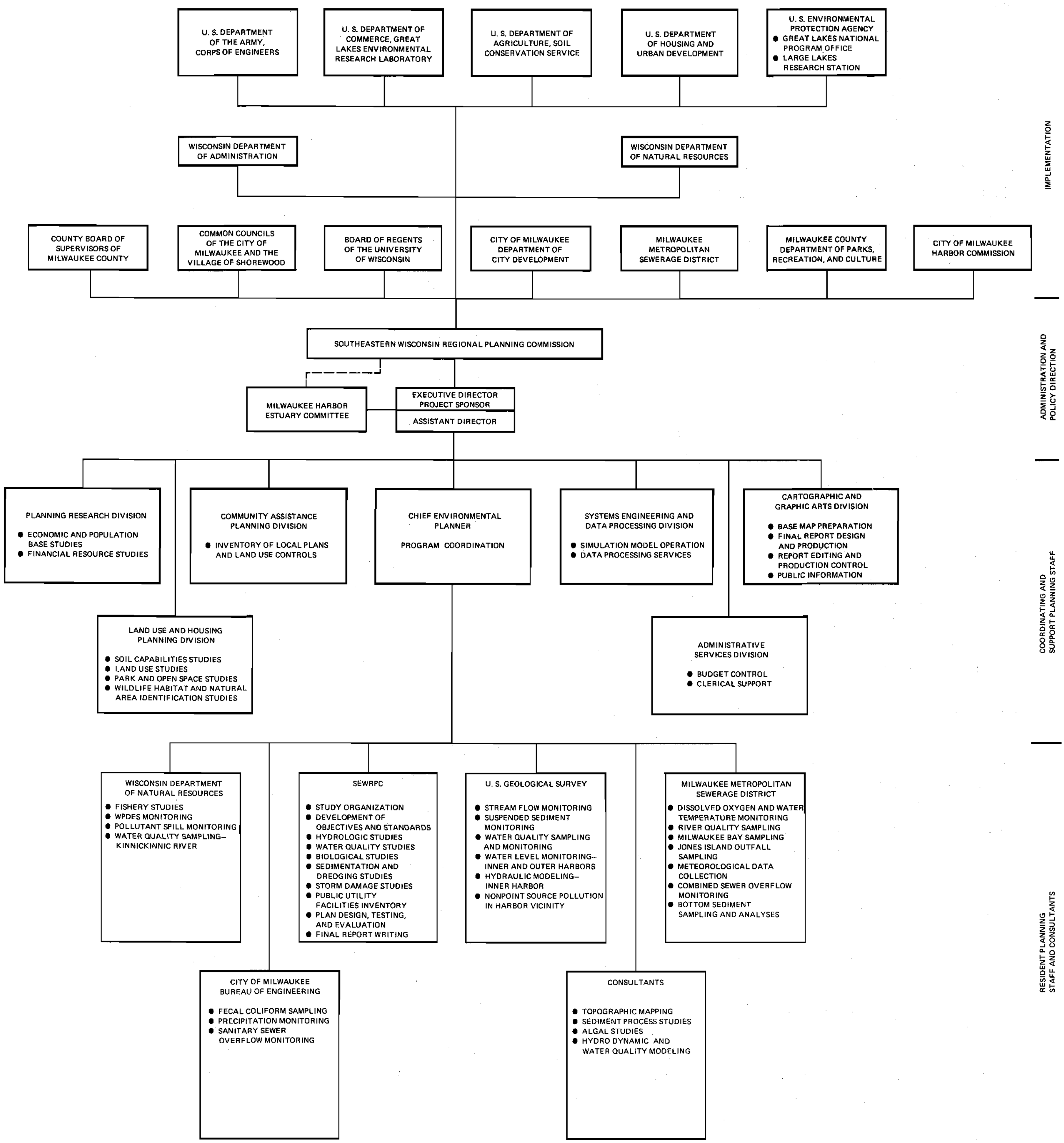
The Wisconsin Department of Natural Resources, under contract, was responsible for the fishery studies.

Figure 2 also specifies the consultants retained to supplement Commission staff skills in certain specialized work efforts. For the purpose of the Milwaukee Harbor estuary planning program, the firms of Aero-Metric Engineering, Inc., and National Survey & Engineering, Inc., were selected to conduct the topographic mapping and attendant control survey work.

The sediment process studies, the algal studies, and the hydrodynamic and water quality modeling work efforts were conducted by HydroQual, Inc., of Mahwah, New Jersey.

Figure 2

ORGANIZATIONAL STRUCTURE FOR THE MILWAUKEE HARBOR ESTUARY COMPREHENSIVE WATER RESOURCES PLANNING STUDY



Source: SEWRPC.

A comprehensive study of the Milwaukee Harbor estuary and its tributary watersheds encompasses a broad spectrum of related governmental and private development programs, and, thus, no single agency, whatever its function or authority, can operate independently in the conduct of such a study. The basic Commission organization provides for the attainment of the necessary interagency coordination and lay citizen advisory function through the establishment of advisory committees, as well as through interagency staff assignments. For the Milwaukee Harbor estuary planning program, one committee was created after careful deliberation to provide for the active participation of governmental bodies, technical agencies, the academic community, and knowledgeable citizen leaders.

The function of the Technical Advisory Committee for the Milwaukee Harbor Estuary Comprehensive Water Resources Management Plan, hereafter referred to as the Milwaukee Harbor Estuary Committee, is to provide technical guidance in the many areas of science and engineering needed in the conduct of this comprehensive study; to place at the disposal of the program the experience, knowledge, and resources of the represented federal, state, and local agencies having responsibilities for initiating and administering water resources management programs; and to provide the overall technical policy direction for the program. In addition, the Committee members act to familiarize local elected officials with the study and its findings and recommendations, and to generate an understanding of the study objectives, the plan recommendations, and the plan implementation procedures among such officials. The Committee has a particularly important role in selecting the final plan and assuring its financial and administrative feasibility. The full membership of this Committee is set forth in Appendix A.

SCHEME OF PRESENTATION

The major findings and recommendations of the Milwaukee Harbor estuary planning program are presented in a two-volume report. This, the first volume of the report, sets forth the basic principles and concepts underlying the planning program, and presents the salient findings of the program inventories and analyses. Separate chapters present data on the socioeconomic and natural resource base of the Region; the hydrologic and hydraulic characteristics of the Milwaukee Harbor estuary; and the water resources monitoring efforts which have been already conducted in the harbor area and its tributaries. Also included in Volume One is a summary description of the historical and existing water resource problems within the estuary and its tributaries, and an overview of the potential sources of water pollution in the study area.

Volume One concludes with a review of the water resource simulation models and other analytical techniques which have been used extensively during this planning effort.

The second volume of this report addresses anticipated growth and change in the Milwaukee Harbor estuary and tributary areas, and will present the objectives, principles, and standards underlying the development of the recommended plan. The second volume also describes alternative water quality management plans, alternative dredging and spoils disposal plans, and alternative storm damage protection and flood control plans. The second volume thus provides a basis for the selection of a final comprehensive plan from among the various alternative water resource management components evaluated. The second volume, therefore, also details the final comprehensive water resource management plan for the Milwaukee Harbor estuary and its tributary areas recommended for adoption and implementation.

This report is intended to allow for careful, critical review of potential water resource management strategies in the Milwaukee Harbor estuary by public officials, agency staff personnel, and citizen leaders within the Region, and to provide the basis for plan implementation by the federal, state, and local agencies of government concerned. This report, however, can only summarize in brief fashion the large volume of information assembled in the extensive data collection, analysis, and forecasting phases of the Milwaukee Harbor estuary planning program. The reproduction of all of this material in report form is prohibitive because of the complexity and magnitude of the material involved. All of the basic data are on file in the Commission offices, and are available at cost to member units and agencies of government and the public in general upon specific request. This report, therefore, serves the additional purpose of indicating the type of data available from the Commission which may be of value in assisting federal, state, and local units of government and private investors in making more advised decisions concerning physical development within the Region.

Chapter II

BASIC PRINCIPLES AND CONCEPTS

INTRODUCTION

The Commission has conducted comprehensive water and water resource-related planning efforts for almost two decades. During this period, the regional sanitary sewerage system and the areawide water quality management planning programs, seven individual watershed studies, and six inland lake studies have all contributed to the advancement and refinement of the comprehensive water resource management planning principles and practices first developed by the Commission in the early 1960's. Planning for the preservation and enhancement of the estuarial environments in the Region represents a logical extension of these historic water resource management planning efforts, and a continuing recognition on the part of the Commission of the importance of this valuable resource to the social and economic development of the Region.

Although the hydraulics of the estuarial systems present a particularly complex planning and engineering problem because of the complex physical interactions of Lake Michigan waters with the tributary river waters, solutions to the broader problem of overall water resource management in the Milwaukee Harbor estuary may be achieved following an approach similar to that used in the development of the areawide water quality management and comprehensive watershed studies. This approach can only be explained in terms of the conceptual relationships existing between water resources planning and regional planning, and the basic principles applicable to water resources planning set within the context of comprehensive regional planning. Only after this foundation of conceptual relationships and applicable principles has been established can the specific problems of the Milwaukee Harbor estuary and the recommended solution to these problems, as presented herein, be properly understood.

Accordingly, this chapter discusses the basic concepts underlying the comprehensive water resources management planning program for the Milwaukee Harbor estuary, sets forth the basic planning problem involved, describes the basic principles upon which the estuary planning effort was conducted, and describes the basic planning process followed in conducting the Milwaukee Harbor estuary study.

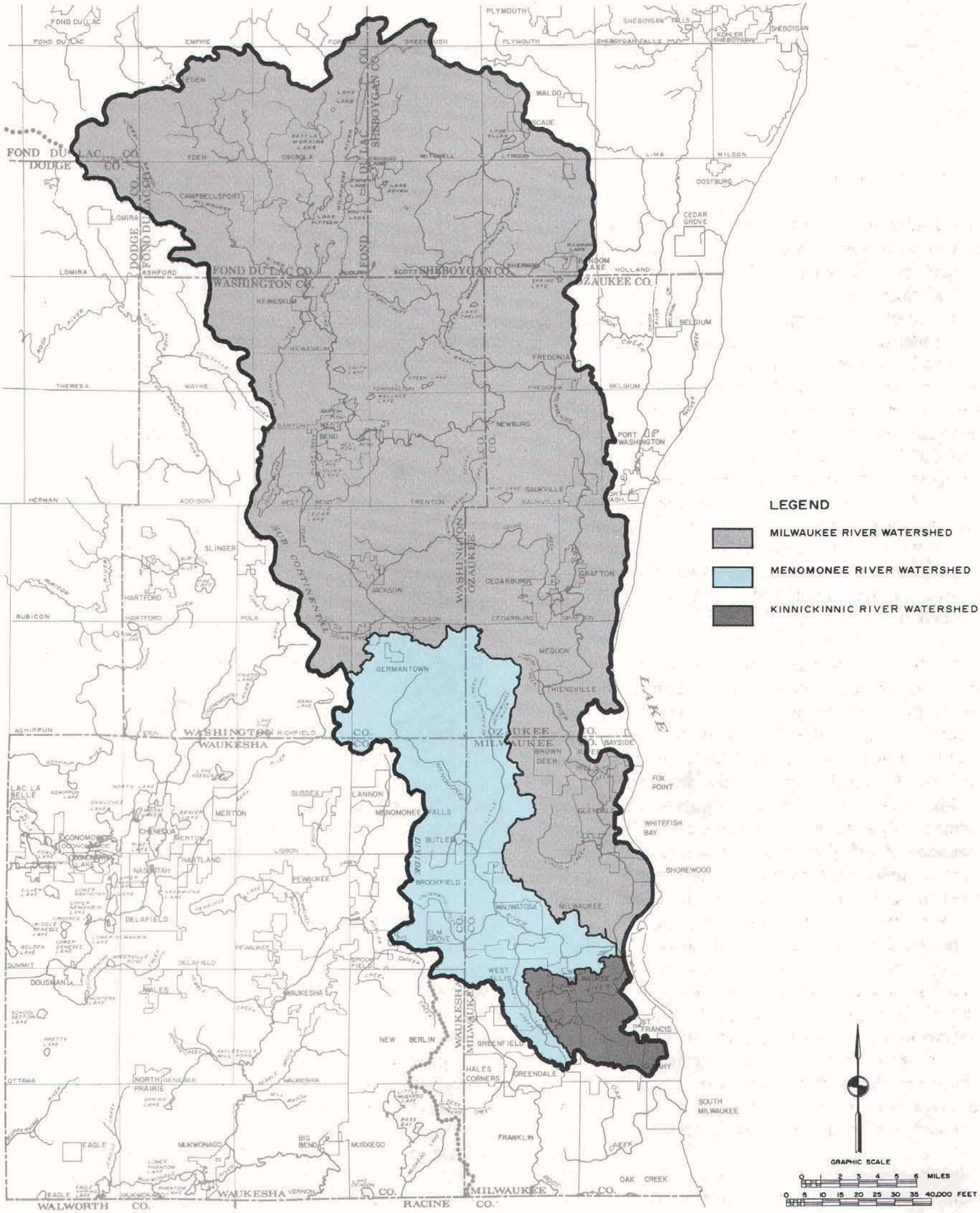
THE GEOGRAPHIC PLANNING UNIT

The Commission has historically favored the use of the watershed as the basic geographic planning unit for water and water-related resource planning efforts, since the watershed, as a natural, physical entity, provides a more rational areal unit for water resource planning than an area defined by governmental jurisdictions or other artificial delineations. Floodland management, flood control, and stormwater drainage problems can best be addressed on a watershed basis. Moreover, while water supply and sewerage frequently involve problems that transcend watershed boundaries, such problems have strong watershed implications if the source of the water supply comes from the surface or shallow groundwater resources of the watershed, or if point and nonpoint sources discharge pollutants into the surface water system. Watersheds also provide the geographic basis for the Milwaukee Harbor estuary planning effort since the problems that must be addressed in a comprehensive study of the estuary are all influenced by the hydrologic, hydraulic, and land use characteristics of the three tributary watersheds which flow into the estuarial waters.

As noted in Chapter I, the Commission has completed and adopted comprehensive studies of the Kinnickinnic, Menomonee, and Milwaukee River watersheds. The areal extent of these three watersheds is indicated on Map 4. With the exception of the flood control and floodland management plan components, however, each of these three watershed studies addressed only those stream reaches lying upstream of the Milwaukee Harbor estuary boundaries. This was because, from a physical standpoint, the hydraulic characteristics and behavior of the three tributary streams above the location where they enter the estuary are distinctly different from, and considerably less complex than, the hydraulic characteristics and behavior of the estuary area. Rivers upstream of the estuary are

Map 4

THE MENOMONEE, MILWAUKEE, AND KINNICKINNIC RIVER WATERSHEDS



The Kinnickinnic, Menomonee, and Milwaukee River watersheds encompass a total area of about 832 square miles, excluding that portion of each watershed lying within the estuary direct drainage area, and contain a combined total of nearly 410 miles of perennial streams. The Commission has completed and adopted comprehensive studies for each of these three watersheds for those stream reaches lying upstream of the Milwaukee Harbor estuary.

Source: SEWRPC.

marked by essentially continuous, downstream flow, and, while discharging to the estuary, are basically unaffected by Lake Michigan water levels. In contrast, the estuary portion of each of the three tributary rivers exhibits frequent rapid flow reversals and stage fluctuations, thermal stratification and related currents, and periods of relative calm, all of which are largely attributable to the intimate hydraulic connection between the estuary and Lake Michigan. It is evident, therefore, that, although the three tributary rivers have an influence on the water resources of the Milwaukee Harbor, the estuary itself comprises a distinct planning unit because of its hydraulic interconnection with Lake Michigan.

Irrespective of the hydraulic distinctions and physical delineations between the Milwaukee Harbor estuary and its tributary rivers, there is a tributary drainage area common to, and part of, the estuary and the three watersheds which is defined by unsewered areas and areas served by the storm and combined sewer systems that discharge directly to the estuary. Within portions of this direct drainage area, stormwater runoff from streets, buildings, and other impervious surfaces is channeled into storm sewers which discharge into the estuarial waters. Other portions of this direct drainage area are served by combined sewers which, during most runoff events, discharge a portion of the flow directly into the estuarial waters. Areas unsewered because of proximity to existing receiving water bodies shed stormwater runoff in the form of sheet flow or by way of artificial or natural surface swales and channels.

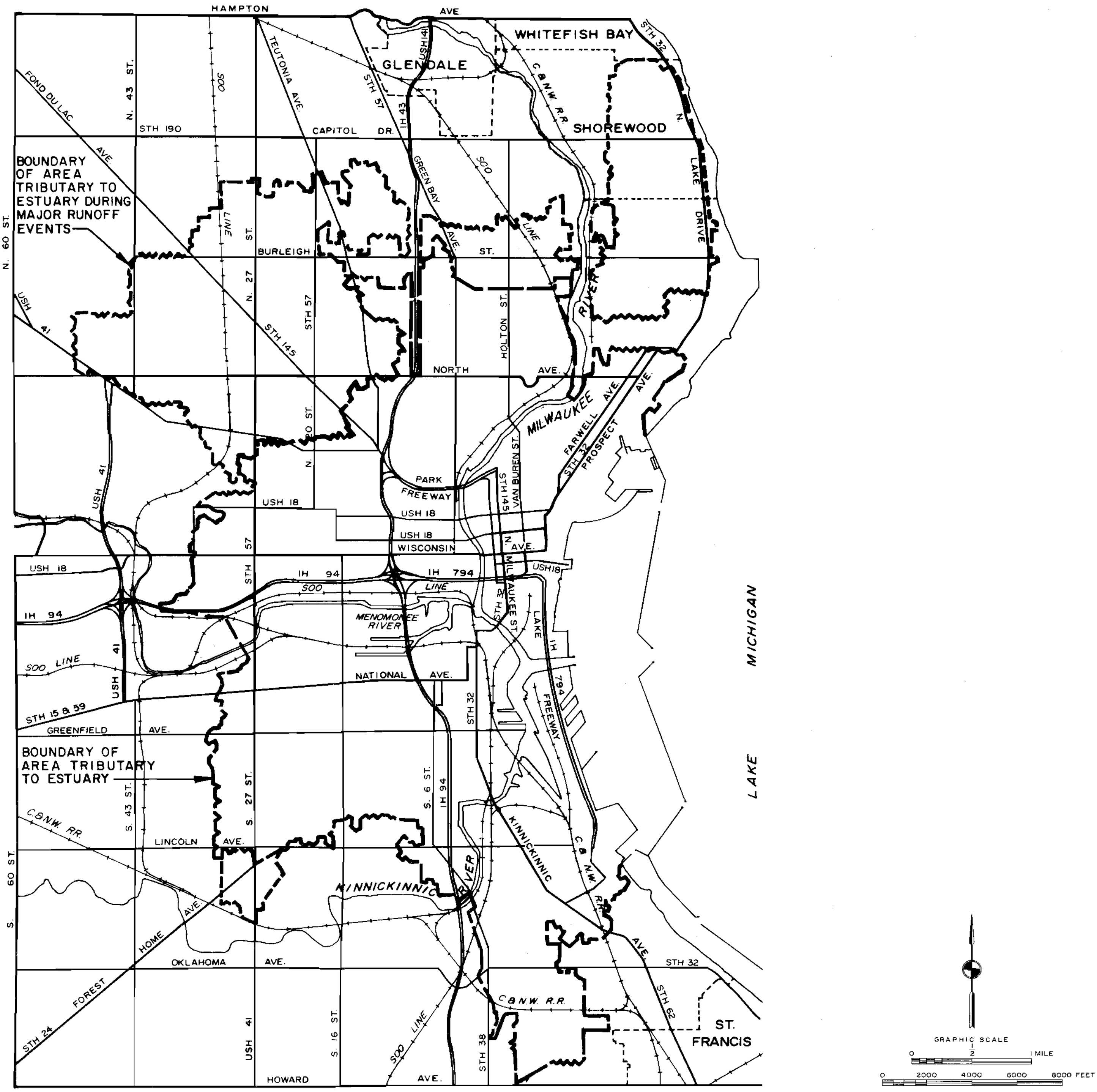
The direct drainage area to the Milwaukee Harbor estuary is shown on Map 5. As may be seen on this map, the separate sewer and combined sewer service areas discharge predominantly to the estuarial waters within the inner harbor. Map 5 also indicates, however, that the southeastern portion of the direct drainage area discharges into the outer harbor. It should be noted that Map 5 identifies portions of the direct drainage area from which surface water runoff entering combined storm and sanitary sewers may be discharged from outfalls located both above and below the upstream boundary of the estuary during runoff events. The proportion of stormwater runoff and combined sewer overflow from these areas contributing to each outfall's discharge is dependent upon both the configuration of the sewer system in each subarea and the runoff event. Since these areas do contribute combined sewer overflows to the estuary at least during some runoff events, and thus directly influence water quality in the estuary, they have been included within the defined limits of the Milwaukee Harbor estuary direct drainage area, but have been designated as being partially tributary to the estuary and partially tributary to the river system above the estuary. In total, the direct drainage area to the Milwaukee Harbor estuary encompasses 22.2 square miles, of which 20.7 square miles, or about 93 percent, drains to the inner harbor, and 1.5 square miles, or about 7 percent, drains to the outer harbor. Because the stormwater and combined sewer discharges to the inner and outer harbors could have significant environmental impacts, particularly with respect to water pollution, the direct drainage area to the Milwaukee Harbor estuary requires special consideration in any comprehensive study of the estuary.

It is important to make a physical distinction between the boundaries of the Milwaukee Harbor and the boundaries of the estuary itself. The Milwaukee Harbor includes the outer harbor area—from the breakwater to the shoreline, excluding the anchorage area protected by the offshore breakwater south of E. Lincoln Avenue extended—and the inner harbor area—which includes those lower reaches of the Kinnickinnic, Menomonee, and Milwaukee Rivers that are maintained to depths which will accommodate navigation by deep draft commercial vessels. The inner harbor is thus bounded by the Becher Street bridge on the Kinnickinnic River, S. 25th Street on the Menomonee River, and Buffalo Street extended on the Milwaukee River. The Milwaukee Harbor estuary itself includes the 3.1-mile reach of the Milwaukee River below the North Avenue dam, the 2.2-mile reach of the Menomonee River below the Falk Corporation dam, and the 2.4-mile reach of the Kinnickinnic River below the Chase Avenue bridge along with the outer harbor to the breakwater structure. Thus defined, the Milwaukee Harbor estuary, as shown on Map 6, has a total length of stream of 9.15 miles, and a total surface water area of approximately 1,630 acres, or about 2.55 square miles.

Table 1 indicates the total stream length and size of the direct drainage area to the Milwaukee Harbor estuary and its three tributary watersheds. As may be seen in this table, the estuary drainage area encompasses about 3 percent of the total direct drainage area of this surface water system.

Map 5

THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA

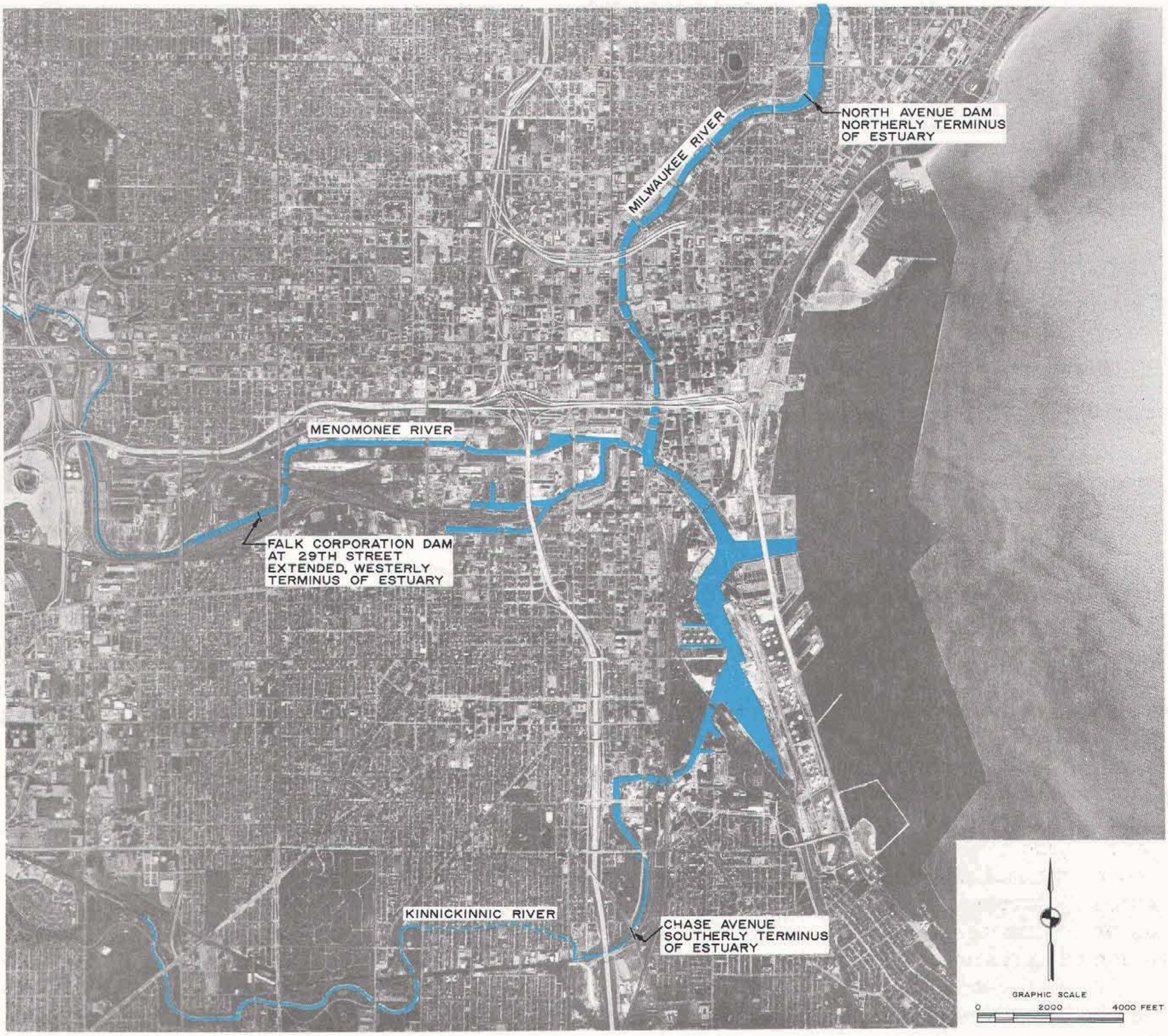


The Milwaukee Harbor estuary direct drainage area is defined by unsewered areas and areas served by the storm and combined sewer systems that discharge directly to the estuary during major precipitation or snowmelt events. The direct drainage area encompasses a total area of 22.2 square miles, of which 20.7 miles, or about 93 percent, drains to the inner harbor, and 1.5 square miles, or about 7 percent, drains to the outer harbor.

Source: SEWRPC.

Map 6

THE MILWAUKEE HARBOR ESTUARY



The Kinnickinnic, Menomonee, and Milwaukee Rivers join in the Lake Michigan estuary and harbor within the City of Milwaukee before discharging to Lake Michigan. The northerly terminus of the estuary is 3.1 miles up the Milwaukee River at the North Avenue dam, the westerly terminus 2.2 miles up the Menomonee River at the Falk Corporation dam, and the southerly terminus 2.4 miles up the Kinnickinnic River at Chase Avenue. The estuary portions of these tributary rivers exhibit frequent rapid flow reversals and stage fluctuations, thermal stratification and related currents, and periods of relative calm, all of which are largely attributable to the intimate hydraulic connection between the estuary and Lake Michigan.

Source: SEWRPC.

It should be noted that the Milwaukee Harbor estuary direct drainage area represents more than a geographic unit contributing surface runoff to a particular body of water. This area, with its complex land use pattern and related physical problems, can also provide a basis for the creation of a community of interest among not only those who live, work, and shop in the area, but the numerous existing and potential recreational, commercial, and industrial users of the estuary. One of the factors which can contribute to the success of the planning process is a community of interest around which to organize enlightened citizen participation.

Table 1

TOTAL STREAM LENGTH AND TOTAL DIRECT DRAINAGE AREA OF THE MILWAUKEE HARBOR ESTUARY AND ITS TRIBUTARY WATERSHEDS

Watershed	Total Perennial Stream Length		Total Direct Drainage Area	
	Miles	Percent	Square Miles	Percent
Milwaukee Harbor Estuary.	9.15	2.18	22.18	2.60
Kinnickinnic River[a].	15.72	3.75	20.46	2.39
Menomonee River[b]	64.95	15.50	132.13	15.47
Milwaukee River[c]	329.10	78.57	679.59	79.54
Total	418.92	100.00	854.36	100.00

[a]*Excludes the 2.4-mile stream reach and associated direct drainage area below the Chase Avenue bridge.*

[b]*Excludes the 2.2-mile stream reach and associated direct drainage area below the Falk Corporation dam.*

[c]*Excludes the 3.1-mile stream reach and associated direct drainage area below the North Avenue dam.*

Source: SEWRPC.

RELATIONSHIP OF THE MILWAUKEE HARBOR ESTUARY STUDY TO THE REGIONAL PLANNING PROGRAM

Important elements of a comprehensive, areawide plan have been provided by several regional programs, including the regional land use and transportation planning programs, the regional sanitary sewerage system planning program, the areawide water quality management planning program, and the regional air quality management planning program. Conversely, within the context of the regional planning program, the comprehensive watershed planning programs completed to date provide, within the limits of each watershed, plans for flood control and water quality maintenance and enhancement. Estuary planning programs, as an adjunct to and extension of watershed studies, can provide an additional component of this long-range plan. While the proposed estuary plans may be focused primarily on water quality management measures, it must be recognized that these measures must be prepared in consideration of the related problems of land and water use and park and open space preservation needs. Recognition of the need to relate water quality management measures and water control facility plans to areawide regional development plans is the primary factor which makes the Commission water resources planning efforts unique. Ultimate completion of planning studies covering all of the watersheds and all of the estuaries within the Region will provide the area with an integrated framework of plans encompassing drainage, flood control, and water pollution control facilities as well as floodland management measures properly related to comprehensive, areawide development plans. These studies will make significant contributions to a framework of regional community facility plans for parks and related open spaces and for water supply and sewerage facilities.

THE ESTUARY PLANNING PROBLEM

Although the water-related resource planning efforts of the Commission are focused on the watershed as a rational planning unit, the watershed planning problem is closely linked to the broader problem of protecting, maintaining, and enhancing the overall quality of the environment in urban and urbanizing areas. Historically, environmental protection, or what was once more commonly termed "conservation," was largely concerned with protecting and preserving in open, natural uses, large tracts of land in both rural and urban areas. This concern was based upon the destruction of natural resources, such as the destruction of soils through erosion, and the possible shortage of essential minerals or other necessary raw materials such as timber as a result of chronic mismanagement. The major problem which environmental protection now faces is occasioned by the ever-increasing areawide diffusion of urban development over large areas of the earth's surface, together with the relentless pursuit of an ever higher material standard of living.

Within the Region the estuarial areas generally represent the older, more developed centers of the urban environment, since it was around the estuaries that early settlements were founded and initial commercial and industrial activities established, and since subsequent urban expansion progressed outward from these areas. Enlightened public officials and citizen leaders have become aware of the pressing need to protect and enhance the physical environment in such older urban areas. The need to adjust the physical fabric of urban development to the ability of the underlying natural resource base to sustain such development is critical in intensively urbanized areas such as the Milwaukee Harbor estuary. In such urbanized areas, as opposed to the more sparsely settled rural watersheds, the overall quality of the environment becomes highly dependent on present and future land use activities and supporting public facilities, and the viable options remaining for environmental protection and enhancement are limited.

BASIC PRINCIPLES

Based upon the foregoing considerations, five basic principles were developed as a basis for the conduct of the Milwaukee Harbor estuary study. These principles are:

1. Planning for the enhancement and preservation of the water and water-related resources in the Milwaukee Harbor estuary must be conducted within the framework of the broader regional planning effort. The development objectives for the estuary must be compatible with regional development objectives and with the evolving comprehensive regional plan based on those objectives, particularly as the plan and objectives relate to the tributary watersheds.

2. Planning for the use of water and water-related resources in the Milwaukee Harbor estuary must recognize the existence of a limited natural resource base to which demands for various land and water uses must be adjusted to ensure a pleasant, functional, and habitable environment.

3. The Milwaukee Harbor estuary can best be considered in five separate but interrelated and overlapping subsystems: the inner harbor; the outer harbor; the estuary subwatershed, including areas served by separate storm sewers and by combined storm and sanitary sewers which drain directly to the estuary during rainfall and snowmelt events; the near-shore unsewered direct drainage area; and the tributary river watersheds. While the estuary planning process must focus on the parts of the whole—that is, on the five subsystems—the interrelationships between those subsystems must always be considered to develop an integrated plan for the entire system.

4. Identification and quantification of the physical processes and phenomena operating in the Milwaukee Harbor estuary are essential to the assessment of the causes of environmental and development problems in the estuary and to the achievement of practicable and lasting solutions to those problems. Many of the environmental and development problems in the estuary are a direct result of actions taken in conflict with, or in ignorance of, these natural processes and phenomena. The natural processes and phenomena occurring in the Milwaukee Harbor estuary are extremely complex and exhibit almost continuous temporal variation, operating within a time frame that varies from seconds to thousands of years. The identification and quantification of such processes and phenomena in the Milwaukee Harbor estuary are also necessary to ensure that seemingly beneficial actions taken to ameliorate existing problems in the short term do not provide potentially adverse effects in the long term.

5. Planning for the amelioration of water and water-related resource problems in the Milwaukee Harbor estuary should seek flexible solutions which provide latitude for continued adaption to changing conditions.

THE ESTUARY PLANNING PROCESS

Based upon the foregoing principles, the Commission developed a seven-step planning process by which the principal functional relationships existing within an estuary can be accurately described, both geographically and numerically; the hydrologic, hydraulic, and water quality characteristics of the estuary simulated; and the effect of different courses of water resource management actions evaluated. The estuary planning process not only provides for the integration of all the complex planning and engineering studies required to prepare a comprehensive estuary plan, but also provides a means whereby the various private and public interests concerned may actively participate in the plan preparation. The process thus provides a mechanism for resolving actual and potential conflicts between such interests; a forum in which the various interests may better understand the interrelated problems of the watershed and the alternative solutions to such problems; and a means whereby all estuary interests may become committed to implementation of the best alternative for the resolution of the problems.

The seven steps involved in the planning process are: 1) study design, 2) formulation of objectives and standards, 3) inventory, 4) analysis and forecast, 5) plan synthesis, 6) plan testing and evaluation, and 7) plan selection and adoption. Plan implementation, although necessarily beyond the foregoing planning process, must be considered throughout the process if the plans are to be realized.

The principal results of the above process are water and water-related resource management plans scaled to future resource demands and consistent with regional development objectives. In addition, the process represents the beginning of a continuing planning effort that permits modification and adoption of plans and a means of adaptation to changing conditions. Each step in this planning process includes many individual operations which must be carefully designed, scheduled, and controlled to fit into the overall process. An understanding of this planning process is essential to an appreciation and understanding of the results. Each step in the planning process, together with its major component operations, is diagrammed in Figure 3 and described briefly below.

Study Design

Every planning program must include a formal structure or study design so that the program can be carried out in a logical and consistent manner. This study design must specify the content of the fact-gathering operations, define the geographic area for which data are to be gathered and plans prepared, outline the manner in which the data collected are to be processed and analyzed, specify requirements for forecasts, and define the nature of the plans to be prepared.

The need for, and objectives of, the Milwaukee Harbor estuary study were set forth in the Lake Michigan Estuary and Direct Drainage Area Subwatersheds Planning Program Prospectus which was completed in September 1978. This prospectus was followed by a Study Design for the Milwaukee Harbor Estuary Comprehensive Water Resources Planning Program, completed in September 1981. This study design set forth a more detailed description of the major work elements of the study, defined the analytical tools to be used, and detailed the time frame within which the study was to be conducted.

The staff of the Southeastern Wisconsin Regional Planning Commission expanded upon and refined this study design, as necessary, during the course of the study as a result of continuous staff level communication with those governmental agencies and private consultants contributing certain specialized services to the planning program, and with the Advisory Committee to the study.

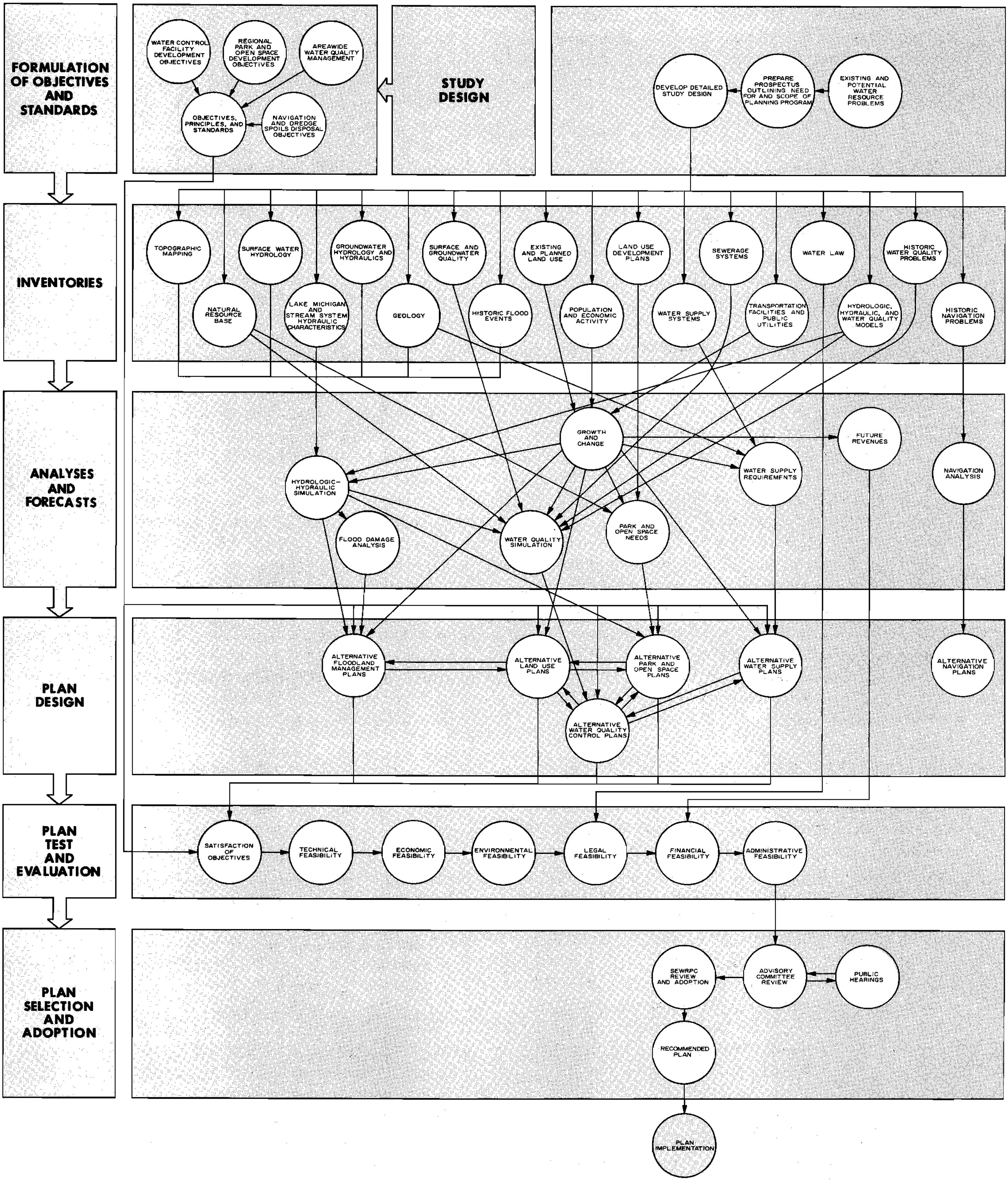
Formulation of Objectives and Standards

In its most basic sense, planning is a rational process for establishing and meeting objectives. It is essential, therefore, that objectives be formulated before plans are prepared. In order to be useful in the estuary planning process, the objectives not only must be clearly stated and logically sound, but must also be related in a demonstrable way to alternative physical development proposals. Only if the objectives are clearly related to physical development and subject to objective test and evaluation can a choice be made from among alternatives of a plan which best meets the agreed-upon objectives. Finally, logically conceived and well-expressed objectives must be translated into detailed design standards to provide the basis for plan preparation, test, and evaluation. Because the formulation of objectives and standards involves both technical and nontechnical policy determinations, all objectives and standards were carefully reviewed and adopted by the Milwaukee Harbor Estuary Committee and by the Commission.

The objectives and standards for the Milwaukee Harbor estuary planning program ranged from general water and water-related resource management objectives to specific design criteria or proce-

Figure 3

GENERAL STEPS IN A COMPREHENSIVE WATERSHED PLANNING PROGRAM



Source: SEWRPC.

dures for solutions to such problems as floods, storm damage, and shoreline erosion. Most of the objectives were extensions of the objectives set forth in previous watershed studies, the areawide water quality management program, and the park and open space planning program.

Inventory

Reliable planning and engineering data collected on a uniform basis are essential to the formulation of workable water resource management plans. Consequently, the conduct of inventories growing out of the study design becomes the first operational step in any planning process. The crucial need for factual information in the planning process should be evident, since no intelligent forecasts can be made or alternative courses of action selected without knowledge of the historic and current state of the system being planned.

The sound formulation of a comprehensive estuary water resources management plan requires that factual data be developed on topographic features, the quantity of surface- and groundwater, precipitation, hydrologic characteristics of the tributary watersheds and Lake Michigan, hydraulic characteristics of the estuarial system, historic flooding, flood and wave damages, water quality, aquatic flora and fauna, wastewater sources, water use, soil capabilities, land use, economic activity, population, recreational facilities, fish and wildlife habitat, unique natural areas, historic sites, water supply and sewerage systems and other public utilities, and water law.

In the Milwaukee Harbor estuary study, data collection efforts included a review of the water resource-related literature; perusal of agency files, particularly files available from the City of Milwaukee and the Milwaukee Metropolitan Sewerage District; original field investigations, particularly involving determination of the physical and chemical characteristics of the estuarial and tributary stream waters and sediments; and exchange of information through interagency staff meetings and committee meetings of staff and technical advisors. Extensive use was also made of the regional planning data base already available through the ongoing comprehensive planning efforts of the Commission.

Analysis and Forecasts

Inventories provide factual information about historic and existing conditions, but analyses and forecasts are necessary to estimate and evaluate future conditions, particularly with regard to the need for sanitary sewerage facilities, stormwater management systems, and commercial and recreational harbor facilities. Future needs must be determined from a sequence of interlocking forecasts. Economic and population forecasts provide estimates of the probable growth in the Region, estimates which can then be translated into future water and water-related resource demands and the attendant impact on water quality. These demands can be scaled against the existing water quality and water-related resource supply, and plans formulated to meet the deficiencies.

Careful analyses of many interrelated factors were required in order to determine future demands on the water resources of the Milwaukee Harbor estuary. Among the factors analyzed were precipitation characteristics; the relationships between precipitation events and storm sewer, combined sewer, and river discharges and water quality; the effect of the hydraulic interaction of Lake Michigan and tributary stream waters; the effect of urbanization and soil properties on runoff volume and timing and on soil erosion and sedimentation; the demand of commercial vessel activities on harbor development and maintenance and associated dredge spoils disposal problems; and the effect of severe storms on shoreline erosion and anchorage protection. On the basis of these analyses, pertinent functional relationships were established between socioeconomic activity, land use development, and water and water-related resource demands.

Plan Synthesis

Plan synthesis or design forms the heart of the planning process. The most well-conceived objective, the most sophisticated data collection, processing, and analysis operations, and the most accurate forecasts are of little value if they do not ultimately result in sound plans. The outputs of each of the three planning operations—formulation of objectives and standards, conduct of inventories, and preparation of analyses and forecasts—become inputs to plan synthesis.

Resolution of the water and water-related resource design problem in the Milwaukee Harbor estuary planning program required consideration of the existing and future pollutant loadings from the tributary river watersheds, stormwater and combined sewer system overflows, sewage treatment plant effluents, and industrial wastewater effluents; existing and future sediment quality conditions;

and existing and future hydrologic and hydraulic characteristics of the estuary system. In the plan design phase, future water and water-related resources are synthesized to satisfy the objectives and standards formulated in the study. The process is a cyclic one of determining the best design solutions, proposing specific solutions to specific problems, and then testing the operation and performance of the proposed solutions through simulation. The initial improvement proposals for each specific problem originated with experienced professional engineers, planners, and resource managers working for federal, state, and local units of government, and having intimate knowledge of and long-standing experience in water and water-related management practices and systems in the Region. In addition, the Advisory Committee members were consulted to review the measures considered.

Plan Test and Evaluation

If the plans developed in the design stage of the planning process are to be realized in terms of actual water and water-related resource management measures, some procedure must be applied to quantitatively test and evaluate alternative plans. The alternative plans must be subject to several levels of review and evaluation, including: 1) engineering and technical feasibility, 2) environmental impact, 3) economic and financial feasibility, 4) legality, and 5) citizen and political reaction and acceptability. Devices used to test and evaluate the alternative plans range from computer simulation programs to evaluate hydrologic-hydraulic water quality responses under alternative plan elements, to interagency meetings and public hearings. Plan test and evaluation should demonstrate clearly which alternative plans or portions of plans are technically sound, economically and financially feasible, legally possible, and politically practicable.

Plan Selection and Adoption

The following general approach was used to select the final Milwaukee Harbor estuary water resources plan from among the alternatives considered. First, the alternatives were presented and analyzed with respect to technical, economic, financial, and legal feasibility. Next, the alternatives were reviewed by the Advisory Committee, and were introduced at interagency meetings, public informational meetings, and public hearings. Finally, an alternative plan was selected and adopted by the Commission in accordance with the provisions of the state regional planning enabling legislation. The role of the Commission is to recommend to federal, state, and local units and agencies of government the best final plan for their consideration and action. This plan, together with specific recommendations for implementation addressed to both the public and private sector, represents the recommended comprehensive water resources management plan for the Milwaukee Harbor estuary. The final decisive step to be taken in the process is the acceptance or rejection of the plan by the units and agencies of government concerned and, upon acceptance, its subsequent implementation through public and private action. Therefore, plan selection and adoption must be founded in the active involvement of the various governmental bodies, technical agencies, and private interest groups concerned with development in the estuary subwatershed. The use of advisory committees and both formal and informal public hearings appears to be the most practical and effective way to achieve such involvement in the planning process, and to openly arrive at agreement on objectives and on a final water resources management plan which can be cooperatively adopted and jointly implemented.

Plan Implementation

Although, as noted, plan implementation is not an element in the seven-step planning process, the recommended plan is not complete until the steps required for its implementation have been specified. Toward this end, the plan must identify the appropriate institutional and administrative structure and mechanisms to implement the plan, as well as identify any changes necessary in legislation and associated regulations relating to water resources management.

The ability of the various governmental units involved in water resource management in the Milwaukee Harbor estuary to meet the water resource management objectives and supporting standards set forth in the plan was analyzed. In addition, available federal and state financial and technical assistance programs were identified. Because of the completely advisory role of the Commission, implementation of the recommended plan will be entirely dependent upon action by local, state, and federal agencies of government and by entities in the private sector. The Commission intends, however, to monitor progress toward plan implementation and, in cooperation with the Milwaukee Harbor Estuary Committee, maintain coordination among the various planning and plan implementation agencies.

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Chapter III

DESCRIPTION OF THE MILWAUKEE HARBOR ESTUARY AND ITS TRIBUTARY WATERSHEDS: MAN-MADE FEATURES AND THE NATURAL RESOURCE BASE

INTRODUCTION

The water resource and water resource-related problems of the Milwaukee Harbor estuary and its tributary watersheds, as well as the ultimate solutions to those problems, are a function of the activities of man within the area, and of the ability of the underlying natural resource base to sustain those activities. The harbor estuary and its tributary watersheds may be viewed as a large ecosystem composed of natural and man-made features, and a resident population, all of which interact to constitute a changing environment for life. Future changes in that ecosystem, and their attendant impact on the quality of life within the area, will be largely determined by man's actions. This is especially true in the Milwaukee Harbor estuary and its tributary watersheds, where urban land uses can be expected to occupy an increasing proportion of the area in the future. Comprehensive planning seeks to rationally direct the future course of human actions affecting the ecosystem so as to favorably affect the overall quality of life.

The purpose of this chapter is, accordingly, to describe the existing ecosystem concerned—that is, the natural resource base and man-made features of the Milwaukee Harbor estuary and its tributary watersheds—thereby establishing an important factual basis for the planning process. This description is presented in this chapter in two major sections, the first of which describes the man-made features and the second of which describes the natural resource base of the study area.

DESCRIPTION OF THE MILWAUKEE HARBOR ESTUARY AND ITS TRIBUTARY WATERSHEDS: MAN-MADE FEATURES

Man-made features which are important to any comprehensive water resources planning effort include political boundaries, land use patterns, public utility networks, and transportation systems. Together with the population residing in and the economic activities taking place within the study area, these features may be thought of as the socioeconomic base of the study area. A description of this base is essential to sound planning, for any attempt to protect and improve the environment must be founded in an understanding of not only the various demands for land and public facilities and resources generated by the population and economic activities of an area, but also the ability of the existing land use patterns, public utility systems, and transportation systems to meet these demands.

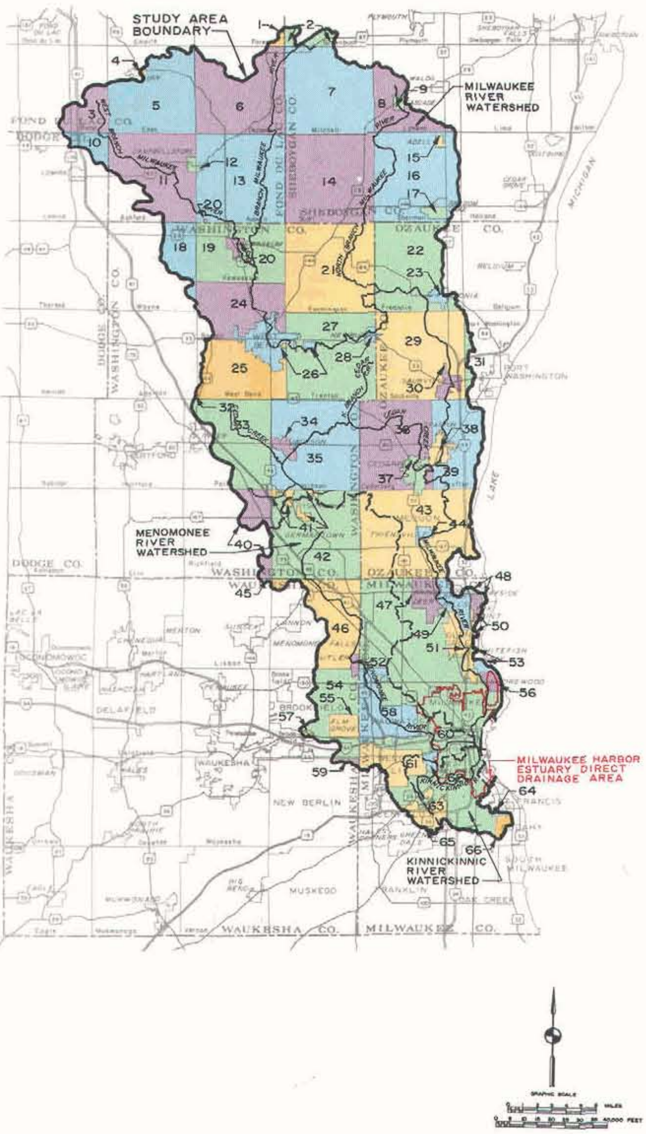
In order to facilitate such understanding, a description of the socioeconomic base of the study area is herein presented in five sections. The first section places the study area into proper perspective as a rational planning unit within a regional setting by delineating its internal political and governmental boundaries and relating these boundaries to the Region as a whole. The second section describes the demographic and economic base of the study area in terms of population size, distribution, and composition and in terms of commercial, industrial, and agricultural activity and employment levels and distribution. The third section describes the land use patterns in the study area in terms of historical development and current conditions. The fourth and fifth sections describe the public utility and transportation facility systems within the study area. A final section at the end of this chapter summarizes the information presented on the man-made features and activities, as well as on the natural resource base.

Regional Setting of the Civil Divisions in the Milwaukee Harbor Estuary and Its Tributary Watersheds

Superimposed on the natural physical boundaries of the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds is a rectangular pattern of local political boundaries, as shown on Map 7. The combined study area of the estuary and its tributary river watersheds occupies portions of four counties in the Southeastern Wisconsin Region—Milwaukee, Ozaukee, Washington, and Waukesha—and portions of Dodge, Fond du Lac, and Sheboygan Counties outside the Region. The study area encompasses all or portions of 12 cities, 24 villages, and 30 towns. The area and portion of the total study area lying within each of these civil

Map 7

CIVIL DIVISIONS IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1980



The Milwaukee Harbor estuary direct drainage area and its tributary river watersheds comprise an 858-square-mile natural surface water drainage basin discharging into Lake Michigan. The combined study area of the estuary and its tributary river watersheds occupies portions of four counties in the Southeastern Wisconsin Region—Milwaukee, Ozaukee, Washington, and Waukesha—and portions of Dodge, Fond du Lac, and Sheboygan Counties outside the Region. The study area encompasses all or portions of 12 cities, 24 villages, and 30 towns.

Source: SEWRPC.

Number on Map	Civil Division
1	Town of Forest
2	Town of Greenbush
3	Town of Byron
4	Village of Eden
5	Town of Eden
6	Town of Osceola
7	Town of Mitchell
8	Town of Lyndon
9	Village of Cascade
10	Town of Lomira
11	Town of Ashford
12	Village of Campbellsport
13	Town of Auburn
14	Town of Scott
15	Village of Adell
16	Town of Sherman
17	Village of Random Lake
18	Town of Wayne
19	Town of Kewaskum
20	Village of Kewaskum
21	Town of Farmington
22	Town of Fredonia
23	Village of Fredonia
24	Town of Barton
25	Town of West Bend
26	City of West Bend
27	Town of Trenton
28	Village of Newburg
29	Town of Saukville
30	Village of Saukville
31	Town of Port Washington
32	Town of Addison
33	Town of Polk
34	Village of Jackson
35	Town of Jackson
36	Town of Cedarburg
37	City of Cedarburg
38	Village of Grafton
39	Town of Grafton
40	Town of Richfield
41	Town of Germantown
42	Village of Germantown
43	City of Mequon
44	Village of Thiensville
45	Town of Lisbon
46	Village of Menomonee Falls
47	Village of Brown Deer
48	Village of Bayside
49	Village of River Hills
50	Village of Fox Point
51	City of Glendale
52	Village of Butler
53	Village of Whitefish Bay
54	City of Brookfield
55	Village of Elm Grove
56	Village of Shorewood
57	Town of Brookfield
58	City of Wauwatosa
59	City of New Berlin
60	City of Milwaukee
61	City of West Allis
62	Village of West Milwaukee
63	City of Greenfield
64	City of St. Francis
65	Village of Greendale
66	City of Cudahy

divisions are set forth in Table 2. Geographic boundaries of the civil divisions are an important consideration since the civil divisions form the basic foundation of the decision-making framework within which environmental and developmental problems must be addressed.

Other Agencies Having Resource Responsibilities: Superimposed on these local and areawide units and agencies of government are the state and federal governments, certain agencies of which have important responsibilities for resource conservation and management. These include the Wisconsin Department of Natural Resources; the Wisconsin Land Conservation Board, Wisconsin Department of Agriculture, Trade and Consumer Protection; the U. S. Department of the Interior, Geological Survey; the U. S. Environmental Protection Agency; the U. S. Department of Agriculture, Soil Conservation Service, the U. S. Army Corps of Engineers; and the International Joint Commission.

Demographic and Economic Base

As in any watershed, there is a direct relationship in the Milwaukee Harbor estuary direct drainage area between population levels and the demand for land, water, and other important elements of the natural resource base, as well as the demand for transportation, utility, recreation, and other community services and facilities. Thus, an understanding of the size, spatial distribution, and characteristics of this population is essential for a sound, comprehensive planning effort. This holds particularly true in the case of the Milwaukee Harbor estuary which, of necessity, must consider the demands of a population distributed within three watersheds over a broad geographic area and encompassing both urban and rural characteristics. The size and other characteristics of the population of an area are greatly influenced by growth and other changes in economic activity. Population features and economic activity must, therefore, be considered together.

It is important to note that the existing and potential water quality and water resource-related problems within the Milwaukee Harbor estuary cannot be fully understood by examining the population characteristics and economic activity within the direct drainage area alone. The competing, and sometimes conflicting, demands on the natural resource base of the estuary and its tributary river watersheds are based in part on the diversity in population features and economic activity that is exhibited over the broad study area as an integral part of a larger metropolitan region. Moreover, many of the social and economic forces which influence population growth and change in the Milwaukee Harbor estuary and its tributary river watersheds are centered outside the study area proper but within the larger metropolitan region. It is necessary, therefore, to relate population characteristics and economic activity within the Milwaukee Harbor estuary and its tributary river watersheds to similar characteristics and activities on a regionwide basis.

Demographic Base: A study of the demographic base of the Milwaukee Harbor estuary and its tributary river watersheds necessarily includes consideration of population size, distribution, and composition.

Population Size: The 1980 resident population of the Milwaukee Harbor estuary direct drainage area was estimated at 255,200 persons, or about 26 percent of the population within the entire study area and about 14 percent of the total population of the Region. The estimated 955,500 persons residing in the Milwaukee Harbor estuary direct drainage area and the southeastern Wisconsin portion of its three tributary river watersheds represent about 54 percent of the estimated 1.76 million persons residing in the seven-county Southeastern Wisconsin Region during 1980. As shown in Table 3, the Milwaukee Harbor estuary direct drainage area exhibited a marked decline in resident population between 1950 and 1980. Over this 30-year period, the population of the direct drainage area decreased by about 162,600 persons, or about 39 percent—from approximately 417,800 persons in 1950 to about 255,200 persons in 1980. However, over this same period, the population of the total study area, including the three tributary river watershed areas, increased by about 154,000 persons, or about 19 percent—from approximately 816,200 persons in 1950 to about 970,200 persons in 1980, although there has been an overall decline in the total study area population since 1970, when about 1.04 million persons resided in the area.

Table 3 indicates that there was a sharp decline in the resident population of the Milwaukee Harbor estuary direct drainage area between 1950 and 1960, while over this same 10-year period the resident population of the three tributary river watersheds increased dramatically. The Milwaukee River watershed, in particular, gained more than 165,200 persons, or about 129 percent—from approximately 128,200 persons in 1950 to about 293,400 persons in 1960. The Milwaukee River watershed is also the only portion of the study

Table 2

AREAL EXTENT OF COUNTIES, CITIES, VILLAGES, AND TOWNS WITHIN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY WATERSHEDS

		Area Located Within									
		Kinnickinnic River Watershed[a]		Menomonee River Watershed[a]		Milwaukee River Watershed[a]		Milwaukee Harbor Estuary Direct Drainage Area		Total Study Area	
County	Civil Division	Square Miles	Percent	Square Miles	Percent	Square Miles	Percent	Square Miles	Percent	Square Miles	Percent
Dodge	Town of Lomira. . .	--	--	--	--	4.63	0.68	--	--	4.63	0.54
	Subtotal	--	--	--	--	4.63	0.68	--	--	4.63	0.54
Fond du Lac	Villages of:										
	Campbellsport . . .	--	--	--	--	0.75	0.11	--	--	0.75	0.09
	Eden	--	--	--	--	0.03	--[b]	--	--	0.03	--[b]
	Kewaskum	--	--	--	--	0.06	0.01	--	--	0.06	0.01
	Towns of:										
	Ashford.	--	--	--	--	28.72	4.23	--	--	28.72	3.36
	Auburn	--	--	--	--	36.11	5.31	--	--	36.11	4.23
	Byron	--	--	--	--	8.90	1.31	--	--	8.90	1.04
	Eden	--	--	--	--	26.70	3.93	--	--	26.70	3.12
	Forest.	--	--	--	--	0.82	0.12	--	--	0.82	0.10
	Osceola	--	--	--	--	30.15	4.44	--	--	30.15	3.53
	Subtotal	--	--	--	--	132.24	19.46	--	--	132.24	15.48
Milwaukee	Cities of:										
	Cudahy	1.60	7.82	--	--	--	--	--	--	1.60	0.19
	Glendale	--	--	--	--	5.95	0.88	--	--	5.95	0.70
	Greenfield	2.28	11.14	2.81	2.13	--	--	--	--	5.09	0.60
	Milwaukee	14.36	70.19	27.95	21.15	27.10	3.99	21.40	96.48	90.81	10.63
	St. Francis	0.11	0.54	--	--	--	--	--	--	0.11	0.01
	Wauwatosa	--	--	13.24	10.02	--	--	--	--	13.24	1.55
	West Allis.	1.62	7.92	6.79	5.14	--	--	--	--	8.41	0.98
	Villages of:										
	Bayside	--	--	--	--	0.36	0.05	--	--	0.36	0.04
	Brown Deer	--	--	--	--	4.37	0.64	--	--	4.37	0.51
	Fox Point.	--	--	--	--	1.55	0.23	--	--	1.55	0.18
	Greendale.	--	--	0.12	0.09	--	--	--	--	0.12	0.01
	River Hills	--	--	--	--	4.21	0.62	--	--	4.21	0.49
	Shorewood	--	--	--	--	0.72	0.10	0.78	3.52	1.50	0.18
	West Milwaukee . .	0.49	2.39	0.31	0.23	--	--	--	--	0.80	0.09
	Whitefish Bay . . .	--	--	--	--	0.76	0.11	--	--	0.76	0.09
	Subtotal	20.46	100.00	51.22	38.76	45.02	6.62	22.18	100.00	138.88	16.25
Ozaukee	Cities of:										
	Cedarburg	--	--	--	--	3.10	0.46	--	--	3.10	0.36
	Mequon.	--	--	11.68	8.84	31.35	4.61	--	--	43.03	5.04
	Villages of:										
	Fredonia	--	--	--	--	1.18	0.17	--	--	1.18	0.14
	Grafton	--	--	--	--	2.44	0.36	--	--	2.44	0.29
	Newburg	--	--	--	--	0.08	0.01	--	--	0.08	0.01
	Saukville	--	--	--	--	2.07	0.31	--	--	2.07	0.24
	Thiensville	--	--	--	--	1.04	0.15	--	--	1.04	0.12
	Towns of:										
	Cedarburg	--	--	--	--	26.85	3.95	--	--	26.85	3.14
	Fredonia	--	--	--	--	28.00	4.12	--	--	28.00	3.28
	Grafton	--	--	--	--	17.86	2.63	--	--	17.86	2.09
	Port Washington . .	--	--	--	--	2.55	0.38	--	--	2.55	0.30
	Saukville	--	--	--	--	34.27	5.04	--	--	34.27	4.01
	Subtotal	--	--	11.68	8.84	150.79	22.19	--	--	162.47	19.09

Table 2 (continued)

County	Civil Division	Area Located Within									
		Kinnickinnic River Watershed[a]		Menomonee River Watershed[a]		Milwaukee River Watershed[a]		Milwaukee Harbor Estuary Direct Drainage Area		Total Study Area	
		Square Miles	Percent	Square Miles	Percent	Square Miles	Percent	Square Miles	Percent	Square Miles	Percent
Sheboygan	Villages of:										
	Adell	--	--	--	--	0.39	0.06	--	--	0.39	0.05
	Cascade	--	--	--	--	0.77	0.11	--	--	0.77	0.09
	Random Lake . . .	--	--	--	--	1.15	0.17	--	--	1.15	0.13
	Towns of:										
	Greenbush	--	--	--	--	3.57	0.53	--	--	3.57	0.42
	Lyndon	--	--	--	--	12.78	1.88	--	--	12.78	1.50
	Mitchell	--	--	--	--	33.45	4.92	--	--	33.45	3.91
	Scott	--	--	--	--	36.57	5.38	--	--	36.57	4.28
	Sherman	--	--	--	--	33.07	4.87	--	--	33.07	3.87
	Subtotal	--	--	--	--	121.75	17.92	--	--	121.75	14.25
Washington	Cities of:										
	Milwaukee	--	--	0.02	--[b]	--	--	--	--	0.02	--[b]
	West Bend	--	--	--	--	8.09	1.19	--	--	8.09	0.95
	Villages of:										
	Germantown	--	--	29.28	22.16	5.22	0.77	--	--	34.50	4.04
	Jackson	--	--	--	--	1.51	0.22	--	--	1.51	0.18
	Kewaskum	--	--	--	--	1.20	0.18	--	--	1.20	0.14
	Newburg	--	--	--	--	0.66	0.10	--	--	0.66	0.08
	Towns of:										
	Addison	--	--	--	--	0.12	0.02	--	--	0.12	0.01
	Barton	--	--	--	--	19.27	2.84	--	--	19.27	2.25
	Farmington	--	--	--	--	36.80	5.41	--	--	36.80	4.31
	Germantown	--	--	0.76	0.58	0.96	0.14	--	--	1.72	0.20
	Jackson	--	--	--	--	35.03	5.15	--	--	35.03	4.10
	Kewaskum	--	--	--	--	23.14	3.40	--	--	23.14	2.71
	Polk	--	--	--	--	24.32	3.58	--	--	24.32	2.84
	Richfield	--	--	1.49	1.13	5.66	0.83	--	--	7.15	0.84
	Trenton	--	--	--	--	34.50	5.08	--	--	34.50	4.04
	Wayne	--	--	--	--	9.12	1.34	--	--	9.12	1.07
	West Bend	--	--	--	--	19.54	2.88	--	--	19.54	2.29
	Subtotal	--	--	31.53	23.87	225.16	33.13	--	--	256.69	30.05
Waukesha	Cities of:										
	Brookfield	--	--	13.59	10.29	--	--	--	--	13.59	1.59
	New Berlin	--	--	0.60	0.45	--	--	--	--	0.60	0.07
	Villages of:										
	Butler	--	--	0.80	0.60	--	--	--	--	0.80	0.09
	Elm Grove	--	--	3.25	2.46	--	--	--	--	3.25	0.38
	Menomonee Falls .	--	--	18.93	14.33	--	--	--	--	18.93	2.22
	Towns of:										
	Brookfield	--	--	0.19	0.14	--	--	--	--	0.19	0.02
	Lisbon	--	--	0.34	0.26	--	--	--	--	0.34	0.04
	Subtotal	--	--	37.70	28.53	--	--	--	--	37.70	4.41
Total		20.46	100.0	132.13	100.00	679.59	100.00	22.18	100.00	854.36	100.00

[a] *Excluding that portion of the watershed lying within the Milwaukee Harbor estuary direct drainage area.*

[b] *Less than one-hundredth of 1 percent.*

Source: SEWRPC.

Table 3

POPULATION IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY WATERSHEDS, THE REGION, WISCONSIN, AND THE UNITED STATES: SELECTED YEARS 1950-1980

Location	Population						
	1950	1960	Percent Change 1950-1960	1970	Percent Change 1960-1970	1980	Percent Change 1970-1980
Milwaukee Harbor Estuary Direct Drainage Area . . .	417,844	358,825	-14.1	304,346	-15.2	255,171	-16.2
Kinnickinnic River Watershed[a]	88,996	121,396	36.4	116,201	-4.3	102,171	-12.1
Milwaukee River Watershed[a]	128,232	293,448	128.8	333,400	12.0	340,968	2.3
Menomonee River Watershed[a]	181,133	255,105	40.8	285,649	12.0	271,917	-4.8
Total Study Area	816,205	1,028,774	26.0	1,039,596	1.1	970,227	-6.7
Southeastern Wisconsin Region	1,240,618	1,573,620	26.8	1,756,086	11.6	1,764,919	0.5
State of Wisconsin	3,434,575	3,952,771	15.1	4,417,933	11.8	4,705,521	6.5
United States	151,325,798	179,323,175	18.5	203,302,031	13.4	226,504,825	11.4

[a] *Excluding that portion of the watershed lying within the Milwaukee Harbor estuary direct drainage area.*

Source: U. S. Bureau of the Census and SEWRPC.

area to exhibit continuous growth in population between 1950 and 1980, although the rate of that growth has slowed substantially—being about 2 percent between 1970 and 1980.

The sharp decline in the resident population of the Milwaukee Harbor estuary direct drainage area is reflective of trends exhibited in many of the large, older metropolitan centers of the United States. The high rates of in-migration in large urban areas which occurred during the 1950's have been reversed to high rates of out-migration during the 1970's. This exodus is indicative of the change in preference for residential development in suburban and rural-urban fringe areas, rather than in older, metropolitan regions.

Population Distribution: The 1970 and 1980 population of the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds is presented by civil division in Table 4. As indicated in this table, population levels in the overall study area decreased by about 69,400 persons, or nearly 7 percent, between 1970 and 1980. Most of this population loss—about 49,200 persons—was due to out-migration from the Milwaukee Harbor estuary direct drainage area. The greatest absolute gain in population within the study area over this 10-year period occurred in the City of West Bend, which increased by more than 5,300 persons, or about 34 percent.

Table 5 sets forth the average population density in the Milwaukee Harbor estuary direct drainage area, its tributary river watersheds, and the Region for the years 1970 and 1980. As shown in this table, the Milwaukee Harbor estuary direct drainage area, which has the highest population density in the study area—about 13,900 persons per square mile on the average in 1970 and about 11,600 persons per square mile in 1980—exhibited the greatest absolute and relative change in population density, decreasing by more than 2,200 persons per square mile, or about 16 percent, over this 10-year period. Within the study area, only the Milwaukee River watershed experienced an overall net increase in population density, increasing by about eight persons per square mile, or about 2 percent, between 1970 and 1980. The Southeastern Wisconsin Region as a whole also demonstrated a slight

Table 4

POPULATION OF THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS BY CIVIL DIVISION: 1970 AND 1980

Civil Division	Population																			
	Kinnickinnic River Watershed[a]				Menomonee River Watershed[a]				Milwaukee River Watershed[a]				Milwaukee Harbor Estuary Direct Drainage Area				Total Study Area			
	1970	1980	Change		1970	1980	Change		1970	1980	Change		1970	1980	Change		1970	1980	Change	
			Absolute	Percent			Absolute	Percent			Absolute	Percent			Absolute	Percent			Absolute	Percent
Dodge County																				
Town of Lomira	--	--	--	--	--	--	--	--	163	182	19	11.7	--	--	--	--	163	182	19	11.7
Subtotal	--	--	--	--	--	--	--	--	163	182	19	11.7	--	--	--	--	163	182	19	11.7
Fond du Lac County																				
Villages of:																				
Campbellsport	--	--	--	--	--	--	--	--	1,681	1,740	59	3.5	--	--	--	--	1,681	1,740	59	3.5
Eden	--	--	--	--	--	--	--	--	65	92	27	41.5	--	--	--	--	65	92	27	41.5
Towns of:																				
Ashford	--	--	--	--	--	--	--	--	1,182	1,283	101	8.5	--	--	--	--	1,182	1,283	101	8.5
Auburn	--	--	--	--	--	--	--	--	1,256	1,816	560	44.6	--	--	--	--	1,256	1,816	560	44.6
Byron	--	--	--	--	--	--	--	--	319	413	94	29.5	--	--	--	--	319	413	94	29.5
Eden	--	--	--	--	--	--	--	--	853	925	72	8.4	--	--	--	--	853	925	72	8.4
Forest	--	--	--	--	--	--	--	--	26	26	0	0.0	--	--	--	--	26	26	0	0.0
Osceola	--	--	--	--	--	--	--	--	924	1,299	375	40.6	--	--	--	--	924	1,299	375	40.6
Subtotal	--	--	--	--	--	--	--	--	6,306	7,594	1,288	20.4	--	--	--	--	6,306	7,594	1,288	20.4
Milwaukee County																				
Cities of:																				
Cudahy	5,080	4,667	-413	-8.1	--	--	--	--	--	--	--	--	--	--	--	--	5,080	4,667	-413	-8.1
Glendale	--	--	--	--	--	--	--	--	17,454	16,685	-769	-4.4	--	--	--	--	17,454	16,685	-769	-4.4
Greenfield	9,930	9,452	-478	-4.8	8,305	10,663	2,358	28.4	--	--	--	--	--	--	--	--	18,235	20,115	1,880	10.3
Milwaukee	75,607	66,397	-9,210	-12.2	105,025	103,410	-1,615	-1.5	197,704	182,194	-15,510	-7.9	295,046	246,944	48,102	-16.3	673,382	598,945	-74,437	-11.1
St. Francis	936	849	-87	-9.3	--	--	--	--	--	--	--	--	--	--	--	--	936	849	-87	-9.3
Wauwatosa	--	--	--	--	59,517	52,094	-7,423	-12.5	--	--	--	--	--	--	--	--	59,517	52,094	-7,423	-12.5
West Allis	23,689	20,015	-3,674	-15.5	41,977	37,038	-4,939	-11.8	--	--	--	--	--	--	--	--	65,666	57,053	-8,613	-13.1
Villages of:																				
Bayside	--	--	--	--	--	--	--	--	234	290	56	23.9	--	--	--	--	234	290	56	23.9
Brown Deer	--	--	--	--	--	--	--	--	12,541	12,906	365	2.9	--	--	--	--	12,541	12,906	365	2.9
Fox Point	--	--	--	--	--	--	--	--	5,742	5,480	-262	-4.6	--	--	--	--	5,742	5,480	-262	-4.6
Greendale	--	--	--	--	492	477	-15	-3.1	--	--	--	--	--	--	--	--	492	477	-15	-3.1
River Hills	--	--	--	--	--	--	--	--	1,513	1,759	246	16.3	--	--	--	--	1,513	1,759	246	16.3
Shorewood	--	--	--	--	--	--	--	--	4,313	4,304	-9	-0.2	9,300	8,227	-1,073	-11.5	13,613	12,531	-1,082	-8.0
West Milwaukee	959	791	-168	-17.5	4,601	3,330	-1,271	-27.6	--	--	--	--	--	--	--	--	5,560	4,121	-1,439	-25.9
Whitefish Bay	--	--	--	--	--	--	--	--	7,138	6,288	-850	-11.9	--	--	--	--	7,138	6,288	-850	-11.9
Subtotal	116,201	102,171	-14,030	-12.1	219,917	207,012	-12,905	-5.9	246,639	229,906	-16,733	-6.8	304,346	255,171	-49,175	-16.2	887,103	794,260	-90,843	-10.2

Table 4 (continued)

Civil Division	Population																			
	Kinnickinnic River Watershed[a]				Menomonee River Watershed[a]				Milwaukee River Watershed[a]				Milwaukee Harbor Estuary Direct Drainage Area				Total Study Area			
			Change				Change				Change				Change				Change	
	1970	1980	Absolute	Percent	1970	1980	Absolute	Percent	1970	1980	Absolute	Percent	1970	1980	Absolute	Percent	1970	1980	Absolute	Percent
Ozaukee County																				
Cities of:																				
Cedarburg	--	--	--	--	--	--	--	--	6,925	8,094	1,169	16.9	--	--	--	--	6,925	8,094	1,169	16.9
Mequon	--	--	--	--	1,852	1,908	56	3.0	8,955	11,102	2,147	24.0	--	--	--	--	10,807	13,010	2,203	20.4
Villages of:																				
Fredonia	--	--	--	--	--	--	--	--	999	1,526	527	52.8	--	--	--	--	999	1,526	527	52.8
Grafton	--	--	--	--	--	--	--	--	5,582	8,014	2,432	43.6	--	--	--	--	5,582	8,014	2,432	43.6
Newburg	--	--	--	--	--	--	--	--	--	95	95	--	--	--	--	--	--	95	95	--
Saukville	--	--	--	--	--	--	--	--	828	3,450	2,622	316.7	--	--	--	--	828	3,450	2,622	316.7
Thiensville	--	--	--	--	--	--	--	--	3,241	3,719	478	14.8	--	--	--	--	3,241	3,719	478	14.8
Towns of:																				
Cedarburg	--	--	--	--	--	--	--	--	4,399	5,947	1,548	35.2	--	--	--	--	4,399	5,947	1,548	35.2
Fredonia	--	--	--	--	--	--	--	--	1,605	1,864	259	16.1	--	--	--	--	1,605	1,864	259	16.1
Grafton	--	--	--	--	--	--	--	--	3,014	3,332	318	10.6	--	--	--	--	3,014	3,332	318	10.6
Port Washington	--	--	--	--	--	--	--	--	374	465	91	24.3	--	--	--	--	374	465	91	24.3
Saukville	--	--	--	--	--	--	--	--	2,077	1,627	-450	-21.7	--	--	--	--	2,077	1,627	-450	-21.7
Subtotal	--	--	--	--	1,852	1,908	56	3.0	37,999	49,235	11,236	29.6	--	--	--	--	39,851	51,143	11,292	28.3
Sheboygan County																				
Villages of:																				
Adell	--	--	--	--	--	--	--	--	380	545	165	43.4	--	--	--	--	380	545	165	43.7
Cascade	--	--	--	--	--	--	--	--	603	615	12	2.0	--	--	--	--	603	615	12	2.0
Random Lake	--	--	--	--	--	--	--	--	1,068	1,287	219	20.5	--	--	--	--	1,068	1,287	219	20.5
Towns of:																				
Greenbush	--	--	--	--	--	--	--	--	154	167	13	8.4	--	--	--	--	154	167	13	8.4
Lyndon	--	--	--	--	--	--	--	--	453	507	54	11.9	--	--	--	--	453	507	54	11.9
Mitchell	--	--	--	--	--	--	--	--	722	834	112	15.5	--	--	--	--	722	834	112	15.5
Scott	--	--	--	--	--	--	--	--	1,451	1,625	174	12.0	--	--	--	--	1,451	1,625	174	12.0
Sherman	--	--	--	--	--	--	--	--	1,376	1,384	8	0.6	--	--	--	--	1,376	1,384	8	0.2
Subtotal	--	--	--	--	--	--	--	--	6,207	6,964	757	12.2	--	--	--	--	6,207	6,964	757	12.2
Washington County																				
Cities of:																				
West Bend	--	--	--	--	--	--	--	--	15,749	21,098	5,349	34.0	--	--	--	--	15,749	21,098	5,349	34.0
Villages of:																				
Germantown	--	--	--	--	6,940	10,425	3,485	50.2	220	193	-27	-12.3	--	--	--	--	7,160	10,618	3,458	48.3
Jackson	--	--	--	--	--	--	--	--	559	1,827	1,268	226.8	--	--	--	--	559	1,827	1,268	226.8
Kewaskum	--	--	--	--	--	--	--	--	1,462	2,351	889	60.8	--	--	--	--	1,462	2,351	889	60.8
Newburg	--	--	--	--	--	--	--	--	--	677	677	--	--	--	--	--	--	677	677	--
Towns of:																				
Addison	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Barton	--	--	--	--	--	--	--	--	1,699	2,289	590	34.7	--	--	--	--	1,699	2,289	590	34.7

Table 4 (continued)

	Population																			
	Kinnickinnic River Watershed[a]				Menomonee River Watershed[a]				Milwaukee River Watershed[a]				Milwaukee Harbor Estuary Direct Drainage Area				Total Study Area			
			Change				Change				Change				Change				Change	
Civil Division	1970	1980	Absolute	Percent	1970	1980	Absolute	Percent	1970	1980	Absolute	Percent	1970	1980	Absolute	Percent	1970	1980	Absolute	Percent
Washington County (continued)																				
Towns of:																				
Farmington	--	--	--	--	--	--	--	--	1,734	2,386	652	37.6	--	--	--	--	1,734	2,386	652	37.6
Germantown	--	--	--	--	197	241	44	22.3	33	139	106	321.2	--	--	--	--	230	380	150	37.6
Jackson	--	--	--	--	--	--	--	--	2,846	3,170	324	11.4	--	--	--	--	2,846	3,170	324	11.4
Kewaskum	--	--	--	--	--	--	--	--	1,630	1,273	-357	-21.9	--	--	--	--	1,630	1,273	-357	-21.9
Polk	--	--	--	--	--	--	--	--	2,220	2,552	332	15.0	--	--	--	--	2,220	2,552	332	15.0
Richfield	--	--	--	--	241	522	281	116.6	1,064	964	-100	-9.4	--	--	--	--	1,305	1,486	181	13.9
Trenton	--	--	--	--	--	--	--	--	3,174	3,988	814	25.7	--	--	--	--	3,174	3,988	814	25.7
Wayne	--	--	--	--	--	--	--	--	325	368	43	13.2	--	--	--	--	325	368	43	13.2
West Bend	--	--	--	--	--	--	--	--	3,371	3,812	441	13.1	--	--	--	--	3,371	3,812	441	13.1
Subtotal	--	--	--	--	7,378	11,188	3,810	51.6	36,086	47,087	11,001	30.5	--	--	--	--	43,464	58,275	14,811	34.1
Waukesha County																				
Cities of:																				
Brookfield	--	--	--	--	19,250	19,037	-213	-1.1	--	--	--	--	--	--	--	--	19,250	19,037	-213	-1.1
New Berlin	--	--	--	--	2,609	2,254	-355	-13.6	--	--	--	--	--	--	--	--	2,609	2,254	-355	-13.6
Villages of:																				
Butler	--	--	--	--	2,151	2,004	-147	-6.8	--	--	--	--	--	--	--	--	2,151	2,004	-147	-6.8
Elm Grove	--	--	--	--	6,554	6,125	-429	-6.6	--	--	--	--	--	--	--	--	6,554	6,125	-429	-6.6
Menomonee Falls	--	--	--	--	25,884	22,352	-3,532	-13.7	--	--	--	--	--	--	--	--	25,884	22,352	-3,532	-13.7
Towns of:																				
Brookfield	--	--	--	--	13	22	9	69.2	--	--	--	--	--	--	--	--	13	22	9	69.2
Lisbon	--	--	--	--	41	15	-26	-63.4	--	--	--	--	--	--	--	--	41	15	-26	-63.4
Subtotal	--	--	--	--	56,502	51,809	-4,693	-8.3	--	--	--	--	--	--	--	--	56,502	51,809	-4,693	-8.3
Total	116,201	102,171	-14,030	12.1	285,649	271,917	-13,732	-4.8	333,400	340,968	7,549	2.3	304,346	255,171	-49,175	-16.2	1,039,596	970,227	-69,369	-6.7

[a] *Not including that portion of the watershed lying within the Milwaukee Harbor estuary direct drainage area.*

Source: U. S. Bureau of the Census and SEWRPC.

Table 5

POPULATION DENSITY IN THE MILWAUKEE HARBOR ESTUARY, ITS TRIBUTARY RIVER WATERSHEDS, AND THE REGION: 1970 AND 1980

Watershed	Population Density (persons per square mile)		Change 1970-1980	
	1970	1980	Absolute	Percent
Milwaukee Harbor Estuary Direct Drainage Area . . .	13,891	11,646	-2,245	-16.16
Kinnickinnic River Watershed[a]	5,668	4,984	-684	-12.07
Menomonee River Watershed[a]	2,139	2,036	-103	-4.82
Milwaukee River Watershed[a]	470	478	8	1.70
Southeastern Wisconsin Region .	653	656	3	0.46

[a] *Excluding that portion of the watershed lying within the Milwaukee Harbor estuary direct drainage area.*

Source: U. S. Bureau of the Census and SEWRPC.

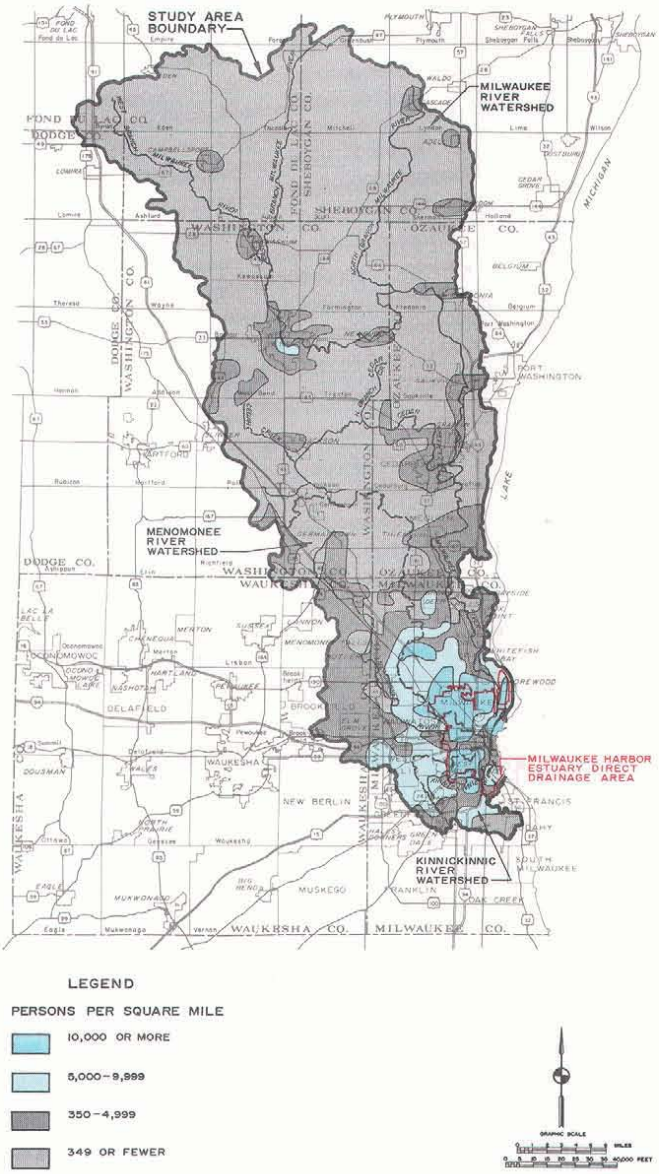
increase in population density, increasing by about three persons per square mile, or less than one-half of 1 percent, over this 10-year period.

As shown on Map 8, there is a wide range in population density throughout the study area. The population density varies from fewer than 350 persons per square mile in the northern, more rural portions of the Menomonee and Milwaukee River watersheds, to more than 25,000 persons per square mile in the highly urbanized Milwaukee Harbor estuary direct drainage area. In general, population densities decrease with increasing distance from the center of the City of Milwaukee.

The Milwaukee Harbor estuary direct drainage area encompasses the most extensively urbanized portion of the Region—including the central business district of the City of Milwaukee and the heavily industrialized Menomonee River Valley. Therefore, the resident population of the direct drainage area is augmented by the daily influx of persons on work trips or shopping trips in the major industrial and commercial centers of the area. To illustrate, based on the latest origin/destination study conducted by the Commission, approximately 131,300 persons entered the central business district of the City of Milwaukee on an average weekday in 1972. These 131,300 persons

Map 8

POPULATION DENSITY IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1980



Within the study area, the population density is the greatest in the Milwaukee Harbor estuary direct drainage area. In 1980 the average population density in that area was more than 11,600 persons per square mile, compared with about 5,000 and 2,000 persons per square mile in the Kinnickinnic and Menomonee River watersheds, respectively. The Milwaukee River watershed, which is predominantly rural in nature outside of Milwaukee County, had an average population density of fewer than 500 persons per square mile in 1980. The Milwaukee River watershed, however, was the only portion of the study area which experienced an increase in population density between 1970 and 1980—about eight persons per square mile—while the direct drainage area and the Kinnickinnic and Menomonee River watersheds experienced a decrease in population density of about 2,200, 700, and 100 persons per square mile, respectively, over this 10-year period.

Source: SEWRPC.

represent a more than 51 percent increase in the resident population of the direct drainage area—255,200 persons.

In addition, it is estimated that 1,046,000 persons attended special ethnic events held at the Summerfest grounds on the North Harbor tract during 1983. These events included Summerfest, Afrofest, Germanfest, Irishfest, Festa Italiana, and Polishfest. Of these festivals, Summerfest, the largest, attracted approximately 657,400 persons, or an average of 65,700 persons per day, over its 10-day period, and accounted for about 63 percent of the total admissions to paid events. In addition, several hundred thousand persons attended two free events along the lakeshore—the City of Festivals parade and Al McGuire's charity run.

Population Composition: The median ages of the resident populations of the Milwaukee Harbor estuary direct drainage area, its tributary river watersheds, and the Region are shown in Table 6. As shown in this table, the median age of the resident population of the direct drainage area in 1980 was 26.8 years, which is significantly younger than the median age of 31.1 years for the total study area and 29.7 years for the Southeastern Wisconsin Region as a whole in that year. The Kinnickinnic River watershed, exclusive of that portion lying within the estuary direct drainage area, exhibited the highest median age in the study area at 33.3 years in 1980. It is significant to note in Table 6 that only in the Milwaukee Harbor estuary direct drainage area did the resident population display a decrease in median age between 1970 and 1980. The median age of the resident population within the total study area increased by about 2.6 years between 1970 and 1980, while the median age of the resident population within the seven-county Southeastern Wisconsin Region increased by about 2.1 years over this 10-year period. The observed increase in the median age of the total study area population and the regional population may be attributed principally to the declining birthrates in the 1970's.

As shown on Map 9, the Milwaukee Harbor estuary direct drainage area has a high concentration of younger residents, while the lower portions of the Kinnickinnic, Menomonee, and Milwaukee River watersheds exhibit an older resident population. The resident population of the upper reaches of the Menomonee and Milwaukee River watersheds is younger than that in the lower reaches, but generally not as young as in the Milwaukee Harbor estuary direct drainage area.

Table 6

MEDIAN AGE IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA, ITS TRIBUTARY RIVER WATERSHEDS, AND THE REGION: 1970 AND 1980

Watershed	Median Age (years) 1970	Median Age (years) 1980	Change (percent)
Milwaukee Harbor Estuary Direct Direct Area	27.1	26.8	-0.3
Kinnickinnic River[a]	29.2	33.3	4.1
Menomonee River[a]	28.8	31.1	2.3
Milwaukee River[a]	28.5	29.9	1.4
Total Study Area	28.5	31.1	2.6
Southeastern Wisconsin Region	27.6	29.7	2.1

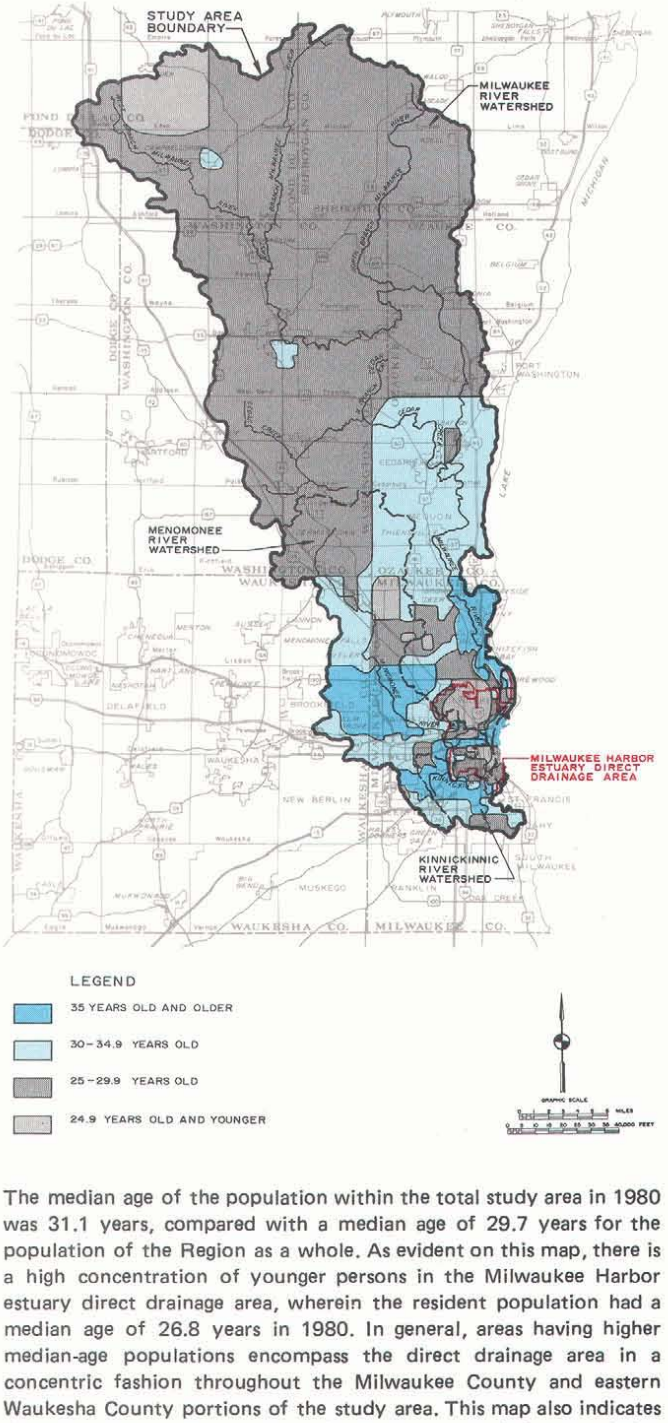
[a] *Not including that portion of the watershed lying within the Milwaukee Harbor estuary direct drainage area.*

Source: U. S. Bureau of the Census and SEWRPC.

Table 7 sets forth the average household income in the Milwaukee Harbor estuary direct drainage area, its tributary river watersheds, and the Region for the years 1969 and 1979 as expressed in constant 1979 dollars. As indicated in this table, the average household income in the Milwaukee Harbor estuary direct drainage area in 1979 was approximately $15,300, significantly lower than the $21,400 average household income for the total study area and the $22,800 average household income for the seven-county Southeastern Wisconsin Region. Table 7 also indicates that the average household income in the direct drainage area and its tributary river watersheds, when expressed in constant 1979 dollars, significantly declined between 1969 and 1979. The average household income declined by more than $1,800, or about 11 percent, over this 10-year period. During this same period, average household income in the total study area decreased by about $400, or about 2 percent, while in the Region as a whole, average household income increased by about $100, or about one-half of 1 percent. Residents of the Milwaukee Harbor estuary direct drainage area in particular, and the total study area in general, did not fare as well economically between 1969 and 1979 as did the overall regional population.

Map 9

MEDIAN AGE OF THE POPULATION WITHIN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1980



The median age of the population within the total study area in 1980 was 31.1 years, compared with a median age of 29.7 years for the population of the Region as a whole. As evident on this map, there is a high concentration of younger persons in the Milwaukee Harbor estuary direct drainage area, wherein the resident population had a median age of 26.8 years in 1980. In general, areas having higher median-age populations encompass the direct drainage area in a concentric fashion throughout the Milwaukee County and eastern Waukesha County portions of the study area. This map also indicates that younger persons are a major component of the population residing in the more rural portions of the Menomonee and Milwaukee River watersheds.

Source: SEWRPC.

Table 7

AVERAGE HOUSEHOLD INCOME IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA, ITS TRIBUTARY RIVER WATERSHEDS, AND THE REGION: 1969 AND 1979

Watershed	Average Household Income (constant 1979 dollars)		Change	
	1969	1979	Absolute	Percent
Milwaukee Harbor Estuary Direct Drainage Area	17,180	15,340	-1,840	-10.7
Kinnickinnic River[a]	21,960	21,200	-760	-3.5
Menomonee River[a]	24,970	23,570	-1,400	-5.6
Milwaukee River[a]	23,340	22,730	-610	-2.6
Total Study Area	21,770	21,410	-360	-1.7
Southeastern Wisconsin Region	22,650	22,760	110	0.5

[a] *Not including that portion of the watershed lying within the Milwaukee Harbor estuary direct drainage area.*

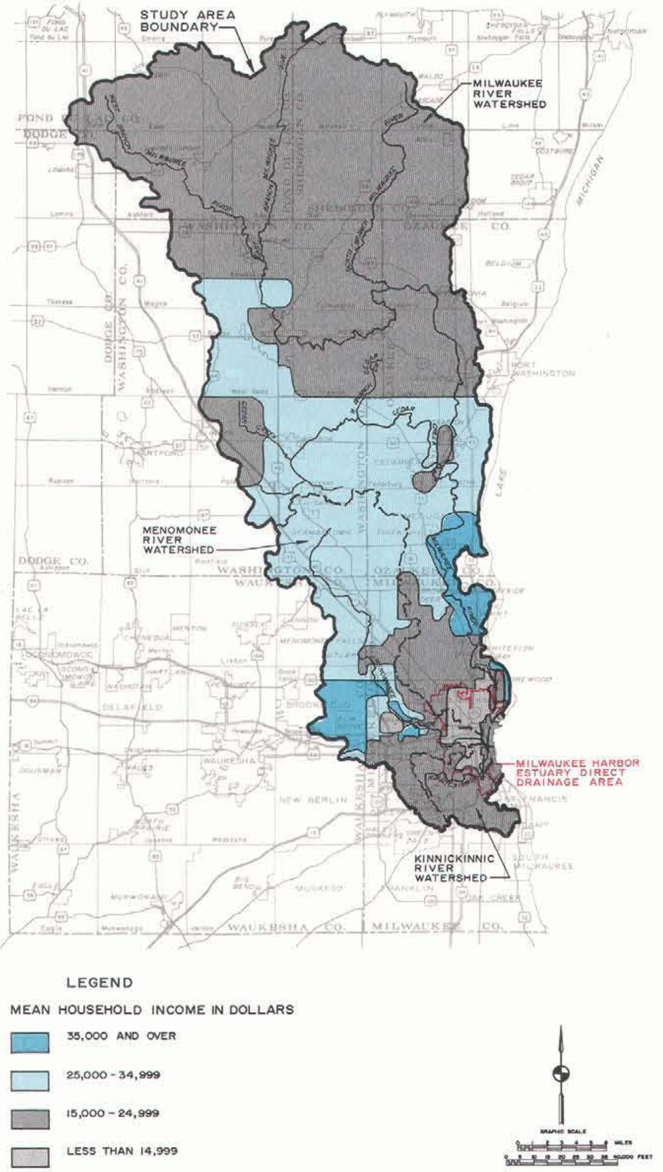
Source: U. S. Bureau of the Census and SEWRPC.

Map 10 depicts the average household income throughout the study area in 1979. As shown on this map, average household income in the study area generally increases with distance from the Milwaukee Harbor estuary direct drainage area until the northern, more rural portions of the Milwaukee River watershed are reached. The highest average household income in the study area—in excess of $35,000—is generally found in northeastern Milwaukee County, southeastern Ozaukee County, and portions of eastern Waukesha County. Lower average household incomes—less than $15,000—are generally concentrated in the central part of the City of Milwaukee.

Table 8 sets forth the average household size in the Milwaukee Harbor estuary direct drainage area, its tributary river watersheds, and the Region for the years 1970 and 1980. As indicated in this table, the average household size in the Milwaukee Harbor estuary direct drainage area in 1980 was 2.33 persons. The average household size in the total study area was 2.52 persons in 1980 and, in the seven-county Southeastern Wisconsin Region, was 2.75 persons. The Milwaukee Harbor estuary direct drainage area thus had the smallest average household size within the total study area during 1980. Table 8 also indicates that average household size, both in the geographic components of the study area and in the Region as a whole, decreased significantly between 1970 and 1980. The average household size declined from 3.05 persons in 1970 to 2.52 persons in 1980 in the total study area, and

Map 10

AVERAGE HOUSEHOLD INCOME WITHIN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1980



The average annual household income within the study area in 1979 was estimated at $21,410, which was lower than the $22,760 average for the Region. The lowest average household incomes—less than $15,000 per year—are concentrated in the Milwaukee Harbor estuary direct drainage areas, while the highest average household incomes—in excess of $35,000 per year—are located in the northeastern Milwaukee County, Southeastern Ozaukee County, and eastern Waukesha County portions of the study area.

Source: SEWRPC.

from 3.20 persons in 1970 to 2.75 persons in 1980 in the Region. These observed decreases in average household size reflect the influence of such socioeconomic factors as declining birthrates and the establishment of more single-person households.

The geographic distribution of selected average household sizes throughout the study area is shown on Map 11. As shown on this map, although the overall average household size in the Milwaukee Harbor estuary was below the average for the total study area and the Region as a whole, there was a concentration of higher-than-average household sizes in the northern and central portions of the direct drainage area. In general, however, the larger average household sizes were found in the more rural portions of the study area and the smaller average household sizes were found in the more urbanized areas.

In summary, the Milwaukee Harbor estuary direct drainage area is characterized by a resident population which is, on the average, younger and less affluent than the resident population in its three tributary river watersheds and in the Region as a whole and which is dwelling in smaller households than is the population of the river watersheds and the Region. The most notable change in the characteristics of the resident population within the direct drainage area between 1970 and 1980 was a decrease in the average age of the population, while for the individual tributary river watersheds, the total study area, and the Region as a whole, the average age of the resident population increased between 1970 and 1980. Also notable is the fact that the resident population within the direct drainage area exhibited the greatest absolute and relative decrease in average household income between 1970 and 1980, compared with the average household income of population within its tributary river watersheds, the total study area, and the Region as a whole.

Economic Base: Changes in the population of the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds may be related to changes in economic activity within the study area. This is true not only because population migration patterns and trends in an area are dependent, in part, upon available job opportunities, but also because jobs must ultimately be available to sustain population increases due to natural increase, and to prevent a forced out-migration of young residents initially entering the labor force. Changes in the level of industrial and agricultural activity in the Milwaukee Harbor estuary direct

Table 8

AVERAGE HOUSEHOLD SIZE IN THE MILWAUKEE HARBOR ESTUARY, ITS TRIBUTARY RIVER WATERSHEDS, AND THE REGION: 1970 AND 1980

Watershed	Total Household Population[a]		Total Year-Round Occupied Housing Units		Average Persons per Household		Change in Average Household Size
	1970	1980	1970	1980	1970	1980	1970-1980
Milwaukee Harbor Estuary Direct Drainage Area	292,663	242,595	105,259	103,957	2.78	2.33	-0.45
Kinnickinnic River[b] . .	115,147	101,381	37,727	41,343	3.05	2.45	-0.60
Menomonee River[b] . .	276,369	264,715	84,695	101,999	3.26	2.60	-0.66
Milwaukee River[b] . . .	318,316	336,868	100,613	127,249	3.16	2.65	-0.51
Total Study Area	1,002,495	945,559	328,294	374,548	3.05	2.52	-0.53
Southeastern Wisconsin Region	1,714,200	1,724,654	536,486	627,955	3.20	2.75	-0.45

[a] *Total household population represents the total population minus the number of persons residing in group-quartered dwellings.*

[b] *Not including that portion of the watershed lying within the Milwaukee Harbor estuary direct drainage area.*

Source: U. S. Bureau of Census and SEWRPC.

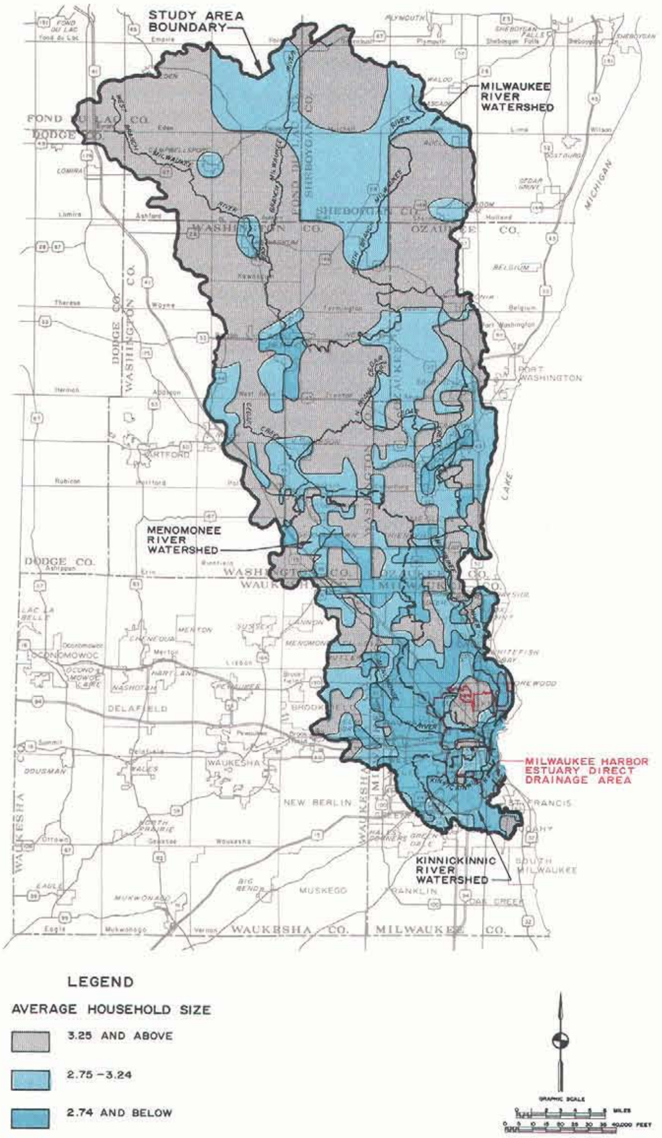
drainage area and its tributary river watersheds have had a substantial influence on the pattern of population growth and distribution within the study area.

Industrial Activity: Figure 4 shows the relative concentrations of jobs by eight major industrial groups in 1980 for the Milwaukee Harbor estuary direct drainage area, and the Kinnickinnic, Menomonee, and Milwaukee River watersheds. For comparative purposes, Figure 4 also shows the relative concentration of these jobs for the seven-county Southeastern Wisconsin Region. As shown in this figure, total employment both in the study area and in the Region is highly concentrated in manufacturing, with over 30 percent of the total jobs being in the manufacturing sector. As for the Region as a whole, the wholesale and retail trade, private service, and government service and education sectors constitute the next largest employers in the total study area. Comparing the Milwaukee Harbor estuary direct drainage area to the other three watersheds in the total study area, it is evident from Figure 4 that the direct drainage area contains the highest concentration of employment in the transportation, utilities, and communication; finance, insurance, and real estate; private services; and government service and education sectors. As may be expected because of its heavily urbanized character, the Milwaukee Harbor estuary direct drainage area contains a low concentration of employment in the construction and mining sector, and has no employment in the agricultural sector.

Figure 5 indicates the relative concentration of jobs within the manufacturing sector—the dominant industry group in both the study area and the Region--in 1980. As indicated in this figure, the principal type of manufacturing in both the study area and the Region is nonelectrical machinery, which accounts for about 28 percent of the jobs in the manufacturing sector in the Region and about 29 percent of such jobs in the study area. The next largest manufacturing employers in both the Region and the study area are engaged in the manufacture of electrical equipment, fabricated metal products, and miscellaneous manufacturing products. Within the Milwaukee Harbor estuary

Map 11

AVERAGE HOUSEHOLD SIZE IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1980

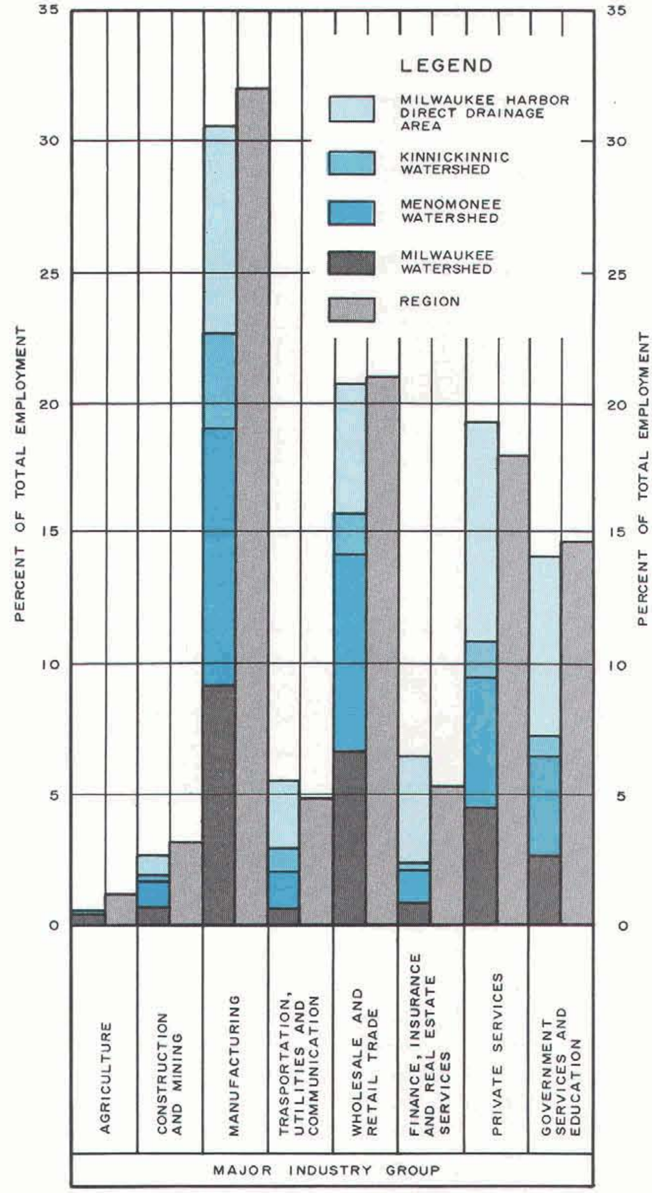


The average household size within the study area was 2.52 persons in 1980. In general, the larger households were located in the more rural portions of the study area, although larger households were also found in the central and north-central portions of the Milwaukee Harbor estuary direct drainage area. Smaller households were found primarily in Milwaukee County in a generally concentric pattern encompassing the higher household sizes found in the central portion of the County.

Source: SEWRPC.

Figure 4

DISTRIBUTION OF TOTAL EMPLOYMENT BY MAJOR INDUSTRY GROUP BY WATERSHED: 1980



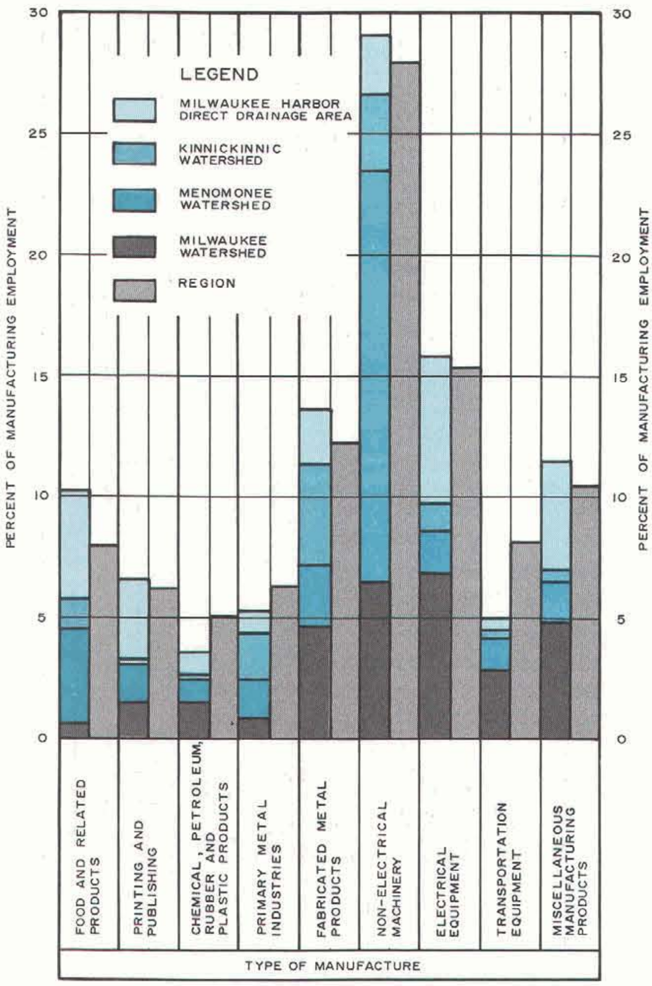
Source: U. S. Department of Industry, Labor and Human Relations; and SEWRPC.

direct drainage area itself, the largest manufacturing employers are engaged in the manufacture of electrical equipment, miscellaneous manufacturing products, and food and related products.

About 64 percent of the total number of jobs available in the Region during 1980 were located within the Milwaukee Harbor estuary direct drainage area and its three tributary watersheds. About 23 percent, 19 percent, 16 percent, and 6 percent of the total jobs in the Region during 1980 were located in the Milwaukee Harbor estuary direct drainage area, the Menomonee River watershed, the Milwaukee River watershed, and the Kinnickinnic River watershed, respectively. For

Figure 5

DISTRIBUTION OF MANUFACTURING EMPLOYMENT BY TYPE OF MANUFACTURING IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA, ITS TRIBUTARY RIVER WATERSHEDS, AND THE REGION: 1980



Source: Wisconsin Department of Industry, Labor and Human Relations; and SEWRPC.

comparative purposes, and to illustrate the geographic distribution of employment in the Region, Map 12 presents a generalized representation of job locations in southeastern Wisconsin during 1980. As shown on this map, Milwaukee County, in particular the estuary direct drainage area, had the highest concentration of job availability in the Region during 1980.

Agricultural Activity: Although agricultural activity is not present in the Milwaukee Harbor estuary direct drainage area because of its intensely urbanized nature, such activity is present in its tributary river watersheds and has significant impacts on the surface water quality in the estuary. Runoff from croplands and animal feedlots can increase the nutrient loadings to the tributary river systems and ultimately increase the water pollution problem in the Milwaukee Harbor estuary.

Most of the agricultural activity in the study area is located within Fond du Lac, Ozaukee, Sheboygan, and Washington Counties, with secondary activity scattered over the northwest corner of Milwaukee County and the northeast portion of Waukesha County. Table 9 provides a summary of selected key agricultural indicators in Fond du Lac, Milwaukee, Ozaukee, Sheboygan, Washington, and Waukesha Counties for the years 1974 and 1979. As shown in this table, the number of farms and the acreage farmed within these six counties declined over this five-year period, while the average farm size, the value of farm products sold, and the average value of farm products sold per farm increased. These data, particularly the statistics on the acreage farmed, suggest that agricultural activity is decreasing within the study area. Nevertheless, the existing level of agricultural activity in the tributary river watersheds will continue to contribute to the water pollution problems in the Milwaukee Harbor estuary in the absence of further nonpoint source pollution abatement controls.

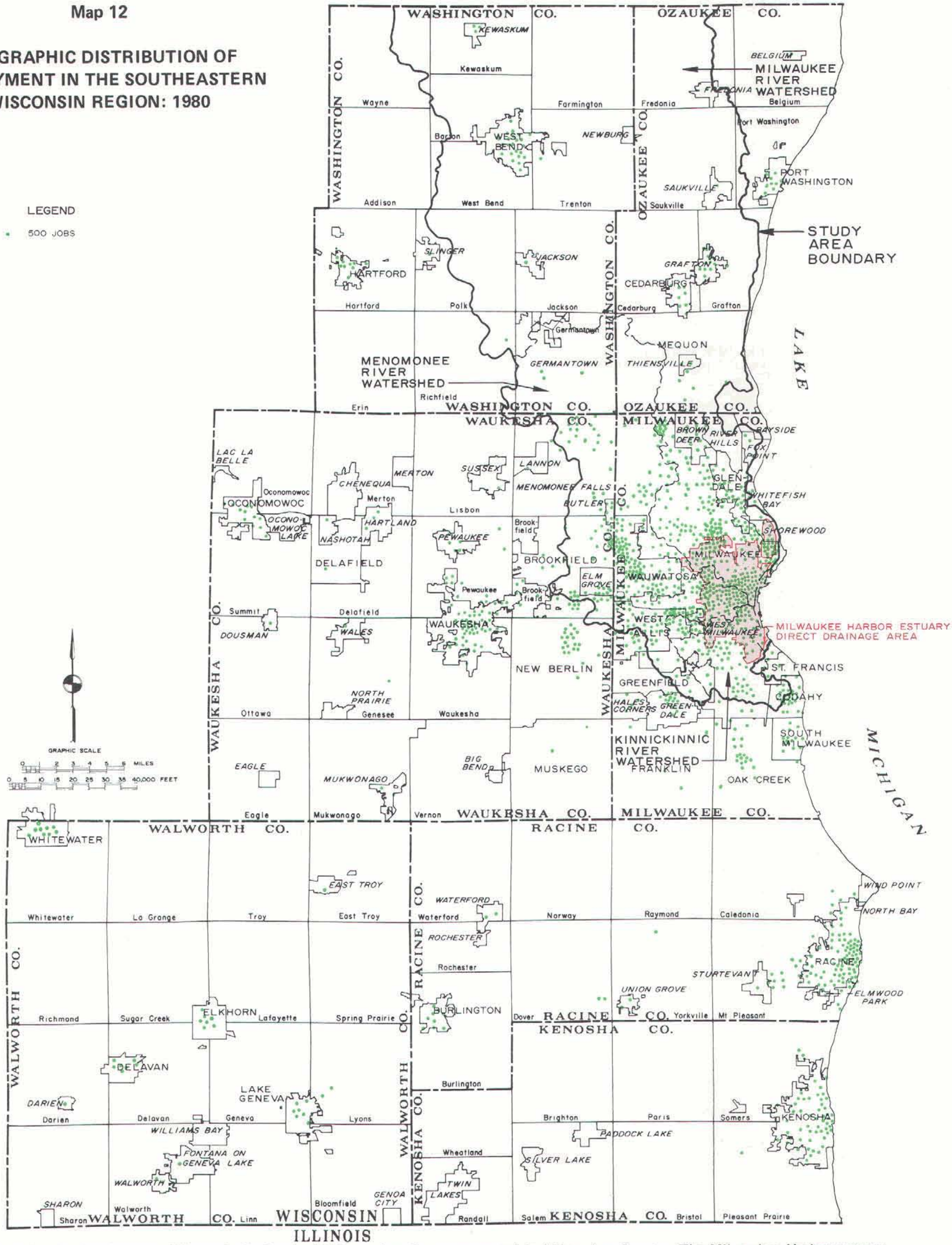
Land Use

One of the central concepts underlying water resources planning is that land use and water quality are inextricably interrelated. The type, intensity, and spatial distribution of land uses determine, to a large extent, the pollutant loadings on surface water systems. Water resource demands can be correlated directly with the quantity and type of land use, as can water quality deterioration. The existing land use pattern can best be understood within the context of its historical development. Accordingly, attention is focused herein upon historic as well as existing land use development patterns.

Historic Growth Patterns: The first permanent European settlement in the Region was established in 1795 as a trading post on the east side of the Milwaukee River, just north of what is now Wisconsin Avenue in the City of Milwaukee. The origins of most of the major cities and villages within the Region can be traced to the establishment of certain types of agricultural services such as saw and grist mills. The location of these earliest urban activities was heavily influenced by water

Map 12

GEOGRAPHIC DISTRIBUTION OF EMPLOYMENT IN THE SOUTHEASTERN WISCONSIN REGION: 1980



Employment in the Southeastern Wisconsin Region in 1980 was heavily concentrated in Milwaukee County. The Milwaukee Harbor estuary direct drainage area in particular exhibited the highest concentration of job availability within the Region in 1980.

Source: SEWRPC.

Table 9

AGRICULTURAL INDICATORS IN MILWAUKEE, OZAUKEE, WASHINGTON, WAUKESHA, FOND DU LAC, AND SHEBOYGAN COUNTIES: 1974-1979

	Milwaukee County				Ozaukee County				Washington County				Waukesha County			
	Year		Change		Year		Change		Year		Change		Year		Change	
Indicator	1974	1979	Absolute	Percent	1974	1979	Absolute	Percent	1974	1979	Absolute	Percent	1974	1979	Absolute	Percent
Number of Farms	200	170	-30	-15.0	660	560	-100	-15.2	1,410	1,230	-180	-12.8	1,230	1,000	-230	-18.7
Acreage Farmed	17,100	15,000	-2,100	-12.3	107,000	99,800	-7,200	-6.7	208,200	198,000	-10,200	-4.9	182,200	170,100	-12,100	-6.6
Average Farm Size	85.5	88.2	2.7	3.2	162.1	178.2	16.1	9.9	147.7	161.0	13.3	9.0	148.1	170.1	22.0	14.9
Value of Farm Products Sold (thousands of dollars)	7,075[a]	8,379[b]	1,304	18.4	15,601[a]	22,880[b]	7,279	46.7	31,329[a]	47,085[b]	15,756	50.3	20,104[a]	27,500[b]	7,396	36.8
Average Value of Farm Products Sold per Farm	35.4	49.3	13.9	39.3	23.6	40.9	17.3	73.3	22.2	38.3	16.1	72.5	16.3	27.5	11.2	68.7

	Fond du Lac County				Sheboygan County				Total			
	Year		Change		Year		Change		Year		Change	
Indicator	1974	1979	Absolute	Percent	1974	1979	Absolute	Percent	1974	1979	Absolute	Percent
Number of Farms	2,350	2,150	-200	-8.5	1,870	1,680	-190	-10.2	7,720	6,790	-930	-12.0
Acreage Farmed	407,100	392,700	-14,400	-3.5	255,300	246,100	-9,200	-3.6	1,176,900	1,121,700	-55,299	-4.7
Average Farm Size	142.2	154.4	12.2	8.6	136.5	146.5	10.0	7.3	142.2	154.4	12.2	8.6
Value of Farm Products Sold (thousands of dollars)	60,425	102,092	41,667	69.0	37,885	64,379	26,494	69.9	172,419	272,315	99,896	57.9
Average Value of Farm Products Sold per Farm	25.7	47.5	21.8	84.8	20.3	38.3	18.0	88.7	23.9	40.3	16.4	68.6

[a] *1973 data.*

[b] *1978 data.*

Source: U. S. Census of Agriculture and SEWRPC.

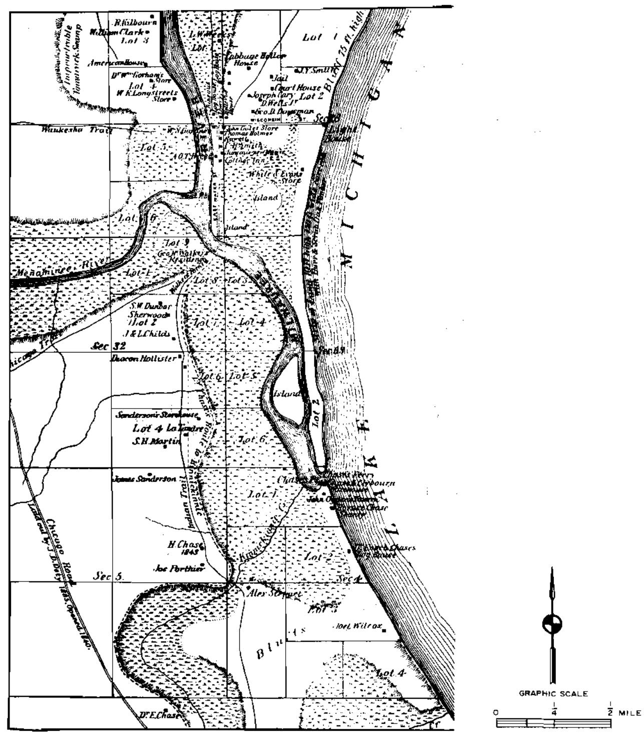
power and water transportation needs. The rapid settlement by Europeans of what is now the Southeastern Wisconsin Region began following the Indian cessations of 1829 and 1833, which transferred to the federal government ownership of all of the lands that now comprise the State of Wisconsin south of the Fox River and east of the Wisconsin River. After the end of the Blackhawk War of 1832, federal land surveyors began to survey, subdivide, and monument the federal lands, and by 1836 the U. S. Public Land Survey had been completed within the Region. The subsequent sale of the public lands brought many settlers from New England, Germany, Austria, and Scandinavia. Initial urban development occurred along the Lake Michigan shoreline at the ports of Milwaukee, Port Washington, Racine, and Southport (now Kenosha), as these settlements were more directly accessible to immigration from the East Coast through the Erie Canal-Great Lakes transportation route. The sheltered harbor formed by the confluence of the Kinnickinnic, Menomonee, and Milwaukee Rivers, as shown on Map 13, made this area particularly attractive to early settlers.

The settlement of the Milwaukee Harbor estuary and its three tributary river watersheds followed establishment of the port city of Milwaukee, with the pattern of historic urban land use development occurring as shown on Map 14. Almost without exception, the pioneer villages in the study area were located along the Kinnickinnic, Menomonee, and Milwaukee Rivers, or on major tributaries to those rivers. Most of the early development in the study area resulted from the sale of nearly 500,000 acres of farmland, at a minimum price of $1.25 per acre, during the great land sale of February and March of 1839. Thus, the period from 1840 to 1860 was one of rapid settlement in the rural areas within the watersheds, with relatively little growth being experienced by the villages.

Until about 1850, the Great Lakes provided Milwaukee with its principal link to other portions of the developing nation. Thus, the early growth and development of the Milwaukee area was heavily dependent on waterborne commerce which, in turn, required safe harborage and good port facilities. The first major port improvement, initially proposed in 1837 and finally completed in 1857, consisted of a change in the location of the entrance to the inner harbor. In this project, which came to be known as the "straight cut," the entrance to the inner harbor was moved to its present location about one-half mile north of the original, natural confluence of the Milwaukee River with Lake Michigan.

Map 13

MILWAUKEE RIVER HARBOR IN 1836



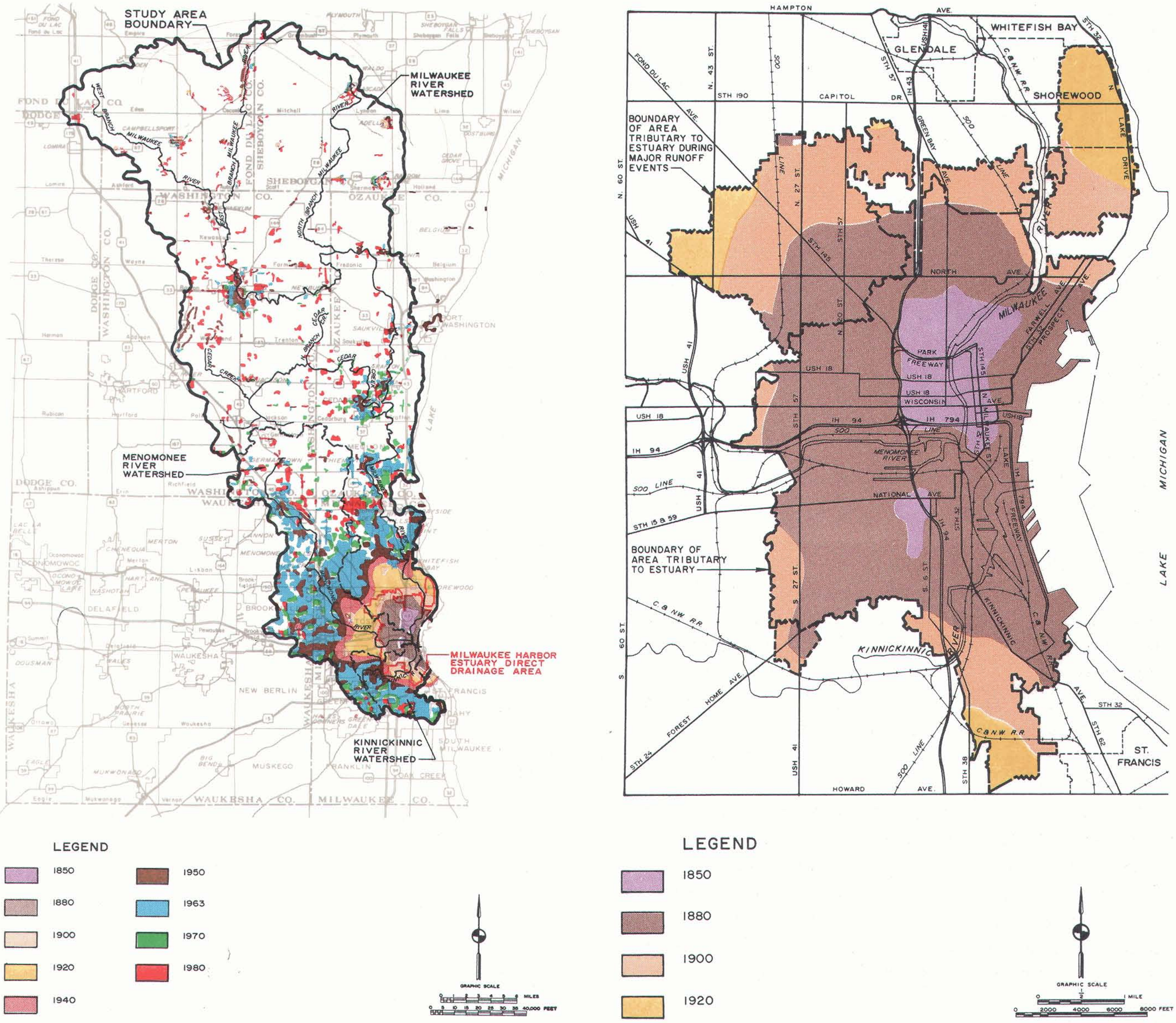
A sheltered harbor formed by the confluence of three rivers attracted the first of Milwaukee's European settlers in the 1830's and was an important factor in the development of the City of Milwaukee. Development of a port began in 1857 when the natural outlet of the Milwaukee and Kinnickinnic Rivers to Lake Michigan was filled and a new passage to Lake Michigan was cut about one-half mile north of the original river mouth. The extensive wetland area, including the "impenetrable Tamarack Swamp" that once existed near the confluence of the Kinnickinnic, Menomonee, and Milwaukee Rivers, has since been filled and developed for industrial, commercial, navigational, and residential uses.

Source: Milwaukee County Historical Society.

At the same time initial improvements to the Port of Milwaukee were being considered, proposals were advanced for connecting Milwaukee with the Southwest through the construction of canals. One project, the Milwaukee and Rock River Canal, was proposed to run from the Milwaukee River at a point near E. North Avenue parallel to the river along what is now Commerce Street to join the Menomonee River. The route was then to follow the Menomonee River, and to cut through to the Rock River, thence through the four lakes of the Madison area to the Wisconsin River, and thence to the Mississippi River. Ground was broken for the canal on July 4, 1839. A dam built to control water supply for the canal was constructed, and within three years, that portion of the canal extending along the Milwaukee River from North Avenue to a point near Cherry Street had been

Map 14

HISTORIC URBAN DEVELOPMENT IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1850-1980



The urbanization process within southeastern Wisconsin began in the mid-nineteenth century and continues to the present. Urbanization has generally occurred in a radial pattern outward from the historic urban centers in the Region. Almost without exception, the initial settlements within the study area were located along the Kinnickinnic, Menomonee, and Milwaukee Rivers. The Milwaukee Harbor estuary direct drainage area was almost entirely urbanized by 1920. Much of the urbanization in the tributary river watershed areas occurred as the population in the direct drainage area migrated outward from this historic urban center into the fertile farmlands and woodlands in the more rural portions of the study area.

Source: SEWRPC.

excavated. Because, with the development of railway transportation, other links in the proposed canal system to the Mississippi River were never constructed, the canal along the Milwaukee River was eventually filled. The last vestiges of the Milwaukee and Rock River Canal disappeared in 1927, when the Harbor Commission and the Common Council of the City of Milwaukee authorized the vacating and filling of the last section remaining between Walnut and Cherry Streets.

In addition to the canal along the Milwaukee River, several canals were constructed along the Menomonee River in order to promote development in the Menomonee Valley. The Menomonee Valley canal system, originally proposed in 1868 and completed in 1874, added about 13,700 feet of dockage to the inner harbor. This canal system included four major east-west canals and one major north-south canal. From north to south the four east-west canals were identified as the Kneeland Canal (named after one of the major Valley developers), the Menomonee or North Menomonee canal, the South Menomonee canal, and the Burnham canal (named after the Burnham brothers, developers of the Valley and owners of a brickyard abutting this canal). The major north-south canal, located just west of 6th Street and connecting the North and South Menomonee canals, was named the Holton canal after the Milwaukee businessman who advocated a system of north-south canals in the Valley. Although the Menomonee Valley canal system greatly advanced economic development in the Valley—handling large volumes of grain, package goods, and coal—the construction of new mooring facilities in the outer harbor, the decreased use of coal, and poor maintenance and dredging practices acted to diminish the importance of the canal system over time. At the present time, only the South Menomonee canal, the Burnham canal, and a small vestige of the Holton canal remain unfilled. Only the South Menomonee canal is maintained for navigation over its full length through periodic maintenance dredging.

Industrial development began to occur rapidly following completion in 1855 of a railroad connecting the Cities of Chicago and Milwaukee. Milwaukee became the most important manufacturing center in the Region, primarily due to the immigration of skilled artisans and mechanics from Germany. Nearly all of the City's major industrial plants can trace their beginnings to the small backyard shops of these immigrants. The rapidly expanding manufacturers had their foundations in the raw materials supplied by the farms and forests within the study area and the State, and its neighbors.

During the 35-year period from 1910 to the end of World War II in 1945, the trend toward more intensive land use continued, marked particularly by the increasing mechanization of farming and the introduction of a modern, all-weather, high-speed highway system. Since 1950, an affluent and mobile population has been converting land from rural to urban use for residential, commercial, institutional, and transportation purposes at an unprecedented rate. In the 17-year period extending from 1963 to 1980, land devoted to urban uses in the Kinnickinnic, Menomonee, and the in-Region portion of the Milwaukee River watersheds increased by approximately 31.7 square miles, or about 17 percent. Much of this urbanization occurred as the population in the Milwaukee Harbor estuary direct drainage area migrated outward from the historic urban center into the fertile farmlands and woodlands in the more rural portions of the study area.

Existing Land Use: The general pattern of existing land use within the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds is shown on Map 15, and more detailed land use data are presented in Table 10. The nine land use categories quantified in Table 10 are a summary of 79 detailed land use categories used by the Commission in the preparation of the 1980 detailed land use inventory.

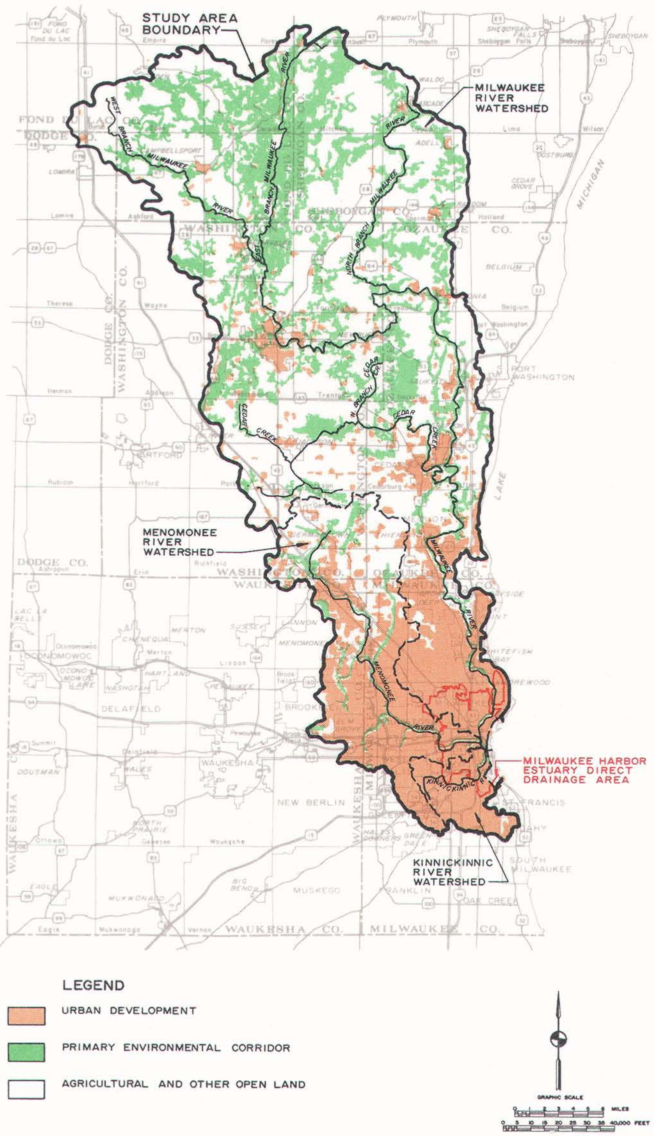
As shown on Map 15 and indicated in Table 10, the Milwaukee Harbor estuary direct drainage area is predominantly devoted to urban land uses—about 93 percent of the area is in urban land uses, with only about 7 percent of the area in the more rural categories of open land use and surface waters. The dominant land uses in the direct drainage area are transportation and utilities and residential uses, accounting for about 16 square miles, or almost 72 percent of all land in the direct drainage area.

Considering the total study area, about 639 square miles, or about 74 percent of the total 858-square-mile area, is in rural land use, predominantly agricultural use. The largest category of urban land use within the total study area is residential, accounting for 101 square miles, or almost 12 percent of the total study area. Transportation and utilities account for approximately 76 square miles, or about 9 percent of the total study area, while all other urban land uses individually are less than 15 square miles in areal extent, or comprise slightly more than 4 percent of the total study area.

Because of the distinct diversity in various land uses throughout the study area—from the predominantly urban land uses in the southeastern portion of the more rural portion of the study area to the

Map 15

GENERALIZED LAND USE IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1980



As of 1980, about 93 percent of the Milwaukee Harbor estuary direct drainage area was devoted to urban land uses. The dominant urban land uses were transportation and utilities and residential, which together account for more than 72 percent of the total land area in the estuary direct drainage area. Considering the entire study area, approximately 26 percent of the total area was in urban use and 74 percent was in rural use as of 1980. More than one-half of the rural lands in the total study area were in agricultural use. Primary environmental corridors encompass almost all of the best woodlands, wetlands, and wildlife habitat areas and almost all the streams and associated undeveloped floodlands and shorelands, as well as many of the significant topographic, geologic, and historic features of the study area. Primary environmental corridors encompassed about 20 percent of the entire study area in 1980. The preservation of these corridors in compatible open space uses is essential to maintaining the quality of the environment in the study area.

Source: SEWRPC.

agricultural land uses in the northern portion of the study area—there are different types of demands on the water resources within the three tributary river watersheds.

New Development Projects: At the request of the Technical Advisory Committee, the City of Milwaukee Department of City Development collated an inventory of all known new public and private sector development projects within the Milwaukee Harbor estuary direct drainage area that would be positively influenced by improved water quality in the estuary area. It was the opinion of the Committee that, since such development projects would be positively influenced by the water resources of the estuary, an understanding of the type and nature of these specific development projects, and an awareness of the possible extent to which new development may be expected to occur in the area, would be useful in the determination of the water use objectives for the estuary.

Table 11 lists development projects as assembled by the Milwaukee Department of City Development in the Milwaukee Harbor estuary direct drainage area. As indicated in Table 11, and located on Map 16, there are 50 development projects that have been proposed or recently completed within the direct drainage area of the estuary. Of these 50 projects, 2 may be defined as public works projects, 12 as commercial projects, 13 as recreational projects, 10 as residential projects, 1 as an industrial project, 3 as institutional projects, 4 as mixed use projects, and 5 as miscellaneous projects. It should be noted that some projects have been recently completed, some projects are in various stages of planning, and some projects may never come to fruition. This inventory was collated merely to provide an indication of the direction and nature of potential development in the Milwaukee Harbor estuary direct drainage area which would be positively influenced by improved water quality in the estuary area.

Public Utility Base

Sanitary Sewer Service: The Milwaukee Harbor estuary direct drainage area is located entirely within the existing service area of the Milwaukee Metropolitan Sewerage District. Sanitary sewage is collected and transmitted for treatment and disposal to the Jones Island sewage treatment plant located along the Lake Michigan shoreline. The Milwaukee Harbor estuary direct drainage area is served entirely by a combined sanitary and

Table 10

LAND USE IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1980

Land Use Category	Kinnickinnic River Watershed Area[a]			Menomonee River Watershed Area[a]			Milwaukee River Watershed Area[a]			Milwaukee Harbor Estuary Direct Drainage Area			Total Study Area	
	Area in Square Miles[b]	Percent of Watershed	Percent of Study Area	Area in Square Miles[b]	Percent of Watershed	Percent of Study Area	Area in Square Miles[b]	Percent of Watershed	Percent of Study Area	Area in Square Miles[b]	Percent of Watershed	Percent of Study Area	Area in Square Miles[b]	Percent of Study Area
Urban														
Residential	6.93	34.68	0.81	34.62	26.48	4.03	51.71	7.54	6.02	7.74	35.10	0.90	100.99	11.77
Commercial	0.57	2.85	0.07	1.99	1.52	0.23	2.28	0.33	0.27	1.14	5.17	0.13	5.98	0.70
Industrial	1.07	5.36	0.12	3.13	2.39	0.37	3.88	0.56	0.45	1.34	6.07	0.16	9.39	1.09
Transportation and Utilities	7.10	35.54	0.83	21.68	16.59	2.53	39.71	5.79	4.62	8.10	36.74	0.94	76.58	8.92
Governmental and Institutional	1.59	7.96	0.18	4.85	3.71	0.57	4.86	0.71	0.57	1.30	5.90	0.15	12.60	1.47
Recreational	0.78	3.90	0.09	4.33	3.32	0.50	7.63	1.12	0.89	0.82	3.72	0.10	13.56	1.58
Subtotal	18.04	90.29	2.10	70.60	54.01	8.23	110.07	16.05	12.82	20.44	92.70	2.38	219.10	25.53
Rural														
Agricultural	0.18	0.90	0.03	35.90	27.46	4.18	370.68	54.09	43.20	--	--	--	406.81	47.41
Open Land	1.73	8.66	0.20	23.64	18.09	2.75	192.89	28.14	22.48	1.12	5.08	0.13	219.38	25.56
Surface Water	0.03	0.15	0.00	0.58	0.44	0.07	11.74	1.72	1.37	0.49	2.22	0.06	12.84	1.50
Subtotal	1.94	9.71	0.23	60.12	45.99	7.00	575.31	83.95	67.05	1.61	7.30	0.19	639.03	74.47
Total	19.98	100.00	2.33	130.72	100.00	15.23	685.38	100.00	79.87	22.05	100.00	2.57	858.13	100.0

[a] *Excludes that portion of the watershed lying within the Milwaukee Harbor estuary direct drainage area.*

[b] *These figures represent the total area as determined by approximating the study area boundaries by U. S. Public Land Survey quarter sections and summing the quarter-section total.*

Source: SEWRPC.

stormwater sewerage system. During even minor rainfall and snowmelt events, this combined system discharges raw sewage with precipitation and snowmelt waters to the Kinnickinnic, Menomonee, and Milwaukee Rivers in the estuary and to Lake Michigan. The water quality impacts of combined sewer discharges in the estuary are addressed in a later chapter of this report.

Virtually all sanitary sewer service in the study area is provided by public agencies. These agencies generally take the form of a metropolitan district in the case of utilities providing areawide sewer service, a department in the case of utilities providing sewer service to an incorporated municipality, and a town sanitary or utility district in the case of utility sewer service to an unincorporated area. As shown in Table 12, there are a total of 42 existing and two proposed sanitary sewerage systems within the study area. Of the 42 existing sanitary sewerage systems, 35 are operated by public agencies and seven are operated by private agencies and serve only individual institutional or industrial concerns. There are 16 sewage treatment plants serving the 35 publicly operated sanitary sewerage systems.

About 186 square miles, or about 22 percent of the total study area, and approximately 903,900 persons, or about 93 percent of the total study area population, were served by public sanitary sewerage facilities in 1980. The existing public sanitary sewer service areas in the study area, and those areas proposed to be served by public sanitary sewerage facilities by the year 2000, are shown on Map 17.

Water Supply Service: Most of the water supply service within the study area is provided by public water utilities. In 1975, there were a total of 25 publicly owned water utilities within the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds. The existing service areas of these utilities are shown on Map 18 and identified in Table 13. Within the direct drainage area itself, public water supply is provided by the Milwaukee Water Works and the Shorewood Municipal Water Utility. Both of these utilities use Lake Michigan as their source of domestic water supply. All of the 11 water utilities within Milwaukee County, in fact, use Lake Michigan as a source of water supply, while the remaining 14 water utilities all use groundwater as the source of water supply.

Table 11

DEVELOPMENT PROJECTS IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA THAT WOULD BE POSITIVELY INFLUENCED BY IMPROVED WATER QUALITY: 1986

Number on Map 16	Type of Project		Description
	Category	Nature	
C-1	Commercial	Mixed Retail	Construction of a major 15,000-square-foot mixed-use retail facility by the Upper Third Street Venture (ICRC/MGIC) at N. 3rd Street and W. North Avenue.
C-2	Commercial	Mixed Retail and Parking	MGIC 640-car parking structure at N. Milwaukee Avenue and E. Wisconsin Avenue. Includes ground-floor retail stores.
C-3	Commercial	Mixed Retail	Rehabilitation of 70,000-square-foot vacant commercial project located at 1101 W. Mitchell Street to commercial and local retail use
C-4	Commercial	Mixed Retail	Possible conversion of old Federal Building and Post Office building into some adaptive, potentially commercial, reuse.
C-5	Commercial	Office Building	Thirty-story, 730,000-square-foot Winmar Office Building at N. Milwaukee Avenue and E. Wisconsin Avenue.
C-6	Commercial	Office Building	Planned 400,000- to 500,000-square-foot office building (River Plaza) by Carley Capital Group at 110 E. Wisconsin Avenue. A temporary park has been constructed on the site.
C-7	Commercial	Office Building	418,000-square-foot office addition and 552-car parking structure for the Wisconsin Electric Power Company at W. Everett Street and N. 4th Street.
C-8	Commercial	Office Building	60,000-square-foot office building for the American Medical Buildings Corporation headquarters at the southeast corner of Kilbourn Avenue and Jefferson Street.
C-9	Commercial	Office Building	Approximately 50,000-square-foot office building at 408 E. Wells Street.
C-10	Commercial	Retail/Office	Renovation of the Iron Block building at N. Water Street and E. Wisconsin Avenue to mixed retail and office space.
C-11	Commercial	Retail Improvement	Proposed construction of a skywalk to connect the Hyatt Regency Hotel to the new Federal Building.
C-12	Commercial	Mixed	Proposed development of "Historic Milwaukee Landing"—a concept for a recreational area at the north end of the present Summerfest site.
IND-1	Industrial	Manufacturing	Usinger Sausage factory addition (15,000 square feet) on the northeast corner of N. 3rd Street and W. State Street. Two subsequent expansion phases planned but not yet scheduled.
INST-1	Institutional	Church	Planned 500-seat worship building by the Ebenezer Church of God at 3100 N. Green Bay Avenue.
INST-2	Institutional	Organizational	Planned two-story, 6,000-square-foot meeting hall addition to an existing building owned and operated by the West Indian American Association, a social fraternal organization, at N. 24th Street and W. Walnut Street.
INST-3	Institutional	Hospital	Addition to Good Samaritan Hospital under construction at N. 21st Street and W. State Street.
PW-1	Public Works	Dam	Rehabilitation of the North Avenue Dam on the Milwaukee River.
PW-2	Public Works	Port Expansion	Acquisition and development of former C&O Railroad property for the expansion of Port of Milwaukee activities.
REC-1	Recreational	Art	Proposed Sculpture Garden at the northeast corner of the existing War Memorial Center.
REC-2	Recreational	Museum	Possible addition to existing War Memorial Center under the Lincoln Memorial Bridge.
REC-3	Recreational	Marina	Proposed completion of development of the McKinley Marina, including the renovation of the former U. S. Coast Guard station into a restaurant by a private developer.
REC-4	Recreational	Marina	Potential service facility, shops, and charter fishing headquarters at the eight-acre undeveloped section of the landfill between the central and south slip areas of the McKinley Marina.
REC-5	Recreational	Marina	New boat launch and storage facility to be developed by Snug Harbor, Inc., on the Kinnickinnic River and Becher Street.
REC-6	Recreational	Island	Construction of a 17-acre recreational island in Lake Michigan off the north harbor tract and Summerfest grounds.
REC-7	Recreational	Riverwalk	Proposed development of riverwalk along the Milwaukee River between State Street and Clybourn Street.
REC-8	Recreational	Summerfest	Milwaukee World Festivals, Inc., Summerfest grounds modifications.

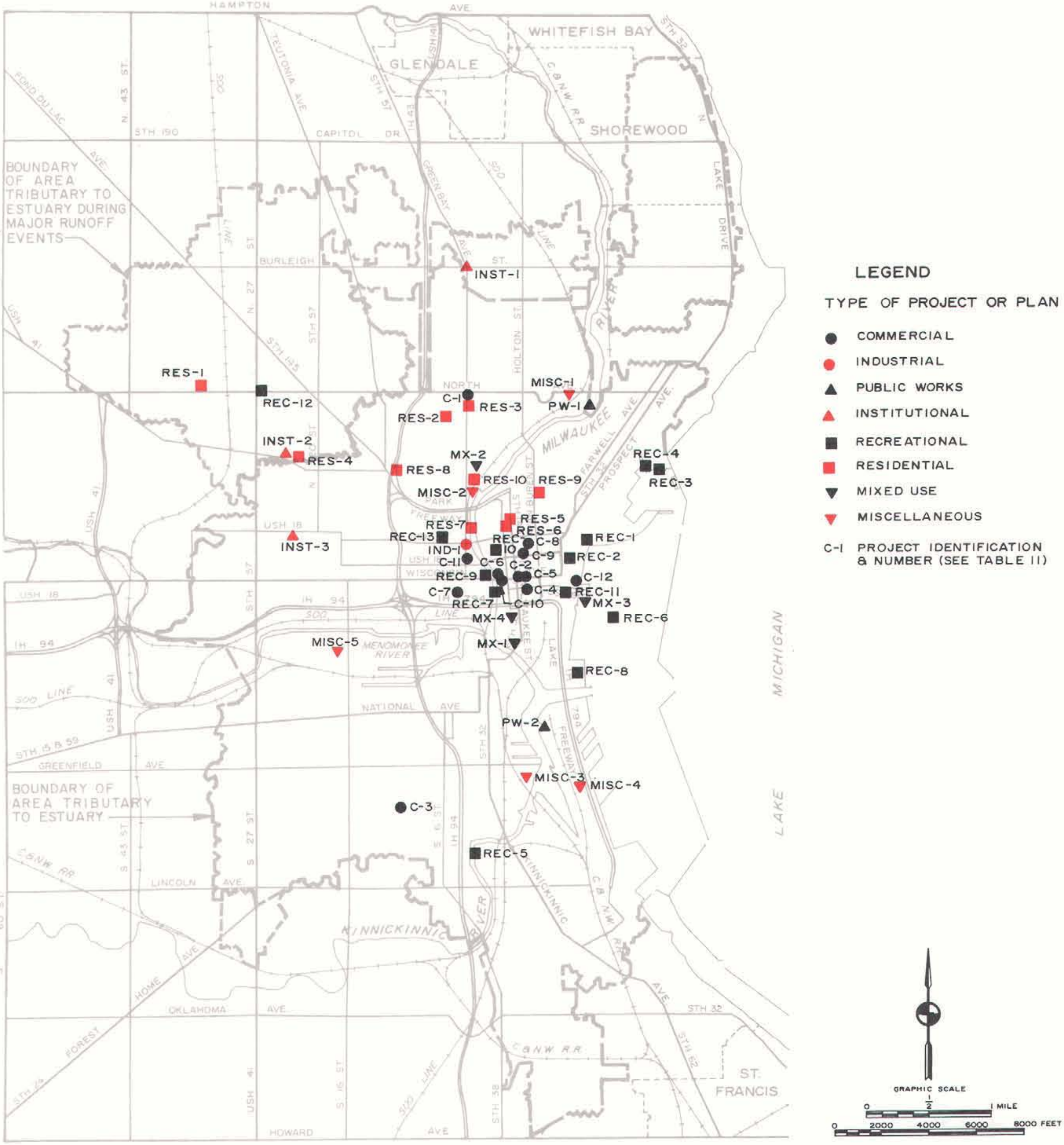
Table 11 (continued)

Number on Map 16	Type of Project		Description
	Category	Nature	
REC-9	Recreational	Theater	More intensive use of Riverside Theatre Building on the northeast corner of W. Wisconsin Avenue and N. Plankinton.
REC-10	Recreational	Theater	Development of Theater District at the southwest corner of Kilbourn Avenue and Water Street having a total area of about 300,000 to 400,000 square feet and housing the Milwaukee Repertory Theatre, a hotel, shops, and restaurants.
REC-11	Recreational	Park	Potential development of cleared Lake Freeway-North lands for park and other development.
REC-12	Recreational	Park	Development of recreational areas in portions of the former Park West corridor.
REC-13	Recreational	Sports	Construction of a sports/entertainment complex—the Bradley Center—located adjacent to the Milwaukee Exposition Center and Arena.
RES-1	Residential	Single Family	Residential development in the former Park West corridor.
RES-2	Residential	Single Family	Construction of up to 13 owner-occupied single-family residences in Halyard Renewal Project at N. 4th Street and W. Lloyd Street.
RES-3	Residential	Multi-family	Planned 50-unit residential addition by Mt. Zion Church, nonprofit housing sponsor, to the elderly apartment building at N. 3rd Street and W. Garfield Avenue.
RES-4	Residential	Multi-family	Construction of up to 12 duplex units at N. 23rd Street and W. Walnut Street by Milwaukee Building Trades Council.
RES-5	Residential	Multi-family	Courtyard Square, a 118-unit apartment building under construction at N. Milwaukee Avenue and W. Juneau Avenue.
RES-6	Residential	Multi-family	Conversion of the former Blatz Brew House at 1101 N. Broadway into residential units.
RES-7	Residential	Multi-family	A 24-unit residential rowhouse development by Ogden River Houses, Inc., at 1100 N. Edison Street.
RES-8	Residential	Mixed	Construction of up to 16 single-family and duplex structures for replacement housing in conjunction with the Hillside Transit facility at either N. 11th Street and W. Galena Street or N. 10th Street and W. Brown Street.
RES-9	Residential	Mixed	Reuse of lands cleared in the Park East corridor for mainly residential and recreational development.
RES-10	Residential	Multi-family	Construction of an apartment and townhouse complex in the area known as "Yankee Hill" adjacent to the Juneau Village Shopping Center on N. Jackson Street.
MX-1	Mixed Use	Commercial/ Residential	Conversion of old loft building at 241 N. Broadway to 40 residential units and commercial space.
MX-2	Mixed Use	Commercial/ Industrial	Conversion of old Schlitz Brewery into retail, office, and manufacturing space.
MX-3	Mixed Use	Commercial/ Recreational	Commercial ferry landing or recreational boat basin at the south end of the Municipal Pier.
MX-4	Mixed Use	Commercial/ Residential	Private residential and commercial redevelopment near "Commission Row."
MISC-1	Miscellaneous	RR Land Conversion	The Humboldt railroad yard at W. North Avenue and Humboldt Boulevard will be offered for sale, making that land available for development.
MISC-2	Miscellaneous	General Development	Retirement of the Commerce Street power plant in 1990 could provide for an adaptive reuse development possibility in conjunction with the Schlitz complex renovation and the riverwalk concept.
MISC-3	Miscellaneous	General Development	The 45-acre site on E. Greenfield Avenue formerly housing the Milwaukee Solvay Coke Company may represent a primary area for waterfront development.
MISC-4	Miscellaneous	General Development	The tank farms on Jones Island are to be removed at the end of the existing lease period, which enables this land to be placed in other land uses.
MISC-5	Miscellaneous	Beautification	As a part of the City of Milwaukee's beautification program for the Menomonee River Valley, junkyards and coal storage yards were acquired and cleared for more intensive uses, and street trees and sidewalk-to-curb landscaping were installed wherever possible.

Source: City of Milwaukee Department of Development and SEWRPC.

Map 16

DEVELOPMENT PROJECTS IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA THAT WOULD BE POSITIVELY INFLUENCED BY IMPROVED WATER QUALITY: 1986



An inventory of development projects, as conducted by the City of Milwaukee, Department of City Development, indicated that there were a significant number of new construction and rehabilitation projects proposed, underway, or recently completed in the Milwaukee Harbor estuary direct drainage area. Of the 50 projects identified under this inventory effort, 2 were public works projects; 12 commercial projects; 13 recreational projects; 10 residential projects; 1 industrial project; 3 institutional projects; 4 mixed use projects; and 5 miscellaneous projects.

Source: SEWRPC.

Table 12

AREAS SERVED BY PUBLIC AND PRIVATE SEWAGE TREATMENT FACILITIES IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1980

Sewage Treatment Facility or Collection System		Area Served Within (square miles)				
Name	Location	Kinnickinnic River Watershed	Menomonee River Watershed	Milwaukee River Watershed	Milwaukee Harbor Estuary Direct Drainage Area	Total
Fond du Lac County						
Village of Campbellsport Sewage Treatment Facility	Village of Campbellsport	--	--	0.44	--	0.44
Kettle Moraine Lake Sewage Treatment Facility[a]	Town of Osceola	--	--	N/A	--	N/A
Forest Lake Sewage Treatment Facility[a]	Town of Auburn	--	--	N/A	--	N/A
	Subtotal	--	--	0.44	--	0.44
Milwaukee County						
City of Cudahy Collection System	City of Cudahy	1.47	--	--	--	1.47
City of Glendale Collection System	City of Glendale	--	--	5.85	--	5.85
City of Greenfield Collection System	City of Greenfield	2.32	3.18	--	--	5.50
City of Milwaukee Collection System	City of Milwaukee	14.42	21.96	24.98	21.12	82.48
City of Wauwatosa Collection System	Cityof Wauwatosa	--	13.23	--	--	13.23
City of West Allis Collection System	City of West Allis	1.66	7.94	--	--	9.60
Village of Bayside Collection System	Village of Bayside	--	--	0.63	--	0.63
Village of Brown Deer Collection System	Village of Brown Deer	--	--	4.37	--	4.37
Village of Fox Point Collection System	Village of Fox Point	--	--	1.21	--	1.21
Village of Greendale Collection System	Village of Greendale	--	0.10	--	--	0.10
Village of River Hills Collection System	Village of River Hills	--	--	4.11	--	4.11
Village of Shorewood Collection System	Village of Shorewood	--	--	0.66	0.79	1.45
Village of West Milwaukee Collection System	Village of West Milwaukee	0.51	0.60	--	--	1.11
Village of Whitefish Bay Collection System	Village of Whitefish Bay	--	--	1.85	--	1.85
	Subtotal	20.38	47.01	43.66	21.91	132.96
Ozaukee County						
City of Cedarburg Sewage Treatment Facility	City of Cedarburg	--	--	3.15	--	3.15
City of Mequon Collection System	City of Mequon	--	0.09	7.75	--	7.84
Village of Fredonia Sewage Treatment Facility	Village of Fredonia	--	--	0.75	--	0.75
Village of Grafton Sewage Treatment Facility	Village of Grafton	--	--	2.32	--	2.32
Village of Saukville Sewage Treatment Facility	Village of Saukville	--	--	0.94	--	0.94
Village of Thiensville Sewage Treatment Facility	Village of Thiensville	--	--	1.16	--	1.16
S&R Cheese[b]	Town of Saukville	--	--	N/A	--	N/A
Justro Feed Corporation[b]	Town of Cedarburg	--	--	N/A	--	N/A
Federal Foods Company[b]	City of Mequon	--	--	N/A	--	N/A
	Subtotal	--	0.09	16.07	--	16.16
Sheboygan County						
Village of Cascade Sewage Treatment Facility	Village of Cascade	--	--	0.30	--	0.30
Village of Adell Sewage Treatment Facility	Village of Adell	--	--	0.14	--	0.14
Village of Random Lake Sewage Treatment Facility	Village of Random Lake	--	--	0.48	--	0.48
Kettle Moraine Correctional Institute[b]	Town of Greenbush	--	--	N/A	--	N/A
	Subtotal	--	--	0.92	--	0.92
Washington County						
City of West Bend Sewage Treatment Facility	City of West Bend	--	--	6.47	--	6.47
Village of Germantown Sewage Treatment Facility	Village of Germantown	--	3.88	--	--	3.88
Village of Jackson Sewage Treatment Facility	Village of Jackson	--	--	0.55	--	0.55
Village of Kewaskum Sewage Treatment Facility	Village of Kewaskum	--	--	0.73	--	0.73
Village of Newburg Sewage Treatment Facility	Village of Newburg	--	--	0.39	--	0.39
Libby, McNeill and Libby[b]	Village of Jackson	--	--	N/A	--	N/A
Level Valley Dairy[b]	Town of Jackson	--	--	N/A	--	N/A
Cedar Lake Rest Home[b]	Town of West Bend	--	--	N/A	--	N/A
	Subtotal	--	3.88	8.14	--	12.02
Waukesha County						
City of Brookfield Sewage Treatment Facility/Collection	City of Brookfield	--	12.42	--	--	12.42
City of New Berlin Collection System	City of New Berlin	--	0.73	--	--	0.73
Village of Menomonee Falls Sewage Treatment Facility	Village of Menomonee Falls	--	6.34	--	--	6.34
Village of Butler Collection System	Village of Butler	--	0.78	--	--	0.78
Village of Elm Grove Collection System	Village of Elm Grove	--	3.25	--	--	3.25
Brookfield Central High School	City of Brookfield	--	N/A	--	--	N/A
	Subtotal	--	23.52	--	--	23.52
	Total	20.38	74.50	69.23	21.91	186.02

NOTE: N/A indicates not applicable. Facility serves only a single institution or has not yet been constructed.

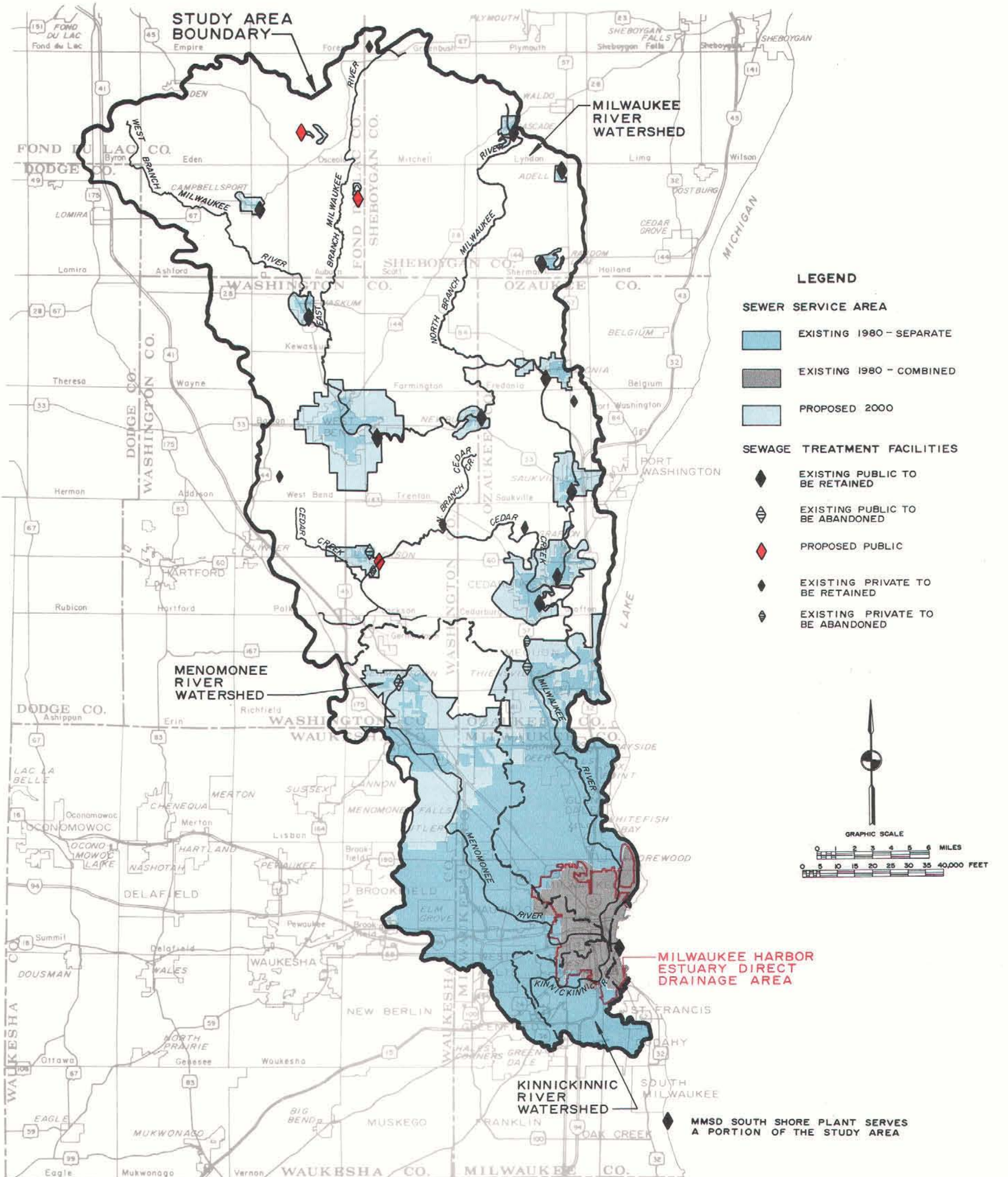
[a] Proposed for construction by the year 2000.

[b] Private facility.

Source: SEWRPC.

Map 17

EXISTING AND PROPOSED SANITARY SEWER SERVICE AREAS IN THE STUDY AREA: 1980

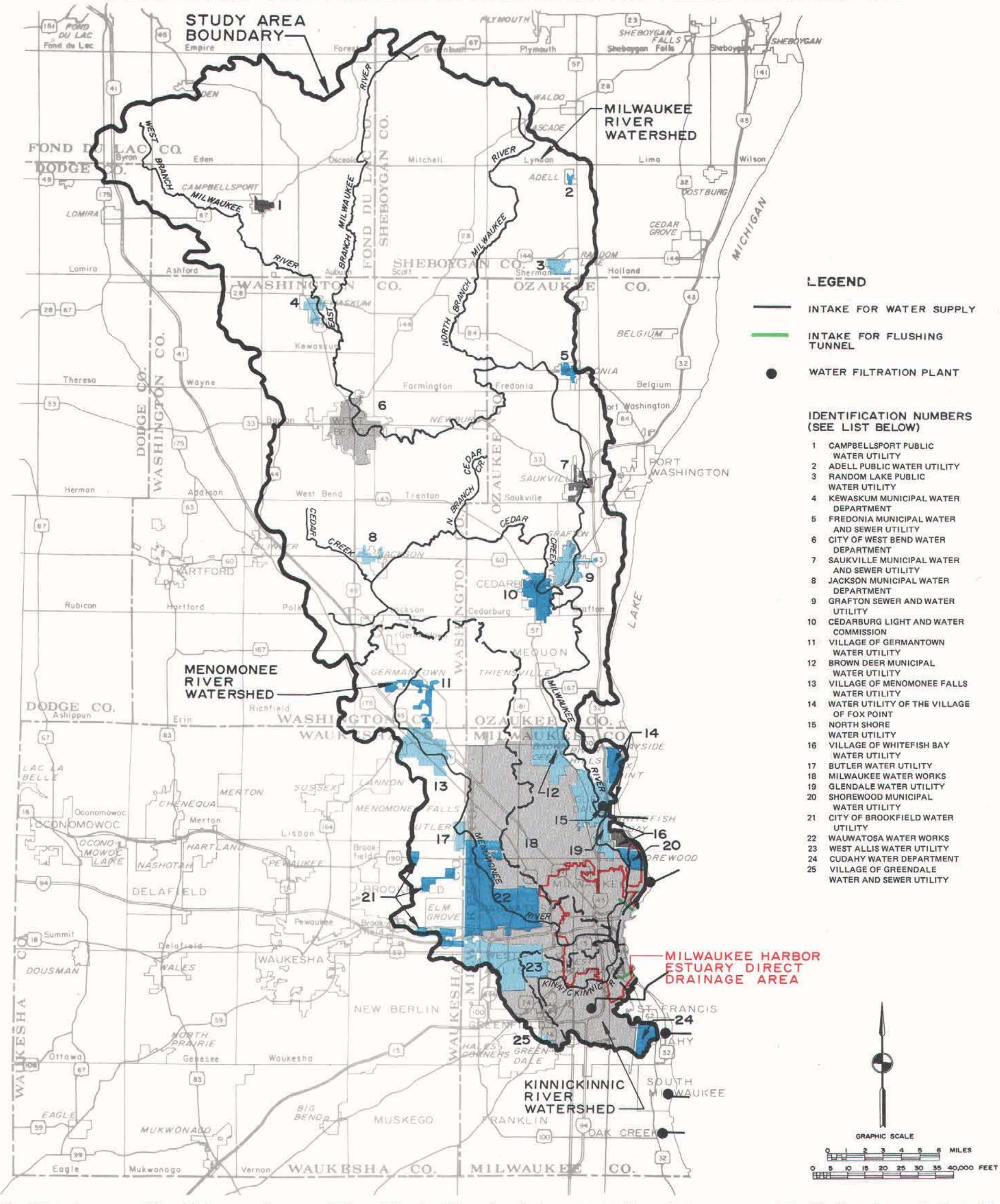


As of 1980, there were 42 existing and 2 proposed sanitary sewerage systems within the study area. Of the 42 existing systems, 35 were operated by public agencies and 7 were operated by private agencies which served only individual institutional or industrial concerns. There were 16 sewage treatment plants serving the 35 publicly operated sanitary sewerage systems. The Milwaukee Harbor estuary direct drainage area is located entirely within the existing service area of the Milwaukee Metropolitan Sewerage District.

Source: SEWRPC.

Map 18

SERVICE AREAS OF THE PUBLICLY OWNED WATER UTILITIES WITHIN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1975



In 1975, there were 25 publicly owned water utilities within the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds. The 11 public water utilities within Milwaukee County used Lake Michigan as a source of water supply, while the remaining 14 water utilities in the study area all used groundwater as a source of water supply. The 25 publicly owned water utilities had a combined service area of about 154 square miles, or about 18 percent of the total study area, and served about 806,000 persons, or about 83 percent of the resident population of the study area. In addition, there were about 23 known private or cooperatively owned water supply systems in the study area serving isolated residential enclaves.

Source: SEWRPC.

Table 13

AREAS SERVED BY PUBLIC WATER UTILITIES IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1975

Public Water Utility		Area Served Within (square miles)				
Name	Location	Kinnickinnic River Watershed	Menomonee River Watershed	Milwaukee River Watershed	Milwaukee Harbor Estuary Direct Drainage Area	Total
Fond du Lac County						
Campbellsport Public Water Utility	Village of Campbellsport	--	--	0.41	--	0.41
	Subtotal	--	--	0.41	--	0.41
Milwaukee County						
Brown Deer Municipal Water Utility[a]	Village of Brown Deer	--	--	4.36	--	4.36
Cudahy Water Department[a]	City of Cudahy	1.47	--	--	--	1.47
Glendale Water Utility[a]	City of Glendale	--	--	5.97	--	5.97
Milwaukee Water Works[a,b]	City of Milwaukee	17.42	29.32	26.88	21.12	94.74
North Shore Water Utility[a,c]	City of Glendale	--	--	--	--	--
Shorewood Municipal Water Utility[a]	Village of Shorewood	--	--	0.66	0.79	1.45
Village of Greendale Water and Sewer Utility[a]	Village of Greendale	--	0.10	--	--	0.10
Village of Whitefish Bay Water Utility[a]	Village of Whitefish Bay	--	--	1.85	--	1.85
Water Utility of the Village of Fox Point[a]	Village of Fox Point	--	--	1.21	--	1.21
Wauwatosa Water Works[a]	City of Wauwatosa	--	13.28	--	--	13.28
West Allis Water Utility[a]	City of West Allis	1.66	6.34	--	--	8.00
	Subtotal	20.55	49.04	40.93	21.91	132.43
Ozaukee County						
Cedarburg Light and Water Commission	City of Cedarburg	--	--	2.56	--	2.56
Fredonia Municipal Water and Sewer Utility.	Village of Fredonia	--	--	0.56	--	0.56
Grafton Sewer and Water Utility	Village of Grafton	--	--	2.21	--	2.21
Saukville Municipal Water and Sewer Utility.	Village of Saukville	--	--	1.06	--	1.06
	Subtotal	--	--	6.39	--	6.39
Sheboygan County						
Adell Public Water Utility	Village of Adell	--	--	0.18	--	0.18
Random Lake Public Water Utility	Village of Random Lake	--	--	0.73	--	0.73
	Subtotal	--	--	0.91	--	0.91
Washington County						
City of West Bend Water Department.	City of West Bend	--	--	5.53	--	5.53
Jackson Municipal Water Department.	Village of Jackson	--	--	0.46	--	0.46
Kewaskum Municipal Water Department	Village of Kewaskum	--	--	0.82	--	0.82
Village of Germantown Water Utility	Village of Germantown	--	1.41	--	--	1.41
	Subtotal	--	1.41	6.81	--	8.22
Waukesha County						
Butler Water Utility	Village of Butler	--	0.80	--	--	0.80
City of Brookfield Water Utility.	City of Brookfield	--	1.72	--	--	1.72
Village of Menomonee Falls	Village of Menomonee Falls	--	4.48	--	--	4.48
	Subtotal	--	7.00	--	--	7.00

[a] *This utility utilizes Lake Michigan as the sole source of water supply.*

[b] *The Milwaukee Water Works provides retail water service to the Cities of Greenfield and St. Francis and the Village of West Milwaukee and a portion of the City of Franklin, and provides wholesale water service to the Cities of Wauwatosa and West Allis and the Villages of Brown Deer, Greendale, and Shorewood. The data presented in this table for the Milwaukee Water Utility include the communities served on a retail basis.*

[c] *The North Shore Water Utility provides no retail water service and exists only to sell water on a wholesale basis to the City of Glendale and the Villages of Fox Point and Whitefish Bay.*

Source: Wisconsin Public Service Commission, Wisconsin Department of Natural Resources, and SEWRPC.

Table 14

PRIVATE WATER UTILITIES
IN THE STUDY AREA: 1975

Name	Civil Division
Milwaukee County	
Northway Co-operative No. 1 . . .	Village of Bayside
Northway Co-operative No. 2 . . .	Village of Bayside
Pelham Health Subdivision.	Village of Bayside
Robert Williams Park	City of Milwaukee
Southgate Manor Estates Subdivision.	City of Greenfield
Town View Water Co-operative Association.	City of Milwaukee
Vista Del Mar Water Trust	Village of Bayside
Ozaukee County	
Alberta Subdivision.	Village of Thiensville
Bonnie Lynn Highlands Subdivision.	City of Mequon
Century Estates Subdivision No. 1 and Additions.	Village of Thiensville
Lac du Cours Subdivision	City of Mequon
Laurel Acres Subdivision.	Village of Thiensville
Mequon Water Trust	City of Mequon
North Shore Estates Subdivision.	City of Mequon
North Shore Heights Subdivision.	City of Mequon
Range Line Hills Subdivision . . .	City of Mequon
Village Heights Co-operative. . . .	Village of Thiensville
Ville du Parc.	City of Mequon
Whitman Place Subdivision	City of Mequon
Waukesha County	
Lynwood Water Company	City of Brookfield
Marion Heights Terrace.	Village of Elm Grove
River View Manors Well Association.	Village of Menomonee Falls
Silver Springs Terrace Subdivision.	Village of Menomonee Falls

Source: SEWRPC.

Of the 23 public water supply utilities serving the tributary river watershed areas, all but one—the North Shore Water Utility in Milwaukee County—provide retail water service to consumers. The North Shore Water Utility provides wholesale water service to only three other water utilities—the Glendale Water Utility, the Village of Whitefish Bay Water Utility, and the Water Utility of the Village of Fox Point. As indicated in Table 13, the 25 publicly owned water utilities in the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds serve a combined area of approximately 154 square miles, or about 18 percent of the total study area, and about 806,000 persons, or about 83 percent of the resident population of the study area.

In addition to the publicly owned water utilities, there are 23 known private or cooperatively owned water supply systems in the study area. Many of these systems serve isolated residential enclaves. Some serve summer residents only and suspend operations during cold weather. Very few of these private systems have standby supply or storage facilities, and the majority do not keep detailed records or file annual reports with state or other regulatory agencies. The locations of these 23 private water supply systems are shown on Map 18 and are identified in Table 14.

Map 18 also indicates the location of the six water supply intakes from Lake Michigan to the public water supply system purification facilities serving Milwaukee County. In addition to being provided to 11 communities in Milwaukee County, Lake Michigan water is diverted to the Milwaukee River and the Kinnickinnic River through flushing tunnels which provide dilution of river water when pollutant levels are high. The locations of the intakes and outfalls for these two flushing tunnels are also indicated on Map 18.

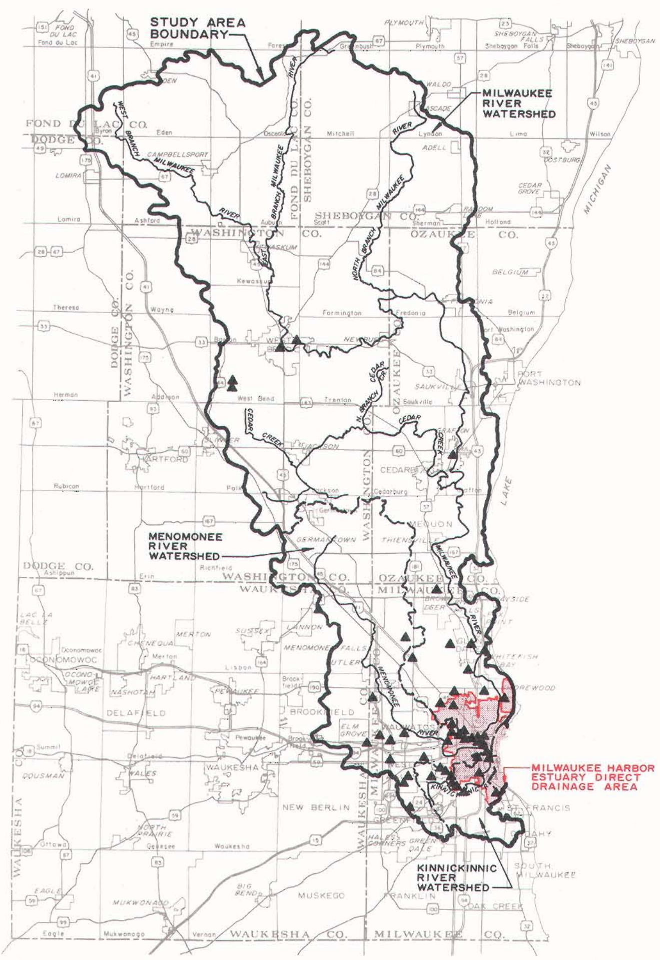
Solid Waste Disposal Facilities: Solid waste generated by the residents in the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds is disposed of through either incineration, landfilling, or resource recovery through recycling operations, or by a combination of such processes. Incineration, or the controlled burning of solid waste, reduces the volume of, and contaminants in, the solid waste prior to disposal in a landfill. Resource recovery operations also reduce the volume of solid waste by extracting materials which can be recycled. Recycling operations include both commercial and nonprofit operations that accept materials commonly found in domestic solid wastes, such as cardboard and other paper, aluminum cans, glass, metals, rags, and oil.

Because of increasing concern regarding the selection of suitable solid waste management systems and disposal sites, the Commission conducted a comprehensive inventory of solid waste management facilities in the Southeastern Wisconsin Region for the year 1980.[1] Map 19 indicates the locations of the known solid waste incinerators within the Milwaukee Harbor estuary direct drainage area and within the in-Region portion of

[1] *See, "Inventory of Solid Waste Management Facilities in Southeastern Wisconsin: 1980," SEWRPC Technical Record, Vol. 4, No. 3, February 1980.*

Map 19

KNOWN SOLID WASTE INCINERATORS IN THE PORTION OF THE STUDY AREA WITHIN THE SOUTHEASTERN WISCONSIN REGION: 1980



LEGEND

▲ INCINERATOR LOCATION

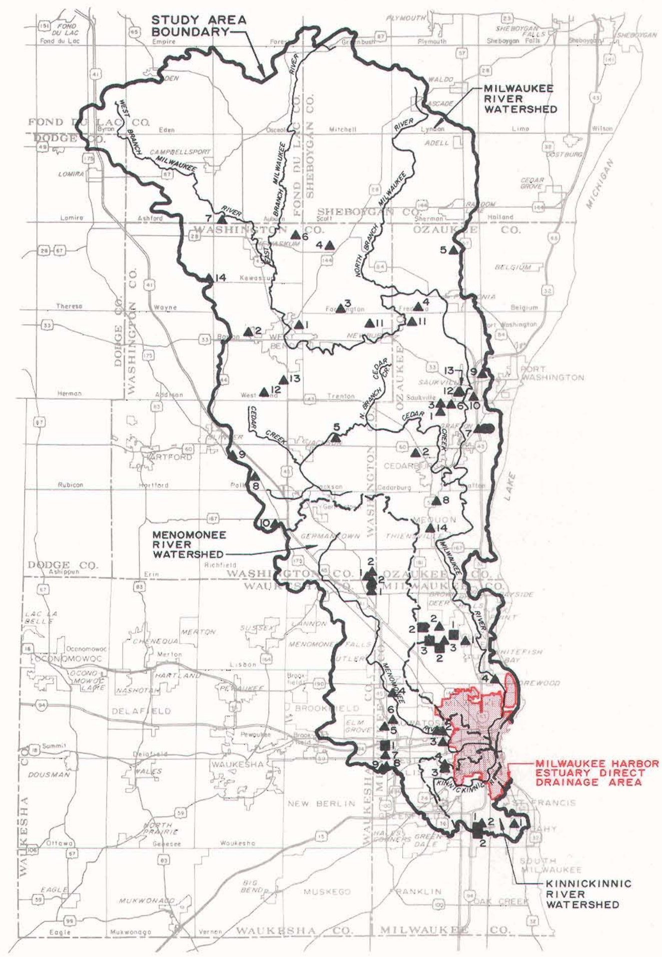
GRAPHIC SCALE

One method utilized for processing solid waste in southeastern Wisconsin is incineration, or the controlled burning of solid wastes. The main purpose of incineration is to reduce the volume of, and the contaminants in, the solid wastes. Within the Milwaukee Harbor estuary direct drainage area and the in-Region portion of its tributary river watersheds, there are 51 known public and private solid waste incinerators.

Source: Wisconsin Department of Natural Resources and SEWRPC.

Map 20

KNOWN EXISTING AND PROPOSED SOLID WASTE LANDFILLS IN THE PORTION OF THE STUDY AREA WITHIN THE SOUTHEASTERN WISCONSIN REGION: 1980



LEGEND

● PROPOSED LANDFILL

▲ EXISTING LANDFILL (SEE TABLE 15)

■ PRE-REGULATION LANDFILL (SEE TABLE 16)

4 LANDFILL NUMBER BY COUNTY

GRAPHIC SCALE

There were 21 public solid waste landfills within the in-Region portion of the study area, of which 13 were active and 8 were abandoned as of 1980. There were also 28 private solid waste landfills within the in-Region portion of the study area, of which 8 were active and 20 were abandoned as of 1980.

Source: Wisconsin Department of Natural Resources and SEWRPC.

its tributary river watersheds as determined through this inventory work effort for 1980.

Map 20 identifies the locations of the existing and proposed solid waste landfills in the Milwaukee Harbor estuary direct drainage area and within the in-Region portion of its tributary river watersheds. Selected characteristics shown on Map 20 are presented in Table 15. Map 20 also indicates the locations of all known preregulation landfills, or "dumps," which generally had exposed areas of uncovered solid waste throughout the site-filling

Table 15

SELECTED CHARACTERISTICS OF KNOWN EXISTING SOLID WASTE LANDFILLS IN THE PORTION OF THE STUDY AREA WITHIN THE SOUTHEASTERN WISCONSIN REGION: 1980[a]

Number on Map 20	Civil Division	Location by U. S. Public Land Survey Section	Operator	License Number	Area (acres)	Use Classification	Status	DNR Capacity Category (cubic yards x 10^3)	Estimated Remaining Service Life (years)	Solid Waste Type Accepted							
										Noncombustible	Wood Matter	Trash and Refuse	Garbage	Demolition	Toxic and Hazardous	Fly Ash	Other
Kinnickinnic River Watershed																	
	Milwaukee County																
1	City of Cudahy	NW ¼, SE ¼, Section 27, T6N, R22E	City of Cudahy	0310	2.5	Public general use	Properly abandoned	N/A	--	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	City of Milwaukee	NW ¼, SW ¼, Section 29, T6N, R22E	Private contractors retained by Wisconsin Department of Transportation	2586	7.0	Private special use	Properly abandoned	N/A	--	--	--	--	--	X	--	--	--
3	Village of West Milwaukee	NE ¼, SE ¼, Section 2, T6N, R21E	Village of West Milwaukee	1272	6.0	Public special use	Active	50	3	X	X	X	--	--	--	--	--
4	Village of West Milwaukee	SE ¼, Section 2, T6N, R21E	Wehr Steel	Unlicensed[f]	N/A	Private special use	Transition abandonment	N/A	N/A	--	--	--	--	--	--	--	Foundry sand, slag balls, scrap metal
Menomonee River Watershed																	
	Milwaukee County																
1	City of Milwaukee	SE ¼, NW ¼, Section 26, T7N, R21E	City of Milwaukee	0426	2.0	Private special use	Properly abandoned	N/A	--	X	X	X	--	--	--	--	--
2	City of Milwaukee	SW ¼, NE ¼, Section 26, T7N, R21E	Falk Corporation	Unlicensed	--	Private special use	Properly abandoned	N/A	--	--	--	--	--	--	--	--	Foundry sand
3	City of Milwaukee	NE ¼, Section 35, T7N, R21E	City of Milwaukee[e]	Unlicensed	N/A	Public general use	Properly abandoned	N/A	--	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4	City of Wauwatosa	NE ¼, SW ¼, Section 8, T7N, R21E	City of Milwaukee (Old Hartung Quarry)	1501	17.0	Private special use	Active	500	3	X	--	--	--	--	--	--	--
5	City of Wauwatosa	SE ¼, SE ¼, Section 19, T7N, R21E	City of Wauwatosa	0525	100.0	Public special use	Active	500	3	X	X	X	--	--	--	--	--
6	City of Wauwatosa	SE ¼, NW ¼ Section 20, T7N, R21E	Milwaukee County Institutions	0194	15.0	Private special use	Properly abandoned	N/A	--	X	X	--	--	X	--	--	--
7	City of West Allis	SE ¼, SE ¼, Section 31, T7N, R21E	N/A	Unlicensed	N/A	Private special use	Abandoned	N/A	--	--	--	--	--	--	--	--	Industrial fill
8	City of West Allis	NE ¼, SE ¼, Section 6, T6N, R21E	N/A	Unlicensed	N/A	Private special use	Abandoned	N/A	--	--	--	--	--	--	--	--	Industrial fill
9	City of West Allis	SW ¼, SE ¼, Section 6, T6N, R21E	Maynard Steel Casting Corporation	Unlicensed	N/A	Private special use	Abandoned	N/A	--	--	--	--	--	--	--	--	Foundry sand

Table 15 (continued)

Number on Map 20	Civil Division	Location by U. S. Public Land Survey Section	Operator	License Number	Area (acres)	Use Classification	Status	DNR Capacity Category (cubic yards x 10^3)	Estimated Remaining Service Life (years)	Solid Waste Type Accepted: Noncombustible	Wood Matter	Trash and Refuse	Garbage	Demolition	Toxic and Hazardous	Fly Ash	Other
Menomonee River Watershed (continued)																	
	Washington County																
1	Village of Germantown	S ½, Section 36, T9N, R20E	Waste Management of Wisconsin (Omega Hills-North)	1678	84.0	Commercial general use	Active	500	10	X	X	X	X	X	X	--	--
2	Village of Germantown	NE ½, SE ¼, Section 36, T9N, R20E	Organic Compost Corporation *Al's Disposal, Inc.*	N/A	N/A	Private special use	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Waukesha County																
1	Village of Menomonee Falls	NE ¼, SE ¼, Section 1, T8N, R20E	Waste Management of Wisconsin (Lauer 1)	0011	20.0	Commercial general use	Active	500	N/A	X	X	X	X	--	--	--	--
2	Village of Menomonee Falls	N ½, NE ¼, Section 1, T8N, R20E	Waste Management of Wisconsin (Omega Hills-South)	1678	84.0	Public general use	Active	500	8	X	X	X	X	X	X	--	--
Milwaukee River Watershed																	
	Milwaukee County																
1	City of Glendale	NW ¼, NW ¼, Section 30, T8N, R22E	City of Glendale	1121	20.0	Public general use	Properly abandoned	N/A	--	X	X	X	X	--	--	--	--
2	City of Milwaukee	NE ¼, NW ¼, Section 23 T8N, R21E	Village of Whitefish Bay	0356	13.0	Private special use	Abandoned	50-500	--	X	--	--	--	--	--	--	--
3	City of Milwaukee	NE ¼, NE ¼, Section 26, T8N, R21E	City of Milwaukee[b]	0423	40.0	Private general use	Abandoned	N/A	--	X	X	X	--	--	--	--	--
4	City of Milwaukee	SW ¼ Section 4, T7N, R22E	City of Milwaukee[c]	0424	10.0	Private special use	Properly abandoned[d]	N/A	--	X	--	X	--	--	--	--	Street sweepings, brush, leaves
	Ozaukee County																
1	Town of Cedarburg	NW ¼, SE ¼, Section 2, T10N, R21E	City and Town of Cedarburg	0271	89.0	Public general use	Active	50-500	2	--	X	X	X	--	--	--	--
2	Town of Cedarburg	SE ¼, NE ¼, Section 21, T10N, R21E	Marvin Procknow	0751	100.0	Private general use	Abandoned	N/A	--	X	X	X	X	--	--	--	--
3	Town of Cedarburg	NW ¼, NE ¼, Section 2, T10N, R21E	Wisconsin Electric Power Company	0603	23.2	Private special use	Abandoned	N/A	--	--	--	--	--	--	--	X	--
4	Town of Fredonia	NE ¼, SE ¼, Section 32, T12N, R21E	Ozaukee County Highway Department	1914	19.8	Private special use	Active	50-500	3	X	X	X	--	--	--	--	--
5	Town of Fredonia	SW ¼, SW ¼, Section 11, T12N, R21E	Town of Fredonia	911	1.5	Public general use	Active	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 15 (continued)

Number on Map 20	Civil Division	Location by U. S. Public Land Survey Section	Operator	License Number	Area (acres)	Use Classification	Status	DNR Capacity Category (cubic yards x 10^3)	Estimated Remaining Service Life (years)	Noncombustible	Solid Waste Type Accepted: Wood Matter	Trash and Refuse	Garbage	Demolition	Toxic and Hazardous	Fly Ash	Other
							Milwaukee River Watershed (continued)										
	Ozaukee County (continued)																
6	Town of Grafton	SE ¼, NW ¼, Section 1, T10N, R21E	Town of Grafton	1133	10.0	Public general use	Active	50-500	3	X	--	X	X	X	--	--	--
7	Town of Grafton	SW ¼, Section 8, T10N, R22E	Wisconsin Electric Power Company	2801	85.0	Private special use	Active	500	3	--	--	--	--	--	--	X	Wastewater treatment solids
8	City of Mequon	SW ¼, SW ¼, Section 2, T9N, R21E	City of Mequon	0429	7.0	Public general use	Active	50-500	N/A	X	X	X	--	X	--	--	--
9	Town of Port Washington	NW ¼, NW ¼, Section 30, T11N, R22E	Town of Port Washington	1098	N/A	Public general use	Properly abandoned	N/A	--	--	X	X	--	--	--	--	--
10	Town of Saukville	SW ¼, SE ¼, Section 36, T11N, R21E	Town of Saukville	1122	2.0	Public general use	Active	50-500	3	X	X	X	X	X	--	--	--
11	Town of Saukville	NE ¼, SW ¼, Section 5, T11N, R21E	Laubenstein Sales and Service, Inc.	0270	2.0	Private general use	Active	50	3	X	X	X	--	X	--	--	--
12	Village of Saukville	SW ¼, NE ¼, Section 35, T11N, R21E	Freeman Chemical	No license required	N/A	Private special use	Active	N/A	N/A	--	--	--	--	--	--	--	Inert ash material
13	Village of Saukville	SW ¼, NE ¼, Section 35, T11N, R21E	Village of Saukville	0856	1.0	Private special use	Properly abandoned	N/A	--	X	X	--	--	--	--	--	--
14	Village of Thiensville	NE ¼, SE ¼, Section 15, T9N, R21E	Village of Thiensville	N/A	N/A	N/A	Properly abandoned	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Washington County																
1	Town of Barton	SE ¼, SE ¼, Section 1, T11N, R19E	N/A	N/A	N/A	Private special use	Inactive	N/A	--	--	--	---	--	X	--	--	Plastics, fiber pipe
2	Town of Barton	SE ¼, NW ¼, Section 9, T11N, R19E	City of West Bend	N/A	30.0	Public general use	Active[g]	500	2	X	X	X	X	--	--	--	--
3	Town of Farmington	NW ¼, SE ¼, Section 33, T12N, R20E	Lazy Days Campground	0408	10.0	Private general use	Properly abandoned	N/A	--	--	--	X	X	--	--	--	--
4	Town of Farmington	SE ¼, NE ¼, Section 8, T12N, R20E	Town of Farmington	0087	1.8	Public general use	Active	50	5	X	X	X	X	X	--	--	--
5	Town of Jackson	SE ¼, NW ¼, Section 15, T10N, R20E	Town of Jackson	0377	1.8	Public general use	Properly abandoned	N/A	--	--	X	X	X	X	--	--	--
6	Town of Kewaskum	NW ¼, SE ¼, Section 1, T12N, R19E	Town of Kewaskum	0917	20.0	Public general use	Active	500	8	X	X	X	X	--	--	--	--

Table 15 (continued)

Number on Map 20	Civil Division	Location by U. S. Public Land Survey Section	Operator	License Number	Area (acres)	Use Classification	Status	DNR Capacity Category (cubic yards x 10^3)	Estimated Remaining Service Life (years)	Noncombustible	Solid Waste Type Accepted: Wood Matter	Trash and Refuse	Garbage	Demolition	Toxic and Hazardous	Fly Ash	Other
Milwaukee River Watershed (continued)																	
	Washington County (continued)																
7	Town of Auburn[h]	SW ¼, SE ½, Section 31, T13N, R19E	Village of Kewaskum	0977	40.0	Public general use	Active	500	5	X	X	X[i]	X[i]	X	--	--	--
8	Town of Polk	NE ¼, NE ¼, Section 34, T10N, R19E	Leroy Schmidt Dump	N/A	N/A	Private special use	Abandoned	N/A	--	--	--	X	--	X	--	--	Concrete pipes, auto tires
9	Town of Polk	NE ¼, SW ¼, Section 21, T10N, R19E	N/A	N/A	N/A	Private special use	Abandoned	N/A	--	--	--	--	--	--	--	--	Brewery wastes, oil skimmer wastes
10	Town of Richfield	SW ¼, NW ¼, Section 13 T9N, R19E	Town of Richfield	1093	4.5	Public general use	Abandoned	N/A	1	X	X	X	X	--	--	--	--
11	Town of Trenton	NW ¼, SE ¼, Section 2, T11N, R20E	Town of Trenton	0377	5.0	Public general use	Properly abandoned	N/A	--	X	X	X	X	X	--	--	--
12	Town of West Bend	SE ¼, NW ¼, Section 34, T11N, R19E	Town of West Bend	1160	7.0	Public general use	Active	N/A	5	--	X	X	X	--	--	--	--
13	Town of West Bend	NE ¼, SE ¼, Section 26, T11N, R19E	N/A	N/A	N/A	Private special use	Properly abandoned	N/A	--	--	X	--	--	X	--	--	Concrete, metal glass, porcelain
14	Town of Wayne	NE ¼, SE ¼, Section 24, T12N, R18E	Town of Wayne	0052	10.0	Private general use	Active	N/A	8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

NOTE: N/A indicates data not available.
Three proposed landfills, two in the Town of Grafton, Ozaukee County, and one in the Village of Menomonee Falls, Waukesha County, are shown on Map 20.

[a] *The information in this table was obtained collectively from SEWRPC inventories conducted under the areawide water quality management plan, county solid waste management plans for Kenosha, Ozaukee, Racine, Washington, and Waukesha Counties, and the Wisconsin Department of Natural Resources files.*

[b] *Formerly the U. S. Government disciplinary barracks site, now known as Havenwood.*

[c] *Formerly known as the Bluehold site.*

[d] *Currently a University of Wisconsin-Milwaukee parking lot.*

[e] *This landfill lies beneath Milwaukee County Stadium.*

[f] *This landfill is in the process of being licensed.*

[g] *The West Bend landfill is scheduled to be abandoned.*

[h] *The Village of Kewaskum disposes of its solid waste at a sanitary landfill located in the Town of Auburn in Fond du Lac County. This site is within the city limits and is owned by the City. However, the site is located just outside the Southeastern Wisconsin Region.*

[i] *These waste types were accepted while under the ownership of Acme Disposal.*

Source: SEWRPC.

period. The locations of these dumps are tabularly presented in Table 16. As indicated in Table 15, there are 21 public solid waste landfills within the in-Region portion of the study area, of which 13 are active and eight are abandoned, either properly, improperly, or in transition. There are also 28 private solid waste landfills within the in-Region portion of the study area, of which eight are active and 20 abandoned. In total, therefore, there were 21 active landfills and 28 abandoned landfills within the in-Region portion of the study area in 1980.

The locations and selected characteristics of known municipal and commercial solid waste recycling operations and incinerators within the Milwaukee Harbor estuary direct drainage area and within the in-Region portion of its tributary river watersheds are set forth in SEWRPC Technical Record, Vol. 4, No. 3.

Electric Power Service and Gas Service: Electric power is provided to all portions of the Milwaukee Harbor estuary direct drainage area by the Wisconsin Electric Power Company (WEPCo). The WEPCo also provides steam for space-heating purposes to major commercial structures in the area of the central business district of the City of Milwaukee. In addition, the WEPCo is authorized to provide electric power to virtually all portions of the Kinnickinnic, Menomonee, and Milwaukee River watersheds, the only exception being small portions of Fond du Lac and Sheboygan Counties which are served by the Wisconsin Power & Light Company. There is only one municipal electric power utility operating in the study area, that being owned by the City of Cedarburg.

As shown on Map 21, natural gas is supplied throughout the Milwaukee Harbor estuary direct drainage area by the Wisconsin Gas Company. The Wisconsin Gas Company also provides service to portions of Sheboygan County; to the Milwaukee, Ozaukee, and Washington County portions of the study area; and to the Village of Menomonee Falls, the eastern half of the City of Brookfield, and the Village of Elm Grove in Waukesha County. The remainder of the study area in Waukesha County is served by the Wisconsin Natural Gas Company. Two other gas companies, the Wisconsin Power & Light Company and the Wisconsin Public Service Corporation, provide service to the Dodge, Fond du Lac, and remaining Sheboygan County portions of the study area. Within the study area, there is no authorized gas utility franchise within the Town of Wayne in Washington County and the Town of Scott in Sheboygan County.

Table 16

PREREGULATION LANDFILLS OR "DUMPS" THAT ARE KNOWN TO EXIST IN THE PORTION OF THE STUDY AREA WITHIN THE SOUTHEASTERN WISCONSIN REGION: 1980[a]

Number on Map 20	Civil Division	Location By U. S. Public Land Survey Section	Size (acres)
Kinnickinnic River Watershed			
1	City of Milwaukee	SW ¼, SW ¼, Section 29, T6N, R22E	19
2	City of Milwaukee	NW ¼, NW ¼, Section 32, T6N, R22E	3
Menomonee River Watershed			
1	City of West Allis	NE ¼, Section 31, T7N, R21E	60
2	City of Milwaukee	SE ¼, NW ¼, Section 22, T8N, R21E	22
Milwaukee River Watershed			
1	City of Milwaukee	SE ¼, SW ¼, Section 24, T8N, R21E	35
2	City of Milwaukee	NE ¼, SW ¼, Section 26, T8N, R21E	25
3	City of Milwaukee	NE ¼, NE ¼, Section 27, T8N, R21E	20

[a] Based on information obtained from soils maps published by the U. S. Department of Agriculture, Soil Conservation Service.

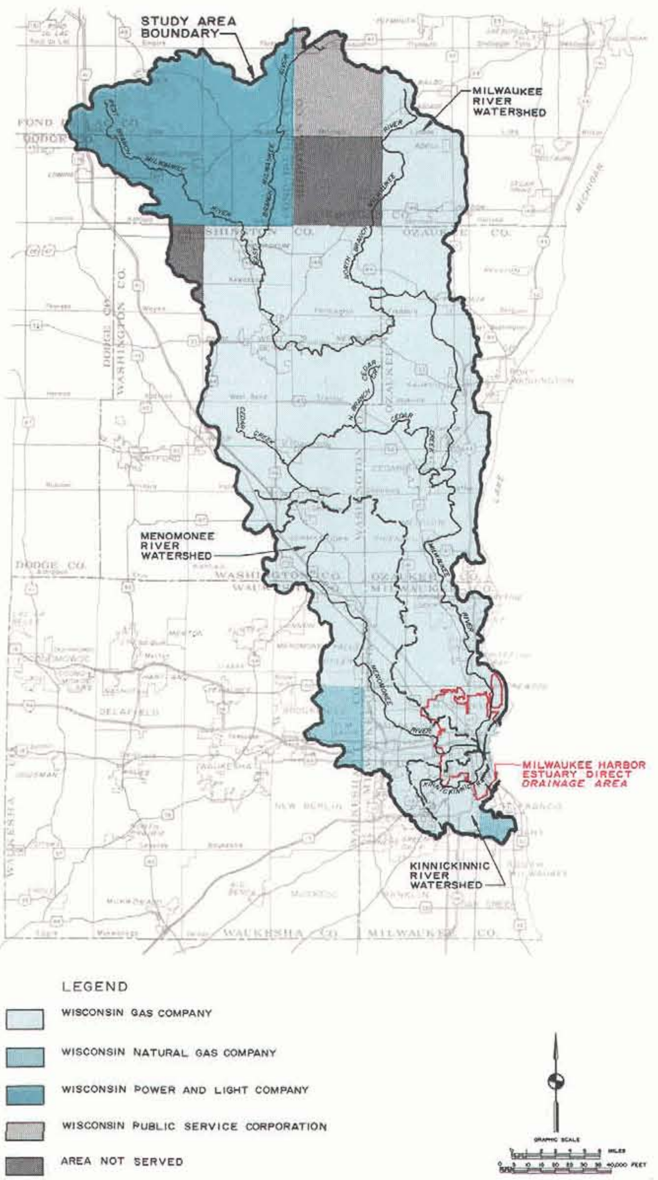
Source: SEWRPC.

Transportation Facilities

Highways: As shown on Map 22, the Milwaukee Harbor estuary direct drainage area is served by an extensive street and highway system, including 12.4 linear miles of freeway and 126.7 linear miles of surface arterials. In addition, there are about 300 miles of collector and land access street facilities in the Milwaukee Harbor estuary direct drainage area. The total study area, comprised of the Milwaukee Harbor estuary direct drainage area and its three tributary river watersheds, is served by 68.6 linear miles of freeway and 869.8 linear miles of surface arterials. The extensive street and highway system within the estuary direct drainage area serves to provide ease of access to the residential, commercial, and industrial land uses in the area, thus supporting those land uses. This arterial

Map 21

NATURAL GAS UTILITIES IN THE STUDY AREA



Natural gas is supplied throughout the Milwaukee Harbor estuary direct drainage area, as well as to most of the in-Region portion of the total study area, by the Wisconsin Gas Company. The Wisconsin Natural Gas Company, the Wisconsin Power & Light Company, and the Wisconsin Public Service Corporation each provide natural gas service to some portion of the study area. Within the study area, only within the Town of Wayne in Washington County and the Town of Scott in Sheboygan County is there no authorized gas utility franchise.

Source: SEWRPC.

street and highway system, however, may have adverse effects on surface water quality in the estuary and its tributary watersheds. For example, rainfall- or snowmelt-induced washoff of substances from the urban land surface, including streets and highways, has an effect on the water quality of the estuary and its tributary rivers and streams.

Bus Service: Two types of bus service serve the transportation needs of the resident population of the Milwaukee Harbor estuary direct drainage area, and of the nonresident population that works or shops within the area: urban mass transit and intercity bus service. Urban mass transit within the Milwaukee Harbor estuary direct drainage area is provided by the Milwaukee County Transit System. An important feature of this service in the area is the express commuter service, known as Freeway Flyer service, provided between the central business district of the City of Milwaukee and, as of 1981, 23 outlying parking terminals. Freeway Flyer bus service is operated by both Milwaukee and Waukesha Counties. This high-speed, nonstop bus service is provided via the existing freeway system, reducing the need for commuting residents outside the direct drainage area to drive automobiles into the central areas of Milwaukee County.

Intercity bus service is provided through the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds by Wisconsin Coach Lines, Inc., which operates routes connecting the central business district of Milwaukee with such cities as Fond du Lac, Kenosha, Racine, and Sheboygan. Additional intercity bus service is provided by Badger Bus Lines, Inc., which operates a fixed route schedule between the central business district of Milwaukee and the City of Madison.

Railway Service. Railway service in the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds is limited to freight hauling, except for scheduled Amtrak passenger service over the lines of the Chicago, Milwaukee, St. Paul & Pacific Railroad Company (Milwaukee Road) between Union Station in the City of Milwaukee, which is the only stop in the study area, and Chicago to the south and Minneapolis-St. Paul to the west. Milwaukee Union Station is the only rail passenger terminal within the study area.

As shown on Map 23, extensive railway freight service is provided throughout the study area by the Milwaukee Road, the Soo Line Railroad, and the Chicago & North Western Railway. The heavily industrialized portion of the Menomonee River Valley in the City of Milwaukee, and within the boundary of the direct drainage area in particular, contains a large concentration of the Milwaukee Road's classification yard and maintenance complex railway trackage. Also within the study area, the "Butler" classification yard of the Chicago & North Western is located immediately east of the Village of Butler in the Cities of Milwaukee and Wauwatosa. In addition, one shortline railway operates within the study area. This railway—the Wisconsin & Southern Railroad Company—provides trackage rights to both the Soo Line Railroad Company and the Milwaukee Road.

Commercial Shipping: As noted in Chapter I, the development of port facilities in Milwaukee Harbor significantly influenced the growth of the City of Milwaukee into a major urban center. Prior to 1850, the primary communication Milwaukee residents had with the rest of the nation and the world was by way of the Great Lakes. Materials and supplies arrived and were sent in small wooden sailing vessels which also brought early settlers and immigrants. Early Milwaukee residents were concerned about safe harborage for the vessels and ships, since only a slightly crescent-shaped natural harbor existed. No breakwaters, lighthouses, or other navigational aids existed to assist and protect these early navigators.

During early settlement, the Milwaukee River discharged to Lake Michigan in a wetland, about one-half mile south of the current harbor entrance near what is now E. Greenfield Avenue. In 1832, the first trading vessel arrived, delivering goods for Solomon Juneau, and docked at a lakefront landing. By 1839, nearly 180 commercial vessels arrived at Milwaukee annually. The first vessel built in Milwaukee—a 90-ton schooner named "Solomon Juneau"—was completed in 1836 in a shipyard on the Milwaukee River near the present Juneau Avenue. The first warehouse was built in 1838 at E. Water Street, and in 1841 Milwaukee's first export cargo of wheat was sent east by way of the Great Lakes. In the 1860's and 1870's, Milwaukee was the largest primary wheat market in the country, leading to the construction of several mills along the banks of the Milwaukee River.

From 1835 through 1837, federal army engineers conducted a harbor survey and recommended a new, man-made channel between the Milwaukee River and Lake Michigan. The U. S. Congress appropriated $30,000 in 1843 for the Milwaukee Harbor project, and by 1857 the Milwaukee River had been diverted to the lake at the existing harbor entrance, thereby providing a protected inner harbor area.

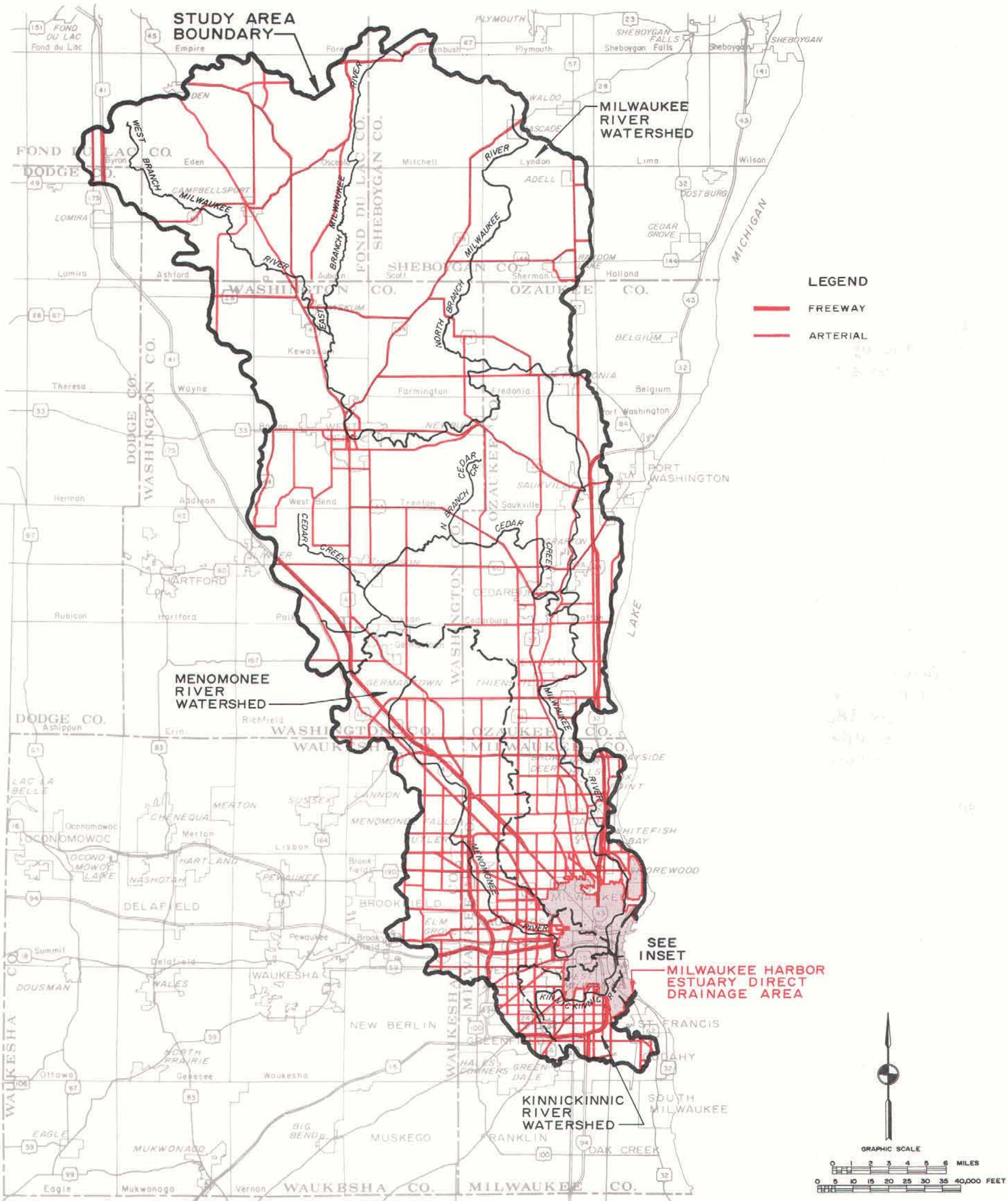
In the 1800's, primary import goods from the east which arrived by schooner or steamer included copper, lumber, tanbark, salt, fruit, vegetables, and coal. Milwaukee shippers exported wheat, oats, barley, beer, fish, salt beef, malt, flour, hides, wool, and cured meats. During the late 1800's, large passenger steamships, such as the "City of Milwaukee" and the "Christopher Columbus," also flourished.

Early in the 1900's, the arrival of the Great Lakes bulk freighters signaled the demise of the sailing ship era. In 1929, the wooden schooner "Lucia A. Simpson" sailed out of Milwaukee, marking the end of more than 100 years of sail navigation at Milwaukee. The bulk freighters, which generally ranged in length from 300 feet to 500 feet or more, led to the construction of numerous docks and unloading bridges in the outer and inner harbors. The freight was shipped as far east as Buffalo, New York, to Canadian ports, to ports on the eastern coast of Lake Michigan, and to other Wisconsin ports. The package freight trade, reduced by competition with railroads, ended when the United States requisitioned the fleet for ocean freight service during World War II. The large steamer passenger ships disappeared in the 1930's. During the mid-1900's, commercial navigation on the rivers also decreased. The last commercial cargo vessel to navigate the Milwaukee River upstream of Buffalo Street was the steamer "Sierra," which delivered a cargo of coal to docks near Humboldt Avenue in 1959.

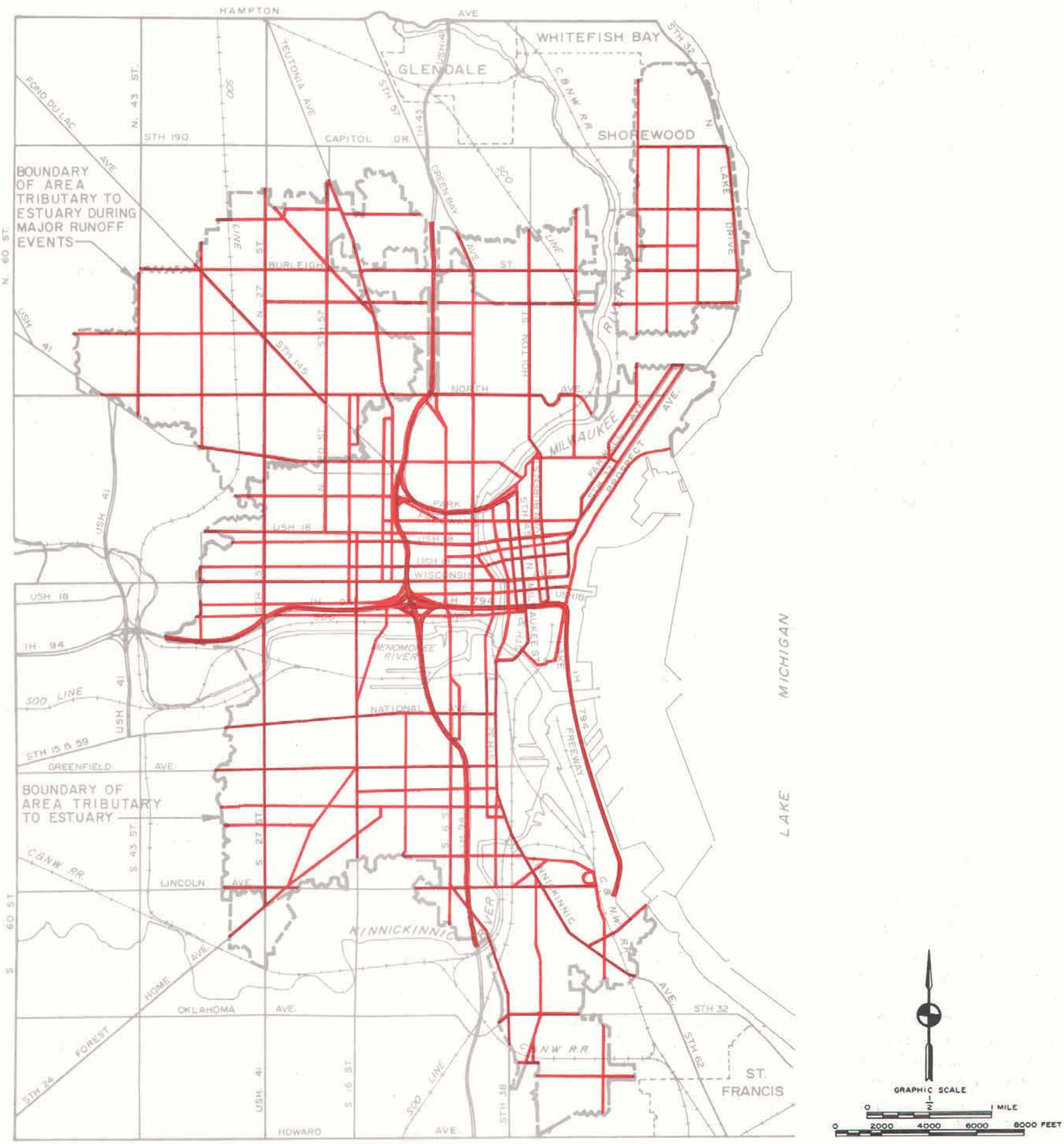
The existing harbor facilities are designed to service ocean steamers, carferries, passenger ships, tanker vessels, barges, and large cargo freighters, and to facilitate the loading and unloading of bulk, heavy liquid, and general cargo. The four-mile breakwater which encloses the outer harbor was begun in 1888. Construction of large cargo-handling facilities began in the late 1920's and 1930's. The carferry terminal, placed in service in 1929 and expanded and renovated in 1960, was Milwaukee's first municipal port facility. In 1931, Bulk Cargo Terminal No. 1 was constructed as the first general cargo terminal. In 1933, Milwaukee's first outer harbor pier—South Pier No. 1—was constructed, followed by the construction of several other cargo piers, docks, and terminals. In 1962, the Harbor Commission purchased the "M.V. Harbor Seagull" to collect litter, dead fish, floating vegetation, and debris from the harbor waters. The U. S. Army Corps of Engineers completed construction of a permanent enclosure to receive and hold the material dredged from the harbor in 1975.

Map 22

ARTERIAL STREET AND HIGHWAY SYSTEM IN THE STUDY AREA



Map 22 (continued)

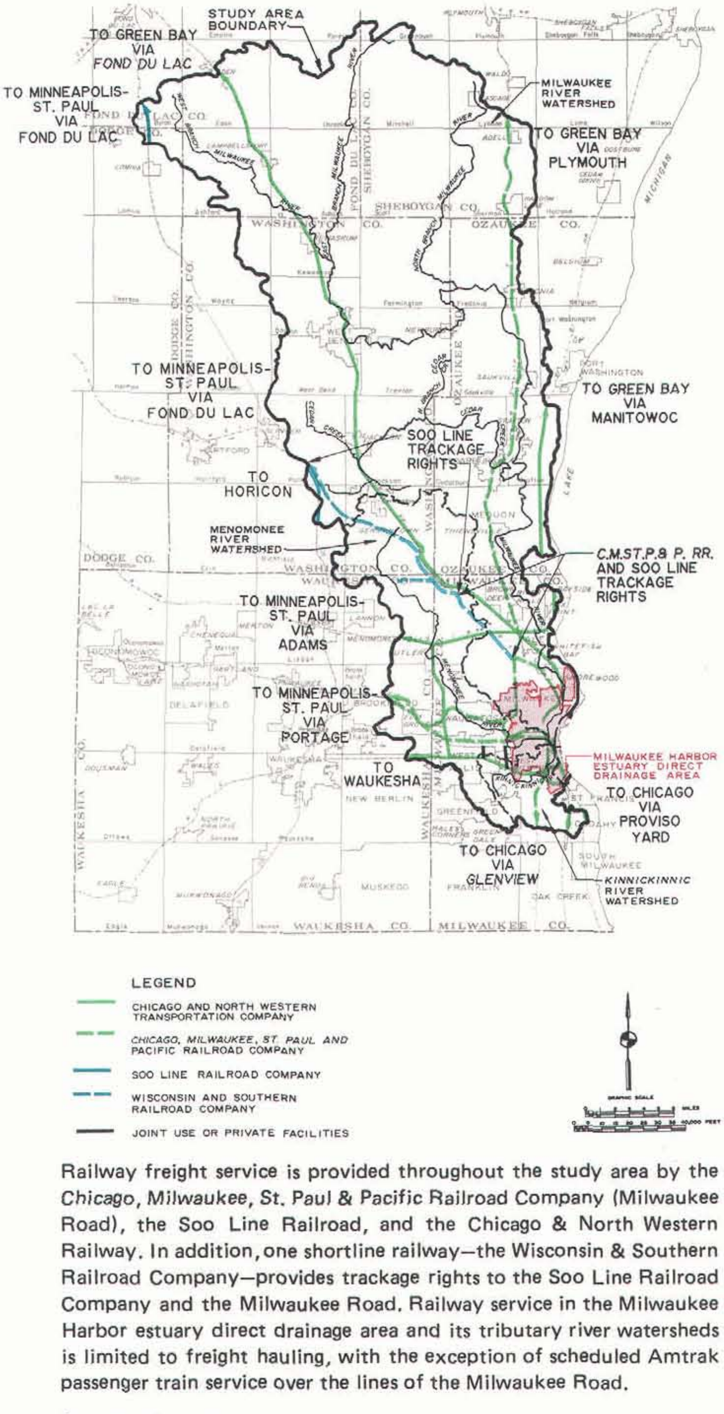


The Milwaukee Harbor estuary direct drainage area is served by an extensive street and highway system, including 12.4 lineal miles of freeway; 126.7 lineal miles of surface arterials; and 298.6 miles of collector and land access streets. The total study area, including the Milwaukee Harbor estuary direct drainage area and its three tributary river watersheds, is served by 68.6 lineal miles of freeway and 869.8 lineal miles of surface arterial facilities, and by 2,343.2 miles of collector and land access streets.

Source: SEWRPC.

Map 23

RAILWAY SERVICE IN THE STUDY AREA: 1984



Railway freight service is provided throughout the study area by the *Chicago, Milwaukee, St. Paul & Pacific* Railroad Company (Milwaukee Road), the Soo Line Railroad, and the Chicago & North Western Railway. In addition, one shortline railway—the Wisconsin & Southern Railroad Company—provides trackage rights to the Soo Line Railroad Company and the Milwaukee Road. Railway service in the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds is limited to freight hauling, with the exception of scheduled Amtrak passenger train service over the lines of the Milwaukee Road.

Source: SEWRPC.

As shown in Figure 6, the Port of Milwaukee consists of an outer harbor protected by four miles of rock breakwater, an inner harbor entrance protected by parallel piers, and an inner harbor that is extensively devoloped with docks, slips, canals, and warehouse facilities. The outer harbor and river channels to port facilities are 28 feet deep—as is the St. Lawrence Seaway, which links Milwaukee with the Atlantic Ocean. The upper reaches of the inner harbor are 21 feet deep.

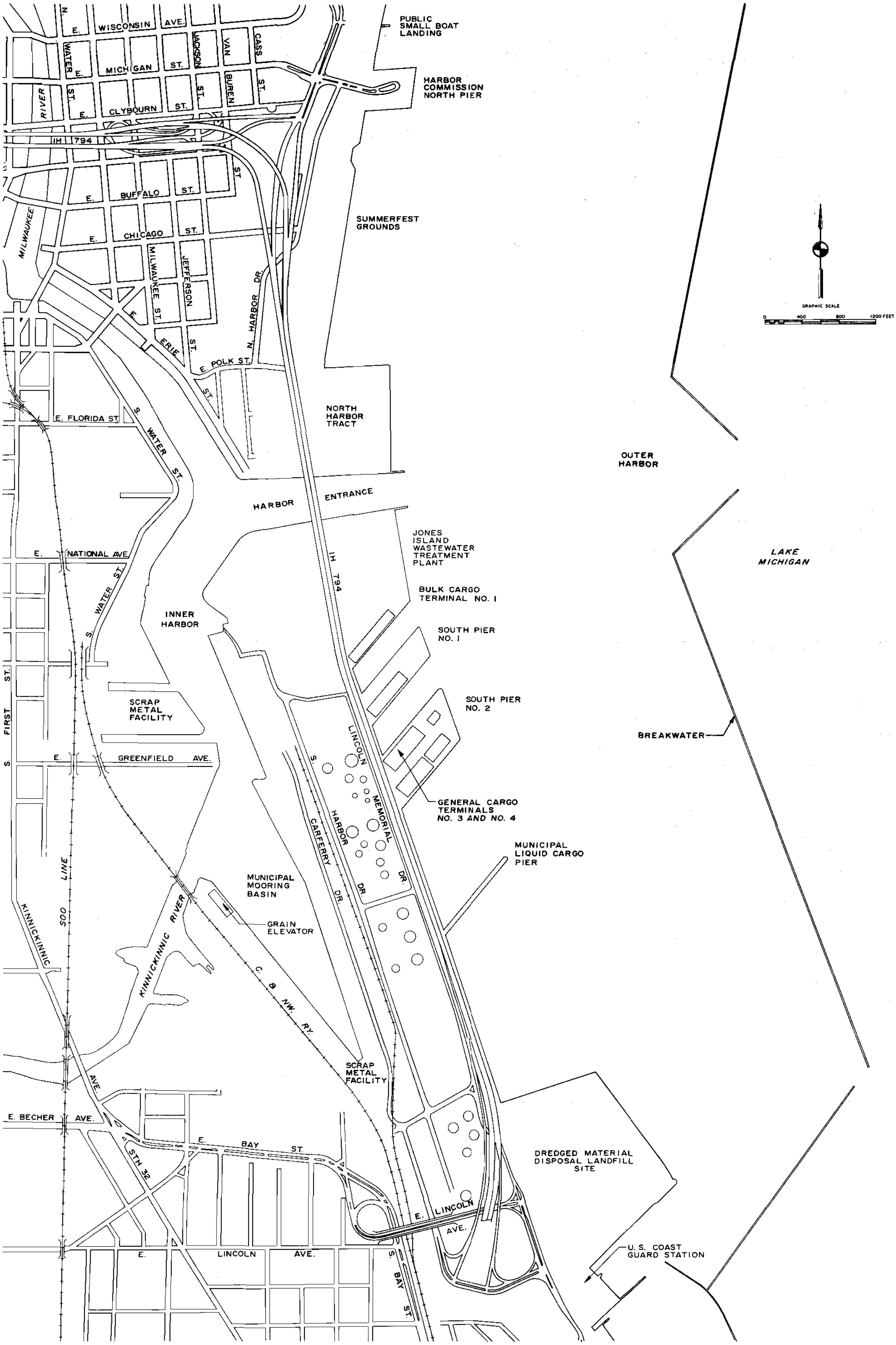
The South Harbor Tract, commonly known as Jones Island, is a peninsula 300 acres in area. The 105-acre North Harbor Tract is separated from Jones Island by the inner harbor channel entrance. The port facilities include several cargo docks, piers, and terminals, a container yard, a municipal mooring basin, grain elevators, scrap metals facilities, and a dredge spoils landfill site.

Ships utilizing the port include ocean ships, lake freighters, tankers, tugs, and barges. About 160 large commercial cargo ships and barges arrived at the port in 1982. Eight overseas lines serve the Port of Milwaukee, offering regular transport to Africa, the Caribbean, South America, the Mediterranean and Red Seas, and the Indian Ocean.

From 1968 through 1982, approximately two to four million tons of commerce were handled annually at the port facilities, as set forth in Table 17. In 1982 more than 683,000 tons of coal, 449,000 tons of grain, 408,000 tons of salt, and 339,000 tons of cement passed through the port. The municipal harbor terminals handle about 41 percent of the total port commerce, with the remaining 59 percent being handled at private terminals. Principal inbound commodities include grain, agricultural implements, cement, coal, salt, limestone, liquor, newsprint and paper products, petroleum, pig iron and steel, and sand and gravel. Principal outbound commodities include agricultural machinery and products, automobiles, canned goods, fats and oils, grain, heavy machinery, hides and skins, industrial tractors, scrap iron and steel, lumber, and appliances. Less than 5 percent of the inbound commerce and 65 percent of the outbound commerce in 1982 arrived from, or was sent to, overseas ports, with the remaining commerce being shipped to or from other Great Lakes ports.

The Port of Milwaukee has a substantial impact on the operation of many local industrial firms. An economic impact study was completed by the Port of Milwaukee staff in 1982 which measured the effects of waterborne commerce on the economy of the Milwaukee Standard Metropolitan Statistical Area, which includes Milwaukee, Ozaukee, Wauke-

Figure 6
PORT OF MILWAUKEE, WISCONSIN



Source: Port of Milwaukee.

Table 17

WATERBORNE COMMERCE AT THE PORT OF MILWAUKEE BY COMMODITY TYPE: 1968-1982

Commodity	Tons Imported or Exported											
	1968			1969			1970			1971		
	Import	Export	Total	Import	Export	Total	Import	Export	Total	Import	Export	Total
Coal.	1,146,336	187,815	1,334,151	862,870	--	862,870	844,982	--	844,982	537,299	22,000	559,299
Cement.	280,785	--	280,785	251,112	--	251,112	314,753	--	314,753	360,331	--	360,331
Sand	62,422	--	62,422	54,688	--	54,688	54,542	--	54,542	54,808	--	54,808
Slag.	32,760	--	32,760	39,420	--	39,420	20,450	--	20,450	12,880	--	12,880
Limestone	326,598	--	326,598	300,078	--	300,078	273,686	--	273,686	261,090	--	261,090
Clinker	168,610	--	168,610	164,480	--	164,480	114,700	--	114,700	84,650	--	84,650
Shale	62,509	--	62,509	68,327	--	68,327	51,244	--	51,244	61,325	--	61,325
Gypsum	14,000	--	14,000	14,499	--	14,499	7,276	--	7,276	15,107	--	15,107
Salt	163,615	--	163,615	195,746	--	195,746	209,271	--	209,271	372,793	--	372,793
Paper Products .	92,227	--	92,227	50,992	--	50,992	39,522	--	39,522	38,590	--	38,590
Grain	145,314	275,138	420,452	137,151	334,352	471,503	384,143	224,675	608,818	79,834	455,418	535,252
Petroleum	801,227	--	801,227	978,826	--	978,826	908,525	--	908,525	641,464	--	641,464
Liquid Cargo. . .	--	22,248	22,248	--	15,372	15,372	846	23,028	23,874	--	29,939	29,939
Scrap	96,281	83,792	180,073	95,416	252,936	348,352	79,734	189,391	269,125	90,974	31,880	122,854
Pig Iron.	44,580	--	44,580	42,140	--	42,140	35,217	--	35,217	43,361	--	43,361
Steel	11,303	400	11,703	100,511	--	100,511	137,053	--	137,053	137,115	--	137,115
General Cargo . .	163,323	210,433	373,756	138,983	274,293	413,276	140,870	221,467	362,337	159,291	303,850	463,141
Dry Bulk Other than Salt	--	--	--	--	--	--	--	--	--	--	--	--
Automobiles on Carferry.	740,593	1,227,287	1,967,880	770,377	1,094,889	1,865,266	779,283	1,101,737	1,881,020	487,827	625,402	1,113,229
Aggregates	--	--	--	--	--	--	--	--	--	7,120	--	7,120
Total	4,352,483	2,007,113	6,359,596	4,265,616	1,971,842	6,237,458	4,396,097	1,760,298	6,156,395	3,445,859	1,468,489	4,914,348

Commodity	Tons Imported or Exported											
	1972			1973			1974			1975		
	Import	Export	Total	Import	Export	Total	Import	Export	Total	Import	Export	Total
Coal.	980,534	--	980,534	1,118,333	--	1,118,333	898,751	--	898,751	827,828	--	827,828
Cement.	354,844	--	354,844	418,934	--	418,934	348,943	--	348,943	392,232	--	392,232
Sand	65,961	--	65,961	94,021	--	94,021	74,939	--	74,939	77,416	--	77,416
Slag.	21,073	--	21,073	--	--	--	--	--	--	--	--	--
Limestone	241,134	--	241,134	274,405	--	274,405	300,623	--	300,623	12,669	--	12,669
Clinker	68,993	--	68,993	75,764	--	75,764	77,049	--	77,049	32,796	--	32,796
Shale	56,285	--	56,285	79,385	--	79,385	61,243	--	61,243	--	--	--
Gypsum	7,570	--	7,570	8,603	--	8,603	8,559	--	8,559	--	--	--
Salt	378,836	--	378,836	310,871	--	310,871	325,678	--	325,678	308,084	--	308,084
Paper Products .	20,825	--	20,825	36,253	--	36,253	--	--	--	--	--	--
Grain	262,434	476,124	738,558	205,588	602,781	808,369	189,146	340,620	529,766	--	249,905	249,905
Petroleum	721,430	--	721,430	781,209	--	781,209	542,737	--	542,737	464,876	--	464,876
Liquid Cargo. . .	--	15,823	15,823	--	13,113	13,113	--	3,930	3,930	--	--	--
Scrap	90,847	86,432	177,279	55,505	189,820	245,325	--	17,998	17,998	--	160,837	160,837
Pig Iron.	47,451	--	47,451	25,429	--	25,429	21,863	--	21,863	45,994	--	45,994
Steel	116,164	--	116,164	119,040	--	119,040	53,850	--	53,850	77,581	--	77,581
General Cargo . .	123,485	144,007	267,492	97,005	156,327	253,332	39,289	134,101	173,390	177,951	170,908	348,859
Dry Bulk Other than Salt	--	--	--	--	--	--	28,900	--	28,900	37,795	--	37,795
Automobiles on Carferry.	451,235	509,684	960,919	353,318	499,274	852,592	244,557	359,434	603,991	224,489	322,788	547,277
Aggregates	21,684	--	21,684	8,015	--	8,015	9,400	--	9,400	--	--	--
Total	4,030,785	1,232,070	5,262,855	4,061,678	1,461,315	5,522,993	3,225,527	856,083	4,081,610	2,679,711	904,438	3,584,149

Table 17 (continued)

Commodity	Tons Imported or Exported: 1976 Import	1976 Export	1976 Total	1977 Import	1977 Export	1977 Total	1978 Import	1978 Export	1978 Total	1979 Import	1979 Export	1979 Total
Coal.	926,791	--	926,791	999,025	--	999,025	945,000	--	945,000	888,000	--	888,000
Cement.	443,748	--	443,748	432,879	--	432,879	600,517	--	600,517	536,318	--	536,318
Sand	68,999	--	68,999	74,122	--	74,122	70,949	--	70,949	98,270	--	98,270
Slag.	--	--	--	--	--	--	--	--	--	--	--	--
Limestone	--	--	--	--	--	--	--	--	--	--	--	--
Clinker	32,016	--	32,016	91,024	--	91,024	75,700	--	75,700	101,951	--	101,951
Shale	--	--	--	--	--	--	--	--	--	--	--	--
Gypsum	--	--	--	7,000	--	7,000	--	--	--	4,181	--	4,181
Salt.	454,383	2,355	456,738	206,244	--	204,244	378,196	--	378,196	315,228	--	315,228
Paper Products .	2,548	--	2,548	2,002	--	2,002	1,039	--	1,039	1,926	--	1,926
Grain	60,866	254,909	315,775	59,880	502,473	562,353	39,767	1,046,836	1,086,603	15,120	1,621,196	1,636,316
Petroleum	438,031	--	438,031	540,119	--	540,119	473,813	--	473,813	429,778	--	429,778
Liquid Cargo. . .	8,649	--	8,649	10,122	--	10,122	5,344	--	5,344	10,034	--	10,034
Scrap	--	111,984	111,984	--	83,636	83,635	--	83,253	83,253	--	115,207	115,207
Pig Iron.	19,311	--	19,311	24,629	--	24,629	27,954	--	27,954	25,613	--	25,613
Steel	33,182	--	33,182	In general cargo	--	--	In general cargo	--	--	173,545	822	174,367
General Cargo . .	87,716	172,848	260,564	87,924	176,891	264,815	87,425	115,909	203,334	83,213	128,849	212,062
Dry Bulk Other than Salt	--	--	--	18,616	--	18,616	36,630	--	36,630	--	--	--
Automobiles on Carferry.	239,566	303,010	542,576	266,229	290,548	556,777	287,105	225,704	512,809	199,346	124,590	323,936
Aggregates	--	--	--	--	--	--	--	--	--	--	--	
Total	2,815,806	845,106	3,660,912	2,819,815	1,053,547	3,873,362	3,029,439	1,471,702	4,501,141	2,882,523	1,990,664	4,873,187

Commodity	Tons Imported or Exported: 1980 Import	1980 Export	1980 Total	1981 Import	1981 Export	1981 Total	1982 Import	1982 Export	1982 Total
Coal.	1,005,754	--	1,005,754	760,399	--	760,399	683,321	--	683,321
Cement.	447,306	--	447,306	416,587	--	416,587	339,258	--	339,258
Sand	65,965	--	65,965	65,534	--	65,534	37,415	--	37,415
Slag.	--	--	--	11,460	--	11,460	--	--	--
Limestone	--	--	--	11,687	--	11,687	--	--	--
Clinker	51,500	--	51,500	--	--	--	32,086	--	32,086
Shale	--	--	--	--	--	--	--	--	--
Gypsum	--	--	--	--	--	--	--	--	--
Salt.	254,725	--	254,725	222,683	--	222,683	408,871	--	408,871
Paper Products .	2,814	--	2,814	4,053	--	4,053	6,728	--	6,728
Grain	--	1,383,747	1,383,747	4,800	1,062,736	1,067,536	28,412	420,608	449,020
Petroleum	446,728	--	446,728	174,935	10,254	185,189	18,996	--	18,996
Liquid Cargo. . .	2,894	14,695	17,589	37,520	13,584	51,104	25,383	10,598	35,981
Scrap	--	179,130	179,130	--	41,598	41,598	--	157,566	157,566
Pig Iron.	31,206	--	31,206	52,558	--	52,558	27,002	--	27,002
Steel	13,024	--	13,024	16,908	--	16,908	16,736	--	16,736
General Cargo . .	55,582	146,179	201,761	35,077	126,186	161,263	21,529	157,382	178,911
Dry Bulk Other than Salt	--	--	--	39,968	--	39,968	21,549	--	21,549
Automobiles on Carferry.	104,528	40,342	144,870	--	--	--	--	--	--
Aggregates	--	--	--	--	--	--	--	--	--
Total	2,482,026	1,764,093	4,246,119	1,854,169	1,254,358	3,108,527	1,667,286	746,154	2,413,440

Source: Port of Milwaukee.

sha, and Washington Counties.[2] According to the study, which included a survey of 340 companies in the four-county area, the Port of Milwaukee in 1979 contributed the equivalent of 5,825 full-time jobs with an annual payroll of $112.6 million, and stimulated the local economy with $1.1 billion in annual sales revenues. Seventy-eight companies directly utilized the port to considerable extent in 1979.

The economic impacts on the different industrial classifications are set forth in Table 18. The study indicated that about one-half of the contributions shown in Table 18 were associated with the direct users or operators of the port facilities, with the remaining one-half of the contributions being secondary or induced benefits, including the purchase of goods and services by port-related industries as well as the internal interchange of goods and services passed through the community as a result of the wages of port industry employees.

It should be noted that there is pending federal legislation which, if approved by Congress, would extend the commercial shipping season into the winter months. This legislation, which is identified as HR 3678 and known as the Roe bill, was introduced into the House of Representatives during the summer of 1983. Section 1123 of the Roe bill recommends an incremental increase in the length of the shipping season on the St. Lawrence Seaway to 10 months, 11 months, and finally year-round. This recommendation was based on the findings of a four-year study conducted by the Detroit District of the U. S. Army Corps of Engineers, the results of which are set forth in a report entitled, Winter Navigation Demonstration Project. The environmental impacts, particularly the impacts on water quality, and the costs associated with this effort would have to be examined in more detail prior to the implementation of an extended shipping season on the Great Lakes. The Roe bill, which is supported by the Western Great Lakes Ports Association, could significantly impact the operations of the Port of Milwaukee—which presently ends operations around December 15 and commences operations on or about April 1 when lake ice clears—and could increase the economic benefits that the Port of Milwaukee contributes to the Region.

[2] *Port of Milwaukee, Economic Impact Study, The Effects of Waterborne Commerce on the Community: A Four-County Standard Metropolitan Statistical Area Study, 1982.*

NATURAL RESOURCE BASE

The natural resource base is an important determinant of the development potential of an area, as well as of the ability of the area to provide a pleasant and habitable environment for all forms of life. The principal elements of the natural resource base are climate, physiography, topography, soils, vegetation, water resources, and fish and wildlife resources. Without a proper understanding of these elements and of their interrelationships, human use and alteration of the natural environment proceed at the risk of excessive costs in terms of both monetary expenditures and destruction of nonrenewable or slowly renewable resources. In this age of high resource demand, urban expansion, and rapidly changing technology, it is particularly important that the natural resource base be a primary consideration in any areawide planning effort.

This portion of the chapter identifies and describes the significant elements of the natural resource base of the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds; indicates and quantifies the spatial distribution and extent of those resources; characterizes, where possible, the quality of each component element of the natural resource base; and seeks to identify those elements and characteristics of the natural resource base which must be considered in the planning process. While all of the above-mentioned components of the natural resource base are described in this chapter, some of these elements are discussed in more detail, as needed, in later chapters.

Climate

General Climatic Conditions: Wisconsin's mid-continental location, far removed from the moderating effect of the oceans, gives the Region a typical continental-type climate characterized by a continuous progression of markedly different seasons and a large range in annual temperature. The summers are relatively warm, influenced by the warm southwesterly winds common during that season, with occasional periods of hot, humid weather and sporadic periods of very cool weather. Winters tend to be cold, cloudy, and snowy, accentuated by prevailing frigid northwesterly winds. There is often a short mid-winter thaw occasioned by brief periods of unseasonably warm weather. Streams and smaller lakes begin to freeze over in November, with the larger and deeper bodies of water usually being covered with ice by

Table 18

ECONOMIC IMPACT OF WATERBORNE COMMERCE THROUGH THE PORT OF MILWAUKEE: 1979

Industry Classification	Employment (full-time jobs)	Payroll (dollars per year)	Sales Revenues (dollars per year)
Port Operation Industries			
Dock and Pier Operations	1,323	$ 32,488,000	$ 662,999,000
Water Transportation Services	767	12,436,000	46,160,000
Surface Transportation Services	268	6,085,000	38,203,000
Marine Repairs, Supplies, and Services. . .	196	4,021,000	20,349,000
Subtotal	2,554	$ 55,030,000	$ 767,711,000
Port Users and Shippers			
Machinery Manufacturers	1,372	$ 24,254,000	$ 130,703,000
Electrical Machinery.	136	2,342,000	10,026,000
Metal Industries.	186	3,232,000	17,129,000
Leather Industries	1,059	19,043,000	84,532,000
Food and Kindred Industries	78	1,108,000	16,332,000
Transportation Equipment Manufacturers.	97	2,039,000	11,489,000
Wholesale Traders	56	1,069,000	13,314,000
Other Manufacturers	290	4,466,000	22,905,000
Subtotal	3,271	$ 57,553,000	$ 306,430,000
Total Economic Impact of Port Industry	5,825	$112,583,000	$1,074,141,000

Source: Port of Milwaukee, Economic Impact Study, The Effects of Waterborne Commerce on the Community: A Four-County Standard Metropolitan Statistical Area Study, 1982.

mid-December. Lake and stream ice breakup occurs in late March or early April owing to increasing amounts of incoming solar radiation.

The Southeastern Wisconsin Region is positioned astride cyclonic storm tracks along which low pressure centers move from the west and southwest. The Region also lies in the path of high pressure centers moving in a generally southeasterly direction. This location at the confluence of major migratory air masses results in the Region as a whole being influenced by a constantly changing pattern of different air masses having alternately high and low pressure centers, and thus frequent weather changes are superimposed on the large range in weather characteristics. This is particularly true in autumn and spring when distinct weather changes consist of marked variations in temperature, type and amounts of precipitation, relative humidity, wind magnitude and direction, and cloud cover.

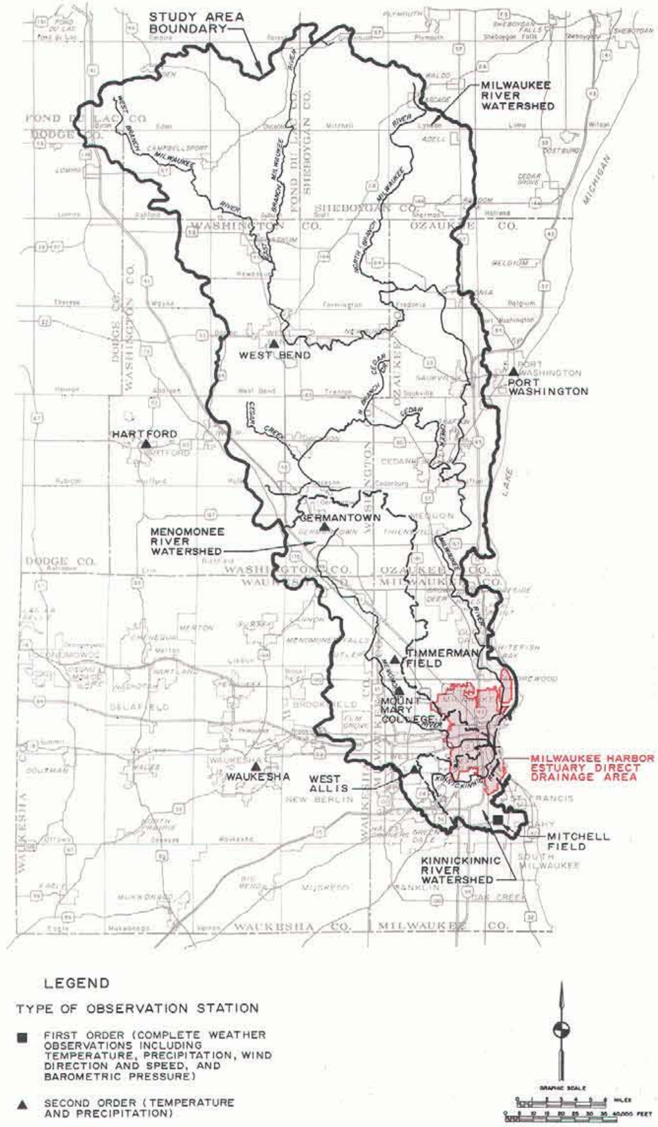
In addition to these distinct temporal variations in weather, the Region exhibits spatial variations in weather as a result of its proximity to Lake Michigan, particularly in the late spring, summer, and early fall seasons when the temperature differential between the lake water and the land air masses tends to be the greatest. During these periods, the presence of the lake tends to moderate the climate of the eastern border of the Region, including all or portions of the Milwaukee Harbor estuary direct drainage area. It is common, for example, for mid-day summer temperatures in shoreline areas to drop abruptly to a level 10°F lower than inland area temperatures because of cooling lake breezes generated by the pressure differences resulting from differential heating of the land and water surfaces. This Lake Michigan temperature influence may penetrate several miles inland but is generally limited to a narrow band of the Region along the shoreline.

The locations of nine long-term meteorological stations in or near the Milwaukee Harbor estuary direct drainage area and its three tributary river watersheds, as well as the meteorological elements measured at each site, are shown on Map 24. As may be seen on Map 24, there is one first-order National Weather Service station in the study area, that being located at Mitchell Field airport in the southeastern corner of the study area. The remaining eight meteorological stations in or near the study area are second-order stations operated by cooperative observers and record only temperature or precipitation or both. In addition to the National Weather Service network of first-and second-order meteorological stations, the City of Milwaukee maintains 15 recording precipitation gages throughout that municipality. The locations and types of precipitation gages operated by the City of Milwaukee are shown on Map 25. Short-term meteorological data stations operated during the field monitoring program for the Milwaukee Harbor estuary study by the Milwaukee Metropolitan Sewerage District and the U. S. Geological Survey are described in Chapter V of this volume, which presents detailed descriptions of all meteorological stations in the Milwaukee Harbor direct drainage area and vicinity.

Temperature: As noted, the temperature in the Milwaukee Harbor estuary and its tributary river watersheds exhibits a large annual range. Seasonal temperatures determine the kinds and intensities of recreational uses to which the surface waters of the estuary and its tributary river watersheds may be put and, consequently, the periods over which the highest levels of water quality should be maintained. More importantly, aerobic and anaerobic biochemical processes fundamental to self-purification of surface waters are temperature dependent, since reaction rates approximately double with each 20°F rise in temperature within the temperature range normally encountered in nature. The supply of oxygen available for such processes is a function of oxygen solubility in water, or the maximum concentration of oxygen that can be retained in solution, which is highly dependent on temperature. A stream at or near freezing temperatures can hold about 15 milligrams per liter (mg/l) of dissolved oxygen, but the dissolved oxygen solubility of surface waters of that same stream on a hot day with the water temperature near 80°F will be

Map 24

METEOROLOGICAL OBSERVATION STATIONS IN OR NEAR THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS



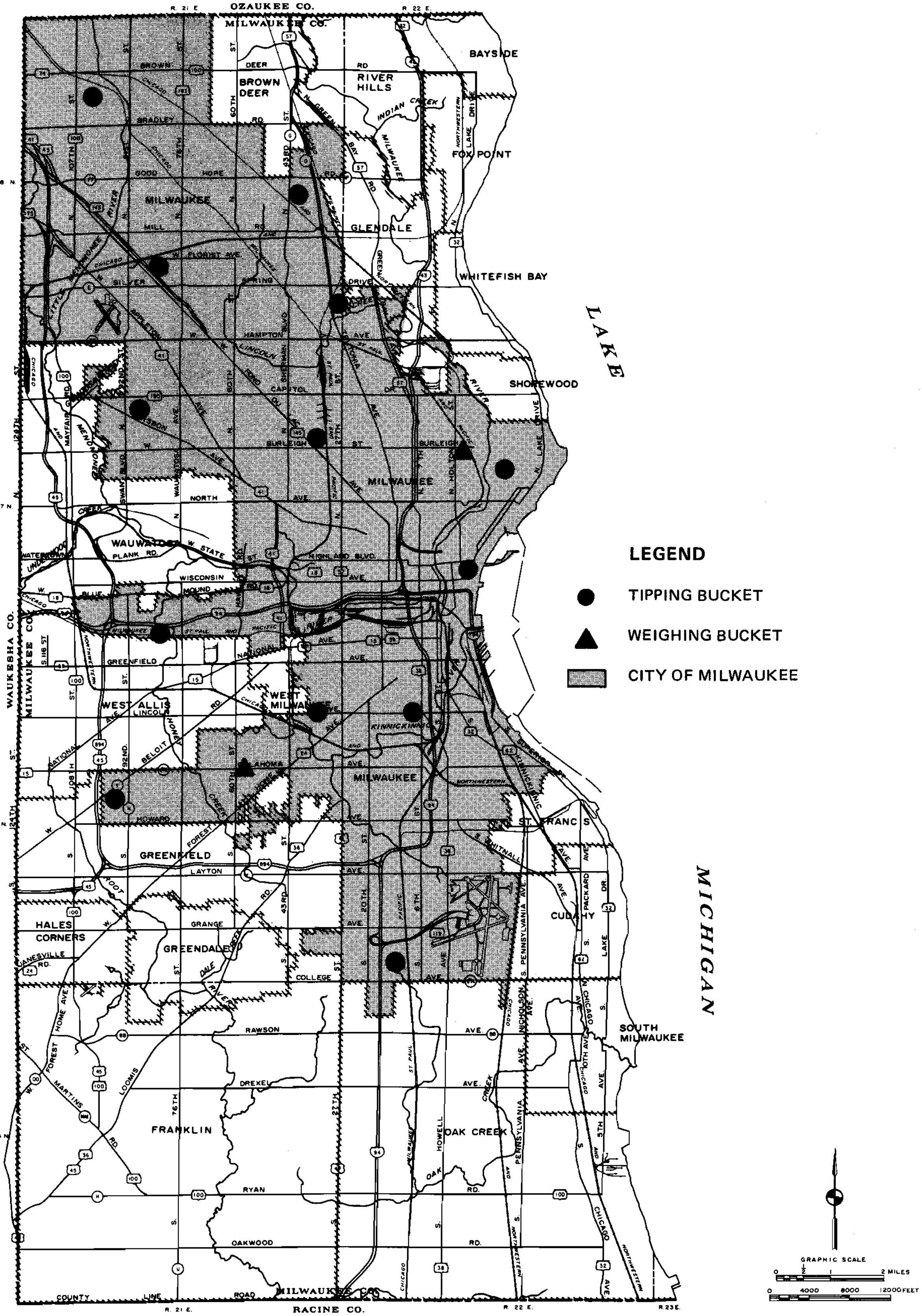
There are nine long-term meteorological data collection stations in or near the Milwaukee Harbor estuary direct drainage area and its three tributary river watersheds. This network of meteorological stations, utilizing uniform observation and data collection techniques, provides information that is essential to understanding the climatic regime of the study area. Data collected at these stations are collated and published by the National Climatic Center, National Oceanic and Atmospheric Administration.

Source: SEWRPC.

reduced by almost one-half. The summer period is, therefore, critical and limiting in both natural and artificially induced aerobic processes, since oxygen demands are at their annual maximum because of accelerated reaction rates, while oxygen supply is at its annual minimum because of solubility limitations associated with high temperatures.

Map 25

LOCATION OF CITY OF MILWAUKEE RAIN GAGES: 1983



The City of Milwaukee, Bureau of Engineering, maintains a network of 15 continuously recording rain gages. These rain gages provide essential data on the distribution of precipitation over the City during major storm events and are integral to the data base established for the hydrologic-hydraulic simulation modeling effort.

Source: SEWRPC.

Table 19

NORMAL AIR TEMPERATURES AT SELECTED METEOROLOGICAL OBSERVATION STATIONS IN OR NEAR THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1951-1980[a]

Month	Meteorological Station Location											
	Milwaukee (Mitchell Field)			Germantown			West Bend			Three-Station Average		
	Average Daily Maximum	Average Daily Minimum	Mean	Average Daily Maximum	Average Daily Minimum	Mean	Average Daily Maximum	Average Daily Minimum	Mean	Average Daily Maximum	Average Daily Minimum	Mean
January. . .	26.0	11.3	18.7	26.0	8.2	17.1	25.4	8.8	17.1	25.8	9.4	17.6
February . .	30.1	15.8	23.0	30.6	12.5	21.6	29.6	13.0	21.3	30.1	13.8	22.0
March. . . .	39.2	24.9	32.1	40.2	22.3	31.3	39.3	22.7	31.0	39.6	23.3	31.5
April	53.5	35.6	44.6	55.4	34.1	44.8	54.9	34.7	44.8	54.6	34.8	44.7
May.	64.8	44.7	54.8	67.8	43.4	55.6	67.3	44.5	55.9	66.6	44.2	55.4
June	75.0	54.7	64.9	77.3	52.9	65.1	76.7	54.1	65.4	76.3	53.9	65.1
July.	79.8	61.1	70.5	82.0	58.0	70.0	81.1	59.6	70.3	81.0	59.6	70.3
August . . .	78.4	60.2	69.3	80.3	56.9	68.6	79.3	58.4	68.9	79.3	58.5	68.9
September .	71.2	52.5	61.9	72.6	49.2	60.9	71.6	50.7	61.2	71.8	50.8	61.3
October . .	59.9	41.9	50.9	61.3	39.5	50.4	60.1	41.0	50.5	60.4	40.8	50.6
November .	44.7	29.9	37.3	45.4	27.7	36.5	44.5	28.5	36.5	44.9	28.7	36.8
December .	32.0	18.2	25.1	32.0	15.2	23.6	31.1	16.0	23.6	31.7	16.5	24.1
Annual	54.6	37.6	46.1	55.9	35.0	45.5	55.1	36.0	45.5	55.2	36.2	45.7

[a] *The 30-year period 1951-1980 is the "standard normal" period which conforms to the World Meteorological Organization standard for climatological normals.*

Source: National Climatic Center and SEWRPC.

Temperature data for three selected meteorological observation stations within the study area—Milwaukee at Mitchell Field, Germantown, and West Bend—are presented in Table 19 and shown graphically in Figure 7. The air temperature data used to develop the table and figure represent the monthly climatic normal averages for the period 1951 through 1980. The use of the 30-year climatic normal period provides for a consistent period of record between stations with varying years of operation, and thus enables more accurate comparisons to be made of prevailing temperature conditions. From a statistical standpoint, a 30-year period of record may be expected to encompass about 95 percent of the total variation experienced by a particular meteorological element at a given location.

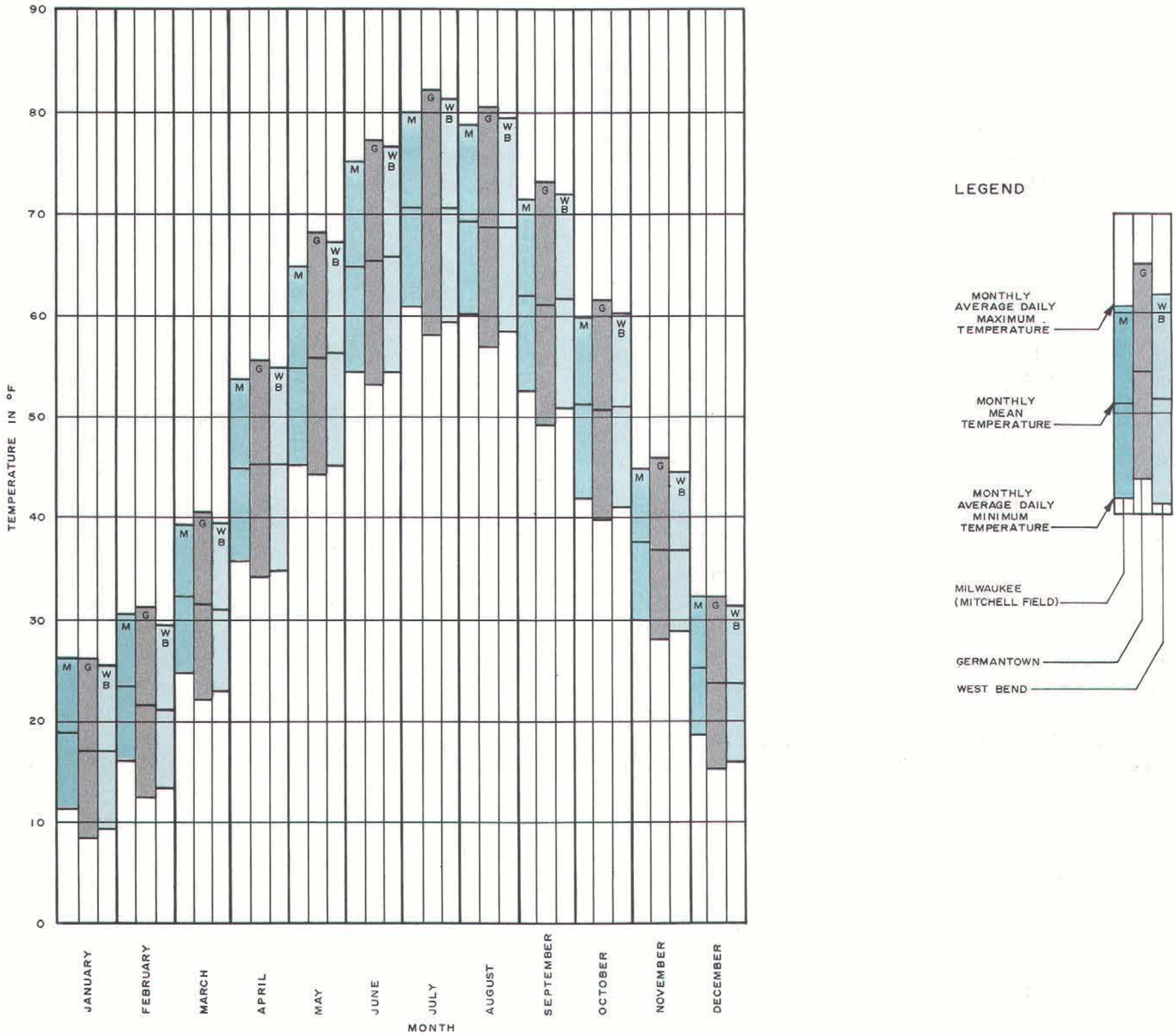
In general, the temperature data for the study area, as reflected by the monthly mean temperatures at the Milwaukee, Germantown, and West Bend observation stations, indicate both spatial and temporal variations. The temperature data also illustrate how air temperatures in the study area lag approximately one month behind the winter and summer solstices during the annual cycle; as a result, July is the warmest month in the study area and January is the coldest.

Mean summer air temperatures in July and August are in the 70°F range within the study area. Average daily maximum temperatures for these two summer months range from 78°F to 82°F, whereas the average daily minimum temperatures vary from 57°F to 61°F. With respect to daily minimum temperatures, the meteorological station network is not sufficient to reflect all the effects of topography. During nighttime hours, cold air, because of its greater density, flows into low-lying areas. Because of this phenomenon, the average daily minimum temperatures in these topographically low areas, particularly during the summer months, will be lower than those recorded at the meteorological stations.

Winter temperatures within the study area, as measured by the monthly means for January and February, range from 17°F to 23°F. Average daily maximum temperatures within the study area for

Figure 7

TEMPERATURE DATA FOR SELECTED METEOROLOGICAL OBSERVATION STATIONS IN OR NEAR THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1951-1980



Source: National Climatic Center and SEWRPC.

these two months vary from about 25°F to 31°F, whereas the average daily minimum temperatures range from about 8°F to 16°F.

The temperature data presented in Table 19 and Figure 7 provide evidence of the moderating effect that Lake Michigan exerts on near-shore temperatures. For example, the Germantown and West Bend meteorological stations exhibit average daily maximum temperatures, particularly during the summer months, of 1°F to 2°F higher than those exhibited at the Mitchell Field station in the City of Milwaukee. Thus, the presence of Lake Michigan and its associated lake breeze phenomenon act to reduce the incidence of higher temperatures in the near-shore environment.

The temperature data for these three stations also provide evidence of an "urban heat island effect." Large urban complexes have been observed to exhibit higher air temperatures than surrounding rural areas. This temperature differential is greatest during the evening hours on clear days and is partly attributable to the numerous heat sources distributed throughout an urban environment. Another factor is the more gradual loss of this heat to the atmosphere because of the dense pattern of the urban structures emitting the radiating heat toward each other rather than into the open atmosphere as in rural areas, and because of the presence of atmospheric contaminants which form a barrier to nighttime radiation from the earth back to the atmosphere.

As shown in Table 19 and in Figure 7, average daily minimum temperatures at Mitchell Field in the City of Milwaukee are consistently 2°F to 3°F higher than the average daily minimum temperatures at either the Germantown station or the West Bend station. Moreover, although the annual average daily maximum temperature at Mitchell Field is on the order of 1°F lower than that at Germantown or West Bend, the annual average temperature at Mitchell Field is about 1°F higher than that at the other two stations. These differences are principally a result of the heat island effect which causes the minimum temperatures at Mitchell Field to average about 1°F to 2°F higher on an annual basis than the average minimum temperatures at either Germantown or West Bend.

Extreme high and low temperatures in the Milwaukee Harbor estuary direct drainage area, based on 112 years of historic record collected in the City of Milwaukee, range from a high of 105°F, recorded in July 1934, to a low of -26°F, measured in January 1982. The growing season, which is defined as the number of days between the last 32°F freeze in spring and the first such event in the fall, averages about 180 days in the study area. The last 32°F frost in the spring normally occurs near the end of April, and the first freeze in the fall usually occurs during the latter half of October.

Precipitation: Precipitation within the study area takes the form of rain, sleet, hail, and snow. Precipitation events may range from gentle showers of trace quantities to destructive thunderstorms, as well as major rainfall-snowmelt events causing property damage, inundation of poorly drained areas, and stream flooding. Existing sewerage system problems such as overflows from combined sewers are the direct result of even small precipitation events. Rainfall events may also cause separate sanitary sewerage systems to surcharge and back up into basements and overflow into surface watercourses, and may require sewage treatment plants to bypass large volumes of partially treated or untreated sewage in excess of the hydraulic capacity of the plants. Such surcharging of separate sanitary sewerage systems is caused by the entry of excessive quantities of rain, snowmelt, and groundwater into the sanitary sewers through manholes, building sewers, building downspouts, and foundation drain connections, and by infiltration through faulty sewer pipe joints, manhole structures, and cracked pipes.

Table 20 and Figure 8 indicate the average precipitation by month for the climatic period 1951 to 1980 for three meteorological stations in the study area—Milwaukee at Mitchell Field, Germantown, and West Bend. Table 20 also presents average snowfall data for these three stations for varying periods of record. The average annual total precipitation in the study area, based on a numerical average of data for Mitchell Field, Germantown, and West Bend, is 30.1 inches, expressed as water equivalent, while the average annual snowfall is 47.8 inches.

Average total monthly precipitation within the study area ranges from a low of 1.04 inches in February to a high of 3.69 inches in July. The principal snowfall months are December, January, February, and March, when average monthly snowfalls are 12.0, 12.0, 8.2, and 11.0 inches, respectively, and during which time about 92 percent of the average annual snowfall may be expected to occur. Snowfall is the predominant form of precipitation during these months, totaling approximately 60 percent of the total precipitation, expressed as water equivalent. More than 19 inches, or about 64 percent, of the average annual precipitation normally occurs during the mid-April to mid-October growing season, primarily as rainfall. Assuming that 10 inches of measured snowfall is equivalent to one inch of water, the average annual snowfall of 47.8 inches is equivalent to 4.78 inches of water, and therefore only 15 percent of the average annual total precipitation occurs as snowfall.

A comparison of precipitation data for the Mitchell Field, Germantown, and West Bend meteorological stations suggests that proximity to Lake Michigan

Table 20

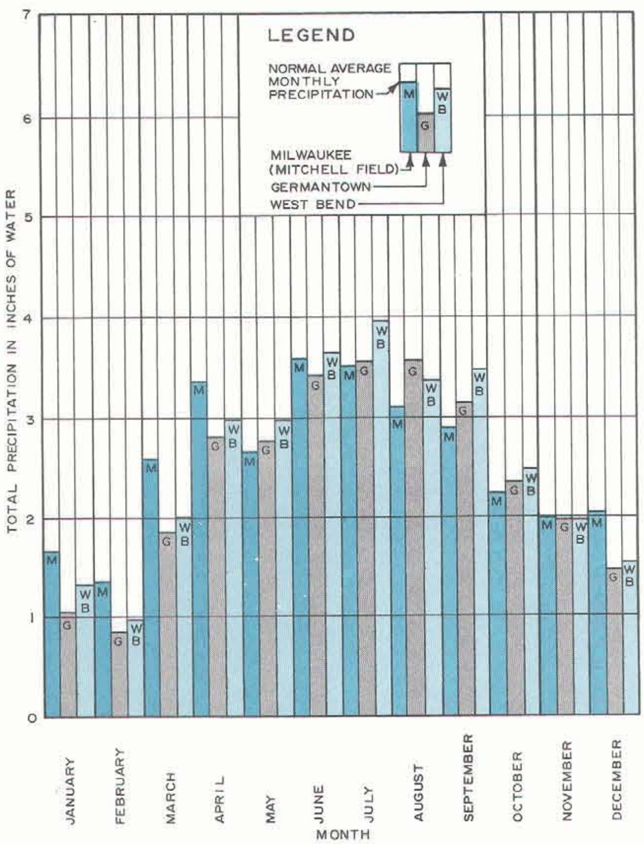
PRECIPITATION CHARACTERISTICS AT SELECTED LOCATIONS WITHIN THE STUDY AREA

Month	Milwaukee (Mitchell Field) Average Normal Precipitation (1951-1980)	Milwaukee (Mitchell Field) Average Snow and Sleet (1951-1980)	Germantown Average Normal Precipitation (1951-1980)	Germantown Average Snow and Sleet (1961-1976)	West Bend Average Normal Precipitation (1951-1980)	West Bend Average Snow and Sleet (1961-1970)	Three-Station Average Average Normal Precipitation (1951-1980)	Three-Station Average Average Snow and Sleet
January. . .	1.64	13.5	1.04	10.2	1.31	12.4	1.33	12.0
February . .	1.33	10.5	0.83	9.4	0.95	4.8	1.04	8.2
March. . . .	2.58	10.1	1.84	11.7	1.99	11.3	2.14	11.0
April	3.37	2.1	2.81	2.6	2.97	1.3	3.05	2.0
May.	2.66	Trace	2.78	0.0	2.97	Trace	2.80	Trace
June	3.59	0.0	3.42	0.0	3.65	0.0	3.55	0.0
July.	3.54	0.0	3.56	0.0	3.97	0.0	3.69	0.0
August . . .	3.09	0.0	3.55	0.0	3.37	0.0	3.33	0.0
September .	2.88	Trace	3.14	Trace	3.48	Trace	3.17	Trace
October . .	2.25	0.2	2.36	0.1	2.48	0.2	2.36	0.2
November .	1.98	3.4	1.97	2.2	1.97	1.5	1.97	2.4
December .	2.03	11.4	1.46	12.1	1.54	12.4	1.68	12.0
Annual	30.94	51.2	28.76	48.3	30.65	43.9	30.11	47.8

Source: National Climatic Center and SEWRPC.

Figure 8

PRECIPITATION CHARACTERISTICS AT SELECTED LOCATIONS WITHIN THE STUDY AREA



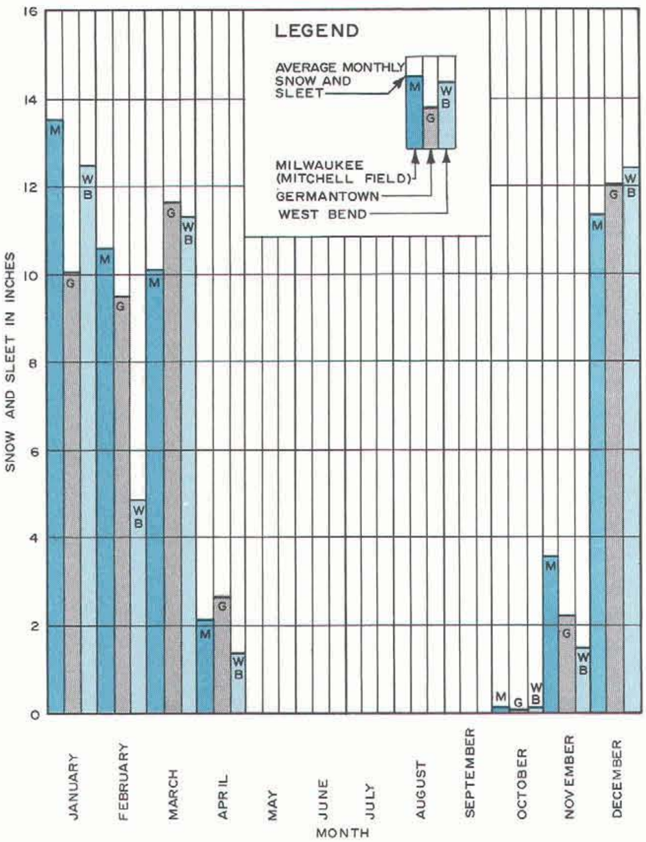
Source: National Climatic Center and SEWRPC.

may induce somewhat greater average snow and sleet accumulations. As shown in Table 20 and in Figure 9, the Mitchell Field station, which is located about 3.5 miles from the Lake Michigan shoreline, has an average seasonal snowfall of about 51 inches, 3 inches more than the 48 inches recorded at the Germantown and West Bend stations. The occurrence of somewhat greater seasonal snowfall amounts along the Lake Michigan shoreline may be attributed to the greater amount of moisture in the air mass immediately above the lake.

Snow Cover: The likelihood of snow cover and the depth of that cover on the ground are important factors influencing the planning, design, construction, and maintenance of public utilities. Because snow acts as a thermal insulator, snow cover, particularly early in the winter season, significantly influences the depth and duration of frozen ground, which in turn affects engineered works involving extensive excavation and underground construction. Snow and ice cover on surface water systems acts to reduce the atmospheric re-aeration rate; this lower re-aeration rate may, in turn, significantly reduce the amount of oxygen available in the water. Photosynthetic oxygen production by aquatic plants also decreases as a result of snow and ice cover on surface waters. Accumulated snow depth at a particular time and place is primarily dependent on antecedent snowfall, rainfall, and temperature characteristics, and the amount of

Figure 9

AVERAGE MONTHLY SNOW AND SLEET DATA AT SELECTED LOCATIONS WITHIN THE STUDY AREA



Source: National Climatic Center and SEWRPC.

solar radiation received. Rainfall is relatively unimportant as a melting agent, but can, because of compaction effects, significantly affect the depth of snow cover on the ground.

Snow depth as measured at Milwaukee for the 70-year period from 1900 through 1969 and published in Snow and Frost in Wisconsin, a 1970 Wisconsin Statistical Reporting Service publication, is summarized in Table 21. It should be noted that the tabulated data pertain to snow depth on the ground as measured at the time and place of observation, and are not a direct measure of average snowfall. Recognizing that snowfall and temperatures and, therefore, snow accumulation on the ground vary spatially within the study area, the Milwaukee data presented in Table 21 should be considered only an approximation of conditions throughout the entire study area. As indicated by the data, snow cover is most likely during the months of December, January, and February, during which at least a 40 percent probability exists of having one inch or more of snow cover in Milwaukee. Furthermore, during January and the first half of February, there is at least a 25 percent probability of having five or more inches of snow on the ground. During March, the month in which severe spring snowmelt-rainfall flood events are most likely to occur, there is at least a 30 percent probability of having one inch or more of snow on the ground during the first half of the month, while the probability of having that much snow on the ground diminishes to 7 percent by the end of the month.

The data presented in Table 21 can be used to estimate the probability that a given snow cover will exist or be exceeded at any given time, and should, therefore, be useful in planning winter outdoor work and construction activities, as well as in estimating runoff for hydrologic purposes. There is, for example, a 7 percent probability of having one inch or more of snow cover on November 15 of any year, whereas there is a much higher probability, 61 percent, of having that much snow cover on January 15.

Frost Depth: Ground frost or frozen ground refers to that condition in which the ground contains variable amounts of water in the form of ice. Frost influences hydrologic processes, particularly the percent of rainfall or snowmelt that will run off the land directly to sewerage systems and to surface watercourses, in contrast to that which will enter and be temporarily detained in the soil. Anticipated frost conditions influence the design of engineered works in that structures and facilities either are developed to prevent the accumulation of water and, therefore, the formation of damaging frost, as in the case of pavements and retaining walls, or are designed to be partially or completely located below the frost susceptible zone in the soil, as in the case of foundations and water mains. For example, in order to avoid or minimize the danger of structural damage, foundation footings must be placed deep enough in the ground to be below that zone in which the soil may be expected to contract, expand, or shift because of frost action. Similar considerations are weighed in the design and construction of sanitary sewers.

Snow cover is a primary determinant of the depth of frost penetration and of the duration of frozen ground. The thermal conductivity of snow cover is less than one-fifth that of moist soil, and thus heat loss from the soil to the cold atmosphere is greatly inhibited by an insulating snow cover. An early, major snowfall that is retained on the

Table 21

SNOW COVER PROBABILITIES AT MILWAUKEE BASED ON DATA FOR THE PERIOD 1900-1969

Date		Snow Cover[a]									
		1.0 Inch or More		5.0 Inches or More		10.0 Inches or More		15.0 Inches or More		Average (inches)	
Month	Day	Number of Occurrences[b]	Probability of Occurrence[c]	Number of Occurrences[b]	Probability of Occurrence[c]	Number of Occurrences[b]	Probability of Occurrence[c]	Number of Occurrences[b]	Probability of Occurrence[c]	Per Occurrence[d]	Overall[e]
November	15	5	0.07	0	0.00	0	0.00	0	0.00	1.2	0.09
	30	12	0.17	1	0.01	1	0.01	0	0.00	2.8	0.49
December	15	33	0.47	10	0.14	0	0.00	0	0.00	3.3	1.54
	31	32	0.46	9	0.13	1	0.01	0	0.00	3.6	1.66
January	15	43	0.61	17	0.24	4	0.06	2	0.03	4.9	2.94
	31	48	0.69	22	0.31	9	0.13	4	0.06	6.2	4.26
February	15	44	0.63	23	0.33	7	0.10	3	0.04	6.0	3.69
	28	27	0.39	8	0.11	3	0.04	1	0.01	4.5	1.69
March	15	23	0.33	6	0.09	4	0.06	0	0.00	3.9	1.21
	31	5	0.07	1	0.01	1	0.01	0	0.00	3.4	0.24

[a] *Data pertain to snow depth on the ground as it was measured at the time and place of observation, and are not a direct measure of average snowfall.*

[b] *Number of occurrences is the number of times during the 70-year period of record when measurements revealed that the indicated snow depth was equaled or exceeded on the indicated date.*

[c] *Probability of occurrence for a given snow depth and date is computed by dividing the number of occurrences by 70, and is defined as the probability that the indicated snow cover will be reached or exceeded on the indicated date.*

[d] *Average snow cover per occurrence is defined as the sum of all snow cover measurements in inches for the indicated date divided by the number of occurrences for that date—that is, the number of times in which 1.0 inch or more of snow cover was recorded.*

[e] *Overall average snow cover is defined as the sum of all snow cover measurements in inches for the indicated date divided by 70—that is, the number of observation times.*

Source: Wisconsin Statistical Reporting Service, National Weather Service, and SEWRPC.

ground as a substantial snow cover will inhibit or prevent frost development in unfrozen ground and may even result in a reduction or elimination of frost in already frozen ground. If an early significant snow cover is maintained by additional regular snowfall throughout the winter season, frozen ground may not develop at all, or, at most, a relatively shallow frost penetration will occur. Frost depth is also dependent on vegetal cover and soil type. Assuming similar soil types, for example, frost will penetrate more deeply into bare, unprotected soil than into soil covered with an insulating layer of sod.

Frost conditions in the Region were published by the Wisconsin Agricultural Reporting Service for the months of November through April based on an eight-year period of record from 1961 through 1977, and are summarized on a semi-monthly basis in Table 22. These data were provided for representative locations on a weekly basis by funeral directors and cemetery officials. Since cemetery soils are normally overlain by an insulating layer of turf, the frost depths shown in Table 22 should be considered minimum values. Frost depths in excess of four feet have been observed in southeastern Wisconsin. Between 1961 and 1977, one of the deepest regionwide frost penetrations occurred in early March 1963, when frost levels penetrated 25 to 30 inches over a broad geographical area.

Table 22 indicates that frozen ground is likely to exist in the study area for approximately four months each winter season, extending from late November through March, with more than six inches of frost normally occurring during January, February, and the first half of March. Historical data indicate that the most severe frost conditions normally occur in February, when 15 or more inches of frost may be expected.

Wind: Figure 10 presents seasonal "wind roses" for the frequency distribution of wind speed and direction as recorded at the National Weather Service office at General Mitchell Field in Milwaukee County during the 10-year period 1964

Table 22

AVERAGE FROST DEPTH IN SOUTHEASTERN WISCONSIN: NOVEMBER TO APRIL

Month and Day	Nominal Frost Depth (inches)[a]
November 30	1
December 15	3
December 31	4
January 15.	9
January 31.	12
February 15.	14
February 28.	15
March 15.	13
March 31.	7
April 15.	3

[a] *Based on 1961-1977 frost depth data for cemeteries as reported by funeral directors and cemetery officials. Since cemeteries have soils that are overlain by an insulating layer of turf, the mapped frost depths should be considered as minimum values.*

Source: Wisconsin Agricultural Reporting Service, Snow and Frost in Wisconsin, October 1978.

through 1973. As shown in this figure, the winds during the summer season have a high southwesterly component, with the quadrant from due south to the west-by-southwest accounting for about 38 percent of the prevailing wind direction. The other three quadrants each account for only about 20 percent of the prevailing wind direction during the summer season. In the winter season, the prevailing winds at Mitchell Field assume a higher west-to-north component. During this season, the winds from the quadrant ranging from due west to north-by-northwest occur with about a 45 percent frequency. On an annual basis, the predominant wind direction is from due west, with these winds occurring with a frequency in excess of 12 percent.

In addition to a clockwise wind shift between summer and winter, there is a noticeable change in the speed of the wind between seasons. As indicated in Figure 10, higher wind speeds are more frequent during the winter months.

On the average, wind speeds less than four knots (4.6 miles per hour) occur with a 25 percent frequency in the winter months as compared with a 35 percent frequency during the summer months. At the other extreme, wind speeds in excess of 17 knots (19.6 miles per hour) occur with a frequency of about 10 percent in winter as compared with only 5 percent in summer. On an average annual basis, wind speeds at General Mitchell Field may be expected to be less than four knots about 25 percent of the time, between 4 and 17 knots about 65 percent of the time, and in excess of 17 knots about 10 percent of the time.

Evaporation: Evaporation is the natural process whereby water is transformed from the liquid or solid state to the vapor state and returned to the atmosphere. Total evaporation includes evaporation from water surfaces and directly from the soil, sublimation from snow surfaces, and the transpiration of precipitation intercepted by vegetation. The magnitude and annual variation in evaporation from water surfaces and the relation of evaporation to precipitation are important because of the key role this process assumes in the hydrologic cycle within the study area.

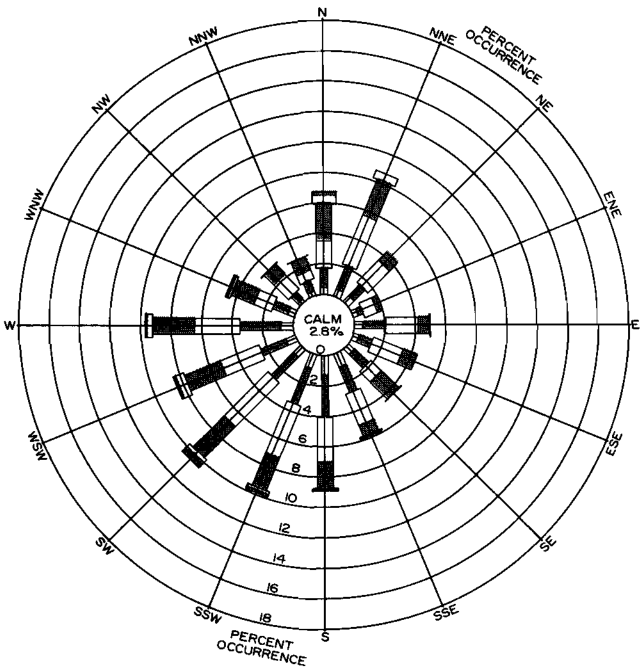
The limited evaporation data available for the study area indicate an average annual evaporation rate from a water surface of about 29 inches, with about three-fourths of this, or about 23.6 inches, occurring in the six-month May through October period. As indicated earlier in this chapter and summarized in Table 20, the average annual precipitation for the study area is about 30 inches, just slightly greater than the average annual evaporation rate. During the six-month May through October period, precipitation over the watershed averages about 18.9 inches and, therefore, evaporation from a water surface may be expected to exceed precipitation by almost five inches during this period.

Daylight and Sky Cover: The annual variation in the time of sunrise and sunset and the daily hours of sunlight in the study area are shown in Figure 11. Expected sky cover information, in the form of the expected percent of clear, partly cloudy, and cloudy days each month, is also presented in Figure 11. These data are useful in analyzing and explaining certain changes in observed surface water quality. For example, marked changes in measured dissolved oxygen levels in a stream are normally correlated with the transition from daytime to nighttime conditions, when photosynthetic oxygen production by algae and aquatic plants is replaced by oxygen utilization through respiration by those plants. As illustrated in Figure 11, the duration of daylight ranges from a mini-

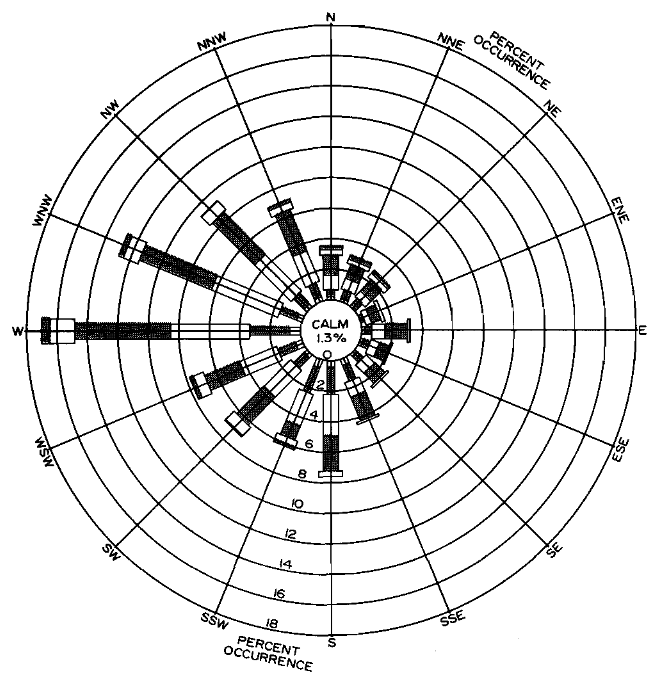
Figure 10

WIND ROSES FOR FREQUENCY DISTRIBUTION OF WIND SPEED AND DIRECTION FOR MILWAUKEE: 1964-1973

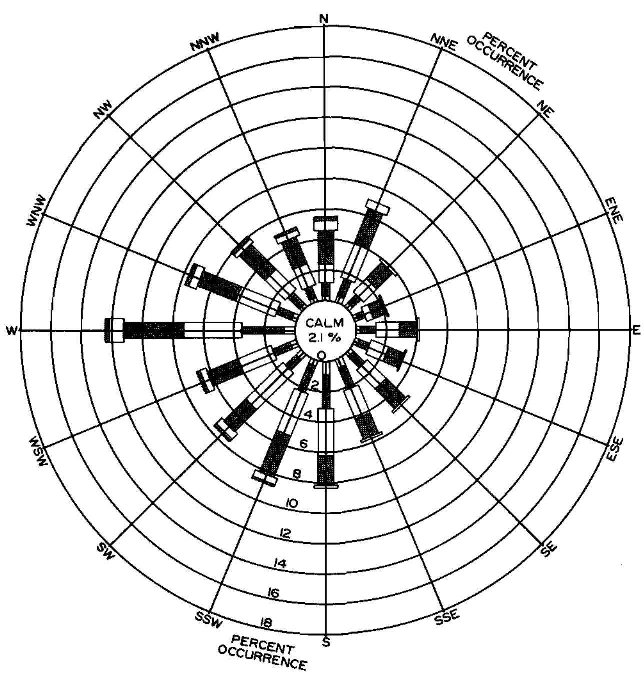
WIND ROSE FOR FREQUENCY DISTRIBUTION OF WINTER WIND DIRECTION FOR MILWAUKEE: 1964-1973



WIND ROSE FOR FREQUENCY DISTRIBUTION OF SUMMER WIND DIRECTION FOR MILWAUKEE: 1964-1973

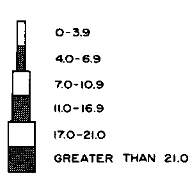


WIND ROSE FOR FREQUENCY DISTRIBUTION OF ANNUAL PREVAILING WIND DIRECTION FOR MILWAUKEE: 1964-1973



LEGEND

WIND SPEED IN KNOTS

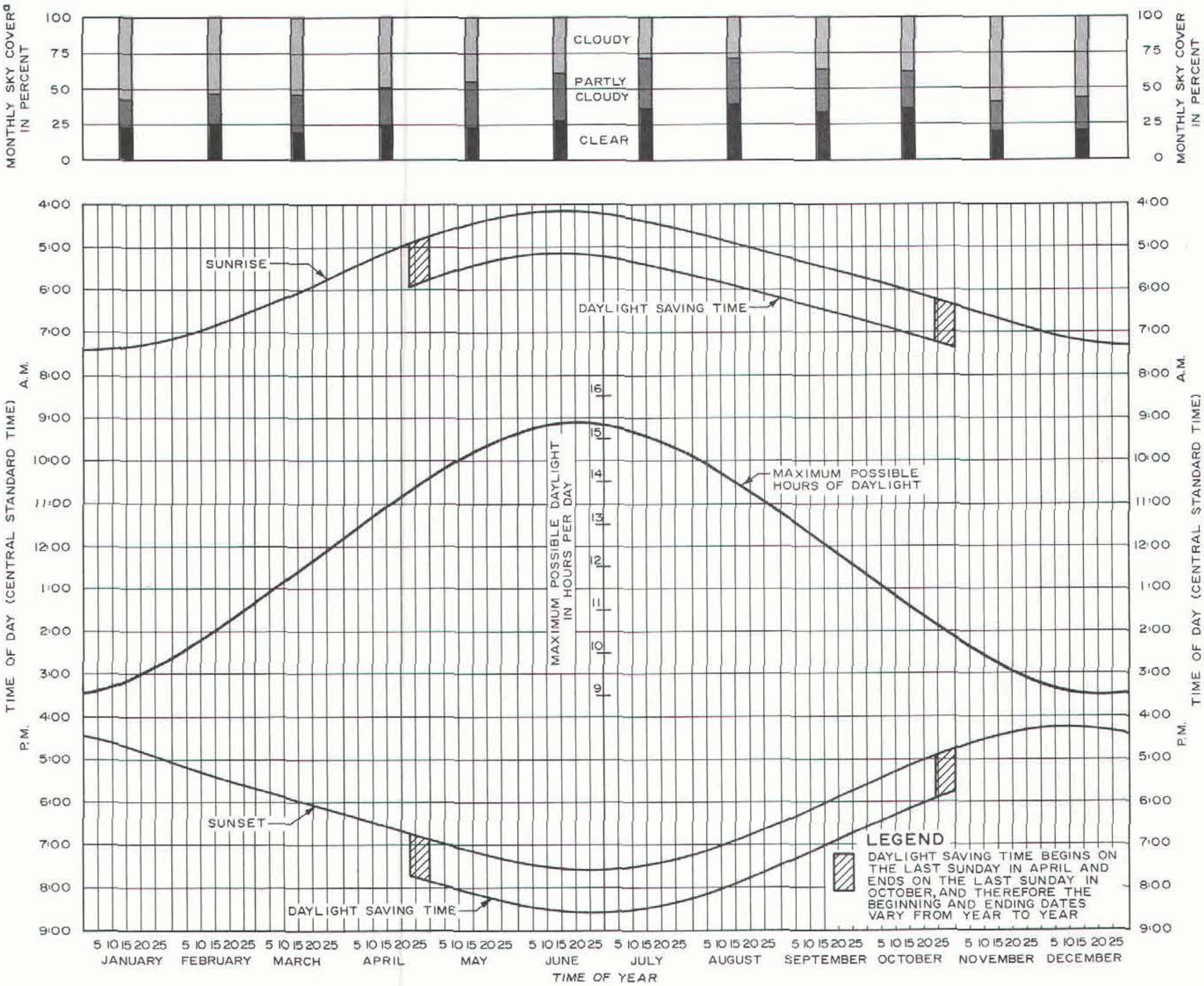


NOTE: 1 NAUTICAL MILE PER HOUR (KNOT) = 1.1516 STATUTE MILES PER HOUR = 0.5144 METERS PER SECOND

Source: National Climatic Center and SEWRPC.

Figure 11

ANNUAL VARIATION IN THE TIME OF SUNRISE AND SUNSET AND IN THE DAILY HOURS OF SUNLIGHT IN THE STUDY AREA



[a]BASED ON MILWAUKEE SKY COVER DATA. THESE MONTHLY DATA ARE SIMILAR TO THOSE OBSERVED AT MADISON AND AT GREEN BAY, WHICH SUGGESTS THAT THERE IS VERY LITTLE VARIATION IN THESE MONTHLY DATA FOR THE LARGE GEOGRAPHIC REGION RELATIVE TO THE OAK CREEK WATERSHED, REPRESENTED BY THESE THREE NATIONAL WEATHER SERVICE STATIONS. THEREFORE, THE MILWAUKEE DAYLIGHT AND SKY COVER MONTHLY DATA MAY BE CONSIDERED APPLICABLE TO THE WATERSHED. SKY COVER CONSISTS OF CLOUDS OR OBSCURING PHENOMENA, AND IS EXPRESSED IN TENTHS. A DAY IS CLASSIFIED AS CLEAR IF THE SKY COVER DURING THE DAYLIGHT PERIOD IS 0-0.3, PARTLY CLOUDY IF THE SKY COVER IS 0.4-0.7, AND CLOUDY IF THE SKY COVER IS 0.8-1.0. MONTHLY SKY COVER INDICATES, BY MONTH, THE PERCENT OF DAYS THAT HISTORICALLY HAVE BEEN CLEAR, PARTLY CLOUDY, OR CLOUDY.

Source: National Climatic Center and SEWRPC.

mum of 9.0 hours on about December 22, the winter solstice, to a maximum of 15.4 hours on about June 22, the summer solstice.

Mean monthly sky cover for the sunrise to sunset period varies somewhat during the year. The smallest amount of daytime sky cover may be expected to occur during the four-month July through October period, when the mean monthly sky cover is at or slightly above 0.5. Clouds or other obscuring phenomena are most prevalent during the five months of November through

March, when the mean monthly daytime sky cover is about 0.7.[3] The tendency for maximum average sky cover to occur in the winter and minimum average sky cover to occur in the summer is also illustrated by examining the expected relative number of days classified as clear, partly cloudy, and cloudy for months in each of those seasons. During the summer months, as shown in Figure 11, about one-third of the days may be expected to be categorized as clear, one-third as partly cloudy, and one-third as cloudy. Greater sky cover occurs in the winter, however, when over one-half of the days are classified as cloudy, with the remainder being about equally divided between partly cloudy and clear.

Physiography

An understanding of the physiography, or the geographic location, of the Milwaukee Harbor estuary direct drainage area and its tributary watersheds within the Southeastern Wisconsin Region can aid in understanding the hydrologic and hydraulic characteristics of this combined surface water drainage system. Accordingly, a brief overview of the physiographic characteristics of the Menomonee, Milwaukee, and Kinnickinnic River watersheds, as well as of the Milwaukee Harbor estuary direct drainage area, is provided herein.

The Menomonee River Watershed: The 132-square-mile Menomonee River watershed is a narrow, irregularly shaped drainage basin, with its major axis oriented in an approximately north-south direction. Its length—measured between the northernmost and southernmost points in the watershed—is approximately 23 miles. Its maximum width, which occurs in the lower third of the watershed along a line extending from the Milwaukee Harbor directly west to the Menomonee River watershed divide, is about 12 miles. The middle portion of the watershed is about five miles wide, while the upper headwater area is approximately nine miles wide.

The Menomonee River watershed adjoins the Milwaukee River watershed on the north and east; the Rock River and the Fox River watersheds on the west, the Root River, the Oak Creek, and the Kinnickinnic River watersheds on the south. The western boundary of the Menomonee River watershed comprises a portion of a major subcontinental divide between the upper Mississippi River drainage basin and the Great Lakes-St. Lawrence River drainage basin.

The Milwaukee River Watershed: The 680-square-mile Milwaukee River watershed is an irregularly shaped drainage basin, with its major axis oriented in an approximately north-south direction. From its northernmost point to its southernmost point the watershed is approximately 46 miles long. Its width varies from approximately 26 miles in the northern headwater portions of the watershed to about four miles in the lower watershed.

The Milwaukee River watershed abuts the Sheboygan River and Wolf-Fox River watersheds on the north; the Rock River watershed on the west; and the Menomonee River watershed on the south. On the east, the Milwaukee River watershed shares a common boundary with the Sauk Creek watershed and with numerous unnamed areas draining directly to Lake Michigan. The northwestern boundary of the Milwaukee River watershed, above its junction with the Menomonee River watershed, forms a major subcontinental divide between the upper Mississippi River drainage basin and the Great Lakes-St. Lawrence River drainage basin.

The Kinnickinnic River Watershed: The 21-square-mile Kinnickinnic River watershed is an irregularly shaped drainage basin, with its major axis oriented in an approximately northwest-southeast direction. Its length—measured from the northwest to the southeast extremity of the basin—is approximately 8.5 miles, and its maximum width, which occurs approximately midway between the northwest and southeast extremities of the basin, is about 5.5 miles.

The Kinnickinnic River watershed adjoins the Menomonee River watershed on the north and west; and it abuts the Oak Creek watershed on the south. To the east, the Kinnickinnic River watershed shares a common boundary with unnamed areas draining directly to Lake Michigan.

The Milwaukee Harbor Estuary Direct Drainage Area: The 22-square-mile Milwaukee Harbor estuary direct drainage area is composed of those areas in the City of Milwaukee and Village of Shorewood which have storm and combined sewer outfalls that discharge directly into the estuary. This direct drainage area is irregularly shaped, having an approximately north-south orientation.

[3] *Sky cover is expressed in tenths. A day is classified as clear if the sky cover during the daylight period is 0-0.3, partly cloudy if the sky cover is 0.4-0.7, and cloudy if the sky cover is 0.8-10.*

Its length—from the northernmost point to the southernmost point—is approximately 10.4 miles. Its maximum width, which includes the distance from the shoreline to the breakwater structure in the outer harbor, is approximately 8.3 miles from about Swan Boulevard along State Street extended.

The Milwaukee Harbor estuary direct drainage area is encompassed by, and is a part of, the Milwaukee River watershed to the north, the Menomonee River watershed to the west, and the Kinnickinnic River watershed to the south. On the east, the estuary direct drainage area adjoins unnamed areas draining directly to Lake Michigan.

Topography

The topography, or variation in elevation, of the Milwaukee Harbor estuary direct drainage area is important in that topographic considerations enter into the selection of sites and routes for public utilities and facilities such as sewerage and water supply systems. Moreover, the topography of the three tributary watersheds is one of the most important factors determining the hydrologic response within the watersheds to rainfall and rainfall-snowmelt events.

Large-scale topographic maps of 7.9 miles of the 22-square-mile Milwaukee Harbor estuary direct drainage area were prepared to Commission standards under this planning program. In addition, as shown on Map 26, some large-scale mapping is available for portions of the three tributary watersheds. Of the total 21-square-mile Kinnickinnic River watershed, 134-square-mile Menomonee River watershed, and 682-square-mile Milwaukee River watershed, approximately 6.3 square miles, 68.5 square miles, and 106.0 square miles, respectively, are covered by large-scale topographic maps prepared to the Commission's specifications. Thus, topographic maps meeting Commission standards have been prepared for about 30 percent of the total area of the Kinnickinnic River watershed, 51 percent of the total area of the Menomonee River watershed, and 16 percent of the total area of the Milwaukee River watershed. For the remaining areas within these watersheds, other large-scale topographic mapping and sanitary and storm sewer maps with or without street grade elevations are available. The available mapping, together with 1 inch equals 400 feet scale aerial photographs, was used in the planning program.

The Milwaukee Harbor estuary direct drainage area and its tributary watersheds lie within the Niagara cuesta section of the Eastern Ridges and Lowlands physiographic province of Wisconsin, and its topography is controlled by both the underlying bedrock and the overlying glacial deposits. The Niagara cuesta underlying the study area is a gently eastward sloping bedrock surface. The topography in this section, as shown on Map 27, is asymmetrical, with the eastern border of the study area being generally lower in elevation than the western border. Glacial deposits overlying the bedrock formations form the irregular surface topography of the study area, characterized by rounded hills or groups of hills, ridges, broad undulating plains, and poorly drained wetlands.

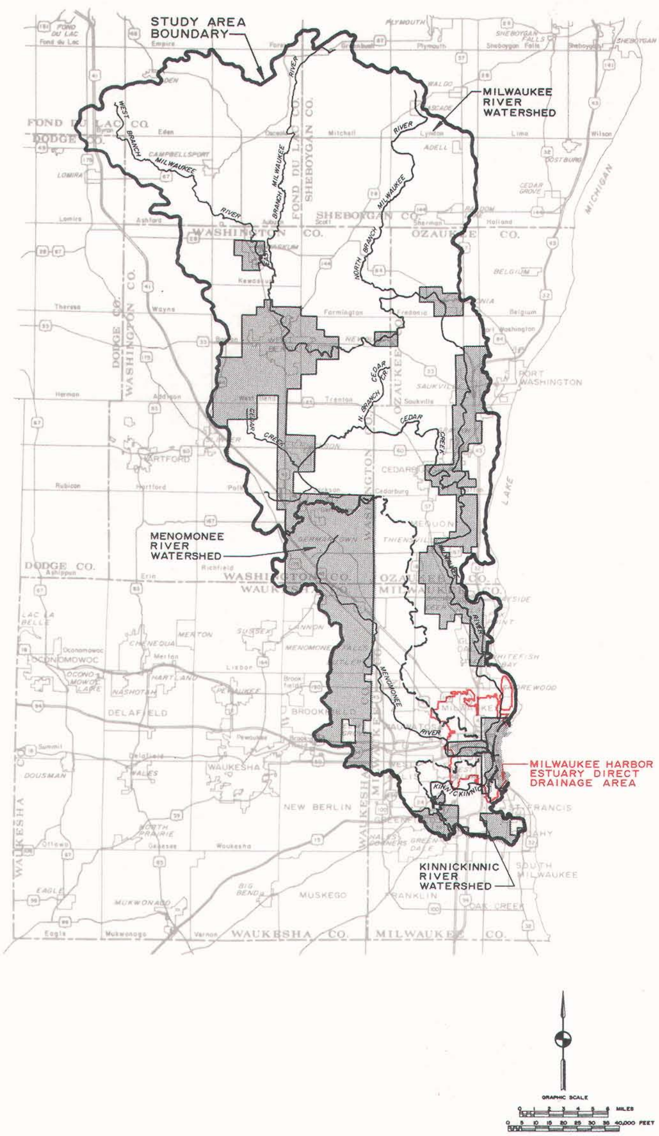
Surface elevations in the study area range from a high of approximately 1,310 feet above National Geodetic Vertical Datum (Mean Sea Level Datum) at Parnell Lookout Tower in the Town of Mitchell, Sheboygan County, to approximately 580 feet NGVD in the Milwaukee Harbor area, a maximum relief of about 730 feet. The areas of greatest local relief are generally in the northwestern portion of the study area and are associated with the glacial deposits known as the Kettle Moraine. The Kettle Moraine system is formed from interlobate deposits left between the Green Bay and Lake Michigan lobes, or tongues, of the continental glacier which moved in a generally southern direction from its point of origin in what is now Canada.

Geology—A Strategraphic and Historic Overview

The geology of the Milwaukee Harbor estuary and its tributary watersheds is a complex system of various layers and ages of rock formations. The type and extent of the various bedrock formations underlying the study area were determined primarily by the environments in which the sediments forming the various rock layers were deposited. The surface of this varied system of rock layers was, moreover, deeply eroded prior to being buried by a blanket of glacial deposits consisting of unconsolidated sand, silt, clay, gravel, and boulders. The bedrock formations underlying the study area consist of, in ascending order, predominantly crystalline rocks of the Precambrian through Devonian Period, sedimentary rocks of the Paleozoic Era, and unconsolidated surficial deposits. Only the glacial deposits and the youngest sedimentary rocks are exposed in the study area. The subsurface stratigraphy of the Milwaukee Harbor estuary and its tributary watersheds is summarized in Table 23, and the geologic sections through the study area are shown in Figure 12.

Map 26

AVAILABILITY OF LARGE-SCALE TOPOGRAPHIC MAPS FOR THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS



Large-scale topographic maps prepared to Regional Planning Commission standards, which include monumented control, are available for 7.9 square miles, or about 36 percent, of the Milwaukee Harbor estuary direct drainage area. In addition, of the total 21-square-mile, 134-square-mile, and 682-square-mile area of the Kinnickinnic, Menomonee, and Milwaukee River watersheds, respectively, 6.3 square miles, 68.5 square miles, and 106.0 square miles, respectively, are covered by such large-scale topographic maps. The large-scale topographic mapping was used in a variety of ways during preparation of the water resources management plan for the estuary, including, importantly, the provision of input to the hydrologic-hydraulic simulation modeling effort. The available large-scale mapping should be valuable during the plan implementation process.

Source: SEWRPC.

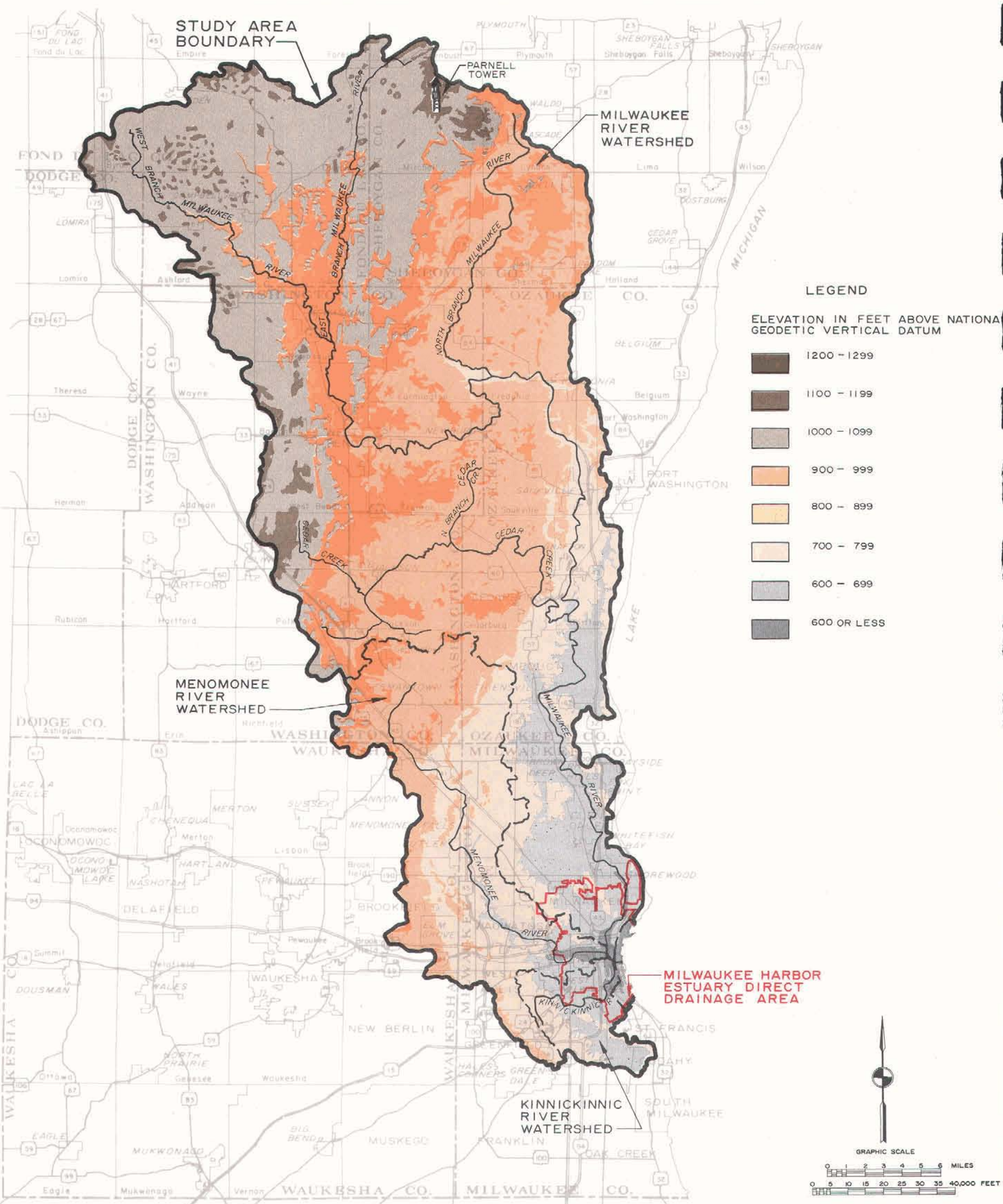
Precambrian Rock Units: Precambrian crystalline rocks thousands of feet thick form the basement on which younger rocks were deposited. Little is known of their origin, but wells which have penetrated this stratum have identified rock types which include quartzite and granite. The Precambrian rocks were extensively eroded to an uneven surface before the overlying sedimentary formations were deposited. Layered sedimentary rocks overlying the Precambrian rocks consist primarily of sandstone, shale, and dolomite. These rocks were deposited during the Cambrian, Ordovician, Silurian, and Devonian geologic time periods, in seas that covered much of the present North American continent.

Cambrian Rock Units: Cambrian rocks in the study area are primarily sandstone, but contain some siltstone, dolomite, and shale. The most dominant Cambrian rock units are the two lowermost units—the Mount Simon sandstone which was deposited on the Precambrian surface, and the Eau Claire sandstone. These two units are present ubiquitously beneath the Milwaukee Harbor estuary and its tributary watersheds. Three other Cambrian rock units—the Galeville sandstone, Franconia sandstone, and Trempealeau Formation—are younger than the Mount Simon and Eau Claire sandstones, but are totally absent in the estuary area. These three sandstones are found locally only in the southern portion of the Menomonee River watershed and the northwestern portion of the Milwaukee River watershed. Their absence in the estuary area is probably attributable to erosion prior to the deposition of Ordovician rock units. Cambrian rocks are thickest in the Milwaukee County area, where the combined thickness of the Mount Simon and Eau Claire sandstone is probably in excess of 1,200 feet, the exact depth being unknown because of the absence of fully penetrating wells or other bore holes. Cambrian rock units reach a minimum thickness within the study area in the northern portions of the Milwaukee River watershed. In this portion of the Milwaukee River watershed, the combined thickness of the Mount Simon and Eau Claire sandstones does not exceed 225 feet.

Ordovician Rock Units: Ordovician rocks in the study area consist of sandstone, dolomite, and shale. The St. Peter sandstone, which was deposited on an irregular erosion surface cut into the underlying Cambrian formations, varies in thickness from about 250 feet in the southeastern portion of the study area—including the Kinnickinnic

Map 27

TOPOGRAPHY OF THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS



Glacial deposits superimposed on underlying bedrock establish the overall topography of the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds. The study area surface generally slopes downward from the north and west to the south and east. Surface elevations in the study area range from a high of approximately 1,310 feet above National Geodetic Vertical Datum (Mean Sea Level Datum) at Parnell Lookout Tower in the Town of Mitchell, Sheboygan County, to approximately 580 feet NGVD in the Milwaukee Harbor area, a maximum relief of about 730 feet. The dominant physiographic feature of the study area is a rolling to gently sloping ground moraine composed of heterogeneous material deposited beneath the several ice sheets that advanced over and receded from the study area in the past.

Source: SEWRPC.

Table 23

STRATIGRAPHY OF THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS

Geologic Age	Stratigraphic Unit	Thickness Range (feet)	Lithology	Areal Extent
Holocene	Alluvium and Marsh Deposits	0-25	Peat, clay, silt, sand, and gravel	Occurs only locally in streams, valleys, and marshes
Pleistocene	Glacial Deposits	0-280	Clay, silt, sand, and gravel	Underlies entire watershed except on rock outcrops
Devonian	Dolomite Undifferentiated	0-35	Dolomite, thick-bedded, gray	Recognized only in three wells in the southeastern part of the watershed
Silurian	Dolomite Undifferentiated	45-445	Dolomite, dense, thick-bedded, light gray; some beds cherty; some coral reefs	Underlies entire watershed
Ordovician	Maquoketa Shale Undifferentiated	100-205	Shale, dolomitic, gray, with interbedded dolomite	Underlies entire watershed
	Galena Dolomite, Decorah Formation, and Platteville Formation, Undifferentiated	215-330	Dolomite, light gray to tan. Sandy dolomite or dolomitic sandstone at base	Underlies entire watershed
	St. Peter Sandstone	80-255	Sandstone, medium to fine grained, dolomitic, white to light gray	Underlies entire watershed
Cambrian	Trempealeau Formation	0-15	Sandstone, very fine to medium grained. Dolomite light gray, interbedded with siltsone in lower part	These units are recognized only in one well in the southwest part of the watershed
	Franconia Sandstone	0-10	Sandstone, very fine to medium grained, glauconitic	
	Galesville Sandstone	0-135	Sandstone, fine to medium grained, light gray	Recognized only in two wells in southern part of watershed
	Eau Claire Sandstone	115-340	Sandstone, very fine to medium grained. Dolomitic and shale	These units underlie entire watershed
	Mount Simon Sandstone	255-1,700	Sandstone, fine to coarse grained, white or light gray. Some interbedded thin shale	
Precambrian	Undifferentiated	Thousands of Feet	Crystalline rocks including granite and quartzite	Underlies entire watershed

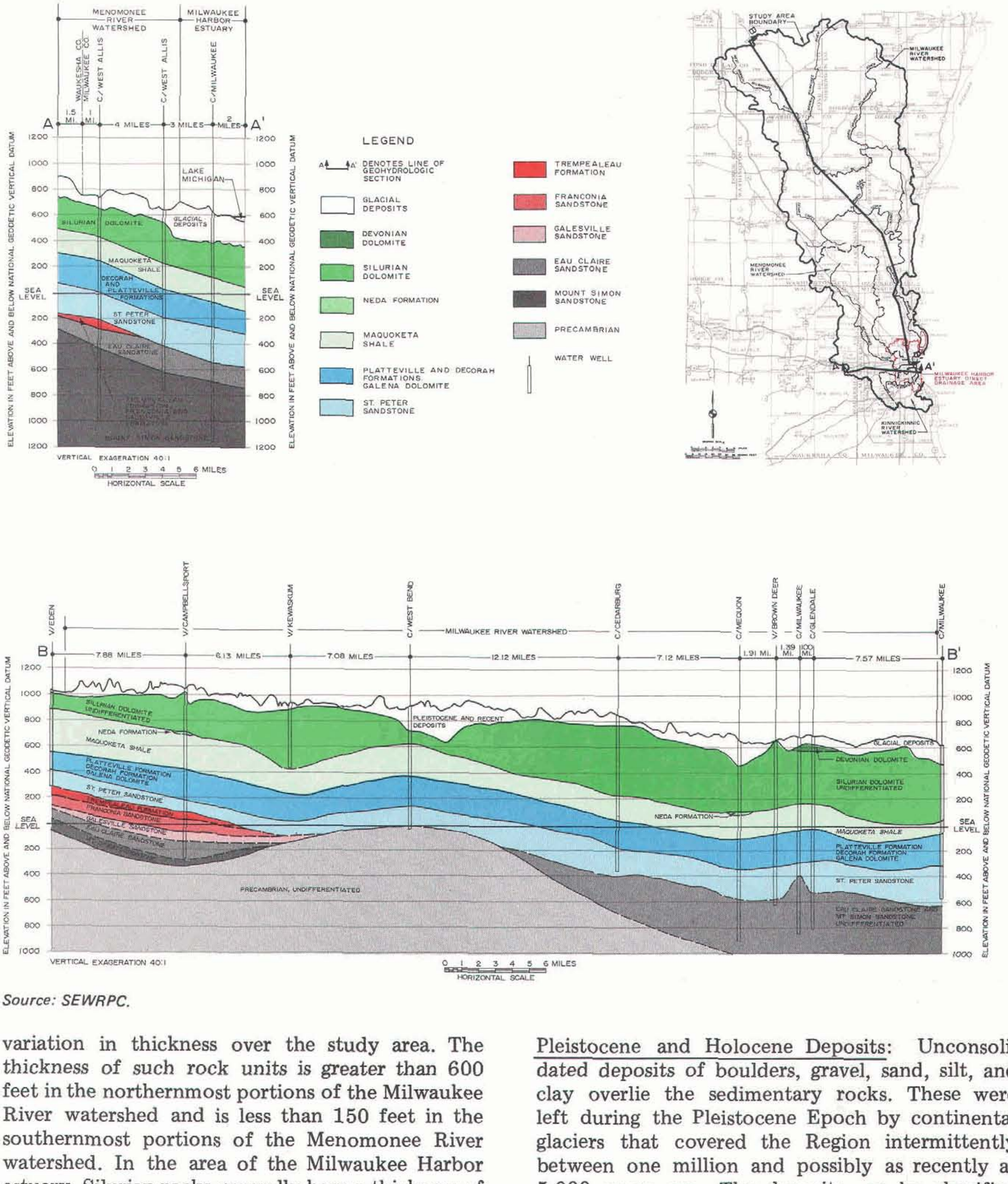
Source: U. S. Geological Survey.

River watershed and much of the estuary—to about 100 feet in the northwestern portions of the Milwaukee River watershed. The Platteville Formation, Decorah Formation, and Galena dolomite were deposited in succession on top of the St. Peter sandstone, but are not differentiated in the study area. The combined thickness of these dolomite rock units is generally between 200 and 300 feet throughout the study area. Above these is the Maquoketa shale, which has a thickness of about 200 feet in the estuary and Kinnickinnic River, Menomonee River, and southern portions of the Milwaukee River watersheds. In the northern portions of the Milwaukee River watershed, the thickness of the Maquoketa shale increases to about 250 feet.

Silurian and Devonian Rock Units: Silurian rocks consisting of undifferentiated dolomite strata overlie the Maquoketa shale. They form the bedrock beneath the glacial deposits in essentially all of the study area. The Silurian rocks exhibit large

Figure 12

SUBSURFACE STRATIGRAPHY OF THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS



Source: SEWRPC.

variation in thickness over the study area. The thickness of such rock units is greater than 600 feet in the northernmost portions of the Milwaukee River watershed and is less than 150 feet in the southernmost portions of the Menomonee River watershed. In the area of the Milwaukee Harbor estuary, Silurian rocks generally have a thickness of about 300 feet. Large local differences in the thickness of the Silurian dolomite deposits are probably due to preglacial and glacial erosion. Dolomitic rocks of the Devonian Period are known to overlie the Silurian dolomite at only three well locations in southeastern portion of the study area.

Pleistocene and Holocene Deposits: Unconsolidated deposits of boulders, gravel, sand, silt, and clay overlie the sedimentary rocks. These were left during the Pleistocene Epoch by continental glaciers that covered the Region intermittently between one million and possibly as recently as 5,000 years ago. The deposits can be classified according to their origin into till and stratified drift. Till, a heterogeneous mixture of clay, silt, sand, gravel, and boulders, was deposited from ice without the sorting action of water. Most of the study area is overlain by till in the form of either ground moraine or end moraine. Stratified drift consists primarily of sand and gravel that was sorted and deposited as outwash by glacial meltwater. Although end moraine deposits are composed mainly of till, they may locally contain stratified drift in the form of outwash sand and gravel.

Holocene materials consist of alluvium and marsh deposits. They occur only along streams and in marshy areas and constitute a very small fraction of the unconsolidated deposits covering the land surface over the study area.

Soils

The nature of the soils within the Milwaukee Harbor estuary direct drainage area and its three tributary river watersheds has been determined primarily by the interaction of the parent glacial deposits covering the Region with topography, climate, plants, animals, and time. Within each soil profile, the effects of these soil-forming factors are reflected in the transformation of soil material in place, chemical removal of soil components by leaching or physical removal by wind or water erosion, additions by chemical precipitation or by physical deposition, and transfer of some soil components from one part of the soil profile to another.

Soil-forming factors, particularly topography and the nature of the parent glacial materials, exhibit wide spatial variation in southeastern Wisconsin, and therefore hundreds of different soil types have developed within the Milwaukee Harbor estuary direct drainage area, its tributary river watersheds, and the Region. In order to assess the significance of these unusually diverse soil types to sound regional development, the Commission in 1963 negotiated a cooperative agreement with the U. S. Soil Conservation Service under which detailed operational soil surveys were completed for most of the Region. The results of the soil survey have been published in SEWRPC Planning Report No. 8, Soils of Southeastern Wisconsin. The regional soil survey has resulted in the mapping of soils within the Region in great detail and provided interpretations of the soil properties for planning, engineering, agricultural, and resource conservation purposes.

Because of the highly urbanized nature of the Milwaukee Harbor estuary direct drainage area, detailed soils data for this portion of the Region have been determined to be of little practical value. Detailed soils data for the tributary river watersheds, however, have extensive application in the hydrologic and hydraulic simulation modeling effort, as well as in the identification of areas having limitations for urban development utilizing onsite waste disposal systems and public sanitary sewer service, identification of prime agricultural lands, and delineation of primary environmental corridors. Because of the paucity of soils data for the heavily urbanized Milwaukee Harbor estuary direct drainage area, the nature of the underlying soils as needed for hydrologic modeling purposes was deduced from the character of the soils and the physiography of contiguous areas for which detailed soils data were available. Additional data on the characteristics of the soils underlying the direct drainage area were available from sewer and water utility construction records maintained by the city engineers of the municipalities concerned and from well-digging logs.

Vegetation

Vegetation at any location at any given time is determined by, or the result of, a variety of factors, including climate, topography, occurrence of fire, soil characteristics, proximity of bedrock, drainage features, and, of course, the activities of man. Because of the temporal and spatial variability of these factors and the sensitivity of vegetation to most of them, vegetation throughout the study area has been a changing mosaic of different types.

The terrestrial vegetation in the study area occupies sites which may be divided into two broad land classifications: wetland and woodland. Wetlands are defined as those lands which are wholly or partially covered with hydrophytic plants and wet and spongy organic soils, and which are generally covered with shallow standing water, intermittently inundated, or have a high water table. Woodlands are defined as lands at least 20 acres in area which are covered by a dense, concentrated stand of trees and associated undergrowth.

The location, extent, type, and quality of wetland and woodland areas are key determinants of the environmental quality of the study area. Wetland and woodland areas can, for example, support a variety of outdoor recreational activities. They offer aesthetic values in that they contribute to the beauty and visual diversity of the environment and function as visual and acoustic shields or barriers. Such areas and the vegetation contained within them serve important ecological functions, since they are typically, on a unit-area basis, the biologically most productive portions of the study area; provide continuous wildlife range and sanctuary for native biota; and help to maintain surface water quality by functioning as sediment and nutrient traps. Finally, certain wetland and woodland areas can be excellent outdoor laboratories for educational and research activities.

Presettlement Woodlands and Wetlands: Prior to the arrival of European settlers, the vegetation in the study area was predominantly a medium wet, or mesic, forest composed of a variety of upland deciduous hardwoods such as maple, beech, basswood, ironwood, red oak, ash, hickory, and slippery elm, and one coniferous species, white pine. Wetter conditions prevailed in floodlands, old glacial lake beds, and other poorly drained low areas. Tamarack, black ash, and shrubs dominated the wetter areas, while silver maple and American elm grew in the seasonally flooded sites. Depending on the susceptibility of certain wetlands to fire, portions of them may have been maintained as open marshes, sedge meadows, and bogs dominated by cattails, grasses, and sedges.

Historical records, including those resulting from the original U. S. Public Land Survey carried out in 1836, provide information and insight into presettlement vegetation characteristics. Based primarily on these records, it has been determined that presettlement vegetation in the study area consisted of nine terrestrial plant community types: 1) dry upland forest; 2) mesic upland hardwood forest; 3) lowland hardwood forest; 4) bogs; 5) fens; 6) small lowland zones of open marsh wetland; 7) small lowland zones of sedge meadow; 8) small lowland areas of shrub wetland; 9) conifer swamp forest elements—tamarack, cedar, and black spruce. Of these nine communities, the mesic upland hardwood forest and the lowland hardwood forest encompassed about 95 percent of the study area. Mesic upland hardwood forest and dry upland forest fall within the broad category of woodlands, whereas the remaining seven plant types—may be categorized as wetlands.

Existing Vegetation: Existing vegetation in the Milwaukee Harbor estuary direct drainage area ranges from small areas of upland hardwoods, such as Downer's Woods at the University of Wisconsin-Milwaukee campus, to the weedy pioneer plant communities seen in vacant lots and other open unused urban lands. Upland woodlots are characterized by mesic—sugar maple and basswood—to dry-mesic hardwoods, such as red oak and hickory. Many of the upland hardwood areas are restricted to urban parks and cemeteries. Wetland areas within the direct drainage area are largely restricted to the riverine areas and are generally found immediately adjacent to the stream channel. The typical wetland plant communities within the direct drainage area include shallow marshes as indicated by the presence of cattails, bur-reed, and arrowhead, and lowland hardwoods such as American elm, black willow, and green ash.

Water Resources

Surface water resources, consisting of streams and associated floodlands, form the singularly most important element of the natural resource base of the study area. Their contribution to the economic development, recreational activity, and aesthetic quality of the area is immeasurable. The groundwater resources of the study area are hydraulically connected to the surface water resources, inasmuch as they provide the base flow of streams. The groundwater resources, along with Lake Michigan, constitute the major sources of supply for domestic, municipal, and industrial water uses. Indeed, the protection, enhancement, and proper development of the invaluable water resources in the Milwaukee Harbor estuary constitute the principal basis for mounting this study.

Surface Water Resources: None of southeastern Wisconsin's—100 major lakes—that is, lakes having 50 acres or more of surface area—are located within the Milwaukee Harbor estuary direct drainage area, the Kinnickinnic River watershed, or the Menomonee River watershed. The Milwaukee River watershed, however, including that portion which lies outside the Region in Fond du Lac and Sheboygan Counties, does encompass 21 major lakes having a combined surface water area of 3,438 acres and providing a total of 59 miles of shoreline. The lakes in the Milwaukee River watershed are mostly of glacial origin, being depressions in gravelly outwash, moraine, or ground moraine deposits. By virtue of their origin, these lakes are fairly regular in shape, with their deepest points predictably near the center of the basin or near the center of each of several connected basins. The beaches are characteristically gravel or sand on the wind-swept north, east, and south shores, while fine sediments and encroaching vegetation are common on the protected west shores and in the bays.

There are 50 minor lakes within the Milwaukee River watershed, including that portion within Fond du Lac and Sheboygan Counties, and 14 minor lakes within the Menomonee River watershed—lakes having surface areas of less than 50 acres in extent. The 50 minor lakes in the Milwaukee River watershed have a combined surface water area of 732 acres with 41 miles of shoreline, while the 14 minor lakes in the Menomonee River watershed have a combined surface area of only 33 acres with four miles of shoreline. There are several small off-stream ponds in the direct drainage area and the Kinnickinnic River watershed, the largest of which are in Milwaukee County parklands. The value of most of these minor lakes and ponds in the study area is largely aesthetic.

The absence of lakes capable of supporting reasonable recreational use with little degradation of the resource in the heavily populated Milwaukee Harbor estuary direct drainage area is significant in that it means that recreational pressures will be more heavily exerted on Lake Michigan, on the estuarial waters, and on the streams and lakes in the adjacent tributary river watersheds. Lake Michigan, in particular, offers great recreational potential, and it is one of the principal objectives of this study to prepare a plan to develop this potential.

Streams: One of the most interesting, variable, and occasionally unpredictable features of the natural resource base is its river and stream system, with its ever-changing, sometimes widely fluctuating, discharges and stages. Within the study area the stream system receives a relatively uniform flow of water from the underlying shallow groundwater reservoir. This groundwater discharge constitutes the baseflow of the streams. The streams also periodically receive surface water runoff from rainfall and snowmelt which, when superimposed on the baseflow, sometimes causes the streams to leave their channels and occupy the adjacent floodplains. The volume of water drained annually from the study area by the stream system is equivalent to about eight inches of water spread over the study area, amounting to about one-fourth of the average annual precipitation.

Perennial streams are defined herein as those streams which maintain at least a small continuous flow throughout the year except under unusual drought conditions. Within the study area there are 418.92 miles of such perennial streams, as shown in Table 24. The study of these perennial streams, particularly those stream reaches within the Milwaukee Harbor estuary, is a principal focus of this planning effort, and subsequent chapters of this report will describe the important interrelationships existing between the stream system and other natural and man-made elements of the watershed.

Floodlands: The natural floodplain of a river is a wide, flat to gently sloping area contiguous to and usually lying on both sides of the channel. The floodplain, which is normally bounded on its outer edges by higher topography, is gradually formed over a long period of time by the river during flood stage as that river meanders in the floodplain, continuously eroding material from concave banks while depositing it on the convex banks. A river or stream may be expected to occupy and flow on its floodplain on the average of once every two years; therefore, the floodplain should be considered to be an integral part of a natural stream system. The extent to which a natural floodplain will be occupied by any given flood will depend upon the severity of the flood and, more particularly, upon its elevation or stage. Thus, an infinite number of outer limits of the natural floodplain may be delineated, each related to a specified flood recurrence interval. The Southeastern Wisconsin Regional Planning Commission recommends, therefore, that the natural floodplains of a river or stream be more specifically defined as those corresponding to a flood having a recurrence interval of 100 years, with the natural floodlands being defined as consisting of the river channel plus the 100-year floodplain.

A floodway is that designated portion of the regulatory floodlands required to convey the 100-year recurrence interval flood discharge. The floodway, which includes the channel, is that portion of the floodlands not suited for human habitation. All fill, structures, and other development that would impair floodwater conveyance by adversely increasing flood stages or velocities, or would itself be subject to flood damage, should be prohibited in the floodway.

The floodplain fringe is that portion of the regulatory floodplain lying outside the floodway. Floodwater depths and velocities are small in this regulatory area relative to the floodway; therefore, in a developed urban area further development may be permitted, although restricted and regulated so as to minimize flood damage. Because the regulatory floodway may result in increases in the stage of the regulatory flood relative to that which would occur under natural conditions, the floodplain fringe may include at its edges areas that would not be subject to inundation under natural conditions, but would be subject to inundation under regulatory floodway conditions.

The delineation of natural floodlands is extremely important to sound planning and development. Because of flood hazards, high water tables, and inadequate soils, floodland areas are generally not well suited to urban development. Furthermore, the regional land use plan indicates that these floodlands are not needed for incremental urban development, that there is sufficient suitable land outside the floodlands. Floodland areas, however, are generally prime locations for much needed park and open space areas, and contain many of the best remaining woodland, wetland, and wildlife habitat areas of the Region. The floodlands also have important floodwater conveyance and storage functions.

Table 24

PERENNIAL STREAMS TRIBUTARY TO THE MILWAUKEE HARBOR ESTUARY

Perennial Stream	Tributary To	Upstream End	Length[a] (miles)	County or Counties in Which Stream is Located
		Milwaukee Harbor Estuary Direct Drainage Area		
Kinnickinnic River	Milwaukee River	S. Chase Avenue	2.4	Milwaukee
Milwaukee River	Lake Michigan	North Avenue Dam	3.1	Milwaukee
Menomonee River.	Milwaukee River	Falk Corporation Dam	2.2	Milwaukee
South Menomonee Canal. . .	Menomonee River	S. 13th Street Extended	0.58	Milwaukee
Subtotal			9.15	
		Kinnickinnic River Watershed[b]		
Kinnickinnic River	Milwaukee River	S. 60th Street	5.65	Milwaukee
Wilson Park Creek.	Kinnickinnic River	End of Channelization in General Mitchell Field	5.25	Milwaukee
Lyons Park Creek	Kinnickinnic River	W. Forest Home Avenue (STH 24)	1.31	Milwaukee
West Milwaukee Ditch	Kinnickinnic River	S. 50th Street Extended	1.10	Milwaukee
Villa Mann Creek	Wilson Park Creek	W. Armor Avenue Extended	1.24	Milwaukee
Holmes Avenue Creek	Wilson Park Creek	W. Edgerton Avenue Extended	1.17	Milwaukee
Subtotal			15.72	
		Menomonee River Watershed[b]		
Menomonee River.	Milwaukee River	Chicago & North Western Railway	25.71	Milwaukee, Washington, and Waukesha
Little Menomonee River . . .	Menomonee River	Sunnyville Road Extended	9.65	Milwaukee and Ozaukee
Honey Creek.	Menomonee River	S. 43rd Street	8.86	Milwaukee
Underwood Creek.	Menomonee River	Calhoun Road (CTH KX)	8.14	Milwaukee and Waukesha
Butler Ditch	Menomonee River	0.15 Mile North of Lisbon Road (CTH K)	3.60	Waukesha
Dousman Ditch	Underwood Creek	Calhoun Road (CTH KX)	2.56	Waukesha
Little Menomonee Creek. . .	Little Menomonee River	0.2 Mile North of Friedstadt Road (CTH F)	2.48	Ozaukee
West Branch Menomonee River	Menomonee River	Private Drive	1.78	Washington
Woods Creek.	Menomonee River	S. 50th Street Extended	1.09	Milwaukee
South Branch Underwood Creek	Underwood Creek	W. Schlinger Avenue	1.08	Milwaukee and Waukesha
Subtotal			64.95	
		Milwaukee River Watershed[b]		
Milwaukee River	Lake Michigan	CTH B	97.9	Fond du Lac, Milwaukee Ozaukee, and Washington
Cedar Creek	Milwaukee River	Cedar Lake	31.5	Ozaukee and Washington
North Branch Milwaukee River.	Milwaukee River	CTH NN	30.0	Sheboygan, Washington, and Ozaukee
West Branch Milwaukee River.	Milwaukee River	CTH F	20.1	Fond du Lac and Washington
East Branch Milwaukee River.	Milwaukee River	Long Lake Dam	14.3	Fond du Lac, Sheboygan, and Washington

Table 24 (continued)

Perennial Stream	Tributary To	Upstream End	Length[a] (miles)	County or Counties in Which Stream is Located
Milwaukee River Watershed[b] (continued)				
Lincoln Creek	Milwaukee River	Mill Road	7.1	Milwaukee
North Branch Cedar Creek	Cedar Creek	0.57 Mile Upstream of Washington-Ozaukee County Line (CTH Y)	7.3	Washington and Ozaukee
Batavia Creek	North Branch Milwaukee River	CTH A	5.0	Sheboygan
Cedarburg Creek	Cedarburg Creek	CTH Y	3.0	Washington
Chambers Creek.	North Branch Milwaukee River	0.34 Mile Upstream of CTH SSS	2.9	Sheboygan
Engmon Creek.	Silver Creek	0.42 Mile Upstream of 18th Avenue	1.5	Washington
Evergreen Creek.	Cedar Creek	STH 143	4.9	Washington
Indian Creek.	Milwaukee River	Dean Road	1.9	Milwaukee
Kewaskum Creek	Milwaukee River	0.57 Mile Upstream of Beaver Dam Road	6.4	Washington
Kressin Creek	Little Cedar Creek	CTH M	4.7	Washington
Lake Fifteen Creek	Milwaukee River	0.80 Mile Upstream of STH 67	7.4	Fond du Lac
Little Cedar Creek	Cedar Creek	Chicago, Milwaukee, St. Paul & Pacific Railroad	6.0	Washington
Melius Creek.	North Branch Milwaukee River	1.09 Mile Upstream of CTH S	3.3	Sheboygan
Mink Creek	North Branch Milwaukee River	0.98 Mile Upstream of CTH F	17.3	Sheboygan
Myra Creek	Milwaukee River	Knollwood Drive	2.6	Washington
Nichols Creek	North Branch Milwaukee River	0.98 Mile Upstream of CTH N	3.3	Sheboygan
Pidgeon Creek.	Milwaukee River	Private Drive	2.4	Ozaukee
Quas Creek.	Milwaukee River	18th Street	5.9	Washington
Silver Creek	North Branch Milwaukee River	Spring Lake	7.1	Sheboygan
Silver Creek	Milwaukee River	Lucas Lake	4.0	Washington
Stony Creek.	North Branch Milwaukee River	0.83 Mile Upstream of CTH DA	10.0	Washington, Fond du Lac and Sheboygan
Ulao Creek.	Milwaukee River	CTH C	1.7	Ozaukee
Virgin Creek.	Lake Fifteen Creek	STH 67	4.5	Fond du Lac
Wallace Creek	North Branch Milwaukee River	0.38 Mile Upstream of Indian Lore Road	8.6	Washington
Water Cress Creek.	East Branch Milwaukee River	0.23 Mile Upstream of Water Cress Road	6.5	Fond du Lac and Sheboygan
Subtotal			329.1	
Total			418.92	

[a] *Total perennial stream length as shown on U. S. Geological Survey quadrangle maps.*

[b] *Stream reaches outside Milwaukee Harbor estuary direct drainage area.*

Source: SEWRPC.

Groundwater Resources: The Southeastern Wisconsin Region is richly endowed with groundwater resources. Although Lake Michigan is the source of water supply for most purposes in the Milwaukee Harbor estuary direct drainage area, groundwater is the source of water supply for approximately 46 percent of the 970,000 persons who reside in the total study area. Groundwater also supplies the base flow to the Kinnickinnic, Menomonee, and Milwaukee Rivers and their tributaries. The amount of groundwater stored in the rocks beneath the study area is enormous, and is estimated to exceed 88 million acre-feet, a quantity sufficient to cover the entire study area to a depth of 160 feet. Unlike the surface water systems of the Kinnickinnic, Menomonee, and Milwaukee River watersheds, which are largely independent of each other, groundwater located directly below these watersheds is an integral part of the groundwater system that lies beneath the entire Southeastern Wisconsin Region. Withdrawals of groundwater within any watershed, therefore, should be evaluated with regard to their impact on the regional groundwater system.

Rock units that yield water in usable amounts to pumped wells and in important amounts to lakes and streams are called aquifers. The aquifers beneath the study area differ widely in water yield capabilities and extend to great depths, probably attaining a thickness in excess of 2,200 feet in the Milwaukee Harbor estuary direct drainage area. There are three major aquifers beneath the study area. These are, in order from the land surface downward: 1) the sand and gravel deposits in the glacial drift; 2) the shallow dolomite strata in the underlying bedrock; and 3) the Cambrian and Ordovician strata, composed of sandstone, dolomite, siltstone, and shale. Because of their relative closeness to the land surface, the first two aquifers are sometimes called "shallow" and the latter the "deep aquifer." Wells tapping these aquifers are referred to as shallow or deep wells, respectively.

The occurrence, distribution, movement, use, and quality of these important groundwater resources and their interrelationship with surface water resources and other elements of the planning study are discussed in considerable detail in subsequent chapters of this report.

Fish and Wildlife Resources

There is a high demand for fishing in the Milwaukee Harbor estuary and the near-shore environment of Lake Michigan because of its position within the larger metropolitan area. Wildlife, such as waterfowl, are also desirable in the Milwaukee Harbor estuary because of their aesthetic and educational values and the element of naturalness and diversity they impart to an urban area.

Fisheries: Available historic data indicate that during the first half of the nineteenth century, commercial as well as sport fishermen in southeastern Wisconsin caught whitefish, large herring, sturgeon, and lake trout in large numbers. Since that time, however, desirable fish populations have declined as a result of the pressure of heavy fishing combined with the rapid urbanization of the Region's coastal areas and the attendant deterioration of water quality, the destruction of spawning areas, and habitat alterations in Lake Michigan and the Milwaukee Harbor estuary and its tributary river watersheds. The lake sturgeon population, for example, was greatly reduced in 1903. The lake sturgeon's eggs were considered a valuable source of caviar by some fishermen, and others tried to eradicate the fish for fouling their nets and supposedly eating the eggs of more desirable food fish. As the numbers of each commercial fish declined, attention shifted to another species until it, too, suffered the effects of overfishing. The total catch of traditional food fish—lake herring, chubs, lake trout, whitefish, perch, and lake sturgeon—had, by 1922, dropped approximately 10 percent from the 1899 level. The total commercial catch began to rise soon after World War I and, with additional target species introduced such as carp and smelt, continued to grow until about 1950. At that time the effects of the sea lamprey, which had invaded the Great Lakes through the Welland Canal in 1921, and the alewife had produced critical habitat pressures on the native fish population of Lake Michigan. The lamprey, which is parasitic on other fish species, had almost eradicated the lake trout population by 1950. Moreover, by 1955 the alewife population, unchecked by predators, had increased to an estimated 90 percent of the total Lake Michigan fish population.

To restore a balance to the lake fishery, massive fish-stocking programs were initiated in the 1960's in order to introduce such deep-water predator species as the Coho and Chinook salmon and to increase the populations of such native species as brook and lake trout. The numbers of these species planted into Lake Michigan between 1963 and 1980 under the Wisconsin Lake Michigan Planting Program conducted by the Wisconsin Department of Natural Resources (DNR) are shown in Table 25. In order to attain maximum benefit from the

Table 25

WISCONSIN'S LAKE MICHIGAN PLANTING PROGRAM SUMMARY

Year	Species						
	Rainbow Trout	Brown Trout	Brook Trout	Coho Salmon	Chinook Salmon	Lake Trout[a]	Tiger Trout[b]
1963	9,000	--	--	--	--	--	--
1964	15,000	--	--	--	--	--	--
1965	27,000	--	--	--	--	205,000	--
1966	59,000	43,000	--	--	--	761,000	--
1967	89,000	47,000	9,000	--	--	1,129,000	--
1968	90,000	205,000	25,000	25,000	--	817,000	--
1969	148,000	171,000	74,000	217,000	66,000	884,000	--
1970	192,000	154,000	82,000	340,000	119,000	900,000	--
1971	179,000	201,000	106,000	267,000	264,000	945,000	--
1972	586,000	737,000	62,000	258,000	317,000	1,284,000	--
1973	657,000	571,000	50,000	257,000	697,000	1,080,000	--
1974	495,000	430,000	34,000	318,000	616,000	880,000	34,000
1975	401,000	356,000	64,000	433,000	927,000	1,054,000	15,000
1976	964,000	292,000	12,000	667,000	1,268,000	1,045,000	23,000
1977	683,000	802,000	643,000	492,000	913,000	970,000	28,000
1978	613,000	1,244,000	243,000	499,000	2,017,000	994,000	--
1979	1,241,000	960,000	185,000	449,000	1,964,000	943,000	--
1980	1,137,000	1,046,000	185,000	492,000	2,430,000	1,255,000	--
1981	1,007,000	1,014,000	200,000	318,000	1,848,000	963,000	--
1982	1,042,000	1,861,000	283,000	216,000	2,521,000	1,891,000[c]	--

[a] *Federally produced fish.*

[b] *Brook X Brown hybrid.*

[c] *Includes 800,000 fry.*

Source: Wisconsin Department of Natural Resources.

stocked species and to curb exploitation by commercial fishermen, introduced fish are limited to sport fishing.

Because harbor structures such as piers and breakwaters are readily accessible in the Milwaukee Harbor estuary, sport fishing in this area has a potentially high recreational value. Unfavorable habitat conditions imposed by stream pollution and channel modifications in its tributary river waters, however, limit the present fishery resources of the Milwaukee Harbor estuary. Most of the resident fish populations found in the estuary are of the more pollution-tolerant species such as carp and black bullheads, which have little recreational fishery value. However, anadromous fish—that is, species that instinctively migrate up tributary streams for the purpose of spawning—such as Coho salmon, presently migrate up the rivers draining into the estuary. Although the temperature and dissolved oxygen conditions are more satisfactory during the spring and fall seasons because of the higher runoff and streamflow that normally occur at these times of the year, natural reproduction of the anadromous fish species is not likely in the Milwaukee Harbor estuary and its tributary rivers because of the poor water quality and lack of suitable spawning areas. Only if the water quality conditions are improved to a level whereby desirable fish and aquatic life may prosper can sport fishing opportunities be provided in the Milwaukee Harbor estuary.

As a part of the comprehensive Milwaukee Harbor estuary planning program, the Wisconsin Department of Natural Resources undertook a study of the fishery resources within the estuary. Under this work effort, the DNR characterized the existing Milwaukee Harbor estuary fishery by sampling the resident and transient fish populations, identified fish spawning areas, and determined the level of toxic substances in the tissues of resident fish species in the estuary. The purpose of this study was to establish baseline data for the fishery so that as changes in water quality occur, changes in the fishery can be determined, to identify fish spawning areas to note the presence and habitat of rare, endangered, or threatened fish species; and to determine the toxic substance concentrations within the body tissues of the Milwaukee Harbor estuary resident fish population. The results and findings of this inventory effort are described in a later chapter of this report.

Wildlife: Various forms of wildlife are desirable in highly urbanized areas such as the Milwaukee Harbor estuary direct drainage area because of their aesthetic values, their importance in the ecological system, their educational value, and their enhancement of certain recreational activities. The location, extent, and quality of wildlife habitat areas and the type of wildlife in those areas are, therefore, important determinants of the overall quality of the environment in the direct drainage area and in its tributary river watersheds.

Because of extensive urbanization, there has been a progressive decline in the diversity and quantity of wildlife, in the Milwaukee Harbor estuary direct drainage area, and the diversity and quantity of wildlife has diminished. This decline had its beginnings in the clearing of forests and prairies and the draining and filling of wetlands in the areas adjacent to the harbor. This process began in the early nineteenth century when European settlers initiated the development of the estuary direct drainage area. The urbanization which progressed from that time proceeded with little explicit concern for wildlife and their habitat. The resiliency of wildlife to such impact is truly remarkable, but a tremendous toll has been taken. Inexorably, the minimum life requirements have disappeared over much of the direct drainage area and, as a result, only remnants remain to continue a precarious existence. The wildlife and wildlife habitat loss is only part of a much greater loss of diversity that is characteristic of some urbanizing areas.

While the wildlife within a given habitat may concentrate most of their activities in a particular wooded area or in and along a given stream reach that constitutes the principal element in the habitat and can be delineated with some precision, even in an urban area their normal range may extend into contiguous surrounding open space and residential areas, the extent of which vary according to the specific wildlife species. As such, a delineation of the range of wildlife habitat in the Milwaukee Harbor estuary direct drainage area is beyond the scope of the report.

The remnant wildlife habitat areas in the Milwaukee Harbor estuary direct drainage area are concentrated in and around existing park and other open space areas. The remnant wildlife population in the direct drainage area consists of the amphibians and reptiles, birds, and mammals listed in Tables 26 through 28. As shown in Table 26, amphibians likely to be found in the direct drainage area include frogs, toads, and salamanders, while turtles and snakes are examples of the reptiles likely to be found.

Table 26

AMPHIBIANS AND REPTILES KNOWN TO OCCUR IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA

Amphibians
Ambystoma tigrinum—Eastern tiger salamander
Necturus maculosus—Mudpuppy
Bufo americanus—American toad
Pseudaeris triseriata—Western chorus frog
Reptiles
Chelydra serpentina—Common snapping turtle
Sternotherus odoratus—Musk turtle
Chrysemys picta marginata—Midland painted turtle
Chrysemys picta belli—Western painted turtle
Storeria dekayi—Brown snake
Storeria occipitomaculata—Northern red-bellied snake
Thamnophis butleri—Butler's garter snake

Source: Edwin D. Pentecost and Richard C. Vogt, Environmental Status of the Lake Michigan Region, Volume 16, Amphibians and Reptiles of the Lake Michigan Drainage Basin, 1976; and Richard C. Vogt, Natural History of Amphibians and Reptiles of Wisconsin, 1981; Milwaukee Public Museum; Milwaukee County Zoo; and SEWRPC.

A large number of birds, ranging in size from large game birds to small songbirds, are found in the Milwaukee Harbor estuary direct drainage area. Game birds which are often found in the estuary, as shown in Table 27, include pheasant, ducks, and coots. Hawks and owls function as major rodent predators within the ecosystem, whereas swallows, whippoorwills, woodpeckers, and nuthatches, as well as several other species of birds found in the direct drainage area, serve as major insect predators. In addition to their ecological roles, birds such as robins, orioles, cardinals, blue jays, and mourning doves serve as subjects for birdwatchers and photographers. Not all birds are viewed as an asset from an ecological, economic, or aesthetic point of view. As a result of urbanization, and therefore the loss of natural habitat, conditions have become less compatible for the more desirable bird species. House sparrows, starlings, grackles, and pigeons have replaced the more desirable birds in a large portion of the direct drainage area because of their tolerance for urban conditions and their highly aggressive behavior.

Mammals likely to be found in the direct drainage area, as shown in Table 28, include shrews, bats, rabbits, woodchucks, squirrels, raccoons, weasels, skunks, mice, and rats. Bats, despite their appearance and nocturnal habits, generally have a positive impact on the urban environment in that they are major insect predators, often consuming up to one-third their weight in insects a night. Some of the mammals likely to be found in the direct drainage area, particularly mice, rats, and skunks, may serve as carriers of diseases.

Outside the Milwaukee Harbor estuary direct drainage area, particularly in the more rural portions of the Menomonee and Milwaukee River watersheds, wildlife habitat areas are more extensive and generally higher in quality. Based on surveys conducted by the Wisconsin Department of Natural Resources and the Commission, a total of 246 wildlife habitat areas were identified and rated, as shown on Map 28.

Five major criteria were used to determine the value of and rate these wildlife habitat areas:

1. Diversity—An area must maintain a high but balanced diversity of species for a temperate climate—balanced in that the proper predator-prey (consumer-food) relationships can occur. In addition, a reproductive interdependence must exist.

2. Territorial Requirements—The maintenance of proper spatial relationships among species which allows for a certain minimum population level can occur only if the territorial requirements of each major species within a particular habitat are met.

3. Vegetative Composition and Structure—The composition and structure of vegetation must be such that the required levels for nesting, travel routes, concealment, and protection from weather are met for each of the major species.

4. Location with Respect to Other Wildlife Habitat Areas—It is very desirable that a wildlife habitat maintain proximity to other wildlife habitat areas.

5. Disturbance—Minimum levels of disturbance from human activities are necessary (other than those activities of a wildlife management nature).

On the basis of these five criteria, the wildlife habitat areas in the study area were rated as being of high, medium, or low quality. The quality ratings used are defined below:

1. High-value wildlife habitat areas contain a good diversity of wildlife, are adequate in size to meet all of the habitat requirements for the species concerned, are generally located in proximity to other wildlife habitat areas, and meet all five criteria listed above.

2. Medium-value wildlife habitat areas generally lack one of the five criteria in the preceding list for a high-value wildlife habitat.

3. Low-value wildlife habitat areas are remnant in nature in that they generally lack two or more of the five criteria for a high-value wildlife habitat but may, nevertheless, be important if located in proximity to medium- and/or high-value habitat areas, if they provide corridors linking higher value wildlife habitat areas, or if they provide the only available range in an area.

Wildlife habitat areas in the study area total about 130 square miles in area, or about 15 percent of the study area. Map 28 and Table 29 indicate that

Table 27

BIRDS KNOWN TO OCCUR IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA

Scientific (Family) and Common Name	Breeding	Wintering	Migrant
Gaviidae			
Red-throated Loon	--	--	R
Common Loon	--	--	X
Podicipedidae			
Pied-billed Grebe	--	--	X
Horned Grebe	--	--	X
Red-necked Grebe	--	--	R(T)
Eared Grebe	--	--	R
Western Grebe	--	--	R
Pelecanidae			
American White Pelican	--	--	R
Phalacrocoracidae			
Double-crested Cormorant	--	--	X(T)
Ardeidae			
American Bittern	--	--	X
Least Bittern	--	--	X
Great Blue Heron	--	--	X
Great Egret	--	--	R(T)
Cattle Egret	--	--	R
Green-backed Heron	X	--	X
Black-crowned Night Heron	--	--	X
Yellow-crowned Night Heron	--	--	R
Anatidae			
Tundra Swan	--	--	X
Mute Swan	--	V	V
Canada Goose	--	X	X
Wood Duck	--	R	X
Green-winged Teal	--	R	X
American Black Duck	--	X	X
Mallard	X	X	X
Northern Pintail	--	R	X
Blue-winged Teal	--	--	X
Northern Shoveler	--	--	X
Gadwall	--	R	X
American Wigeon	--	R	X
Canvasback	--	R	X
Redhead	--	R	X
Ring-necked Duck	--	R	X
Greater Scaup	--	X	X
Lesser Scaup	--	R	X
Harlequin Duck	--	V	V
Oldsquaw	--	X	X
Black Scoter	--	R	R
Surf Scoter	--	--	R
White-winged Scoter	--	R	X
Common Goldeneye	--	X	X
Barrow's Goldeneye	--	R	--
Bufflehead	--	X	X
Hooded Merganser	--	R	X
Common Merganser	--	X	X
Red-breasted Merganser	--	X	X
Ruddy Duck	--	R	X
Cathartidae			
Turkey Vulture	--	--	X
Pandionidae			
Osprey	--	--	X(E)
Accipitridae			
Bald Eagle	--	--	R(E)
Northern Harrier	--	--	X
Sharp-shinned Hawk	--	R	X
Cooper's Hawk	--	R(T)	X(T)
Northern Goshawk	--	R	X
Red-shouldered Hawk	--	--	X(T)
Broad-winged Hawk	--	--	X
Red-tailed Hawk	--	X	X
Accipitridae (continued)			
Rough-legged Hawk	--	X	X
Falconidae			
American Kestrel	X	X	X
Merlin	--	--	X
Peregrine Falcon	--	--	R(E)
Phasianidae			
Ring-necked Pheasant	R	R	N/A
Rallidae			
Yellow Rail	--	--	R
Virginia Rail	--	--	X
Sora	--	--	X
Common Moorhen	--	--	R
American Coot	--	R	X
Gruidae			
Sandhill Crane	--	--	R
Charadriidae			
Black-bellied Plover	--	--	X
Lesser Golden-Plover	--	--	X
Semipalmated Plover	--	--	X
Piping Plover	--	--	R(E)
Killdeer	X	--	X
Recurvirostridae			
American Avocet	--	--	V
Scolopacidae			
Greater Yellowlegs	--	--	X
Lesser Yellowlegs	--	--	X
Solitary Sandpiper	--	--	X
Willet	--	--	R
Spotted Sandpiper	R	--	X
Upland Sandpiper	--	--	X
Whimbrel	--	--	R
Hudsonian Godwit	--	--	R
Marbled Godwit	--	--	R
Ruddy Turnstone	--	--	X
Red Knot	--	--	R
Sanderling	--	--	X
Semipalmated Sandpiper	--	--	X
Western Sandpiper	--	--	R
White-rumped Sandpiper	--	--	R
Baird's Sandpiper	--	--	X
Pectoral Sandpiper	--	--	X
Purple Sandpiper	--	V	--
Dunlin	--	--	X
Stilt Sandpiper	--	--	R
Buff-breasted Sandpiper	--	--	R
Short-billed Dowitcher	--	--	X
Long-billed Dowitcher	--	--	X
Common Snipe	--	--	X
American Woodcock	--	--	X
Phalaropodidae			
Wilson's Phalarope	--	--	X
Red-necked Phalarope	--	--	R
Laridae			
Franklin's Gull	--	--	X
Little Gull	--	R	R
Common Black-headed Gull	--	--	V
Bonapart's Gull	--	R	V
Ring-billed Gull	--	X	X
Herring Gull	--	X	X
Iceland Gull	--	R	--
Glaucous Gull	--	R	R
Great Black-backed Gull	--	V	V
Caspian Tern	--	--	X
Common Tern	--	--	X(E)

Table 27 (continued)

Scientific (Family) and Common Name	Breeding	Wintering	Migrant
Laridae (continued)			
Arctic Tern	--	--	R
Forster's Tern	--	--	X(E)
Least Tern	--	--	V
Black Tern	--	--	X
Columbidae			
Rock Dove	X	X	N/A
Mourning Dove	X	X	X
Cuculidae			
Black-billed Cuckoo	--	--	X
Yellow-billed Cuckoo	--	--	X
Strigidae			
Eastern Screech-Owl	X	X	N/A
Great Horned Owl	R	X	N/A
Snowy Owl	--	X	X
Long-eared Owl	--	R	R
Short-eared Owl	--	R	R
Northern Saw-whet Owl	--	--	R
Caprimulgidae			
Common Nighthawk	X	--	X
Whip-poor-will	--	--	X
Apodidae			
Chimney Swift	X	--	X
Trochilidae			
Ruby-throated Hummingbird	X	--	X
Alcedinidae			
Belted Kingfisher	X	--	X
Picidae			
Red-headed Woodpecker	R	R	X
Red-bellied Woodpecker	R	R	N/A
Yellow-bellied Sapsucker	--	--	X
Downy Woodpecker	X	X	N/A
Hairy Woodpecker	X	X	N/A
Northern Flicker	X	--	X
Pileated Woodpecker	--	--	V
Tyrannidae			
Olive-sided Flycatcher	--	--	X
Eastern Wood-Pewee	R	--	X
Yellow-bellied Flycatcher	--	--	X
Acadian Flycatcher	--	--	X
Alder Flycatcher	--	--	X
Willow Flycatcher	--	--	X
Least Flycatcher	--	--	X
Eastern Phoebe	--	--	X
Great Crested Flycatcher	R	--	X
Western Kingbird	--	--	V
Eastern Kingbird	X	--	X
Alaudidae			
Horned Lark	--	R	X
Hirundinidae			
Purple Martin	X	--	X
Tree Swallow	X	--	X
Northern Rough-winged Swallow	X	--	X
Bank Swallow	R	--	X
Cliff Swallow	--	--	X
Barn Swallow	X	--	X
Corvidae			
Blue Jay	X	X	X
American Crow	X	X	X
Paridae			
Black-capped Chickadee	X	X	X
Sittidae			
Red-breasted Nuthatch	--	R	X
White-breasted Nuthatch	X	X	N/A
Certhiidae			
Brown Creeper	--	R	X

Scientific (Family) and Common Name	Breeding	Wintering	Migrant
Troglodytidae			
Carolina Wren	--	--	R
House Wren	X	--	X
Winter Wren	--	--	X
Sedge Wren	--	--	X
Marsh Wren	--	--	X
Muscicapidae			
Golden-crowned Kinglet	--	X	R
Ruby-crowned Kinglet	--	--	X
Blue-gray Gnatcatcher	--	--	X
Eastern Bluebird	--	--	X
Veery	--	--	X
Gray-cheeked Thrush	--	--	X
Swainson's Thrush	--	--	X
Hermit Thrush	--	--	X
Wood Thrush	R	--	X
American Robin	X	X	X
Mimidae			
Gray Catbird	X	--	X
Northern Mockingbird	--	--	R
Brown Thrasher	X	--	X
Montacillidae			
Water Pipit	--	--	X
Bombycillidae			
Bohemian Waxwing	--	--	--
Cedar Waxwing	X	X	X
Laniidae			
Northern Shrike	--	R	X
Sturnidae			
European Starling	X	X	X
Vireonidae			
White-eyed Vireo	--	--	R
Bell's Vireo	--	--	R
Solitary Vireo	--	--	X
Yellow-throated Vireo	--	--	X
Warbling Vireo	R	--	X
Philadelphia Vireo	--	--	X
Red-eyed Vireo	R	--	X
Emberizidae			
Blue-winged Warbler	--	--	X
Golden-winged Warbler	--	--	X
Tennessee Warbler	--	--	X
Orange-crowned Warbler	--	--	X
Nashville Warbler	--	--	X
Northern Parula	--	--	X
Yellow Warbler	X	--	X
Chestnut-sided Warbler	--	--	X
Magnolia Warbler	--	--	X
Cape Map Warbler	--	--	X
Black-throated Blue Warbler	--	--	X
Yellow-rumped Warbler	--	--	X
Black-throated Green Warbler	--	--	X
Blackburnian Warbler	--	--	X
Pine Warbler	--	--	R
Prairie Warbler	--	--	R
Palm Warbler	--	--	X
Bay-breasted Warbler	--	--	X
Blackpoll Warbler	--	--	X
Cerulean Warbler	--	--	X
Black-and-White Warbler	--	--	X
American Redstart	--	--	X
Prothonotary Warbler	--	--	R
Worm-eating Warbler	--	--	R
Ovenbird	--	--	X
Northern Waterthrush	--	--	X
Louisiana Waterthrush	--	--	R
Kentucky Warbler	--	--	R

Table 27 (continued)

Scientific (Family) and Common Name	Breeding	Wintering	Migrant
Emberizidae (continued)			
Connecticut Warbler	--	--	X
Mourning Warbler	--	--	R
Common Yellowthroat	X	--	X
Hooded Warbler	--	--	R
Wilson's Warbler	--	--	X
Canada Warbler	--	--	X
Yellow-breasted Chat	--	--	R
Summer Tanager	--	--	R
Scarlet Tanager	--	--	X
Northern Cardinal	X	X	N/A
Rose-breasted Grosbeak	R	--	X
Indigo Bunting	X	--	X
Dickcissel	--	--	R
Rufous-sided Towhee	--	--	X
American Tree Sparrow	--	X	X
Chipping Sparrow	X	--	X
Clay-colored Sparrow	--	--	X
Field Sparrow	--	--	X
Vesper Sparrow	--	--	X
Lark Sparrow	--	--	R
Black-throated Sparrow	--	--	V
Lark Bunting	--	--	V
Savannah Sparrow	R	--	X
Grasshopper Sparrow	--	--	R
Henslow's Sparrow	--	--	R
LeConte's Sparrow	--	--	R
Sharp-tailed Sparrow	--	--	R
Fox Sparrow	--	R	X
Song Sparrow	X	X	X
Lincoln's Sparrow	--	--	X
Swamp Sparrow	--	R	X
White-throated Sparrow	--	R	X
White-crowned Sparrow	--	--	X
Harris' Sparrow	--	--	R
Dark-eyed Junco	--	X	X
Lapland Longspur	--	--	X
Snow Bunting	--	R	X
Bobolink	--	--	X
Red-winged Blackbird	X	X	X
Eastern Meadowlark	--	--	X
Western Meadowlark	--	--	R
Yellow-headed Blackbird	--	--	R
Rusty Blackbird	--	--	X
Brewer's Blackbird	--	--	X
Common Grackle	X	R	X
Brown-headed Cowbird	X	R	X
Orchard Oriole	--	--	R
Northern Oriole	X	--	X
Fringillidae			
Pine Grosbeak	--	--	R
Purple Finch	--	X	X
Red Crossbill	--	R	R
White-winged Crossbill	--	R	R
Common Redpoll	--	R	X
Pine Siskin	--	X	X
American Goldfinch	X	X	X
Evening Grosbeak	--	X	X
Ploceidae			
House Sparrow	X	X	N/A

NOTE: N/A indicates data not available.

Breeding: Nesting species (nonnesting species present in summer are not included).
Wintering: Present in January and February.
Migrant: Spring and fall transient.

X - Present, not rare
R - Rare
V - Vagrant (not regularly occurring in southeastern Wisconsin)
(T) - Threatened species in Wisconsin
(E) - Endangered species in Wisconsin (bald eagle also U. S. threatened; peregrine falcon also U. S. endangered)

Source: SEWRPC.

most of the wildlife habitat areas remaining in the study area are medium-value areas. Of the total 130 square miles of wildlife habitat in the study area, 57 square miles, or 44 percent, are rated as medium value. High-value wildlife habitat accounts for 45 square miles, or about 35 percent, of the total wildlife habitat area, while low-value habitat encompasses about 28 square miles, or approximately 21 percent, of the total wildlife habitat area within the study area.

Environmental Corridors

The Environmental Corridor Concept: One of the most important tasks undertaken by the Commission as part of its regional planning effort was the identification and delineation of those areas of the Region having high concentrations of natural, recreational, historic, aesthetic, and scenic resources and which, therefore, should be preserved and protected in order to maintain the overall quality of the environment. Such areas normally include one or more of the following seven elements of the natural resource base which are essential to the maintenance of both the ecological balance and natural beauty of the Region: 1) lakes, rivers, and streams and the associated undeveloped shorelands and floodlands; 2) wetlands; 3) woodlands; 4) prairies; 5) wildlife habitat areas; 6) wet, poorly drained, and organic soils; and 7) rugged terrain and high-relief topography. While the foregoing seven elements constitute integral parts of the natural resource base, there are five additional elements which, although not a part of the natural resource base per se, are closely related to or centered on that base and therefore are important considerations in identifying and delineating areas with scenic, recreational, and educational value. These additional elements are: 1) existing outdoor recreation sites; 2) potential outdoor recreation and related open space sites; 3) historic, archaeological, and other cultural sites; 4) significant scenic areas and vistas and 5) natural and scientific areas.

The delineation of these 12 natural resource and natural resource-related elements on a map results in an essentially linear pattern of relatively narrow, elongated areas which have been termed "environmental corridors" by the Commission. Primary environmental corridors include a wide variety of the above-mentioned important resource and resource-related elements and are at least 400 acres in size, two miles in length, and 200 feet in width. Secondary environmental corridors typically connect with primary environmental corridors and are at least 100 acres in size and one mile in length.

Table 28

MAMMALS KNOWN TO OCCUR IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA

Marsupialia
Didelphis marsupialis—Virginia opossum
Insectivora
Sorex cinereus—Cinereous shrew
Microsorex hoyi—American pigmy shrew
Blarina brevicauda—Kirtland's short-tailed shrew
Chiroptera
Myotis lucifugus—Little brown bat
Lasionycteris noctivagans[a]—Silver hair bat
Eptesicus fuscus—Big brown bat
Lasiurus borealis—Red bat
Lasiurus cinereus[a]—Hoary bat
Lagomorpha
Sylvilagus floridanus—Mearn's cottontail
Rodentia
Marmota monax—Southern woodchuck
Spermophilus tridecemlineatus—Striped ground squirrel
Tamias striatus—Gray chipmunk
Sciurus carolinensis—Minnesota gray squirrel
Sciurus niger—Western fox squirrel
Glaucomys volans—Southern flying squirrel
Peromyscus maniculatus—Prairie deer mouse
Peromyscus leucopus—Northern white-footed mouse
Microtus pennsylvanicus—Meadow vole
Ondatra zibethicus—Common muskrat
Rattus norvegicus[b]—Norway rat
Mus musculus[b]—House mouse
Zapus hudsonius—Meadow jumping mouse
Carnivora
Vulpes fulva[c]—Eastern red fox
Procyon lotor—Western raccoon
Mustela frenata—Long-tailed weasel
Mustela vison[c]—American mink
Mephitis mephitis—Northern plains skunk
Artiodactyla
Odocoileus virginianus[c]—Northern white-tailed deer

[a] *Identified by Dr. Marlin Tuttle, Curator of Mammals, Milwaukee Public Museum.*

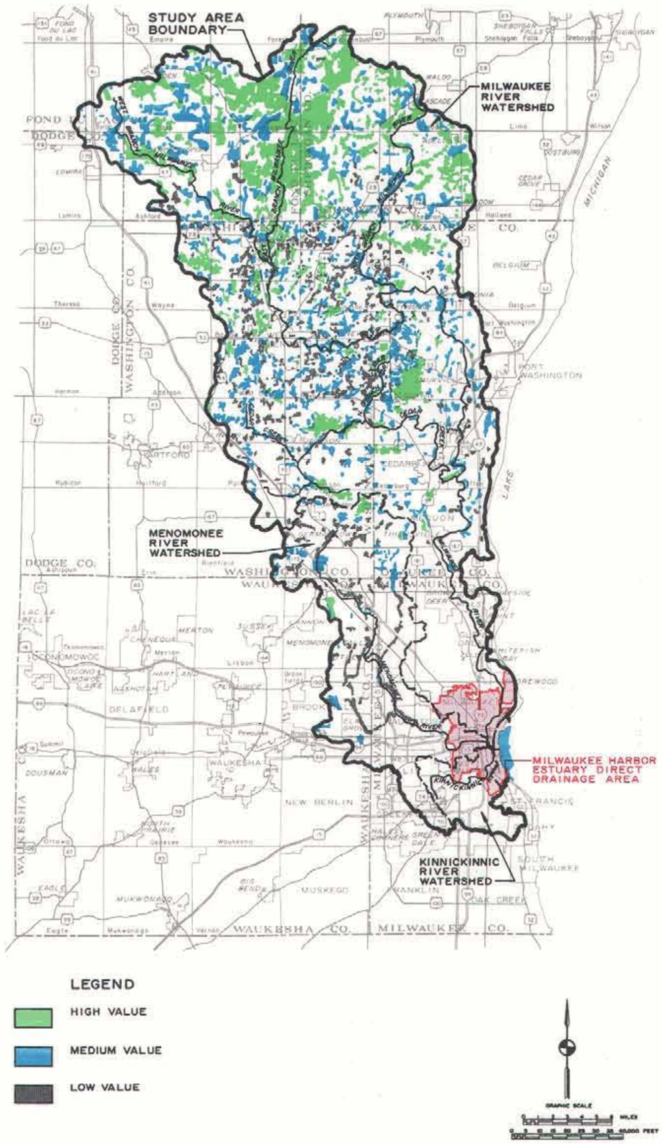
[b] *Alien or nonnative to North America.*

[c] *Is found occasionally in the subwatershed.*

Source: Hartley H. T. Jackson, Mammals of Wisconsin, 1961; Charles A. Long, Environmental Status of the Lake Michigan Region, Volume 15, Mammals of the Lake Michigan Drainage Basin, 1974; Milwaukee Public Museum; and SEWRPC.

Map 28

WILDLIFE HABITAT AREAS IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1980



The most recent inventory of wildlife habitat revealed that a total of 246 significant habitat areas, totaling 125 square miles in area, remained within the study area. The few remaining high-value and medium-value wildlife habitat areas are located predominantly in the more rural portions of the Menomonee and Milwaukee River watersheds. Unless consciously protected, these remaining high-value and medium-value wildlife habitat areas will diminish in both quantity and quality as pressures for scattered urban expansion increase.

Source: SEWRPC.

Table 29

WILDLIFE HABITAT AREAS IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1980

Watershed	County	Wildlife Habitat						County Total
		High Value		Medium Value		Low Value		
		Acreage	Percent of Total	Acreage	Percent of Total	Acreage	Percent of Total	
Milwaukee Harbor Estuary Direct Drainage Area	Milwaukee	- -	- -	1,437	- -	- -	- -	1,437
	Subtotal	- -	- -	1,437	- -	- -	- -	1,437
Milwaukee River Watershed[a]	Dodge	185	100	- -	- -	- -	- -	185
	Fond du Lac. . . .	12,367	62	5,877	30	1,590	8	19,834
	Milwaukee	- -	- -	- -	- -	- -	- -	- -
	Ozaukee	5,284	42	6,267	50	978	8	12,529
	Sheboygan	883	13	5,015	73	997	14	6,895
	Washington	10,605	38	11,273	40	6,341	22	28,219
	Subtotal	29,324	43	28,432	42	9,906	15	67,662
Menomonee River Watershed	Milwaukee	- -	- -	1,760	100	- -	- -	1,760
	Ozaukee	- -	- -	1,520	100	- -	- -	1,520
	Washington	560	13	3,360	78	400	9	4,320
	Waukesha	480	13	2,560	71	560	16	3,600
	Subtotal	1,040	9	9,200	83	960	9	11,200
Kinnickinnic River Watershed	Milwaukee	- -	- -	- -	- -	- -	- -	- -
	Subtotal	- -	- -	- -	- -	- -	- -	- -
Total		30,364	38	39,069	49	10,866	13	80,299

[a] *For purposes of acreage totals for the Menomonee River watershed, the size of each wildlife habitat area was taken as the midpoint in the following acreage ranges: 0-160, 161-320, 321-480, 481-640, 641-800. For example, a habitat area in the 161-320 acreage range was assigned a nominal area of 240 acres. The sum of the nominal areas for each of the three wildlife habitat categories was then determined and listed by county.*

Source: SEWRPC.

It is important to point out that, because of the many interlocking and interacting relationships between living organisms and their environment, the destruction or deterioration of one element of the total environment may lead to a chain reaction of destruction and deterioration. The drainage of wetlands, for example, may have far-reaching effects, since such drainage may destroy fish spawning grounds, wildlife habitat, groundwater recharge areas, and natural filtration and floodwater storage areas of interconnecting lake and stream systems. The resulting deterioration of surface water quality may, in turn, lead to a deterioration of the quality of the groundwater. Groundwater serves as a source of domestic, municipal, and industrial water supply and provides a basis for low flows in rivers and streams. Similarly, the destruction of woodland cover, which may have taken a century or more to develop, may result in soil erosion and stream siltation and in more rapid runoff and increased flooding, as well as the destruction of wildlife habitat. Although the effects of any one of these environmental changes may not in and of itself be overwhelming, the combined effects may lead eventually to the deterioration of the underlying and supporting natural resource base, and of the overall quality of the environment for life. The need to protect and preserve the remaining environmental corridors within the study area thus is apparent.

Primary Environmental Corridors: Primary environmental corridors were identified within the Region in 1963 as part of the original regional land use planning effort of the Commission, and were subsequently refined under the Commission's

Table 30

ENVIRONMENTAL CORRIDORS AND ISOLATED NATURAL AREAS IN THE MILWAUKEE HARBOR ESTUARY DIRECT DRAINAGE AREA AND ITS TRIBUTARY RIVER WATERSHEDS: 1980

Natural Features	Primary Environmental Corridor		Secondary Environmental Corridor		Isolated Natural Area		Total	
	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent
Surface Water . .	6,529	6.1	293	2.3	273	2.2	7,095	5.4
Wetlands	61,379	57.3	7,396	57.9	4,447	35.1	73,222	55.3
Woodlands	28,066	26.2	2,394	18.7	7,103	56.1	37,563	28.3
Other	11,081	10.4	2,698	21.1	835	6.6	14,614	11.0
Total	107,055	100.0	12,781	100.0	12,658	100.0	132,494	100.0

Source: SEWRPC.

watershed studies and regional park and open space planning program. The initial corridor delineations, even as modified under major planning programs undertaken by the Commission, were made at the systems level of planning and were thus relatively general. A more detailed delineation of environmental corridors is needed for the detailed project level planning and other local planning efforts. The Commission recently completed such a detailed delineation of environmental corridors for the study area.

The primary environmental corridors in the study area generally lie along major stream valleys and around major lakes, and contain almost all of the remaining high-value woodlands, wetlands, and wildlife habitat areas and major bodies of surface water and related undeveloped floodlands and shorelands. These corridors also contain many of the best remaining potential park sites. The primary environmental corridors are, in effect, a composite of the best individual elements of the natural resource base, and have truly immeasurable environmental and recreational value. As indicated in Table 30, and shown on Map 15, primary environmental corridors encompassed 107,055 acres, or about 19.5 percent, of the total study area in 1980—6,529 acres of surface water, 61,379 acres of wetlands, 28,066 acres of woodlands, and 11,081 acres of other lands.

Primary environmental corridors may be subject to urban encroachment because of their desirable natural resource amenities. Unplanned or poorly planned intrusion of urban development into these corridors, however, not only tends to destroy the very resources and related amenities sought by the development, but tends to create severe environmental and developmental problems as well.

Secondary Environmental Corridors: The secondary environmental corridors within the study area are located generally along intermittent streams or serve as links between segments of primary environmental corridors. These secondary environmental corridors contain a variety of resource elements, often remnant resources from primary environmental corridors which have been developed for intensive agricultural purposes or urban land uses. Secondary environmental corridors facilitate surface water drainage, maintain "pockets" of natural resource features, and provide for the movement of wildlife, as well as for the movement and dispersal of seeds for a variety of plant species. Such corridors, while not as important as the primary environmental corridors, should be preserved in essentially open, natural uses as urban development proceeds within the study area, particularly when the opportunity is presented to incorporate the corridors into urban stormwater detention areas, associated drainageways, and neighborhood parks. As indicated in Table 30, secondary environmental corridors encompassed 12,781 acres, or about 2.3 percent, of the total study area in 1980. Such corridors include 293 acres of surface water, 7,396 acres of wetlands, 2,394 acres of woodlands, and 2,698 acres of other land.

Isolated Natural Areas: In addition to the primary and secondary environmental corridors, other, small concentrations of natural resource base elements exist within the study area. These resource base elements are isolated from the environmental corridors by urban development or agricultural uses and, although separated from the environmental corridor network, also have important natural values. Isolated natural areas may provide the only available wildlife habitat in an area, provide good locations for local parks and nature study areas, and lend an aesthetic character or natural diversity to an area. Important isolated natural features include a geographically well-distributed variety of isolated wetlands, woodlands, and wildlife habitat. These isolated natural features should also be protected and preserved in a natural state whenever possible. As indicated in Table 30, isolated natural areas five acres or more in size encompassed about 12,658 acres, or about 2.3 percent of the study area, in 1980. Such areas include 273 acres of surface water, 4,447 acres of wetlands, 7,103 acres of woodlands, and 835 acres of other lands.

SUMMARY

The Milwaukee Harbor estuary direct drainage area and its tributary river watersheds is a large ecosystem composed of both man-made and natural features which interact to form a changing environment for life. Future changes in that ecosystem will be largely determined by man's actions. The Milwaukee Harbor estuary comprehensive water resources planning program seeks to rationally direct those actions so as to favorably affect the overall quality of life. This chapter has described the existing ecosystem of the study area—the man-made features and the natural resource base—thereby establishing a factual base upon which the planning process may be built.

The man-made features of the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds include the political boundaries, land use patterns, public utility network, and transportation systems. These features, along with the resident population and economic activities, may be thought of as the socioeconomic base of the study area.

The Milwaukee Harbor estuary direct drainage area is approximately 22 square miles in areal extent. The total study area, which includes the direct drainage area and its three tributary river watersheds—the Kinnickinnic River watershed, the Menomonee River watershed, and the Milwaukee River watershed—encompass a combined area of approximately 854 square miles. The study area encompasses all or portions of 12 cities, 24 villages, and 30 towns.

The 1980 resident population of the direct drainage area was estimated at 255,200 persons, or about 14 percent of the total population of the Region. Within the southeastern Wisconsin portion of the total study area, the 1980 resident population was estimated at 955,500 persons, or about 54 percent of the estimated 1.76 million persons residing in the seven-county Southeastern Wisconsin Region. Between 1950 and 1980, the Milwaukee Harbor estuary direct drainage area exhibited a marked decline in resident population. Over this 30-year period, the population of the direct drainage area decreased by about 162,600 persons, or by about 39 percent—from approximately 417,800 persons in 1950 to about 255,200 persons in 1980. Over this same period, however, the population within the total study area increased by about 154,000 persons or about 19 percent—from approximately 816,200 persons in 1950 to about 970,200 persons in 1980, although there has been an overall decline in the total study area population since 1970, when about 1.04 million persons resided in the area. The continuous decline in population in the Milwaukee Harbor estuary direct drainage area since 1950, and in the total study area since 1960, reflects trends exhibited in many of the older metropolitan centers of the United States.

The Milwaukee Harbor estuary direct drainage area encompasses the most extensively urbanized portion of the Region, including the central business district of the City of Milwaukee and the heavily industrialized Menomonee River Valley. Accordingly, the population density within the direct drainage area is relatively high. The resident population density in the direct drainage area was approximately 11,600 persons per square mile in 1980. Overall resident population densities in the three tributary river watersheds in 1980 were about 5,000, 2,000, and 500 persons per square mile for the Kinnickinnic, Menomonee, and Milwaukee River watersheds, respectively. The Southeastern Wisconsin Region as a whole had a population density of about 650 persons per square mile in 1980. The direct drainage area, however, exhibited a marked decrease in population density between 1970 and 1980, declining by about 2,300 persons per square mile, or by about 16 percent—from about 13,900 persons per square mile in 1970 to about 11,600 persons per square mile in 1980. Augmenting the resident population of the direct drainage area is the daily influx of persons into the central business district of the City of Milwaukee on work and shopping trips. Based on the latest available origin-destination survey conducted by the Commission, approximately 131,300 persons entered the central business district of the City of Milwaukee on an average weekday in 1972. This daily influx of persons on work, shopping, or other trips represents a more than 50 percent increase in the 255,200-person resident population of the direct drainage area.

Age, household size, and household income data available from the 1980 census indicate that the resident population of the Milwaukee Harbor estuary direct drainage area is, on the average, younger and less affluent than the resident population of its three tributary river watersheds and the Region as a whole, and is dwelling in smaller households than is the populations of the river watersheds and the Region. The most notable change in the characteristics of the resident population within the direct drainage area between 1970 and 1980 is a decrease in the average age of the population, while for the individual tributary river watersheds, the total study area, and the Region as a whole, the average age of the resident population increased markedly between 1970 and 1980. Also notable is the fact that the resident population within the direct drainage area exhibited the greatest absolute and relative decrease in average household income between 1970 and 1980 when compared with the average household income of the population within the individual tributary river watersheds, the total study area, and the Region as a whole.

As would be expected because of the heavily urbanized character of the Milwaukee Harbor estuary direct drainage area, employment in the area is highly concentrated in the manufacturing, wholesale and retail trade, and private services sectors of the economy. Manufacturing alone accounts for more than 30 percent of the jobs in the total study area, with the principal type of manufacturing being nonelectrical machinery. The production of nonelectrical machinery accounts for about 29 percent of the manufacturing jobs in the total study area, with the manufacture of electrical equipment, fabricated metal products, and miscellaneous metal products accounting for an additional 29 percent of the jobs in the study area. Agricultural activity, which is virtually nonexistent in the heavily urbanized direct drainage area, declined in the overall study area between 1974 and 1979, as evidenced by a 12 percent reduction in the number of farms and a nearly 5 percent reduction in the acreage farmed over this five-year period.

The settlement of the Milwaukee Harbor estuary direct drainage area followed the establishment of the Port of Milwaukee, with the pattern of historic growth generally occurring in expanding, concentric rings around the port area. Much of the urbanization which took place in the tributary river watershed areas over the past century occurred as the population in the direct drainage area migrated outward from the historic urban center into the more rural portions of the study area.

At the present time, approximately 93 percent of the Milwaukee Harbor estuary direct drainage area is in urban land uses, with only about 7 percent of the area in the more rural categories of open lands and surface waters. The dominant land uses in the direct drainage area are transportation and utilities and residential uses, accounting together for about 16 square miles, or almost 72 percent of all the land in this drainage area. Considering the total study area, about 639 square miles, or about 74 percent of the total 858-square-mile area, is still in rural land uses, predominantly agricultural.

The public utility base in the study area is composed of its sanitary sewerage systems, water supply systems, electric power service, and gas service. Adequate supplies of both electric power and natural gas are available, or could be provided, to all portions of the study area. About 186 square miles, or about 22 percent of the total study area, and approximately 903,900 persons, or about 93 percent of the total study area population, were served by public sanitary sewerage facilities during 1980. The entire population of the Milwaukee Harbor estuary direct drainage area was served by the sewerage facilities provided by the Milwaukee Metropolitan Sewerage District in 1980. Public water supply in the direct drainage area is provided by Milwaukee Water Works and the Shorewood Municipal Water Utility. There are 23 additional publicly owned water utilities serving other portions of the study area. In total, these 25 utilities provide water supply over a combined area of about 154 square miles, or about 18 percent of the total study area, and serve approximately 806,000 persons, or about 83 percent of the resident population of the study area. Of these 25 public water utilities, 11 utilities—all in Milwaukee County—use Lake Michigan as their source of water supply, while the remaining 14 use groundwater as their source of water supply.

The Milwaukee Harbor estuary direct drainage area and its tributary river watersheds are well served by an extensive all-weather, high-speed highway system which includes 68.6 linear miles of freeway and 869.8 linear miles of surface arterials. The study area is also well served by two types of bus service: urban mass transit and intercity bus service. Railway service in the direct drainage area and its tributary river watersheds is limited to freight hauling except for scheduled Amtrak passenger service over the lines of the Chicago, Milwaukee, St. Paul & Pacific Railroad Company (Milwaukee Road).

Commercial shipping, which significantly influenced the growth of the City of Milwaukee into a major urban center, continues to have an important impact on the regional economy. From 1968 through 1982, approximately two to four million tons of commerce were handled annually at the Port of Milwaukee facilities. In 1982, more than 683,000 tons of coal, 449,000 tons of grain, 408,000 tons of salt, and 339,000 tons of cement passed through the port. The municipal harbor terminals handle about 41 percent of the total port commerce, with the remaining 59 percent being handled at private terminals. An economic impact study conducted by the Port of Milwaukee estimated that port activities contributed the equivalent of 5,825 full-time jobs with an annual payroll of $112.6 million, and stimulated the economy within the Milwaukee Standard Metropolitan Statistical Area with $1.1 billion in annual sales revenue.

The natural resource base is an important determinant of the development potential of an area, as well as of the ability of an area to provide a pleasant and habitable environment for all forms of life. The principal elements of the natural resource base are climate, physiography, topography, soils, vegetation, water resources, and fish and wildlife resources. Inasmuch as the underlying and sustaining natural resource base is highly vulnerable to misuse and destruction, the management of the natural resource base must be a primary consideration in the Milwaukee Harbor estuary comprehensive water resources planning program.

Because of its mid-continental location, far removed from the moderating effect of the oceans, the Milwaukee Harbor estuary direct drainage area, along with its tributary river watersheds, has a climate characterized by a progression of markedly different seasons. An essentially continuous pattern of distinct weather changes occurring at two- to three-day intervals is superimposed on the seasonal pattern. Air temperatures in the study area range from a daily average of about 18°F in January to about 70°F in July. Temperature extremes, as measured at the City of Milwaukee over a 112-year period, range from a high of 105°F to a low of -26°F.

Average annual precipitation in the study area is about 30.1 inches expressed as water equivalent, and average monthly amounts range from a low of 1.04 inches in February to 3.69 inches in July. The average annual amount of snow and sleet in the study area is 47.8 inches. About 90 percent of the annual snowfall occurs in the four months of December, January, February, and March. Snowfall has historically exhibited a wider year-to-year variation than has total precipitation, with the annual snowfall ranging from a low of five inches to a high of approximately 109 inches.

With respect to snow cover, there is a 25 percent probability of having five or more inches of snow on the ground during January and the first half of February. There is normally six or more inches of frozen ground in the study area during January, February, and the first half of March. Annual potential evaporation in the study area is about 29 inches and closely approximates average annual precipitation. Prevailing winds follow a clockwise directional pattern over the seasons of the year, being predominantly southwesterly in the summer and shifting to predominantly northwesterly in the winter.

Daylight in the study area ranges from a minimum of 9.0 hours on or about December 22 to a maximum of 15.4 hours on or about June 22. The least amount of daytime sky cover occurs from July through October, when the mean monthly daytime sky cover is approximately 0.5, whereas a sky cover of about 0.7 may be expected from November through March.

The topographic and physiographic features of the study area have largely been determined by the underlying bedrock and overlying glacial deposits. The last of four major stages of glaciation occurred about 11,000 years ago, and was the most influential in sculpturing the land surface of the study area. The Niagara cuesta on which the study area lies is a gently sloping bedrock surface. The topography of the study area is asymmetrical, with the eastern border of the study area being generally lower in elevation than the western border.

The geology of the study area is a complex system of various layers and ages of rock formations. These formations slope gently toward the east and consist of, in ascending order, predominantly crystalline rocks of the Precambrian through Devonian Period sedimentary rocks of the Paleozoic Era, and unconsolidated surficial deposits.

A wide variety of soil types occur within the study area. Although a detailed soil survey was conducted for most of the study area, detailed soils data are generally not available for the Milwaukee Harbor estuary direct drainage area because of the extensively urbanized and highly developed nature of the area. The nature and characteristics of the soils underlying the direct drainage area may, however, be inferred from utility, construction, and well digging logs.

The quantity and quality of vegetation in the study area is at any given point in time determined by, or the result of, numerous influences, including climate, topography, glacial history, occurrence of fire, soil characteristics, proximity to bedrock, drainage features, and, especially, the activities of man. Prior to the arrival of European settlers, the vegetation in the study area was predominantly a medium wet, or mesic, forest composed of a variety of upland deciduous hardwoods. The extensive urban development which has occurred in the direct drainage area since the initial settlement, however, has reduced this original vegetation to isolated areas of upland hardwoods and weedy pioneer plant communities seen in vacant lots and other open unused urban lands.

Streams and associated floodlands comprise the most important element of the natural resource base of the study area, primarily because of their associated aesthetic, recreational, and economic values. There are about 419 linear miles of perennial streams within the study area. There are no major lakes of 50 acres or more in areal extent within the direct drainage area, although there are 50 minor lakes—lakes having less than 50 acres in areal extent—in the Milwaukee River watershed and 14 minor lakes within the Menomonee River watershed. The 50 minor lakes in the Milwaukee River watershed have a combined surface water area of 732 acres with 41 miles of shoreline, while the 14 minor lakes in the Menomonee River watershed have a combined surface water area of 33 acres with four miles of shoreline.

Extensive groundwater resources underlie the study area and are an integral part of the much larger groundwater system that lies beneath the Southeastern Wisconsin Planning Region. The aquifers beneath the study area, which can attain a combined thickness in excess of 2,200 feet, may be subdivided so as to identify three distinct groundwater sources. In order from the land surface downward they are the sand and gravel deposits in the glacial drift, the shallow dolomite strata in the underlying bedrock, and the deeper bedrock strata composed of sandstone, dolomite, siltstone, and shale. It is estimated that the groundwater stored beneath the study area exceeds 88 million acre-feet, a quantity sufficient to cover the entire study area to a depth of 160 feet.

The remaining fish and wildlife resources in the Milwaukee Harbor estuary direct drainage area are particularly important because of their recreational, educational, and aesthetic values, and because of the naturalness and diversity that they impart to the urban environment. The Milwaukee Harbor estuary fishery is presently marginal because of low oxygen levels and generally small streamflows, and currently has little value for sport fishing purposes.

The delineation of selected natural resource and natural resource-related elements on a map of the study area produces an essentially linear pattern encompassed in narrow, elongated areas which have been termed environmental corridors by the Regional Planning Commission. As of 1980, primary environmental corridors occupied approximately 167 square miles, or 19.5 percent of the total study area, and contained almost all of the remaining high-value wildlife habitat areas and woodlands; most of the wetlands, lakes and streams, and associated floodlands; and many significant physiographic features and historic sites. The primary environmental corridors are a composite of the best of the individual elements comprising the natural resource base of the study area. The preservation of these corridors in a natural state or in park and related open space uses is essential to maintaining a high level of environmental quality in the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds.

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Chapter IV

WATER RESOURCES MONITORING IN THE MILWAUKEE HARBOR WATERSHED

INTRODUCTION

An extensive water resources monitoring program was conducted as a part of the Milwaukee Harbor estuary comprehensive water resources planning effort. This chapter describes that monitoring program, with the results of the program being presented in other chapters of this report as appropriate. Monitoring programs conducted concurrently by other agencies are also described herein if the data from such programs were also utilized in the estuary planning effort.

The field work required to develop primary data for the planning effort was conducted in calendar years 1982, 1983, and 1984. In addition, baseline water quality data collected by the Milwaukee Metropolitan Sewerage District in 1981 were used in the study. Monitored during the three-year program were meteorological phenomena such as precipitation, wind speed and direction, solar insolation, air temperature, and relative humidity; groundwater levels and quality; lake water levels and quality; streamflow quantity and quality; physical and chemical characteristics of bottom and suspended sediments; and aquatic fauna and flora.

Data were collected to: 1) characterize the quality and quantity of runoff water from rural areas, separate sewer service areas, combined sewer service areas, and riparian lands bordering the estuary; 2) characterize the quality of groundwater discharging to the estuary; 3) provide a sound basis for the calibration and verification of the mathematical water level, flow, and quality simulation models utilized for hindcasting water quality for critical periods prior to the monitoring program, for characterizing water quality conditions on an areawide basis, for forecasting water quality under alternative future scenarios, and in computing flood flows and stages and storm damage in the estuary; 4) help determine the need for dredging in the estuary for both navigation and water quality enhancement; and 5) characterize existing aquatic fauna, flora, and habitat in the estuary.

METEOROLOGICAL DATA COLLECTION

Meteorological data were collected for the Milwaukee Harbor estuary and the watersheds tributary thereto over the three-year monitoring period by the National Weather Service; the City of Milwaukee, Bureau of Engineers; the Milwaukee Metropolitan Sewerage District; and the U. S. Geological Survey. The locations of the meteorological monitoring sites are shown on Maps 24 and 25 in Chapter III of this volume. Table 31 provides additional information for each station, including the period of record for each variable monitored. The resulting meteorological data utilized in the estuary study are summarized in Chapter IX of this volume.

National Weather Service

Of the 13 National Weather Service precipitation stations located in or near the watersheds tributary to the Milwaukee Harbor estuary listed in Table 31, 10 are nonrecording, reporting only daily precipitation. Hourly precipitation is recorded at four stations—Milwaukee Mitchell Field, Hartford, Horicon, and Eldorado. All hourly and daily precipitation data collected since 1940 are stored in the Commission computer files for use in hydrologic and water quality modeling. Also stored in the computer files are data on air temperature, wind speed, cloud cover, and dewpoint temperature for sites where such data have been collected since 1940. Solar radiation, computed using percent sunshine or cloud cover data, is also stored in the computer file.

City of Milwaukee

During the three-year monitoring program, the City of Milwaukee, Bureau of Engineers, operated 15 continuous strip-chart rain gages, also listed in Table 31, to assist in the monitoring and operation of the city sewer systems. The locations of these gages are shown on Map 25. Fifteen of these gages are of the tipping bucket variety, with the data collected at these sites being telemetered automatically to continuous strip-chart recorders at the offices of the Bureau. The remaining three are weighing bucket rain gages with self-contained strip-chart recorders. Rainfall is recorded in increments of 0.01 inch on 24-hour continuous strip charts. Of these 18 rain gages, 16 were winterized and operated year-round, but not always for the entire period of record as indicated in Table 31. The remaining gages were operated from April through October. These rain gages were placed into service during the period 1968 to 1978, as indicated in Table 31.

Table 31

METEOROLOGICAL DATA COLLECTION STATIONS OPERATED IN AND NEAR THE MILWAUKEE HARBOR WATERSHED DURING THE ESTUARY STUDY FIELD DATA COLLECTION PERIOD

Station[a]	Data Set	Data Source[b]	Period of Available Record
National Weather Service			
El Dorado	Hourly Precipitation	NCC, ACOE	1948-1981
Hartford	Daily Precipitation	NCC, OP, SC	1948-present
	Temperature		1953-present
Horicon	Hourly Precipitation	NCC	Data lacked required precision
Milwaukee-WBAP (General Mitchell Field)	Hourly Precipitation	NCC	1940-present
	Cloud Cover	NCC	1940-present
	Percent Possible Sunshine	NCC	1940-present
	Temperature	NCC	1940-present
	Wind	NCC	1940-present
	Dewpoint	NCC	1940-present
	Solar Radiation	NCC	1940-present
	Potential Evaporation	NCC	1940-present
Milwaukee-Mt. Mary	Hourly Precipitation	NCC	1940-present
	Temperature	NCC	1940-present
Milwaukee-North Side	Daily Precipitation	NCC	1949-1959, 1966-1976
	Temperature	NCC	1949-1959, 1966-1976
Plymouth	Daily Precipitation	NCC	1940-present
	Temperature	NCC, OP, SC	1940-present
Port Washington	Daily Precipitation	NCC, SC, OP	1940-present
	Temperature	NCC, SC, OP	1959-present
Sheboygan	Daily Precipitation	NCC, SC, OP	1940-present
	Temperature	NCC, SC, OP	1940-present
Waukesha	Daily Precipitation	NCC, SC, OP	1940-present
	Temperature	NCC, SC, OP	1940-present
West Allis	Daily Precipitation	NCC, SC, OP	1940-present
	Temperature	NCC, SC, OP	1940-present
West Bend	Daily Precipitation	NCC, SC, OP	1940-present
	Temperature	NCC, SC, OP	1940-present
Germantown	Hourly Precipitation	NCC	1940-present
	Temperature	NCC	1940-present
City of Milwaukee, Bureau of Engineers			
841 N. Broadway	Continuous Precipitation[c]	City of Milwaukee	1966-1982
841 N. Broadway	Continuous Precipitation[f]	City of Milwaukee	1982-present
2009 W. Hampton Avenue	Continuous Precipitation[d]	City of Milwaukee	1967-1982
245 W. Lincoln Avenue	Continuous Precipitation[d]	City of Milwaukee	1966-1982
245 W. Lincoln Avenue	Continuous Precipitation[f]	City of Milwaukee	1982-present
407 N. Hawley Road	Continuous Precipitation[d]	City of Milwaukee	1971-1982
6945 N. 41st Street	Continuous Precipitation[d]	City of Milwaukee	1971-1982
6945 N. 41st Street	Continuous Precipitation[f]	City of Milwaukee	1982-present
3172 N. 36th Street	Continuous Precipitation[f]	City of Milwaukee	1970-present
8414 W. Florist Avenue	Continuous Precipitation[d]	City of Milwaukee	1966-1982
8414 W. Florist Avenue	Continuous Precipitation[f]	City of Milwaukee	1982-present
3715 W. Lincoln Avenue	Continuous Precipitation[f]	City of Milwaukee	1966-present
8463 N. Granville Road	Continuous Precipitation[f]	City of Milwaukee	1967-present
8814 W. Lisbon Avenue	Continuous Precipitation[f]	City of Milwaukee	1962-present
5600 W. Oklahoma Avenue	Continuous Precipitation[e]	City of Milwaukee	1963-present

Table 31 (continued)

Station[a]	Data Set	Data Source[b]	Period of Available Record
City of Milwaukee, Bureau of Engineers (cont.)			
2647 N. Bartlett Avenue	Continuous Precipitation[f]	City of Milwaukee	1973-present
6074 S. 13th Street	Continuous Precipitation[f]	City of Milwaukee	1977-present
2825 N. Holton Street	Continuous Precipitation[e]	City of Milwaukee	1968-present
7717 W. Good Hope Road	Continuous Precipitation[e]	City of Milwaukee	1977-1982
3563 S. 97th Street	Continuous Precipitation[f]	City of Milwaukee	1978-present
5335 N. Teutonia Avenue	Continuous Precipitation[f]	City of Milwaukee	1982-present
300 S. 84th Street	Continuous Precipitation[f]	City of Milwaukee	1983-present
Milwaukee Metropolitan Sewerage District			
Milwaukee River at Pioneer Road	Continuous Precipitation	MMSD	1981-present
Kinnickinnic River at S. 1st Street	Continuous Precipitation	MMSD	1982-present
Menomonee River at Muskego	Continuous Precipitation	MMSD	1982-present
Milwaukee Lighthouse	5 minute interval precipitation	MMSD	1980-1983
	5 minute interval wind speed	MMSD	1980-1983
	5 minute interval wind direction	MMSD	1980-1983
	5 minute interval air temperature	MMSD	1980-1983
	5 minute interval solar radiation	MMSD	1980-1983
	5 minute interval relative humidity	MMSD	1980-1983
Harbor Commission Pier	5 minute interval precipitation	MMSD	1983-present
	5 minute interval wind speed	MMSD	1983-present
	5 minute interval wind direction	MMSD	1983-present
	5 minute interval air temperature	MMSD	1983-present
	5 minute interval solar radiation	MMSD	1983-present
	5 minute interval relative humidity	MMSD	1983-present
U. S. Geological Survey			
Underwood Creek at USH 45	5 minute interval precipitation	USGS	1975-1979, 1981-present
Menomonee River at 70th Street	5 minute interval precipitation	USGS	1975-1980, 1981-present

[a] Site locations are shown on Map 24 and Map 25 in Chapter III of this volume.

[b] NCC: National Climatic Center and Weather Bureau Publications
SC: State Climatologist
OP: Operator
ACOE: Army Corps of Engineers
Data from these sources are on file at SEWRPC.

[c] Tipping bucket with light bulb.

[d] Tipping bucket with no heating element.

[e] Weighing bucket with antifreeze.

[f] Tipping bucket with heating element.

Source: SEWRPC.

At weekly intervals the Bureau prepared a table summarizing the data collected at all of the rain gages, including total precipitation for each storm, starting and ending time for each storm, and maximum five-minute intensity for each storm. The city rainfall records for selected storms were digitized by the Commission to provide five-minute interval data for use in the flow simulation model of the combined sewer system developed under the Milwaukee pollution abatement program.

Milwaukee Metropolitan Sewerage District

During the three-year monitoring period, the Milwaukee Metropolitan Sewerage District, Water Resources Research Group, operated four continuous record rain gages, the location of which are shown on Map 29. Of these four stations, three recorded precipitation at one-minute intervals using tipping bucket rain gages with bucket volumes of 0.01 inch. The data were telemetered automatically to a computer located at the offices of the Milwaukee Metropolitan Sewerage District. The fourth station, also a tipping bucket rain gage located formerly at the Milwaukee lighthouse at the main entrance to the outer harbor, and subsequently relocated to the Harbor Commission Pier in the outer harbor, recorded precipitation, wind speed, wind direction, air temperature, solar radiation, and relative humidity at five-minute intervals. These data were also telemetered to the District computer. The rain gage was the same type as those located at the other three sites.

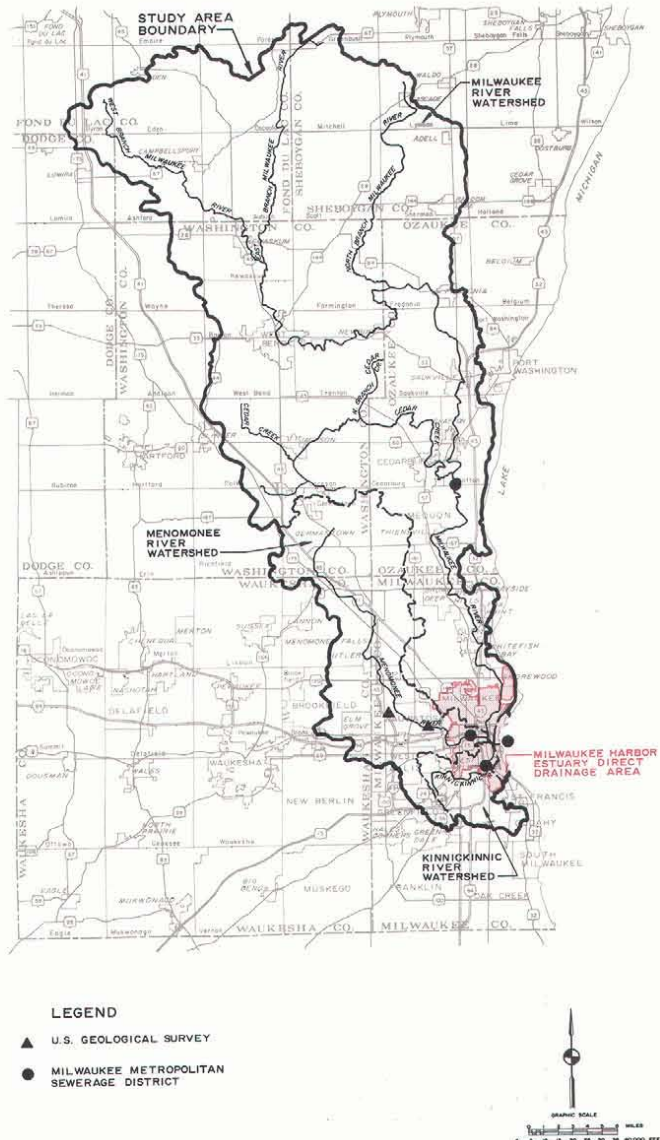
The rainfall data collected at the three sites within the City of Milwaukee were utilized by the Commission in the simulation of combined sewer overflows, and in the simulation of runoff from the separate sewer service areas tributary to the Milwaukee River in Milwaukee County. In addition, the continuous meteorological data collected at the site in the outer harbor were used in algal productivity and hydraulic modeling studies of the inner harbor, and in storm damage studies of the outer harbor.

U. S. Geological Survey

During the three-year monitoring period, the U. S. Geological Survey (USGS) operated two recording rain gages in the Menomonee River watershed at the sites shown on Map 29. Both sites, listed in Table 31, were located at USGS gaging stations, both in the City of Wauwatosa—on Underwood Creek at USH 45 and on the Menomonee River at N. 70th Street. An eight-inch-diameter collector at each gage funneled precipitation into a vertical

Map 29

LOCATIONS OF SHORT-TERM METEOROLOGICAL DATA COLLECTION STATIONS IN THE MILWAUKEE HARBOR WATERSHED OPERATED BY THE MILWAUKEE METROPOLITAN SEWERAGE DISTRICT AND THE U. S. GEOLOGICAL SURVEY DURING THE ESTUARY STUDY FIELD DATA COLLECTION PERIOD



During the intensive field investigation period of this study, the Milwaukee Metropolitan Sewerage District (MMSD) and the U. S. Geological Survey (USGS) operated special meteorological monitoring stations within the study area in order to gather data in support of the hydrologic and hydraulic simulation modeling effort. The two monitoring stations operated by the USGS and three of the four stations operated by the MMSD recorded continuous precipitation levels only. The fourth station operated by the MMSD at the Harbor Commission pier recorded, in addition to precipitation levels, wind direction, air temperature, solar radiation, and relative humidity.

Source: SEWRPC.

three-inch-diameter containment, the water level in which was measured by a float-activated digital recorder with a five-minute interval.

GROUNDWATER

Groundwater level data were systematically collected in the study area and vicinity by the USGS. Long-term records have been collected by the USGS in cooperation with the Wisconsin Geological and Natural History Survey at sites in the Counties of Milwaukee, Ozaukee, Sheboygan, and Waukesha. These data are summarized in Chapter V of this report. Short-term groundwater level and groundwater quality data were collected by the USGS in the Menomonee Valley during the two-year monitoring period. The short-term data are summarized in Chapter VIII of this volume.

Long-Term Groundwater Level Monitoring

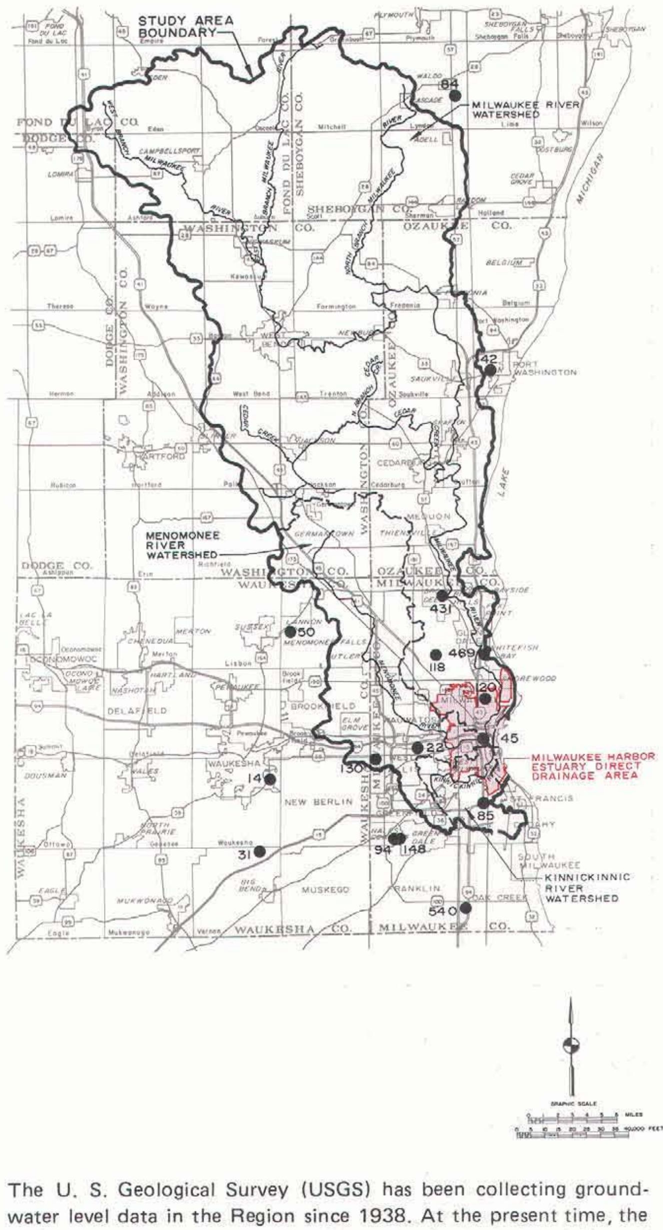
Long-term groundwater level data were collected by the USGS in the Milwaukee Harbor watershed and vicinity at the 16 sites shown on Map 30 and listed in Table 32. The data were collected in cooperation with the Wisconsin Geological and Natural History Survey to determine short-term changes and long-term trends in groundwater levels, and to relate these changes to changes in groundwater reservoir storage.[1] All groundwater level observation wells were operated during the estuary study field monitoring period but, as Table 32 indicates, collection of these records began long before initiation of the estuary study, as early as 1938. Water level data were collected in unconfined aquifers at three of the 16 sites, with the remainder being collected in confined aquifers. Of the 16 sites, data were collected at irregular intervals at one site, monthly at 10 sites, and continuously at five sites. The data were stored in USGS files and presented in hydrograph form in periodically updated reports.

The long-term groundwater level data were used in the estuary study both to characterize groundwater conditions in the study area and to complement the short-term groundwater levels and groundwater quality data collected in the Menomonee Valley by the USGS under the planning program.

[1] *R. M. Erickson and R. D. Cotter, Trends in Ground-Water Levels in Wisconsin Through 1981, University of Wisconsin-Extension, Geological and Natural History Survey Information Circular 43, Madison, Wisconsin, 1983, 139 pages.*

Map 30

LOCATIONS OF LONG-TERM GROUNDWATER LEVEL OBSERVATION WELLS OPERATED BY THE U. S. GEOLOGICAL SURVEY IN THE MILWAUKEE HARBOR WATERSHED AND VICINITY DURING THE ESTUARY STUDY FIELD DATA COLLECTION PERIOD



The U. S. Geological Survey (USGS) has been collecting groundwater level data in the Region since 1938. At the present time, the USGS, in cooperation with the Wisconsin Geological and Natural History Survey, operates 16 groundwater level monitoring stations in or near the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds.

Source: U. S. Geological Survey.

Groundwater Level and Groundwater Quality Data Collection in the Menomonee Valley

Specifically for the Milwaukee Harbor estuary study, the USGS collected groundwater level and

Table 32

LONG-TERM GROUNDWATER LEVEL OBSERVATION WELLS OPERATED BY THE U. S. GEOLOGICAL SURVEY DURING THE ESTUARY STUDY FIELD MONITORING PERIOD[a]

County	Well Number[b]	Measurement Frequency	Aquifer	Water Table	Artesian	Period of Record (month/year)
Milwaukee	22	Monthly	Niagara and Sandstone	- -	X	3/39 to 9/80
	45	Continuous	Niagara	- -	X	9/46 to 7/83[c]
	85	Continuous	Sandstone	- -	X	1938-1944, 1946, 1950, 1952, 1961, 1973 to present[d]
	94	Monthly	Sandstone	- -	X	7/46 to present
	118	Monthly	Niagara	- -	X	4/46 to present
	120	Continuous	Niagara	- -	X	4/46 to present
	130	Monthly	Niagara	- -	X	6/46 to 12/81[c]
	148	Monthly	Niagara	X	- -	9/46 to present
	431	Irregular	Sandstone	- -	X	7/66 to 4/77[e]
	469	Monthly	Niagara	X	- -	10/63 to 8/75[f]
	540	Monthly	Sandstone	- -	X	11/74 to present
Waukesha						
	14	Continuous	Sandstone	--	X	9/46 to present
	31	Continuous	Niagara	- -	X	5/47 to present
	50	Monthly	Niagara	- -	X	2/52 to present
Sheboygan	84	Monthly	Niagara	- -	X	5/74 to present
Ozaukee	42	Monthly	Niagara	X	- -	12/67 to present

[a] *Long-term hydrographs through 1981 are published in Trends in Ground-Water Levels in Wisconsin Through 1981, University of Wisconsin-Extension Information Circular 43 by R. M. Erickson and R. D. Cotter.;*

[b] *The locations of these wells are shown on Map 30.*

[c] *Discontinued operation.*

[d] *Years noted are water years.*

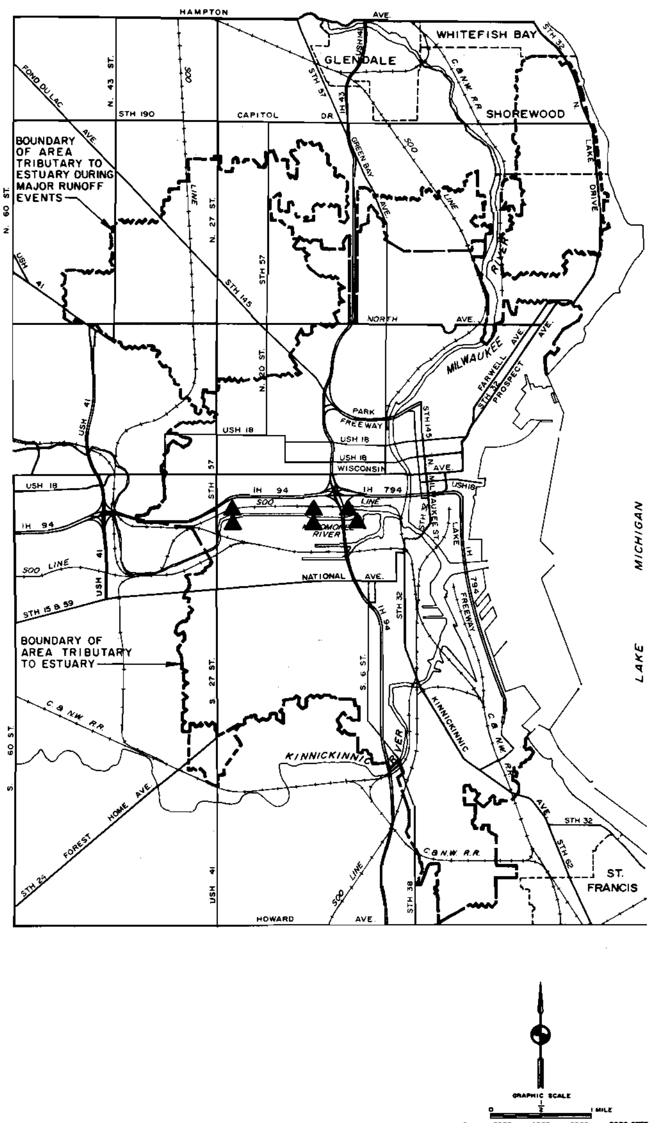
[e] *Discontinued.*

Source: U. S. Geological Survey.

quality data at six observation wells installed by that agency in the Menomonee Valley at the locations shown on Map 31. As the map indicates, observation wells were grouped in pairs, with each well of each pair being located on opposite sides of the Menomonee River estuary. Water levels were measured manually each week by the USGS, the elevations being referred to National Geodetic Vertical Datum. Groundwater quality samples were taken from each well four times during 1983 using a peristaltic pump. Approximately five gallons of water were pumped initially to clear out the well.

Map 31

LOCATIONS OF GROUNDWATER LEVEL AND QUALITY OBSERVATION WELLS IN THE MENOMONEE VALLEY OPERATED BY THE U. S. GEOLOGICAL SURVEY DURING THE ESTUARY FIELD DATA COLLECTION PERIOD



During the intensive field investigation period of the study, the U. S. Geological Survey (USGS) installed and operated six special-purpose groundwater level and quality observation wells along the estuary portion of the Menomonee River. The purpose of these six observation wells was to provide data for a mathematical simulation model of groundwater pollutant loadings in the estuary from the industrialized portion of the Menomonee River Valley.

Source: U. S. Geological Survey and SEWRPC.

Following water level recovery, samples were pumped from the well and filtered on site. Samples were analyzed for the variables listed in Table 33.

Table 33

GROUNDWATER QUALITY VARIABLES ANALYZED FOR THE MENOMONEE VALLEY OBSERVATION WELLS OPERATED BY THE U. S. GEOLOGICAL SURVEY[a]

Aluminum	Cobalt	Phosphorus
Antimony	Copper	Potassium
Arsenic	Iron	Selenium
Barium	Lead	Silver
Beryllium	Lithium	Sodium
Boron	Magnesium	Strontium
Cadmium	Manganese	Thallium
Calcium	Mercury	Tin
Chlorine	Molybdenum	Vanadium
Chromium	Nickle	Zinc

[a]*Sample frequency: Samples taken at each well four times between February 1983 and October 1983.*

Samples analyzed by: MMSD

In February 1983, additional samples were taken by the USGS and analyzed for phenols and organo-chlorides in addition to the elements listed above.

Source: U. S. Geological Survey.

Necessary laboratory analyses were conducted by the USGS and the Milwaukee Metropolitan Sewerage District (MMSD).

The groundwater level and quality data were utilized by the USGS in conjunction with water level data collected for the Menomonee River estuary by the MMSD to estimate groundwater flow into the Menomonee estuary and attendant groundwater pollutant loadings as described in Chapter VI of this report.

SURFACE WATER FLOW AND LEVELS

Continuous streamflow and water level data were collected during the three-year monitoring period by the USGS, the Milwaukee Metropolitan Sewerage District, the City of Milwaukee, and the National Ocean Survey. Intermittent streamflow data were collected by the Regional Planning Commission at selected sites where continuous data were not available. The locations of the streamflow monitoring sites are shown on Map 32. The locations of the water level monitoring sites—all within the Milwaukee Harbor estuary—are shown on Map 33.

Streamflow data were collected to assist in characterization of the tributary hydrologic systems and to compute pollutant transport using water quality data collected under the planning program.

Water level data were collected for use in hydraulic simulation modeling of the inner harbor, to assist in evaluation of Lake Michigan seiche effects upon outer harbor water levels and circulation, and to supplement long-term water level data collected by the National Ocean Survey.

Streamflow and water level data are summarized in Chapter V of this report.

Continuous Streamflow Monitoring

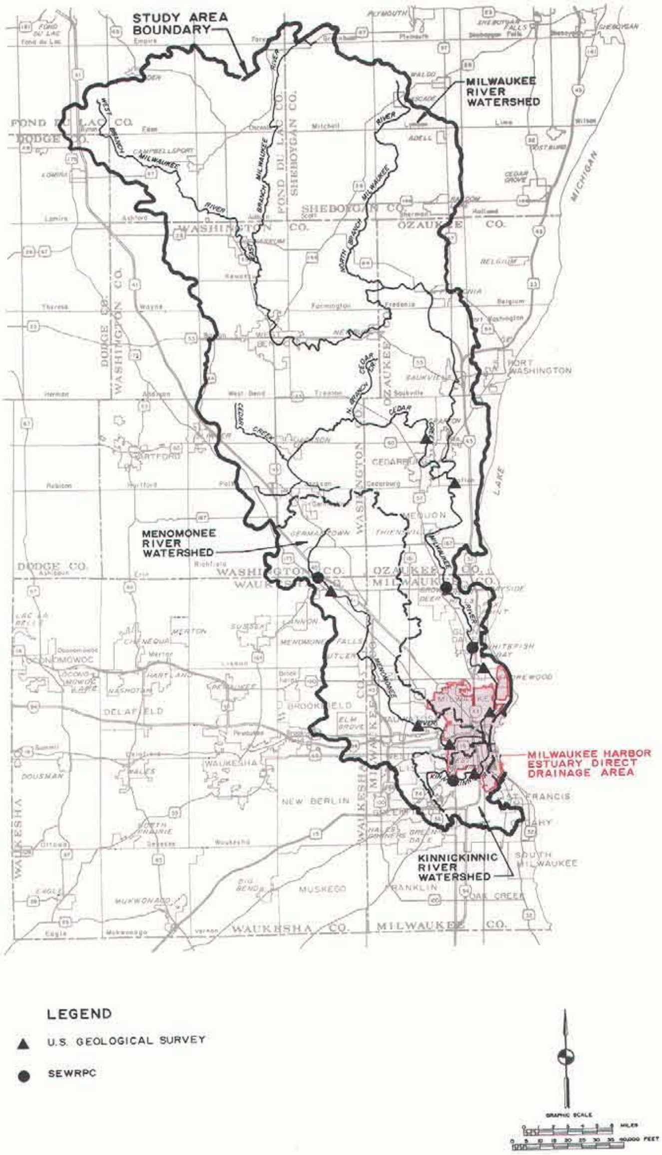
Continuous streamflow monitoring was conducted by the USGS at eight locations on streams tributary to the harbor during the three-year monitoring period at the sites shown on Map 32 and listed in Table 34. All these stations were in operation prior to the start of the planning program except the gage on the Milwaukee River at North Avenue, the gage on the Kinnickinnic River at S. 11th Street, and the station on Cedar Creek at Cedarburg which had been discontinued in 1981 and was reactivated in 1983. The gage on the Kinnickinnic River was relocated from its former site at S. 7th Street.

Streamflow was computed at each gaging station utilizing continuous-record water level data in combination with a stage-discharge relationship developed at each site using current meter measurements of flow throughout the range of stage observed. An example of such a relationship is presented in Figure 13. Stage-discharge relationships must be checked periodically by current meter flow measurement since such relationships are subject to change by natural or man-made phenomena.

As Table 34 indicates, two basic types of stream gaging stations were operated by the USGS. Two of the stations were of the stilling well type, as illustrated in Figure 14. A float in a protected stilling well connected to the river by pipelines automatically records the water level in the well continuously or at fixed time intervals. A detailed description of stilling well gaging stations can be found in the U. S. Geological Survey report, Stage Measurement at Gaging Stations.[2]

Map 32

LOCATIONS OF CONTINUOUS AND INTERMITTENT STREAMFLOW DATA COLLECTION SITES IN THE MILWAUKEE HARBOR WATERSHED OPERATED BY THE U. S. GEOLOGICAL SURVEY AND THE REGIONAL PLANNING COMMISSION DURING THE ESTUARY STUDY FIELD MONITORING PERIOD



During the intensive field investigation period of the study, the U. S. Geological Survey (USGS) operated eight continuous-record streamflow gaging stations within the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds. In addition, the Commission collected intermittent streamflow data at four sites in the study area. The data collected by the USGS and the Commission under this work effort were used to calibrate hydrologic and hydraulic simulation models and to compute pollutant transport in rural, separate sewer, and combined sewer service areas. See Table 34 for types of data collected and period of record at each site.

Source: SEWRPC.

[2] *Thomas J. Buchanan and William P. Somers, Stage Measurement at Gaging Stations: U. S. Geological Survey Techniques of Water Resources Investigations, Book 3 Chapter A7 (U. S. Government Printing Office, Washington, D. C., 1968).*

The other gaging stations operated by the USGS were of the bubble-gage type, as illustrated in Figure 15. The pressure head of water in the river is transmitted to a manometer inside a gage house, which in turn converts the pressure sensed to an electric motor connected to a digital stage recorder. A detailed description of bubble-gage stations can be found in the U. S. Geological report, Bubble Gage Installation and Service Manual.[3]

All of the USGS gaging stations utilized battery-operated digital recorders with 16-channel paper punch tape. Stage was recorded in intervals of 0.01 foot and in fixed time intervals ranging from 5 to 15 minutes depending on the rate of change of stage. For example, the small urbanized Kinnickinnic River basin concentrates runoff rapidly in its largely artificial channel, periodically resulting in flow increases of more than 100 percent in 15 minutes. Therefore, a five-minute recording interval was utilized at the gaging station at S. 11th Street to provide a more accurate representation of storm event hydrographs.

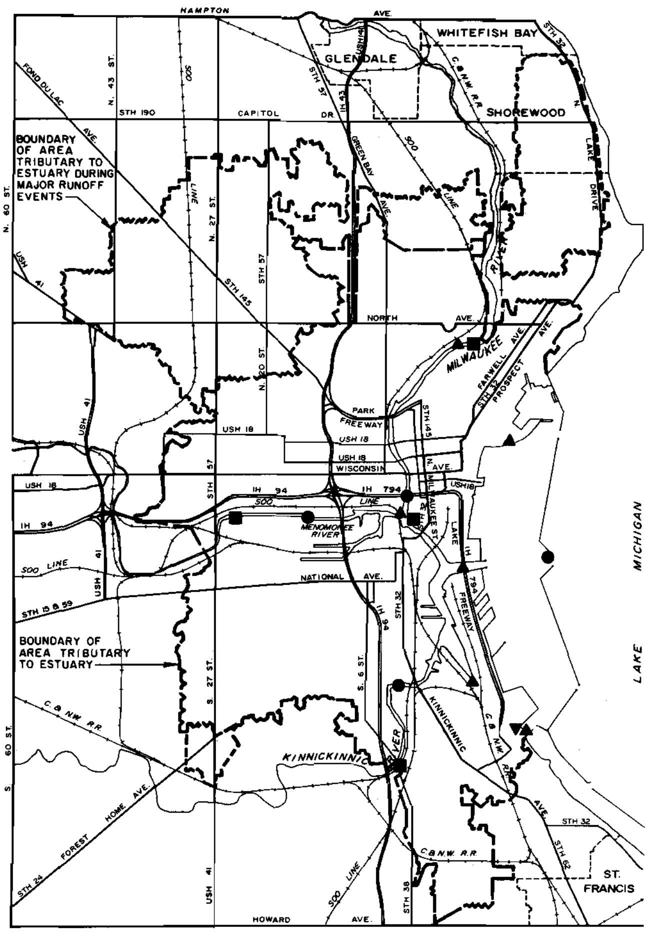
In contrast, the Milwaukee River at Pioneer Road exhibits relatively slow stage and flow changes because runoff from the large, primarily rural watershed is not rapidly concentrated in the receiving channels because of higher infiltration rates, longer travel distances, and floodplain storage. Consequently, a 15-minute recording interval was used at this station to reduce station operation costs.

Stage data for a given site were read by an electronic processor into a computer program which determined the flow for each recorded stage utilizing the stage-discharge relationship for that site. The use of the digital recorder facilitated computation of streamflow by digital computer, and provided increased accuracy through utilization of smaller computation intervals than normally employed in manual computation. The computer programs provided—on paper or magnetic tape—streamflows computed at the recorder time interval (unit values) or at longer time intervals, such as 24 hours (mean daily flows).

[3] *U. S. Geological Survey, Surface Water Branch, Bubble Gage Installation and Service Manual, (U. S. Geological Survey Research Section, Columbus, Ohio, 1962).*

Map 33

LOCATIONS OF CONTINUOUS WATER LEVEL MONITORING SITES IN THE MILWAUKEE HARBOR ESTUARY OPERATED BY THE U. S. GEOLOGICAL SURVEY; THE MILWAUKEE METROPOLITAN SEWERAGE DISTRICT; THE CITY OF MILWAUKEE, BUREAU OF ENGINEERS; AND THE NATIONAL OCEAN SURVEY DURING THE ESTUARY STUDY FIELD MONITORING PERIOD



LEGEND

- ● MILWAUKEE METROPOLITAN SEWERAGE DISTRICT
- ▲ U. S. GEOLOGICAL SURVEY
- ▼ NATIONAL OCEAN SURVEY
- ■ CITY OF MILWAUKEE, BUREAU OF ENGINEERS

During the intensive field investigation period of the study, continuous water level data were collected at 15 stations by the U. S. Geological Survey (USGS); the Milwaukee Metropolitan Sewerage District (MMSD); the City of Milwaukee, Bureau of Engineers; and the National Ocean Survey. These water level data were used in the hydraulic simulation modeling effort for the inner and outer harbors and adjacent Milwaukee Bay. See Table 35 for the types of data collected and period of record at each site.

Source: SEWRPC.

Table 34

LOCATIONS OF CONTINUOUS AND INTERMITTENT STREAMFLOW DATA COLLECTION SITES IN THE MILWAUKEE HARBOR WATERSHED OPERATED BY THE U. S. GEOLOGICAL SURVEY AND THE REGIONAL PLANNING COMMISSION DURING THE ESTUARY STUDY FIELD MONITORING PERIOD[a]

River	Location	Period of Record (month/year)	Type of Record[b]	Equipment Type[c]	Flow Recording Time Interval (minutes)	Agency Responsible
Cedar Creek	Highway 60	8/30-9/70, 7/73-9/81, 7/83-present	C	B, Sg	15	USGS
Milwaukee	Pioneer Road	11/81-present	C	W, Sg, R, S, Q, Csg	15	USGS
Milwaukee	Brown Deer Road	6/82-8/84	I	Wwg, Csg	- -	SEWRPC
Milwaukee	Silver Spring Drive	6/82-8/84	I	Wwg, Csg	- -	SEWRPC
Milwaukee	Estabrook Park	4/14-present	C	W, S	15	USGS
Milwaukee	North Avenue Dam	6/82-10/84	C	B, S, Q, S	5	USGS
Menomonee	County Line Road	6/82-8/84	I	Sg, Csg	- -	SEWRPC
Menomonee	Pilgrim Road	11/74-9/74, 7/79-present	C	B, S, Csg	5	USGS
Menomonee	N. 70th Street	12/66-9/77, 6/82-present	C	B, R, S, Wwg, Csg	5	USGS
Menomonee	S. 7th Street[e] eet[d]	12/81-present	C	B, S, Sg	5	USGS
Kinnickinnic	S. 29th Street	6/82-8/84	I	Wwg, Csg	- -	SEWRPC
Kinnickinnic	S. 11th Street	10/82-present	C	B, S, Sg	5	USGS
Kinnickinnic	S. 7th Street	9/76-1/83	C	B	5	USGS

[a] *See Map 32 for locations of streamflow data collection sites.*

[b] *C - continuous; I - intermittent*

[c] *B - bubble gage*
W - stilling well
R - rain gage
S - automatic suspended sediment sampler
Q - continuous water quality monitor (operated by MMSD)
Wwg - wire-weight gage
Csg - crest-stage gage
Sg - staff-gage

[d] *This gaging station utilizes two stage recorders 0.56 mile apart to measure changes in water surface slope caused by variable backwater from Lake Michigan.*

[e] *This gage on the Kinnickinnic River was relocated to S. 11th Street.*

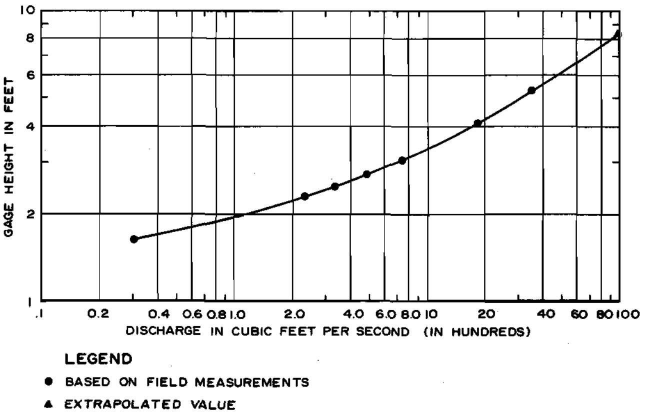
Source: SEWRPC.

report series entitled, Water Resources Data, Wisconsin. The mean daily flows, as well as unit value flows, collected at the gaging stations operated for the estuary study are stored on magnetic

Mean daily flows for the gaging stations utilized in the estuary study were published along with similar data for other gaging stations operated in Wisconsin by the USGS on an annual basis in a

Figure 13

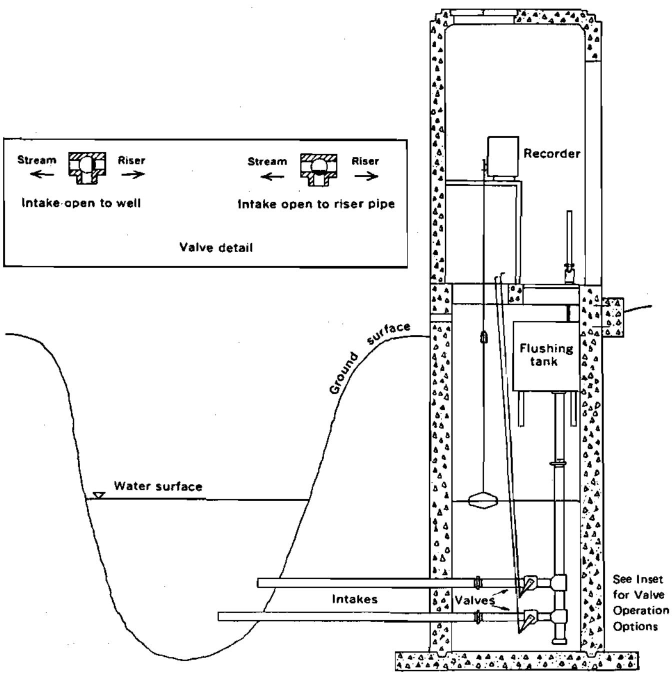
STAGE-DISCHARGE RELATIONSHIP FOR THE U. S. GEOLOGICAL SURVEY GAGING STATION ON THE MILWAUKEE RIVER AT ESTABROOK PARK IN MILWAUKEE



Source: SEWRPC.

Figure 14

TYPICAL STILLING WELL FOR CONTINUOUS STREAMFLOW OR WATER LEVEL GAGING STATION OPERATED BY THE U. S. GEOLOGICAL SURVEY

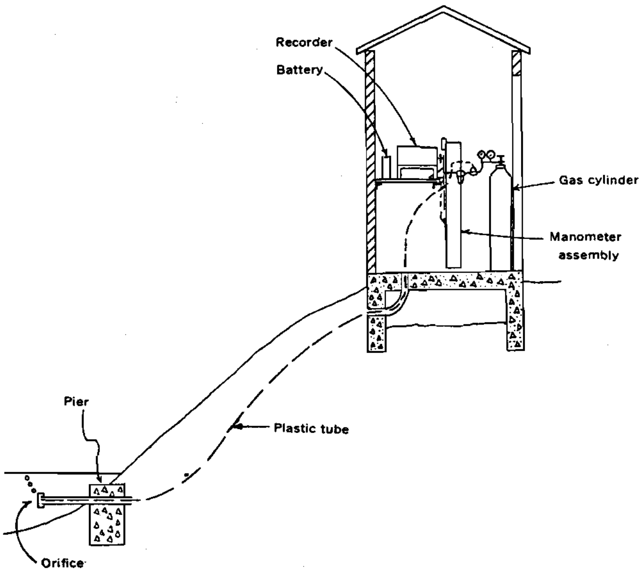


Source: U. S. Geological Survey.

tape at the U. S. Geological Survey, Wisconsin District Office, in Madison, as well as at the offices of the Regional Planning Commission.

Figure 15

TYPICAL BUBBLE GAGE FOR CONTINUOUS STREAMFLOW OR WATER LEVEL GAGING STATION OPERATED BY THE U. S. GEOLOGICAL SURVEY



Source: Thomas J. Buchanan and William P. Somers, Stage Measurement at Gaging Stations: U. S. Geological Survey Techniques of Water Resources Investigations, Book 3 Chapter A7 (U. S. Government Printing Office, Washington, D. C., 1968).

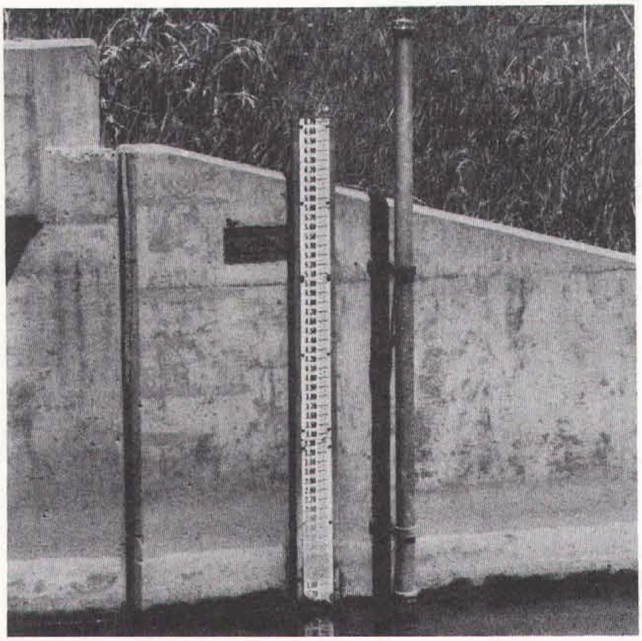
Intermittent Streamflow Monitoring

The Regional Planning Commission collected streamflow data on an intermittent basis at the four sites shown on Map 32 to provide stage-discharge relationships at these locations--which are also water quality sampling sites--to assist in computation of pollutant loads. In the spring of 1982, Commission staff installed stage measuring equipment provided by the U. S. Geological Survey at these four sites. This equipment consisted of either staff gages or wire-weight gages, as illustrated in Figures 16 and 17. In addition, crest-stage gages were installed by the Commission at these four sites for determination of peak stages and corresponding peak discharges for storm events which occurred during the monitoring period. A typical crest-stage gage is illustrated in Figure 18. The equipment installed by the Commission at each of the four sites is listed in Table 34.

Stage-discharge relationships were developed at each site utilizing current meter measurements of streamflow and concurrent stage measurements to plot the curves shown in Figures 19 through 22. Appropriate computational methods such as step-backwater analysis or flow routing through hydrau-

Figure 16

VERTICAL STAFF GAGE FOR WATER LEVEL MEASUREMENT



Source: U. S. Geological Survey and SEWRPC.

lic structures were employed to provide additional points with which to plot the graphs. Current meter measurements of streamflow were made according to procedures developed by the U. S. Geological Society as set forth in the USGS report, Discharge Measurements at Gaging Stations.[4] Step-backwater computations were made using the U. S. Army Corps of Engineers HEC-2 computer program.[5] Flow routing computations for the culvert located on the Menomonee River at County Line Road were made using procedures described by the USGS.[6] Stage-discharge relationships were prepared using procedures also described by the USGS.[7] The stage-discharge relationships for the Milwaukee River at Silver Spring Drive presented in Figure 20 were affected by the dam in Estabrook Park which was operated by Milwaukee County. The dam had a concrete spillway and 10 vertical lift gates, all of which were usually closed in May each year and opened in November. Therefore, it was necessary to develop two stage-discharge relationships for the Silver Spring Drive site.

Stage-discharge relationships were typically stable for all flows except the lower streamflows, which were subject, in part, to variable backwater effects caused by aquatic plant growth, and by scour and deposition within the channel caused by periodic high flows. Stage-discharge relationships were periodically checked by current meter measurements of flow to establish their validity for use during given time periods and flow regimes. Therefore, the relationships presented in Figures 13, 19, 20, 21, and 22 must be utilized with care, bearing in mind the variable hydraulic factors which can affect stage-discharge relationships.

The stage-discharge relationships, developed as described above, were utilized to: 1) determine streamflow during water quality sampling; 2) estimate daily flows at each of the four sites by correlation with nearby continuous record gaging stations; and 3) develop hydrographs for these sites for storm events intensively sampled as part of the runoff event sampling program. During low-flow periods when unstable stage-discharge relationships occurred at some sites, daily flows at the affected sites were estimated through correlations developed with flows recorded at nearby USGS gaging stations.

Continuous Water Level Monitoring

During the three-year monitoring period, continuous water level monitoring was conducted in the Milwaukee Harbor estuary by the U. S. Geological Survey, the Milwaukee Metropolitan Sewerage

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[4] *Thomas J. Buchanan and William P. Somers, Discharge Measurements at Gaging Stations: Techniques of Water Resources Investigations of the U. S. Geological Survey, Book 3 Chapter A8 (U. S. Government Printing Office, Washington, D. C., 1969).*

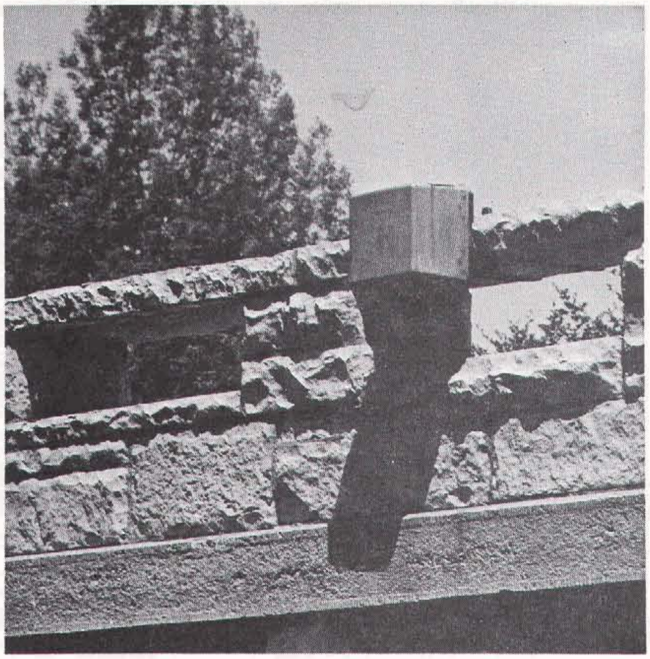
[5] *U. S. Army Corps of Engineers, HEC-2 Water Surface Profiles, Uses Manual, Hydrologic Engineering Center Computer Program Documentation 723-X6-L202A, Davis, California, 1982.*

[6] *G. L. Bodhaine, Measurement of Peak Discharge at Culverts by Indirect Methods, Techniques of Water Resources Investigations of the U. S. Geological Survey, Book 3 Chapter A3 (U. S. Government Printing Office, Washington, D. C., 1968).*

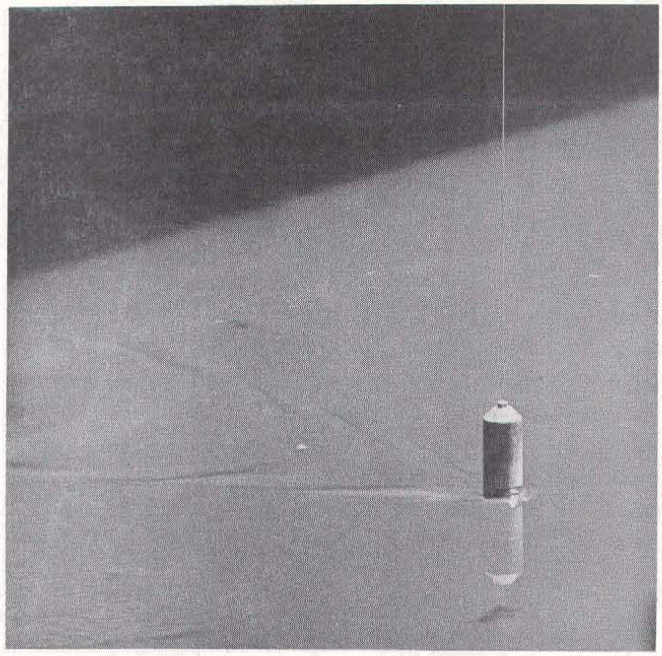
[7] *U. S. Geological Survey, Discharge Ratings at Gaging Stations, Hydraulic Measurement and Computation, Surface Water Techniques, Book 1 Chapter 12 (U. S. Government Printing Office, Washington, D. C., 1965).*

Figure 17

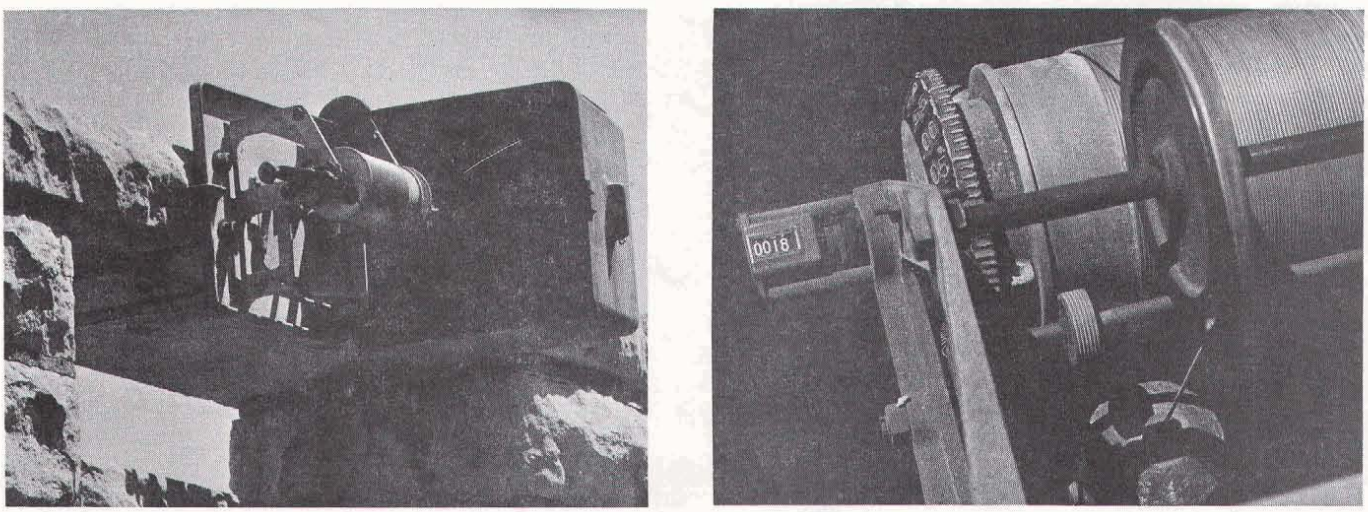
WIRE-WEIGHT GAGE FOR WATER LEVEL MEASUREMENT



Gage Housing Mounted on Bridge Rail



Wire-Weight Lowered to Water Surface During Stage Measurement



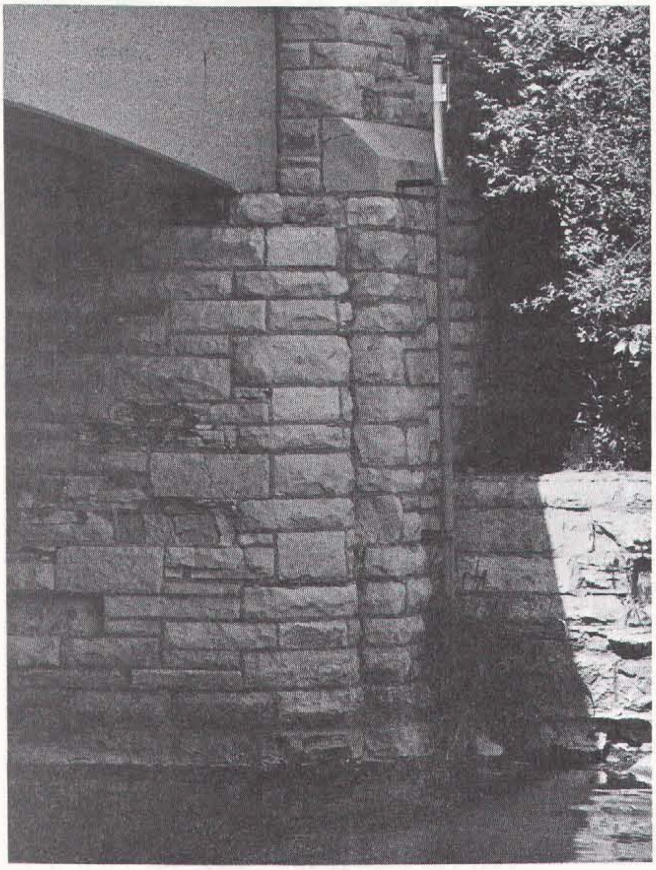
Drum, Wire, and Weight Inside Gage Housing

Wire-Weight Gage Located at the 70th Street Crossing of the lower Menomonee River.

Source: U. S. Geological Survey and SEWRPC.

Figure 18

TYPICAL CREST-STAGE GAGE FOR WATER LEVEL MEASUREMENT

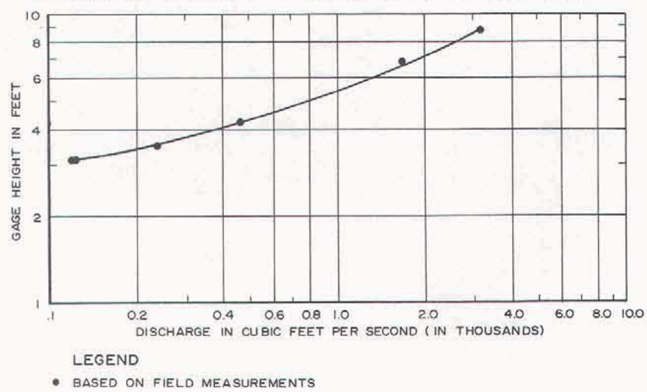


Crest stage gage located at the 70th Street crossing of the lower Menomonee River in the City of Wauwatosa.

Source: SEWRPC.

Figure 19

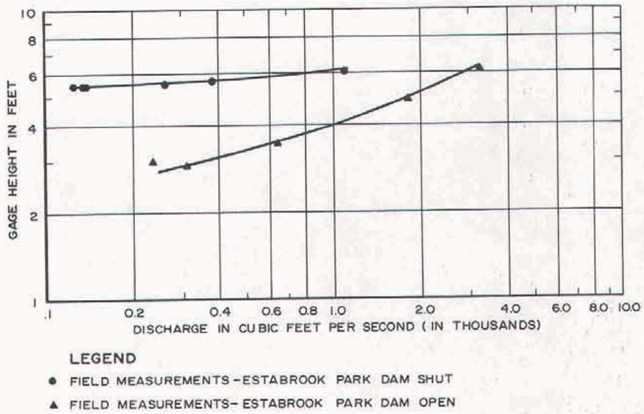
STAGE-DISCHARGE RELATIONSHIP DEVELOPED BY THE REGIONAL PLANNING COMMISSION FOR THE MILWAUKEE RIVER AT BROWN DEER ROAD



Source: SEWRPC.

Figure 20

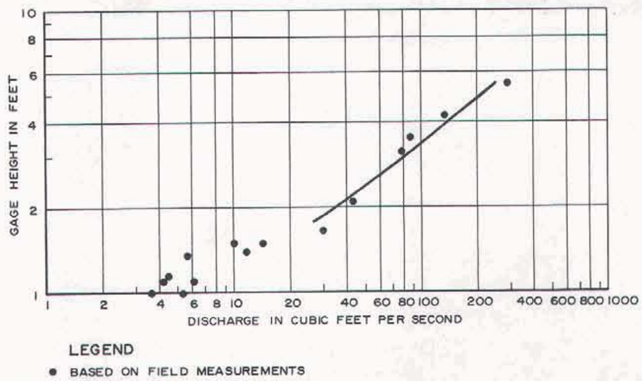
STAGE-DISCHARGE RELATIONSHIP DEVELOPED BY THE REGIONAL PLANNING COMMISSION FOR THE MILWAUKEE RIVER AT SILVER SPRING DRIVE



Source: SEWRPC.

Figure 21

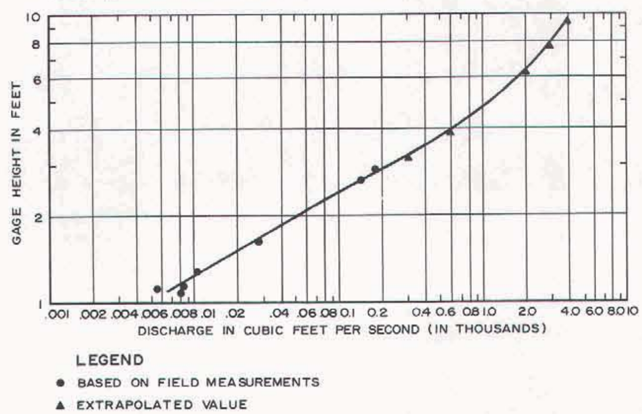
STAGE-DISCHARGE RELATIONSHIP DEVELOPED BY THE REGIONAL PLANNING COMMISSION FOR THE MENOMONEE RIVER AT COUNTY LINE ROAD



Source: SEWRPC.

Figure 22

STAGE-DISCHARGE RELATIONSHIP DEVELOPED BY THE REGIONAL PLANNING COMMISSION FOR THE KINNICKINNIC RIVER AT S. 29TH STREET



Source: SEWRPC.

District, the City of Milwaukee, and the National Ocean Survey. The locations of the monitoring stations are shown on Map 33. Table 35 presents pertinent information on each of the water level monitoring stations such as period of record, type of record, and type of instrumentation.

U. S. Geological Survey: The U. S. Geological Survey operated six continuous, digital, water level recording stations in the Milwaukee Harbor estuary, two of which were located in the outer harbor as indicated on Map 33. Table 35 presents pertinent information regarding the operation of these six stations, which were installed specifically for the Milwaukee Harbor estuary study. As the table indicates, all the stations recorded water levels at five-minute intervals, the elevation being related to the National Geodetic Vertical Datum. Two of the stations used stilling well equipment—the gage at the U. S. Coast Guard Station in the outer harbor and the gage at the south end of the Kinnickinnic River turning basin. The remaining four stations used bubble gage equipment.

The water level recorder at the U. S. Coast Guard Station was located in the same gage house housing the water level recorder operated by the National Ocean Survey. This parallel operation provided for the more timely retrieval of the water level data since the National Ocean Survey processed the recorder digital tapes at annual intervals only, whereas the USGS inspected the station, removed the record, and processed it at approximately three-week intervals. As Table 35 indicates, periods of record were lost at the water level station operated on the McKinley Park landfill in the northern part of the outer harbor. Frequent vandalism at this site necessitated reconstruction of the station below ground level.

Periods of record were also lost at the water level recorder at the Daniel Hoan Memorial Bridge station because the original bubble gage installation did not accurately record the very frequent, rapid changes in water level at this location caused primarily by waves from the outer harbor. A stilling well gage was subsequently installed at this location and operated in parallel with the bubble gage. The problems affected the stilling well gage but to a lesser degree, with final resolution of the problem achieved by provision of only a 0.2-square-inch intake to the stilling well.

The water level records were computed by the USGS in both five-minute and daily intervals, with the daily value being the mean of all the five-minute values for the day. These data were stored on magnetic tape in the files of both the USGS and the Regional Planning Commission. Mean daily water levels were published in the USGS annual series of water data reports.[8]

The water level data for the inner harbor stations were used to calibrate two hydraulic simulation models. One model, the Branch Network Model, was prepared and operated by the USGS to compute one-dimensional mean daily flow for selected portions of the monitoring period at selected locations within the inner harbor. The second model, prepared and operated by Dynalysis of Princeton, Inc., subcontractor to HydroQual, Inc.—consultant to the Commission—utilized the water level data to simulate two-dimensional flow for selected time periods in order that mixing coefficients could be developed for use in water quality simulation modeling studies.

The outer harbor water level data were used by the Regional Planning Commission to analyze the effects of long- and short-term lake level oscillations upon water level and circulation in the outer harbor for water quality and navigation studies.

Milwaukee Metropolitan Sewerage District: The Milwaukee Metropolitan Sewerage District, Water Resources Research Group, operated four water level monitoring stations in the Milwaukee Harbor estuary during the monitoring period of the estuary study. Of these four stations, one was located in the outer harbor and three were located in the inner harbor, as shown on Map 33. All of the stations used stilling well equipment, as indicated in Table 35. Digital stage recorders were operated at all four sites, with recording time intervals of one minute at the three inner harbor stations and five minutes at the outer harbor station. The inner harbor station data were transmitted directly by telemetry to computer storage files of the Milwaukee Metropolitan Sewerage District. The outer harbor stage data were recorded on 16-channel paper punch tape processed by the U. S. Geological Survey.

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[8] *U. S. Geological Survey,* Water Resources Data, Wisconsin, *Madison, Wisconsin, published annually.*

Table 35

CONTINUOUS WATER LEVEL MONITORING STATIONS OPERATED IN THE MILWAUKEE HARBOR ESTUARY STUDY FIELD DATA COLLECTION PERIOD BY THE U. S. GEOLOGICAL SURVEY; THE MILWAUKEE METROPOLITAN SEWERAGE DISTRICT; THE CITY OF MILWAUKEE, BUREAU OF ENGINEERS; AND THE NATIONAL OCEAN SURVEY

River	Location[a]	Period of Record	Equipment Used[b]	Recording Time Interval	Agency Responsible
Milwaukee	Humboldt Avenue	May 12, 1982 to present	BG, LS	5 minutes	USGS[c]
Milwaukee	Water Street	June 15, 1982 to present	BG, LS	5 minutes	USGS[c]
Milwaukee	Jones Island	May 11, 1982 to present	LS, BG, SW	5 minutes	USGS[c]
Kinnickinnic	Turning Basin	July 14, 1982 to present	BG, LS	5 minutes	USGS[c]
Outer Harbor	Juneau Park	September 8, 1982 to present	BG, LS	5 minutes	USGS[c]
Outer Harbor	Coast Guard Station	April 22, 1982 to present	SW, LS	5 minutes	USGS[c]
Milwaukee	Broadway Street	April 21, 1975 to present	SF	continuous	City of Milwaukee
Milwaukee	N. Commerce Street	April 21, 1975 to present	SF	continuous	City of Milwaukee
Menomonee	S. 24th Street	April 21, 1975 to present	SF	continuous	City of Milwaukee
Kinnickinnic	S. Chase Avenue	April 21, 1975 to present	SF	continuous	City of Milwaukee
Outer Harbor	Coast Guard Station	1860 to present	LS	60 minutes	National Ocean Survey
Milwaukee	St. Paul Avenue	November 1981-December 1984	LS, T	1 minute	MMSD
Menomonee	Muskego Avenue	March 1983-December 1984	LS, T	1 minute	MMSD
Kinnickinnic	First Street	March 1983-December 1984	LS, T	1 minute	MMSD
Outer Harbor	Milwaukee Light	May 1982-December 1984	LS, SW	1 minute	MMSD

[a] *See Map 33 for location of water level sites.*

[b] *Equipment abbreviations:*
LS - Leopold-Stevens Digital Recorder
SW - stilling well
BG - servo-manometer bubble gage
SF - Stevens type F analog recorder
T - telemetry

[c] *Intermittent records due to equipment malfunction and/or vandalism.*

Source: SEWRPC.

The water level data collected in the inner harbor supplemented similar data collected by the USGS—as described above—for use in hydraulic simulation modeling of the inner harbor. The water level data collected in the outer harbor by MMSD were used along with the USGS outer harbor water level data to analyze long- and short-term water level fluctuations of Lake Michigan.

City of Milwaukee: During the monitoring period, the City of Milwaukee, Bureau of Engineers, operated four continuous water level recording gages in the Milwaukee Harbor estuary at the locations shown on Map 33. The gages were placed in operation on April 21, 1975. All of the stations used stilling well equipment, as indicated in Table 35. Water levels were recorded continuously in graphic form on weekly charts, the elevations being referred to City of Milwaukee datum. These water level records were utilized in the estuary study to supplement other data of this kind for periods when nearby gages operated by the U. S. Geological Survey and the Milwaukee Metropolitan Sewerage District were malfunctioning. All recording charts are on file at the Bureau of Engineers.

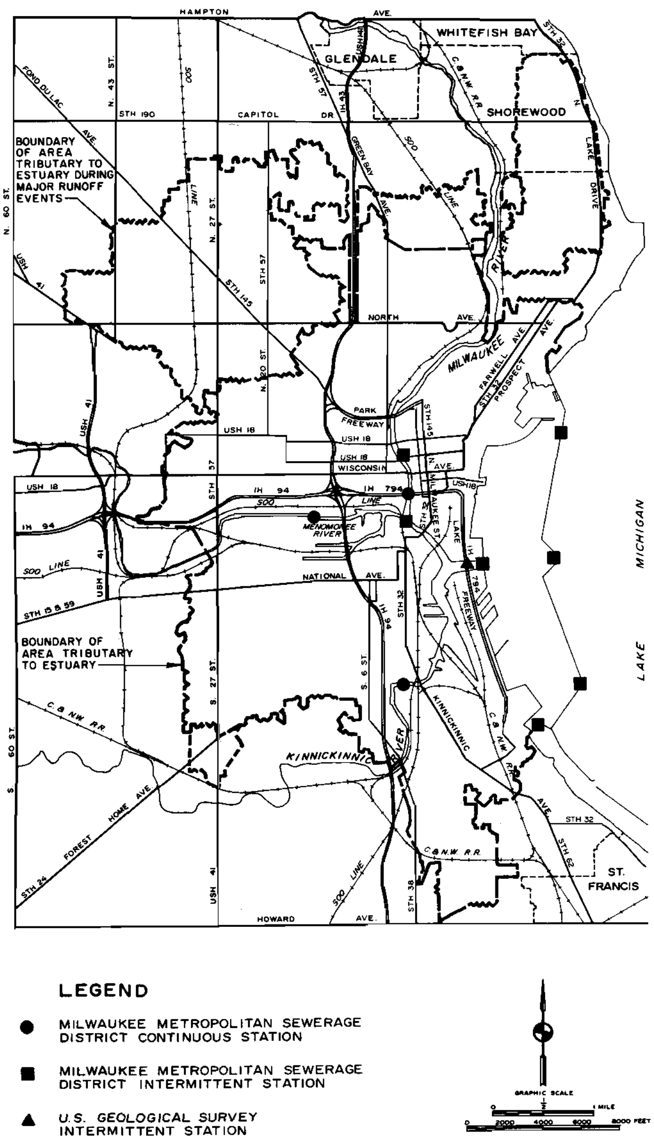
National Ocean Survey: The National Ocean Survey (NOS), a bureau of the National Oceanic and Atmospheric Administration, operated one continuous water level monitoring station during the monitoring period, that station being located at the U. S. Coast Guard Station near the south end of the outer harbor. The location of this site is shown on Map 33. As indicated in Table 35, the National Ocean Survey and its predecessor agency, the U. S. Lake Survey, began systematic water level data collection in the Milwaukee Harbor in 1860. The monitoring station operated during the field data collection program used stilling well equipment. The digital recorder used operated at a 60-minute interval. As already noted, the USGS housed in the same shelter a continuous water level recorder. The data from this recorder were more readily available to the estuary study program than were the NOS water level data, which were processed only on an annual basis. The NOS recorder, however, served as a backup when the USGS recorder malfunctioned. The long-term records at the NOS station were used to develop stage-frequency relationships which are presented in Chapter V of this volume. The NOS gage was formerly located on the breakwater at the main entrance to the Milwaukee Harbor. Water level data were published by the NOS in an annual report series.[9]

Monitoring of Current Speed and Direction

Current speed and direction at multiple depths in the Milwaukee Harbor estuary were measured on both a continuous and an intermittent basis by the Milwaukee Metropolitan Sewerage District, and intermittently by the U. S. Geological Survey, at the locations shown on Map 34 during the monitoring period. Pertinent information regarding the data collection sites is provided in Table 36. The data were collected to: 1) document qualitatively

Map 34

LOCATIONS OF CONTINUOUS AND INTERMITTENT CURRENT SPEED AND DIRECTION MONITORING SITES OPERATED BY THE MILWAUKEE METROPOLITAN SEWERAGE DISTRICT AND THE U. S. GEOLOGICAL SURVEY DURING THE ESTUARY STUDY FIELD DATA COLLECTION PERIOD



During the intensive field investigation period of the study, the U. S. Geological Survey (USGS) and the Milwaukee Metropolitan Sewerage District (MMSD) collected continuous and intermittent current velocity data at 11 stations in the inner and outer harbors of the Milwaukee Harbor estuary. These current velocity data were used in the hydraulic simulation modeling effort for the inner and outer harbors and adjacent Milwaukee Bay.

Source: SEWRPC.

and quantitatively the effects of Lake Michigan on circulation in the estuary; 2) document qualitatively and quantitatively the effects of the Wisconsin Electric Power Company valley power plant on

[9] *National Ocean Survey, Great Lakes Water Levels, U. S. Department of Commerce, National Oceanic and Atmospheric Administration, Rockville, Maryland, published annually.*

Table 36

CONTINUOUS AND INTERMITTENT MONITORING OF CURRENT SPEED AND DIRECTION IN THE MILWAUKEE HARBOR ESTUARY BY THE MILWAUKEE METROPOLITAN SEWERAGE DISTRICT AND THE U. S. GEOLOGICAL SURVEY DURING THE ESTUARY STUDY FIELD DATA COLLECTION PERIOD[a]

River	Location	Period of Record	Type of Record[b]	Equipment Used[c]	Sampling Frequency	Depths of Measurement[d]	Agency Responsible
Milwaukee	Wells Street	January 1982 to present	I	PMM	Weekly	P	MMSD
Milwaukee	St. Paul Avenue	March 1983-December 1984	C	MM, LS	1 minute	B	MMSD
Milwaukee	Water Street	January 1982 to present	I	PMM	Weekly	P	MMSD
Milwaukee	Jones Island	June 1983 to present	I	NB	Monthly	T	USGS
Menomonee	Muskego Avenue	March 1983-December 1984	C	MM, LS	1 minute	M, B	MMSD
Kinnickinnic	1st Street	March 1983-December 1984	C	MM, LS	1 minute	M	MMSD
Outer Harbor-1	Channel entrance	May 1982-December 1984	I	PMM	--[e]	P	MMSD
Outer Harbor-5	N. Fairweather gap	March 1980-December 1984	I	PMM	Weekly	P	MMSD
Outer Harbor-7	Main Harbor entrance	March 1980-December 1984	I	PMM	--[e]	P	MMSD
Outer Harbor-9	S. Fairweather gap	March 1980-December 1984	I	PMM	Weekly	P	MMSD
Outer Harbor-10	Russell Avenue gap	March 1980-December 1984	I	PMM	Weekly	P	MMSD

[a] *See Map 34 for locations of monitoring stations.*

[b] *I - intermittent; C - continuous*

[c] *NB - Neil-Brown velocity meter; 30-second damping interval*
MM - Marsh-McBurney velocity meter; 10-second damping interval
PMM - Portable Marsh-McBurney velocity meter; 10-second damping interval
LS - Leopold-Stevens Digital Recorder

[d] *T - Velocity measurements were made at two-tenths of the total depth below the surface and above the bottom.*
M - Mid-depth
B - Three feet above the bottom
P - Profile taken every one meter below surface.

[e] *Samples taken on May 3, August 23, August 30, September 7, September 27, and October 25, 1982.*

Source: Milwaukee Metropolitan Sewerage District and U. S. Geological Survey.

circulation in the estuary; 3) estimate discharge at the mouth of the Milwaukee River to assist in calibration of the U. S. Geological Survey one-dimensional branch network flow simulation model; and 4) provide calibration and verification data for a two-dimensional hydrodynamic model of the inner harbor operated by Dynalysis of Princeton, Inc., subcontractor to HydroQual, Inc., consultant to the Regional Planning Commission.

The ultimate purpose of these data collection efforts was to provide the flow and other hydraulic characteristics data required to understand existing water quality conditions in the estuary, and to provide a well-founded basis for predicting water quality conditions under alternative pollution abatement plans.

Milwaukee Metropolitan Sewerage District: The Milwaukee Metropolitan Sewerage District (MMSD) monitored current speed and direction continuously at three locations in the inner harbor, intermittently at two other locations in the inner harbor, and intermittently at five locations in the outer harbor at the sites shown on Map 34 during the data collection program. Pertinent information regarding data collection at these sites—such as types of instrumentation and methodology—is presented in Table 36.

The continuous monitoring stations were located on the Milwaukee River at St. Paul Avenue, the Menomonee River at Muskego Avenue, and the Kinnickinnic River at S. 1st Street. Electromagnetic probes placed at fixed elevations in the water column electronically sensed both current speed and current direction in degrees of azimuth. An electronic damping system averaged the current speed for a preset time interval to eliminate erratic fluctuations which commonly occurred in the estuary. Data were recorded at discrete one-minute intervals, however, and transmitted directly via telemetry to computer storage at the District offices.

The intermittent monitoring stations were located in the inner harbor on the Milwaukee River both at E. Wells Street and N. Water Street, and in the outer harbor at the mouth of the Milwaukee River, as well as at all four navigation gaps in the breakwater. Velocity measurements were made at these sites at mid-channel from a moored boat from which a portable electromagnetic velocity meter was suspended manually. Velocity measurements were made at intervals of approximately three feet throughout the water column, with data manually recorded from an on-board remote readout which displayed current speed in feet per second and current direction in degrees of azimuth. Velocity data were stored on magnetic tape at the District offices.

U. S. Geological Survey: The U. S. Geological Survey (USGS) periodically measured current speed and direction in the Milwaukee River at the Daniel Hoan Memorial Bridge. Velocity was measured at numerous locations across the channel at two points in the vertical—more specifically, at the two-tenths and eight-tenths depth levels. Measurements were made from a moored boat with a crane which was suspended from an electromagnetic current meter with an internal compass which sensed current direction electronically. Data from the submerged meter were read from an on-board digital display which indicated average current speed for the preceding time interval, preset at either 10 or 30 seconds, thus damping out erratic fluctuations which commonly occurred in the estuary.

The USGS utilized the data described above to compute discharge in the channel. During the field data collection period, six such discharge measurements were made by the USGS for use in calibration of the one-dimensional Branch Network Model of flow operated by the agency for the inner harbor of Milwaukee. These data are on file at the USGS and the Regional Planning Commission.

SURFACE WATER QUALITY

The surface water quality data collection program for the Milwaukee Harbor estuary study was comprised of five distinct sampling programs—namely, weekly and monthly baseline sampling throughout the year for conventional pollutants and heavy metals, respectively; intensive sampling of selected runoff events for conventional pollutants; continuous automatic water quality monitoring; sampling of direct runoff from estuary riparian lands; and reconnaissance sampling of toxic metals and organic substances. The overall purpose of these programs was 1) to identify sources of pollution by sampling at strategically located sites within rural areas, and at sites in separate sewer, combined sewer, and unsewered areas within urban areas; 2) to evaluate the effects of these pollutants on receiving water quality; and 3) to provide data for calibration and verification of mathematical water quality simulation models to be used for predicting water quality conditions for selected critical historical periods, and for preparing alternative future land use and pollution abatement measures.

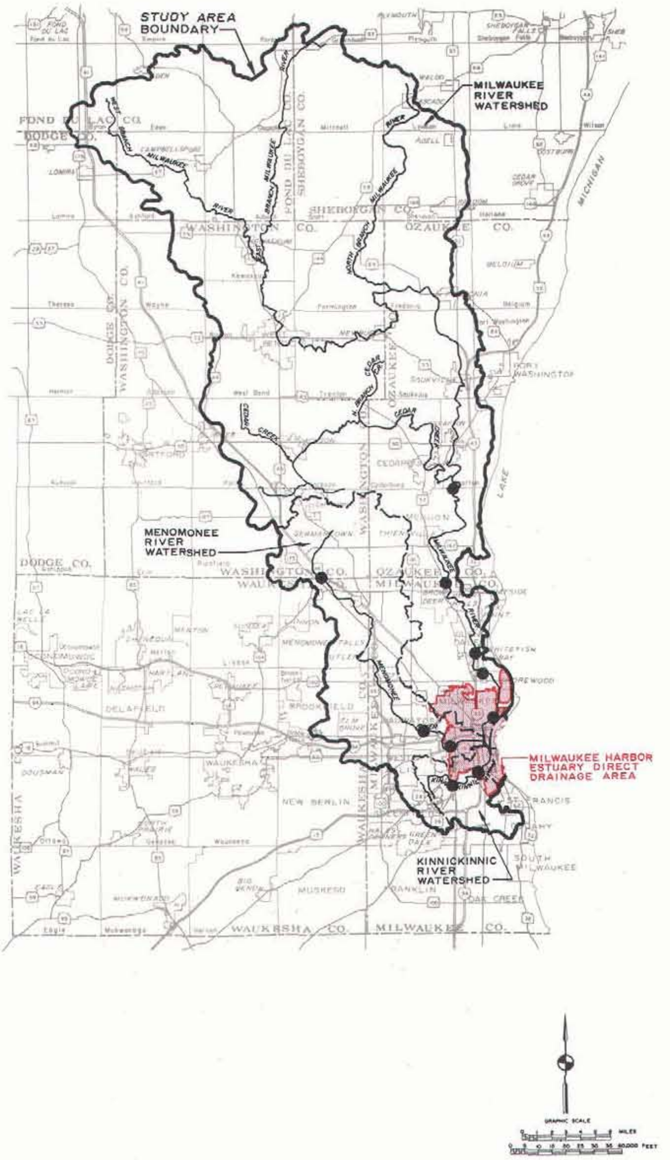
The water quality data were collected by the Milwaukee Metropolitan Sewerage District and the U. S. Geological Survey. Laboratory analyses were provided by the District. All data are on file on magnetic tape at the Regional Planning Commission. The locations of the sampling sites are shown on Maps 35 and 36. Water quality variables measured are listed in Tables 37, 38, 39, and 40. A more detailed description of the surface water quality monitoring program is presented in the following sections of this chapter, which include a brief discussion of the purpose for sampling each of the variables analyzed. Surface water quality data are summarized in Chapter VII of this volume.

Baseline Sampling

The baseline water quality sampling program for the Milwaukee Harbor estuary study was con-

Map 35

SURFACE WATER QUALITY MONITORING SITES IN RIVERS TRIBUTARY TO THE MILWAUKEE HARBOR ESTUARY SAMPLED DURING THE ESTUARY STUDY FIELD DATA COLLECTION PERIOD BY THE MILWAUKEE METROPOLITAN SEWERAGE DISTRICT, THE U. S. GEOLOGICAL SURVEY, AND THE REGIONAL PLANNING COMMISSION

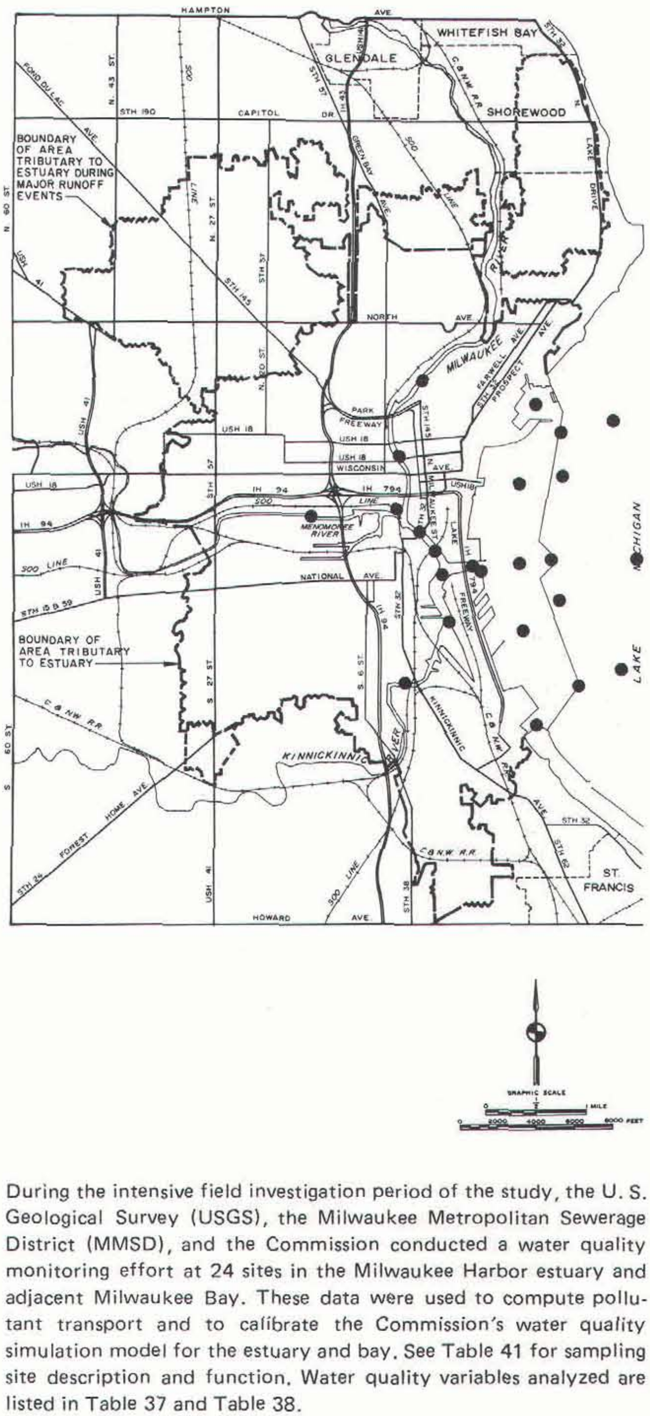


During the intensive field investigation period of the study, the U. S. Geological Survey (USGS), the Milwaukee Metropolitan Sewerage District (MMSD), and the Commission conducted a streamwater quality monitoring effort at 10 sites along the rivers tributary to the Milwaukee Harbor estuary. These data were used to compute pollutant transport and to calibrate the Commission's water quality simulation model. See Table 41 for sampling site description and function. Water quality variables analyzed are listed in Table 37 and Table 38.

Source: SEWRPC.

Map 36

WATER QUALITY MONITORING SITES IN THE MILWAUKEE HARBOR ESTUARY SAMPLED DURING THE ESTUARY STUDY FIELD DATA COLLECTION PERIOD BY THE MILWAUKEE METROPOLITAN SEWERAGE DISTRICT, THE U. S. GEOLOGICAL SURVEY, AND THE REGIONAL PLANNING COMMISSION



During the intensive field investigation period of the study, the U. S. Geological Survey (USGS), the Milwaukee Metropolitan Sewerage District (MMSD), and the Commission conducted a water quality monitoring effort at 24 sites in the Milwaukee Harbor estuary and adjacent Milwaukee Bay. These data were used to compute pollutant transport and to calibrate the Commission's water quality simulation model for the estuary and bay. See Table 41 for sampling site description and function. Water quality variables analyzed are listed in Table 37 and Table 38.

Source: SEWRPC.

Table 37

WATER QUALITY VARIABLES ANALYZED UNDER THE BASELINE SAMPLING PROGRAM[a]

Frequency	Parameters
Monthly Sampling—Rivers and Inner Harbor	Copper, iron, chromium, lead, zinc, cadmium, BOD_{ult}, BOD_{20}
Routine Weekly Sampling—Rivers and Inner Harbor	Total phosphorus, dissolved phosphorus, ammonia N; total organic carbon, dissolved organic carbon, total inorganic carbon Nitrate N, nitrite N, TKN; chlorides, COD, BOD_5 Total solids, suspended solids, volatile suspended solids, suspended sediment; fecal coliforms, chlorophyll-a, light penetration Total alkalinity, hardness, temperature, pH, dissolved oxygen, specific conductance, turbidity
Monthly Sampling—Outer Harbor	Copper, iron, chromium, lead, zinc, cadmium
Routine Weekly Sampling—Outer Harbor	Total phosphorus, dissolved phosphorus, ammonia N; total organic carbon, phytoplankton, zooplankton Nitrate N, nitrite N, TKN; chlorides, COD, BOD_5, BOD_{20} Total solids, suspended solids, volatile suspended solids, turbidity; fecal coliforms, chlorophyll-a, light penetration Total alkalinity, hardness, temperature, pH, dissolved oxygen, dissolved silica, specific conductance

[a]*See Map 35 and Map 36 for locations of sampling sites, and Table 41 for sampling site description and function.*

Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

ducted by the Milwaukee Metropolitan Sewerage District, which also provided the laboratory analyses of the samples. Laboratory analyses of water samples were conducted using methods described by the American Public Health Association[10] and by Russell H. Plumb.[11]

[10] *American Public Health Association, Standard Methods for the Examination of Water and Wastewater, 14th Edition, New York, 1975.*

[11] *Russell H. Plumb, Jr., Procedures for Handling and Chemical Analysis of Sediment and Water Samples, U. S. Environmental Protection Agency and U. S. Army Corps of Engineers Technical Report, EPA/CE-81-1 (Environmental Laboratory, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, 1981).*

Locations of Sampling Stations and Sampling Frequency: Baseline water quality samples were taken on Monday of each week from January 1982 through November 1984. On eight occasions, baseline sampling was done on Tuesdays when the preceding Monday was a work holiday. Sampling on the same day of the week throughout the year was done, in part, to generate a statistically unbiased set of water quality data. The U. S. Geological Survey also collected suspended sediment samples on Mondays about 30 times each year. That sampling program is described under the sediment sampling section of this chapter.

Sampling sites were located strategically at the points shown on Maps 35 and 36 to assist in identifying pollutant source areas and associated pollutant loading rates; to evaluate the effects of

Table 38

WATER QUALITY VARIABLES ANALYZED UNDER THE RUNOFF SAMPLING PROGRAM

General Location of Sample Site	Parameters
Tributary Rivers and Inner Harbor	Total phosphorus, dissolved phosphorus, ammonia N; total organic carbon, total inorganic carbon Nitrate N, nitrite N, TKN; chlorides, COD, BOD_5 Total solids, suspended solids, volatile suspended solids, turbidity, suspended sediment; fecal coliforms Alkalinity, temperature, pH, dissolved oxygen, specific conductance, dissolved silica
Outer Harbor	Total phosphorus, dissolved phosphorus, ammonia N; total organic carbon; nitrate N, nitrite N, TKN; chlorides Total solids, suspended solids, volatile suspended solids, turbidity; fecal coliforms, light penetration, secchi depth Alkalinity, pH, temperature, dissolved oxygen, specific conductance, dissolved silica

Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Table 39

WATER QUALITY VARIABLES ANALYZED UNDER THE ESTUARY SHORELAND RUNOFF SAMPLING PROGRAM

Organochlorides	Metals	Other
Aldrin	Arsenic	Chloride
Chlordane	Cadmium	Phenols
DDD, DDE, DDT	Chromium	Sulfate
Dieldrin	Copper	
Endosulfan	Lead	
Endrin	Mercury	
Heptachlor	Nickel	
Heptachlor epoxide	Selenium	
Lindane	Thallium	
Methoxychlor	Zinc	
Mirex		
PCB		
PCN		
Perthane		
Toxaphene		

Source: SEWRPC.

pollutants on receiving water quality; and to provide water quality data at adequate spatial intervals for water quality modeling analysis.

Table 41 lists the water quality sampling sites and purpose of the sampling at each of the sites. As already noted, sites were located to represent conditions in rural areas and in urban separate sewer, combined sewer, and unsewered estuarine shoreland areas. Sites were also selected based on anticipated hydraulic characteristics as affected by Lake Michigan and power plant cooling water withdrawals and discharge. Sites were also located at confluences of the three rivers tributary to the estuary and near the confluence of Lincoln Creek and the Milwaukee River; in areas of existing and anticipated recreational use, such as the McKinley Marina; at the navigation openings in the breakwater and east of the breakwater to provide data for the evaluation of effects of river-transported pollution on Lake Michigan; at locations complementary to the bottom sediment sampling pro-

Table 40

WATER QUALITY VARIABLES MEASURED AT CONTINUOUS MONITORING SITES[a]

River	Site	Variables Measured			
		Dissolved Oxygen	Temperature	Specific Conductivity	Turbidity
Milwaukee	Pioneer Road[b]	X	X	X	X
Milwaukee	North Avenue dam[b]	X	X	- -	- -
Milwaukee	St. Paul Avenue[c]	X	X	X	X
Menomonee	Muskego Avenue[c]	X	X	X	X
Kinnickinnic	1st Street[d]	X	X	X	X

[a] *The locations of the monitoring sites are shown on Maps 35 and 36.*

[b] *Variables measured at one depth—approximately mid-depth.*

[c] *Variables measured at three depths: one meter below surface, mid-depth, and one meter above bottom.*

[d] *Variables measured at two depths: one meter below surface and mid-depth.*

Source: Milwaukee Metropolitan Sewerage District.

gram; at the upstream terminus of each of the three estuaries to provide pollutant inflow histories from the rivers; near long-term streamflow gaging stations operated by the USGS; and at locations providing adequate spatial resolution for mathematical modeling of dispersion, water quality reaction kinetics, and sedimentation.

Water Quality Variables Analyzed: The water quality variables analyzed for the baseline sampling program are listed in Table 37. These variables are, for the most part, constituents which affect dissolved oxygen (DO), which is the variable of principal interest. Phosphorus and nitrogen, for example, are constituents which affect algal productivity. These aquatic plants, in turn, affect dissolved oxygen levels in the rivers and the estuary through photosynthetic production of oxygen, and consumption of oxygen during respiration. When these plants die, bacterial decay removes oxygen from the water column. Other faunal aquatic life depend in part on algae as a source of food—namely, zooplankton and higher levels of animal life which feed directly on algae or upon algal consumers. These fauna consume oxygen directly by respiration while alive, and indirectly after death while serving as food supply to respiring bacteria. Phosphorus and nitrogen, as nutrients contained in organic sediments, are also vital for bacteria which feed on these sediments. Thus, phosphorus and nitrogen as nutrients have a strong effect on river and estuary water quality and, consequently, were included as variables to be analyzed under the estuary study.

Nitrogen compounds in the water column were also analyzed, in part to determine rates at which free oxygen was removed in association with nitrogen transformations. Such rates were utilized in the operation of water quality simulation models.

Organic and inorganic carbon levels in the water column were analyzed for use in both water column and bottom sediment studies. The transformation of organic carbon into inorganic carbon was evaluated using stoichiometric procedures to estimate oxygen consumption in the water column to supplement analogous information provided by measurements of carbonaceous biochemical oxygen demand, a more expensive laboratory procedure. For sediment process studies, particulate organic carbon in sediments was related to organic carbon in the water column to trace the source and fate of this substance, which is a major nutrient

Table 41

BASELINE AND RUNOFF EVENT WATER QUALITY SAMPLING SITE FUNCTION AND DESCRIPTION

Location	Reference Number	Site	Sampling Platform	Number of Vertical Sampling Points[a]	Function
Milwaukee River	RIV-1	Pioneer Road (River Mile 26.25)	Bridge	1	To reflect the impacts of rural and urban areas on river water quality upstream of the limits of Milwaukee Metropolitan Sewerage District service area
	RIV-2	Brown Deer Road[b] (River Mile 14.99)	Bridge	1	To reflect the impacts of separate sewer service areas upstream of combined sewer service area
	RIV-3	Silver Spring Drive[b] (River Mile 8.49)	Bridge	1	To reflect the impacts of separate sewer service area upstream of combined sewer service area
	RIV-4	Port Washington Road (River Mile 6.91)	Bridge	1	To reflect the impacts of combined sewer service area contributions from Lincoln Creek, upstream of estuary
	RIV-5	North Avenue dam (River Mile 3.10)	Bridge	1	To quantify pollutant loadings at upstream limit of estuary, and to provide a continuous dissolved oxygen (DO) monitoring site in the combined sewer service area
	RIV-6	Walnut Street (River Mile 2.25)	Bridge	3	To reflect conditions in the Milwaukee River portion of the estuary and to provide a continuous DO monitoring site in the combined sewer service area
	RIV-7	Wells Street (River Mile 1.41)	Bridge	3	To reflect conditions in the Milwaukee River estuary above the confluence with the Menomonee River
	RIV-8	Broadway Street (River Mile 0.63)	Bridge	3	To reflect conditions in the Milwaukee River estuary below the confluence with the Menomonee River
	RIV-15	C&NW Railway (River Mile 0.44)	Boat	3	To reflect conditions in the estuary above the confluence of the Milwaukee River with the Kinnickinnic River estuary, and in the central turning basin
	OH-1	Hoan Bridge-River Mouth (River Mile 0.00)	Boat	3	To reflect conditions in the estuary below the confluence with the Kinnickinnic River and to quantify pollutant loadings to the outer harbor
Menomonee River	RIV-16	County Line Road[b] (River Mile 23.47)	Bridge	1	To reflect the impacts of rural and urban areas upon river quality upstream of the limits of the Milwaukee Metropolitan Sewerage District service area
	RIV-9	N. 70th Street (River Mile 6.10)	Bridge	1	To reflect conditions in the separate sewer service area upstream of the combined sewer service area
	RIV-10	38th Street foot bridge (River Mile 2.78)	Bridge	1	To quantify pollutant loadings into the upstream limit of the estuary and to reflect water quality conditions within the combined sewer service area

Table 41 (continued)

Location	Reference Number	Site	Sampling Platform	Number of Vertical Sampling Points[a]	Function
Menomonee River (continued)	RIV-11	Muskego Avenue (River Mile 0.92)	Bridge	3	To reflect conditions in the Menomonee River estuary and to provide a continuous DO monitoring site
	RIV-17	Milwaukee Road (River Mile 0.02)	Bridge	3	To reflect conditions at the downstream end of the Menomonee River estuary
Kinnickinnic River	RIV-12	S. 29th Street[b] (River Mile 5.03)	Bridge	1	To reflect conditions in the separate sewer service area upstream of the combined sewer service area
	RIV-13	S. 9th Place (River Mile 3.08)	Bridge	1	To quantify pollutant loadings into the upstream end of the estuary and to reflect conditions in the combined sewer service area
	RIV-14	S. 1st Street (River Mile 1.43)	Bridge	3	To reflect conditions in the estuary and to provide limited continuous water quality monitoring
	RIV-18	Greenfield Avenue extended (River Mile 0.57)	Boat	3	To reflect conditions in the Kinnickinnic turning basin in the estuary
	RIV-19	Jones Island Ferry (River Mile 0.15)	Boat	3	To reflect conditions near the mouth of the Kinnickinnic estuary
Outer Harbor	OH-7	Main Harbor Entrance at the Breakwater	Boat	3	To measure the amount and quality of discharge to/from Lake Michigan
	OH-5	North fairweather gap	Boat	3	To measure the amount and quality of discharge to/from Lake Michigan
	OH-9	South fairweather gap	Boat	3	To measure the amount and quality of discharge to/from Lake Michigan
	OH-10	Russell Avenue gap	Boat	3	To measure the amount and quality of discharge to/from Lake Michigan
	OH-15	McKinley Marina	Boat	3	To determine water quality conditions in the marina area
	OH-2	Jones Island STP Plume	Boat	3	To determine sewage treatment plant effluent impacts on water quality
	OH-4 OH-3 OH-11	Outer Harbor—North, Central, and South	Boat	3	To characterize dilution effects upon harbor water quality
	OH-6, 8, OH-12, 13, OH-14	Lake Michigan waters in Milwaukee Bay (five sites)	Boat	3	To characterize dilution effects upon Lake Michigan water quality

NOTE: See Maps 35 and 36 for sampling site locations.

[a] *Discrete samples were taken at mid-depth unless three sampling points are indicated. In this case discrete samples were also taken one meter below the water surface and one meter above the bottom.*

[b] *Streamflow was determined for each water sample using stage-discharge relationships developed by current meter measurement.*

Source: SEWRPC.

source for both aerobic and anaerobic bacteria. The respiration of such bacteria directly or indirectly removes free oxygen from the water column.

Total solids in the water column is a general indicator of overall water quality easily measured in a laboratory. Total solids is also utilized to evaluate the suitability of a water supply for industrial and domestic use.

Total dissolved solids, determined by the difference between total solids and suspended solids, was computed for use as a tracer for evaluation of dilution and dispersion within the estuary and Lake Michigan.

Suspended solids analyses were conducted for all samples taken to determine the source and fate of these pollutants. The organic portion of these solids, known as volatile suspended solids, is organic material, including both organic nitrogen and organic carbon. The volatile suspended solids data supplemented the particulate organic carbon determinations. The suspended solids analyses were relatively inexpensive to conduct, and were used to supplement the carbon and nitrogen analyses.

Chemical oxygen demand and biochemical oxygen demand were analyzed for the estuary study to determine the potential effect of oxygen-demanding materials in the water column. Each test is not sensitive to some compounds to which the other test is sensitive, so analyses were conducted for both. Chemical oxygen demand in bottom sediments was compared to that in the water column as part of the sediment process studies.

Fecal coliform bacteria are indicators of fecal contamination by man and other warm-blooded animals and were analyzed to identify the sources and magnitude of such contamination.

Chlorides found in the water column are derived, in part, from natural sources, domestic and industrial wastewaters, and deicers used in the winter for street and highway maintenance. Chlorides are relatively conservative substances and consequently can serve as tracers for the identification of pollution sources. Therefore, chloride analyses were conducted for all baseline samples taken for the estuary study.

Alkalinity and hardness were principally utilized in the estuary study as tracers for water—i.e., river water and Lake Michigan water, which have markedly different values of alkalinity and hardness—in order to determine mixing coefficients for water quality modeling studies. Alkalinity measurements were also used in primary productivity studies because alkalinity reflects the availability of carbon for photosynthesis.

Chlorophyll-a was analyzed for the estuary study because it is an indirect measure of algal biomass and is readily measured. Chlorophyll-a and light penetration data were utilized in algal productivity studies of the estuary and to estimate productivity in the tributary rivers.

Turbidity is an indicator of the amount of particulates in suspension in the water column and is readily measured either in-situ or in the laboratory. Turbidity was measured to supplement the suspended solids and light penetration data described above.

Water temperature, pH, and specific conductance are readily measured in situ using portable field meters. Water temperature is a fundamental variable used in physical, chemical, and biological analyses of the aquatic environment. An indicator of hydrogen ion concentration, pH affects the availability of nutrients, biological processes, and the impacts of certain toxic substances. Specific conductance is an indicator of total dissolved ionic matter in the water column. These three variables, all of fundamental importance in water pollution studies, were also measured for all samples taken in the estuary study.

Dissolved oxygen was measured for the estuary study for nearly all samples taken because this variable is necessary for all desirable forms of aquatic life.

Phytoplankton are the primary producers in the aquatic community, representing the first trophic level upon which all higher trophic levels are dependent for nourishment. In addition, production and consumption of dissolved oxygen by phytoplankton have a significant effect upon the dissolved oxygen regimen in the estuary. Therefore, phytoplankton measurements were taken as part of the baseline water quality sampling program. Dissolved silica, an essential nutrient for the alga Diatomaceae, commonly known as diatoms, was measured to provide data supplemental to the data collected for phytoplankton.

Zooplankton feed upon phytoplankton and are fed upon by the higher trophic levels, and thus constitute an important position in the food web.

Grazing upon phytoplankton by zooplankton also affects the dissolved oxygen regimen by limiting algal population levels. Zooplankton and phytoplankton data also provided supplementary information for evaluation of the estuary fishery.

The metals copper, chromium, cadmium, iron, lead, and zinc were found in significantly high concentrations in previous studies to warrant inclusion in the estuary study monitoring program, and were sampled on a monthly basis during the baseline surveys.

The water quality variables listed in Table 37 are discussed further in Chapter VII of this report.

Field Sampling Methods: Baseline water quality samples were taken in the field using either the acrylic van Dorn sampler shown in Figure 23, or the acrylic Kemmerer sampler, which is similar to the van Dorn sampler except the longitudinal axis of the sampler is vertical rather than horizontal. These samplers were utilized to collect discrete samples at specific depths in the water column. As Figure 23 suggests, after the sampler was lowered to the appropriate depth, it was triggered mechanically, closing the stoppers on each end and trapping the sample inside for retrieval. The van Dorn sampler was used at sites where depths were too shallow for use of the Kemmerer sampler.

Samples were taken at mid-channel and at mid-depth at all the river sampling sites shown on Map 35 and listed in Table 41. In the estuary upstream of the outer harbor, samples were taken at mid-channel and at three depths—three feet below the surface, at mid-depth, and three feet above the bottom. In the outer harbor and adjacent Lake Michigan, sampling sites were found each week by radio triangulation using two shore-based transmitters and an on-board receiver specially made for this purpose. Samples were taken at three depths as in the inner harbor. In-situ measurements of dissolved oxygen and water temperature were made using portable field meters with submersible probes. Specific conductance and pH were measured either in-situ or in the laboratory, depending upon the availability of portable equipment during each baseline survey.

Runoff Event Sampling

Runoff event sampling for the estuary study was conducted by the U. S. Geological Survey, the Milwaukee Metropolitan Sewerage District, and the Regional Planning Commission. The District conducted all the laboratory analyses except the suspended sediment analysis, which was analyzed by the USGS. Seven intensive runoff event surveys were conducted during the monitoring program.

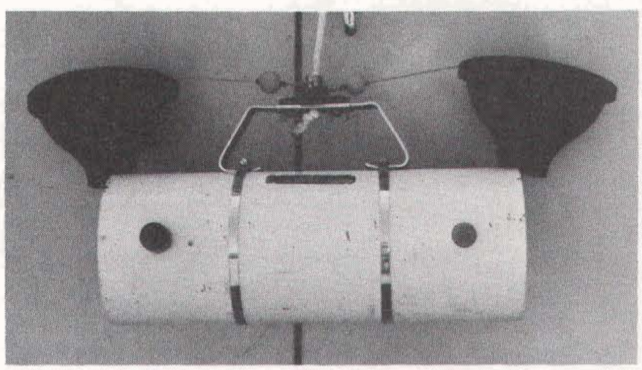
Locations of Sampling Stations and Sampling Frequency: The locations of the runoff event sampling sites for the Milwaukee Harbor estuary study are shown on Maps 35 and Map 36 for the rivers tributary to the estuary and for the estuary, respectively.

All the event sampling sites coincide with baseline water quality sampling sites. As were the baseline sampling sites, the event sampling sites were strategically positioned in rural areas and in urban areas served by both separate sewers and combined sewers. Table 41 lists the sites and the purpose for sampling at each of the sites.

Runoff events selected for sampling in the monitoring program included a snowmelt event, a first major spring rainfall event, two summer thunderstorm events, and three fall rainfall events. The snowmelt event was sampled to measure the wash-off of pollutant loads accumulated on the land surface during the previous winter months. A first major spring rainfall runoff event was sampled to measure, in part, winter-accumulated pollutants flushed from separate sewers, combined sewers, and the land surface. Summer rainfall runoff events were sampled not only to measure pollutant loads,

Figure 23

THE VAN DORN SAMPLER USED FOR BASELINE WATER QUALITY SAMPLING



Source: Owen T. Lind, Handbook of Common Methods in Limnology, (C. V. Mosby Company, St. Louis, Missouri, 1974).

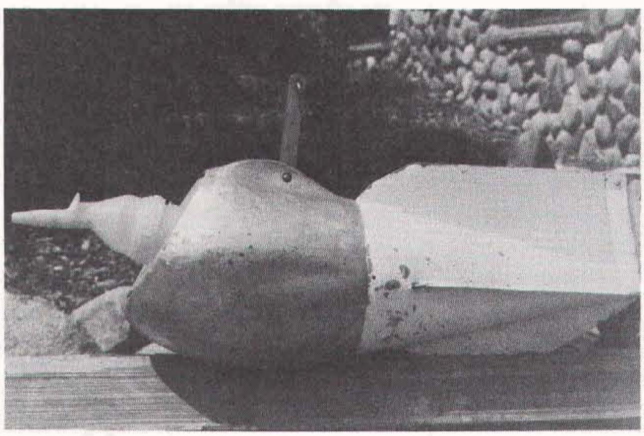
but also to provide estuary water quality model calibration data during warm water conditions, when significant dissolved oxygen depletion was most likely to occur. Fall rainfall runoff events were sampled following the defoliage of deciduous trees and the associated decline of transpiration, which causes increased stormwater runoff rates and volumes in rural areas and attendant increased pollutant loads from these areas.

Runoff event surveys were conducted to provide water quality data throughout the runoff event period, with sampling initiated prior to the start of the event to provide baseline data, followed by intensive sampling during the rising flow period to measure "first flush" concentrations, and completed by less intensive sampling throughout the flow recession period to complete measurement of the total pollutant transport load and water quality recovery.

Sampling at the 16 bridge sites listed in Table 41 was carried out by the USGS assisted by Commission staff. Sampling at the 12 boat sites was carried out by the District staff. Sampling was conducted around the clock at the bridge sites by four two-man crews working in 12-hour shifts during the intensive sampling periods, with reduction to two crews during flow recession. Laboratory analyses for water quality samples for conventional pollutants were conducted by the District. Suspended sediment analyses were provided by the USGS laboratory in Madison, Wisconsin.

Figure 24

U. S. GEOLOGICAL SURVEY D-77 INTEGRATING SAMPLER



Source: U. S. Geological Survey.

Water Quality Variables Analyzed: The water quality variables analyzed for the routine runoff event sampling program are listed in Table 38. This list is similar to that for the baseline water quality variables, but it is somewhat abbreviated to reduce the amount of laboratory work required to be performed by the Milwaukee Metropolitan Sewerage District laboratory during such events. Not included on the list of variables for routine runoff event sampling for the rivers and inner harbor are dissolved organic carbon, chlorophyll-a, 20-day biochemical oxygen demand (BOD), and ultimate BOD.

Field Sampling Methods: Runoff event samples were taken using either the two- or six-liter acrylic van Dorn sampler or the acrylic Kemmerer sampler as described earlier for the baseline sampling program. For sites with high velocities, either van Dorn samplers provided with external lead weights were utilized to hold the samplers in position, or a two-liter USGS D-77 sampler was used, as illustrated in Figure 24.

In the rivers tributary to the estuary, the depth-integrating D-77 was the preferred sampler because it provided a velocity-weighted average sample of the entire water column at mid-channel. This sampler, however, could not be used in the high velocities of the Kinnickinnic River, where use of the van Dorn sampler was justified because of the relatively shallow depths and very turbulent mixing conditions extant there.

In the inner harbor, the van Dorn sampler was used to collect discrete samples at mid-channel at three depths: three feet below the surface, at mid-depth, and three feet above the bottom. In the Kinnickinnic River at mid-channel at S. 1st Street, samples were taken three feet below the surface and three feet off the bottom because of the shallow depths there. In the outer harbor, samples were taken at three depths using the Kemmerer sampler.

In-situ measurements of dissolved oxygen, temperature, pH, and specific conductance were made using portable equipment provided by the USGS and the Sewerage District. In the tributary rivers such measurements were made at mid-depth. In the inner and outer harbors, measurements were made at three depths except at S. 1st Street in the Kinnickinnic River, where measurements were made at two depths.

Continuous Water Quality Monitoring

Continuous water quality monitoring for the Milwaukee Harbor estuary study was conducted by the Milwaukee Metropolitan Sewerage District at the five sites so designated on Maps 35 and 36. The water quality variables monitored are listed in Table 40. Two of the sites were on the Milwaukee River upstream of the estuary at the North Avenue dam in the City of Milwaukee and at Pioneer Road (CTH C) in the northern corporate limits of the City of Mequon. The remaining three sites were located within the estuary on the Milwaukee River at St. Paul Avenue, the Menomonee River at Muskego Avenue, and the Kinnickinnic River at S. 1st Street. The monitoring was conducted at either two or three depths as indicated in Table 40.

Continuous monitoring of dissolved oxygen, water temperature, specific conductance, and turbidity was conducted at four of the stations. At the fifth station on the Milwaukee River at the upstream side of the North Avenue dam, water temperature and dissolved oxygen only were monitored. Data were automatically transmitted over telephone lines at one-minute intervals to the District computer for storage.

At each site, water was pumped through a fixed intake in the river to a tank containing sensors for each of the variables to be measured. The flow rate was established so that well-mixed conditions were maintained in the tank. Sutron Corporation instrumentation at four sites measured all variables except turbidity, which was measured by equipment manufactured by the Hach Corporation. At the fifth site, the Milwaukee River at St. Paul Avenue, Rexnord Corporation instrumentation measured all water quality variables. Monitor calibration checks for all variables were made at weekly intervals. Water quality data are stored on magnetic tape at the Sewerage District offices.

Daily and storm event monitoring of suspended sediment by seven automatic pumping samplers operated by the USGS is described under the sediment sampling section of this chapter.

Estuary Shoreland Runoff Quality Sampling

To assess the magnitude of pollutant washoff from storm-sewered and unsewered estuary shorelands, which are largely utilized for commercial and industrial activities, two stormwater runoff quality surveys were conducted. These surveys determined the types and concentrations of pollutants.

Two summer rainfall events were sampled at the eight sites shown on Map 37. Results of the study are presented in Chapter VI. Samples were collected by one of two methods. At some sites, two-liter plastic sample bottles were buried up to the neck in rills draining the area of interest. Covers above the collectors were provided to prevent rainfall from entering directly. At other sites, samples were pumped from catch basins during or immediately following the storm. The water quality variables analyzed are listed in Table 39.

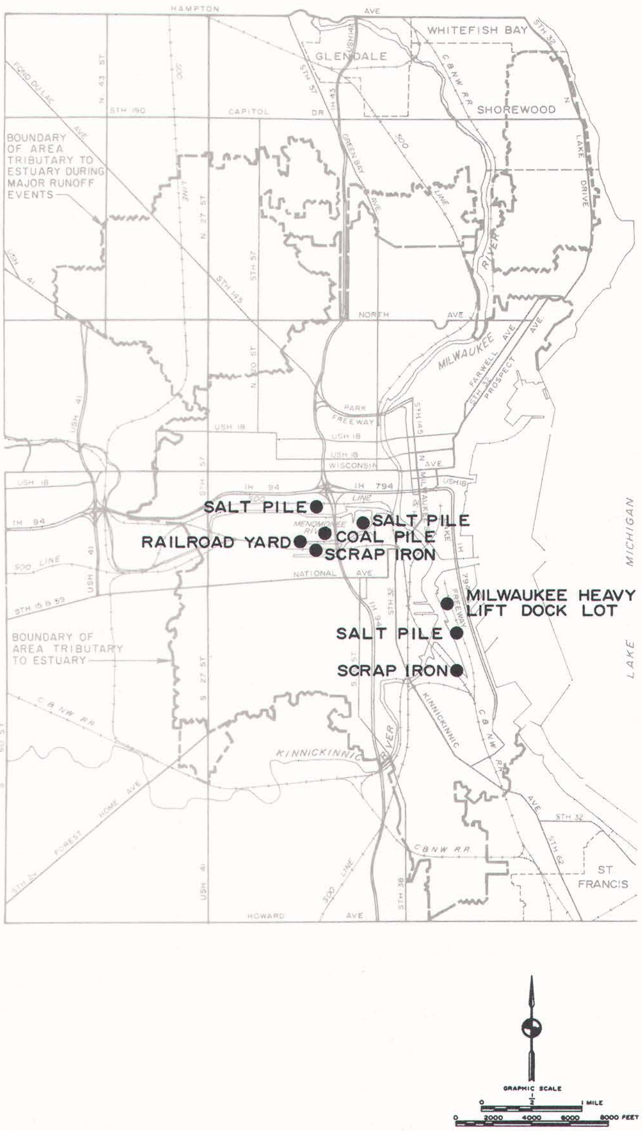
SEDIMENT

Intensive sampling of bottom sediments and suspended sediments was conducted by the Sewerage District and the USGS, respectively. The District responsibilities included core sampling of bottom sediments, measurement of interstitial water quality, measurement of sediment gas production rates, measurement of sediment oxygen demand, sediment trap measurement of deposition rates and chemistry, and suspended solids sampling at weekly intervals. The USGS responsibilities included automatic sampling of suspended sediment at daily or more frequent intervals at seven gaging stations, and intensive manual sampling at nine other sites during storm event surveys. The locations of the sampling sites are shown on Map 38 and Map 39. The types of bottom sediment data collected at each site are listed in Table 42.

The sediment sampling program was a particularly important element of the estuary study because bottom sediments in the inner harbor of Milwaukee have serious adverse impacts upon water quality. To address these impacts, an understanding of sediment processes in the estuary, heretofore not well understood, had to be developed. To gain the knowledge required, an intensive and comprehensive sampling program, perhaps unprecedented in scope and magnitude, was carried out by the Water Resources Research Group of the Sewerage District, with technical assistance provided by HydroQual, Inc., consultant to the Commission. The sampling program was designed to provide

Map 37

LOCATIONS OF DIRECT RUNOFF SAMPLING SITES FROM SHORELAND AREAS IN THE MILWAUKEE HARBOR ESTUARY



During two storm events occurring in August and September 1984, the runoff samples were collected at eight sites draining shoreland areas of the Menomonee and Kinnickinnic River estuaries to determine types and approximate concentrations of pollutants washing off from storage areas for coal, salt, and scrap iron, from a railroad yard, and from the docking work area in the Kinnickinnic turning basin. The results of the surveys, including pollutant loading estimates, are presented in Chapter VI of this volume.

Source: U. S. Geological Survey and SEWRPC.

data for analysis of bottom sediment processes, to determine the source and magnitude of constituents important in these processes, to provide calibration data for sediment algorithms used in the estuary water quality model, and to provide data for dredging and dredge spoils disposal studies conducted as part of the estuary planning program. The sediment sampling programs are described in detail below. Sediment data are summarized in Chapter VII of this volume. Laboratory analyses of sediment samples were conducted using methods described by Harold P. Guy[12] and Russell H. Plumb.[13]

Sediment Core Sampling

The Milwaukee Metropolitan Sewerage District, Water Resources Research Group, took sediment core samples in the inner harbor and tributary rivers at the 15 locations listed in Table 42. At each site, samples were taken manually four to six times during each year of the two-year field sampling period by a "hard hat" surface supply diver. Samples were collected by twisting an open-ended lexon tube vertically into the bottom sediments. The depth of penetration was marked on the tube while the tube was still in place. The top of the tube was capped with an expandable stopper, then the bottom of the tube was carefully exposed by excavation and capped before removal. The tube was then transported to the surface where it was placed in a vertical position on the diving barge. Water was removed through drainage ports in the coring tube above the sediment surface. The depth of the sediments was again measured in the tube after surface drainage was completed. The core was then removed from the tube, measured, and quickly sliced into segments to minimize contact with the air, and placed in air-tight containers for transport to the laboratory. The segments were made one centimeter thick for the top five centimeters of the core, and 2.5 centimeters thick below that, for a total of 10 segments. An additional segment was utilized for quality assurance. The sediment quality variables analyzed are listed in Table 43. Impressions based on a visual inspection and a description of each core segment were also recorded.

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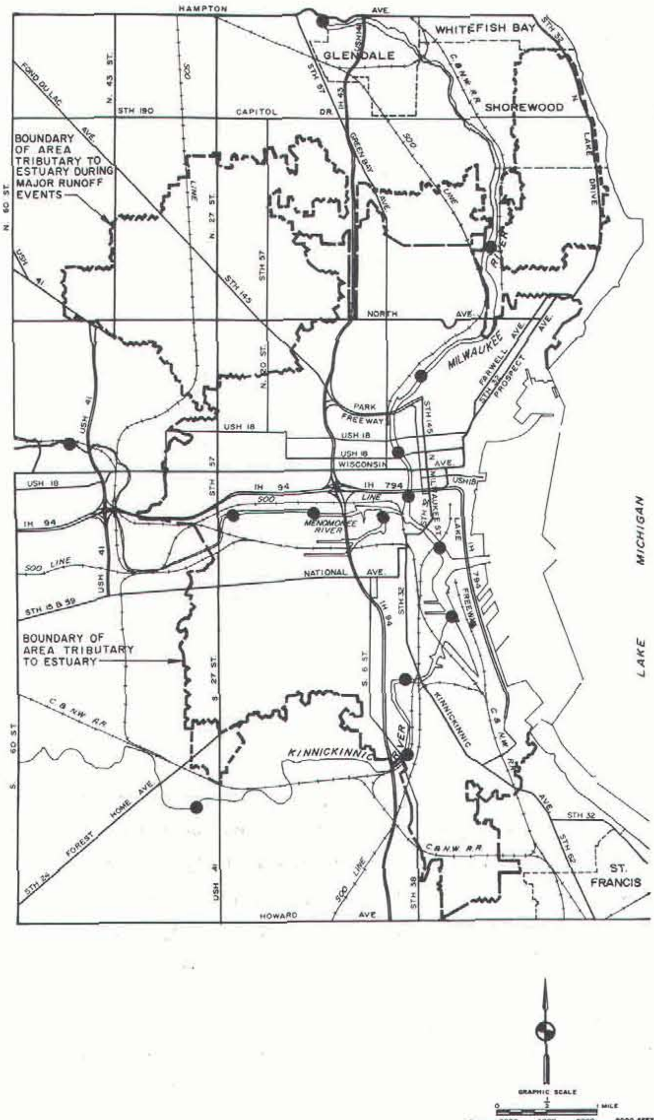
[12] *Harold P. Guy, Laboratory Theory and Methods for Sediment Analysis, U. S. Geological Survey Techniques of Water Resource Investigations, Book 5 Chapter C1 (U. S. Government Printing Office, Washington, D. C., 1969).*

[13] *Russell H. Plumb, Jr., op. cit.*

Map 38

LOCATIONS OF BOTTOM SEDIMENT SAMPLING SITES OF THE MILWAUKEE METROPOLITAN SEWERAGE DISTRICT FOR ESTUARY FIELD DATA COLLECTION PROGRAM

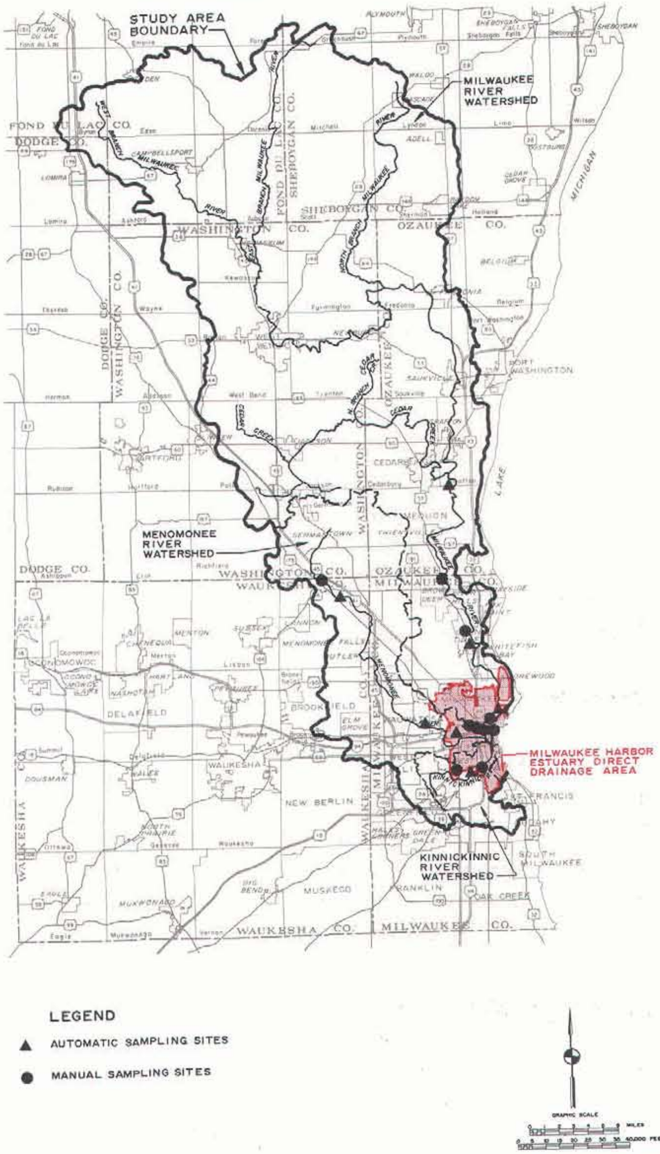


During the intensive field investigation period of the study, the Milwaukee Metropolitan Sewerage District (MMSD) collected data at 15 sites on bottom sediment chemistry, interstitial water chemistry, sediment deposition rates, sediment gas production, and benthic oxygen production/consumption rates. These data were collected for calibration of the sediment submodel of the estuary water quality simulation model and for use in the evaluation of dredging for the maintenance of navigation and water quality enhancement. One of the sites, not shown on Map 38, is located on the Menomonee River at Hampton Avenue.

Source: SEWRPC.

Map 39

LOCATIONS OF SITES SAMPLED FOR SUSPENDED SEDIMENT BY THE U. S. GEOLOGICAL SURVEY FOR THE ESTUARY STUDY FIELD DATA COLLECTION PROGRAM



During the intensive field investigation period of the study, the U. S. Geological Survey (USGS) collected suspended sediment data at 17 sites in the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds. These data were used to determine sources and quantities of suspended sediments transported into the estuary and to determine the movement of sediments within the estuary.

Source: SEWRPC.

Table 42

BOTTOM SEDIMENT SAMPLING STATIONS AND DATA TYPES COLLECTED BY THE MILWAUKEE METROPOLITAN SEWERAGE DISTRICT[a]

River	Location	Sediment Chemistry	Interstitial Water Chemistry	Sediment (Traps) Deposition Rates	Gas Production	Benthic Oxygen Production/ Consumption
Milwaukee	Hampton Avenue	X	X	X	--	--
	Locust Street	X	X	X	--	--
	Walnut Street	X	X	X	X	X
	Wells Street	X	X	X	X	X
	St. Paul Avenue	X	X	--	X	X
	Chicago & North Western bridge	X	X	X	X	X
Menomonee	Hampton Avenue	X	X	X	--	--
	Hawley Road	X	X	--	--	--
	Falk dam	X	X	--	X	X
	Muskego Avenue	X	X	--	X	X
	Burnham Canal	X	X	--	--	--
Kinnickinnic	Wilson Park Creek	X	X	--	--	--
	Chase Avenue	X	X	X	--	--
	S. 1st Street	X	X	X	X	X
	Greenfield Avenue extended	X	X	X	X	X

[a] *The sediment sampling sites are shown on Map 38. The variables analyzed and sampling frequencies are listed in Table 43.*

Source: Milwaukee Metropolitan Sewerage District.

The sediment core data were used by HydroQual, Inc., consultant to the Commission, to assess sediment decomposition with depth in the sediment column as part of the sediment oxygen demand studies conducted by that firm.

Interstitial Water Quality

The quality of pore water (interstitial water) from the bottom sediment cores sampled under the Milwaukee Harbor estuary study at the 15 sites listed in Table 42 was analyzed. Each sample was squeezed individually by a hydraulic press under an argon atmosphere to provide pore water which was analyzed for the variables listed in Table 43 by the Sewerage District laboratory.

Pore water constituents were utilized in studies of sediment chemical transformations to provide estimates of the mass of dissolved reduced substances in the sediments which exert an immediate oxygen demand when scoured up into the water column by high-velocity combined sewer overflow outfall discharges and by ship traffic, and to supplement data from in-situ measurements of sediment oxygen demand at the sediment-water column interface during quiescent flow conditions. As indicated in Table 43, interstitial water quality was analyzed monthly during the sampling season, which did not include the winter months.

Sediment Gas Production

Because decomposing organic sediments release gases to the water column which can be both deleterious to water quality and indicative of sediment quality conditions, the Sewerage District designed and constructed samplers for seasonal measuring of gas production volumes and rates at eight of the sediment sampling sites listed in Table 42. Figure 25 illustrates the sampler, which consists of a five-foot-diameter inverted stainless steel cone with an opening at the vertex over which a glass vessel was installed to store gas from the sediments. The cone was placed on the bottom of each of the designated estuary sediment sampling stations on legs driven into the bottom, with the base about one-half foot above the sediments. Gases rising from the sediments were funneled into

Table 43

SEDIMENT CHEMISTRY AND RELATED PARAMETERS BEING ANALYZED UNDER THE MILWAUKEE HARBOR ESTUARY WATER RESOURCES PLANNING STUDY[a]

Type of Data	Sampling Frequency	Parameters	
Sediment Traps[b]	Weekly to bi-weekly	Total organic carbon Total inorganic carbon Chemical oxygen demand Total suspended solids	Total solids Volatile suspended solids Total volatile solids
Gas Generation	Seasonally	Methane Hydrogen sulfide	Carbon dioxide Nitrogen
Sediment Cores[c]	Monthly during sampling season	Total solids Total volatile solids Specific gravity Chemical oxygen demand Immediate oxygen demand Total Kjeldahl nitrogen Ammonia nitrogen	Total phosphorus Total organic carbon Total inorganic carbon Porosity pH Oxidation reduction potential Sediment temperature
Interstitial Water[d]	Monthly during sampling season	Chemical oxygen demand Immediate oxygen demand Total phosphorus Total Kjeldahl nitrogen Ammonia-nitrogen	pH Oxidation reduction potential Specific conductance Total organic carbon Total inorganic carbon
Sediment Oxygen Demand (in-situ)[d]	Monthly during sampling season	Dissolved oxygen profile Turbidity[e]	Water temperature profile Chlorophyll-a[c] Light intensity profile

[a] *The sampling sites are shown on Map 38. The types of data collected at each site are listed in Table 42.*

[b] *Sediment traps were placed two meters below the surface and one meter above the bottom of each site. An additional trap was placed at mid-depth in the Milwaukee River estuary at the Chicago & North Western bridge and in the Kinnickinnic River estuary at Greenfield Avenue extended.*

[c] *Collected at 15 sites. Impressions based on a visual inspection and a description of each core segment were recorded by MMSD.*

[d] *Collected at 15 sites.*

[e] *Measured near the surface, at mid-depth, and near the bottom.*

Source: Milwaukee Metropolitan Sewerage District.

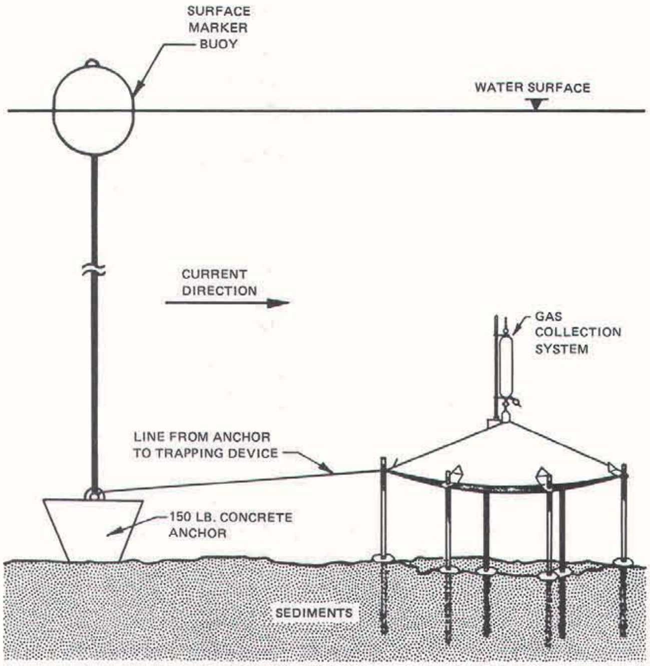
the glass vessel, which contained a number of valves, one of which was located near the bottom to release water in the vessel being forced out by the accumulating gas. Following the accumulation of gas adequate in volume for laboratory analysis, a diver would close the appropriate valves and transport the glass vessel to the surface. Laboratory analyses were then conducted at the Sewerage District laboratory for methane, hydrogen sulfide, carbon dioxide, and nitrogen. During warm water periods when gas production rates were relatively high, gas samplers were suspended from a crane above the bottom sediments for from four to six hours to collect the volume of gas required for laboratory analysis. Nine sites were monitored four to six times annually during the estuary study field data collection period.

Sediment Oxygen Demand

Sediment oxygen demand (SOD) was measured monthly by the Sewerage District staff at the eight sediment sampling sites designated on Table 42 during the estuary study field data collection period. SOD was measured in-situ by light and dark respirometers placed on the surface of the bottom sediments and sealed by divers to trap a fixed volume of water inside. A light (transparent) SOD chamber is shown in Figure 26.

Figure 25

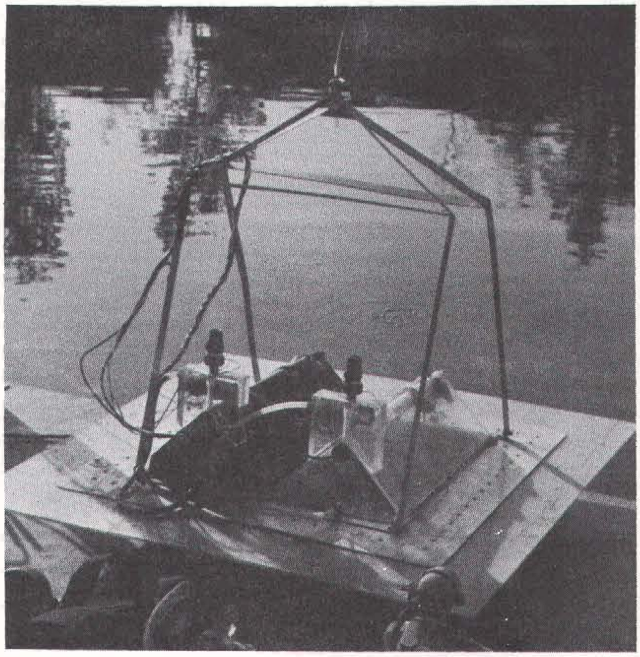
SEDIMENT GAS GENERATION SAMPLER DEVELOPED BY THE MILWAUKEE METROPOLITAN SEWERAGE DISTRICT FOR THE MILWAUKEE HARBOR ESTUARY STUDY



Source: Milwaukee Metropolitan Sewerage District.

Figure 26

SEDIMENT OXYGEN DEMAND RESPIROMETER DEVELOPED BY THE MILWAUKEE METROPOLITAN SEWERAGE DISTRICT FOR THE MILWAUKEE HARBOR ESTUARY STUDY



Source: Milwaukee Metropolitan Sewerage District.

An open valve at the top of each respirometer permits entrapped air to escape during placement on the bottom, after which the valve is closed. A dissolved oxygen and water temperature probe, with a stirring device to circulate water slowly inside, is mounted near the top of each respirometer and connected by electrical cable to a recorder placed above the water surface. Light and dark respirometers are placed in tandem to measure the effects, if any, of light upon dissolved oxygen levels in the respirometers. The dissolved oxygen concentration was recorded from early morning to late afternoon. Concurrent measurements were made at each site of water column profiles of dissolved oxygen, water temperature, light intensity, turbidity, and chlorophyll-a, all as indicated in Table 42. Continuous solar radiation data collected at the meteorological stations described earlier in this chapter were also utilized in the SOD studies, as described in Chapter VII of this volume.

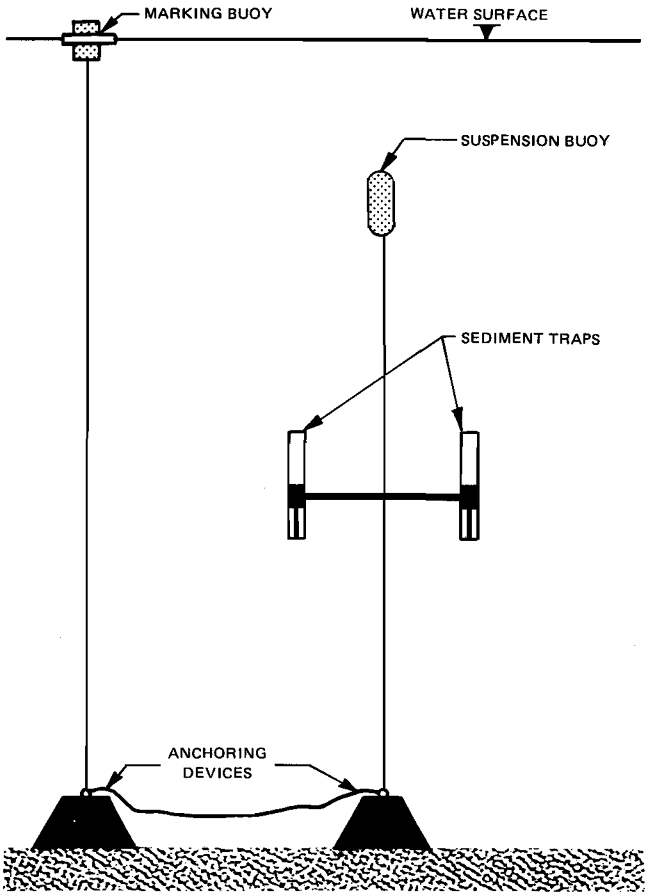
SOD rates were measured to supplement studies of chemical transformation of sediments, to provide SOD input for water quality simulation modeling, and to estimate benthic algal productivity.

Sediment Deposition

Sediment deposition rates and quality were measured by the Sewerage District staff at the nine sites indicated in Table 42. Figure 27 illustrates the sediment traps used. The traps were suspended in the water column six feet below the surface and three feet above the bottom. The traps were sampled at weekly to bi-weekly intervals by divers. Deposits found in the sediment traps were analyzed for the variables listed in Table 43. Sediment trap data were collected to assist in identifying sources of deleterious deposits, to determine rates of deposition and changes thereof seasonally, and to characterize the quality of these deposits spatially and seasonally.

Figure 27

SEDIMENT TRAP DEVELOPED BY THE MILWAUKEE METROPOLITAN SEWERAGE DISTRICT FOR THE MILWAUKEE HARBOR ESTUARY STUDY



Source: Milwaukee Metropolitan Sewerage District.

Suspended Sediment

Suspended sediment samples were collected by the U.S. Geological Survey at the 17 sites designated on Map 39. At seven of the locations, all at USGS stream gaging stations, automatic samplers pumped water samples from fixed intakes from the rivers. At five of these seven sites, the USGS operated PS-69 pump samplers containing 72 bottles. At the remaining two sites, both on the Milwaukee River at Estabrook Park and the North Avenue dam, the USGS operated ISCO samplers, which had a maximum capacity of 28 bottles.

The automatic samplers were actuated once daily at noon except during high-flow periods sensed by water level sensors connected to the samplers. During rising stages of high-flow periods, the samplers were automatically actuated at 15-minute intervals. The samplers were calibrated by the USGS using manually collected samples taken at equal-width intervals across the river with depth-integrating samplers such as the D-77 sampler. This sampling provided a discharge-weighted average of suspended sediment concentration. After determining the correlation between the average concentrations and the concentrations of pumped samples, the pump sample concentrations were adjusted to estimate mean concentration in the river. The methods utilized by the USGS for measuring fluvial sediment discharge are further described in a U. S. Geological Survey report, Field Methods for Measurement of Fluvial Sediment.[14]

At 10 sites the USGS collected suspended sediment samples at mid-channel using depth-integrating samplers. Samples were taken at weekly intervals except during late fall and winter baseflow periods, when samples were taken at bi-weekly to monthly intervals.

Suspended sediment data collected at the gaging stations were utilized by the USGS to compute daily and runoff event suspended sediment loads. Suspended sediment data collected at the remaining sites were used by the Regional Planning Commission to estimate monthly loads at those sites.

The USGS also collected a limited number of bedload samples using the Helley-Smith sampler to compare the significance of bedload transport with that of suspended sediment transport. All suspended sediment loads were used to determine the source and fate of such sediments and to provide calibration data for the hydrologic simulation model of the rivers tributary to the estuary.

AQUATIC LIFE

Because aquatic life can have significant effects upon water quality, and, conversely, because water quality can affect desirable forms of aquatic life, data on aquatic life were collected during the estuary study field monitoring program. A fishery survey of the estuary was conducted by staff of the Wisconsin Department of Natural Resources under contract to the Regional Planning Commission, and algal productivity measurements were made by the

[14] *Harold P. Guy and Vernon W. Norman, Field Methods for Measurement of Fluvial Sediment, U. S. Geological Survey Techniques of Water Resources Investigations, Book 3 Chapter C2 (U. S. Government Printing Office, Washington, D. C., 1970).*

Sewerage District staff. The following sections describe these data programs. Plankton data collection in the outer harbor by the MMSD is described earlier in this chapter. Fishery survey and algal productivity data are summarized in Chapter VII of this volume.

Fishery Surveys by the Wisconsin Department of Natural Resources

A fishery survey of the Milwaukee Harbor estuary was conducted by staff of the Wisconsin Department of Natural Resources (DNR) to qualify and quantify species; identify important spawning areas; evaluate the effects of toxic substances; and identify rare, endangered, or threatened species. More specifically, the purpose of the fishery survey was to: 1) establish a baseline fishery inventory prior to completion of the District pollution abatement program; 2) identify spawning areas worthy of protection; 3) identify rare, endangered, or threatened species, and their habitat; and 4) determine levels of toxic substances in fish tissue to establish fish consumption advisories, and to assist to the extent possible in relating such substances to their general sources.

Sampling was conducted in the Milwaukee, Menomonee, and Kinnickinnic River estuaries, in the outer harbor, and inside the breakwater south of the outer harbor at the 42 sites shown on Map 40. Fish were captured using fyke nets or gill nets, or through use of electro-shocking methods. Netting was conducted four days each week from March 28, 1983, through October 4, 1983. Electroshocking was conducted monthly at selected locations only.

Fish were identified to the lowest possible taxonomic level, counted by species, and the age of selected individuals was estimated. Fish spawning areas in the outer harbor were identified and mapped. The tissue of selected individuals from six of the sampling sites was analyzed for the 24 toxic substances listed in Table 44. Three composite tissue samples with five fish in each sample were prepared and analyzed for fish collected at each site.

Algal Productivity Measurements by the Milwaukee Metropolitan Sewerage District

Algal productivity data were collected for the Milwaukee Harbor estuary study by the District staff at five locations: the Milwaukee River at the upstream side of the North Avenue dam, at E. Walnut Street, and at the Chicago & North Western bridge; the Menomonee River at S. 25th Street; and the Kinnickinnic River at S. 1st Street and at E. Greenfield Avenue extended. Produc-

Table 44

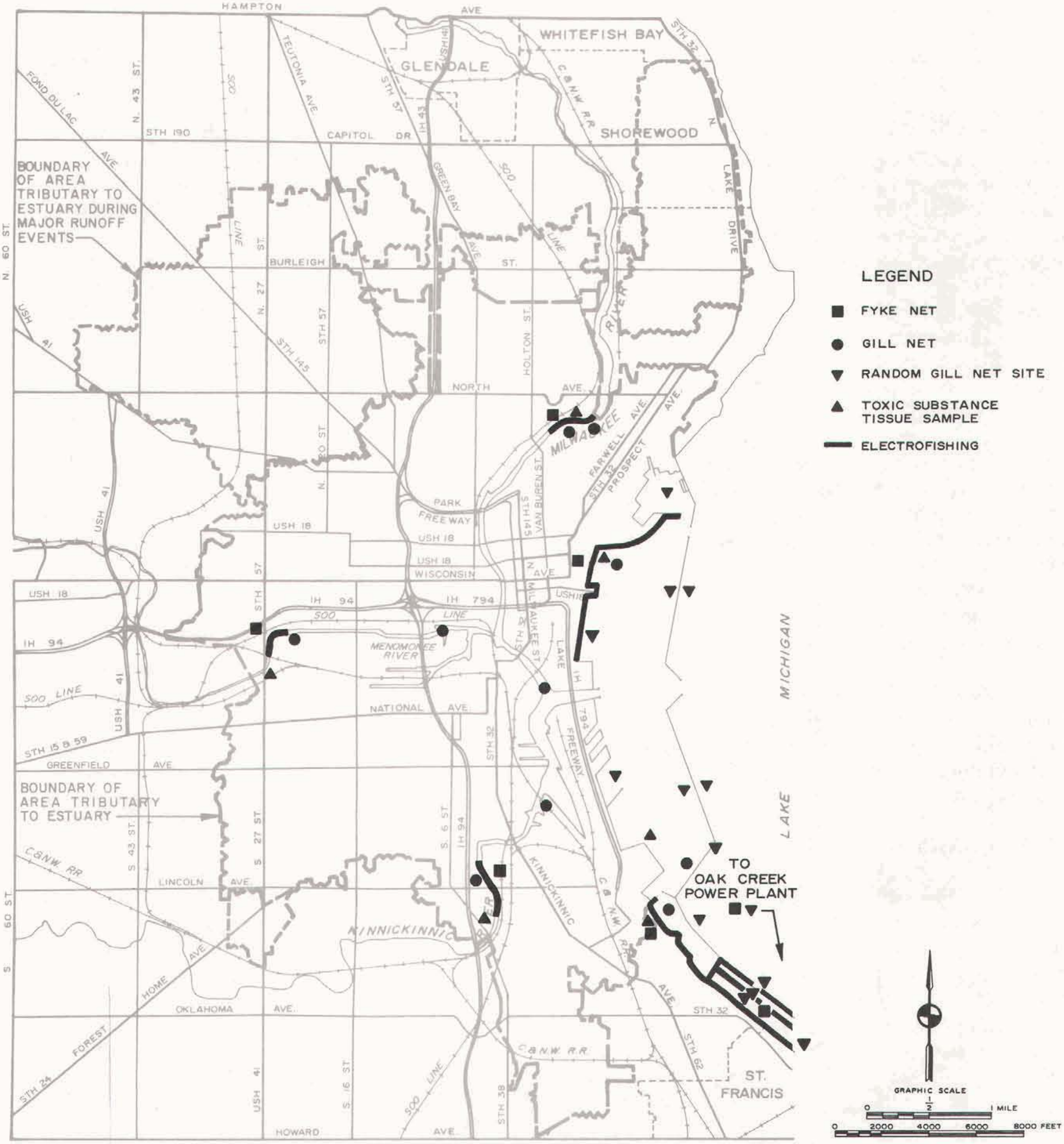
TOXIC SUBSTANCES ANALYZED IN FISH TISSUE FOR THE MILWAUKEE HARBOR ESTUARY FISH SURVEY BY THE WISCONSIN DEPARTMENT OF NATURAL RESOURCES

Pesticides	Metals	Other
Aldrin	Arsenic	Polychlorinated biphenyls (PCB's)
Bis (2-ethylhexyl)-Phthalate (DEHP)	Cadmium	
Chlordane	Chromium	
Dichloro-diphenyl-trichloro-ethane (DDT) and its metabolites DDD and DDE	Cobalt	
Dieldrin	Copper	
2, 4 dinitrotoluene (2, 4-D)	Lead	
Endrin	Mercury	
Heptachlor	Zinc	
Hexachlorobenzine		
Hexachlorocyclohexane		
Methoxychlor		
Napthalene		
Pentachlorophenol		
Polynuclear Aromatic Hydrocarbons (PNA's or PAH's)		
Toxaphene		

Source: SEWRPC.

Map 40

LOCATIONS OF FISHERY SURVEY SITES SAMPLED BY THE WISCONSIN DEPARTMENT OF NATURAL RESOURCES IN 1983 FOR THE MILWAUKEE HARBOR ESTUARY STUDY



During the intensive field investigation period of the study, the Commission, in cooperation with the Wisconsin Department of Natural Resources (DNR), conducted a survey of the fishery of the Milwaukee Harbor estuary and adjacent Milwaukee Bay. This survey was conducted for the purpose of establishing a baseline fishery inventory prior to the completion of the pollution abatement program; to identify spawning areas worthy of protection; to identify rare, endangered, or threatened species and their habitat; and to determine the levels of toxic substances in fish tissue.

Source: SEWRPC.

tivity measurements were taken at each site three times in each year of the two-year field data collection period.

The light-dark method was used to measure productivity, with measurements made at multiple depths at each site. More specifically, the measurements were made near the surface and at about 0.8, 1.4, 1.9, 2.4, 2.9, 3.4, 3.9, 5.9, 10.9, 15.9, and 20.9 feet below the surface as depth permitted. Four sets of bottles were deployed near dawn in a rack that minimized shading, with a rack of bottles being removed at three-hour intervals for measurement of the dissolved oxygen concentration in each bottle. Dissolved oxygen was measured using a probe calibrated by the Winkler titration method. In some cases, the initial dissolved oxygen content was chemically reduced to a concentration between 2 and 3 milligrams per liter to avoid the development of supersaturated levels during the incubation period.

Complementary data collected at each site during the productivity tests included vertical profiles of dissolved oxygen, water temperature, specific conductance, pH, and light intensity. At the beginning and end of each test, water samples were taken at each bottle depth and analyzed for nutrients and chlorophyll-a to determine changes during the test period.

Algal productivity data were collected to provide the input needed for the simulation of dissolved oxygen and to assist in the evaluation of potential algal biomass in the estuary following pollution abatement.

SPECIAL TOXICITY SURVEYS

To provide information on acute or chronic toxic conditions within the upstream river reaches, inner harbor, outer harbor, and Lake Michigan, a series of five toxicity surveys was conducted over the period August 20, 1984, through November 8, 1984. During each survey, water samples were collected at the 16 sites. Individuals of the zooplankton (Ceriodaphnia affinis/dubia) were then exposed to the water for a seven-day period using a procedure described by Mount and Norberg of the U. S. Environmental Protection Agency.[15] The survival of adults and the reproduction of young Ceriodaphnia were recorded on the third, fifth, and seventh days of exposure to determine any acute or chronic toxic effects. Concurrently, water quality analyses were conducted on the water samples to measure the concentration of the 29 metals.

Of the five surveys conducted, three were considered wet-weather surveys because significant rainfall occurred either on the day of sampling or on one of three days preceding the sampling day. Based on these data, the surveys of September 10, September 24, and October 8, 1984, were classified as wet-weather event surveys, while the surveys of August 20 and November 8, 1984, were classified as dry-weather surveys.

SUMMARY

The water resources monitoring program for the Milwaukee Harbor estuary study included an extensive data collection and collation effort, including the collection and collation of definitive data on meteorology, groundwater levels and quality, streamflow and quality, estuary and lake water levels and currents, bottom and suspended sediment quantity and quality, and the fishery resources and algal productivity of the estuary.

Data were collected to: 1) characterize the quality and quantity of runoff water from rural areas, from urban areas served by separate sewer systems and by combined sewer systems, and from riparian lands bordering the estuary; 2) characterize the quality of groundwater discharging to the estuary; 3) provide a sound basis for the calibration and verification of the mathematical water level, flow, and quality simulation models utilized for characterizing water quality conditions on an areawide basis, for hindcasting water quality for critical periods prior to the monitoring program, for forecasting water quality under alternative future scenarios, and in computing flood flows and stages and storm damage in the estuary; 4) help determine the need for dredging in the estuary for both navigation and water quality enhancement; and 5) characterize existing aquatic fauna, flora, and habitat in the estuary.

Meteorological data were collected during the field data collection program at 13 sites operated by the National Weather Service; 15 sites operated by the City of Milwaukee, Bureau of Engineers; four sites operated by the Milwaukee Metropolitan Sewerage District (MMSD); and two

[15] *D. I. Mount and T. J. Norberg, "A Seven-Day Life-Cycle Cladoceran Toxicity Test," Environmental Toxicology and Chemistry, Vol. 3, No. 3, September 1984.*

sites operated by the U. S. Geological Survey (USGS). The records consisted, for the most part, of precipitation data, However, other meteorological variables, including wind speed and direction, solar insolation, air temperature, and relative humidity, were also collected at selected stations on a continuous basis during the monitoring period. Data were collected in order to ascertain the relationship of prevailing meteorology to water quality conditions. The data were used to characterize meteorological conditions during the monitoring program and as input to hydrologic, hydraulic, and water quality models. The data were also used in algal productivity studies.

A long-term groundwater monitoring program—extant prior to the start of the estuary study—was continued during the study by the USGS at 16 sites in and near the Milwaukee Harbor watershed. The resulting data were used to characterize long-term groundwater conditions in the study area and as a comparison with groundwater conditions existing during the monitoring program. Groundwater level and quality data were collected at six new observation wells installed by the USGS in the Menomonee Valley specifically for the estuary study. These data, collected from October 1982 through July 1984, were used to estimate the potential impact on surface water flow and quality of groundwater flow and associated pollutant loadings.

Streamflow data collection included the operation of eight continuous record gaging stations by the USGS, and the periodic measurement of streamflow at four additional sites by the Regional Planning Commission. The resulting data were used to assist in characterizing the hydrologic and hydraulic conditions of the rivers tributary to the estuary and discharges from the combined sewer system; to assist in calibrating and verifying the hydrologic and hydraulic simulation models of the estuary, the results of which were used, in turn, as input to the water quality simulation model; and to compute pollutant transport loads using water quality data collected during the monitoring program.

Continuous water level monitoring was conducted at six sites in the harbor estuary by the USGS; at four sites by the Sewerage District; at four sites by the City of Milwaukee, Bureau of Engineers; and at one site by the National Ocean Survey. Data were collected from these sites from January 1982 through November 1984. The water level data collected in the inner harbor were used to assist in the hydrodynamic characterization of the inner harbor estuary. The data served as the basis for the calibration and verification of a one-dimensional flow simulation model and a two-dimensional hydrodynamic model, which in turn were used as input to the water quality models of the estuary. The outer harbor data were used to analyze the effects of long- and short-term lake level oscillations upon water levels, circulation, and pollutant dispersion for water quality and navigation studies.

Continuous monitoring of current speed and direction at multiple depths in the estuary was conducted by the MMSD at three locations. In addition, the USGS took periodic measurements near the mouth of the Milwaukee River, and the MMSD took periodic measurements at two sites in the inner harbor and five sites in the outer harbor. These data were collected to document qualitatively and quantitatively the effect of Lake Michigan on estuary circulation; document qualitatively and quantitatively the effects of the Wisconsin Electric Power Company valley power plant on circulation in the estuary; estimate discharge at the downstream limits of the inner harbor to assist in calibration of the one-dimensional flow model of the inner harbor; and provide calibration and verification data for the two-dimensional hydrodynamic model of the inner harbor.

The surface water quality data collection program in the rivers, the estuary, and Milwaukee Bay included weekly baseline sampling at 34 sites by the MMSD; and intensive sampling of selected runoff events at these 34 sites by the USGS, the Sewerage District, and the Regional Planning Commission. These data were collected over the period from January 1982 through November 1984. Continuous water quality monitoring at three sites in the estuary and two sites on the Milwaukee River was also conducted by the Sewerage District. Monitoring was conducted from January 1982 through November 1984. Estuary shoreland runoff sampling was conducted during two runoff events at eight sites by the Commission staff and a consultant. The water quality variables measured were, for the most part, conventional pollutants affecting dissolved oxygen, including phosphorus, nitrogen, organic carbon, biochemical oxygen demand, chemical oxygen demand, and suspended solids. In addition, heavy metals were measured. The overall purpose of the surface water quality monitoring program was to identify sources of pollution by sampling at strategically located sites within rural areas, and at sites in separate sewer, combined sewer, and unsewered areas within urban areas; evaluate the effects of pollutants on receiving water quality; and provide data for calibration and verification of water quality simulation models to be used for predicting water quality during selected critical historical periods, and for preparing alternative future land use and pollution abatement measures.

The sediment data program conducted by the Sewerage District included the collection at 15 sites of sediment cores, which were analyzed for both physical and chemical characteristics with changing depth, and of interstitial water quality; at eight sites of sediment gas production and sediment oxygen demand; and at nine sites of sediment deposition. These data were collected over the period from April 1982 through December 1983. The USGS monitored suspended sediment at seven gaging stations on a daily basis, with more intensive automatic sampling during runoff events. At 10 other sites the USGS sampled suspended sediment on a weekly to monthly basis, with more intensive sampling during selected runoff events. These data were collected during the period from June 1982 through December 1983. The USGS also took a limited number of measurements of bedload sediment transport to supplement the suspended sediment data. These data were collected for use in analyzing bottom sediment processes, to determine the source and magnitude of constituents important in those processes, to provide calibration and verification data for sediment algorithms used in the estuary water quality model, and to provide data for dredging and dredge spoils disposal studies.

Aquatic biology data collected during the field monitoring program included plankton sampling at four sites by the District staff during baseline water quality surveys, algal productivity surveys at five sites by the District staff, and fish surveys at 42 sites by the Wisconsin Department of Natural Resources. These fishery data were collected during the period from March 1983 through October 1984. Algal productivity data were collected from July 1982 through July 1984. These data were collected to provide a baseline for plankton and the fishery prior to the completion of the Milwaukee Metropolitan Sewerage District pollution abatement plan; to identify spawning areas worthy of protection; to identify rare, endangered, or threatened species and their habitat; to determine the levels of toxic substances in fish tissues; to provide algal productivity data for input to the estuary water quality simulation model; and to predict algal biomass in the estuary following pollution abatement.

The Milwaukee Harbor estuary study water resources monitoring program was one of the most intensive such programs ever conducted. The sediment and water quality sampling programs, in particular, were very comprehensive in scope and intensive in sampling frequency, both temporally and spatially. This intensive sampling program was necessary to provide the data required to develop a thorough understanding of this complex estuarine system. Only then could reliable analyses be conducted of the effects of alternative means of pollution abatement in the estuary.

Chapter V

DESCRIPTION OF THE HYDROLOGIC-HYDRAULIC CHARACTERISTICS OF THE MILWAUKEE HARBOR ESTUARY

INTRODUCTION

Hydrology may be defined as the study of the physical behavior of the water resource from its occurrence as precipitation to its entry into streams and lakes and its return to the atmosphere via evapotranspiration. In accordance with this definition, an inventory and analysis of the hydrology of an estuary may include consideration of precipitation, evapotranspiration, and other elements of the hydrologic budget; examination of such factors as soil types and land use that affect rainfall-runoff relationships; review of stream gaging records to ascertain the volume and timing of that portion of the precipitation that ultimately reaches the surface water system of the estuary as runoff; determination of inflow to the estuary from the downstream end, in this case inflow from Lake Michigan; and determination of the volume of water that moves to and from, and is contained within, the aquifers lying beneath the study area.

Hydraulics may be defined as the study of those factors that affect the physical behavior of water as it flows within stream channels and associated natural floodlands, under bridges, through estuaries and lakes, and within the underlying aquifer system. In accordance with this definition, an inventory and analysis of the hydraulics of the study area may include examination of the length, slope, flow resistance, and other characteristics of stream reaches within the study area; determination of the hydraulic significance of the bridges located throughout the estuarial system; characterization of Lake Michigan flood and ebb flows and wave conditions within the Milwaukee Harbor estuary; and determination of the flow characteristics of the aquifers underlying the study area.

Comprehensive planning for the sound management of the water resources within the Milwaukee Harbor estuary requires a knowledge and understanding of hydrologic-hydraulic processes and the role of these processes in the cause and resolution of developmental and environmental problems. A clear understanding of the physical factors which influence the hydrologic-hydraulic structure of the estuary is also necessary. Among these physical factors are waves, currents, dispersion, stratification, tides, wind set-up, upwellings, seiche, long-term water level fluctuations, and runoff and tributary inflows. The objective of this chapter is to investigate the effect of such physical factors on the estuarial environment and to describe the hydrologic-hydraulic system of the Milwaukee Harbor estuary. An understanding of this system is important to the Milwaukee Harbor estuary planning program inasmuch as the system and the processes that occur there form the framework within which all the water resource and water resource-related problems of the estuary must be analyzed and resolved. Because of the interdependence between land use and surface water quality and quantity, any planned modification to, or development of, one element of the hydrologic-hydraulic system must consider the potential effect on all other elements of the system.

LAKE MICHIGAN PHYSICAL PROCESSES AND PHENOMENA

Among the physical factors affecting the hydrologic-hydraulic system of Lake Michigan and, in turn, the Milwaukee Harbor estuary are water stratification, wind set-up, seiche, upwelling and downwelling, ice action, waves, currents, and long-term water-level fluctuations in the Lake Michigan-Huron system. These factors are defined and described in more detail below.

Water Stratification

Water stratification is the process by which a body of water is divided into distinct layers by differences in density. Density differences may occur with varying concentrations of soluble or insoluble substances, or with changes in temperature, the latter being the dominant factor in Lake Michigan.

Lake Michigan undergoes an annual temperature cycle, as do most lakes in the temperate zone. This temperature cycle is considered to begin with the spring overturn when the entire water column is uniform in temperature and wind can vertically mix the waters of the lake. Whereas the duration of the spring overturn is largely dependent upon the climatic conditions, wind-induced mixing will continue to prolong the homogeneous temperature of the water. With the seasonal increase in solar radiation, the surface waters of the lake begin to warm, producing a thermal gradient in the water column. The temperature gradient usually does not become established immediately following overturn, however, as it is disrupted by wind and wave action causing warmer surface water to be mixed throughout the water column. The temperature to which the bottom waters of Lake Michigan may rise is determined by these meteorological factors. Surface warming over long periods of relatively calm weather permits the formation of a strong thermal gradient, and the wind energy needed to disrupt this gradient increases as the temperature difference increases. The thermocline, or metalimnion, the layer of water which exhibits the greatest rate of temperature change, lies between the epilimnion, the well-mixed wind-affected surface layer of the lake, and the hypolimnion, the heavy, cold, bottom layer of the lake which is minimally affected by wind and generally exhibits lower dissolved oxygen levels. The thermocline develops as surface heating proceeds, with the stability of the separate water layers increasing until the thermocline essentially maintains a constant boundary. This is the situation which is present in Lake Michigan during the summer months.

In autumn the processes are reversed, as solar radiation decreases to a point where heat loss exceeds heat intake and the temperature of the epilimnion decreases. Accordingly, stratification becomes less stable and a period occurs when winds are able to induce a complete mixing of the water column. This event is referred to as the fall overturn and is, as stated above, dependent upon meteorological conditions and upon the depth and morphology of the lake. A less distinct thermocline may form during the winter. When the surface waters of Lake Michigan reach a temperature close to the freezing point (32° F), the water is less dense than water at 39° F, which settles to the bottom, with the 32-degree water remaining near the surface. The density difference between the two temperatures, however, is very small, and the resulting stratification may easily be broken down by light winds where water depths are relatively shallow. Winter stratification persists, however, during periods of ice cover, which impedes wind-induced mixing. The great volume of water in Lake Michigan has usually been warmed enough during the summer so as to prevent the formation of ice—a usual occurrence on smaller lakes in the temperate zone—over all of the lake during winter. Ice does form, however, in the shallow coastal areas.

During the fall and spring overturns, nutrients from degradation of organic material in the hypolimnion are introduced into the surface waters for uptake and utilization by phytoplankton. This cycling of nutrients is an extremely important factor in the biological activity of Lake Michigan.

Water stratification may also be caused by the difference in density in water containing soluble or insoluble substances. Density stratifications of this nature, however, are not as prevalent in the southeastern Wisconsin coastal waters as are thermal stratifications. The density changes resulting from such substances may counteract or augment density changes caused by thermal effects.

Several factors determine the characteristics of thermally induced water stratification, including the temperature of the water at different points in the water column, the amount and rate of heat addition or loss, and the amount and rate of heat dispersion. The determining factors for water stratifications caused by sediment, salt, or other soluble or insoluble substances are the density profile caused by the substance, the amount of mixing, and the rate of addition and resulting concentration of the substance.

Water stratification may affect certain phenomena such as nutrient and oxygen exchange between the layers. Different materials introduced into a water body may be limited to a certain stratified layer. The spring and fall stratification processes act to segregate the water column into a nutrient-consuming portion located in the epilimnion where, because light is adequate, the majority of biological production and activity occurs, and the hypolimnion, where decomposition of the organic material originating, for the most part, in the epilimnion occurs. As already noted, during periods of small temperature differences between the layers, the water column may fully mix, introducing nutrients from the hypolimnion into the epilimnion and oxygen from the epilimnion into the hypolimnion.

Another phenomenon caused by stratification is the "thermal bar." Lake water begins to warm in the spring, with the shallower coastal waters warming faster than the deeper waters. This is due to the fact that shallower waters are able to mix more completely sooner than deeper waters are able to mix. A sharp differentiation occurs at the intersection of the quickly warming shallow waters and the colder deeper waters. At this intersection, mixing occurs which results in intermediate temperature ranges. Because of the behavior of water densities at temperatures of approximately 39° F, the density of this mixed water mass would be greater than the density of either of the colder or warmer parent water masses. The mass then sinks toward the bottom. As the shallower water continues to warm, the thermal bar migrates outward away from the shore. Thermal bars can impede outflow from rivers into the lake, thus temporarily containing a large part of these waters in the nearshore zone.

The significance of water stratification is that it may separate the water body into different environments, and, through such partitioning, it affects the distribution of biota and the chemical and physical characteristics of the lake water.

Wind Set-Up

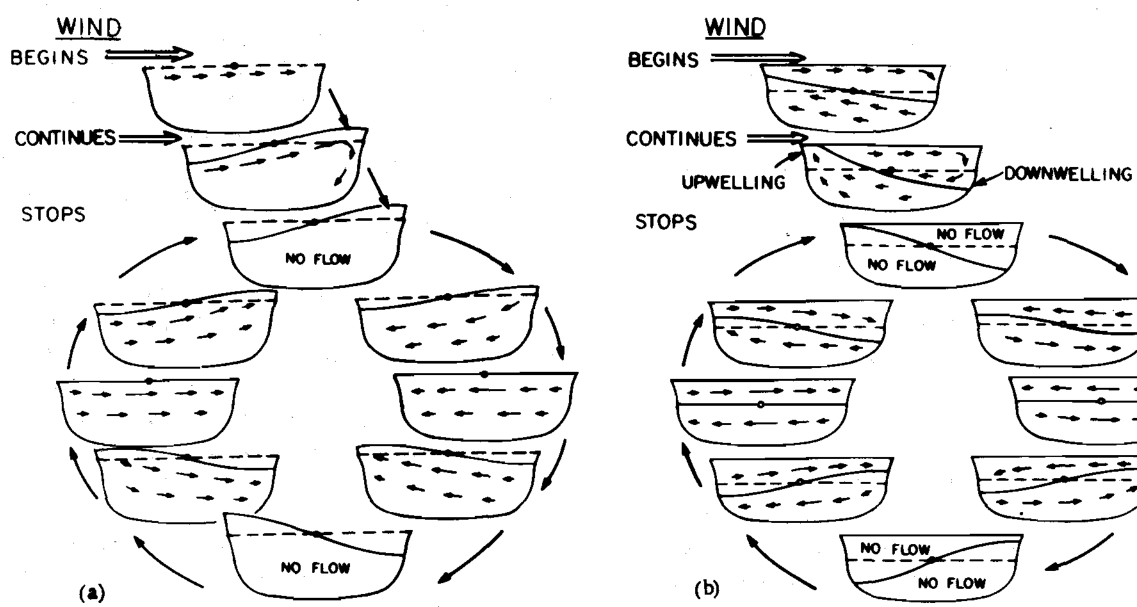
The application of a wind with a relatively steady speed and direction can, if it is of sufficient duration, cause a buildup of water—known as set-up—on the lee side of the lake. A set-up can occur on the lake regardless of whether it has a relatively homogeneous density—as Lake Michigan is likely to have from late fall to early spring—or is density-stratified—as Lake Michigan is likely to be during the remainder of the year.

In a lake as large as Lake Michigan, a set-up is also influenced by the rotation of the earth. The principle of the conservation of angular momentum indicates that the effect of such rotation is to produce a force—called the Coriolis force, which deflects all horizontal motion to the right in the northern hemisphere—which also causes a secondary set-up to occur across the wind direction rather than just directly downwind.

Wind Set-Up on an Unstratified Lake: Figure 28 (a) presents a schematic representation of wind set-up on a lake when the lake has a homogeneous density. Given sufficient time, the wind and Coriolis force responsible for veering water to one side of the lake come into equilibrium with the gravity force acting as a result of the inclined water surface. This is a quasi-steady condition in that although the upper boundary of the lake may assume a fixed position, surface waters at that boundary are moving up the incline, as shown in (a) of Figure 28, and there is a return flow toward the windward side of the lake at some depth below the lake surface. One significant effect of wind set-up on the lake when the lake is homogeneous is that it may initiate, as discussed below, a standing wave motion known as a seiche, involving the entire lake.

Figure 28

SCHEMATIC REPRESENTATION OF WIND SET-UP, UPWELLING AND DOWNWELLING, AND SEICHE IN UNSTRATIFIED AND STRATIFIED LAKES



NOTE: Models of (a) a surface seiche in a homogeneous lake and (b) an internal seiche in a two-layered lake. The initial action of the wind and one cycle of the ensuing oscillation is shown. The broken line represents the equilibrium position of the water surface in (a) and of the interface in (b).

Source: C. H. Mortimer.

Wind Set-Up on a Stratified Lake: Figure 28 (b) presents a schematic representation of wind set-up on a lake when it has a two-layered, density-stratified structure. Given sufficient time, the wind and Coriolis force moving the water up the inclined lake surface come into equilibrium with the gravity forces acting as a result of inclined lake surface and the inclined interface between the upper layer of the lake and the denser lower layer. As in the case of the homogeneous lake, this is a quasi-steady condition since, although the lake surface and the interface between the upper and lower layers may assume fixed positions, water motion occurs in both the upper and lower layers of the lake in response to the shear stress exerted by the wind.

When wind set-up occurs in a thermally stratified lake and equilibrium is reached, hydrostatic equilibrium requires that the movement of the thermocline between the two layers be much larger than the magnitude of the set-up of the water surface immediately above. Assume, for example, that it is the summer season and Lake Michigan is in a stratified condition that can be approximated as two layers—an upper layer at a temperature of approximately 65°F and a lower layer at a temperature of approximately 45°F—and that a set-up occurs along the eastern shore. Under these conditions, each unit of set-up along the eastern shore will be accompanied by about 700 units of decline in the thermocline along the eastern shore, and a rise of similar magnitude along the western shore. Thus, a 0.1-foot set-up along the eastern shore will depress the thermocline about 70 feet on the east side of the lake and elevate it the same distance on the west side of the lake.

An example of a wind set-up condition is provided by a useful set of water level observations made around the periphery of Lake Michigan on September 13, 1963. The observations indicated that an approximately 30-mile-per-hour wind from the north-northeast direction produced a set-up of about one foot along the Lake Michigan shore between Milwaukee and Chicago.

Seiche

Upon cessation of the winds that produced set-up in either stratified or unstratified lakes, a condition of nonequilibrium exists. The lake responds by moving toward the equilibrium state, which is a horizontal position for the lake surface and, if the lake is thermally stratified, a horizontal position for the thermocline. In moving toward equilibrium, however, the lake surface and/or thermocline at a given location may fluctuate vertically, with the fluctuations diminishing in size with time. This phenomenon is referred to as a seiche.

Although seiches in Lake Michigan are most often caused by cessation of winds that produce set-up, they can be brought about by other processes that tend to temporarily move a portion of the water surface from its equilibrium position. For example, seiches have been known to be generated in Lake Michigan by sudden barometric pressure increases associated with summer squall lines moving across the lake.

Seiche in an Unstratified Lake: Figure 28 (a) is a schematic representation of the occurrence of a seiche following wind set-up in an unstratified lake. Upon cessation of the wind, the initial overall motion of the water in the lake is from the higher side, where the set-up occurred, to the lower side. The motion continues in this direction such that the water surface passes through the equilibrium position, producing a similar magnitude increase above prestorm water level on the opposite side of the lake. This oscillating pattern continues with diminishing amplitude until equilibrium is achieved.

Seiche in a Stratified Lake: Figure 28 (b) is a schematic representation of the occurrence of a seiche in a two-layered stratified lake. Upon cessation of the wind, the lake undergoes a period of damped oscillations, with flow in the epilimniom and hypolimnion generally moving in opposite directions until both the lake surface and the interface between the upper and lower layers assume the horizontal equilibrium position. As noted in the discussion of wind set-up in a two-layered stratified lake, the amplitude of the interface oscillation may be expected to be much larger than the amplitude of the oscillation of the water surface.

An example of a seiche is provided by the set of water level observations made around the periphery of Lake Michigan on September 13, 1963, which indicate that the seiche wave at the lake surface had an amplitude of about 0.5 foot along the southwestern shore of the lake and an oscillation period of close to nine hours.

A seiche can be a significant phenomenon on Lake Michigan because of the resulting fluctuations in temperature and water quality in the coastal areas associated with upwelling and downwelling—phenomena described below—which affect recreational activities, and municipal and industrial water supply. A seiche on the open lake and the associated influx of water into long narrow tributary areas such as bays and estuaries can, because of lateral constriction of the flow, cause larger fluctuations in the water level of the confined bodies of water concerned than in the open lake. For example, during the September 13, 1963 seiche action on Lake Michigan, when the amplitude of the seiche wave was about 0.5 foot, an oscillation at the southern end of Green Bay exhibited an amplitude of about 2.5 feet. Waves of such large amplitude in protected areas like bays and estuaries, which are frequently used for mooring commercial ships and recreational vessels, can cause damage to the craft and to the mooring facilities.

Upwelling and Downwelling

Assuming that a lake is stratified and that a large set-up occurs along one boundary of the lake, the phenomenon of downwelling will occur along that boundary of the lake while upwelling will occur along the opposite boundary of the lake. Figure 28 (b) includes a schematic representation of upwelling and downwelling in the case of a two-layered stratified lake. Upwelling, which is common along the western shore of Lake Michigan during the late summer and into the fall when offshore winds predominate, is the process whereby some of the colder, more dense bottom waters from the hypolimnion move up to the surface as a result of severe inclination of the thermocline.

A significant effect of upwelling is the occurrence of cold water in the near-shore zone with the associated undesirable effect on swimming, but perhaps desirable effects on fishing and on municipal or industrial water supply. Upwelling does provide a mechanism for the transfer of some nutrients from the hypolimnion to the epilimnion, which may have adverse impacts, especially in eutrophic lakes, while downwelling permits the introduction of oxygen into the hypolimnion, which may have a favorable effect.

An example of wind set-up on Lake Michigan producing upwelling at Milwaukee in August 1942 is shown in Figure 29 by means of an east-west cross-section through the lake in a vertical plane—from Milwaukee, Wisconsin to Muskegon, Michigan—onto which are superimposed isotherms—lines of constant temperature. Thermal stratification, indicating density stratification, is clearly evident in that the surface waters of the lake are mixed and at a temperature of about 70° F, while the lower, thicker, more dense layer is much colder, having a temperature in the 40° F to 50° F range. Wind direction was from the south on the day on which the data were obtained and, therefore, a secondary wind set-up occurred across and to the right of the wind direction.

Although the surface set-up is not shown in Figure 29, the occurrence of this set-up is clearly indicated by the inclined interface between the warm upper layer and the colder, more dense lower layer. That interface intersects the lake surface at Milwaukee with a water temperature of about 50° F and slopes down from the west to the east at about one foot per mile, and is about 80 feet below the lake surface off Muskegon, where the surface temperature was about 70° F.

Ice Phenomena

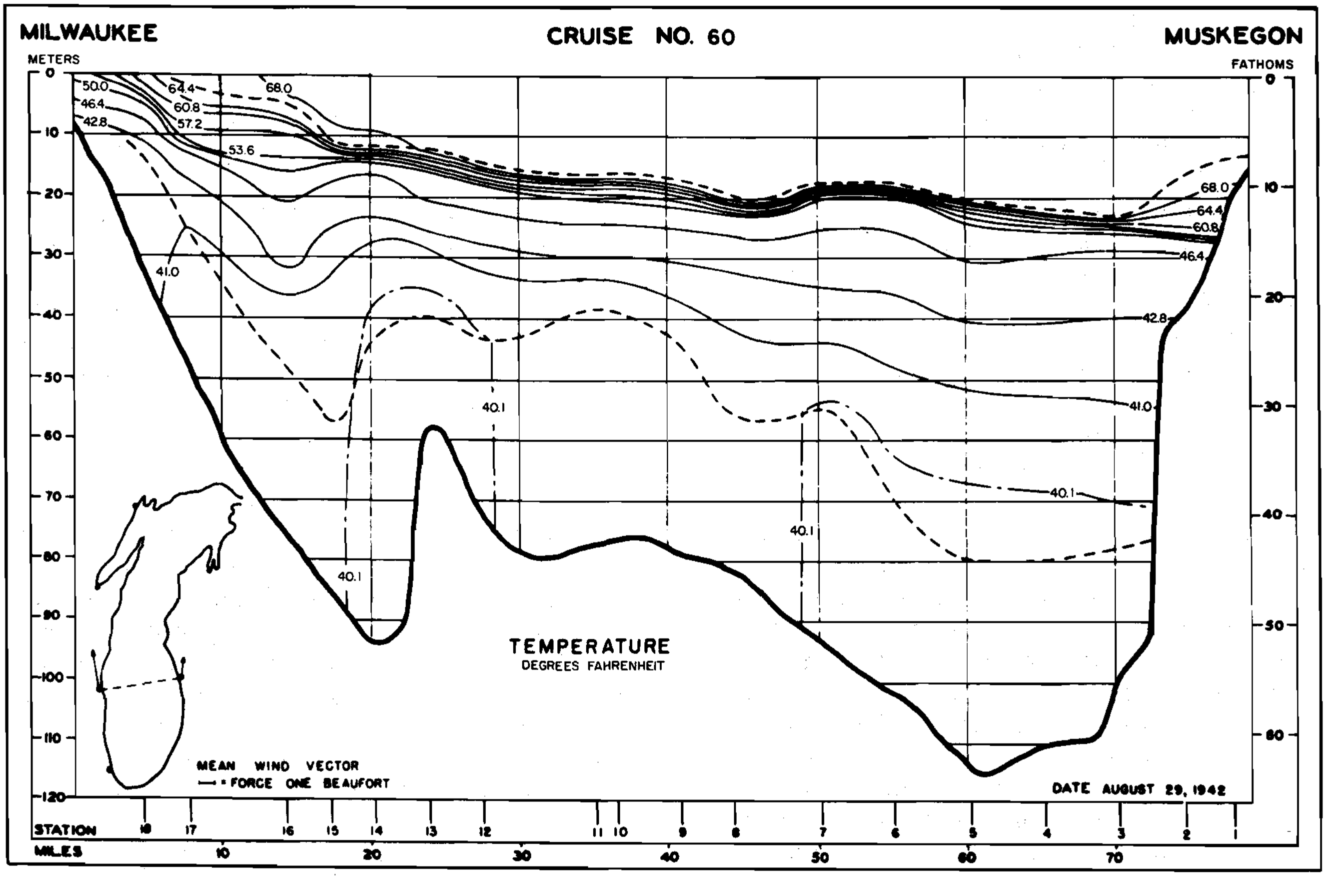
Ice behavior and the associated favorable and unfavorable effects constitute an important consideration in understanding environmental and developmental problems in the coastal system, and are of particular importance to the proper engineering of structures and facilities in both the nearshore and estuary subsystems. Ice phenomena are an annual occurrence in the coastal system of the Region because of the severe winters that characterize the climate of the area.

In order to relate ice phenomena and the associated problems to the coastal zone of southeastern Wisconsin, ice types can be broadly categorized as stationary ice, such as that present along the shore and in parts of the estuary areas during the winter period, and ice floes, such as those present during the ice breakup period in late winter or early spring and, to a lesser extent, during the ice formation period in late fall and early winter.

The Formation and Characteristics of Stationary Ice: The life cycle of a stationary ice formation is composed of three relatively distinct periods: the freeze-up period, the ice growth period, and the ice-melting period, which correspond, respectively, to the late fall-early winter, winter, and late winter-early spring seasons. The rate and extent of ice formation during the freeze-up period are a function of heat exchange between the water and atmosphere, which is in turn influenced by air temperature, wind velocity, and solar radiation; the initial amount of heat stored in the water body, which is in turn dependent, in part, on water depth and temperature; and the amount of inflow of warm water to the site, which is in turn dependent on the rate and temperature of inflowing water.

Figure 29

WIND SET-UP AND UPWELLING IN LAKE MICHIGAN: AUGUST 29, 1942



DISRIBUTION OF TEMPERATURE, °F, ALONG THE MILWAUKEE-MUSKEGON TRANSECTION

Source: C. H. Mortimer.

The first or freeze-up period approaches its final stage as a thin sheet of ice appears on the lake surface, usually beginning along the edges of the lake and growing outward into the lake.

The second, or ice-growth, period occurs when the thickness of the ice increases. It is a period of particular interest to engineers because the greatest horizontal and vertical forces generally associated with ice occur during this period. The ice sheet normally grows downward into the water as a result of the conduction of heat energy from the water up through the ice and into the atmosphere. Because of the insulating effect of the ice and, sometimes, of snow accumulation on the ice, the rate of heat transfer decreases as the ice thickens and as snow cover deepens and, accordingly, the rate of ice thickening decreases.

Several factors are operative during the third or ice-melting period, including heat gain from the atmosphere through radiation and conduction; the presence of snow on the ice surface, which determines the reflectivity of the surface; the mechanical breaking action of wind and currents on the weakened ice; and the inflow of warm water onto or underneath the ice sheet.

The normal length of the freezing season along the coastal system of southeastern Wisconsin is about three and one-half months, extending from about the first of December through mid-March. Stationary ice typically begins to appear along the shores of southeastern Wisconsin about the middle of December, and by early January an initial ice sheet of about one-half-foot thickness may be formed. The initial ice sheet is likely to be broken up by wind and wave action, thus restarting the process that ultimately leads to the development of a stable ice sheet. By the end of the second or ice-growth period, ice within protected areas along the coastal system of southeastern Wisconsin may be expected to achieve a thickness of about three feet.

Ice-Related Problems: Floating ice blocks and fragments can scour beaches and undermine bluff toes, thereby contributing to both beach and bluff erosion. On the positive side, however, the stationary ice along the shore during much of the winter serves as a natural protective barrier against wave action, thus protecting both the beach and bluff area during that period.

The freezing of wave wash and spray, perhaps accompanied by the wave-induced piling of ice blocks and fragments, on structures intended for harbor protection or other purposes in the coastal zone can exert large downward pressures on these structures that may lead to structural damage and failure. Vertical forces, both upward and downward, may also be exerted on such structures as a result of the upward and downward motion of the ice plate in an estuary area as it moves in response to water-level fluctuations associated with such phenomena as wind set-ups or seiches. The vertical motion of the ice plate may be transferred to hydraulic and other structures by adhesion or mechanical connection of the ice to the structures or, in the case of upward motion, by lifting of the structures such as piers as a result of buoyant forces on stationary ice formed beneath such structures.

Large stationary ice sheets may actually encase entire structures or portions of structures, such as the large rock used to form breakwaters, and physically carry such structures or portions of the structures away as the sheets begin to break up. As a result of such ice action, objects are known to have been moved miles from their point of origin.

Lateral ice pressures will be imposed on structures as a result of warming and, therefore, expansion of ice sheets confined in estuary areas. The magnitude of the resulting ice pressures is dependent on factors such as the rate of air temperature rise, the rate of heat transfer down into the ice sheets, and whether the structures experiencing the thrust are flexible or rigid—ice forces being stronger when the structures are rigid.

Ice can inflict abrasion damage to wooden and concrete structures and can result in freeze-thaw spalling of concrete surfaces. Ice blocks and fragments driven by wind, waves, and currents can also inflict damage on hydraulic structures and various types of commercial and recreational craft moored or in transit through the coastal system.

A favorable feature of stationary ice is that it can provide a very suitable platform for winter construction activities such as pile driving and dredging in estuary areas. Techniques developed to thicken and strengthen ice to improve its suitability as a base for winter construction include surface flooding and snow removal or compaction, the latter of which is done to minimize the insulating effect of the accumulated snow.

Waves

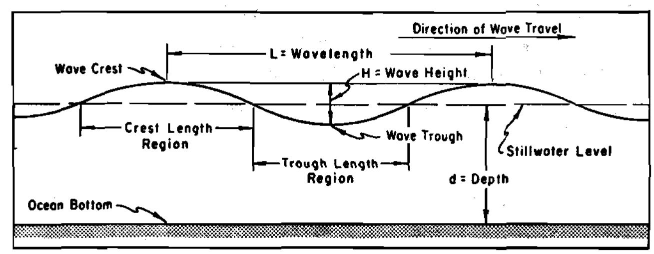
Waves are integrally involved in many estuarial and coastal area processes and properties. Waves are responsible for the production of littoral drift—the movement of sediment along shore. Wave energy is also a major factor in producing turbidity and dispersion. Furthermore, recreational and commercial fishermen and boaters must be concerned about waves because of safety and damage potential. Harbors, marinas, and other man-made shore structures must be designed and built to withstand the actions and effects of waves. An understanding, therefore, of the characteristics and behavior of waves is important to an understanding of other natural characteristics occurring in the estuary and of the consequences resulting from actions or structures imposed by man.

Progressive surface waves—waves which move horizontally away from the source of wave energy and extend from the water surface downward—may be caused by several factors, including, principally, wind and watercraft, and rarely, tectonic disturbances. Unless stated otherwise, the term wave will refer herein to a progressive surface wave. Wind is the factor which accounts for the majority of wave formation in the Great Lakes. Wind waves result from the transfer of energy from moving air to the water through a combination of shear stress and pressure fluctuation. The rate and amount of energy transfer are regulated by the difference in densities between the air and water and the wind velocity and duration. The energy imparted to waves as a result of wind action is dissipated internally within the fluid by interaction with the air above, and in shallow depths, with the bottom; by turbulence on breaking; and by contact with man-made structures.

Watercraft produce waves similar to those developed under the influence of wind. Such waves, however, are weaker, having only the transient presence of watercraft as an energy source, while wind waves are produced by a more continuous force. In addition, watercraft-produced waves are more intermittent than those caused by wind. A third causative agent is a tectonic disturbance such as an underwater eruption or earthquake. The resulting waves of such an action are termed tsunamis (aften mistakenly called "tidal waves"). The occurrence of a tsunami has not been recorded on Lake Michigan because of the absence of strong tectonic movements. Moreover, the tsunamis that could occur on Lake Michigan may be expected to have little impact on the southeastern Wisconsin shoreline because such disturbances in this Region are usually relatively weak.

Figure 30

WAVE CHARACTERISTICS



Source: U. S. Army Corps of Engineers.

Wave Characteristics: Waves are characterized by their height, velocity, period or frequency, length, and energy.

As indicated in Figure 30, wave height is the vertical distance from crest to trough, as distinguished from wave amplitude which is one-half of the wave height. The waves to be encountered within the coastal area of southeastern Wisconsin range in height from surface ripples to approximately 15 feet. Offshore from Milwaukee, the significant deep water wave height—that is, the average height of the largest one-third of the waves in a given group—may be expected to reach 16 feet about once in 10 years and 24 feet about once in 100 years, as shown in Figure 31. The major determinants of wave height in deep water are wind speed and duration, wind direction, and fetch length. Fetch length may be defined as the horizontal distance wind moves over water. The longest possible fetch length relative to the Region is approximately 250 miles in the north/northeast direction over Lake Michigan.

In shallow water along an open coast, wave height is determined by the characteristics of the incoming deep water waves and by bottom topography. As the water depth decreases, the phenomenon of shoaling occurs whereby wave height increases rapidly until breaking occurs.

Wave period is defined as the time which elapses between two successive crests passing an identical point. Wave frequency is the reciprocal of wave period. Wave period and frequency, like wave height, are affected by wind velocity and duration, and additionally by internal viscous damping—the reduction of the period due to the effects of the viscosity of the water. Internal viscous damping is responsible for eliminating the very short-period waves. Longer period waves are little affected by this degenerating mechanism.

Wave velocity includes the speed and direction of a wave. Wave direction is perpendicular to the wave crest and wave speed is the rate at which a wave moves. There are two types of velocities considered in a group of waves: phase velocity and group velocity. Each individual wave has a velocity which is referred to as the phase velocity. A group of waves, however, has a velocity, termed the group velocity, which may not always equal the phase velocity. In deep water the group velocity is approximately one-half the phase velocity. As the water becomes shallower the group velocity increases with respect to the phase velocity until they are both equal in shallow water.

Wave length is the distance between analogous points on two successive waves and is determined by wind speed, wind duration, and water depth. Wave length, period, and velocity are all interrelated. This relationship is shown by the simple equation:

$$C = \frac{L}{T},$$

where: C is wave (phase) speed (feet per second),
L is wave length (feet), and
T is wave period (seconds).

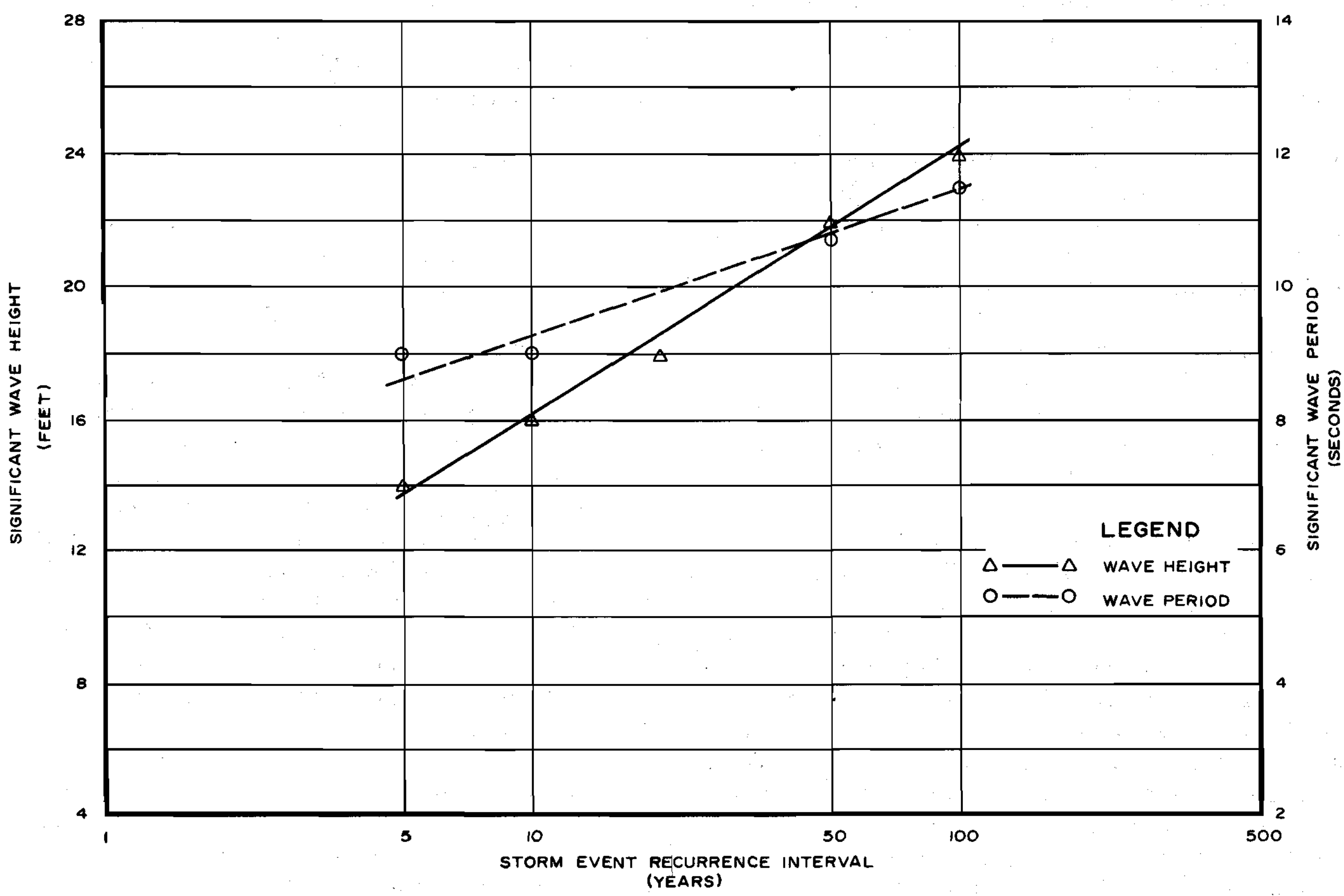
Deep water waves move at a speed calculated as:

$$C = (gL/2\ 11)^{0.5},$$

where: C is wave speed (feet per second),
L is wave length (feet), and
g is the acceleration of gravity (32.2 feet/second/second).

Figure 31

SIGNIFICANT WAVE HEIGHT AND PERIOD FREQUENCY DIAGRAM



NOTE: THE SIGNIFICANT WAVE PERIOD AND WAVE HEIGHT ARE THOSE AVERAGE CHARACTERISTICS EXHIBITED BY THE LARGEST ONE-THIRD OF THE WAVES OCCURRING DURING THE RECURRENCE INTERVAL STORM EVENT.

Source: J. P. Keillor, University of Wisconsin-Sea Grant Institute, Letter to Earl K. Anderson, Port of Milwaukee Harbor Engineer, September 14, 1983; and U. S. Army Corps of Engineers, Design Wave Information for the Great Lakes, Report No. 3, Lake Michigan, Technical Report H-76-1, November 1976.

Shallow-water waves move at a speed calculated as:

$$C = (gD)^{0.5},$$

where: C is wave speed (feet per second),
D is water depth (feet), and
g is the acceleration of gravity (feet/second/second).

Waves may be classified according to a variety of schemes, including form, generating agent, or frequency. In this report, progressive surface waves will be categorized by the depth of water in which they travel: deep water waves, shallow water waves, and transitional waves. Deep water waves—also known as short waves—are waves having a wave length that is equal to two times or less the still water depth. Such waves are too short to be affected by bottom topography. Shallow water waves—also known as long waves—have a length that is equal to 20 times or more the still water depth, with the behavior thereof being strongly influenced by bottom topography. Finally, transitional waves—also known as intermediate waves—are waves with a length/depth ratio greater than two but less than 20, and range from slightly to strongly affected by bottom topography.

As waves travel from deep water to shallow water and ultimately to the shore, their form changes. The transformation begins when the waves first "feel bottom" which occurs when the depth of water is approximately one-half the deep-water wave length. In deep water, the water particles of a wave circumscribe a nearby circular orbit, with only the wave energy being transferred horizontally with the wave form. The water particles return to nearly the same location after the passing of a wave, with usually just a small forward progression being attained. As the waves become transitional and thereafter shallow water waves, the water particle orbits change to an elliptical form with the horizontal axis greater than the vertical axis. This alteration continues until the wave begins to break, at which time turbulent motion replaces the periodic motion. At this point both wave energy and water mass move forward.

Wave decay or the dissolution of the wave form occurs through four main mechanisms: internal dissipation within the water, interaction with the air above, turbulent action upon breaking, and energy dissipation with the bottom.

The breaking form of a wave is usually considered to be one of three types—spilling, plunging, or surging—although all three types are merely graduations of a continual change in breaker form. Spilling breakers are recognized as shallow water waves whose peaks grow until they become unstable and "spill" down the face of the water as foam. Plunging breakers have crests which curl over and plunge downward, with the water mass staying intact until after the crest has overtopped. Surging breakers act initially like plunging breakers but after peaking do not plunge, but rather, the base surges forward causing the crest to collapse.

Wave energy is the sum of a wave's kinetic and potential energies. Theoretically, kinetic energy—which is that energy actively being applied—is located in that portion of the wave which is below the still-water level, while potential energy—which is that energy available for use—is located in the remaining portion of the wave located above the still-water level.

The average energy per square foot in a sinusoidal wave can be computed as:

$$E = \frac{wH^2}{8},$$

where: E is surface energy density in foot-pounds,
w is the unit weight of water in pounds per cubic foot, and
H is wave height in feet.

For $w = 62.4$ pounds per cubic foot, $E = 7.8H^2$.

Wave power—also termed the wave energy flux—is the rate at which energy is transmitted in the direction of wave propagation across a vertical plane perpendicular to the direction of wave advance and extending down the entire depth. Wave power per unit crest width for shallow water waves can be calculated as:

$$P = Ec,$$

where: P is wave power in foot-pounds/second,
E is surface energy density in foot-pounds, and
c is group wave speed in feet per second.

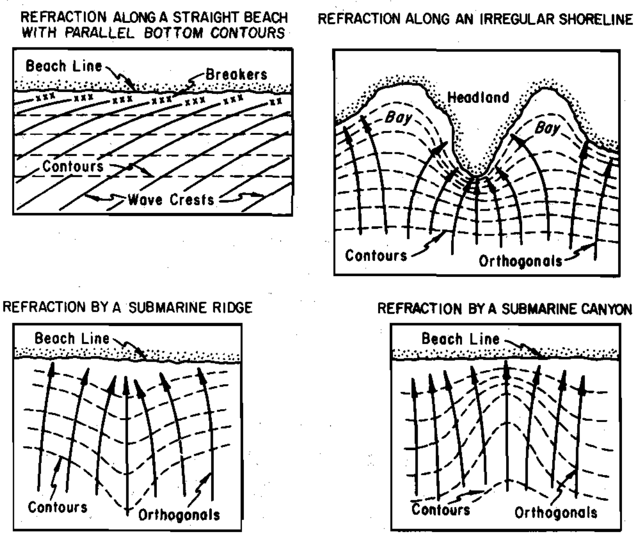
Wave Refraction: Wave refraction, a phenomenon which is largely restricted to the near-shore area, occurs as waves approach a shoreline where the incoming wave crests are not parallel to the topographic contours of the bottom of the near-shore area. The waves are increasingly slowed as a result of the decreasing still-water depth. As a result, the wave crest tends to bend toward an alignment parallel with the shoreline and the bottom contours as the end of the wave crest closest to shore feels bottom first and, consequently, begins to slow down sooner.

Refraction is an important wave phenomenon because the process of refraction can cause convergence and resultant amplification of wave energy and, therefore, significantly affect forces exerted by waves on beaches and bluffs as well as man-made structures. Wave refraction patterns along a straight beach with parallel bottom contours are shown in Figure 32, along with the more complex refraction patterns resulting from irregular shorelines and submarine canyons and ridges which cause the divergence or convergence of wave energy.

Wave Diffraction: Wave diffraction occurs when incident waves encounter an object such as the end of a pier, an opening in a breakwater, or a space between islands. As a result, energy is transferred laterally along the increasing longer wave crests on the lee side of the barrier as the waves bend, assuming a somewhat radial pattern in this protected area. Wave diffraction may be expected to occur primarily in the harbor estuary area, with the actual diffraction patterns being dependent upon the direction of the incident waves and the nature of the hydraulic structures involved. It is often difficult to determine if the bending of the waves into the area on the lee side of a structure is

Figure 32

WAVE REFRACTION PATTERNS



NOTE: Orthogonals indicate direction of wave motion and are perpendicular to wave crests which are not shown.

Source: U. S. Army Corps of Engineers.

entirely attributable to diffraction, since sloping lake bottoms in the vicinity of such structures may also cause wave refraction.

Wave Reflection: Wave reflection occurs when incident waves strike a boundary surface such as a pier, groin, breakwater, or beach and a portion of the wave energy is reflected, as opposed to being dissipated in turbulence or breaking. The angle between the incident waves and the reflecting surface is equal to the angle between the reflected waves and the reflecting surface. An impermeable vertical wall may be expected to reflect essentially all of the incident wave energy, whereas an inclined wall or sloping beach will reflect only a portion of the incident energy. Perfectly reflected waves have essentially the same period as incident waves and can combine with incident waves to produce a standing wave with a height about twice as large as the incident wave. Although the resultant wave does not change position horizontally, the amplified vertical motion may result in disruption to navigation and damage to moored boats and ships, with possible damage to bulkheads and seawalls.

Because significant wave reflection can occur where incident waves encounter vertical barriers and since vertical barriers are common in harbor and estuarial areas, it follows that the magnitude and direction of wave reflection is an important consideration in the design and analysis of harbor and estuary structures. In contrast to the vertical-walled shoreline structures common to harbor and estuary areas, a natural beach with its mild slope is a very effective dissipater of wave energy and produces minimal wave reflection.

Wave Run-Up: Wave run-up is the process whereby a wave breaks on the beach or upon a sloping man-made structure and moves up the slope some distance above the still-water surface. Run-up is the difference between the maximum elevation to which the wave moves up the slope and the lake surface elevation under still-water conditions prior to wave generation. Wave run-up is a function of beach or structure slope and roughness, and the ratio of wave height to wave length. Wave run-up is significant because of its potential effect on beach erosion and accretion, on bluff erosion, and on overtopping of man-made structures.

Standing Waves: Standing waves are waves that appear to be stationary, oscillating in the vertical direction only. Standing waves frequently form when reflected waves moving offshore combine with incoming waves of the same period. Another form of standing wave, but having a period on the order of hours rather than seconds, is called a seiche. As already noted, seiches on Lake Michigan are commonly initiated by strong winds or large barometric pressure differences over the lake. The primary east-west seiche is a standing wave with the crest occurring on one side of the lake and the trough concurrently occurring on the opposite side of the lake. A north-south seiche also occurs on Lake Michigan. Seiches cause currents which may transport large volumes of lake water into and out of the Milwaukee Harbor.

Internal Waves: Internal waves are those waves which form on internal interfaces of a body of water. These waves will typically be found along water stratification boundaries which form by differences in internal density, such as the thermocline in thermally stratified lakes. The waves are usually formed by movement in the upper layer of water which, when large enough, will transfer energy to the lower water layer, setting it in motion. Seiches which have formed on the thermocline are typical internal waves. Internal waves can occur as either standing waves or progressive waves. Large volumes of water can be transported by currents associated with internal waves.

Currents and Related Phenomena

A variety of current types—longshore currents, density currents, rip currents, near-shore currents, and seiche-induced currents—occur in response to the individual or combined action of wind and gravity forces and wave action. The various currents are discussed in the following paragraphs with the exception of the seiche-induced current, which was discussed earlier in this chapter. Currents range in size from very local occurrences such as rip currents which are on the order of tens of feet long to large-scale currents which may be hundreds of miles in extent. Currents may form somewhat circular or longitudinal patterns and can reverse in direction of flow. Furthermore, one type of current may show several of these variations over time and/or distance.

Longshore Currents: Longshore currents are produced by incoming waves which travel obliquely to the shoreline. These currents occur in the surf zone which extends from the shoreline to the breaker line. Because the longshore current is, during a given weather period and attendant incident wave pattern, a continuous current, structures such as groins, piers, or breakwaters may interrupt the flow, and the current will thus require a downdrift distance of approximately 10 widths of the surf zone to fully recover again with respect to equilibrium width and velocity.

Longshore currents transport sediment and other particulate matter which is suspended in the current or bounced and rolled along the lake bottom parallel to the shore, and also transport colloidal and dissolved substances. The overall movement of sediment and other substances along the shoreline within the longshore current is called littoral drift. While the longshore currents within the coastal zone of southeastern Wisconsin may move in either a northerly or southerly direction in response to the direction of the incident waves, the net annual sediment transport is to the south. Clear evidence of this is the tendency for beaches to exhibit accretion on the north side of groins, piers, and other structures, while erosion occurs on the southerly side of such structures.

Special Report No. 5 of the Wisconsin Geological and Natural History Survey, Shoreline Erosion in Southeastern Wisconsin, notes that the southeastern Wisconsin area provides relatively little material to the near-shore zone for transport by littoral drift, therefore making the area particularly sensitive to further reductions in the sediment supply. One of the factors responsible for the small supply of sediment is the relatively small size of the tributary land area lying east of the subcontinental divide. Another factor is that the lake bluffs within the Region are composed largely of fine-grained former lake sediments and silty and clay glacial till. When such fine, light material is eroded from bluffs into the surf, it tends to be carried out into the lake in suspension rather than being retained on the beaches and within the domain of the littoral drift. The third factor limiting the amount of sediment available for littoral drift is the relatively large number of structures along the coast—for example, groins, piers, revetments, and offshore breakwaters—that either reduce the supply of eroded material from the bluffs or restrict its movement along the coast as littoral drift.

Density Currents: Hydrostatic nonequilibrium occurs within the stratified waters comprising the near-shore subsystem when the surfaces of equal density are temporarily forced into a nonhorizontal position. A density current results as the liquid mass responds and moves under the influence of gravity toward an equilibrium state. Such density differences are caused by temperature changes and by the presence of silt, sediment, and dissolved substances. In addition, localized density currents may occur along a sloping bottom of the near-shore zone as a result of the diffusion of substances from the bottom sediment into the overlying waters, which increases the density of those waters and induces motion.

A density current may move from an estuary subsystem into and along the bottom of the near-shore subsystem during the spring when sediment-laden spring rainfall and snowmelt runoff water is transported from inland areas by tributary streamflows through the estuary and into the well-mixed, less dense near-shore waters. Conversely, a density current from the near-shore subsystem into the estuary subsystem during the summer when the bottom, colder, more dense waters of the thermally stratified near-shore zone may flow from that zone into the estuary area under the warmer, less dense river water.

Density currents may also occur on the surface of a receiving body of water. An example of a density current flowing from the estuary subsystem into and along the surface of the near-shore subsystem is the winter discharge of cooling water from a power plant located within an estuary area. The warmer, less dense cooling water moves through the estuary opening onto the surface of the water in the near-shore subsystem.

Density currents respond to very slight changes in density. As already noted, a phenomenon of density currents is the thermal bar. During the spring warming or the winter cooling of the lake, a situation sometimes occurs in which the temperature of one water mass is warmer than 39° F—the temperature at which water has its greatest density—and the temperature of an adjacent water mass is colder than 39° F. As these two masses mix, denser waters with a temperature of 39° F may occur. These denser waters will cause the formation of a thermal bar or vertical current which persists until the entire water mass is either warmer or colder in temperature than 39° F. The significance of a thermal bar is that it forms a barrier which may prevent the transfer of water or materials.

Rip Currents and Undertow: Relative to longshore and density currents, rip currents are ephemeral, localized currents which move perpendicular to the shoreline. A rip current, which is initiated under high wave conditions by wave run-up onto a beach, is the concentrated jet of water produced as the water flows back down the beach and into and through the surf zone. Rip currents move generally perpendicular to the shoreline and are the most noticeable means of exchange of water from the surf zone into the near-shore area outside the surf zone.

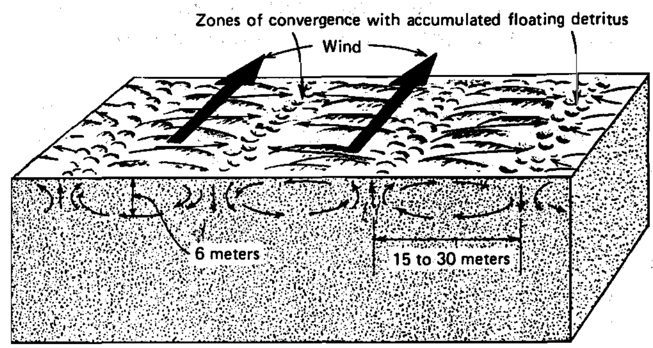
Rip currents are commonly part of a water transport cycle. Water is moved shoreward by wave and breaker action. Upon reaching the shore, the water flows to an adjacent rip current and then from there out through the surf zone into the lake. These circulation systems may be either stationary or moving, depending on whether a sufficiently strong longshore current is present to provide lateral motion.

Another type of current common to the beach area is the shallow diffuse return flow, sometimes referred to as an undertow, which occurs, as does the rip current, after wave run-up as the water flows back down the beach into the surf zone. Unlike the rip current, the undertow is spread out rather than concentrated at discrete locations and extends down the beach face only a short distance into the surf zone.

Other localized currents may occur that exhibit behavior similar to that of rip currents except that their origin may be traced either to concentrated flows down ravines in the bluff or beach face into and through the surf zone or to point discharges from storm or combined sewers or from industrial

Figure 33

LANGMUIR CIRCULATION



Oily surface films and debris form windrows along lines of convergence in the Langmuir circulation set up by a steady wind.

Source: M. Grant Gross, Oceanography—A View of the Earth, Second Edition, Prentice-Hall, Inc., 1977.

and commercial sources. Significant aspects of the above types of currents are that they may result in localized sorting of sediments in the beach area and, particularly in the case of rip currents, they can be hazardous to swimmers.

Langmuir Currents: Langmuir currents are long, slender, helical circulation cells, the specific causes of which are still being studied, although it is generally agreed that wind is the primary cause of these currents. Figure 33 shows the Langmuir circulation cells and their associated water currents. Associated with the surface convergence areas are lines or "streaks" of foam, sometimes called windrows, and other surface debris caused by downwelling. Between these downwellings are zones of upwelling ranging from about 50 to 100 feet in width in oceans and large lakes such as Lake Michigan. Vertical circulation has been observed to depths of over 22 feet in large lakes. Langmuir currents may be formed when wind speeds surpass a few miles per hour.

Large-Scale Currents: Data on Lake Michigan currents are available, in part, from a study conducted by the Federal Water Pollution Control Administration (FWPCA).[1] Information pertinent to south-

[1] *U. S. Department of the Interior, Federal Water Pollution Control Administration, Region V, A Comprehensive Water Pollution Control Program, Lake Michigan, Milwaukee Area, Chicago, Illinois, 1966.*

eastern Wisconsin extracted from that study is presented herein for the purposes of characterizing the behavior of lake currents near the Region and evaluating some implications of current phenomena to the estuarial and near-shore environments.

Near-shore and Offshore Currents: Water movements in the southern basin of Lake Michigan near the Region occur in two rather separate configurations referred to as the near-shore and offshore current patterns, as shown in Figure 34. The near-shore currents also contain the longshore currents discussed above. Near-shore currents are much wider than, and may have directional and velocity patterns different from, longshore currents. Longshore currents occur along the coastal edge of the near-shore currents. The areal extent of the offshore current pattern is large relative to the near-shore currents.

The width of the near-shore current varies during the year from about 2 to 10 miles. Thus, while the near-shore current is a widely fluctuating band, the narrowest limit of the band—about two miles—will always encompass that narrow zone paralleling the shore in which most of man's uses are concentrated. For example, municipal sewage treatment plant outfalls in the Cities of Port Washington, South Milwaukee, Racine, and Kenosha, along with those of the North Park Sanitary District and the Milwaukee Metropolitan Sewerage District, either are located on the shore or discharge within one-half mile of the shore. Sewage treatment plant outfalls all discharge within about 25 feet of the water surface. Municipal water treatment plant intakes in the Cities of Port Washington, Milwaukee, Cudahy, South Milwaukee, Oak Creek, Racine, and Kenosha, as well as that of the North Shore Water Utility, are all located within 1.5 miles of the shore and withdraw water from within approximately 50 feet of the lake surface. Therefore, the sewage treatment plant outfalls and the water supply intakes all appear to lie within the confines of the near-shore current.

Regardless of the season of the year, the primary driving force for the near-shore currents is the prevailing wind, with the general direction of these currents being determined by wind direction combined with the tendency of the coastal boundary to orient the flows in a northerly or southerly direction parallel to the shore. Regardless of whether the motion is northerly or southerly, near-shore currents may be expected to move at a velocity of about 2.5 to 5.5 miles per day. Based on drogue studies conducted by the Federal Water Pollution Control Administration, the near-shore current appears to flow northerly about two-thirds of the time in the Southeastern Wisconsin Region and southerly about one-third of the time. However, wind and simultaneous current data collected from 1962 to 1964 by the FWPCA adjacent to the Milwaukee Harbor showed that during any one-day period the flows moved against the wind. Currents in the surf zone are not influenced by near-shore currents, but by the angle of the breaking waves.

The offshore currents occupy a much larger area than do the near-shore currents. The offshore currents flow counterclockwise between 70 and 75 percent of the year and clockwise for about 25 to 30 percent of the year, which corresponds to their main driving force, the prevailing winds. The offshore currents have circulation patterns which are usually opposite to those of the near-shore currents and, therefore, little interaction occurs between the two separate current systems.

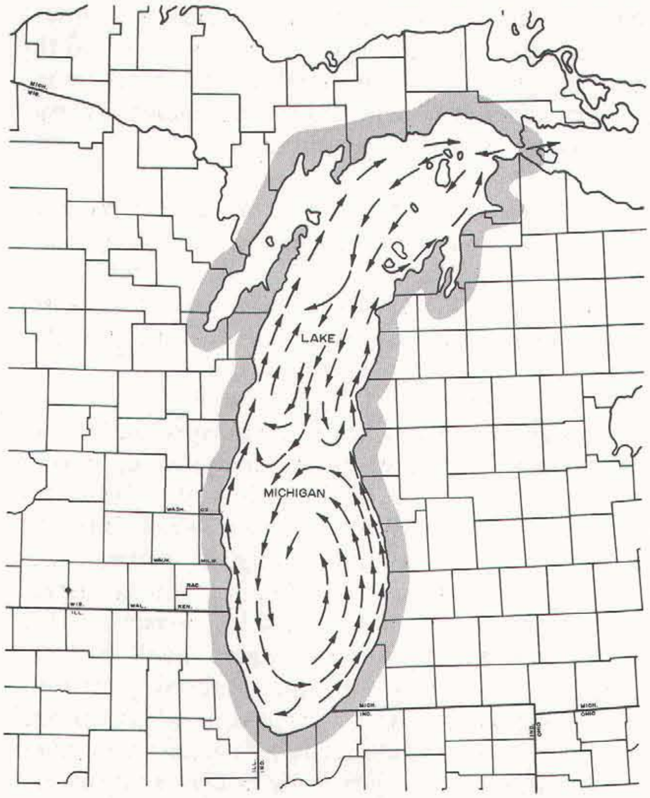
Dispersion

Dispersion is the process by which substances, both organic and inorganic and dissolved and undissolved, and heat discharged to the coastal system are transported and mixed. Dispersion, for the purpose of this report, includes the separate processes of transport and mixing. Transport is the transfer of a given mass of a substance or substances by one or more of the types of currents described in the previous section. Mixing is the process that is caused by secondary currents and involves the expansion of a given mass of substance into contiguous waters, in effect diluting the substance. Mixing is primarily the result of the irregular random motions which are normally present in various types of currents moving in estuarine and near-shore areas.

The process of dispersion may be visualized as occurring within a plume originating at the source of water containing pollution. A plume is an area of water in which substances assume a recognizable configuration. The transport process is shown as the net movement of pollutants in the direction of plume flow. The mixing process is evident by comparing pollution concentration distributions at various locations along the length of the plume and noting that the peak concentration decreases with distance along the plume while the width of the plume increases. Dispersion is characterized by the rate of mixing, extent of mixing (both vertical and horizontal), concentration of substance within the plume, and pattern of transporting currents.

Figure 34

LARGE-SCALE CURRENT PATTERNS IN LAKE MICHIGAN



SUMMER CIRCULATION INFLUENCED BY WINDS FROM SOUTH TO SOUTHWEST (40% OF YEAR)

SUMMER CIRCULATION INFLUENCED BY WINDS FROM NORTH TO NORTHEAST (10% OF YEAR)

WINTER CIRCULATION INFLUENCED BY WINDS FROM NORTH TO NORTHWEST (25-30% OF YEAR)

WINTER CIRCULATION INFLUENCED BY WINDS FROM SOUTH TO SOUTHWEST (20-25% OF YEAR)

Source: Federal Water Pollution Control Administration.

The mixing phase of the dispersion process—that is, the rate at which the pollutant plume expands vertically and horizontally—is influenced by several factors, including the scale of the turbulence, the presence of confining boundaries, and the nature of the pollutants. Each of these factors is briefly discussed below.

It should be noted that in the absence of currents and, therefore, pollutant transport, the process of diffusion will still occur. Rather than being characterized by a plume, this situation is characterized by an approximately circular area centered on the pollutant source, with pollutant concentration decreasing radially with distance from the source.

Turbulent flow may be visualized as the superposition of eddies, which are more or less closed flow structures, of various sizes. The size of eddies within turbulent flow relative to the width of a pollutant plume is one factor that determines the rate of expansion of the plume. Eddies having diameters that are very small compared to the width of the plume result in relatively little mixing except for a small rate of expansion at the plume fringes. Eddies having diameters very large compared to the width of the plume are relatively ineffective in inducing mixing, since the large eddy encompasses the entire plume. Eddies having a diameter approximately the width of the plume are most effective in inducing mixing of the plume with the contiguous waters.

Another factor influencing mixing of a plume with contiguous waters is the presence of a boundary above, below, or on one or both sides of the plume, because the boundary retards plume expansion in that direction. Examples of boundaries that may inhibit or prevent the lateral or vertical expansion of a horizontal plume are: bulkhead walls and other structures, the beach, the free water surface, the bottom of the water body, or the presence of a more dense fluid below the plume or a less dense fluid above the plume.

The characteristics of the pollutant within the plume also influence the average and maximum concentration of the substance at various points along the plume. While mixing alone determines the concentration of conservative substances such as chloride at various points along the plume, the concentration of nonconservative substances is influenced by factors in addition to mixing. For example, the concentration of fecal coliform bacteria is determined in part by the rate at which the bacteria die-off; the concentration of suspended sediment is determined in part by the rate at which the sediment settles from a plume to the bottom; and the concentration of biochemical oxygen demand is affected by oxidation by bacteria occurring within the plume.

As already noted, the transport and mixing of pollutants is important because of the potentially conflicting functions of the water resource—functions which include wastewater disposal, water supply, recreational use, and aesthetic enjoyment.

Hydrologic Budget

The hydrologic budget of a stream system, lake, or other body of water is an accounting, over a specified time period, of the inflow of water to the body, the outflow and other loss of water from the body, and the resultant change in storage. The hydrologic budget of Lake Michigan is significant because it determines monthly, seasonal, and annual background or base water levels in Lake Michigan onto which are superimposed short-term fluctuations attributable to waves, wind set-up, and seiches as described earlier in this chapter. Furthermore, the results of hydrologic budget analyses can provide information useful in assessing the retention time of pollutants introduced into the lake.

For purposes of constructing a hydrologic budget, it is necessary to consider Lake Michigan and Lake Huron as a single body of water. These two lakes are at the same average level as a result of the connection formed by the Straits of Mackinaw. It is difficult to estimate the net flow from Lake Michigan to or from Lake Huron through the Straits of Mackinaw with the same degree of accuracy that other components of the hydrologic budget can be estimated. This necessitates, for hydrologic budget purposes, the combined treatment of Lakes Michigan and Huron. The most important components of the hydrologic budgets of each of the two lakes are thought to be similar and, therefore, a brief review of the budget of the combined lakes is informative.

Water enters the Lakes Michigan-Huron basin by inflow from Lake Superior, by runoff from land within the combined drainage basin of the two lakes, and by precipitation directly on lake surfaces. Water loss from Lakes Michigan and Huron occurs as outflow from the southern end of Lake Huron through the St. Clair River, outflow from the southern end of Lake Michigan through the Illinois sanitary and ship canal, and evaporation from the surface of the lakes. This budget assumes a zero net interchange of water between the lake and the underlying groundwater on an annual basis. Regardless of the time frame considered—weeks, months, years—a difference in the inflow and outflow is reflected in a net increase or decrease in water stored in the lakes and, therefore, a change in lake level or stage.

Three components of the hydrologic budget—namely, inflow from Lake Superior, precipitation directly on the lakes, and outflow from the lakes—exhibit minor variations from the seasonal variations evident in inflow occurring as runoff from the land and outflow occurring as evaporation from the water surface. Runoff from the land tends to be higher during the six-month February-through-July period than during the remaining six months of the year, when evaporation rates are generally the lowest. These two components— runoff and evaporation—dominate the seasonal hydrologic cycle, with the result being that inflow into the Lakes Michigan and Huron basin exceeds outflow during the six-month February-through-July period and outflow exceeds inflow during the remaining six months. Accordingly, lake storage and levels generally increase from February through July and decrease during the remaining months, producing an annual cycle.

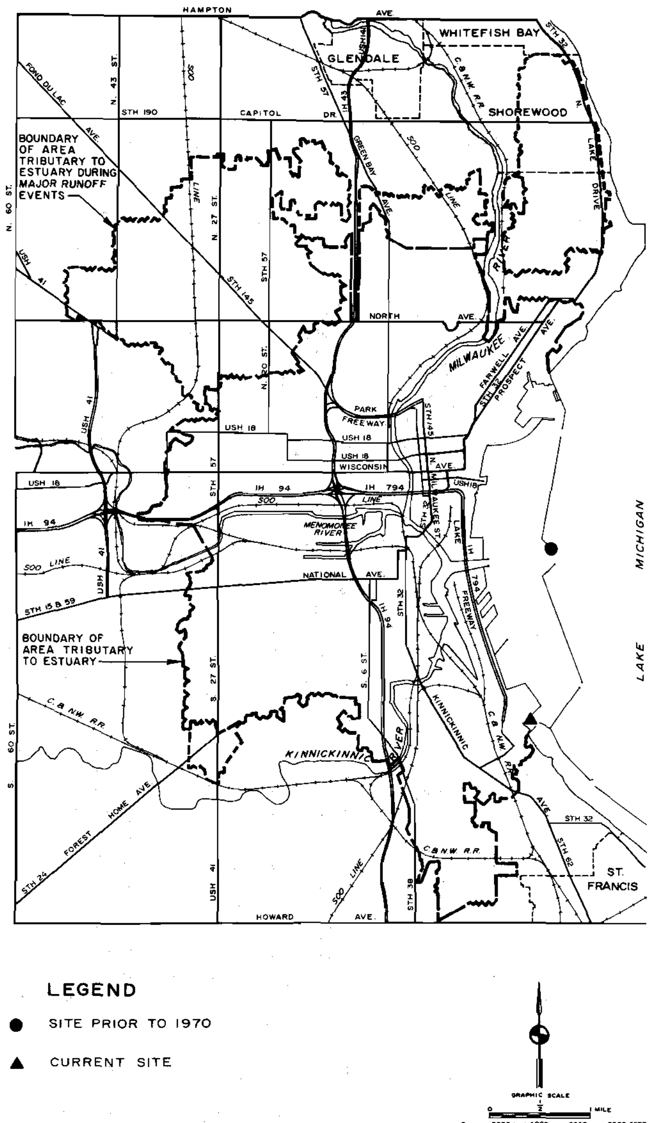
Long-Term Water Level Fluctuation

Long-term water level records collected in Milwaukee Harbor provide very useful data for the design of not only shoreline structures, but also offshore structures and navigation channels. Useful records include frequency analyses of annual average and quarterly water levels, annual maximum monthly mean water levels, maximum daily mean water levels, and annual instantaneous maximum water levels; annual, quarterly, and monthly rise frequency; and frequency of annual minimum monthly mean water levels, minimum daily mean water levels, and annual instantaneous minimum water levels. Lake Michigan water levels are affected by diversions to and from the Lakes Michigan-Huron system, by outflow from Lake Superior, and by changes in certain hydraulic structures and outlet channels in the system, as well as by regulation. The effects of the existing diversions, outlets, and regulation schedules are reflected in the frequency analyses described in this chapter.

Water Level Records: Water level records have been systematically collected in Milwaukee Harbor since 1860 by the National Ocean Survey (NOS) and its predecessor agencies. The NOS water level monitoring station is presently located at the U. S. Coast Guard station at the south end of the outer harbor, as shown on Map 41. Prior to 1970, the gage was located at the lighthouse on the breakwater at the main entrance to the outer harbor, also as shown on Map 41.

Map 41

LOCATION OF THE NATIONAL OCEAN SURVEY LAKE MICHIGAN WATER LEVEL MONITORING STATION IN MILWAUKEE



The National Oceanic and Atmospheric Administration, National Ocean Survey, and its predecessor agencies have systematically collected and reported water stage data for the Milwaukee Harbor since 1860. The locations of the lake level monitoring stations used in this data collection effort from 1899 to 1985 are shown on this map.

Source: SEWRPC.

The NOS gage is of the stilling well type and presently utilizes a digital recorder from which hourly water level data can be obtained. The NOS publishes the water level data in an annual report entitled Great Lakes Water Levels, which includes daily, monthly, and annual mean water levels and other relevant statistics. Table 45 illustrates the report format for the Milwaukee Harbor. The NOS has also published a data summary report entitled Great Lakes Water Levels, 1860-1980, which presents annual and monthly mean water levels for that period, along with relevant statistics. Pertinent data from that report for the Milwaukee station are reproduced in Table 46. The water levels are reported using the International Great Lakes Datum (IGLD), 1955. To convert this datum to National Geodetic Vertical Datum (NGVD)—Mean Sea Level Datum—add 1.30 feet.

Annual, Monthly, Daily, and Instantaneous Extreme Water Levels: The annual cycle in Lake Michigan water levels is shown in Figure 35, which graphically summarizes average and extreme monthly mean water levels in Lakes Michigan and Huron for

Table 45

NATIONAL OCEAN SURVEY ANNUAL WATER LEVEL REPORT FORMAT: MILWAUKEE HARBOR, 1982

INTERNATIONAL GREAT LAKES DATUM (1955)

DAILY MEAN WATER LEVELS, MONTHLY MEANS AND EXTREMES, 1982

Station 7057: Milwaukee, Wisconsin on Lake Michigan

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	578.53	578.46	578.26	-- [b]	578.84	579.00	579.09	579.12	579.15	579.07	579.00	579.07
2	578.71	578.47	578.42	-- [b]	578.81	579.05	579.12	579.32	578.95	579.10	579.04	579.06
3	578.91	578.68	578.45	-- [b]	578.92	579.14	579.14	579.32	578.78	578.99	578.75	579.03
4	579.28	578.48	578.61	-- [b]	578.99	579.11	579.13	579.36	578.92	578.97	578.58	578.94
5	578.77	578.54	578.29	-- [b]	579.00	579.08	579.13	579.34	579.01	579.05	578.62	579.38
6	578.65	578.23	578.25	578.67[a]	578.92	579.03	579.10	579.39	579.26	579.05	578.34	579.02
7	578.31	578.09	578.30	578.57	578.79	579.18	578.97	579.35	579.22	578.91	578.59	578.85
8	578.30	578.21	578.22	578.58	578.90	579.08	578.98	579.26	579.05	578.93	578.70	579.06
9	578.34	578.26	578.33	578.57	578.93	579.10	579.00	579.15	578.97	579.22	578.90	578.94
10	578.06	578.12	578.28	578.44	579.02	579.03	579.16	579.09	579.03	579.34	579.06	578.81
11	578.01	578.17	578.33	578.57	579.02	578.96	579.13	579.20	578.97	578.96	578.90	578.77
12	578.53	578.38	578.26	578.63	578.94	579.04	578.91	579.20	578.99	578.80	578.72	578.87
13	578.71	578.39	578.01	578.69	579.10	578.96	579.18	579.16	579.03	578.87	578.66	578.72
14	578.67	578.40	578.10	578.66	579.12	579.02	579.22	579.15	579.18	578.64	578.89	578.87
15	578.49	578.45	578.40	578.77	579.06	579.18	579.19	579.17	579.30	578.67	578.59	579.12
16	578.20	578.52	578.62	578.78	579.00	579.05	579.16	579.11	579.04	578.76	578.51	579.14
17	578.13	578.66	578.55	578.66	579.09	579.07	579.12	579.06	578.99	578.78	578.83	579.04
18	578.49	578.52	578.42	578.49	579.02	579.22	579.16	579.08	578.97	578.70	578.90	579.04
19	578.59	578.34	578.56	578.91	578.92	579.08	579.21	578.95	578.91	578.80	578.95	579.07
20	578.71	578.34	578.75	578.94	579.01	579.11	579.25	579.08	579.09	578.75	578.99	578.93
21	578.79	578.37	578.49	578.64	579.20	579.10	579.26	579.06	579.08	578.64	578.75	578.96
22	579.00	578.30	578.32	578.68	579.28	579.08	579.32	578.85	579.08	578.81	578.92	579.08
23	578.41	578.67	578.37	578.61	579.14	579.06	579.30	578.99	578.95	578.71	578.96	579.29
24	578.39	578.59	578.36	578.58	579.02	579.08	579.24	579.14	579.11	578.67	578.57	579.27
25	578.45	578.42	578.37	578.73	579.01	579.11	579.14	579.01	579.32	578.68	578.41	579.17
26	578.40	578.24	578.50	578.89	579.10	579.22	579.22	578.92	579.13	578.80	578.83	578.97
27	578.30	578.35	578.41	578.81	579.16	579.20	579.28	579.09	579.07	578.85	578.77	579.27
28	578.25	578.36	578.25	578.89	579.11	579.15	579.23	578.97	579.12	578.87	579.00	578.99
29	578.18		578.39[a]	578.96	579.10	579.20	579.17	579.02	579.11	578.64	578.94	578.87
30	578.51		-- [b]	578.95	579.09	579.04	579.25	579.02	578.99	578.53	578.93	578.76
31	578.72		-- [b]		579.07		579.14	579.16		578.82		578.77
MEAN	578.51	578.39	578.37	578.71	579.02	579.09	579.16	579.13	579.06	578.85	578.79	579.00
MAX.	579.68	579.29	579.41	579.22	579.45	579.64	579.63	579.65	579.70	579.50	579.49	579.73
	0400/04	2400/23	0700/20	2300/19	1400/22	0300/07	0500/07	1200/05	1200/01	0600/10	0200/02	1300/05
MIN.	577.73	577.74	577.48	578.28	578.38	578.53	578.63	578.67	578.66	578.25	578.20	578.45
	2300/10	2300/06	1100/13	2100/10	0700/07	2000/06	0200/07	0700/22	0600/03	0300/20	0600/25	2200/13

ANNUAL MEAN: 578.84

a Indicates Less than 90% of the Hourly Data Available.
b Indicates No Data.

NOTE: Elevations are in feet above the International Great Lakes Datum-1955 (IGLD). To convert to National Geodetic Vertical Datum (NGVD), add 1.30 feet.

Source: National Ocean Survey.

Table 46

SAMPLE NATIONAL OCEAN SURVEY SUMMARY WATER LEVEL STATISTICS: LAKE MICHIGAN AT MILWAUKEE: 1860-1969

U. S. DEPARTMENT OF COMMERCE
NOAA - NOS ROCKVILLE, MARYLAND
GREAT LAKES WATER LEVELS, C234

MONTHLY AND ANNUAL AVERAGE ELEVATIONS
WATER LEVELS IN FEET, IGLD (1955)

Station 7058 : Milwaukee, Wisconsin on Lake Michigan

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL AVG
1860	580.56	580.74	580.77	580.90	581.02	581.14	581.18	580.99	580.79	580.48	580.15	579.99	580.73
1861	579.88	579.97	580.36	580.46	580.88	581.04	581.17	581.41	581.10	580.98	580.75	580.58	580.72
1862	580.38	580.23	580.53	580.69	580.94	581.07	580.97	580.96	580.89	580.78	580.39	580.25	580.67
1863	580.18	580.23	580.22	580.22	580.43	580.52	580.47	580.34	580.16	580.07	579.90	579.97	580.23
1864	579.74	579.60	579.85	580.00	580.07	580.06	579.96	579.78	579.51	579.12	578.95	578.82	579.62
1865	578.61	578.70	578.87	579.36	579.52	579.56	579.99	580.01	579.89	579.65	579.09	578.78	579.34
1866	578.52	578.28	578.33	578.78	578.96	579.25	579.51	579.57	579.42	579.31	579.22	578.96	579.01
1867	578.94	578.99	579.17	579.46	579.68	579.99	580.14	580.07	579.80	579.47	579.01	578.66	579.45
1868	578.50	578.46	579.14	579.04	579.32	579.53	579.56	579.22	578.98	578.75	578.68	578.40	578.96
1869	578.30	578.37	578.11	578.48	578.81	579.34	579.72	579.98	579.87	579.51	579.39	579.11	579.08
1870	579.17	579.26	579.56	579.98	580.32	580.46	580.57	580.48	580.62	580.22	579.82	579.47	579.99
1871	579.62	579.54	580.14	580.34	580.69	580.73	580.76	580.53	579.86	579.17	579.12	578.53	579.92
1872	578.40	578.40	578.18	578.43	578.68	579.05	579.38	579.36	579.29	579.17	578.88	578.22	578.79
1873	578.22	578.26	578.57	579.14	579.70	580.03	579.99	580.09	579.90	579.84	579.61	579.57	579.41
1874	579.53	579.82	579.97	579.87	579.85	580.22	580.15	580.16	579.91	579.50	579.30	578.96	579.77
1875	578.82	578.69	578.75	579.11	579.67	579.91	579.94	580.11	580.04	579.89	579.68	579.49	579.51
1876	579.44	579.64	579.97	580.17	580.79	581.20	581.54	581.47	581.42	580.84	580.94	580.47	580.66
1877	580.33	580.34	580.34	580.72	580.61	580.68	580.65	580.53	580.32	580.33	580.21	580.15	580.43
1878	580.03	579.96	580.12	580.14	580.44	580.58	580.59	580.27	580.07	579.96	579.83	579.51	580.12
1879	579.20	579.21	579.25	579.24	579.37	579.44	579.53	579.34	579.22	579.00	578.78	578.81	579.20
1880	578.85	578.76	578.80	578.97	579.31	579.82	580.04	580.07	579.77	579.43	579.11	578.94	579.32
1881	578.95	579.16	579.45	580.36	579.87	580.10	580.07	580.07	579.84	580.17	580.00	579.90	579.83
1882	579.68	579.67	580.04	580.17	580.27	580.54	580.60	580.79	580.67	580.26	580.05	579.72	580.20
1883	579.46	579.50	579.59	579.80	580.28	580.64	581.24	581.21	581.02	580.80	580.08	580.27	580.32
1884	580.05	580.17	580.42	580.60	580.81	580.97	580.81	580.67	580.42	580.42	580.06	580.03	580.45
1885	580.04	580.27	580.23	580.42	580.78	580.99	581.08	581.29	581.15	581.01	580.71	580.42	580.70
1886	580.65	580.67	580.95	581.22	581.48	581.55	581.36	581.13	580.89	580.79	580.45	580.12	580.94
1887	580.04	580.41	580.57	580.52	580.72	580.85	580.79	580.65	580.31	579.85	579.53	579.40	580.30
1888	579.22	579.18	579.36	579.57	579.95	580.22	580.23	580.11	579.96	579.71	579.66	579.08	579.69
1889	579.06	579.03	579.01	579.02	579.10	579.56	579.74	579.50	579.33	579.08	578.73	578.55	579.14
1890	578.63	578.59	578.57	578.89	579.12	579.53	579.60	579.52	579.32	579.21	578.87	578.52	579.03
1891	578.50	578.26	578.45	578.76	578.86	579.01	578.84	578.77	578.54	578.18	577.78	577.74	578.47
1892	577.84	578.03	577.93	577.99	578.41	578.86	578.94	579.02	578.82	578.58	578.31	578.04	578.40
1893	578.03	578.17	578.28	578.74	579.04	579.37	579.39	579.22	578.90	578.76	578.37	578.30	578.71
1894	578.31	578.34	578.60	578.75	579.29	579.45	579.48	579.40	578.97	578.76	578.49	578.14	578.83
1895	577.96	577.85	577.82	578.01	578.18	578.23	578.12	578.00	577.73	577.36	577.14	577.03	577.79
1896	577.11	577.15	577.16	577.34	577.62	577.94	577.88	577.81	577.71	577.66	577.44	577.39	577.52
1897	577.38	577.46	577.77	577.94	578.43	578.70	578.89	578.83	578.58	578.29	578.03	577.81	578.18
1898	577.76	577.90	578.22	578.54	578.82	578.95	578.93	578.73	578.38	578.37	577.96	577.62	578.35
1899	577.57	577.65	577.85	578.12	578.56	578.87	579.09	579.01	578.87	578.55	578.36	577.86	578.36
1900	577.72	577.83	577.99	578.13	578.37	578.48	578.58	578.75	578.70	578.71	578.57	578.24	578.34
1901	578.01	577.98	578.40	578.55	578.98	579.03	579.12	579.17	578.98	578.62	578.29	578.01	578.60
1902	577.81	577.66	577.89	577.96	578.34	578.54	578.87	578.89	578.51	578.32	578.24	577.95	578.25
1903	577.73	577.89	578.10	578.38	578.47	578.65	578.83	578.76	578.81	578.62	578.26	577.91	578.37
1904	577.97	577.98	578.26	578.72	579.09	579.47	579.47	579.38	579.31	579.18	578.88	578.54	578.85
1905	578.39	578.27	578.45	578.83	579.09	579.48	579.62	579.59	579.49	579.05	578.78	578.63	578.97
1906	578.61	578.76	578.91	579.09	579.35	579.47	579.48	579.45	579.10	578.91	578.75	578.70	579.05
1907	578.63	578.69	578.74	579.00	579.16	579.52	579.52	579.44	579.42	579.17	578.76	578.65	579.06
1908	578.48	578.57	578.64	578.93	579.50	579.63	579.83	579.72	579.28	578.92	578.27	578.13	578.99
1909	577.88	578.02	578.10	578.36	578.89	579.08	579.05	579.07	578.80	578.32	578.18	578.18	578.49
1910	577.95	577.94	578.01	578.37	578.49	578.57	578.49	578.32	578.28	578.09	577.78	577.45	578.14
1911	577.20	577.40	577.23	577.49	577.76	578.04	577.88	577.84	577.77	577.64	577.36	577.44	577.59
1912	577.28	577.30	577.36	577.53	578.05	578.47	578.56	578.64	578.72	578.42	578.43	578.19	578.08
1913	578.02	577.85	578.14	578.84	579.15	579.28	579.28	579.27	578.99	578.78	578.45	578.30	578.70
1914	578.08	578.07	578.02	578.18	578.39	578.67	578.82	578.72	578.52	578.40	577.85	577.56	578.27
1915	577.48	577.70	577.63	577.59	577.73	577.89	577.99	578.21	578.01	577.81	577.48	577.43	577.75
1916	577.16	577.30	577.46	577.95	578.52	579.15	579.34	579.09	578.68	578.64	578.67	578.58	578.38
1917	578.46	578.38	578.51	578.87	579.20	579.65	579.99	579.93	579.73	579.41	579.22	578.79	579.18
1918	578.84	578.86	579.15	579.52	579.77	580.00	579.99	579.89	579.51	579.22	579.09	579.15	579.42
1919	578.79	578.73	578.83	579.16	579.48	579.62	579.39	579.14	578.79	578.70	578.44	578.10	578.93

Table 46 (continued)

U. S. DEPARTMENT OF COMMERCE
NOAA - NOS ROCKVILLE, MARYLAND
GREAT LAKES WATER LEVELS, C234

MONTHLY AND ANNUAL AVERAGE ELEVATIONS
WATER LEVELS IN FEET, IGLD (1955)

Station 7058 : Milwaukee, Wisconsin on Lake Michigan

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL AVG
1920	578.02	578.06	578.21	578.59	578.84	578.95	579.10	579.13	578.95	578.61	578.34	578.12	578.58
1921	577.93	577.89	577.99	578.47	578.65	578.67	578.50	578.20	578.05	577.89	577.71	577.53	578.12
1922	577.31	577.27	577.52	578.06	578.54	578.64	578.75	578.66	578.45	578.03	577.61	577.16	578.00
1923	577.12	576.85	577.06	577.29	577.72	577.92	577.98	577.81	577.71	577.43	577.11	576.83	577.40
1924	576.57	576.80	576.78	577.02	577.32	577.48	577.56	577.70	577.58	577.33	576.81	576.50	577.12
1925	576.33	576.28	576.36	576.54	576.48	576.53	576.62	576.55	576.35	575.95	575.71	575.52	576.27
1926	575.40	575.53	575.64	575.90	576.28	576.48	576.62	576.77	576.66	576.38	576.35	576.29	576.19
1927	576.27	576.31	576.60	576.92	577.27	577.51	577.64	577.52	577.27	577.15	576.96	576.80	577.02
1928	576.69	576.88	576.98	577.62	578.03	578.27	578.51	578.64	578.47	578.52	578.66	578.71	578.00
1929	578.58	578.75	578.72	579.55	580.11	580.31	580.43	580.25	579.88	579.60	579.14	578.89	579.52
1930	578.65	578.64	578.76	578.89	579.06	579.13	579.32	579.17	578.69	578.34	577.88	577.49	578.67
1931	577.23	577.13	577.26	577.10	577.21	577.29	577.17	577.03	576.71	576.54	576.35	576.34	576.95
1932	576.35	576.21	576.24	576.49	576.69	576.77	576.67	576.57	576.28	576.14	575.98	575.71	576.34
1933	575.75	575.67	575.79	576.12	576.66	576.79	576.82	576.60	576.30	575.94	575.73	575.62	576.15
1934	575.56	575.56	575.54	575.76	575.99	576.11	576.21	576.09	576.05	575.73	575.71	575.77	575.84
1935	575.68	575.76	575.91	576.18	576.33	576.51	576.71	576.70	576.45	576.18	576.23	576.11	576.23
1936	576.08	575.97	576.12	576.32	576.66	576.85	576.80	576.67	576.71	576.49	576.17	575.91	576.40
1937	575.95	575.97	576.07	576.32	576.65	576.76	576.82	576.78	576.63	576.33	576.03	575.84	576.35
1938	575.89	576.24	576.40	576.89	577.25	577.52	577.71	577.68	577.83	577.59	577.23	576.95	577.10
1939	576.89	576.88	577.02	577.18	577.62	578.02	578.12	578.14	578.11	577.70	577.49	577.15	577.53
1940	576.89	576.96	576.80	576.85	577.12	577.35	577.47	577.65	577.54	577.31	576.91	576.85	577.14
1941	576.97	576.87	576.84	577.00	577.20	577.32	577.20	577.01	576.87	576.97	577.16	577.11	577.04
1942	576.98	577.13	577.29	577.64	577.99	578.37	578.34	578.27	578.06	577.83	577.67	577.43	577.75
1943	577.54	577.49	577.76	578.10	578.58	579.20	579.56	579.67	579.45	579.32	579.10	578.58	578.70
1944	578.46	578.41	578.48	578.67	578.86	578.99	579.00	578.86	578.79	578.66	578.50	578.00	578.64
1945	577.80	577.73	577.90	578.16	578.52	579.07	579.20	579.07	578.98	578.69	578.69	578.54	578.53
1946	578.39	578.53	578.86	578.97	579.08	579.17	579.29	579.02	578.69	578.26	577.95	577.61	578.65
1947	577.58	577.43	577.46	577.96	578.59	579.14	579.27	579.35	579.22	579.18	578.83	578.53	578.54
1948	578.18	577.99	578.31	578.76	579.05	579.11	579.08	578.84	578.61	578.03	577.78	577.46	578.43
1949	577.29	577.30	577.33	577.52	577.71	577.83	577.98	577.82	577.27	577.06	576.69	576.37	577.35
1950	576.43	576.68	576.72	577.30	577.63	577.75	578.03	578.19	578.20	577.97	577.72	577.74	577.53
1951	577.78	577.82	578.09	578.63	579.19	579.41	579.65	579.86	579.68	579.83	579.80	579.80	579.13
1952	579.83	579.96	580.02	580.38	580.60	580.75	580.79	580.95	580.64	580.03	579.79	579.72	580.29
1953	579.56	579.32	579.50	579.82	580.10	580.27	580.36	580.37	580.00	579.79	579.35	579.01	579.79
1954	578.89	578.74	578.86	579.14	579.45	579.80	579.89	579.87	579.79	579.96	579.83	579.70	579.49
1955	579.44	579.35	579.22	579.51	579.62	579.75	579.59	579.31	578.80	578.45	578.13	577.92	579.09
1956	577.85	577.72	577.90	577.97	578.41	578.59	578.78	578.75	578.56	578.27	577.91	577.62	578.19
1957	577.36	577.37	577.36	577.49	577.79	577.89	578.11	578.00	577.80	577.59	577.27	577.21	577.60
1958	577.25	577.16	577.17	577.22	577.06	577.09	577.27	577.04	576.87	576.63	576.26	576.02	576.92
1959	575.94	575.95	576.20	576.59	577.07	577.17	577.12	577.14	577.03	577.10	577.10	577.20	576.80
1960	577.19	577.39	577.34	577.61	578.48	578.88	579.11	579.30	579.21	578.81	578.50	578.18	578.33
1961	577.99	577.90	578.03	578.06	578.22	578.24	578.32	578.29	578.17	577.97	577.78	577.54	578.04
1962	577.31	577.48	577.56	577.70	578.00	578.10	577.98	577.86	577.53	577.42	577.01	576.62	577.55
1963	576.36	576.30	576.40	576.63	576.90	577.01	576.95	576.92	576.87	576.47	576.04	575.80	576.55
1964	575.51	575.42	575.52	575.66	575.95	576.02	576.15	576.07	575.93	575.75	575.62	575.54	575.76
1965	575.48	575.54	575.84	576.16	576.66	576.88	576.90	576.95	577.05	577.10	576.96	577.13	576.55
1966	577.11	577.11	577.35	577.59	577.67	577.74	577.71	577.58	577.47	576.90	576.92	577.05	577.35
1967	576.96	577.05	577.04	577.60	578.01	578.33	578.44	578.39	578.22	577.94	577.88		577.81
1968		577.62	577.77	578.00	578.28	578.44	578.58	578.66	578.80	578.58	578.52	578.44	578.34
1969	578.30		578.44	578.72	579.20	579.56	579.94	579.85	579.68	579.36	579.10	578.95	579.19
1970						STATION CLOSED							
1971													
1972													
1973													
1974													
1975													
1976													
1977													
1978													
1979													

Table 46 (continued)

U. S. DEPARTMENT OF COMMERCE
NOAA - NOS ROCKVILLE, MARYLAND
GREAT LAKES WATER LEVELS, C234

SUMMARY OF AVERAGE AND EXTREME LEVELS
WATER LEVELS IN FEET, IGLD (1955)

Station 7058 : Milwaukee, Wisconsin on Lake Michigan

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL AVG
MONTHLY AVERAGE FOR PERIOD 1860 THRU 1968	578.03	578.04	578.18	578.44	578.73	578.95	579.03	578.98	578.79	578.56	578.31	578.11	578.51
MONTHLY AVERAGE FOR PERIOD 1900 THRU 1968	577.43	577.44	577.56	577.85	578.16	578.36	578.44	578.39	578.21	577.98	577.75	577.56	577.93
MONTHLY AVERAGE FOR PERIOD 1959 THRU 1968	576.65	576.78	576.90	577.16	577.52	577.68	577.73	577.72	577.63	577.40	577.23	577.06	577.29
HIGHEST MONTHLY AVERAGE FOR PERIOD 1860 THRU 1968													
LEVEL	580.65	580.74	580.95	581.22	581.48	581.55	581.54	581.47	581.42	581.01	580.94	580.58	580.94
YEAR	1886	1860	1886	1886	1886	1886	1876	1876	1876	1885	1876	1861	1886
LOWEST MONTHLY AVERAGE FOR PERIOD 1860 THRU 1968													
LEVEL	575.40	575.42	575.52	575.66	575.95	576.02	576.15	576.07	575.93	575.73	575.62	575.52	575.76
YEAR	1926	1964	1964	1964	1964	1964	1964	1964	1964	1934	1964	1925	1964

HIGHEST MONTHLY AVERAGE FOR PERIOD 1860 THRU 1968 ....581.55 JUN 1886

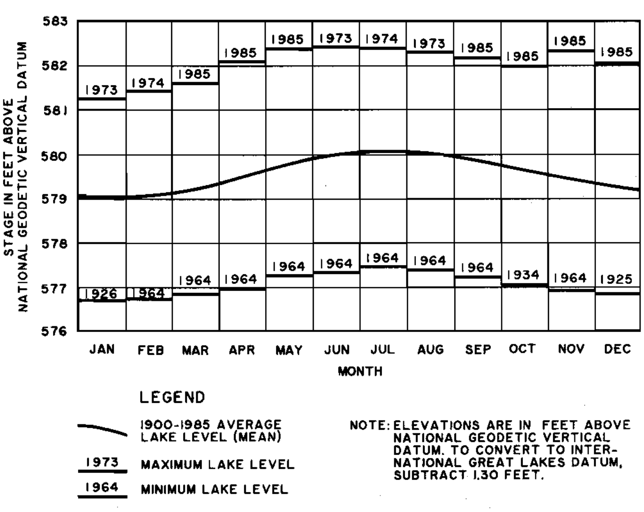
LOWEST MONTHLY AVERAGE FOR PERIOD 1860 THRU 1968 .....575.40 JAN 1926

NOTE: Elevations are in feet above the International Great Lakes Datum-1955 (IGLD). To convert to National Geodetic Vertical Datum (NGVD), add 1.30 feet.

Source: National Ocean Survey.

Figure 35

VARIATIONS IN MONTHLY MEAN WATER LEVELS FOR LAKE MICHIGAN AT MILWAUKEE: 1900-1985



Source: U. S. Department of Commerce, National Oceanic and Atmospheric Administration, and SEWRPC.

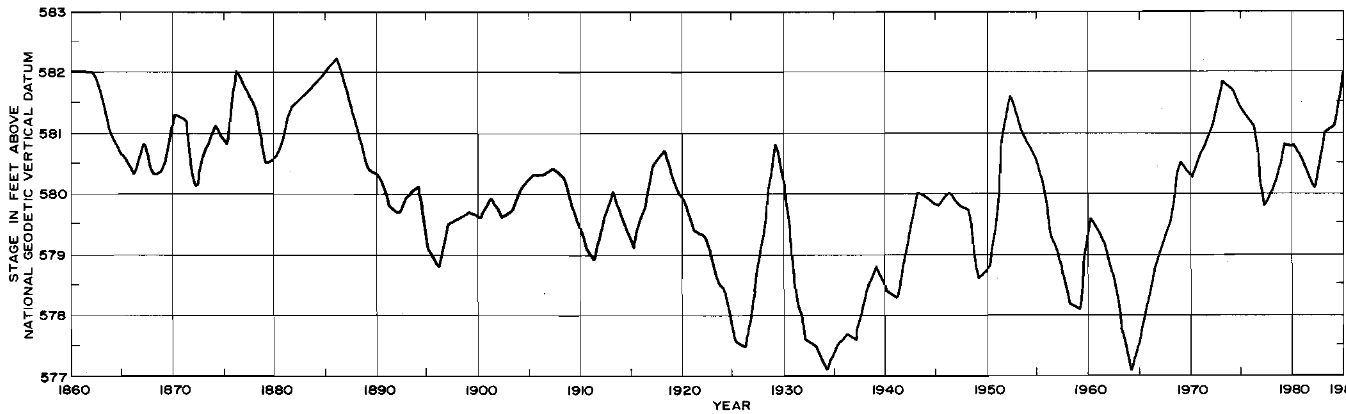
the 86-year period from 1900 through 1985. As predicted by the hydrologic budget, lake levels generally rise from February through July and fall during the remainder of the year. In a given one-year period, the range in base lake levels may be expected to be about one foot. The historic range between maximum and minimum annual mean water levels for the Lakes Michigan-Huron system is about five feet.

Figure 36 shows the annual mean water level for Lake Michigan recorded at Milwaukee for the period 1860 through 1985. Long-term variations in lake levels are obvious, but are not well understood or predictable. The historic low and high annual mean lake levels at Milwaukee occurred in 1964 and 1886, respectively, and differed by 5.2 feet.

Figure 37 compares annual monthly maximum and instantaneous annual maximum water levels for Lake Michigan at Milwaukee during the period 1904-1985. Figure 38 is similar but shows annual monthly minimum and instantaneous minimum

Figure 36

LAKE MICHIGAN ANNUAL MEAN WATER LEVELS AT MILWAUKEE: 1860-1985

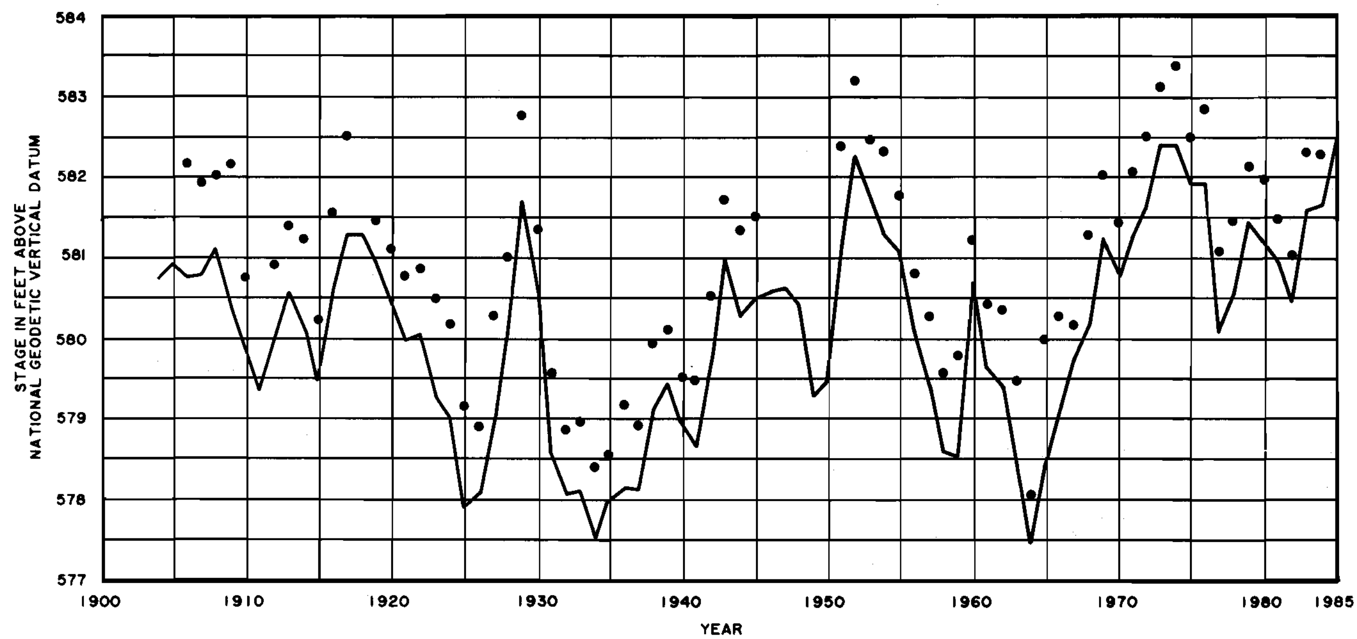


NOTE: ELEVATIONS ARE IN FEET ABOVE NATIONAL GEODETIC VERTICAL DATUM. TO CONVERT TO INTERNATIONAL GREAT LAKES DATUM, SUBTRACT 1.30 FEET.

Source: SEWRPC.

Figure 37

LAKE MICHIGAN ANNUAL MONTHLY MEAN MAXIMUM AND INSTANTANEOUS MAXIMUM STAGES AT MILWAUKEE: 1904-1985



LEGEND

MONTHLY MAXIMUM

INSTANTANEOUS MAXIMUM

NOTE: ELEVATIONS ARE IN FEET ABOVE NATIONAL GEODETIC VERTICAL DATUM. TO CONVERT TO INTERNATIONAL GREAT LAKES DATUM SUBTRACT 1.30 FEET.

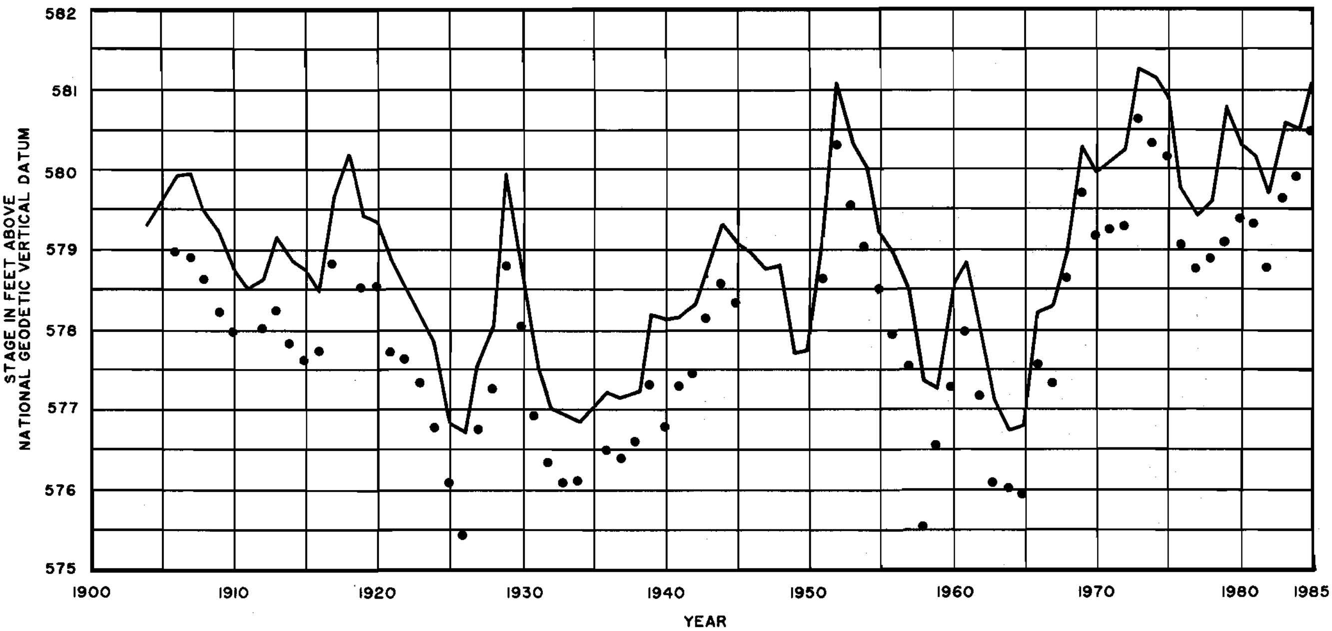
Source: National Ocean Survey and SEWRPC.

water levels for the same period. Data plotted in these figures are tabulated in Table 47 along with annual mean water levels. The maxima and minima data in Table 47 are provided by the National Ocean Survey upon request.

As the data indicate, from 1904 through 1985, the maximum recorded monthly mean water level occurred in June 1973, July 1974, and May 1985. The instantaneous annual maximum occurred on November 9, 1985. During the same period, the minimum monthly mean water level occurred in February 1964. The instantaneous annual minimum occurred on January 23, 1926. The recorded mean monthly maximum and minimum stages differed by 5.7 feet, whereas the instantaneous maximum and minimum stages differed by 8.2 feet.

Figure 38

LAKE MICHIGAN ANNUAL MONTHLY MEAN MINIMUM AND INSTANTANEOUS MINIMUM STAGES AT MILWAUKEE: 1904-1985



Source: National Ocean Survey and SEWRPC.

Water Level Frequency Analyses: The water level data collected for Lake Michigan at Milwaukee by the NOS were subjected to several frequency analyses to provide information useful in the design of offshore and shoreline structures and navigation channels, and for floodplain management purposes. Because Lake Michigan water levels are affected by diversions into and from the Lakes Michigan-Huron system, by outflow from Lake Superior, and by changes that have occurred in hydraulic conditions in the outlet channels and structures, the long-term water level data collected at Milwaukee are not all from the same statistical population, and were adjusted as described in the following paragraphs to represent existing conditions. The adjusted water levels subsequently were used in the frequency analyses. A prerequisite to the use of normal probability theory in the development of a water level stage-probability model is that the annual data be independent of one another. Autocorrelation analyses of the annual stage series for Lake Michigan at Milwaukee found strong correlations between water levels in adjacent years, and in two-year lags. A four-year lag was found to produce little autocorrelation and, consequently, only annual data at four-year intervals were used in the probability analysis.

Adjustment of Recorded Water Levels to Existing Conditions: To provide statistical estimates of instantaneous maximum water levels for floodplain and shoreland management purposes, the U. S. Army Corps of Engineers, at the request of the Federal Insurance Administration, conducted frequency analyses of annual instantaneous maximum water levels recorded at Milwaukee and elsewhere in the Great Lakes. Prior to the frequency analyses, however, the Corps adjusted the long-term water levels from 1900-1974 to represent existing diversion and hydraulic outlet conditions and existing regulation.[2] No such adjustments were necessary after 1974. Net historic basin supplies routed through and from Lake Superior were routed through the Lakes Michigan-Huron system minus a constant diversion of 3,200 cubic feet per second (cfs) at Chicago to compute annual and monthly mean water levels for existing conditions. It was

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[2] *U. S. Army Corps of Engineers,* Report on Great Lakes Open-Coast Flood Levels, *Detroit, Michigan, prepared for Federal Insurance Administration, 1977.*

Table 47

MEAN, MINIMUM, AND MAXIMUM WATER LEVEL DATA FOR LAKE MICHIGAN AT MILWAUKEE: 1904-1985[a]

YEAR	ANNUAL MEAN	Maximum MONTHLY MEAN	Maximum DAILY MEAN	Maximum INSTAN-TANEOUS	Minimum MONTHLY MEAN	Minimum DAILY MEAN	Minimum INSTAN-TANEOUS
1904	578.85	579.47	579.66	--	577.97	577.39	577.02[b]
1905	578.97	579.62	579.78	--	578.27	577.72	577.35[b]
1906	579.05	579.48	579.78	580.90	578.61	578.27	577.69
1907	579.06	579.52	579.79	580.67	578.63	578.07	577.59
1908	578.99	579.83	580.05	580.75	578.13	577.64	577.34
1909	578.49	579.08	579.29	580.88	577.88	577.44	576.93
1910	578.14	578.57	578.85	579.47	577.45	576.90	576.67
1911	577.59	578.04	578.26	--	577.20	576.73	576.34[b]
1912	578.08	578.72	579.08	579.65	577.28	576.96	576.72
1913	578.70	579.28	579.66	580.12	577.85	577.35	576.95
1914	578.27	578.82	579.09	579.96	577.56	576.90	576.53
1915	577.75	578.21	578.71	578.94	577.43	577.02	576.32
1916	578.38	579.34	579.55	580.28	577.16	576.72	576.44
1917	579.18	579.99	580.17	581.24	578.38	577.88	577.52
1918	579.42	580.00	580.18	--	578.84	578.58	578.23[b]
1919	578.93	579.62	579.81	580.17	578.10	577.67	577.24
1920	578.58	579.13	579.28	579.83	578.02	577.56	577.26
1921	578.12	578.67	579.01	579.50	577.53	577.22	576.43
1922	578.00	578.75	578.97	579.59	577.16	576.66	576.34
1923	577.40	577.98	578.10	579.22	576.83	576.43	576.04
1924	577.12	577.70	577.84	578.89	576.50	575.91	575.49
1925	576.27	576.62	576.89	577.87	575.52	575.04	574.80
1926	576.19	576.77	577.16	577.62	575.40	574.92	574.15
1927	577.02	577.64	577.85	579.01	576.27	575.96	575.48
1928	578.00	578.71	579.17	579.73	576.69	576.24	575.97
1929	579.52	580.43	580.55	581.47	578.58	578.04	577.49
1930	578.67	579.32	579.55	580.06	577.49	577.05	576.75
1931	576.95	577.29	577.85	578.28	576.34	575.93	575.65
1932	576.34	576.77	577.16	577.57	575.71	575.31	575.06
1933	576.15	576.82	576.98	577.68	575.62	575.22	574.82
1934	575.84	576.21	576.39	577.12	575.54	575.13	574.82
1935	576.23	576.71	577.00	577.27	575.68	575.27	575.00
1936	576.40	576.85	577.02	577.90	575.91	575.52	575.22
1937	576.35	576.82	576.98	577.62	575.84	575.29	575.11
1938	577.10	577.83	578.10	578.66	575.89	575.49	575.32
1939	577.53	578.14	578.40	578.82	576.88	576.42	576.02
1940	577.14	577.65	577.88	578.23	576.80	576.38	575.50
1941	577.04	577.32	577.65	578.19	576.84	576.37	576.01
1942	577.75	578.37	578.56	579.26	576.98	576.41	576.16
1943	578.70	579.67	579.93	580.45	577.49	577.23	576.84
1944	578.64	579.00	579.22	580.06	578.00	577.58	577.29
1945	578.53	579.20	579.45	580.23	577.73	577.38	577.06

Table 47 (continued)

YEAR	ANNUAL MEAN	Maximum MONTHLY MEAN	Maximum DAILY MEAN	Maximum INSTANTANEOUS	Minimum MONTHLY MEAN	Minimum DAILY MEAN	Minimum INSTANTANEOUS
1946	578.65	579.29	579.65	--	577.61	576.86	576.48[b]
1947	578.54	579.35	579.62	--	577.43	576.91	576.53[b]
1948	578.43	579.11	579.40	--	577.46	576.90	576.52[b]
1949	577.35	577.98	578.29	--	576.37	575.58	575.17[b]
1950	577.53	578.20	578.58	--	576.43	575.65	575.24[b]
1951	579.13	579.86	580.64	581.08	577.78	577.42	577.36
1952	580.29	580.95	581.14	581.89	579.72	579.30	578.99
1953	579.79	580.37	580.73	581.18	579.01	578.50	578.26
1954	579.49	579.96	580.31	581.03	578.74	578.36	577.74
1955	579.09	579.75	580.06	580.47	577.92	577.55	577.20
1956	578.19	578.78	579.03	579.51	577.62	577.25	576.65
1957	577.60	578.11	578.33	578.97	577.21	576.70	576.26
1958	576.92	577.27	577.98	578.28	576.02	575.48	574.25
1959	576.80	577.20	578.05	578.47	575.94	575.62	575.27
1960	578.33	579.30	579.49	579.93	577.19	576.53	575.99
1961	578.04	578.32	578.59	579.12	577.54	577.10	576.68
1962	577.55	578.10	578.25	579.05	576.62	576.24	575.88
1963	576.55	577.01	577.28	578.18	575.80	575.27	574.81
1964	575.76	576.15	576.50	576.77	575.42	575.05	574.76
1965	576.55	577.13	577.97	578.68	575.48	575.10	574.69
1966	577.35	577.74	578.35	578.97	576.90	576.46	576.28
1967	577.81	578.44	578.69	578.87	576.96	576.54	576.04
1968	578.34	578.80	579.53	579.97	577.62	577.53	577.36
1969	579.19	579.93	580.26	580.72	578.30	578.62	578.42
1970	579.05	579.41	579.71	580.13	578.60	578.35	577.88
1971	579.39	579.95	580.22	580.76	578.78	578.28	577.95
1972	579.75	580.30	580.78	581.21	578.91	578.47	578.00
1973	580.55	581.09	581.36	581.82	579.93	579.55	579.33
1974	580.42	581.09	581.29	582.08	579.84	579.39	579.03
1975	580.04	580.59	580.85	581.19	579.57	579.12	578.87
1976	579.78	580.62	580.99	581.53	578.38	578.00	577.73
1977	578.51	578.80	579.18	579.78	578.08	577.60	577.47
1978	578.81	579.26	579.80	580.15	578.28	577.97	577.60
1979	579.49	580.14	580.33	580.82	578.49	577.98	577.80
1980	579.51	579.92	580.15	580.67	578.97	578.49	578.07
1981	579.21	579.65	579.94	580.18	578.83	578.19	578.03
1982	578.84	579.16	579.39	579.73	578.37	578.01	577.48
1983	579.67	580.28	580.60	580.98	579.26	578.67	578.36
1984	579.84	580.34	580.55	580.96	579.16	578.85	578.62
1985	580.66	581.09	581.78	582.43	579.78	579.41	579.18

[a] Elevations are in feet above the International Great Lakes Datum(1955). To convert to National Geodetic Vertical Datum, add 1.30 feet.

[b] Estimated using regression equation.

Source: National Ocean Survey and SEWRPC.

necessary to use an iterative procedure to incorporate variable backwater effects from Lakes Erie and St. Clair. The computed hydrograph was compared with the historic hydrograph and the differences in mean water level for each month were calculated. The differences for Lakes Michigan-Huron ranged from -0.5 to +0.4 foot. The monthly differences were then added by the Corps to the historic monthly means, and subsequently to the annual instantaneous maxima recorded at individual water level gaging stations, to yield adjusted instantaneous maximum water levels representing existing conditions. The Commission obtained the adjustments to the monthly mean water level data for Lake Michigan at Milwaukee and applied the differences to the recorded annual maximum and minimum monthly and daily means, and also to recorded instantaneous minimum values. Adjusted annual means were determined by computing the mean of the differences for each year, and then adding that to the recorded annual mean water level. The frequency analyses subsequently conducted as discussed in the following sections are, except as noted, for the period 1915 through 1985. Table 48 presents the recorded water level data adjusted to existing conditions for this period.

Annual Mean Frequency Analysis: A frequency analysis was applied to the annual mean water levels recorded at Milwaukee for the period 1915 through 1985 using the water level differences

Table 48

MEAN, MINIMUM, AND MAXIMUM WATER LEVELS FOR LAKE MICHIGAN AT MILWAUKEE ADJUSTED TO EXISTING DIVERSION, OUTLET, AND REGULATION CONDITIONS: 1915-1985[a]

		Maximum			Minimum		
YEAR	ANNUAL MEAN	MONTHLY MEAN	DAILY MEAN	INSTANTANEOUS	MONTHLY MEAN	DAILY MEAN	INSTANTANEOUS
1915	577.62	578.03	578.53	578.76	577.29	576.86	576.17
1916	578.38	579.40	579.59	580.32	577.05	576.61	576.33
1917	579.16	579.97	580.15	581.21	578.33	577.83	577.47
1918	579.36	579.94	580.11	580.68[b]	578.84	578.58	578.23[b]
1919	579.01	579.71	579.90	580.24	578.22	577.79	577.36
1920	578.69	579.24	579.39	579.94	578.14	577.66	577.38
1921	578.22	578.77	579.11	579.60	577.63	577.32	576.53
1922	578.11	578.87	579.09	579.71	577.28	576.78	576.46
1923	577.49	578.07	578.19	579.32	576.89	576.55	576.16
1924	577.20	577.79	577.92	578.97	576.61	576.02	575.60
1925	576.26	576.60	576.94	577.92	575.38	574.90	574.66
1926	576.05	576.65	577.04	577.53	575.24	574.76	573.99
1927	576.91	577.49	577.70	578.85	576.18	575.87	575.32
1928	578.11	578.91	579.36	579.92	576.69	576.24	575.97
1929	579.82	580.74	580.86	581.83	578.79	578.40	577.73
1930	579.02	579.67	579.90	580.41	577.79	577.35	577.05
1931	577.24	577.57	578.13	578.56	576.63	576.22	575.94
1932	576.58	577.01	577.44	577.84	575.92	575.52	575.27
1933	576.34	577.01	577.17	577.87	575.77	575.42	574.98
1934	575.92	576.29	576.47	577.20	575.66	575.27	574.96
1935	576.22	576.69	576.98	577.25	575.69	575.28	575.01
1936	576.38	576.82	576.99	577.87	575.90	575.51	575.21
1937	576.43	576.90	577.10	577.69	576.02	575.47	575.11
1938	577.32	578.05	578.31	578.88	576.09	575.69	575.52
1939	577.64	578.21	578.46	578.88	577.06	576.60	576.20
1940	577.22	577.74	577.97	578.32	576.86	576.46	575.58
1941	577.05	577.33	577.61	578.22	576.89	576.42	576.05
1942	577.74	578.35	578.55	579.25	576.94	576.37	576.12
1943	578.69	579.60	579.86	580.38	577.59	577.32	576.93

Table 48 (continued)

YEAR	ANNUAL MEAN	Maximum MONTHLY MEAN	Maximum DAILY MEAN	Maximum INSTANTANEOUS	Minimum MONTHLY MEAN	Minimum DAILY MEAN	Minimum INSTANTANEOUS
1944	578.52	578.88	579.10	579.94	577.85	577.43	577.14
1945	578.36	579.03	579.28	580.06	577.57	577.22	576.90
1946	578.43	579.06	579.43	580.01[b]	577.35	576.60	576.22[b]
1947	578.25	579.06	579.33	579.91[b]	577.15	576.64	576.26[b]
1948	578.05	578.71	579.00	579.58[b]	577.08	576.52	576.14[b]
1949	576.99	577.62	577.91	578.51[b]	576.05	575.26	574.85[b]
1950	577.21	577.88	578.26	578.86[b]	576.12	575.34	574.93[b]
1951	578.70	579.41	580.17	580.61	577.40	577.04	576.98
1952	579.90	580.60	580.79	581.52	579.25	578.83	578.52
1953	579.45	580.02	580.38	580.86	578.71	578.20	577.96
1954	579.09	579.56	579.92	580.62	578.34	577.96	577.33
1955	578.72	579.39	579.70	580.11	577.56	577.19	576.84
1956	577.82	578.41	578.66	579.14	577.23	576.86	576.26
1957	577.27	577.77	577.99	578.63	576.89	576.38	575.94
1958	576.57	576.91	577.64	577.94	575.67	575.12	573.89
1959	576.50	576.94	577.79	578.21	575.59	575.28	574.93
1960	578.05	579.00	579.19	579.63	576.93	576.27	575.73
1961	577.82	578.10	578.32	578.93	577.40	576.96	576.54
1962	577.44	578.00	578.15	578.95	576.49	576.11	575.75
1963	576.40	576.85	577.12	578.03	575.65	575.12	574.66
1964	575.63	576.03	576.38	576.65	575.28	574.90	574.62
1965	576.46	577.06	577.90	578.61	575.37	574.99	574.58
1966	577.30	577.68	578.29	578.91	576.86	576.42	576.24
1967	577.81	578.44	578.70	578.88	576.93	576.51	576.01
1968	578.35	578.80	579.51	579.95	577.65	577.56	577.39
1969	579.14	579.88	580.21	580.67	578.27	578.54	578.35
1970	578.95	579.31	579.61	580.03	578.51	578.26	577.79
1971	579.27	579.83	580.10	580.64	578.66	578.16	577.83
1972	579.67	580.24	580.72	581.15	578.80	578.36	577.89
1973	580.53	581.06	581.32	581.78	579.88	579.50	579.28
1974	580.54	581.21	581.41	582.20	580.01	579.56	579.20
1975	580.04	580.59	580.85	581.19	579.57	579.12	578.87
1976	579.78	580.62	580.99	581.53	578.38	578.00	577.73
1977	578.51	578.80	579.18	579.78	578.08	577.60	577.47
1978	578.81	579.26	579.80	580.15	578.28	577.97	577.60
1979	579.49	580.14	580.33	580.82	578.49	577.98	577.80
1980	579.51	579.92	580.15	580.67	578.97	578.49	578.07
1981	579.21	579.65	579.94	580.18	578.83	578.19	578.03
1982	578.84	579.16	579.39	579.73	578.37	578.01	577.48
1983	579.67	580.28	580.60	580.98	579.26	578.67	578.36
1984	579.84	580.34	580.55	580.96	579.16	578.85	578.62
1985	580.66	581.09	581.78	582.43	579.78	579.41	579.18

[a] Elevations are in feet above the International Great Lakes Datum(1955). To convert to National Geodetic Vertical Datum, add 1.30 feet.

[b] Estimated using regression equation.

Source: National Ocean Survey, U. S. Army Corps of Engineers, and SEWRPC.

computed by the Corps of Engineers to adjust the recorded data to present diversions, outlets, and regulation schedules. As stated earlier, only data collected at four-year intervals were used in the probability analysis to maintain independence. A normal distribution for the data was computed and plotted on normal probability paper along with the data points. The computed curve is shown in Figure 39, along with other computed curves to be discussed in subsequent sections of this chapter.

The recorded annual mean lake levels plotted versus time in Figure 36 are reproduced in Figure 40 for the period 1915 through 1984, along with the annual minimum 7-day low flow recorded at the U. S. Geological Survey gaging station on the Milwaukee River in Milwaukee. As Figure 40 indicates, the lower annual mean lake levels usually occur during years in which streamflow is relatively low also. Similarly, higher lake levels often occur when streamflow is relatively high.

Based upon the computed normal distribution, and assuming the period 1915 through 1985 to be statistically representative, there is a probability of 1 percent that the annual mean lake levels will exceed 582.9 feet NGVD or 581.6 feet IGLD, and a probability of 10 percent that they will exceed 581.4 feet NGVD or 580.1 feet IGLD, under existing conditions. The mean annual lake level (arithmetic mean of all annual means) is 579.5 feet NGVD or 578.2 feet IGLD.

Quarterly Frequency Analysis: The U. S. Army Corps of Engineers, in an unpublished report, presented standardized frequency curves for use in determining design water levels for the Great Lakes.[3] Log Pearson Type III frequency analyses were conducted for the maximum monthly mean water level of each quarter of each year for the period 1915 through 1974. Recorded water levels were first adjusted to reflect existing diversions, outlets, and regulation schedules as described earlier. A log-normal distribution was assumed in the analysis. Figure 41 presents the frequency curves so developed for all four quarters of the year. Third-quarter water levels are statistically the highest.

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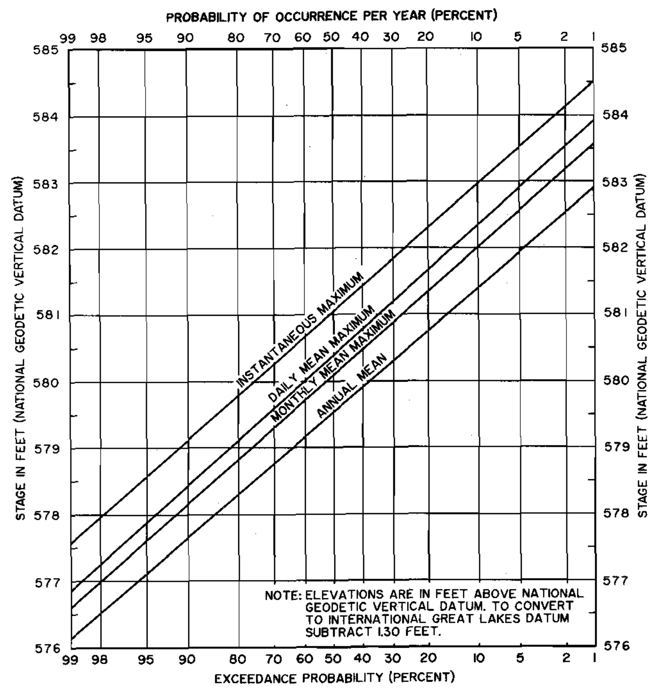
[3] *U. S. Army Corps of Engineers, "Standardized Frequency Curves for Design Water Level Determinations on the Great Lakes," Detroit District, unpublished report.*

Figure 39

FREQUENCY CURVES FOR LAKE MICHIGAN ANNUAL MAXIMUM AND ANNUAL MEAN WATER LEVELS AT MILWAUKEE FOR EXISTING DIVERSIONS, OUTLETS AND REGULATION SCHEDULES



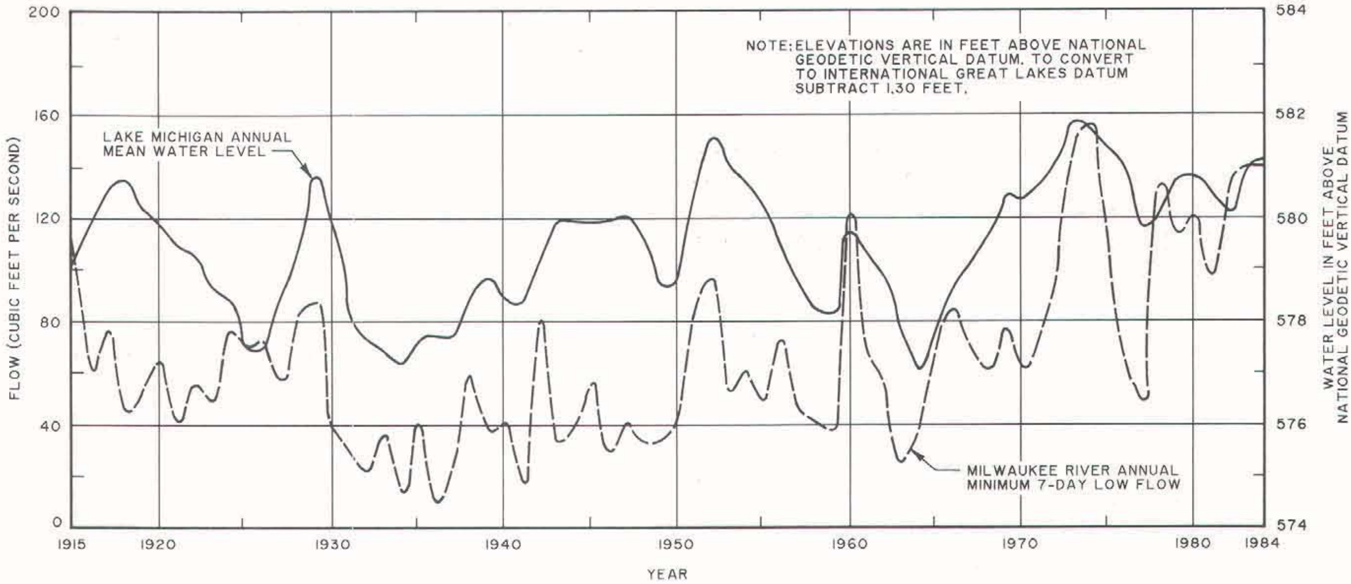
Source: U. S. Army Corps of Engineers.

Annual Monthly Maxima Frequency Analysis: A frequency analysis of the maximum monthly mean water level that occurred each year for Lake Michigan in Milwaukee was conducted by the Commission for existing diversions, outlets, and regulation schedules for the period 1915 through 1985. The data were subjected to the same analysis applied to annual mean water levels described earlier in this chapter.

Based upon the computed normal distribution, and assuming the period 1915 through 1985 to be statistically representative, there is a probability of 1 percent that the annual maximum monthly mean water levels for existing conditions will exceed 583.5 feet NGVD or 582.2 feet IGLD, and about a 10 percent probability that they will exceed 582.0 feet NGVD or 580.7 feet IGLD. The mean annual monthly mean maximum is 580.0 feet NGVD or 578.7 feet IGLD.

Figure 40

COMPARISON OF LAKE MICHIGAN RECORDED ANNUAL MEAN WATER LEVELS AT MILWAUKEE AND MILWAUKEE RIVER ANNUAL MINIMUM SEVEN-DAY FLOW: 1915-1984



Source: SEWRPC.

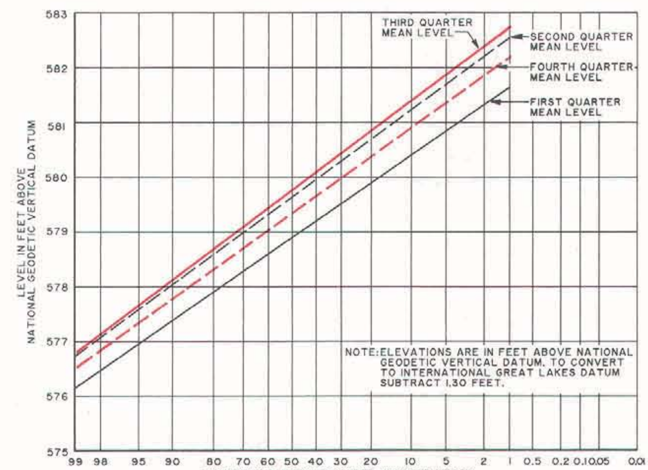
Annual Daily Maxima Frequency Analysis: A frequency analysis for existing diversions, outlets, and regulation schedules was also conducted of the maximum daily mean water level that occurred each year during the period 1915-1985 similar to that described earlier for annual mean water levels. Figure 39 shows the computed normal distribution for a four-year lag period.

Using the computed distribution, and assuming the period 1915 through 1985 to be statistically representative, there is a probability of 1 percent that the annual daily mean maximum lake levels for existing diversions, outlets, and regulation conditions will exceed 583.9 feet NGVD or 582.6 feet IGLD, and a 10 percent probability of exceeding 582.3 feet NGVD or 581.0 feet IGLD. The mean annual daily mean maximum is 580.4 feet NGVD or 579.1 feet IGLD.

Annual Instantaneous Maxima Frequency Analysis: A frequency analysis under existing diversions, outlets, and regulation schedules was also conducted of the instantaneous maximum water level that occurred each year during the period 1915 through 1985, similar to that described earlier for annual mean water levels. Figure 39 shows the computed normal distribution for a four-year lag period.

Figure 41

FREQUENCY CURVES FOR LAKE MICHIGAN QUARTERLY WATER LEVELS: 1915-1974



Source: U. S. Army Corps of Engineers.

Using the computed distribution, and assuming the period 1915 through 1985 to be statistically representative, there is a probability of 1 percent that the annual instantaneous maximum water level for existing diversions, outlets, and regulation conditions will exceed 584.5 feet NGVD or 583.2 feet IGLD, and a 10 percent probability of exceeding 582.9 feet NGVD or 581.6 feet IGLD. The mean annual instantaneous maximum water level is 581.0 feet NGVD or 579.7 feet IGLD. A similar analysis for the period 1900 through 1974 was conducted by the U. S. Army Corps of Engineers.[4] The present analysis is intended to update that presented by the Corps through 1985 in the Milwaukee area. Table 49 summarizes the revised probability data. The maximum instantaneous recorded water level of 583.73 feet NGVD or 582.43 feet IGLD on November 9, 1985, was slightly—0.03 foot—higher than the 100-year lake level based on the analysis by the Corps of Engineers. Based on the updated analysis, however, the recurrence interval of that event is estimated to be about 30 years for existing conditions.

Annual, Quarterly, and Monthly Maximum Rise Frequency Analysis: The U. S. Army Corps of Engineers, in an unpublished report cited earlier in this chapter, presented standardized frequency curves for the period 1915 through 1974 for use in determining design water levels for the Great Lakes. As part of the analysis, water-level rise frequency computations were made using data collected at Milwaukee Harbor on an annual, quarterly, and monthly basis. Rise was defined as the difference between the instantaneous maximum water level during a given month and the corresponding monthly mean water level.

The annual analysis utilized the maximum monthly rise that occurred each year. A log Pearson Type III analysis was conducted assuming a log-normal distribution. The resulting rise frequency curve is shown in Figure 42. The curve indicates that the 100-year recurrence interval annual maximum rise is 1.9 feet and the 10-year rise is 1.6 feet.

A similar analysis was conducted using the maximum monthly rise that occurred in each quarter of each year. The frequency curves for all four quarters are shown in Figure 43. The maximum 100-year and 10-year recurrence interval rises both occur in the first quarter and are 1.8 and 1.4 feet, respectively.

[4] *U. S. Army Corps of Engineers, Report on Great Lakes Open-Coast Flood Levels, Detroit, Michigan, prepared for Federal Insurance Administration, 1977.*

Table 49

OPEN-COAST INSTANTANEOUS MAXIMUM WATER LEVELS FOR VARIOUS RECURRENCE INTERVALS FOR LAKE MICHIGAN AT MILWAUKEE[a]

Recurrence Interval (years)[b]	Instantaneous Maximum Water Level (feet)[c]
10	582.9
50	584.1
100	584.5
500	585.3

[a] *Based on water level records for the period 1915-1985.*

[b] *Exceedance probability in percent = (recurrence interval in years)* $^{-1}$ *x 100.*

[c] *Elevations are in feet above National Geodetic Vertical Datum (NGVD).*

Source: SEWRPC.

Frequency analyses of annual monthly maximum rises were also conducted; the resulting frequency curves are shown in Figure 44. The annual maximum monthly rises for both the 100-year and 10-year recurrence intervals occur in December and are 2.0 and 1.4 feet, respectively. August has the smallest 100- and 10-year rises of 0.8 and 0.6 foot, respectively.

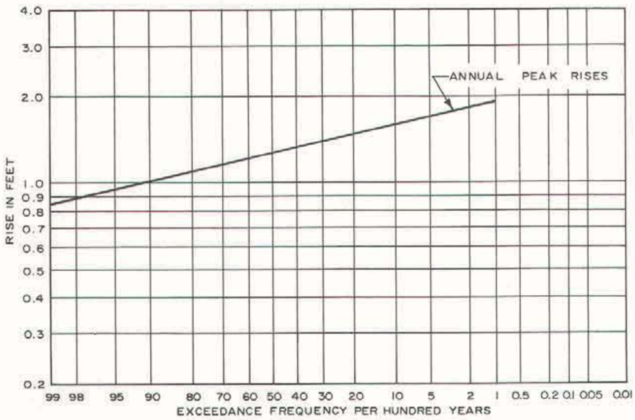
The Corps of Engineers recommends the use of rise frequency data for design water levels for harbor and shore protection and protection of coastal structures. Below is an example provided in the previously cited Corps report for determining design water level for Lake Huron at Harbor Beach, Michigan:

20-year annual mean water level = 581.9 feet NGVD or 580.6 feet IGLD probability = 0.05
1-year annual peak rise - 0.6, probability = 1.00
Design water level = 582.5 feet NGVD or 581.2 feet IGLD
Joint probability = 0.05, 20-year recurrence interval.

The Corps report states that other combinations of frequencies and seasons may be used as design conditions warrant.

Figure 42

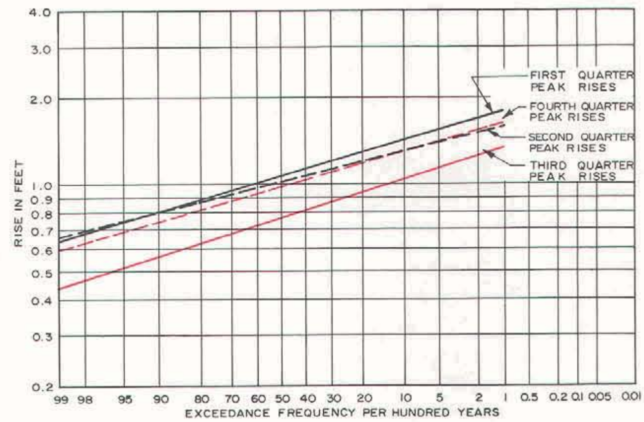
FREQUENCY CURVE FOR LAKE MICHIGAN ANNUAL MAXIMUM RISE AT MILWAUKEE: 1915-1974



Source: U. S. Army Corps of Engineers.

Figure 43

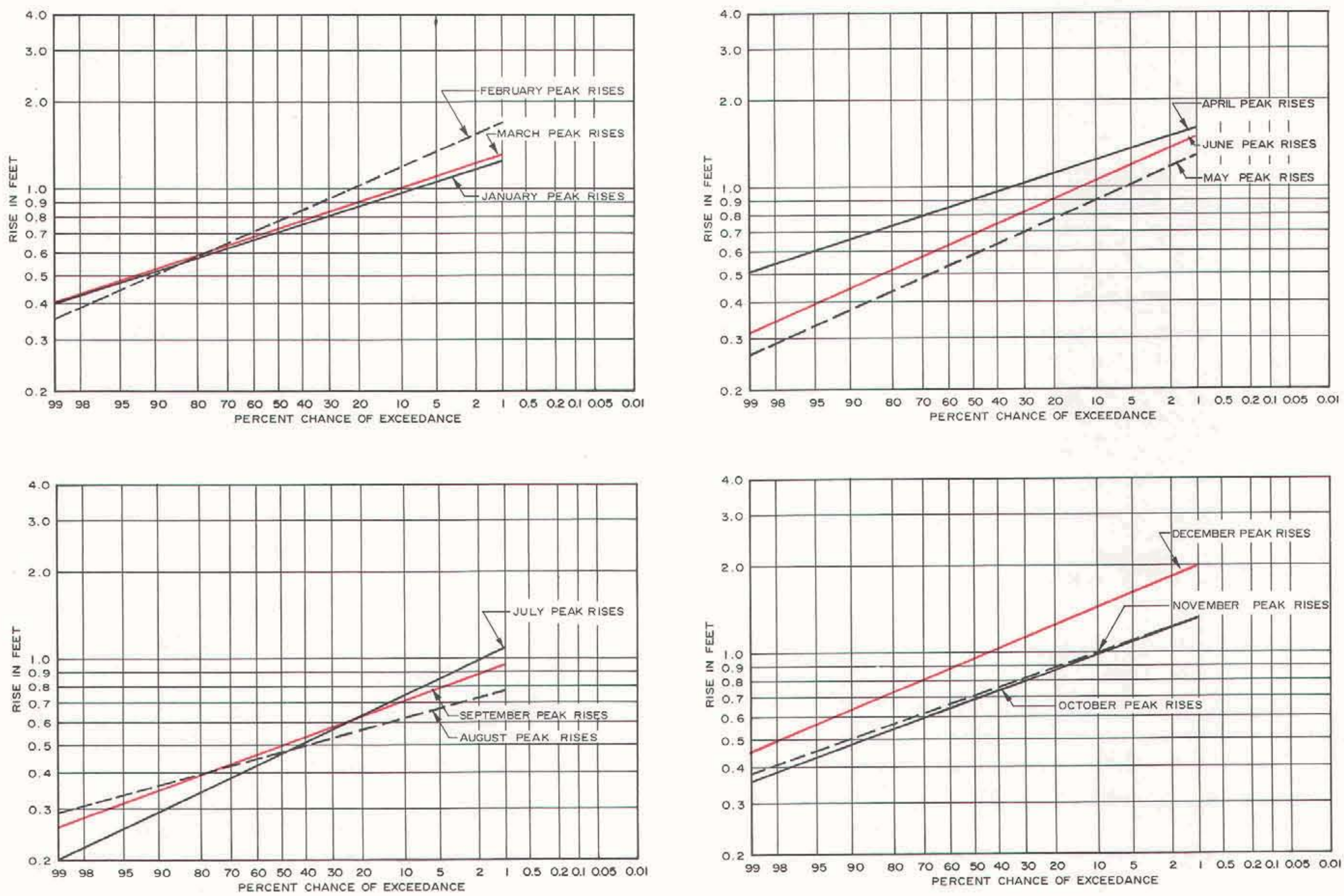
FREQUENCY CURVES FOR LAKE MICHIGAN QUARTERLY MAXIMUM RISE AT MILWAUKEE: 1915-1974



Source: U. S. Army Corps of Engineers.

Figure 44

FREQUENCY CURVES FOR LAKE MICHIGAN MONTHLY MAXIMUM RISE AT MILWAUKEE: 1965-1977



Source: U. S. Army Corps of Engineers.

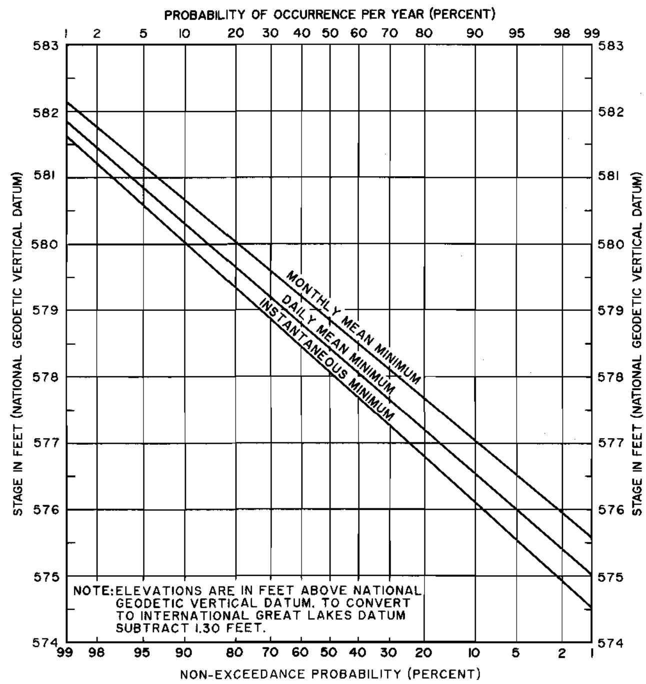
Annual Monthly Minima Frequency Analysis: A frequency analysis under existing diversions, outlets, and regulation schedules was also conducted of the minimum monthly mean water level that occurred each year during the period 1915 through 1985, similar to that described earlier for annual mean water levels. Figure 45 shows the computed normal distribution for a four-year lag period. Using the computed distribution, and assuming the period 1915 through 1985 to be statistically representative, there is a probability of 1 percent that the annual monthly minimum water level for existing diversions, outlets, and regulation conditions will be less than 575.5 feet NGVD or 574.2 feet IGLD, and a 10 percent probability of being less than 577.0 feet NGVD or 575.7 feet IGLD. The mean annual monthly minimum water level is 578.8 feet NGVD or 577.5 feet IGLD.

Annual Daily Minima Frequency Analysis: A frequency analysis under existing diversions, outlets, and regulation schedules was also conducted of the minimum daily mean water level that occurred each year during the period 1915 through 1985, similar to that described earlier for annual mean water levels. Figure 45 shows the computed normal distribution for a four-year lag period. Using the computed distribution, and assuming the period 1915 through 1985 to be statistically representative, there is a probability of 1 percent that the annual minimum daily mean water level for existing diversions, outlets, and regulation conditions will be less than 575.0 feet NGVD or 573.7 feet IGLD, and a 10 percent probability of being less than 576.5 feet NGVD or 575.2 feet IGLD. The mean annual minimum daily water level is 578.4 feet NGVD or 577.1 feet IGLD.

Annual Instantaneous Minima Frequency Analysis: Similar to the analysis described above, a frequency analysis was conducted using the instantaneous minimum water level that occurred each year during the period 1915-1985, adjusted to reflect existing diversions, outlets, and regulation schedules. Because there were nine years during this period in which instantaneous minimum levels were not recorded, a linear regression analysis was performed on the recorded data to provide a means of synthesizing the missing values. The regression analysis correlated annual instantaneous minima with annual daily mean minima. The regression analysis yielded a correlation coefficient of 0.989 and a standard error of estimate of 0.19 foot, and is of the form:

Figure 45

FREQUENCY CURVES FOR LAKE MICHIGAN ANNUAL MINIMUM WATER LEVELS AT MILWAUKEE FOR EXISTING DIVERSIONS, OUTLETS, AND REGULATION SCHEDULES: 1915-1985



Source: U. S. Army Corps of Engineers.

$$I = 1.019D - 11.44,$$

where: D = annual minimum daily mean (feet NGVD), and

I = annual instantaneous minimum (feet NGVD) for the same year.

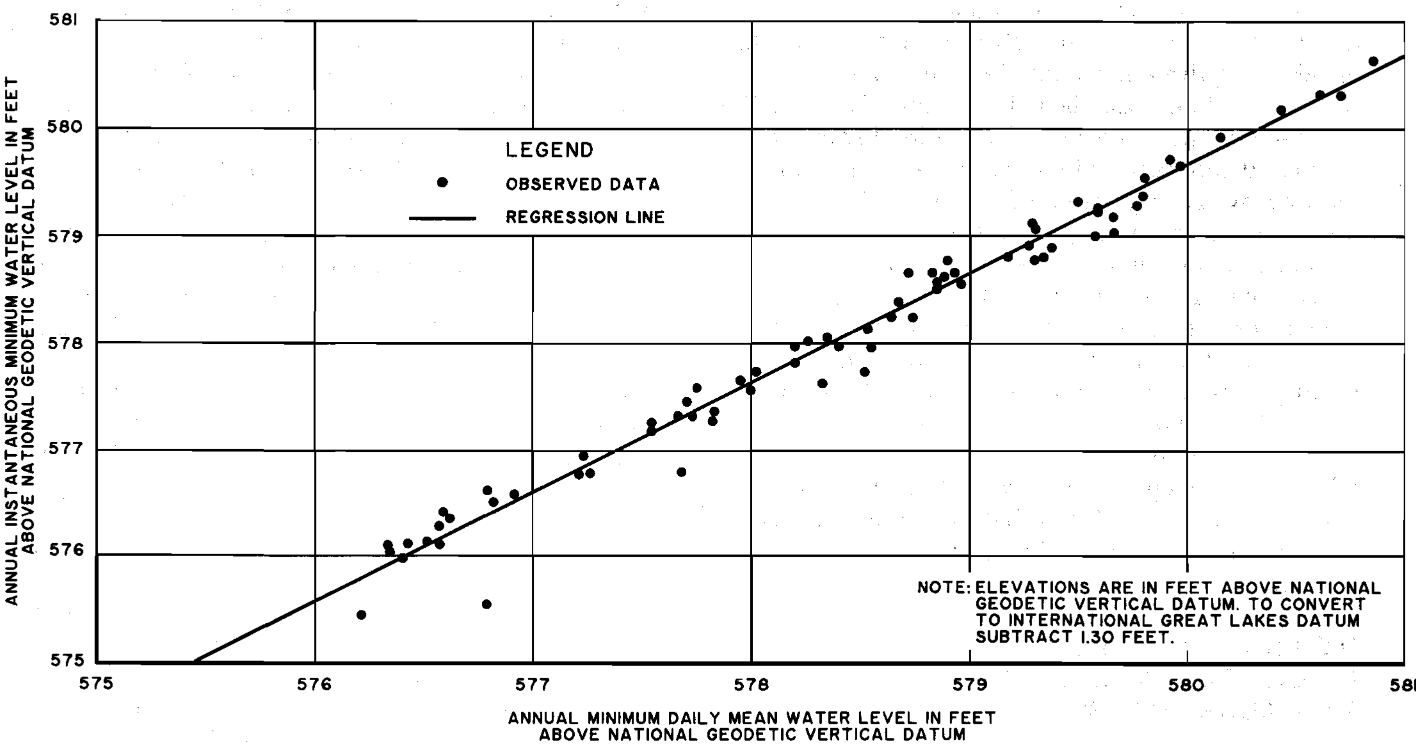
The regression analysis was performed without the data for 1976, during which year the instantaneous minimum value appeared to be a low outlier. Figure 46 is a plot of instantaneous versus daily minimum levels through which the line from the above regression equation is drawn for comparison.

The regression equation was then used to estimate the nine instantaneous minimum values using the recorded daily minima for those nine years—1904, 1905, 1911, 1918, and 1946-50. The synthesized values are provided in Table 47, which contains all the annual recorded data.

Subsequent to the regression analysis, a frequency analysis similar to those described above was performed for the period 1915 through 1985.

Figure 46

CORRELATION OF ANNUAL INSTANTANEOUS AND DAILY MEAN MINIMUM RECORDED WATER LEVELS FOR LAKE MICHIGAN AT MILWAUKEE: 1906-1984



Source: SEWRPC.

Figure 45 contains the plot of the normal probability distribution for four-year lag data. The distribution closely fits all the data except the low outlier which was recorded on May 29, 1976, and has an elevation of 574.03 feet NGVD or 572.73 feet IGLD.

Assuming the period 1915 through 1985 to be statistically representative, then 10 and 1 percent of the instantaneous minimum lake levels at Milwaukee for existing conditions may be expected to be less than 576.1 feet NGVD or 574.8 feet IGLD and 574.5 feet NGVD or 573.2 feet IGLD, respectively. The minimum recorded value in 1976 is about 0.5 foot lower than the computed 1 percent value.

Tides

Tides are defined as the periodic rise and fall of a water surface in response primarily to the gravitational attraction of the sun and the moon. The timing of the tides is coordinated with the angular position of the sun and the moon relative to the earth. Although the causative gravitational forces are exerted by the sun and the moon on both the liquid and solid portions of the earth, tides are significantly more pronounced in the liquid portion. The effect of the moon on tides is significantly greater than that of the sun—the tidal effect of the larger mass of the sun being offset by the relative closeness of the moon to the earth.

Tides exert a significant influence on water levels in the oceans. The tidal range at Milwaukee is 1.1 inches.[5] Lake Michigan tidal action, therefore, may be considered to be insignificant in comparison to the various other processes and phenomena that individually or cumulatively affect lake stages within the coastal zone of southeastern Wisconsin.

[5] *C. H. Mortimer, "Spectra of Long Surface Waves and Tides in Lake Michigan and at Green Bay, Wisconsin," University of Michigan, Great Lakes Research Division, Pub. No. 13, 1965, pp. 304-325.*

Lake Michigan Retention Time: The average discharge from the northern end of Lake Michigan through the Straits of Mackinaw has been roughly estimated at 48,000 cubic feet per second which, when combined with the 3,200 feet per second diversion at Chicago through the sanitary and ship canal, is equivalent to 2.6 feet of water over the surface of Lake Michigan in a year. Dividing the 1,180-cubic-mile volume of Lake Michigan by the estimated discharge rate yields a theoretical emptying or flow-through time of 108 years for continuous, complete mixing conditions in the lake. Actual flushing time of the lake is probably much longer owing, primarily, to thermal stratification which persists much of the year. Thus, the volume of water discharged annually from the lake is slightly less than 1 percent of the volume of the lake. This value for flow-through time is long compared to that for most natural and artificial lakes. For example, the theoretical flow-through times for the other Great Lakes—Superior, Huron, Ontario, and Erie—are 182, 21, 8, and 3 years, respectively.

HYDROLOGIC-HYDRAULIC CHARACTERISTICS OF THE MILWAUKEE HARBOR ESTUARY

The occurrence and movement of water within the Milwaukee Harbor estuary is affected by inflows from the drainage areas of the three tributary rivers—namely, the Kinnickinnic, Menomonee, and Milwaukee Rivers—and by inflows from Lake Michigan. Inflows from the tributary river drainage areas are comprised principally of surface runoff, groundwater inflow, and combined sewer overflows. Inflows from Lake Michigan include dilution water pumped through two tunnels from Lake Michigan, one discharging into the Kinnickinnic River just downstream from Chase Avenue, and the other discharging into the Milwaukee River just downstream from the North Avenue dam. The major source of lake water inflow to the estuary, however, is frequent lake level fluctuations which produce relatively large flood and ebb flows within the inner harbor channels.

Hydraulic conditions in the estuary are influenced by the timing and magnitude of the inflows described above, by condensor cooling water withdrawals and discharges by the Valley power plant, and by density differences between river and lake water. These phenomena are described in more detail in the subsequent sections of this chapter.

Hydrologic Characteristics of the Kinnickinnic, Menomonee, and Milwaukee Rivers

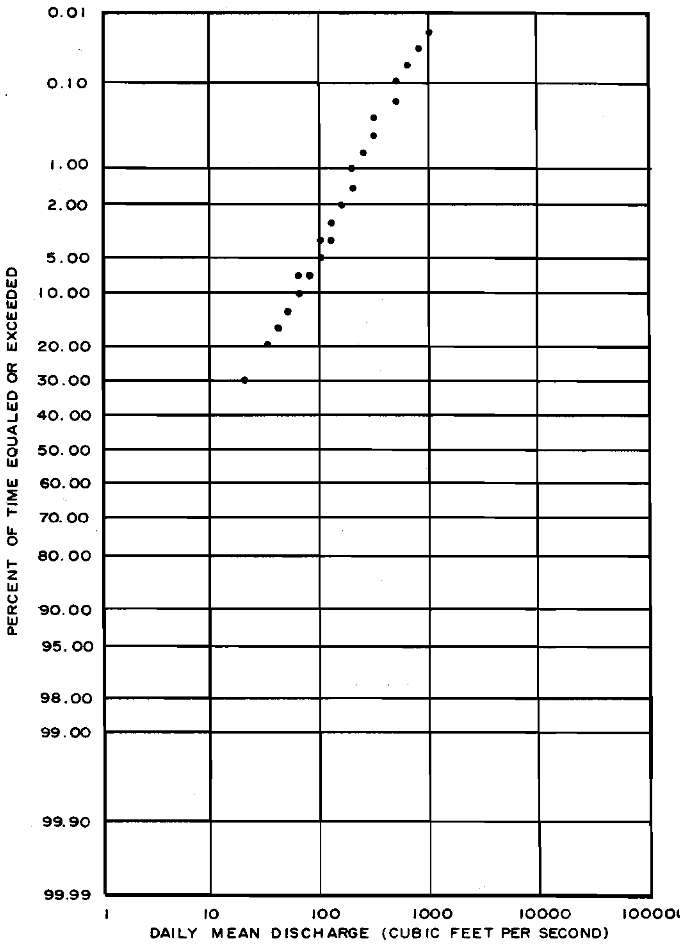
The timing and magnitude of flows from the Kinnickinnic, Menomonee, and Milwaukee Rivers affect not only flow but also water quality conditions in the Milwaukee Harbor estuary. Presented in this section are discussions of flow duration, annual mean flow variation, low-flow frequency, high-flow frequency, and peak-discharge frequency at two long-term streamflow gaging stations, one each on the Menomonee and Milwaukee Rivers, operated by the U. S. Geological Survey. Because the U. S. Geological Survey (USGS) did not begin collecting streamflow data for the Kinnickinnic River until 1976, it was necessary to utilize simulated long-term data from a continuous process hydrologic/hydraulic model. Because the streamflow data utilized in the frequency analyses represent annual series, the computed probabilities represent exceedance probabilities in any given year.

Flow Duration: Unpublished streamflow duration analyses were conducted by the USGS through 1982 for the Kinnickinnic River in Milwaukee (station ID 4-0871.6), the Menomonee River in Wauwatosa (4-0871.2), and the Milwaukee River in Milwaukee (4-0870). The Kinnickinnic River station data were collected at S. 7th Street, where the drainage area is 20.4 square miles. The Menomonee River station is at N. 70th Street, where the drainage area is 123 square miles. The Milwaukee River station is in Estabrook Park just downstream from the dam below Port Washington Road. The drainage area at this gaging station is 696 square miles. Streamflow records have been collected by the USGS at the Kinnickinnic, Menomonee, and Milwaukee River sites since 1976, 1961, and 1914, respectively.

The flow duration analyses of the streamflow records made by the USGS consisted of determining the percent of time given magnitudes of flow were equaled or exceeded over the period of record. The water year October 1 through September 30 was utilized in the computations. Daily mean flows only were used in the analysis. Because of the very short streamflow record available for the Kinnickinnic River, flow duration data simulated by a continuous-process hydrologic/hydraulic model from the Kinnickinnic River watershed study, completed by the Commission in 1978, were utilized in the analysis. The resulting flow duration curves are shown in Figures 47, 48, and 49 for each of the three rivers. Table 50 lists selected data taken from

Figure 47

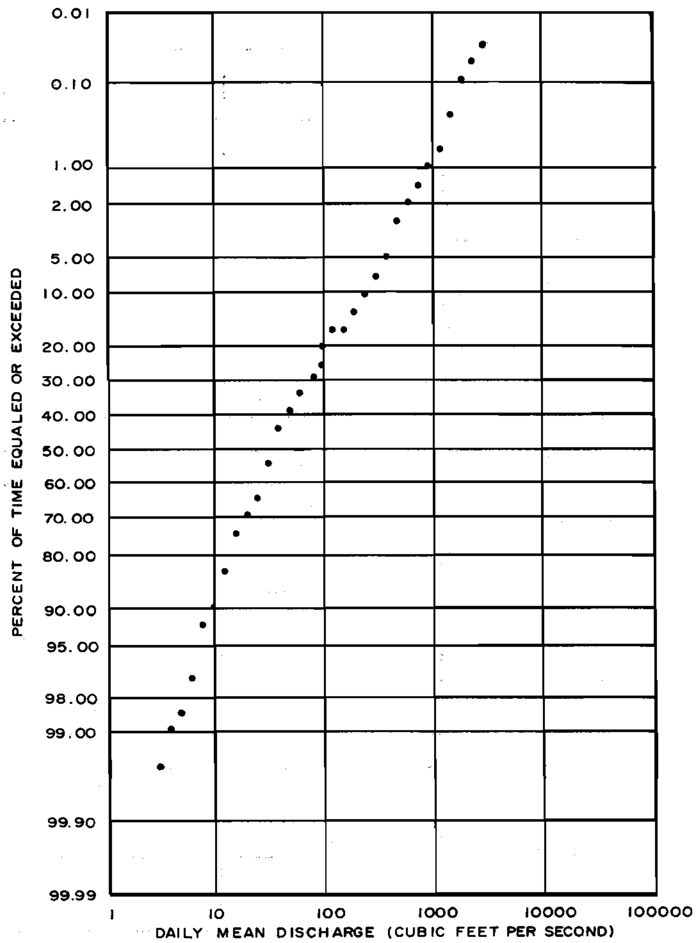
FLOW DURATION RELATIONSHIP FOR THE KINNICKINNIC RIVER AT S. 7TH STREET: 1940-1976



Source: U. S. Geological Survey and SEWRPC.

Figure 48

FLOW DURATION RELATIONSHIP FOR THE MENOMONEE RIVER AT N. 70TH STREET: 1962-1982



Source: U. S. Geological Survey and SEWRPC.

these curves. As the data indicate, 90 percent of the daily mean flows for the Kinnickinnic, Menomonee, and Milwaukee Rivers equaled or exceeded 11.8, 10.6, and 65.3 cubic feet per second (cfs), respectively. The 50 percent values were, respectively, 15.2, 35.7, and 200 cfs; whereas the 10 percent values were 52, 207, and 948 cfs.

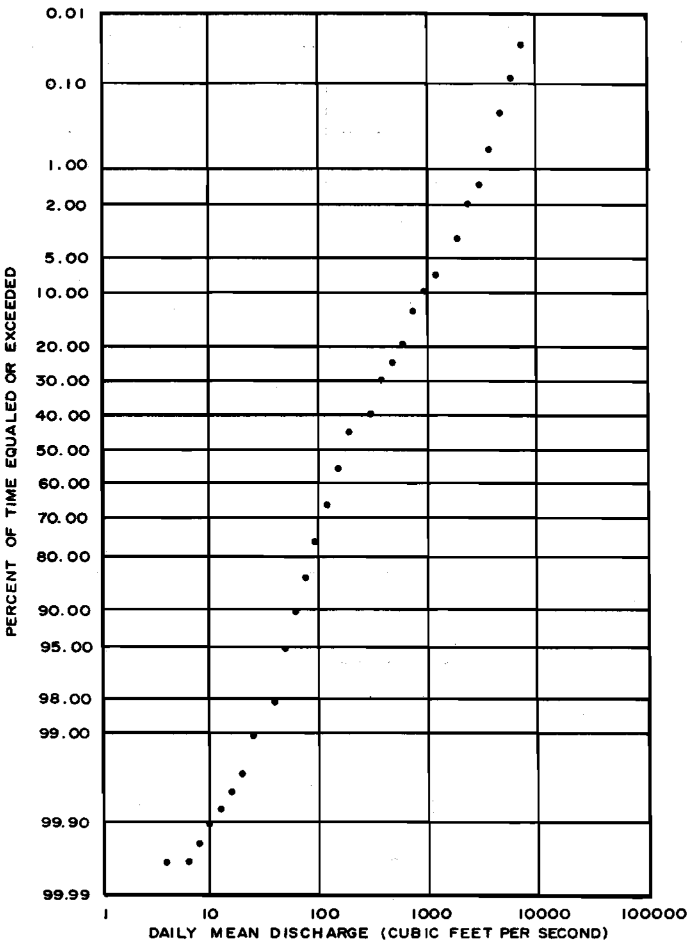
Annual Mean Flow Frequency: The USGS conducted a frequency analysis of the recorded annual mean flows through 1982 for each year of record for each of the two long-term gaging stations on the Menomonee and Milwaukee Rivers. The water year October 1-September 30 was the basis for each analysis. Simulated data, described above, were used in the Kinnickinnic River analysis. Figure 50 presents the respective frequency curves which were calculated using the log Pearson Type III procedure. As the curves indicate, for an exceedance probability of 10 percent, the respective annual mean discharges are 30.8, 138, and 639 cfs. For a probability of 50 percent, the respective flows are 22.7, 90, and 389 cfs; and for a probability of 90 percent, 16.8, 45, and 206 cfs. Selected data from these curves are provided in Tables 51, 52, and 53 under high flow, 365 days.

The mean annual streamflows for the Kinnickinnic, Menomonee, and Milwaukee Rivers are, respectively, 23.3, 90.3, and 408 cfs. The mean annual discharge is the average of the annual mean flows, and is not the same as the flow from a log-normal frequency curve at probability equal to 50 percent.

Low-Flow Frequency: The USGS analysis of annual low flows at the two long-term gaging stations on

Figure 49

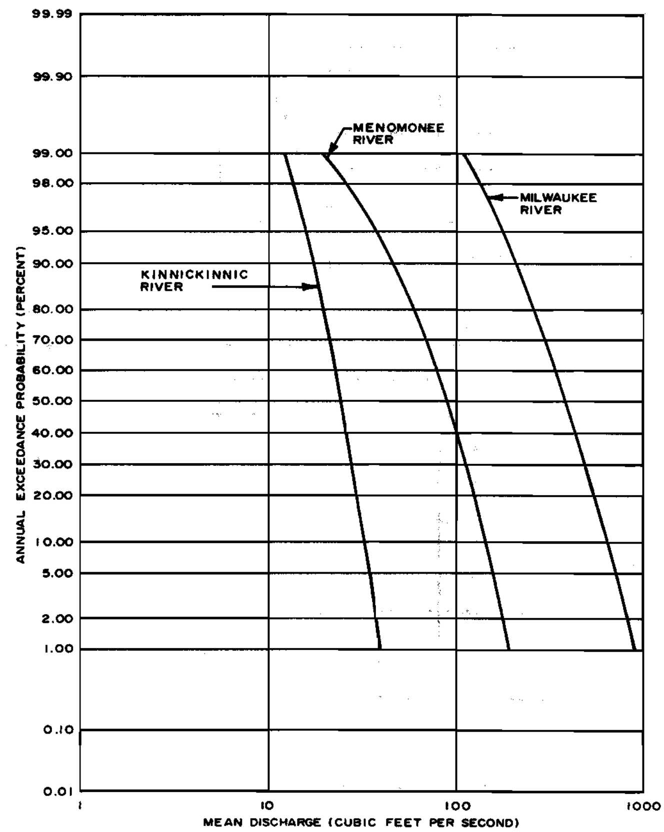
FLOW DURATION RELATIONSHIP FOR THE MILWAUKEE RIVER AT ESTABROOK PARK: 1915-1982



Source: U. S. Geological Survey and SEWRPC.

Figure 50

FREQUENCY CURVES FOR ANNUAL MEAN DISCHARGES OF THE KINNICKINNIC, MENOMONEE, AND MILWAUKEE RIVERS



Source: SEWRPC.

Table 50

FLOW DURATION DATA FOR THE KINNICKINNIC, MENOMONEE, AND MILWAUKEE RIVERS[a]

River	Percent of Time Flow Equaled or Exceeded						
	95	90	75	70	50	25	10
	Daily Mean Discharge (cfs)						
Kinnickinnic	11.3	11.8	13.0	13.3	15.2	22.0	52.0
Menomonee	7.9	10.6	19.3	22.0	35.7	82.2	207
Milwaukee	49.1	65.3	103	117	200	427	948

[a]*Data represent 1940-1975, 1962-1982, and 1915-1982, respectively. Sites are located at S. 7th Street on the Kinnickinnic River, N. 70th Street on the Menomonee River, and Estabrook Park on the Milwaukee River, respectively. The Kinnickinnic River data were simulated.*

Source: U. S. Geological Survey and SEWRPC.

the Menomonee and Milwaukee Rivers was conducted using daily mean flows for the period of record through 1982. The climatic year April 1 through March 31 was used in this analysis to ensure that no low-flow periods occurred at the end of one year and the beginning of the next. Simulated low-flow data for the period 1940-1976 were utilized for the Kinnickinnic River because of the lack of adequate actual streamflow data. A series of such analyses were made utilizing the minimum mean flow each year for a given number of consecutive days. For example, a frequency analysis was conducted using the annual minimum daily mean flow for each year of record, the annual minimum consecutive three-day mean, the annual seven-day mean, and so on up to the annual

Table 51

LOW, HIGH, AND PEAK DISCHARGE FREQUENCY DATA FOR THE KINNICKINNIC RIVER AT S. 7TH STREET[a]

Days	Annual Exceedance Probability (percent)[b]									
	99	95	90	80	50	20	10	4	2	1
	Low Flow (cfs)									
1	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
7	5.5	5.9	6.0	6.0	6.0	6.1	6.3	6.5	6.7	6.9
30	5.5	5.9	6.1	6.5	7.2	8.2	8.7	9.5	10.0	10.5
120	8.2	9.2	9.9	10.9	13.2	16.5	18.7	21.5	23.7	26.0
	High Flow (cfs)									
1	132	187	225	280	421	627	768	949	1,090	1,230
7	41.4	61.5	74.9	93.7	138	194	227	265	290	314
30	22.4	31.6	37.2	44.8	60.8	77.8	86.7	95.9	101	106
120	14.9	19.8	22.7	26.5	34.6	43.2	47.8	52.7	55.8	58.5
365	13.1	15.4	16.8	18.6	22.7	27.7	30.8	34.4	36.9	39.3

Annual Exceedance Probability (percent)[b]				
50	20	10	2	1
Peak Discharge (cfs)				
1,600	2,300	2,800	4,350	5,000

[a]*All discharges are period means except peak discharges, which are instantaneous values.*

[b]*Simulated data 1940-1976.*

Source: SEWRPC.

183-day minimum mean flow. A computer program searched the 365 daily mean flows for each year of record and selected for each designated consecutive time period the minimum mean flow for each year. These annual minimums were then subjected to a frequency analysis using the log Pearson Type III method. The results of these analyses are shown in the low-flow frequency curves in Figures 51, 52, 53, 54, and 55. Two figures are presented for the Menomonee and Milwaukee Rivers for legibility.

Of special significance is the 7-day low-flow frequency curve because Wisconsin water quality standards are generally applied to the annual 7-day minimum low flow, which occurs every 10 years on average. The 10-year recurrence interval corresponds to an exceedance probability of 90 percent on the low-flow frequency curves. These data, however, are also presented in Tables 51, 52, and 53 for convenience. The 7-day, 10-year low flows at the long-term gaging stations on the Kinnickinnic, Menomonee, and Milwaukee Rivers were found to be 6.0, 4.7, and 25.1 cfs, respectively, for the period of record through 1982.

High-Flow Frequency: An analysis was made by the USGS of the annual high flows recorded at the two long-term gaging stations on the Menomonee and Milwaukee Rivers for the period of record through 1982. The procedure utilized was similar to that used in the low-flow frequency analysis. The water year October 1-September 30 was used, however, because annual high flows do not typically occur during autumn. Simulated high-flow data for the period 1940-1976 were utilized for the Kinnickinnic River because of a lack of streamflow data.

Frequency analyses were conducted of maximum daily mean flows for consecutive periods of 1, 3, 7, 15, 30, 60, 90, 120, and 183 days. Plots of the

Table 52

LOW, HIGH, AND PEAK DISCHARGE FREQUENCY DATA FOR THE MENOMONEE RIVER AT N. 70TH STREET[a]

Days	Annual Exceedance Probability (percent)[b]										
	99	98	95	90	80	50	20	10	4	2	1
	Low Flow (cfs)										
1	1.83	2.34	3.31	4.38	5.97	9.89	14.70	17.40	20.30	22.10	23.60
3	1.81	2.34	3.35	4.49	6.20	10.50	15.80	18.90	22.10	24.10	25.80
7	1.87	2.43	3.51	4.73	6.59	11.30	17.20	20.60	24.20	26.50	28.40
14	2.02	2.65	3.86	5.24	7.35	12.70	19.50	23.30	27.40	29.90	32.10
30	2.51	3.25	4.66	6.28	8.76	15.30	24.00	29.30	35.30	39.20	42.80
60	3.05	4.06	6.04	8.31	11.74	20.20	30.30	35.60	40.90	43.90	46.40
90	3.52	4.68	6.98	9.68	13.90	25.00	39.70	48.30	57.70	63.60	68.80
120	4.28	5.62	8.26	11.40	16.20	29.10	47.00	57.90	70.40	78.60	86.10
183	5.24	6.82	9.98	13.80	20.00	38.50	69.10	91.30	120.00	142.00	165.00

Days	Annual Exceedance Probability (percent)[b]										
	99	95	90	80	50	20	10	4	2	1	0.5
	High Flow (cfs)										
1	411	608	750	969	1,590	2,628	3,427	4,556	5,482	6,480	7,557
3	245	412	531	706	1,141	1,703	2,038	2,417	2,668	2,896	3,104
7	190	306	386	500	769	1,093	1,275	1,474	1,600	1,712	1,812
15	130	199	247	316	486	710	849	1,012	1,125	1,232	1,334
30	83	128	159	204	318	474	574	696	783	867	948
60	55	90	114	149	235	344	409	481	529	572	612
90	47	75	95	123	191	275	325	379	415	447	476
120	42	67	85	109	166	232	268	305	329	349	366
183	34	55	70	89	134	183	208	233	248	261	271
365	20	35	45	59	90	123	138	153	161	168	173

Annual Exceedance Probability (percent)[c]				
20	10	4	2	1
Peak Discharge (cfs)				
5,800	6,900	9,200	11,200	13,500

[a]*All discharges are period means except peak discharges, which are instantaneous values.*

[b]*Exceedance probability, 1962-1982, observed data.*

[c]*Exceedance probability, 1940-1974, simulated data.*

Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

high-flow frequency relationships are shown in Figures 56, 57, 58, 59, and 60. Selected data points from these figures are listed in Tables 51, 52, and 53.

Peak Discharge Frequency: Peak discharge frequency analyses were conducted by the Commission as part of the comprehensive watershed planning studies for the Kinnickinnic, Menomonee, and Milwaukee Rivers. The Kinnickinnic River watershed study utilized a continuous-process hydrologic simulation model of 1975 land use and channel conditions to compute annual peak discharges throughout the watershed for the period 1940-1976 because of a lack of recorded streamflow data. A log Pearson Type III frequency analysis was conducted of the discharges and is reproduced as Figure 61.

Table 53

LOW, HIGH, AND PEAK DISCHARGE FREQUENCY DATA FOR THE MILWAUKEE RIVER AT ESTABROOK PARK[a]

Days	Annual Exceedance Probability (percent)[b]										
	99	98	95	90	80	50	20	10	4	2	1
	Low Flow (cfs)										
1	1.84	2.72	4.74	7.53	12.70	30.80	64.70	90.50	125.00	150.00	175.00
3	4.05	6.08	10.60	16.30	25.90	51.20	80.60	94.60	107.00	113.00	118.00
7	10.60	13.50	19.00	25.10	34.40	58.20	89.60	109.00	130.00	144.00	157.00
14	12.80	16.10	22.20	29.10	39.30	65.30	99.40	120.00	143.00	158.00	172.00
30	16.10	19.80	26.50	34.10	45.50	75.70	119.00	148.00	183.00	209.00	233.00
60	23.40	27.60	35.20	43.60	56.20	89.70	140.00	176.00	223.00	258.00	295.00
90	28.80	33.40	41.70	50.90	64.90	103.00	165.00	210.00	273.00	323.00	377.00
120	33.70	39.10	48.90	59.80	76.20	121.00	194.00	248.00	323.00	384.00	448.00
183	39.20	45.80	58.00	71.80	93.40	157.00	267.00	356.00	486.00	596.00	718.00

Days	Annual Exceedance Probability (percent)[b]										
	99	95	90	80	50	20	10	4	2	1	0.5
	High Flow (cfs)										
1	708	1,229	1,620	2,225	3,889	6,384	8,077	10,201	11,752	13,266	14,750
3	600	1,076	1,435	1,991	3,496	5,667	7,079	8,781	9,978	11,112	12,188
7	507	892	1,177	1,612	2,756	4,347	5,351	6,534	7,349	8,108	8,819
15	372	655	864	1,178	1,996	3,105	3,790	4,582	5,119	5,612	6,068
30	308	511	656	872	1,425	2,179	2,653	3,212	3,600	3,964	4,308
60	248	409	521	684	1,079	1,575	1,863	2,184	2,394	2,582	2,752
90	208	345	439	574	888	1,252	1,450	1,656	1,783	1,891	1,985
120	182	303	385	501	767	1,064	1,218	1,374	1,468	1,545	1,610
183	153	246	309	398	602	835	960	1,090	1,170	1,238	1,297
365	110	168	206	261	389	546	639	742	811	874	931

Annual Exceedance Probability (percent)[c]						
90	50	20	10	5	2	1
Peak Discharge (cfs)						
2,100	4,600	7,300	9,200	11,100	13,900	16,000

[a] *All discharges are period means except peak discharges, which are instantaneous values.*

[b] *Exceedance probability, 1915-1982.*

[c] *Exceedance probability, 1915-1965.*

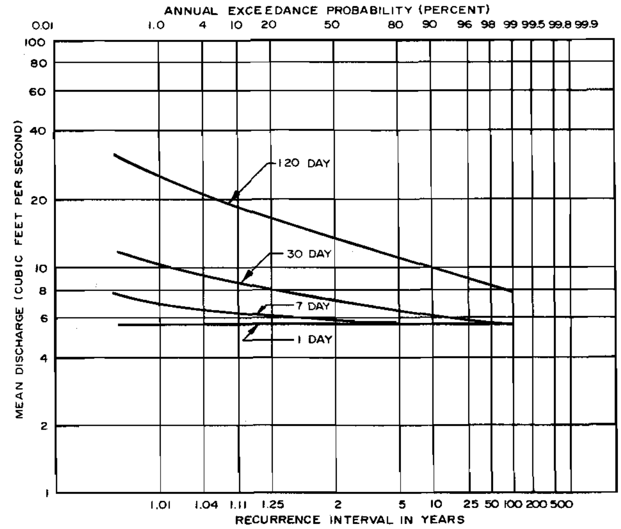
Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Similarly, for the Menomonee River watershed study, a modeling approach was utilized because of the lack of sufficient long-term streamflow data for peak discharge frequency analysis, the simulation period being 1940-1975 and the conditions also being for 1975 land use and channels. The log Pearson Type III frequency curve from this study is shown as Figure 62.

Streamflow monitoring data available for 1915 to 1965 were utilized to conduct a log Pearson Type III frequency analysis of annual peak discharges for

Figure 51

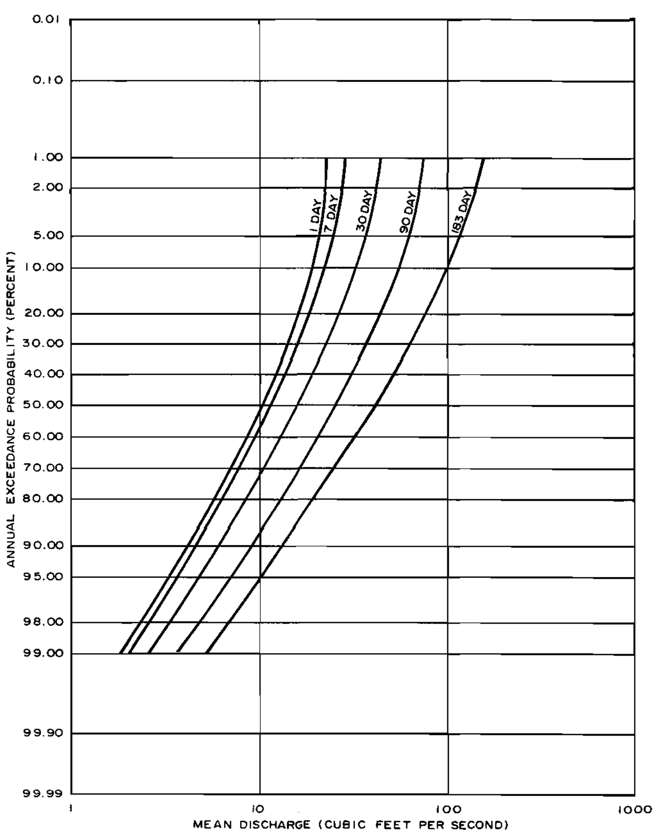
LOW-FLOW DISCHARGE-FREQUENCY RELATIONSHIPS OF THE KINNICKINNIC RIVER AT S. 7TH STREET: EXISTING LAND USE-FLOODLAND DEVELOPMENT CONDITIONS



Source: SEWRPC.

Figure 52

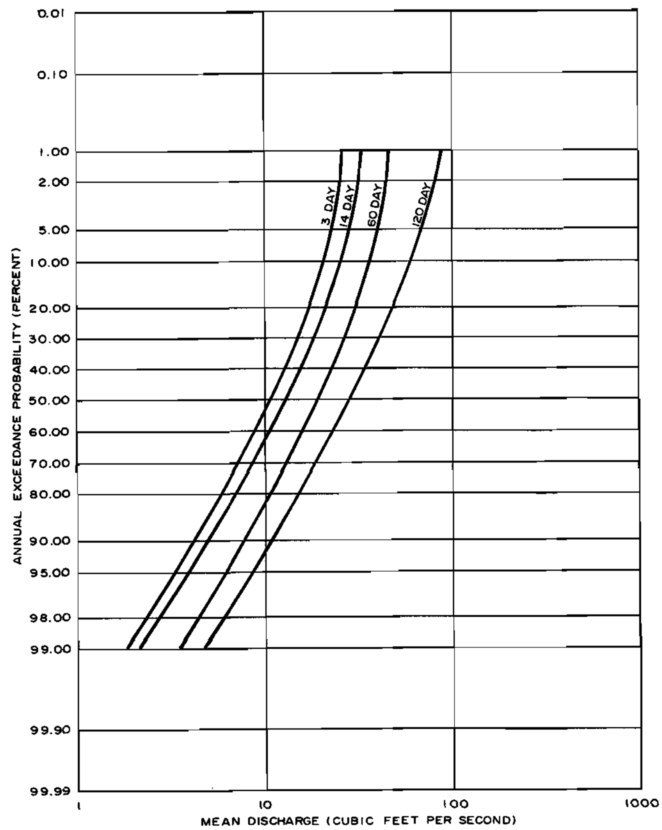
LOW-FLOW FREQUENCY RELATIONSHIPS FOR DURATIONS OF 1, 7, 30, 90, AND 183 CONSECUTIVE DAYS–MENOMONEE RIVER AT N. 70TH STREET: 1962-1982



Source: SEWRPC.

Figure 53

LOW-FLOW FREQUENCY RELATIONSHIPS FOR DURATIONS OF 3, 14, 60, AND 120 CONSECUTIVE DAYS–MENOMONEE RIVER AT N. 70TH STREET: 1962-1982



Source: SEWRPC.

the Milwaukee River watershed study. The frequency curve from this study is presented herein as Figure 63.

The peak discharge frequency data listed in Tables 51, 52, and 53 represent selected points from the frequency curves and are presented for convenience.

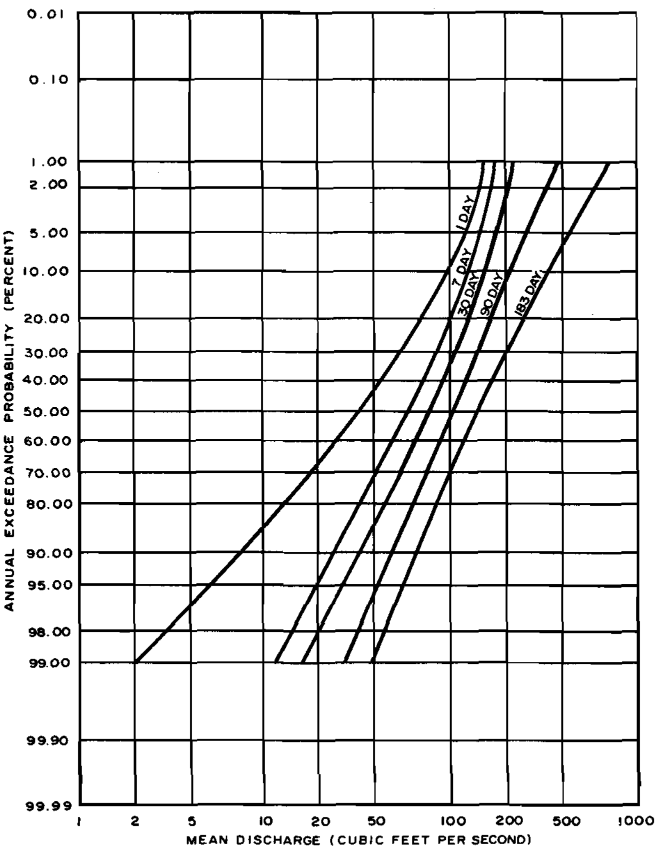
The discharges with nonexceedance probabilities of 0.01, 0.02, and 0.10 represent average return periods, or recurrence intervals, of 100, 50, and 10 years, respectively. Peak discharges for these recurrence intervals are frequently used for hydraulic structure design and floodland management purposes.

Combined Sewer Overflows

The combined sewer system of Milwaukee contains 109 combined sewer outfalls, many of which are interconnected to provide relief to one another as storm conditions may dictate. Map 5 in Chapter II shows the 15.8-square-mile service area for combined sewers in Milwaukee County tributary to the Kinnickinnic, Menomonee, and Milwaukee River

Figure 54

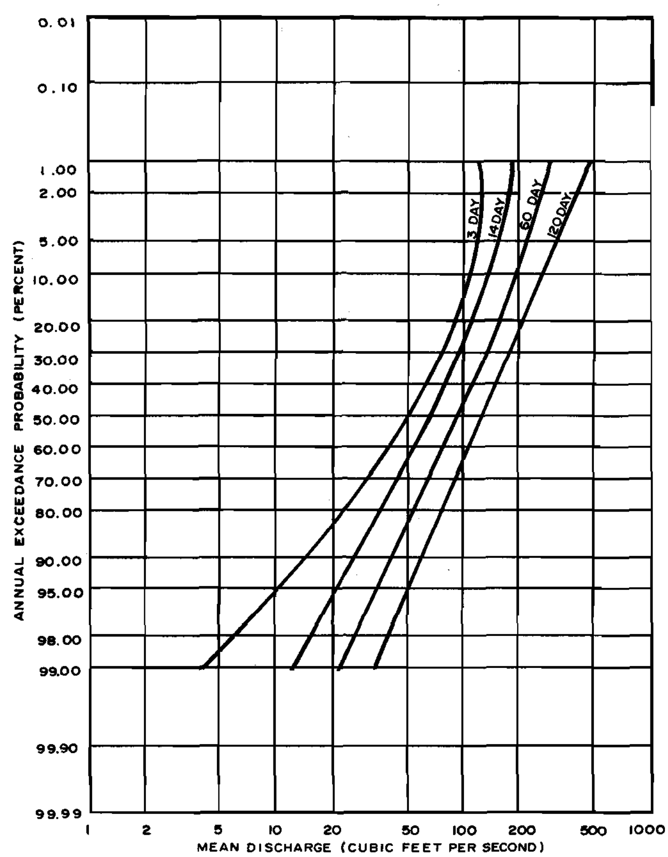
LOW-FLOW FREQUENCY RELATIONSHIPS FOR DURATIONS OF 1, 7, 30, 90, AND 183 CONSECUTIVE DAYS–MILWAUKEE RIVER AT ESTABROOK PARK: 1915-1982



Source: SEWRPC.

Figure 55

LOW-FLOW FREQUENCY RELATIONSHIPS FOR DURATIONS OF 3, 14, 60, AND 120 CONSECUTIVE DAYS–MILWAUKEE RIVER AT ESTABROOK PARK: 1915-1982



Source: SEWRPC.

estuaries and the outer harbor. An additional 8.0 square miles of combined sewer service area overflows directly to the tributary rivers upstream from the estuary.

Combined sewer overflow (CSO) occurs on the order of 50 times per year, discharging domestic and industrial waste along with surface runoff contaminants into the Milwaukee Harbor estuary and tributary rivers. CSO volume was estimated using an equation from the U. S. Army Corps of Engineers STORM model:[6]

$$R_v = 0.15 + 0.75f,$$

where: f is the impervious fraction of the combined sewer service area, and
R_v is the runoff coefficient.

The equation was validated against field data collected in other cities in Figure 64, which is a plot of measured runoff coefficients versus percent impervious area. A line representing the STORM equation is also shown on the plot for comparison. For the period January 1, 1940 to September 30, 1983, during which the mean annual precipitation was 30.9 inches, the mean annual CSO flow rate which delivers the annual CSO volume was computed using:

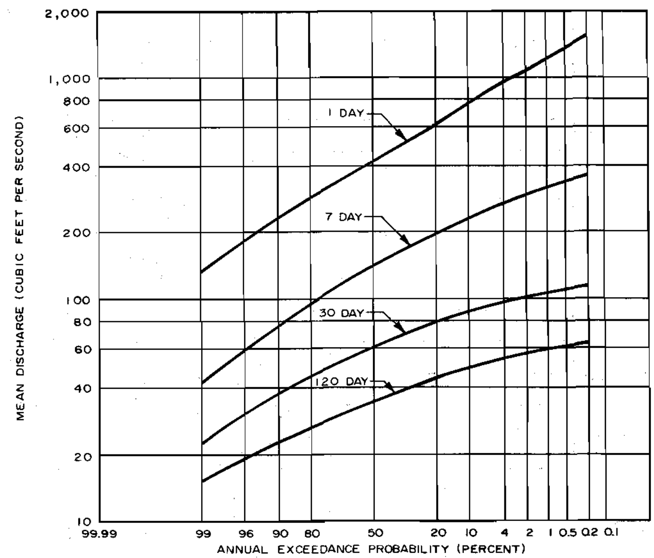
$$Q_r = R_v IA,$$

where: Q_r is mean annual combined sewer overflow (cfs)
I is the average annual rainfall intensity (0.00353 in/hour),
A is the total CSO drainage area (15,245 acres), and
R_v is the runoff coefficient (0.606).

[6] *U. S. Army Corps of Engineers, Urban Storm Water Runoff (STORM): Hydrologic Engineering Center, Generalized Computer Program No. 723-58-L2520, draft user's manual, 1974.*

Figure 56

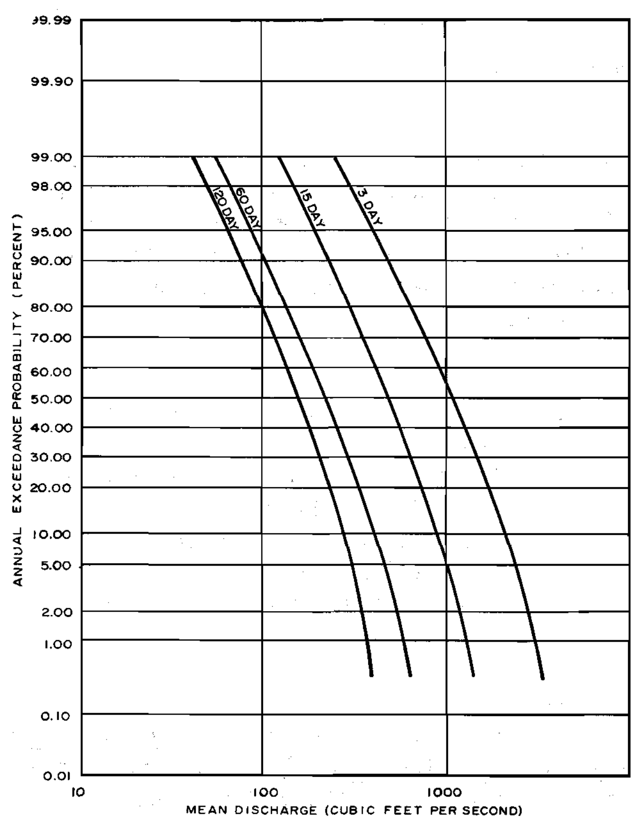
HIGH-FLOW DISCHARGE-FREQUENCY RELATIONSHIPS OF THE KINNICKINNIC RIVER AT S. 7TH STREET: EXISTING LAND USE-FLOODLAND DEVELOPMENT CONDITIONS



Source: SEWRPC.

Figure 58

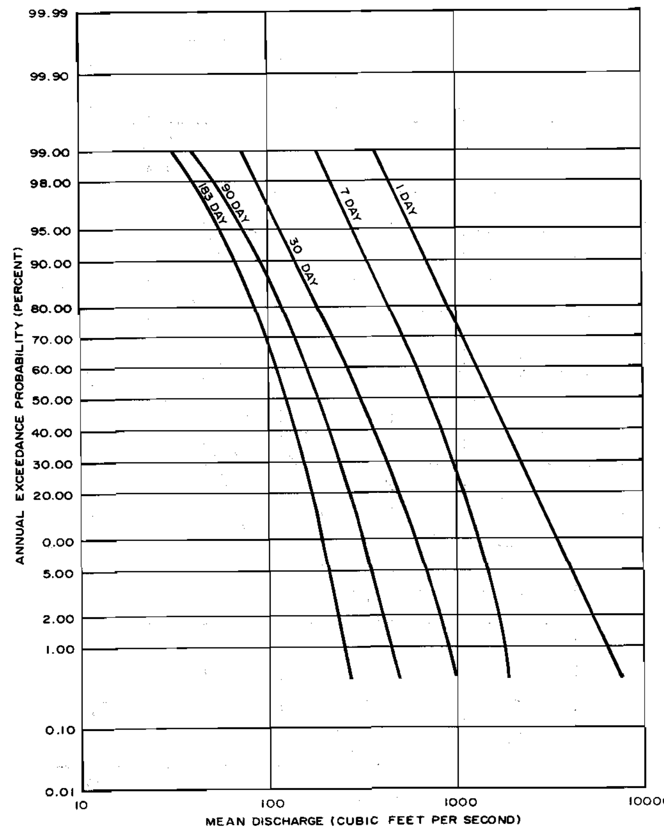
HIGH-FLOW FREQUENCY RELATIONSHIPS FOR DURATIONS OF 3, 15, 60, AND 120 CONSECUTIVE DAYS–MENOMONEE RIVER AT N. 70TH STREET: 1962-1982



Source: SEWRPC.

Figure 57

HIGH-FLOW FREQUENCY RELATIONSHIPS FOR DURATIONS OF 1, 7, 30, 90, AND 183 CONSECUTIVE DAYS–MENOMONEE RIVER AT N. 70TH STREET: 1962-1982



Source: SEWRPC.

CSO rates computed with the above equation do not account for storage in the conveyance system, nor for the runoff which did not overflow but succeeded in reaching the Jones Island wastewater treatment plant. Therefore, the equation may overestimate CSO rates, but probably not much, because the capacity of the old interceptor sewer system is relatively small compared to storm runoff volumes, as is the volume of runoff which reaches the treatment plant.

The CSO flow rate equation was tested by comparison with a much more sophisticated CSO estimation tool—namely, the Systems Analysis Model (SAM) developed for the Milwaukee combined sewer service area by the Milwaukee Metropolitan Sewerage District.[7] SAM is a complex sewer

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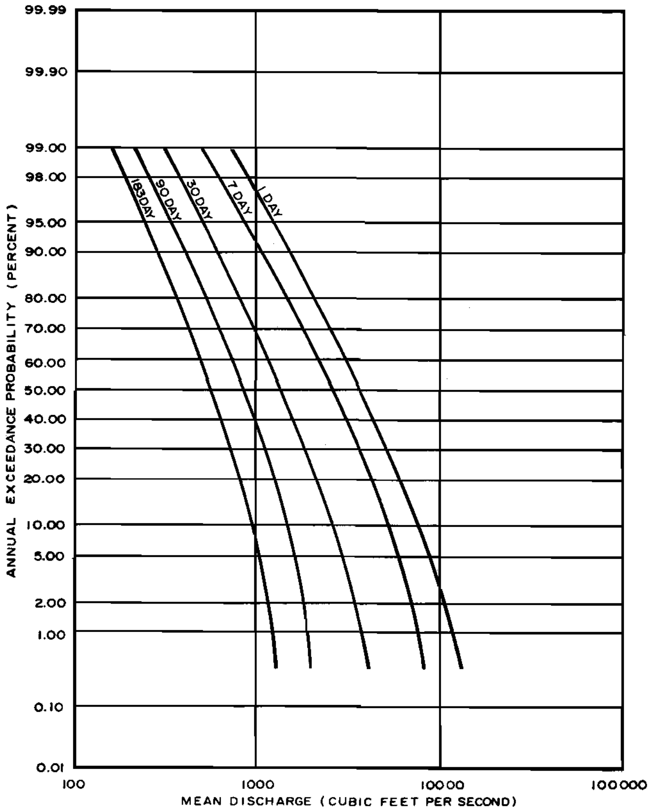
[7] *Wesley G. O'Neil, Allen L. Davis, and Kenneth W. VanDusen, Wastewater Collection System Analysis Model SAM, CH2M Hill, Inc., Corvallis, Oregon, 1976.*

Figure 59

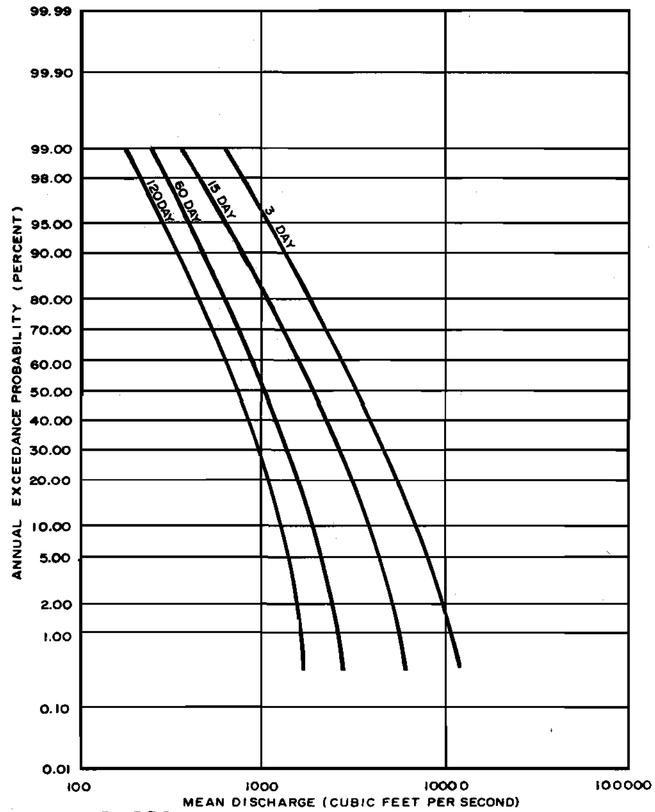
HIGH-FLOW FREQUENCY RELATIONSHIPS FOR DURATIONS OF 1, 7, 30, 90, AND 183 CONSECUTIVE DAYS—MILWAUKEE RIVER ESTABROOK PARK: 1915-1982



Source: SEWRPC.

Figure 60

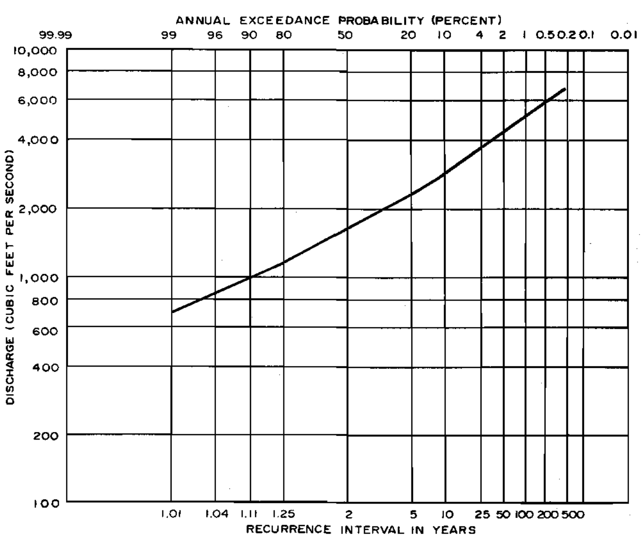
HIGH-FLOW FREQUENCY RELATIONSHIPS FOR DURATIONS OF 3, 15, 60, AND 120 CONSECUTIVE DAYS—MILWAUKEE RIVER AT ESTABROOK PARK: 1915-1982



Source: SEWRPC.

Figure 61

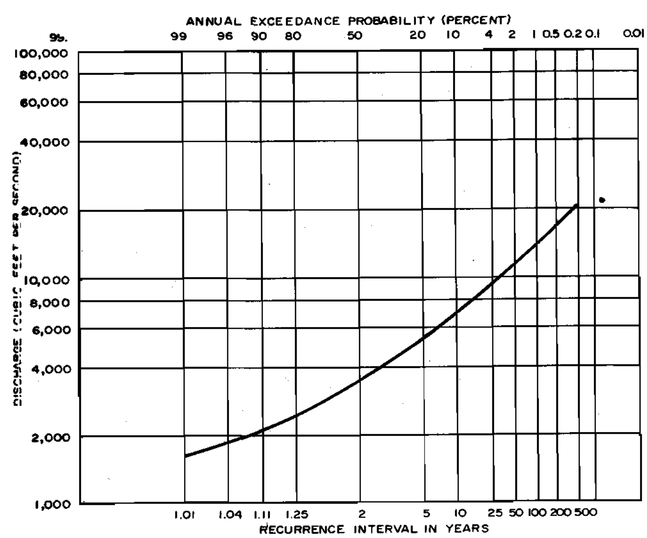
PEAK DISCHARGE FREQUENCY FOR THE KINNICKINNIC RIVER AT S. 7TH STREET FOR WATER YEARS 1940-1976



Source: SEWRPC.

Figure 62

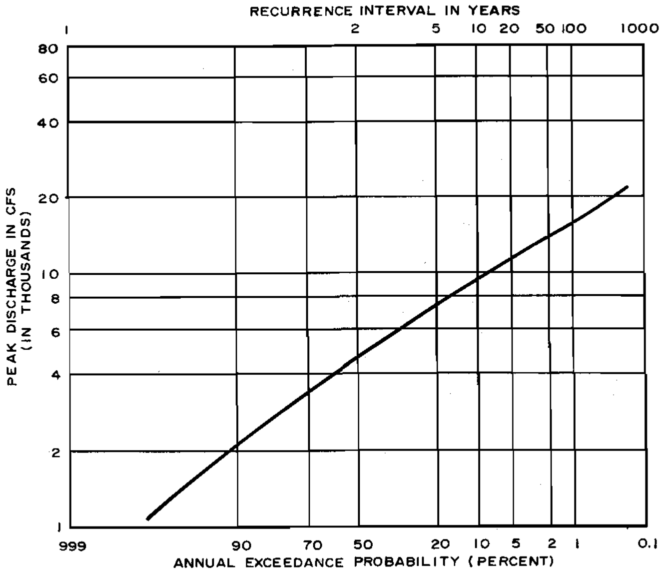
PEAK DISCHARGE FREQUENCY FOR THE MENOMONEE RIVER AT N. 70TH STREET FOR WATER YEARS 1962-1982



Source: SEWRPC.

Figure 63

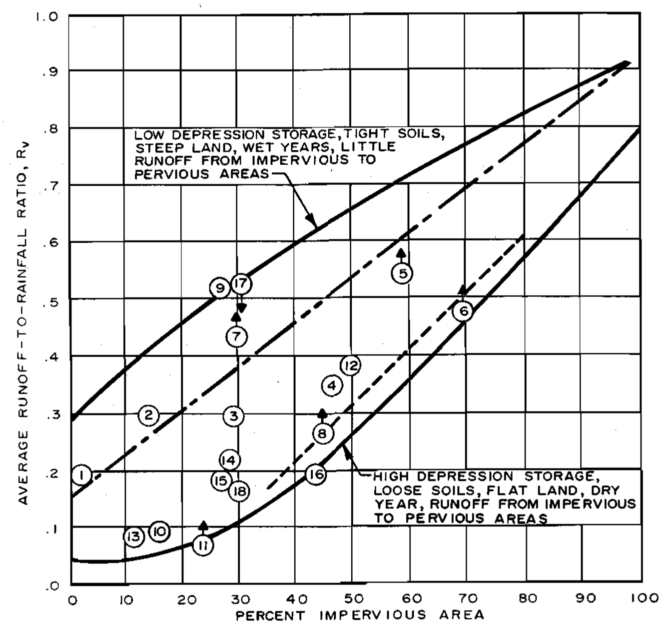
PEAK DISCHARGE FREQUENCY FOR THE MILWAUKEE RIVER AT MILWAUKEE FOR WATER YEARS 1915-1982



Source: Harza Engineering and SEWRPC.

Figure 64

RELATIONSHIP BETWEEN IMPERVIOUS AREA AND RUNOFF-TO-RAINFALL RATIO



STUDY LOCATION CODE

1 UPPER WHITE ROCK, DALLAS	10 FIRST CREEK, KNOXVILLE
2 LOWER WHITE ROCK, DALLAS	11 PLANTATION HILLS, KNOXVILLE
3 BACHMAN BRANCH, DALLAS	12 NORTHAMPTION, ENGLAND
4 TURTLE CREEK, DALLAS	13 BRIGHOUSE, ENGLAND
5 HENDRIX CREEK, NEW YORK CITY	14 BRADFORD, ENGLAND
6 SPRING CREEK EAST, NEW YORK CITY	15 MADISON, WISCONSIN
7 THURSTON BASIN, NEW YORK CITY	16 TULSA, OKLAHOMA
8 FOURTH CREEK, KNOXVILLE	17 DURHAM, NORTH CAROLINA
9 THIRD CREEK, KNOXVILLE	18 TROUT RUN, ROANOKE, VIRGINIA

LEGEND

"STORM" EQUATION ESTIMATE (12)

EXTENSION OF MILLER AND VIESSMAN (11)

SUSPECT ERROR, DIRECTION OF PROBABLE CORRECTION

Source: U. S. Environmental Protection Agency.

system hydraulic simulation program which is driven by an input hyetograph and computes surface runoff hydrographs and receiving sewer system hydrographs. The program can also simulate the various types of diversions within the Milwaukee combined sewer system. The SAM model for Milwaukee was operated for the storm of September 10, 1983, during which about 0.5 inch of rain fell on the combined sewer service area. CSO volumes computed by SAM for each outfall are compared with volumes computed using the STORM runoff method shown in Figure 65. As indicated by the line of perfect agreement, a very good conformance was evident between the STORM method and the SAM results. Based upon this comparison, it was concluded that the simplified STORM method was adequate for estimating CSO volumes for pollutant-loading computation purposes.

Based on the above relationship and on rainfall data collected by the National Weather Service at Mitchell Field in Milwaukee, the mean annual CSO flow rate is 32 cubic feet per second, as compared to the sum of the mean annual flow of the tributary Kinnickinnic, Menomonee, and Milwaukee Rivers which is 521 cfs, or 6 percent of the total tributary area flow.

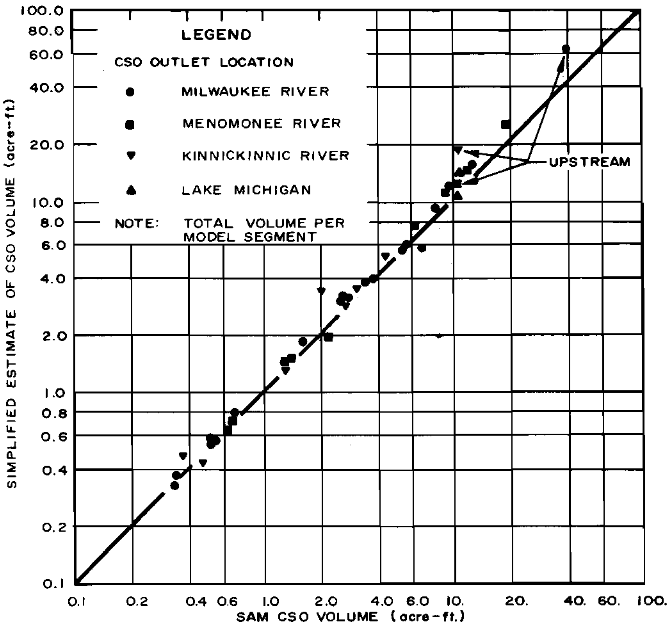
Flushing Tunnel Flows

Dilution water tunnels, locally referred to as flushing tunnels, connect Lake Michigan with the Milwaukee River estuary just downstream from the North Avenue Dam, and with the Kinnickinnic River just downstream from Chase Avenue.

During the field sampling period, the pumping rate for the Milwaukee tunnel was 350 cfs, and for the Kinnickinnic tunnel, 400 cfs. The Milwaukee tunnel pumping capacity subsequently was increased to 600 cfs by the Milwaukee Metropolitan Sewerage District (MMSD).

Figure 65

COMPARISON OF CSO VOLUME ESTIMATION TECHNIQUES



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

The flushing tunnels are operated by the MMSD when dissolved oxygen levels decline to 2.0 milligrams per liter (mg/l), which is the present state standard for the inner harbor of Milwaukee. Periods of operation of the Kinnickinnic and Milwaukee River flushing tunnels for 1982 through September 1984 are listed in Tables 54 and 55, respectively. During the periods August 30 through September 3, 1982, and September 11-15, 1984, the tunnels were operated every day during water quality surveys of effects of tunnel discharges on inner harbor water quality.

Groundwater Inflow

Groundwater inflow into the Milwaukee Harbor estuary is probably insignificant relative to surface inflows. The reasons are at least two-fold:

1. The normal water table underlying the Menomonee and Milwaukee River estuaries is approximately 20 to 40 feet lower than the water surface of these two rivers, as indicated by Map 42. The water table underlying the Kinnickinnic River estuary lies approximately 10 feet below the river surface. Therefore, rather than flow moving from the groundwater reservoir into the rivers, the reverse may be true. Pumping by large industrial wells could be the cause of this phenomenon.

Table 54

PERIODS OF OPERATION OF THE MILWAUKEE RIVER FLUSHING TUNNEL: 1982-1984

Date	Hours of Operation
January 6, 1982	16
January 7, 1982	8
January 8, 1982	8
June 15, 1982	16
June 16, 1982	8
June 17, 1982	8
June 18, 1982	8
August 9, 1982	8
August 20, 1982	8
August 30, 1982	24
August 31, 1982	24
September 1, 1982	24
September 2, 1982	24
September 3, 1982	24
September 16, 1982	8
September 17, 1982	8
July 25, 1983	8
July 26, 1983	8
July 27, 1983	16
July 28, 1983	16
July 29, 1983	16
August 12, 1983	16
September 1, 1983	16
September 2, 1983	16
June 20, 1984	8
June 21, 1984	8
June 22, 1984	8
August 16, 1984	8
August 17, 1984	8
August 22, 1984	8
August 23, 1984	8
August 24, 1984	8
September 11, 1984	16
September 12, 1984	24
September 13, 1984	24
September 14, 1984	24
September 15, 1984	12

Source: Milwaukee Metropolitan Sewerage District.

Table 55

PERIODS OF OPERATION OF THE KINNICKINNIC RIVER FLUSHING TUNNELS: 1982-1984

Date	Hours of Operation
January 7, 1982	13.0
January 8, 1982	8.5
January 13, 1982	7.7
January 14, 1982	8.1
January 15, 1982	7.8
January 18, 1982	8.3
January 19, 1982	3.4
January 21, 1982	4.0
January 22, 1982	5.9
February 10, 1982	3.1
February 11, 1982	9.2
February 12, 1982	8.1
February 15, 1982	10.2
February 16, 1982	8.1
May 12, 1982	8.6
May 13, 1982	8.4
May 14, 1982	8.2
May 17, 1982	8.4
May 18, 1982	10.3
May 19, 1982	8.4
May 20, 1982	8.4
May 21, 1982	10.9
May 24, 1982	8.4
May 25, 1982	8.2
May 26, 1982	7.9
May 27, 1982	9.0
May 20, 1982	8.3
June 1, 1982	8.7
June 2, 1982	8.3
June 4, 1982	6.1
June 7, 1982	6.0
June 8, 1982	6.0
June 9, 1982	5.5
June 10, 1982	5.8
June 11, 1982	5.4
June 14, 1982	8.5
June 16, 1982	8.6
June 17, 1982	9.2
June 21, 1982	8.1
June 22, 1982	8.9
June 23, 1982	8.6
June 24, 1982	3.0
July 1, 1982	8.1
July 2, 1982	8.2
July 6, 1982	8.1
July 27, 1982	18.6
July 28, 1982	8.9

Date	Hours of Operation
August 6, 1982	5.6
August 9, 1982	8.3
August 10, 1982	8.7
August 11, 1982	9.2
August 12, 1982	8.4
August 13, 1982	8.4
August 19, 1982	8.7
August 20, 1982	7.7
August 23, 1982	8.0
August 24, 1982	8.2
August 25, 1982	8.5
August 26, 1982	8.4
August 27, 1982	8.8
September 16, 1982	6.1
September 17, 1982	6.7
September 20, 1982	4.6
September 21, 1982	5.8
September 22, 1982	4.9
October 5, 1982	8.6
October 6, 1982	8.5
October 7, 1982	8.2
October 8, 1982	7.8
December 20 and 21, 1982	23.3
May 19, 1983	9.0
May 27, 1983	9.0
June 1, 1983	10.5
June 2, 1983	9.2
June 3, 1983	9.1
June 8, 1983	5.3
June 9, 1983	8.5
June 10, 1983	6.6
June 14, 1983	6.6
June 15, 1983	8.5
June 16, 1983	9.0
June 17, 1983	8.5
June 23, 1983	8.6
June 27, 1983	8.7
June 28, 1983	8.5
July 2, 1983	8.2
July 3, 1983	9.0
July 4, 1983	7.6
July 9, 1983	9.6
July 10, 1983	9.5
July 11, 1983	8.8
July 22, 1983	8.5

Table 55 (continued)

Date	Hours of Operation
July 23, 1983	9.7
July 24, 1983	9.7
July 27, 1983	9.4
July 28, 1983	9.1
July 29, 1983	8.6
August 10, 1983	9.3
August 11, 1983	8.5
August 12, 1983	8.9
August 15, 1983	8.7
August 16, 1983	8.8
August 25, 1983	10.6
August 26, 1983	9.3
August 29, 1983	8.5
August 30, 1983	9.7
August 31, 1983	9.2
September 1, 1983	8.3
September 2, 1983	8.8
September 12, 1983	5.4
September 13, 1983	8.5
September 14, 1983	8.2
September 15, 1983	8.4
October 5, 1983	7.8
October 6, 1983	8.8
June 5, 1984	8.0
June 6, 1984	8.4
July 2, 1984	6.7
July 3, 1984	8.9
July 4, 1984	8.4
July 13, 1984	6.1
July 16, 1984	9.6
July 17, 1984	9.1
July 18, 1984	9.0
July 19, 1984	9.2
July 20, 1984	8.6
August 16, 1984	9.4
August 17, 1984	8.5
August 20, 1984	9.1
August 21, 1984	9.0
August 22, 1984	8.8
August 23, 1984	9.0
August 24, 1984	8.7
August 29, 1984	9.2
August 30, 1984	9.4
August 31, 1984	9.2

Continuous Operation -
September 11 to September 15 = 95.5 Hours

Source: Milwaukee Metropolitan Sewerage District.

2. Hydraulic conductivity tests of six shallow wells in the Menomonee River by the USGS for the estuary study found that groundwater movement was relatively slow, with hydraulic conductivities ranging from 0.014 foot to 6.96 feet per day. A groundwater simulation model using the well water surface and river surface elevations computed a groundwater flow for these conditions of less than 0.1 cfs into the Menomonee estuary. Hydraulic conductivity of the shallow aquifer adjacent to the Menomonee estuary and most likely the Kinnickinnic estuary is very low because these areas were wetlands prior to urbanization of the area. These wetlands were filled in with rubble and other waste more or less suitable for fill, which may be expected to impede the movement of groundwater because of its relatively impervious composition.

Lake Michigan Inflow

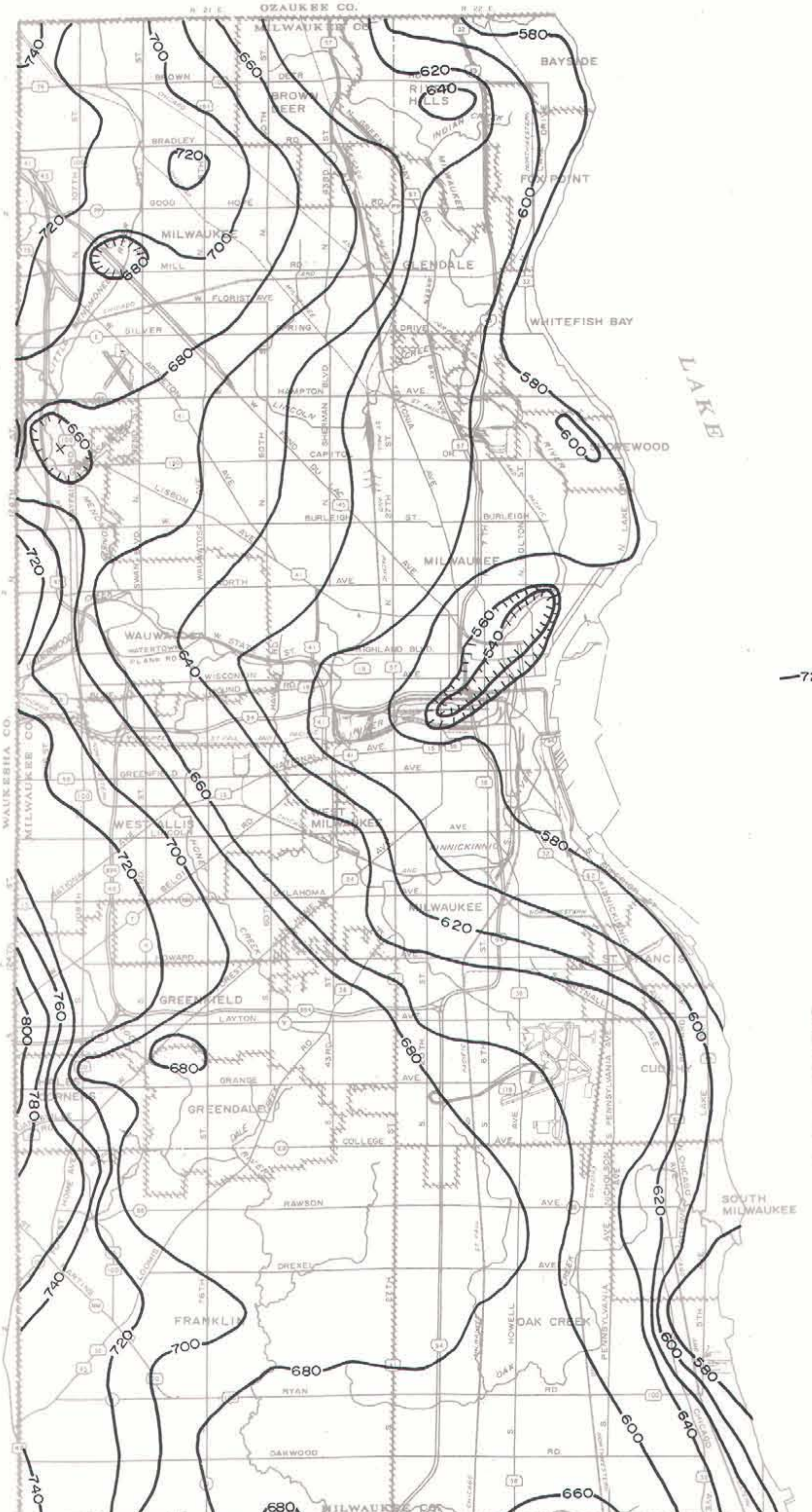
Flood and ebb flow in the inner harbor of Milwaukee attributable to the action of Lake Michigan was simulated by the U. S. Geological Survey using the Branch Network Model,[8] which was developed by that agency for the Milwaukee Harbor estuary study. The model is a one-dimensional simulator driven by water level changes and restricted by channel geometry. The model is capable of simulating flow in both the "upstream" and "downstream" directions in a variable backwater environment.

Upstream (flood) and downstream (ebb) flows from Lake Michigan into and out of the inner harbor can be quite large relative to the tributary river inflows. For the period June 15, 1982 through July 31, 1982, for example, the net daily mean flow of the Milwaukee River at the mouth simulated by the Branch Network Model ranged from 165 to 814 cfs, as indicated in Table 56. The instantaneous maximum upstream flow, however, ranged from 1,640 to 13,210 cfs. The instantaneous maximum downstream flow ranged from 1,360 to 11,400 cfs. Therefore, the flow within the inner harbor at any time, except near "slack tide," could be about 10 times higher than the net flow which represents the tributary river inflows. Thus, the flood and ebb flows caused by Lake Michigan

[8] *R. W. Schaffranek, R. A. Baltzer, and D. E. Goldberg, A Model for Simulation of Flow in Singular and Interconnected Channels, U. S. Geological Survey, Techniques of Water Resources Investigations, Book 7, Chapter C3, 1981.*

Map 42

WATER TABLE OF MILWAUKEE COUNTY



LEGEND

—720— WATER-TABLE CONTOUR SHOWS ALTITUDE OF WATER TABLE. CONTOUR INTERVAL 20 FEET. DATUM IS NATIONAL GEODETIC VERTICAL DATUM

GRAPHIC SCALE
0 1 2 MILES
0 4000 8000 12000 16000 FEET

The water table is defined as the upper surface of the zone of saturation in the soil or bedrock. It is defined by the levels at which water stands in wells that penetrate the groundwater body just far enough to hold standing water. In wells that penetrate to greater depths, the water level may stand above or below the water table. This map shows the elevation of the water table in Milwaukee County. The data used to make this map were compiled from a number of sources and include water levels from different years and seasons. An effort was made in the preparation of the map to use data that represented average water levels.

Source: U. S. Geological Survey

Table 56

SUMMARY OF SIMULATED FLOW DATA FOR THE MILWAUKEE RIVER AT MOUTH BY THE U. S. GEOLOGICAL SURVEY BRANCH NETWORK MODEL

Date (mo/day)	Discharge (cubic feet per second) minimum	mean	maximum	Velocity (feet per second) minimum	maximum
6/15	-6970	812	6860	-0.48	0.48
6/16	-4560	353	5650	-0.31	0.39
6/17	-3240	361	2300	-0.22	0.16
6/18	-2760	349	3330	-0.19	0.23
6/19	-2140	370	2800	-0.15	0.19
6/20	-2860	306	6420	-0.20	0.45
6/21	-3060	374	5250	-0.21	0.36
6/22	-5350	299	5610	-0.37	0.39
6/23	-2850	288	2580	-0.20	0.18
6/24	-4030	244	4110	-0.28	0.28
6/25	-2870	570	4540	-0.20	0.31
6/26	-2270	299	2890	-0.16	0.20
6/27	-2510	286	3110	-0.17	0.21
6/28	-2650	270	2140	-0.18	0.15
6/29	-2250	374	3280	-0.15	0.23
6/30	-2920	332	3230	-0.20	0.22
7/1	-1960	376	2990	-0.13	0.21
7/2	-2960	297	3430	-0.20	0.24
7/3	-5720	251	3860	-0.39	0.27
7/4	-5030	258	5820	-0.35	0.41
7/5	-3210	165	4280	-0.22	0.30
7/6	-8500	414	5990	-0.58	0.42
7/7	-11400	813	13200	-0.78	0.93
7/8	-5120	356	9370	-0.35	0.66
7/9	-4000	359	4100	-0.27	0.29
7/10	-6020	449	5240	-0.41	0.36
7/11	-4250	425	6290	-0.29	0.43
7/12	-2030	348	2800	-0.14	0.19
7/13	-3040	275	3110	-0.21	0.21
7/14	-2700	325	3880	-0.18	0.27
7/15	-2740	287	3420	-0.19	0.24
7/16	-3650	290	4030	-0.25	0.28
7/17	-6540	306	5590	-0.45	0.39
7/18	-6480	282	7860	-0.44	0.55
7/19	-3800	282	4370	-0.26	0.30
7/20	-2950	271	3820	-0.20	0.26
7/21	-5750	383	3940	-0.39	0.27
7/22	-2100	814	3900	-0.14	0.27
7/23	-2820	342	3630	-0.19	0.25
7/24	-2860	336	4470	-0.20	0.31
7/25	-3470	272	4990	-0.24	0.35
7/26	-5710	364	6550	-0.39	0.45
7/27	-3630	310	2980	-0.25	0.21
7/28	-3430	314	2750	-0.23	0.19
7/29	-1720	228	2600	-0.12	0.18
7/30	-2920	228	2400	-0.20	0.17
7/31	-1360	264	1640	-0.09	0.11
Average	-3850	353	4410	-0.26	0.31
Maximum	-1360	814	13200	-0.09	0.93
Minimum	-11400	165	1640	-0.78	0.11

Source: U. S. Geological Survey

generally are much larger than the river inflows and, consequently, must be considered in any water quality analyses.

Estuary Hydraulics

Flow rates and circulation patterns within the Milwaukee Harbor estuary, particularly within the inner harbor, are influenced by runoff from the tributary drainage area, by flood and ebb flows caused by Lake Michigan water level oscillations, by flushing tunnel flows from Lake Michigan discharging near the upstream end of the Kinnickinnic and Milwaukee River estuaries, and by the effects of condenser cooling water withdrawals and discharges made by the Valley power plant in the Menomonee River estuary. Frequent water level fluctuations on Lake Michigan are the primary cause of the large flood and ebb flows within the inner harbor.

Characterization of Principal Seiche-Induced Flow in the Inner Harbor: Although the one-dimensional Branch Network Model operated by the U. S. Geological Survey provided much useful information regarding the magnitude of flood and ebb flows of lake water within the inner harbor of Milwaukee, more detailed hydraulic information was required to support the water quality analyses conducted under the study. Additional information was required about velocity variation in the vertical so that mixing coefficients could be computed in order to determine dilution and dispersion of water quality constituents.

Because the Lake Michigan seiches appear to be the principal hydrodynamic driving force in the inner harbor, the natural period of resonance of the inner harbor and of the principal lake level oscillations affecting the flow therein needed to be characterized.

Natural Period of Resonance of Inner Harbor: Whenever the length of an embayment or estuary, such as the inner harbor estuary of Milwaukee, is approximately equal to one-quarter of the length of a Lake Michigan wave, the lake wave can cause inner harbor water levels to oscillate with a period:

$$Tc = 4Lc/(gD)^{0.5},$$

where: Lc is the length of the estuary (feet),
D is the mean depth (feet),
g is the acceleration of gravity (32.3 feet/second/second), and
Tc is the natural period of resonance for the estuary (seconds).

The importance of this phenomenon is that the vertical movement of the water surface is greater at the head of the estuary than at the mouth. Such amplification results in movement of large volumes of lake water to and from the estuary. The above equation assumes a uniform depth in the estuary, which is not in accord with reality in the inner harbor. However, the resonance period for an irregular estuary can be computed in a step-by-step procedure by segmentation of the estuary into reaches, each of relatively uniform depth. This procedure was utilized for the Milwaukee River from the mouth to the North Avenue dam; the resultant resonance period was 24 minutes. The weighted mean depth of that reach was 15.2 feet below low-water datum. The reach length was 16,100 feet. For the outer harbor, using an average depth of 22.3 feet below low-water datum and a north-south basin length of 3.2 miles, the natural period of resonance for a uninodal seiche is 21 minutes. This calculation procedure, however, yields, at best, an approximation in such an irregularly shaped estuary as the inner harbor of Milwaukee, and does not provide an estimate of wave amplitudes or of seiche-induced flow.

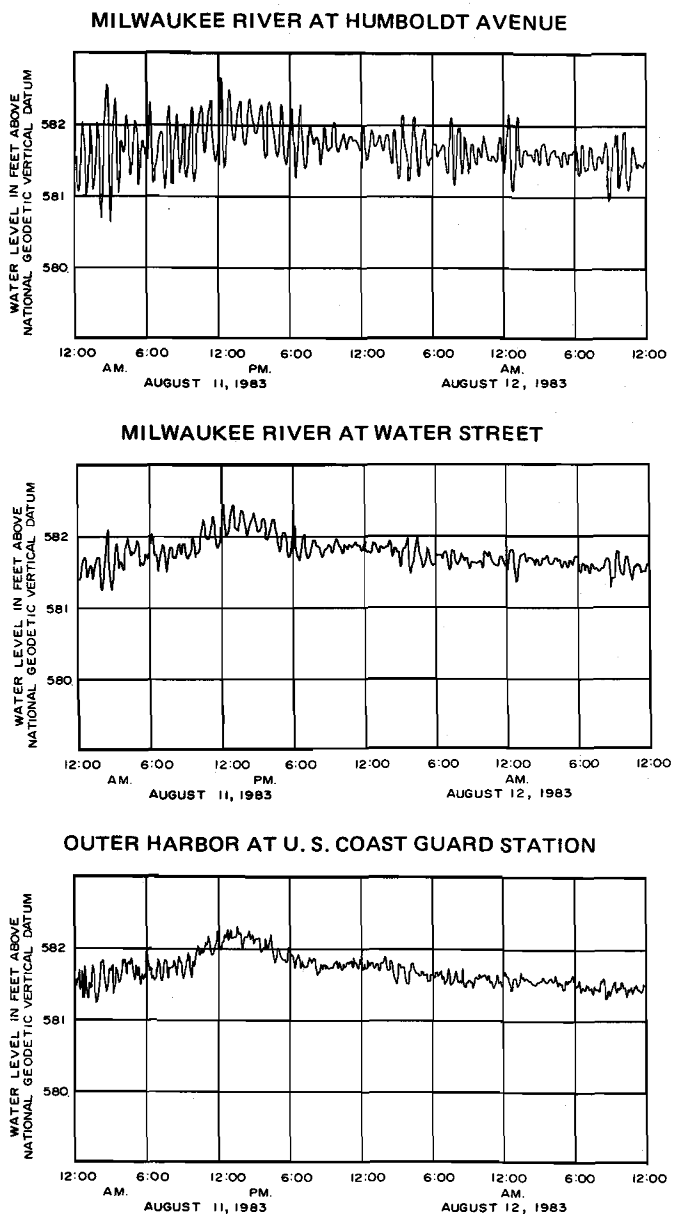
Time Series Analysis of Water Level Records: A better approach than that described above to determine the effects of Lake Michigan seiches on water level changes is to apply time series analysis to recorded water level data to describe mathematically the characteristics of the seiche waves of principal importance. The waves so identified would be input to a multilayered hydrodynamic model which would compute flow and vertical mixing to be used for subsequent water quality analyses.

In order to determine the hydraulic characteristics of the inner and outer harbors, available water level data extracted from observations taken during selected storm events and during a "steady state" period were mathematically analyzed using statistical techniques. Principal among these statistical techniques were harmonic analysis, autocorrelation analysis, and spectral analysis. These techniques are particularly useful in identifying underlying regular periodicities in "time series" data, such as may be present in the water level records obtained in the inner and outer harbors. A plot of a sample water level record at three of the monitoring stations is shown in Figure 66 for a two-day period.

In general, harmonic analysis may be used to provide a mathematical representation of both regular and irregular cycles within any given period

Figure 66

COMPARISON OF WATER LEVEL RECORDS FOR MILWAUKEE RIVER AT HUMBOLDT AVENUE AND AT WATER STREET WITH OUTER HARBOR AT U. S. COAST GUARD STATION: AUGUST 11-12, 1983



Source: National Ocean Survey, U. S. Geological Survey, and SEWRPC.

of water level record. Autocorrelation is also useful for identifying regular fluctuations in water level data. For example, a wave crest at one point in a time series will exhibit a high positive correlation with wave crests occurring later in the series, and a high negative correlation with subsequent wave troughs. Thus, large autocorrelation coefficients at a certain lag time indicate the presence of a regular oscillation at a fixed period. Spectral analysis is a means whereby the contribution of regular oscillations at various frequencies to the total variance of the time series may be mathematically defined. In physical terms, spectral analysis provides an estimate of the wave energy contribution of each wave period to the total energy of the wave system. In practice, spectral analysis is performed by determining the autocorrelation coefficients within the time series for a given number of lag periods, and then conducting a harmonic analysis on these autocorrelation coefficients.

Utilizing these statistical techniques on water level data collected at five-minute intervals by the U. S. Geological Survey in the inner harbor, a storm event period—September 10-14, 1983—was selected for analysis. The water level data for this period were obtained from a recording station located at Water Street on the Milwaukee River. During this period, water levels reached a maximum of 581.61 feet (NGVD) and a minimum of 580.61 feet—a range of one foot.

Using the statistical procedures indicated above, the dominant wave in the spectrum by far was found to be one with a period of 52 minutes and a corresponding amplitude of 0.12 foot. Another period during which a storm occurred—August 7-11, 1984—was similarly analyzed and the 52-minute wave was again found to dominate the spectrum, but with an amplitude of 0.17 foot. The 52-minute wave was relatively insignificant in a similar analysis conducted for records collected in the outer harbor at the station operated jointly by the National Ocean Survey and the U. S. Geological Survey. Therefore, it appears that the 52-minute-period wave on Lake Michigan is amplified in the inner harbor, as suggested by Figure 66. However, the apparent amplitude increases from the outer harbor to Humboldt Avenue also may be attributable to a decrease in channel size, which is significant between there and the mouth of the Milwaukee River.

The natural period of resonance of the Milwaukee River estuary was estimated in the previous section of this chapter to be 24 minutes, which is approximately one-half the period of the dominant inner harbor wave computed by the time series analysis. The 24-minute wave could then be in phase with the incoming 52-minute wave from Lake Michigan, producing the apparent amplification observed in the water level data. The 52-minute wave may be from a multinodal seiche.

A time series analysis was also conducted in July 1982 during a period when no storms occurred and weather was relatively calm. During this period the 52-minute wave was relatively insignificant, the dominant wave being that with a period of 2.18 hours and with a amplitude of about 0.03 foot. This wave period corresponds to that identified by Mortimer[9] as the transverse (east-west) seiche of Lake Michigan, having a period of 2.2 hours.

Inner Harbor Circulation: Flow and the associated circulation of the inner harbor of Milwaukee were simulated by a 10-layered, two-dimensional hydrodynamic model documented in Chapter VIII of this report. The model was driven principally by the Lake Michigan long waves described in the previous section and superimposed upon the daily mean water levels of the periods of simulation.

One of the primary uses of a circulation model is to compute the general circulation in a region given observations only at the boundaries. Data specific to July 26, 1982, were used to illustrate the general circulation. Many physical water quality observations were taken during that time period and the period was relatively stable—that is, the boundary values were, for the most part, relatively constant.

The discharges input to the model are tabulated in Table 57. The boundary values of the temperature and conductivity (the tracer selected for this case) are provided in Table 58. The effluent from the power plant was established at 91.4°F (33°C), as reported by the Wisconsin Electric Power Company.

The wind record obtained from nearby Mitchell Field for the simulation period was examined. The wind that occurred on the days of the data collection effort was generally light and, thus, is not discussed here. Because there were storm-free conditions, only the two-hour-period seiche was used at the outer harbor boundary.

The general circulation of the inner harbor is best presented by the use of maps and graphs. The net flow rate is shown on Map 43. The mean circulation of water flowing from the heads of each river to the lake is evident. The dramatic influence of the power plant is also depicted. Here, a tremendous recirculation is found. It is much larger than that attributable to the boundary discharges. To show the vertical extent of the flow, the transport in the top third, middle third, and bottom third of the water column is shown on Map 44. Both the Menomonee and Kinnickinnic Rivers appear to have a three-layer circulation—that is, upstream (away from the outer harbor) flow in the surface and bottom layers, and downstream (toward the outer harbor) flow in the middle portion of the water column. The power plant does not appear to ingest its effluent, the result of a well-stratified situation. The heated effluent is, however, responsible for the three-layered flow in the upper portions of the Menomonee River. The relatively large discharge at the head of the Milwaukee River and the shallow depth limits the penetration of lake water in that river, whereas the low discharge in the other rivers and the deep navigation channels allow the lake water to traverse nearly the entire lengths of the rivers.

Table 57

HYDRODYNAMIC MODEL INPUT DISCHARGES FOR SIMULATION FOR JULY 26, 1982

Location	Discharge (cfs)
Milwaukee River at North Avenue Dam	282
Menomonee River at Falk Corporation Dam	24
Kinnickinnic River at Chase Avenue	13
Valley Power Plant	
Intake	-250
Outfall	250
Milwaukee River Flushing Tunnel	0
Kinnickinnic River Flushing Tunnel	0

Source: SEWRPC.

The vertical distributions of currents, temperatures, and conductivity throughout the length of each river are shown in Figures 67, 68, and 69. The three-layered circulation is clear. The temperature profile shows the classical patterns that arise from cold lake water flowing under warmer water coming in at the estuary head. The conductivity, with the outer harbor being a source of low values

[9] *C. H. Mortimer, "Physical Characteristics of Lake Michigan and Its Response to Applied Forces,"* Physical Limnology of Lake Michigan, *Part 1, Argonne National Laboratory report, ANL/ES-40, Volume 2, 1975.*

Table 58

HYDRODYNAMIC MODEL RIVER INPUT TEMPERATURE AND SPECIFIC CONDUCTANCE FOR SIMULATION FOR JULY 26, 1982

Depth (feet)	Hoan Bridge	Walnut Street	Muskego Avenue	First Street
	Temperature (degrees Celsius)			
0	19.6	26.5	25.0	21.0
6.6	19.2	26.5	25.0	20.0
13.1	18.4	26.5	25.0	20.0
19.7	17.2	- -	25.0	20.0
26.2	15.7	- -	- -	- -
32.8	14.1	- -	- -	- -
	Specific Conductance (micromhos/cm)			
0	420	535	708	715
6.6	428	535	708	503
13.1	445	535	708	503
19.7	425	- -	708	503
26.2	368	- -	- -	- -
32.8	312	- -	- -	- -

Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

and the tributary rivers having relatively high values, shows a similar behavior except in the Menomonee River. Here, a large source of conductivity coming into this river coupled with a mid-depth downstream flow produces a tongue-like distribution. In addition, the power plant acts as a vertical mixer for conductivity. It ingests bottom water with a certain conductivity and then discharges it near the surface with the same concentration that it had initially.

SUMMARY

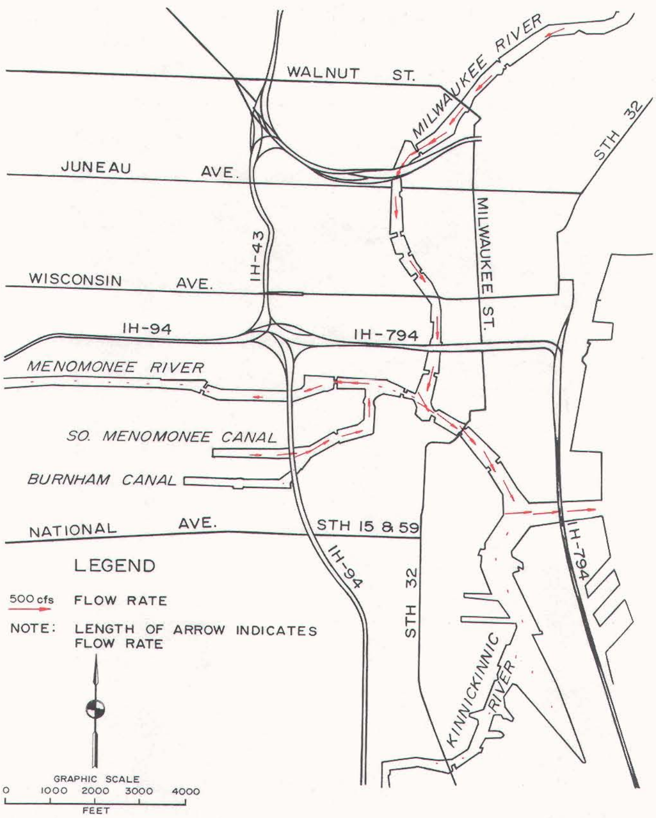
This chapter describes certain physical phenomena and processes relevant to water resources planning for the Milwaukee Harbor estuary. Lake Michigan processes described include thermal stratification, wind set-up, seiche, upwelling and downwelling, and ice formation. Wave action is described including the characteristics of progressive surface waves, wave refraction, diffraction, reflection, and run-up. The types of currents occurring in Lake Michigan are identified—including longshore, density, rip, Langmuir, large-scale, and near-shore and offshore currents—and the effect of currents on the dispersion of substances in the water column described.

Review of water level records collected for Lake Michigan at Milwaukee indicates that the maximum annual mean level of 582.2 feet National Geodetic Vertical Datum (NGVD) or 580.9 feet International Great Lakes Datum (IGLD) of 1955 occurred in 1886, with the second highest annual mean level of record being 582.0 feet NGVD or 580.7 feet IGLD in 1985. The 20th century instantaneous maximum lake level of 583.73 feet NGVD or 582.43 feet IGLD occurred on November 9, 1985. The minimum annual mean level occurred in 1964—577.1 feet NGVD or 575.8 feet IGLD. The instantaneous minimum recorded elevation was 575.5 feet NGVD or 574.2 feet IGLD on January 23, 1926. The range between the maximum and minimum annual mean levels was, therefore, 5.1 feet, with the difference between maximum and minimum instantaneous levels recorded being 8.2 feet.

Frequency analyses of water level records indicated that the mean annual lake level under existing diversions, outlets, and regulation schedules was 579.5 feet NGVD or 578.2 feet IGLD, with the 1 percent exceedance frequency level being 3.4 feet higher at an elevation of 582.9 feet NGVD or

Map 43

SIMULATED NET FLOW DIRECTION AND MAGNITUDE IN THE INNER HARBOR BY THE HYDRODYNAMIC MODEL: JULY 26, 1982



Flows in the inner harbor of Milwaukee are governed primarily by tributary river flow rates, inflow from Lake Michigan induced by seiche, and condenser cooling water withdrawals from the Menomonee River estuary by the Valley power plant. As shown on this map, however, the net daily mean flow is generally downstream toward Lake Michigan, except in that portion of the Menomonee River estuary affected by the circulation induced by the power plant, wherein the net flow is generally in the upstream direction.

Source: HydroQual, Inc., and SEWRPC.

581.6 feet IGLD. The elevation of the instantaneous maximum water level at the 1 percent exceedance probability is 584.5 feet NGVD or 583.2 feet IGLD. The 99 percent exceedance frequency lake levels for the minimum annual mean and instantaneous minimum were found to be 576.1 feet NGVD or 574.8 feet IGLD and 574.5 feet NGVD or 573.2 feet IGLD, respectively.

Analyses of short-term rises in lake levels attributable to storm surges and seiches found the 100-year recurrence interval rise to be 1.9 feet at Milwaukee. The tidal range at Milwaukee is about 0.09 foot.

Analyses were also conducted of hydrologic data for the rivers tributary to Milwaukee Harbor. The mean annual flows of the Kinnickinnic, Menomonee, and Milwaukee Rivers were determined to be 23, 90, and 408 cubic feet per second (cfs), respectively. In comparison, the mean annual overflow from the combined sewers tributary to the harbor estuary was estimated to be 32 cfs and directly tributary separate storm sewer flows to be less than 2 cfs. The 7-day, 10-year low flows of the tributary rivers were determined to be, respectively, 6.0, 4.7, and 25.1 cfs. In comparison, the flushing tunnel flows discharging Lake Michigan waters to the upstream termini of the Kinnickinnic and Milwaukee River estuaries are estimated to be 400 and 350 cfs, respectively. The Milwaukee River flushing tunnel discharge capacity was increased in 1985 to 600 cfs. The condenser cooling water withdrawal and discharge rates for the Wisconsin Electric Power Company Valley power plant on the Menomonee River estuary, consisting primarily of Lake Michigan water, are about 250 cfs. Lake Michigan flood and ebb flows in the inner harbor are estimated to reach from 2,000 to 13,000 cfs on a daily basis. The larger flows to and from the lake are attributable to seiche action.

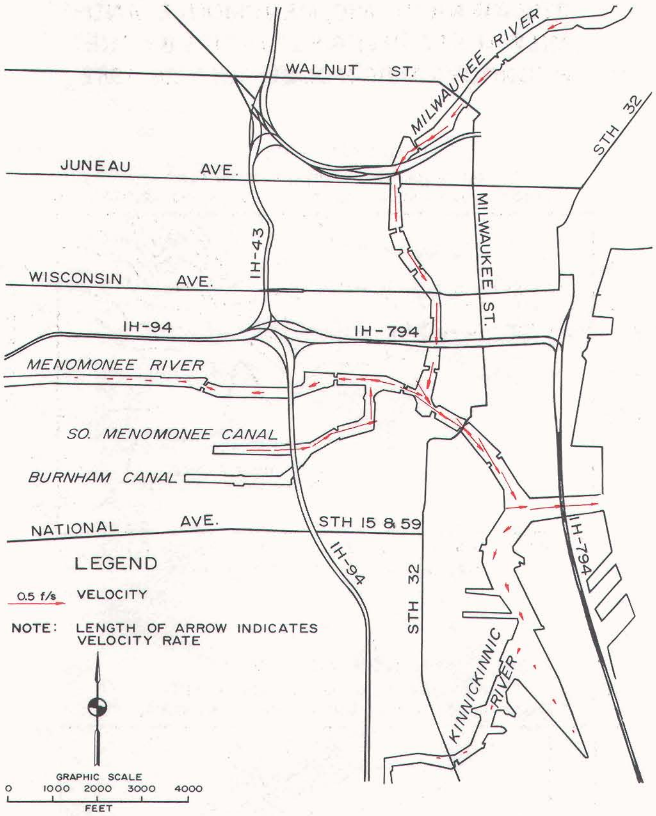
A time series analysis of water level records in the inner harbor found two significant long waves from Lake Michigan, which travel through the inner harbor at periods of 0.9 hour and 2.2 hours. The 0.9-hour wave may be a multinodal seiche. The 2.2-hour wave is probably the transverse seiche of Lake Michigan which is generated by meteorological disturbances. The 0.9-hour wave height was found to be on the order of 0.1 to 0.4 foot; whereas the 2.2-hour seiche was found to be of variable height, but on the order of 0.1 to 1.0 foot in the estuary. The principal significance of these waves is that they generate large inflows of water from Lake Michigan into the inner harbor, thereby affecting the mixing and dilution of pollutants from the rivers, combined sewer overflows, separate storm sewer inflows, and direct surface runoff.

Water circulation within the inner harbor was simulated using a 10-layered, two-dimensional hydrodynamic model which found that circulation in the inner harbor was dominated by Lake Michigan flood and ebb flows and, to a lower degree, by condenser cooling water withdrawals and discharges from the Valley power plant on the Menomonee River estuary, and flushing tunnel flows when in operation. During calm weather, the

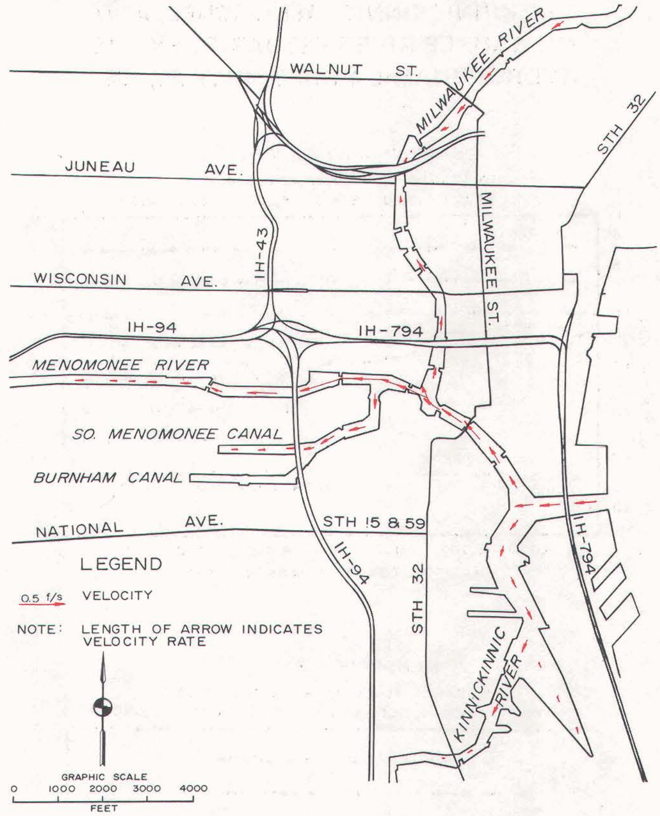
Map 44

SIMULATED FLOW DIRECTION AND MAGNITUDE IN THE INNER HARBOR BY THE HYDRODYNAMIC MODEL: JULY 26, 1982

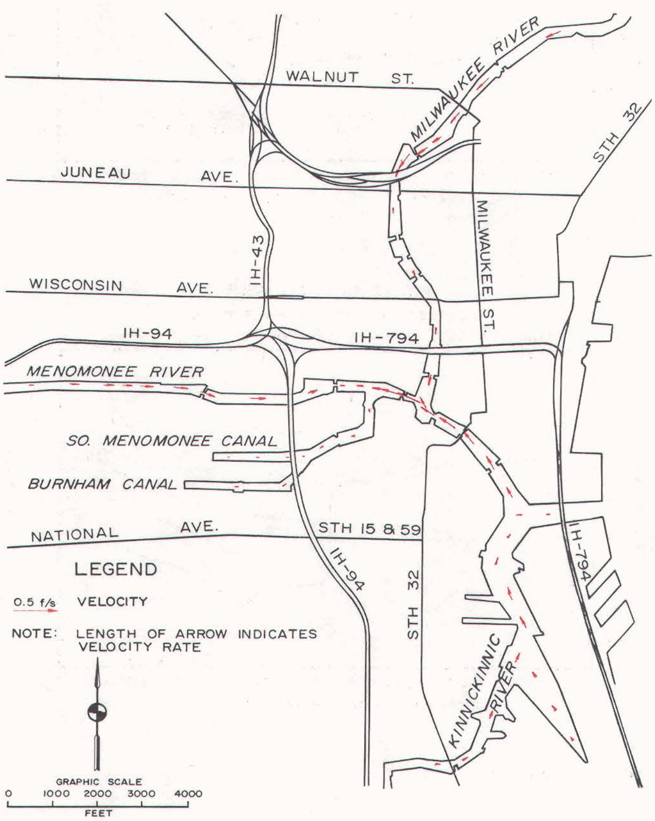
SURFACE



BOTTOM



MID-DEPTH

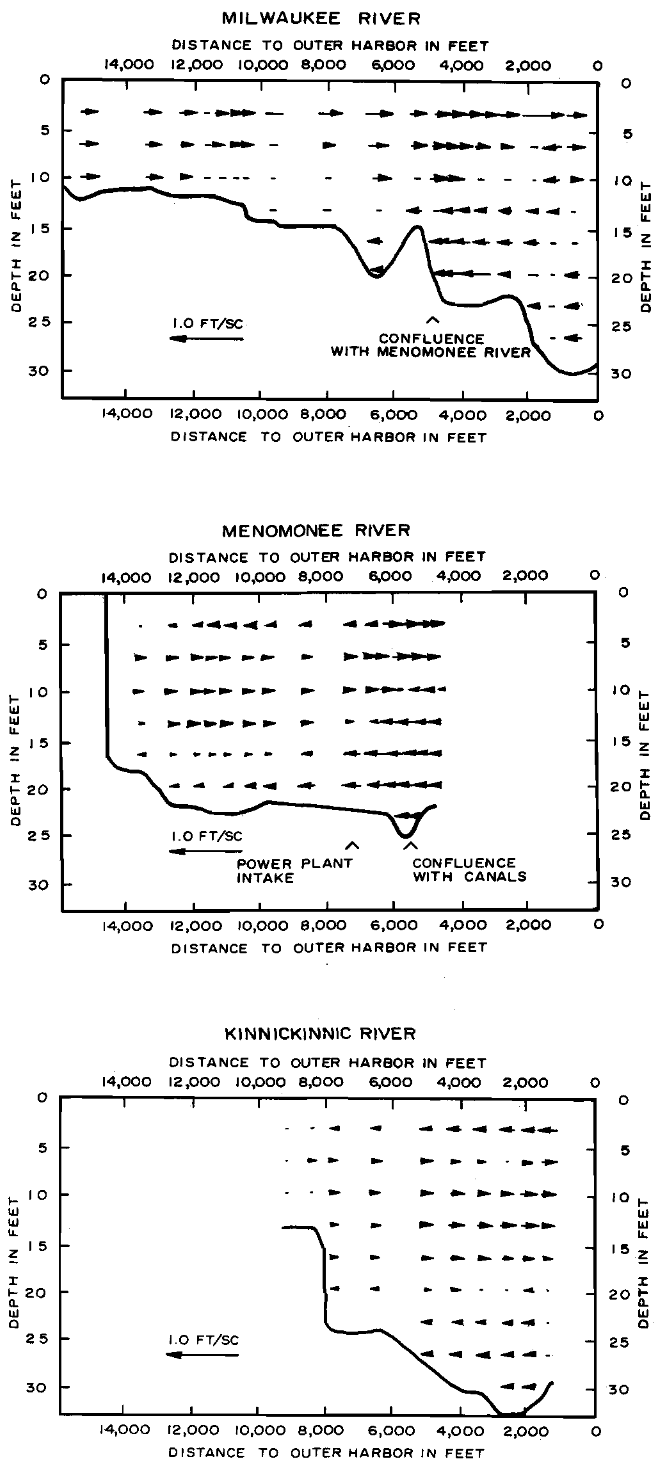


Multi-layered flow commonly occurs in much of the inner harbor of Milwaukee and is largely governed by inflows from the tributary rivers and from Lake Michigan, and by power plant withdrawal and discharge. The temperatures of the inflows and thermal discharges, the channel geometry, and the level of Lake Michigan are important additional factors affecting the development of layered flow. Hydrodynamic simulation modeling of this multi-layered flow was conducted under the estuary study. The upper left of this figure depicts the results of such modeling for July 26, 1982, with respect to near surface flows. The modeling indicated that the net flow at the surface of the Milwaukee River estuary was downstream toward Lake Michigan, whereas much of the surface flow in the Kinnickinnic and Menomonee River estuaries was in the upstream direction. The left part of this figure depicts the results of the modeling with respect to near mid-depth flows on the same date. The modeling indicated that the net flow near mid-depth was in the downstream direction toward Lake Michigan in most of the inner harbor. However, upstream flow prevailed near mid-depth in the Milwaukee River estuary from the mouth to the confluence with the Menomonee River. The upper right part of this figure depicts the results of the modeling with respect to near bottom flows on the same date. The modeling indicated that the net flow near the bottom was in the upstream direction away from Lake Michigan in most of the inner harbor. However, downstream flow prevailed near the upper reaches of the Milwaukee River estuary from the North Avenue dam to approximately Cherry Street.

Source: HydroQual, Inc., and SEWRPC.

Figure 67

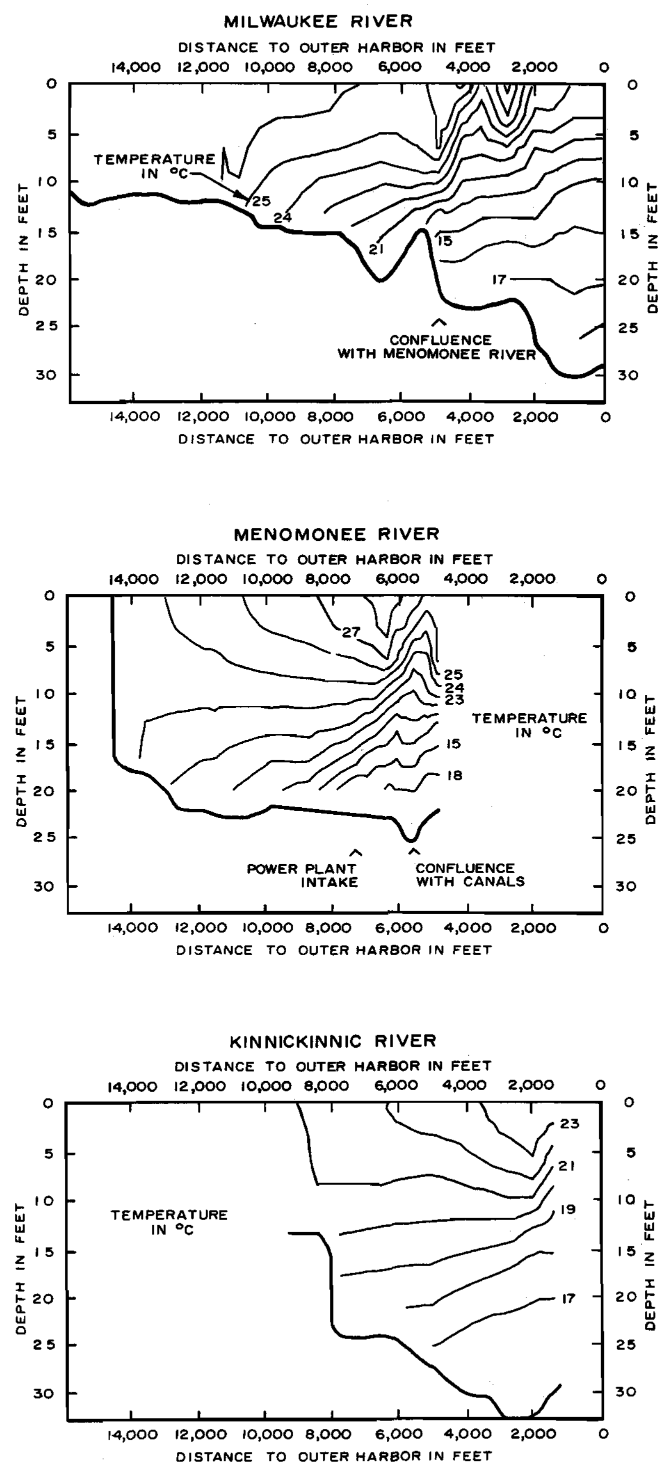
COMPUTED VERTICAL VELOCITY IN THE KINNICKINNIC, MENOMONEE, AND MILWAUKEE RIVER ESTUARIES BY THE HYDRODYNAMIC MODEL: JULY 26, 1982



Source: HydroQual, Inc.

Figure 68

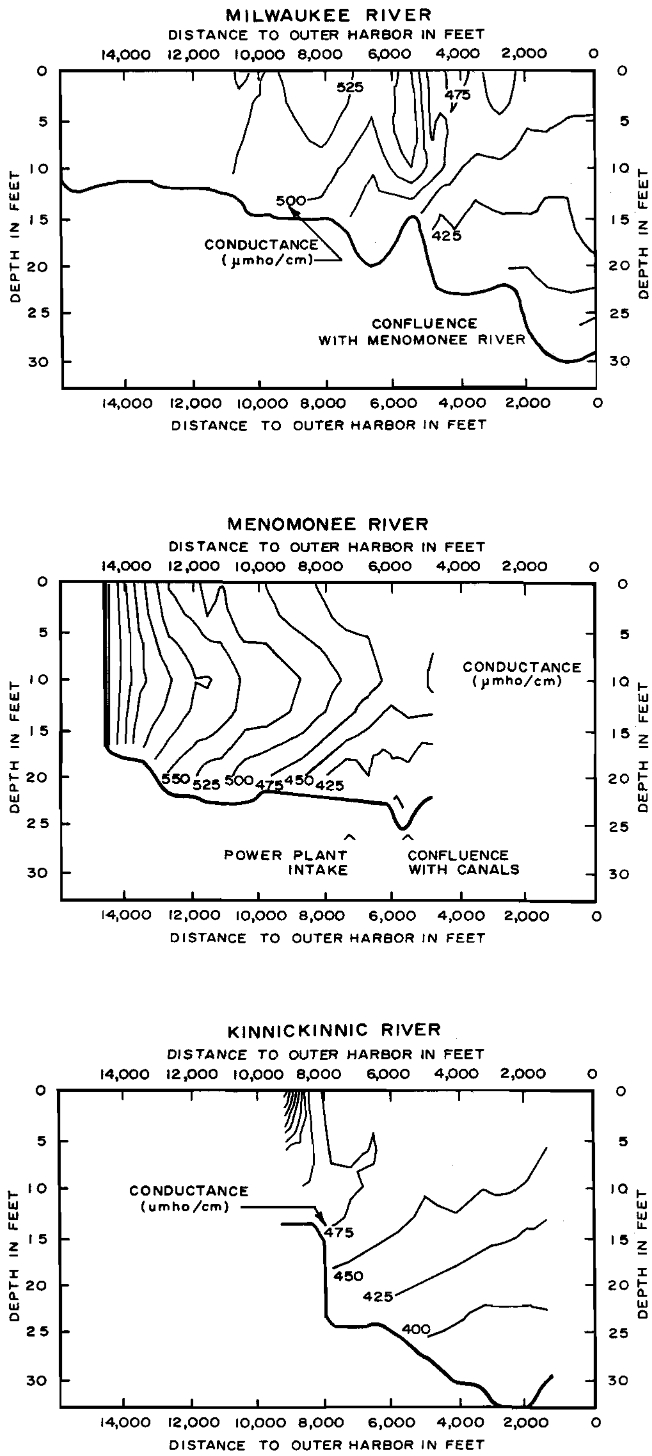
COMPUTED VERTICAL TEMPERATURE IN THE KINNICKINNIC, MENOMONEE, AND MILWAUKEE RIVER ESTUARIES BY THE HYDRODYNAMIC MODEL: JULY 26, 1982



Source: HydroQual, Inc.

Figure 69

COMPUTED VERTICAL SPECIFIC CONDUCTANCE IN THE KINNICKINNIC, MENOMONEE, AND MILWAUKEE RIVER ESTUARIES BY THE HYDRODYNAMIC MODEL: JULY 26, 1982



Source: HydroQual, Inc.

simulation model indicated that in the Menomonee and Kinnickinnic estuaries, currents may be expected to move upstream on the surface and near the bottom, with a return flow near mid-depth, and in the Milwaukee River estuary upstream to its confluence with the Menomonee River estuary. The model studies indicated that the Milwaukee River estuary upstream of the confluence with the Menomonee River estuary may be expected to exhibit a two-layered flow system up to about Cherry Street, with surface currents moving downstream and bottom currents upstream. Currents in the Kinnickinnic and Menomonee estuaries move upstream on the surface at about 0.1 foot per second (fps), and move along the bottom at about 0.1 fps in the Kinnickinnic estuary and at between 0.1 and 0.3 fps in the Menomonee estuary. The higher flow rates in the Menomonee estuary are caused by the cooling water withdrawal by the Valley power plant. Return flows are near mid-depth at about 0.1 fps in both the Kinnickinnic and Menomonee Rivers. In the Milwaukee estuary, surface currents generally move downstream at velocities ranging from 0.1 to 0.3 fps, with bottom currents generally moving upstream at about 0.1 to 0.2 fps. Lake water may be expected to penetrate nearly the entire length of the Kinnickinnic and Menomonee estuaries because of the relatively small river flows and the relatively deep navigation channels. Penetration of lake waters into the Milwaukee River estuary north of the confluence with the Menomonee River estuary is restricted by the relatively large flow of that river and because of the relatively shallow depths. While lake waters apparently do not move all the way up the river estuary, the levels and flow patterns in that estuary upstream from Cherry Street are nevertheless impacted significantly.

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Chapter VI

EXISTING WATER QUALITY, SEDIMENT QUALITY, AND BIOLOGICAL CHARACTERISTICS AND CONDITIONS, AND POLLUTION SOURCES

INTRODUCTION

Water resources planning efforts in general, and the Milwaukee Harbor estuary planning program in particular, must include an evaluation of historic and existing water quality conditions and of the relationship of those conditions to existing land and water uses. The purpose of this chapter is to determine the extent to which the Milwaukee Harbor estuary is polluted, and to identify the probable causes for, or sources of, that pollution. More specifically, this chapter describes existing water quality, sediment quality, and biological conditions in the Milwaukee Harbor estuary using the extensive data collected under this study. It explores the differences between wet- and dry-weather water quality phenomena; quantifies pollutant loadings to the estuarine system and the behavior of these pollutants within the estuary; and identifies, characterizes, and quantifies the sources of pollution discharged to the Milwaukee Harbor estuary. The information presented herein provides an important basis for the development and testing of the alternative water quality control plans under the Milwaukee Harbor estuary study.

A total of 63 studies related to water quality conditions in the Milwaukee Harbor estuary are known to have been conducted between 1952 and 1981. These studies included the collection, analysis, and interpretation of data concerning wet- and dry-weather water quality conditions, hydrologic and hydraulic processes, biological conditions, suspended sediment and bottom sediment conditions, point and nonpoint sources of pollution, bathymetry, meteorology, and climatology. These studies, however, did not provide a data base adequate for the Milwaukee Harbor estuary planning study, particularly with regard to the effects of combined sewer overflows and sediment-water interactions. Consequently, an extensive surface water quality sampling program comprised of a "baseline" component and an "event-related" component was undertaken in calender years 1982, 1983, and 1984 as a part of the harbor estuary study. In addition, baseline water quality data collected by the Milwaukee Metropolitan Sewerage District were used in the study. A sampling program for sediment quality and processes was also conducted over the period 1982-1983. This chapter summarizes the findings of these data collection efforts for the Milwaukee Harbor estuary and its tributary drainage areas.

The water quality sampling program was undertaken to characterize conditions in the upstream reaches of the Milwaukee, Menomonee, and Kinnickinnic Rivers, the inner harbor, the outer harbor, and the Lake Michigan near-shore waters. Baseline sampling was conducted at 10 stations in the free-flowing rivers upstream of the estuary, nine inner harbor stations, 10 outer harbor stations, and five near-shore Lake Michigan stations. The location of the sampling stations and the rationale used to select these stations are set forth in Chapter IV of this report volume. All stations were sampled once per week throughout the year, with the exception of periods of winter ice cover. The sampling included both wet- and dry-weather conditions. Riverine stations were sampled at a single depth, while most inner harbor, outer harbor, and near-shore Lake Michigan stations were sampled at a depth of three feet below the water surface, at mid-depth, and three feet above the bottom. In addition, five runoff event sampling surveys were conducted during the water quality sampling program. In all, approximately 10,300 baseline and runoff event water quality samples were taken over the three-year study period.

The sediment sampling program was conducted from 1982 through 1983. Sediment samples were taken from 15 inner harbor stations on a rotating basis such that each station was sampled from six to eight times per year. Sediment core samples were usually subsampled at 0.5-inch increments for the first two inches, and at 1-inch increments below that, for a total of 10 samples. In all, approximately 1,500 sediment samples were taken over the two-year study period.

In addition, biological surveys conducted by the Wisconsin Department of Natural Resources under the harbor estuary study describe the biological conditions of the the inner and outer harbors. The biological surveys provide a list of existing biota, set forth impairing factors, and provide a habitat evaluation.

WATER QUALITY, SEDIMENT QUALITY, AND BIOLOGICAL CHARACTERISTICS OF ESTUARINE ENVIRONMENTS

Water Quality Characteristics

The water quality of an estuarine environment, like streamwater and lake water quality, is dynamic in nature and contains variations which are both spatial and temporal. The hydraulic conditions within the Milwaukee Harbor estuary are complex because of the influence of the Milwaukee, Menomonee, and Kinnickinnic Rivers, and of Lake Michigan itself. Factors which affect water quality include depth of water, frequency and intensity of rainfall, surface runoff, amount and quality of inflowing surface waters, groundwater quality and contribution, daily and seasonal temperature changes, seasonal growth and decay of aquatic plants and animals, and diurnal and seasonal changes in insolation and the associated photosynthetic processes of aquatic plant life. In addition, channel morphology, geology, soils, land use patterns, and recreational and commercial uses of the estuarine area affect the water quality of the estuarine system.

Chemical, physical, and bacteriological tests of representative water samples are used to evaluate the water quality of an estuarine environment. These tests, or analyses, are developed for the specific purpose of measuring the quantity or concentration of a given element or compound, physical property, or organism present in a given quantity of sampled water. The elements or compounds in solution or suspension in water, the macroscopic and microscopic organisms, and the chemical and physical properties of water are commonly referred to as "water quality" indicators; and the quantity or concentration of the water quality indicators is expressed on a numerical scale.

Water quality indicators are the result of a wide variety of sources. The erosion of soils and rock and the associated runoff within the tributary drainage basin are major sources of chemicals to the estuarine system. Municipal and industrial wastewater treatment plants and other point sources such as sewerage system overflows and power plant cooling water discharges also add chemicals to the Milwaukee Harbor estuary. Atmospheric fallout, both wet and dry, is another contributor of chemicals to the waters of the estuary, as is the inflow of groundwater.

Specific water quality indicators present in the estuarine environment may also be the result of the alteration of some component already present in the water or sediments. Therefore, an examination of the chemical processes and reactions which are active in an estuarine environment is necessary in interpreting the behavior of water quality indicators. These chemical processes and reactions affect not only the presence and concentration of chemical constituents, but also the biota of the estuarine system. These chemical processes and reactions include precipitation, dissolution, gas transfer, reduction and oxidation, complexation, absorption, and adsorption. Table 59 lists the processes which commonly occur and describes the effects they have on water quality.

There are literally hundreds of water quality indicators, and the number can be expected to increase as new processes, products, and materials are developed by a highly industrialized and technological society. Water quality analyses generally are expensive to perform and often time-consuming. Therefore, a water quality surveillance must, of necessity, select for determination from the hundreds of indicators those which best meet the objectives of the study and which have numeric values that are the most useful for determining the suitability of the water quality for the intended water uses. The water quality sampling program conducted under the Milwaukee Harbor estuary planning study included a total of 38 water quality indicators which were analyzed in both the baseline and event-related monitoring programs.

Sediment Quality Characteristics

Sediment is an important element in an estuarine environment because of the physical and chemical effects it has on the overlying waters, and because of the large number of biological species that rely on the sediment environment for food, shelter, and reproduction. Sediments may be suspended in the water column, may travel along the bottom of a channel as bedload, or, in areas with low hydraulic energy such as an estuary, may be deposited and accumulated on the channel bottom. The bottom sediments of an estuary consist of both inorganic and organic material. The inorganic material of bottom sediment is typically of fine texture such as silts and clays. These fine sediments have an affinity for adsorption and absorption of nutrients, trace metals, and other materials. By characterizing the different types of sediments in the estuary, a better understanding of the dynamic processes affecting the relationship between sediment quality and water quality is provided.

Table 59

CHEMICAL PROCESSES AND REACTIONS FOUND IN ESTUARINE ENVIRONMENTS

Chemical Process	Description of Process	Effects on Water Quality	Other Factors Affecting Rate of Process
Precipitation	Substance in water settles due to physical or chemical change	Important reaction in many biological, geological, and chemical cycles for substances such as phosphorus, iron, and calcium	Temperature, pressure, and other substances in solution
Dissolution	Substance will combine with water to form a solution	Important reaction in many biological, geological, and chemical cycles for substances such as phosphorus, iron, and calcium	Temperature, pressure, and other substances in solution
Gas Transfer	Gases enter through the air-water interface and through several in-water methods: Oxygen—product of photosynthesis Carbon dioxide—result of respiratory and degradation activity Methane—from anaerobic decomposition of organic matter Hydrogen sulfide—from in-lake bacterial and chemical activity Ammonia—from heterotrophic bacterial breakdown of organic material	Important in biological processes	Temperature, pressure, and biological processes
Reduction and Oxidation	Reactions involving transfer of electrons: Reduction—acquisition of electrons Oxidation—loss of electrons	Reactions involving the degradation of organic matter, nitrification and de-nitrification processes, iron and manganese solubility, and disinfection by chlorine and ozone	pH and biological processes
Absorption/ Adsorption	Process by which ions or molecules tend to concentrate onto, or within, selected ions or molecules of a different phase	Important consideration when investigating the transfer and behavior of materials in the aquatic environment	Surface area of the materials involved

Source: SEWRPC.

Tests of representative sediment samples were used to evaluate the chemical and physical characteristics of estuarine sediments. Sediment core samples allow the nature of the sediments to be defined, along with the extent—both vertically and spatially—of given elements or compounds within the sediments. Sediment contamination levels may vary widely, sometimes increasing with depth, since deeper, older sediments may have been contaminated by past, largely unregulated discharges. Vertical profiles do not, however, accurately represent a time history of sediment deposition because, unlike in a deep lake depositional area, sediments in the estuary rivers are not likely to have been deposited in a vertically sequential manner owing to disturbances from dredging and resuspension from navigation, combined sewer overflow discharges, and stormwater flows.

The physical characteristics of the sediments are important indicators of sediment quality. Observations made at the time of field sampling usually prove to be reliable indicators of the condition of the sediment. Important factors are color, texture, odor, presence of detritus, and presence of oily material.

Biological Characteristics

The biological communities within the Milwaukee Harbor estuary are a reflection of the physical, hydraulic, and chemical environments, and serve as an indication of the overall quality, or health, of the water body. A biological community, being dependent upon the conditions and resources of its location, can adjust and adapt to environmental changes. The greater the environmental change, the more serious may be the required adjustment, and environmental change beyond some point will reduce the probable success of the organism or the population.

Some biochemical, physiological, and morphological changes in organisms in response to variations in their environment may lead directly to their death or may so reduce their biological capabilities as to decrease their probability of surviving or reproducing. Because of complex interrelationships, variations in the environment which cause populations of one or more organisms to change may cause other populations to change or be replaced. This will result in another assemblage of species distinguishable as a different community.

In some instances, the organisms residing in a water body may provide a more sensitive and reliable measure of the quality of the water resource than do chemical and physical measurements. Based on the theory that changes in the environment will favor some species, harm other species, and have little effect on the remainder, the appearance or disappearance of particular species as well as changes in the composition of the community should be indicative of water quality and related conditions. Indicator organisms which have been used include diatoms, fish, and benthic invertebrates.

There are far more important reasons for evaluating aquatic communities than to use organisms as indicators of environmental change, useful as the latter may be. These communities are essential components of energy and material cycles. The aquatic communities typical of surface waters in southeastern Wisconsin provide important recreational benefits to residents of the Region. To meet recommended water use objectives, stable and diverse communities of organisms are desired. Certain types of biological communities can also cause problems which affect water uses, such as aesthetic and odor problems caused by algae, turbid water caused by bottom-dwelling fish, and navigation impeded by excessive macrophyte biomass.

Water quality standards are generally used to protect desired forms of fish and aquatic life. These standards may be useful in determining whether certain pollution sources or levels of pollution pose a threat to particular types of organisms. One of the primary reasons for developing water quality standards is to avoid the necessity of having to periodically conduct extensive biological investigations of every water body receiving wastes. Once the limits of biological change have been established, the physical and chemical characteristics of the water can be monitored to determine the degree of protection afforded the desired species.

The description and evaluation of the existing biological conditions thus provides needed information on the resident biological communities which have adapted to the existing habitats, water quality conditions, and impairing factors; indicates the overall ecological health and stability of the water bodies; and provides data needed to determine desired and attainable future water use objectives.

To provide a valid assessment of water quality, a variety of biological communities at various trophic levels are summarized in this chapter. Organisms which provide good indications of water quality include algae, benthic macroinvertebrates, fish, and bacteria. The following is a description of these organisms, and of their interrelationship with the chemical and physical characteristics of the estuary.

Algae: Algae are small, generally microscopic plants that form the base of the aquatic food chain. Through photosynthesis, algae convert energy and nutrients to the compounds necessary to support life in the aquatic system. High levels of primary productivity occur in an estuarine environment because of the high nutrient loads present, particularly in the surface layer of water. Algae are present in the estuary as periphyton and as phytoplankton. The algal component of periphyton, or attached biological growth, is generally dominated by diatoms. Periphyton are typically the primary producer in rivers and streams and, therefore, provide a good indication of the prevailing levels of water quality in the upper reaches of the estuary where tributary streams have their greatest effect. Factors affecting the periphyton community are the type and availability of substrate, light penetration, the availability of nutrients, and the presence of toxic substances. Phytoplankton are free-floating or swimming algae. Phytoplankton develop in impoundments, backwater areas, or stagnant water areas, and are therefore most important within the lower reaches of the estuary and the Lake Michigan near-shore waters. The distribution of phytoplankton within the estuary is dependent on the concentrations and availability of nutrients, timing and extent of the mixing process, temperature, pH, and the presence of toxic substances. Algae are good indicators of water quality because their rapid reproduction responds quickly to alterations to the environment.

Benthic Macroinvertebrates: The benthic macroinvertebrate communities of the estuary are an important part of the food web, acting as food and as processors of the organic material that accumulates on the bottom sediment. Benthic macroinvertebrates are well suited for water quality evaluation studies because of their diversity, relative immobility, sensitivity, and fast reaction time to contaminants, and the ease of their collection and identification. The distribution of benthic macroinvertebrates is dependent on the temperature of the water, the water current, the water transparency, the dissolved oxygen content, the presence of toxic substances, and the habitat characteristics such as the presence of suitable substrate, pools, and riffles. Benthic macroinvertebrates can be used to evaluate the short- and long-term effects of organic and toxic pollution.

Fish: Fish are the top of the aquatic food chain, using organic detritus, plankton, and other fish as food sources. Fish are useful as water quality indicators but are more difficult to correlate with water quality than are macroinvertebrates or algae. The mobility of fish makes them difficult to collect for quantitative evaluation because fish often respond to environmental stress by moving to a more conducive environment. Fish may be affected directly or indirectly by changes in their environment, such as the killing or replacement of lower levels of the food chain. Turbidity and siltation adversely affect fish populations because they influence the feeding and reproduction habits of many species.

Bacteria : Bacteria are microorganisms found in the water column bottom sediments, in detritus, and on and in aquatic flora and fauna. They act as decomposers and recyclers of organic matter in an environment, or host organism. The distribution and composition of bacteria within an estuary is dependent on oxygen concentrations, availability of appropriate substrate, food sources, and water quality conditions. The presence and number of certain bacteria, such as fecal coliform, may determine the quality of the water and the associated risk of humans contracting an illness by using the water for recreational purposes.

WATER QUALITY CONDITIONS

Water Quality—Baseline Conditions

As a part of the Milwaukee Harbor estuary study, baseline water quality samples were collected and analyzed by the Milwaukee Metropolitan Sewerage District (MMSD) staff at 34 sampling stations once each week from March 1981 through December 1983. A total of 7,940 baseline water samples were collected and analyzed over the sampling period. The baseline sampling program was conducted to help identify pollutant source areas, to estimate pollutant loading rates, to evaluate the effects of pollutants on receiving water quality, and to provide data for water quality simulation modeling purposes. A more detailed description of the baseline water quality sampling program, including the locations of the sampling stations, the water quality indicators analyzed, and the field sampling methods used, is provided in Chapter IV of this volume.

The following is a description of the findings of the baseline water quality sampling program. The description includes a statistical summary of the concentrations of indicators at selected stations, an analysis of spatial and temporal variations in water quality conditions, and an evaluation of the level of water quality relative to standards set forth in Chapter II of Volume Two of this report.

The acute and chronic standards for metals, developed and promulgated by the U. S. Environmental Protection Agency since the completion of the data collection efforts under the Milwaukee Harbor estuary study, which are set forth in Chapter II of Volume Two, are expressed in terms of acid-soluble concentrations. The baseline sampling program, however, measured the concentrations of total metals, since the standards in effect at the time of the sampling program were related to total metals. Nevertheless, the total metals data collected under the Milwaukee Harbor estuary study are compared in this chapter to the acid-soluble metal standards. Where the measured total metal concentrations met the standards, it can be concluded that toxic conditions did not exist. Where the measured total metal concentrations violated the standards, however, it cannot necessarily be concluded that toxic conditions existed. Dissolved metal concentrations within the inner harbor measured in other studies were therefore also used to help determine compliance with the metal standards. There were no measurements available of dissolved metals within the outer harbor.

To help present the voluminous water quality data collected, the water quality data are herein summarized for eight representative sampling stations: three upstream stations, three inner harbor stations, and two outer harbor stations. The three upstream stations—the Milwaukee River at the North Avenue dam, the Menomonee River at S. 37th Street, and the Kinnickinnic River at S. 9th Place—are located just upstream of the inner harbor, and are thus best representative of water quality conditions entering this harbor. The three inner harbor stations—the Milwaukee River at Wells Street, the Menomonee River at Muskego Avenue, and the Kinnickinnic River at S. 1st Street—are located near the midpoint of the inner harbor portions of each of the three rivers and are, therefore, most indicative of overall inner harbor conditions. The outer harbor station at the Hoan Bridge was selected as representative of the portion of the outer harbor most affected by inflow from the inner harbor. The station in the south outer harbor was selected as representative of the main body of the outer harbor, and is affected by both inflow from the inner harbor and by effluent discharged from the Jones Island wastewater treatment plant.

Annual and Summer Data: A summary of the concentrations of selected water quality indicators measured over the entire three-year sampling period at the eight representative sampling stations is presented in Table 60. Spatial variations in the levels of 13 selected water quality indicators are shown on Maps 45 through 57. In order to compare average annual water quality conditions to summer conditions, the data collected during the summer months of June, July, and August are summarized in Table 61.

To help display, examine, and analyze the data collected under the baseline sampling program, statistical analyses were performed to produce water quality probability plots for the water quality indicators at each sampling station. A water quality probability plot is a graph indicating on the horizontal axis the percent of time during which the level of water quality indicator is less than the level shown on the vertical axis. The probability plots summarize the baseline water quality conditions over the three-year sampling period. Probability plots of the annual data—collected throughout the year—and of the summer data—collected only in June, July, and August—are set forth in Figures 70 through 82 for selected water quality indicators at the representative sampling stations.

Dissolved Oxygen: Mean annual dissolved oxygen levels ranged from 5.3 to 15.0 milligrams per liter (mg/l), while mean summer levels ranged from 1.0 to 14.3 mg/l. The lowest concentrations of dissolved oxygen generally occurred during summer. The recommended 30-day mean, one-day mean, and absolute minimum dissolved oxygen standards set forth in Chapter II of Volume Two of this report are shown on the probability plots in Figure 70. The 30-day mean standards for dissolved oxygen were violated at all of the inner harbor stations during some months between June and October, while all upstream stations met the applicable 30-day mean standards. The Milwaukee River estuary violations of the 30-day mean dissolved oxygen standards were less frequent and severe than in the Menomonee and Kinnickinnic River estuaries. At the outer harbor stations, only one very slight violation of the 30-day mean dissolved oxygen standard, occurring at the Hoan Bridge station, was observed over the three-year sampling period. As shown in Figure 70, the one-day mean standards were violated less than 10 percent of the time at the upstream or outer harbor stations on both an annual and summer basis. At the inner harbor stations, the one-day mean standards were violated about 15 to 45 percent of the time on an annual basis, and from about 40 to 80 percent of the time during the summer months. The one-day mean standards were not violated at the outer harbor stations. The absolute minimum dissolved oxygen standards were not violated at the upstream or outer harbor stations. However, the absolute standards were violated from about 1 to 25 percent of the time within the inner harbor stations on an annual basis, and from about 1 to nearly 50 percent of the time during the summer months. Violations of the absolute, as well as one-day mean, standards occur less often in the

Table 60

SUMMARY OF ANNUAL BASELINE WATER QUALITY DATA AT SELECTED STATIONS: 1981-1983

Sampling Station	Statistical Variable	Dissolved Oxygen (mg/l)	Fecal Coliform (MPN/100ml)	Total Suspended Solids (mg/l)	Total Phosphorus (mg/l)	Ammonia Nitrogen (mg/l)	Un-ionized Ammonia Nitrogen (mg/l)	Volatile Suspended Solids (mg/l)	BOD_5 (mg/l)	Chlorophyll-*a* (μg/l)	Cadmium[a] (μg/l)	Copper (μg/l)	Lead (μg/l)	Zinc (μg/l)
Upstream Stations														
Milwaukee River at North Avenue Dam (RIV-5)	Number of Samples	129	136	133	135	139	128	129	120	137	10	21	21	21
	Minimum	3.5	30	1.0	0.02	0.02	0.000	1.0	0.8	0.7	2.0	1.0	12.0	0.4
	Mean	10.1	4,200	25.0	0.14	0.17	0.007	9.0	3.3	42.4	2.1	22.7	41.1	13.5
	Maximum	20.0	43,000	106.0	0.34	0.90	0.040	33.0	8.0	329.9	3.0	413.0	105.0	54.3
	Standard Deviation	2.9	8,000	17.0	0.06	0.15	0.006	6.0	1.9	54.1	0.3	89.5	29.0	14.3
Menomonee River at S. 37th Street (RIV-10)	Number of Samples	115	124	125	126	129	118	121	59	125	11	20	20	20
	Minimum	5.0	0	1.0	0.01	0.02	0.000	0.0	1.4	0.8	2.0	1.0	12.0	0.2
	Mean	11.0	13,000	18.0	0.17	0.24	0.007	6.0	3.5	10.4	2.3	6.4	54.9	14.1
	Maximum	18.0	240,000	341.0	0.98	0.93	0.041	136.0	14.0	57.6	3.0	19.0	207.0	33.7
	Standard Deviation	2.9	27,000	37.0	0.16	0.16	0.006	13.0	2.0	9.6	0.5	5.4	48.2	10.4
Kinnickinnic River at S. 9th Place (RIV-13)	Number of Samples	117	120	124	126	129	117	121	55	124	10	20	20	20
	Minimum	2.0	3	2.0	0.01	0.02	0.001	1.0	0.8	0.3	2.0	1.0	10.0	1.0
	Mean	15.0	7,500	13.0	0.06	0.14	0.011	5.0	5.1	8.4	2.3	6.6	48.7	25.6
	Maximum	20.0	240,000	149.0	0.40	0.90	0.071	63.0	76.5	56.5	3.0	15.0	202.0	72.4
	Standard Deviation	3.6	31,000	19.0	0.07	0.15	0.013	7.0	10.1	10.0	0.5	4.0	43.8	20.1
Inner Harbor Stations														
Milwaukee River at Wells Street (RIV-7)	Number of Samples	385	132	392	404	407	385	379	171	404	34	60	60	60
	Minimum	1.2	40	1.0	0.03	0.02	0.000	1.0	0.3	0.4	2.0	1.0	10.0	0.4
	Mean	8.9	12,000	24.0	0.14	0.25	0.009	8.0	3.2	34.6	2.3	18.8	48.5	12.3
	Maximum	17.8	240,000	148.0	0.65	1.12	0.057	57.0	10.0	265.1	3.0	478.0	154.0	54.0
	Standard Deviation	3.6	34,000	18.0	0.06	0.19	0.007	7.0	2.0	44.9	0.5	71.1	39.0	13.8
Menomonee River at Muskego Avenue (RIV-11)	Number of Samples	350	123	374	378	376	349	364	358	376	33	60	60	60
	Minimum	< 0.1	3	3.0	0.01	0.02	0.000	0.0	0.4	0.6	2.0	1.0	9.0	0.0
	Mean	5.3	23,000	16.0	0.12	0.47	0.007	5.6	3.4	10.0	2.8	12.4	55.4	14.9
	Maximum	16.0	430,000	114.0	0.36	1.73	0.046	81.0	26.0	105.6	10.0	302.0	218.0	55.9
	Standard Deviation	4.2	63,000	15.0	0.06	0.28	0.005	7.6	3.0	15.0	1.8	8.7	49.5	13.3
Kinnickinnic River at S. 1st Street (RIV-14)	Number of Samples	323	115	325	330	333	322	319	320	324	28	56	56	56
	Minimum	< 0.1	9	2.0	0.01	0.05	0.000	1.9	1.2	0.4	2.0	1.0	1.0	0.5
	Mean	5.3	25,000	35.0	0.13	0.54	0.005	8.2	3.5	10.0	2.4	12.5	63.1	26.7
	Maximum	15.4	930,000	480.0	0.43	1.42	0.047	97.0	14.0	133.0	4.0	275.0	265.0	74.2
	Standard Deviation	3.9	98,000	54.0	0.06	0.21	0.004	10.6	1.9	17.2	0.7	37.9	59.7	19.8
Outer Harbor Stations														
Hoan Bridge[b] (OH-1)	Number of Samples	284	88	92	277	275	275	88	56	281	33	77	78	78
	Minimum	3.6	3	2.0	0.02	0.08	0.000	0.0	0.1	1.3	2.0	1.0	9.0	0.5
	Mean	8.2	5,600	12.0	0.08	0.59	0.006	4.0	1.5	10.7	31.4	8.4	50.2	11.5
	Maximum	14.8	240,000	83.0	0.35	3.84	0.035	12.0	8.1	88.9	942.0	97.0	100.0	59.0
	Standard Deviation	2.2	26,000	11.0	0.05	0.47	0.005	2.0	1.1	11.4	163.5	14.0	32.8	11.3
South Outer Harbor[b] (OH-11)	Number of Samples	285	90	94	277	283	283	92	57	282	29	77	77	77
	Minimum	3.8	3	1.0	0.01	0.03	0.000	0.0	0.1	0.7	2.0	1.0	9.0	0.3
	Mean	9.5	160	9.1	0.05	0.66	0.008	3.0	1.6	6.7	3.4	7.2	56.2	7.7
	Maximum	15.1	2,300	100.0	0.17	2.44	0.082	19.0	6.2	65.7	17.0	62.0	100.0	45.0
	Standard Deviation	1.8	420	12.1	0.03	0.38	0.008	3.0	0.9	6.8	2.8	10.2	31.0	8.1

[a] *The cadmium statistics exclude measurements of 1.0 μg/l, which was the laboratory detection limit, or less.*

[b] *Concentrations of BOD_5 were not measured at stations OH-1 and OH-11. Therefore, concentrations of BOD_5 measured at OH-7, located at the main harbor entrance, are presented for OH-1, and concentrations of BOD_5 measured at OH-3, located in the central outer harbor, are presented for OH-11.*

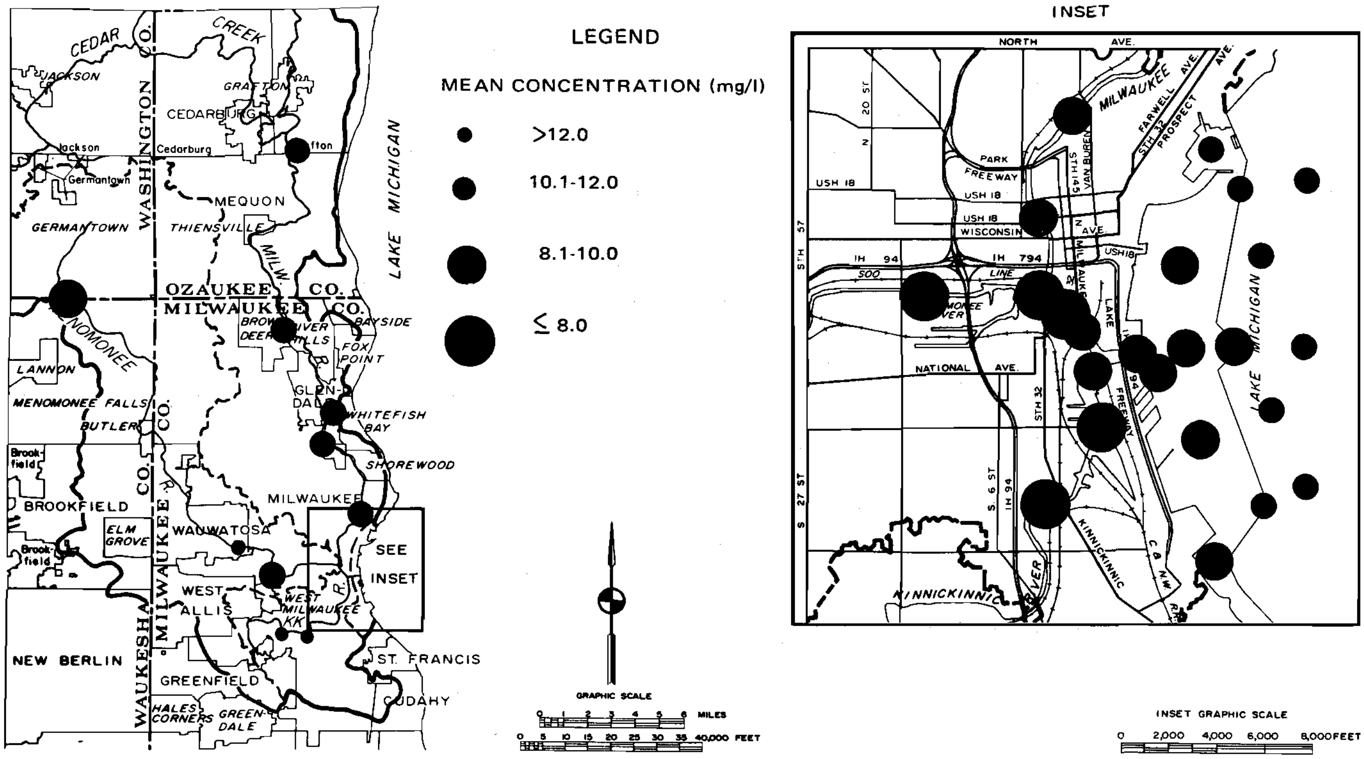
Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Milwaukee River estuary than in the Menomonee and Kinnickinnic River estuaries. These violations place a significant stress on the survival, growth, and reproduction of resident fish and other aquatic life.

Fecal Coliform: Arithmetic mean annual fecal coliform levels ranged from 160 to 25,000 most probable number per 100 milliliters (MPN/100 ml), while mean summer levels ranged from 100 to 48,000 MPN/100 ml. In general, fecal coliform levels during the summer were similar to levels found during the remainder of the year. For analysis purposes, the recommended 30-day maximum geometric mean standard for fecal coliform of 200 MPN/100 ml is shown on the probability

Map 45

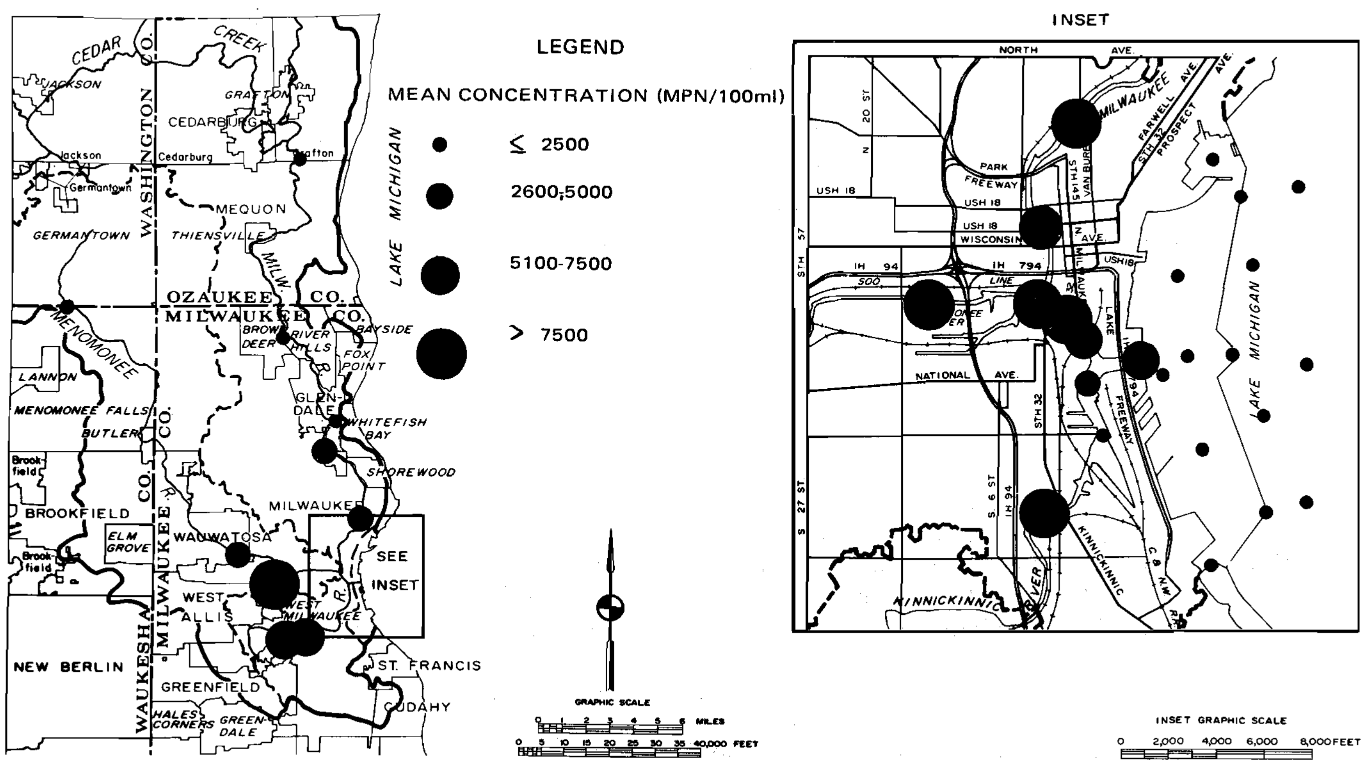
MEAN ANNUAL CONCENTRATIONS OF DISSOLVED OXYGEN IN THE BASELINE WATER QUALITY SAMPLES: 1981-1983



Source: SEWRPC.

Map 46

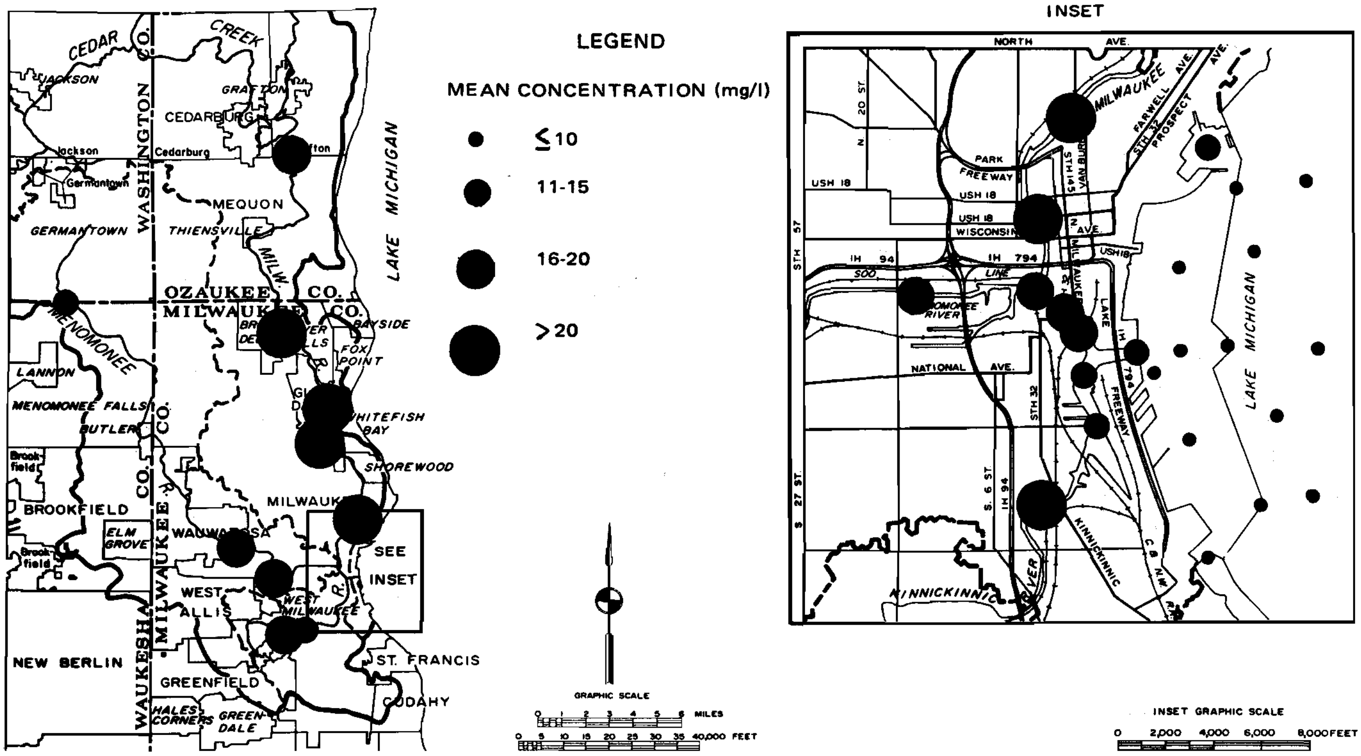
MEAN ANNUAL CONCENTRATIONS OF FECAL COLIFORM IN THE BASELINE WATER QUALITY SAMPLES: 1981-1983



Source: SEWRPC.

Map 47

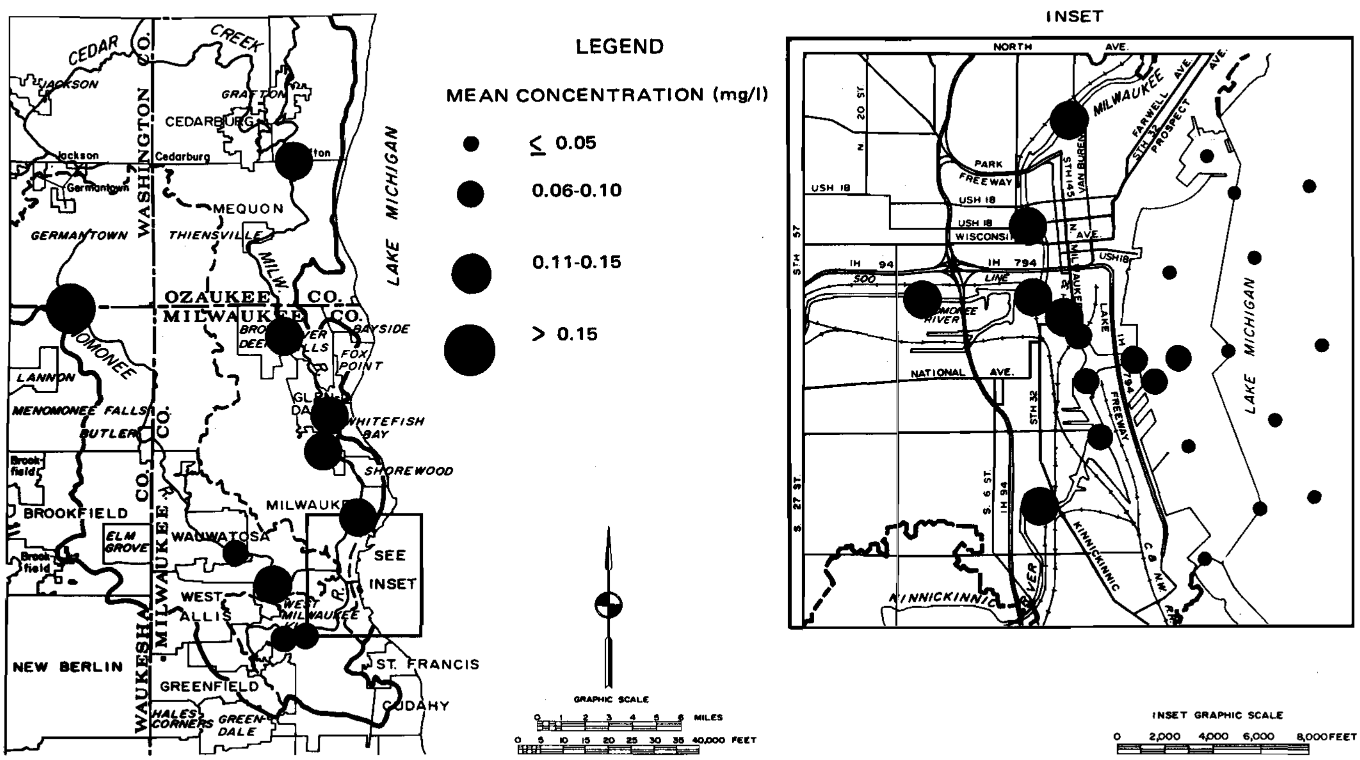
MEAN ANNUAL CONCENTRATIONS OF TOTAL SUSPENDED SOLIDS IN THE BASELINE WATER QUALITY SAMPLES: 1981-1983



Source: SEWRPC.

Map 48

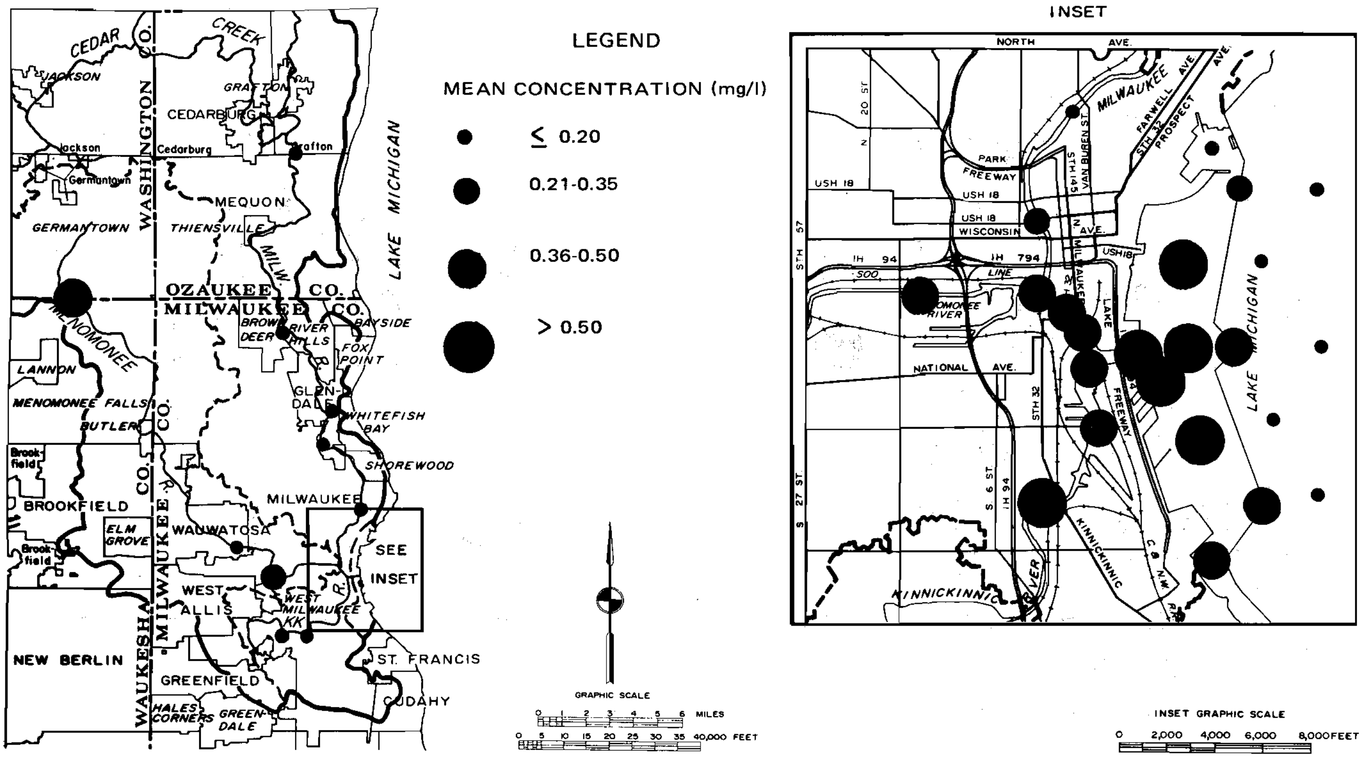
MEAN ANNUAL CONCENTRATIONS OF TOTAL PHOSPHORUS IN THE BASELINE WATER QUALITY SAMPLES: 1981-1983



Source: SEWRPC.

Map 49

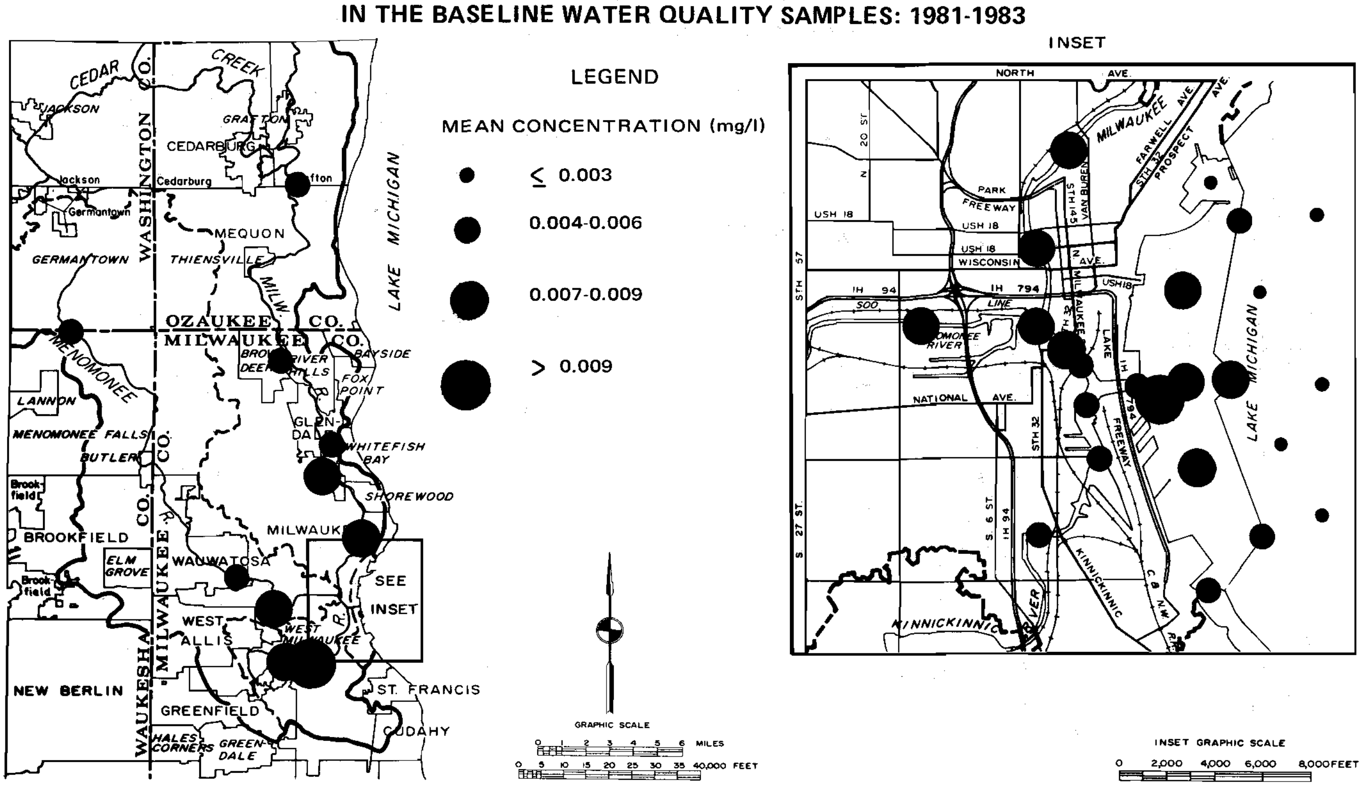
MEAN ANNUAL CONCENTRATIONS OF AMMONIA NITROGEN IN THE BASELINE WATER QUALITY SAMPLES: 1981-1983



Source: SEWRPC.

Map 50

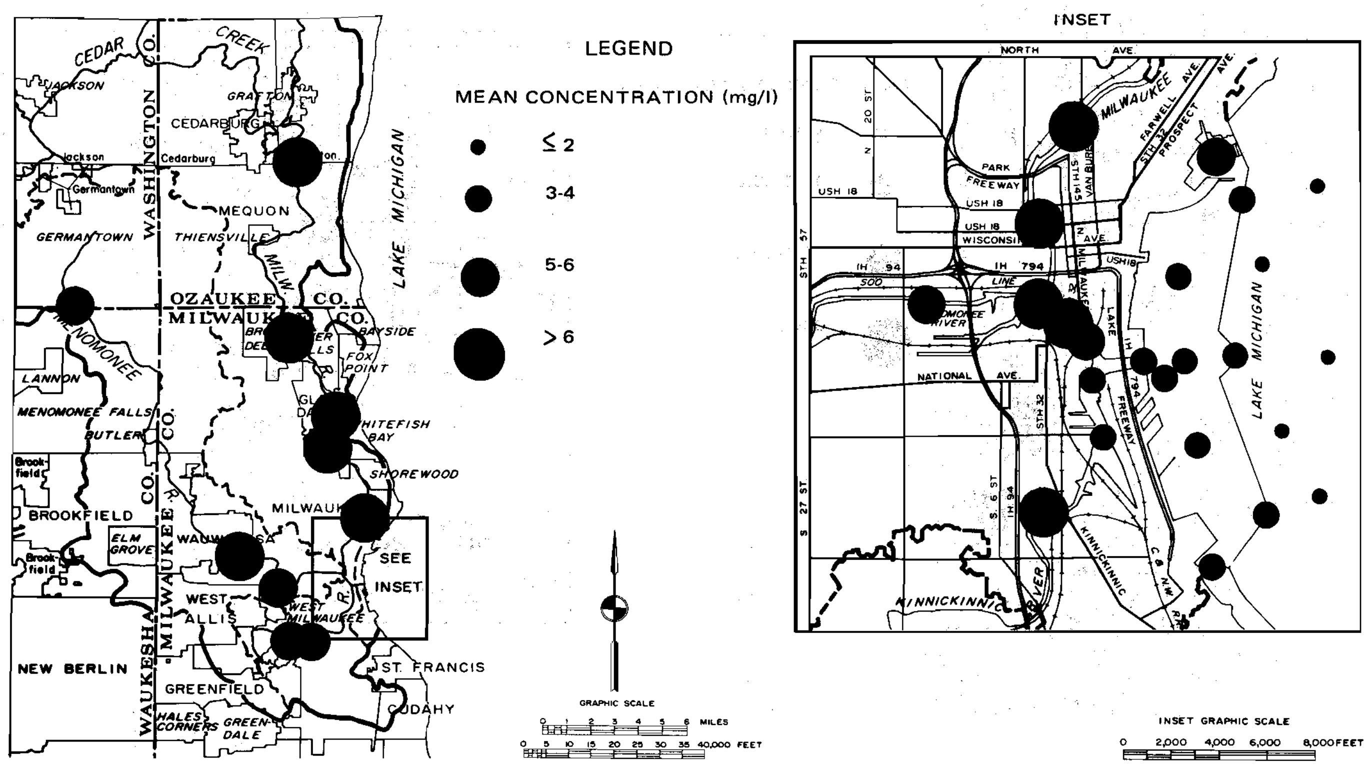
MEAN ANNUAL CONCENTRATIONS OF UN-IONIZED AMMONIA NITROGEN IN THE BASELINE WATER QUALITY SAMPLES: 1981-1983



Source: SEWRPC.

Map 51

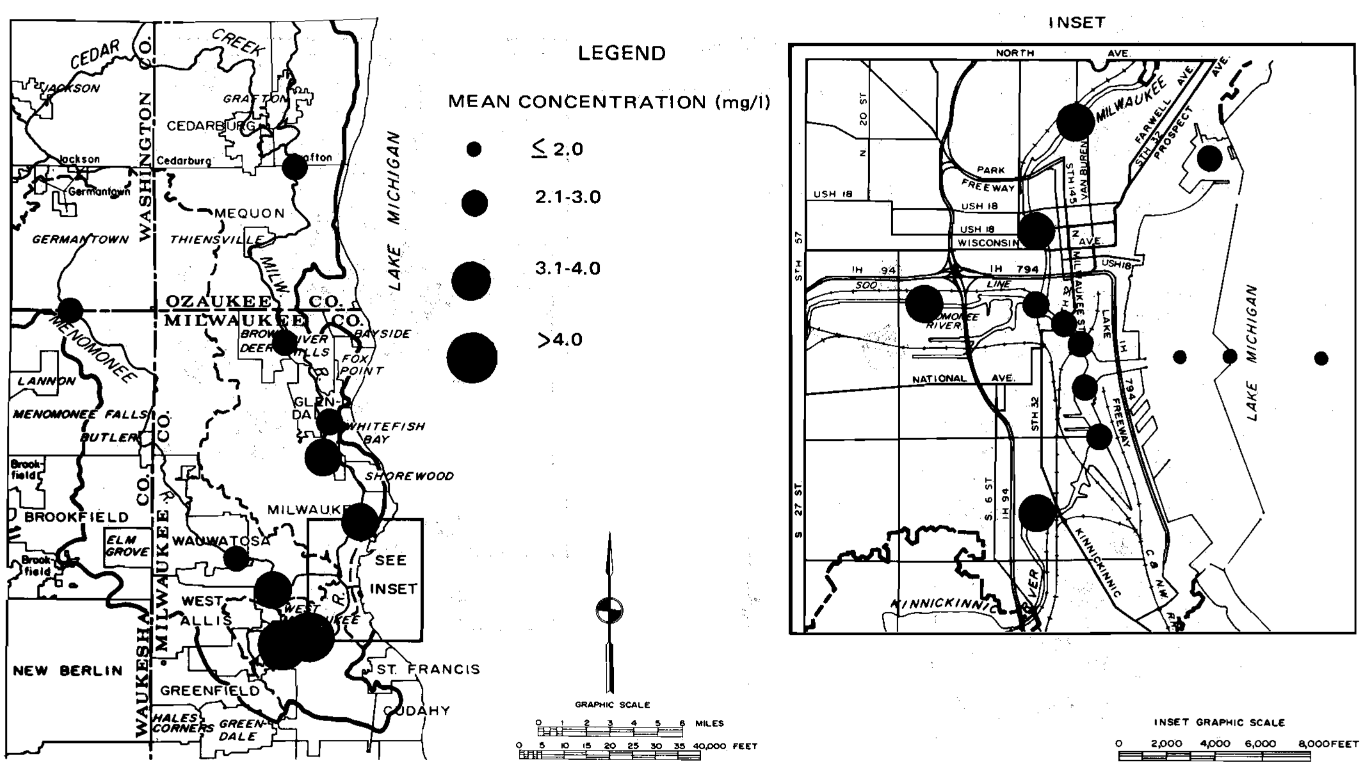
MEAN ANNUAL CONCENTRATIONS OF VOLATILE SUSPENDED SOLIDS IN THE BASELINE WATER QUALITY SAMPLES: 1981-1983



Source: SEWRPC.

Map 52

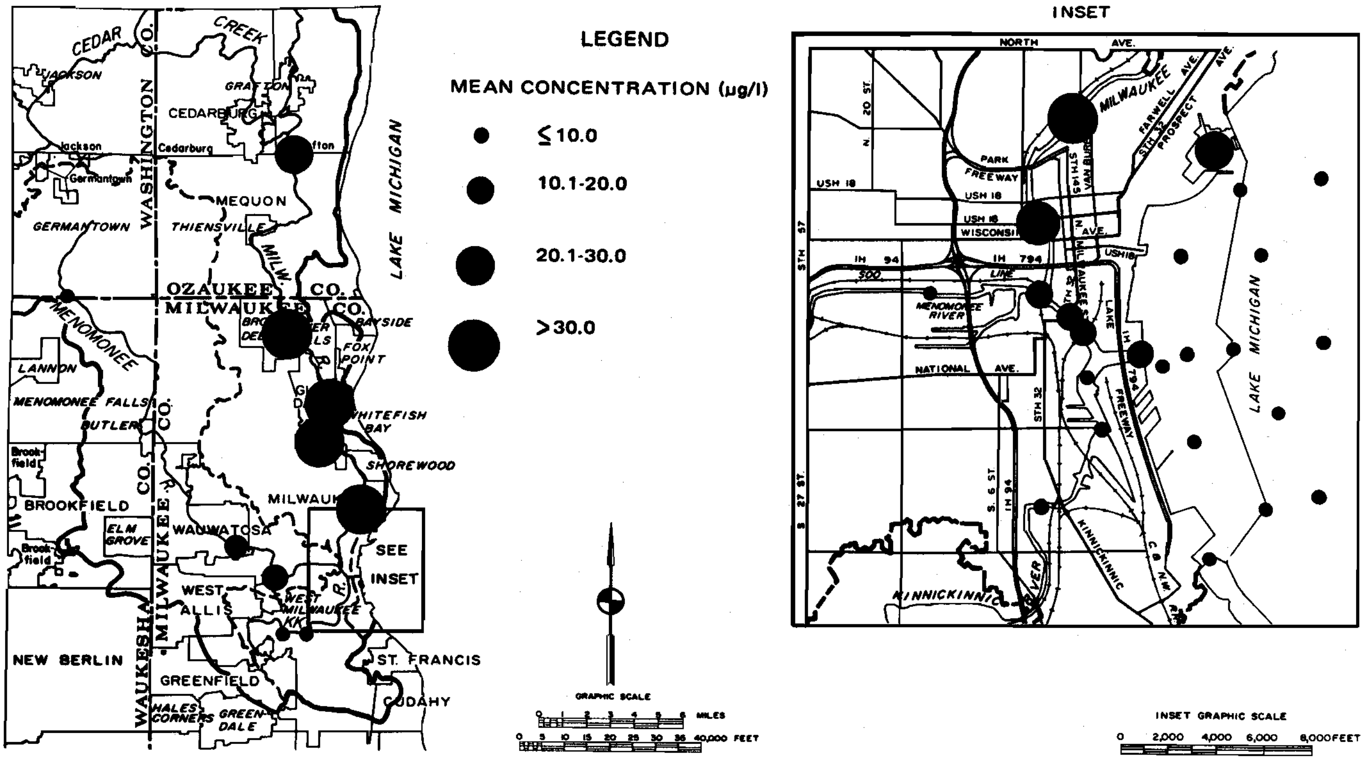
MEAN ANNUAL CONCENTRATIONS OF BOD_5 IN THE BASELINE WATER QUALITY SAMPLES: 1981-1983



Source: SEWRPC.

Map 53

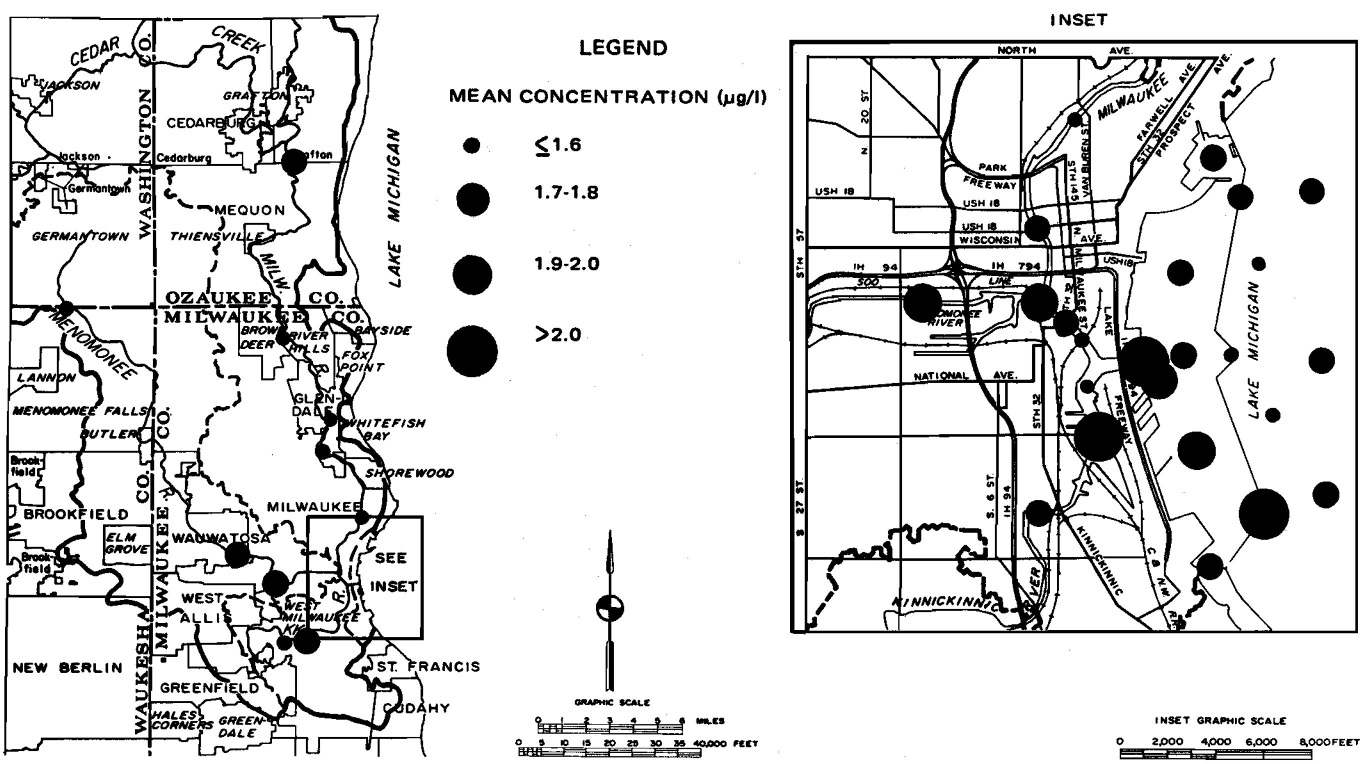
MEAN ANNUAL CONCENTRATIONS OF CHLOROPHYLL-a IN THE BASELINE WATER QUALITY SAMPLES:1981-1983



Source: SEWRPC.

Map 54

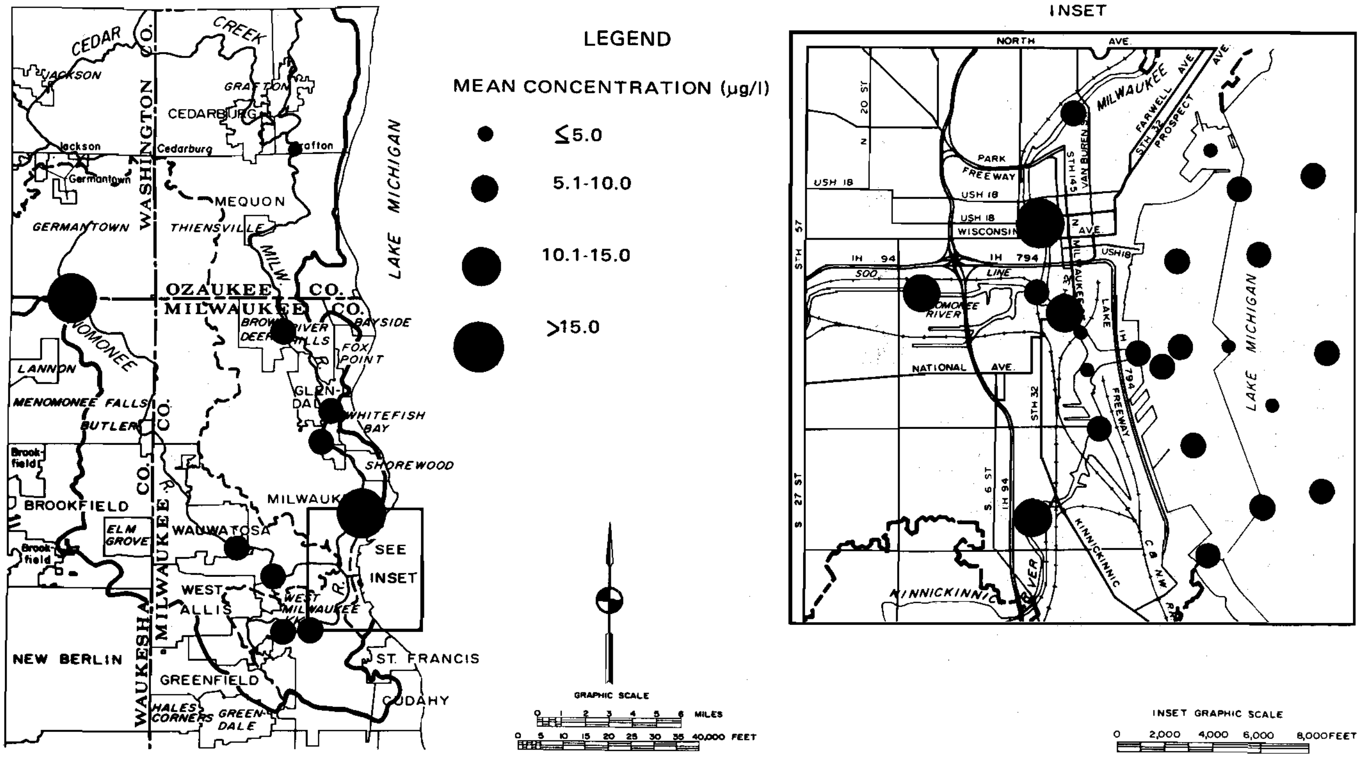
MEAN ANNUAL CONCENTRATIONS OF CADMIUM IN THE BASELINE WATER QUALITY SAMPLES: 1981-1983



Source: SEWRPC.

Map 55

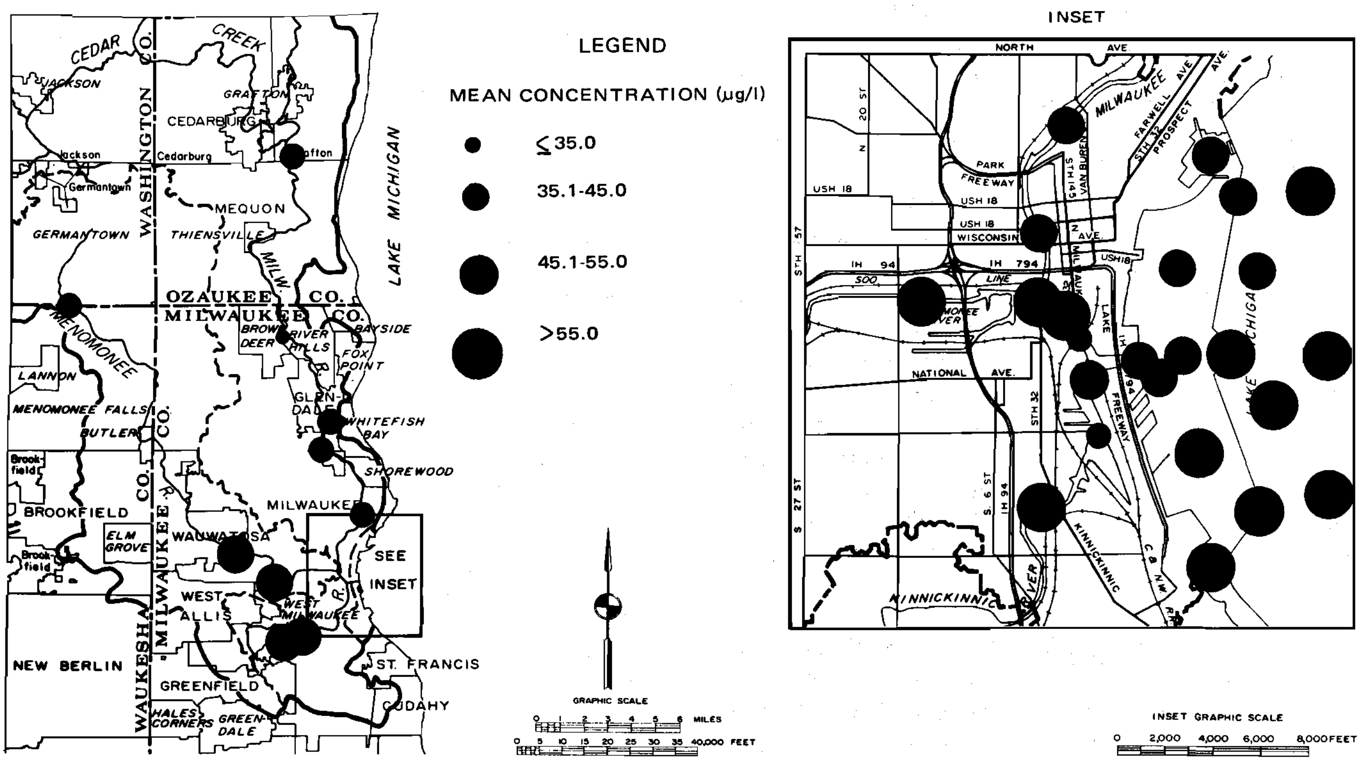
MEAN ANNUAL CONCENTRATIONS OF COPPER IN THE BASELINE WATER QUALITY SAMPLES: 1981-1983



Source: SEWRPC.

Map 56

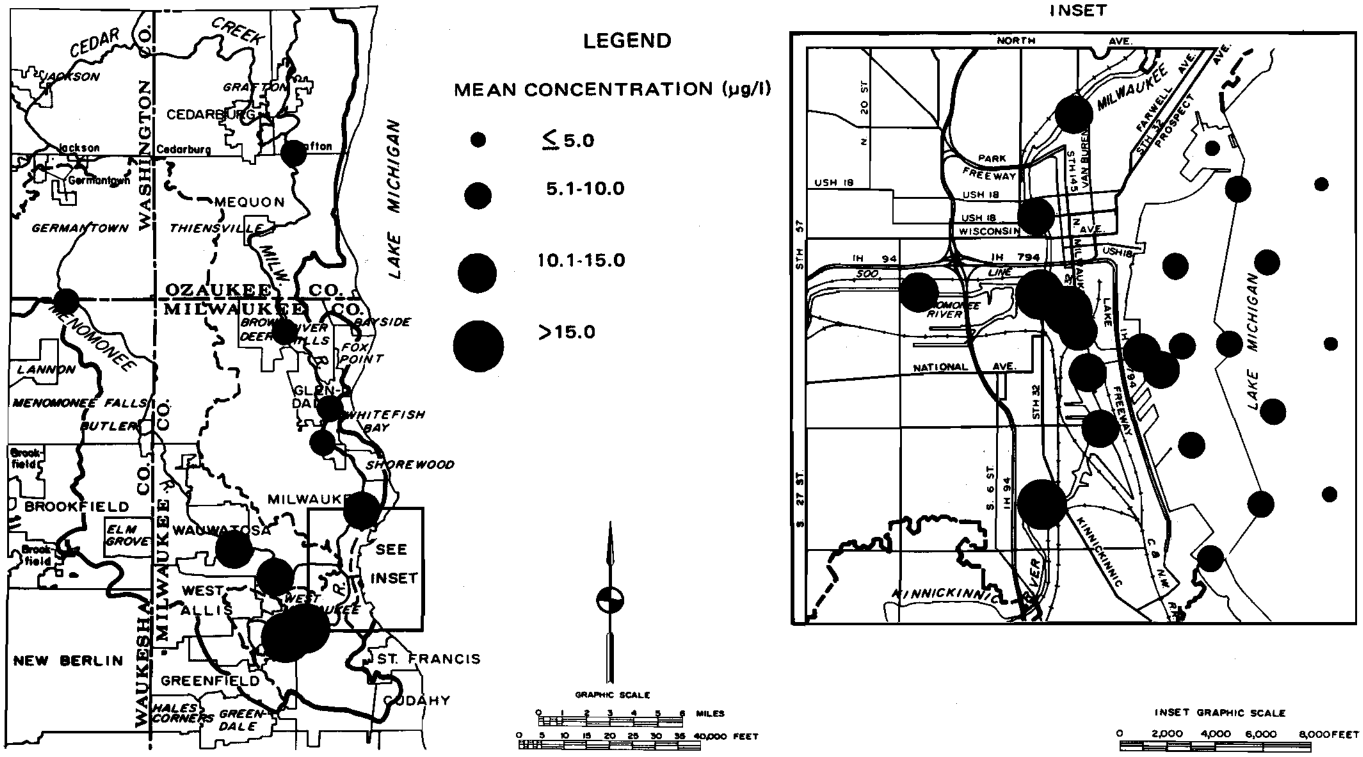
MEAN ANNUAL CONCENTRATIONS OF LEAD IN THE BASELINE WATER QUALITY SAMPLES: 1981-1983



Source: SEWRPC.

Map 57

MEAN ANNUAL CONCENTRATIONS OF ZINC IN THE BASELINE WATER QUALITY SAMPLES: 1981-1983



Source: SEWRPC.

plots in Figure 71. At the upstream stations, the standard was violated from about 90 to essentially 100 percent of the time on an annual basis. An analysis of the monthly mean fecal coliform levels indicated that the standard was violated more than 90 percent of the time at the upstream stations. In the inner harbor, the standard was violated about 90 percent of the time on an annual basis. The fecal coliform standard was violated during more than 90 percent of the months at the inner harbor stations. In the outer harbor at the Hoan Bridge station, the fecal coliform standard was violated about 60 percent of the time, while the standard was violated at the south outer harbor station only about 25 percent of the time. The standard was also violated during about 25 to 60 percent of the months at the outer harbor stations. The violation of the recommended fecal coliform standard presents a potential health hazard to recreational users of the surface waters.

Total Suspended Solids: Mean annual total suspended solids levels ranged from 9 to 35 mg/l, while mean summer levels ranged from 4 to 34 mg/l. In general, summer total suspended solid concentrations were about the same as annual concentrations except in the Milwaukee River at the North Avenue dam, where the summer values were typically slightly higher than the annual values, as shown in Figure 72. In the Milwaukee and Menomonee River estuary and upstream reaches, the mean total suspended solids concentrations were about the same; however, within the Kinnickinnic River estuary the mean concentration was higher than the mean upstream concentration. The lowest total suspended solids concentrations were found in the outer harbor. There is no recommended standard for total suspended solids.

Total Phosphorus: Mean annual total phosphorus levels ranged from 0.05 to 0.17 mg/l, while mean summer levels ranged from 0.04 to 0.19 mg/l. In the Milwaukee and Menomonee River estuary stations, the mean total phosphorus concentrations were about the same as at the upstream stations. The mean concentration at the Kinnickinnic River estuary station, however, was higher than the upstream station mean concentration. The lowest total phosphorus concentrations were found in the outer harbor. The recommended maximum total

Table 61

SUMMARY OF SUMMER BASELINE WATER QUALITY DATA AT SELECTED STATIONS: 1981-1983

Sampling Station	Statistical Variable	Dissolved Oxygen (mg/l)	Fecal Coliform (MPN/100ml)	Total Suspended Solids (mg/l)	Total Phosphorus (mg/l)	Ammonia Nitrogen (mg/l)	Un-ionized Ammonia Nitrogen (mg/l)	Volatile Suspended Solids (mg/l)	BOD_5 (mg/l)	Chlorophyll-a (μg/l)	Cadmium[a] (μg/l)	Copper (μg/l)	Lead (μg/l)	Zinc (μg/l)
Upstream Stations														
Milwaukee River at North Avenue Dam (RIV-5)	Number of Samples	52	52	52	52	53	52	50	47	53	4	9	9	9
	Minimum	3.5	40	2.0	0.09	0.02	0.002	1.0	1.0	7.3	2.0	1.0	12.0	0.5
	Mean	7.7	3,500	34.0	0.18	0.14	0.011	13.0	4.7	85.9	2.4	4.0	38.7	13.7
	Maximum	11.8	43,000	76.0	0.32	0.40	0.040	33.0	8.0	329.9	2.0	17.0	100.0	38.6
	Standard Deviation	1.8	7,600	12.0	0.05	0.10	0.008	6.0	1.7	61.8	0.0	5.4	26.8	13.3
Menomonee River at S. 37th Street (RIV-10)	Number of Samples	51	50	52	50	52	51	52	16	51	5	8	8	8
	Minimum	5.0	0	3.0	0.07	0.05	0.001	1.0	1.9	3.5	2.0	1.0	12.0	0.2
	Mean	9.1	12,000	24.8	0.19	0.25	0.010	8.0	3.9	13.4	2.2	5.6	37.4	9.4
	Maximum	16.2	93,000	341.0	0.77	0.91	0.041	136.0	7.6	49.0	3.0	15.0	73.0	29.7
	Standard Deviation	2.6	20,000	53.0	0.14	0.15	0.008	19.0	1.8	9.6	0.5	4.5	20.9	10.9
Kinnickinnic River at S. 9th Place (RIV-13)	Number of Samples	51	48	52	49	52	50	51	16	51	4	8	8	8
	Minimum	7.2	3	2.0	0.01	0.02	0.001	1.0	0.8	1.4	2.0	1.0	10.0	1.0
	Mean	14.3	9,900	12.0	0.06	0.10	0.015	4.0	3.1	9.1	2.5	6.3	33.5	12.9
	Maximum	20.0	230,000	67.0	0.40	0.90	0.058	41.0	7.6	44.0	3.0	12.0	73.0	30.4
	Standard Deviation	3.3	34,000	15.0	0.06	0.13	0.014	6.0	1.8	9.9	0.6	3.8	23.0	9.4
Inner Harbor Stations														
Milwaukee River at Wells Street (RIV-7)	Number of Samples	159	50	157	156	159	158	155	50	158	15	24	24	24
	Minimum	1.2	40	8.0	0.09	0.02	0.002	3.0	1.2	3.6	2.0	1.0	10.0	0.4
	Mean	5.7	17,000	29.0	0.18	0.26	0.013	11.0	4.4	68.7	2.3	6.2	34.5	12.4
	Maximum	10.4	240,000	114.0	0.33	0.79	0.057	57.0	7.2	265.1	3.0	44.0	88.0	54.0
	Standard Deviation	2.0	50,000	14.0	0.05	0.15	0.007	8.0	1.6	52.6	0.5	8.9	20.7	16.2
Menomonee River at Muskego Avenue (RIV-11)	Number of Samples	155	48	155	150	150	150	155	139	154	15	24	24	24
	Minimum	0.0	3	3.0	0.06	0.13	0.001	0.0	0.4	1.8	2.0	1.0	9.0	0.0
	Mean	2.0	44,000	16.0	0.15	0.63	0.009	7.0	3.7	17.4	3.3	5.5	34.7	8.5
	Maximum	9.7	430,000	95.0	0.33	1.73	0.046	81.0	12.0	105.6	10.0	30.0	77.0	40.4
	Standard Deviation	1.9	93,000	17.0	0.06	0.27	0.006	10.0	2.2	15.3	2.6	6.6	22.1	12.4
Kinnickinnic River at S. 1st Street (RIV-14)	Number of Samples	145	48	142	140	144	143	140	141	141	11	24	24	24
	Minimum	0.0	9	4.0	0.03	0.05	0.000	1.0	1.2	2.1	2.0	1.0	1.0	0.5
	Mean	3.6	48,000	30.0	0.12	0.57	0.006	8.0	3.1	14.8	2.8	7.9	72.1	16.8
	Maximum	11.1	930,000	480.0	0.38	1.42	0.029	97.0	11.0	115.0	4.0	57.0	265.0	46.0
	Standard Deviation	3.1	150,000	59.0	0.06	0.22	0.004	14.0	1.5	18.1	0.9	15.4	75.2	14.7
Outer Harbor Stations														
Hoan Bridge[b] (OH-1)	Number of Samples	137	45	45	133	137	137	43	27	137	9	33	33	33
	Minimum	3.6	7	2.0	0.02	0.08	0.001	1.0	0.4	1.6	2.0	1.0	9.0	0.5
	Mean	7.3	7,700	8.0	0.07	0.55	0.007	4.0	1.4	14.6	2.3	5.3	38.5	7.7
	Maximum	12.4	240,000	27.0	0.18	1.87	0.035	8.0	3.3	88.9	4.0	32.0	100.0	28.3
	Standard Deviation	1.8	36,000	4.3	0.03	0.35	0.005	2.0	0.7	13.9	0.7	7.5	31.3	9.0
South Outer Harbor[b] (OH-11)	Number of Samples	138	45	45	134	138	138	44	27	138	9	32	32	32
	Minimum	3.8	3	1.0	0.01	0.03	0.000	0.0	0.4	1.3	2.0	1.0	18.0	0.3
	Mean	8.8	100	4.2	0.04	0.60	0.009	2.0	1.6	9.2	4.0	2.8	48.3	4.6
	Maximum	12.5	1,100	14.0	0.12	2.40	0.082	4.0	3.7	65.7	17.0	9.0	100.0	21.0
	Standard Deviation	1.6	240	2.0	0.02	0.43	0.010	1.0	0.7	8.7	4.9	2.8	30.5	6.3

[a] *The cadmium statistics exclude measurements of 1.0 μg/l, which was the laboratory detection limit, or less.*

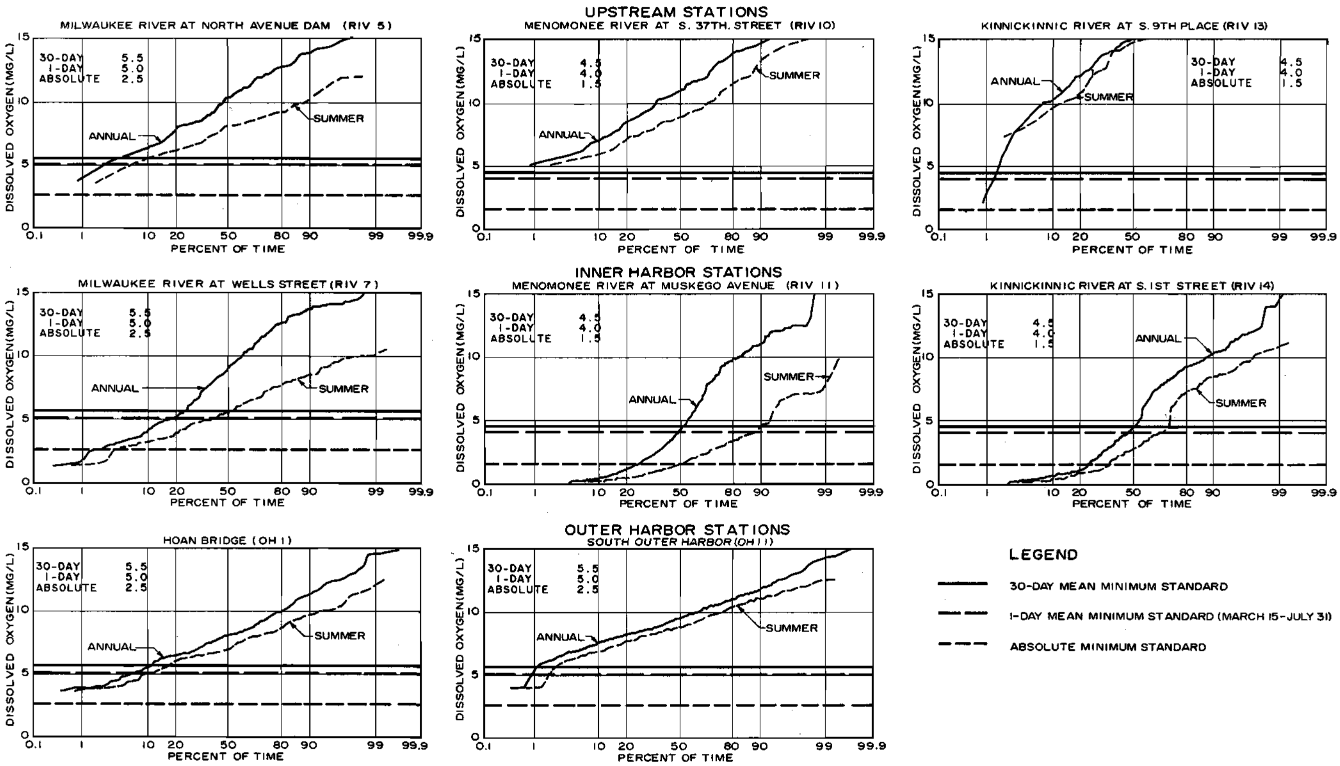
[b] *Concentrations of BOD_5 were not measured at stations OH-1 and OH-11. Therefore, concentrations of BOD_5 measured at OH-7, located at the main harbor entrance, are presented for OH-1, and concentrations of BOD_5 measured at OH-3, located in the central outer harbor, are presented for OH-11.*

Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

phosphorus standard of 0.1 mg/l shown on the probability plots in Figure 73 applies only to the Milwaukee River and outer harbor. At the Milwaukee River upstream station at the North Avenue dam, the standard was violated about 80 percent of the time on an annual basis, and more than 90 percent of the time during the summer months. The Milwaukee River estuary phosphorus levels were quite similar to the upstream levels, with the violations of the standard at Wells Street occurring about 70 percent of the time on an annual basis, and more than 90 percent of the time on a summer basis. At the outer harbor stations, the phosphorus standard was violated from less than 10 to 15 percent of the time on an annual basis, and less than 10 percent of the time during the summer months. The violation of the phosphorus standard, particularly during the summer, could result in excessive

Figure 70

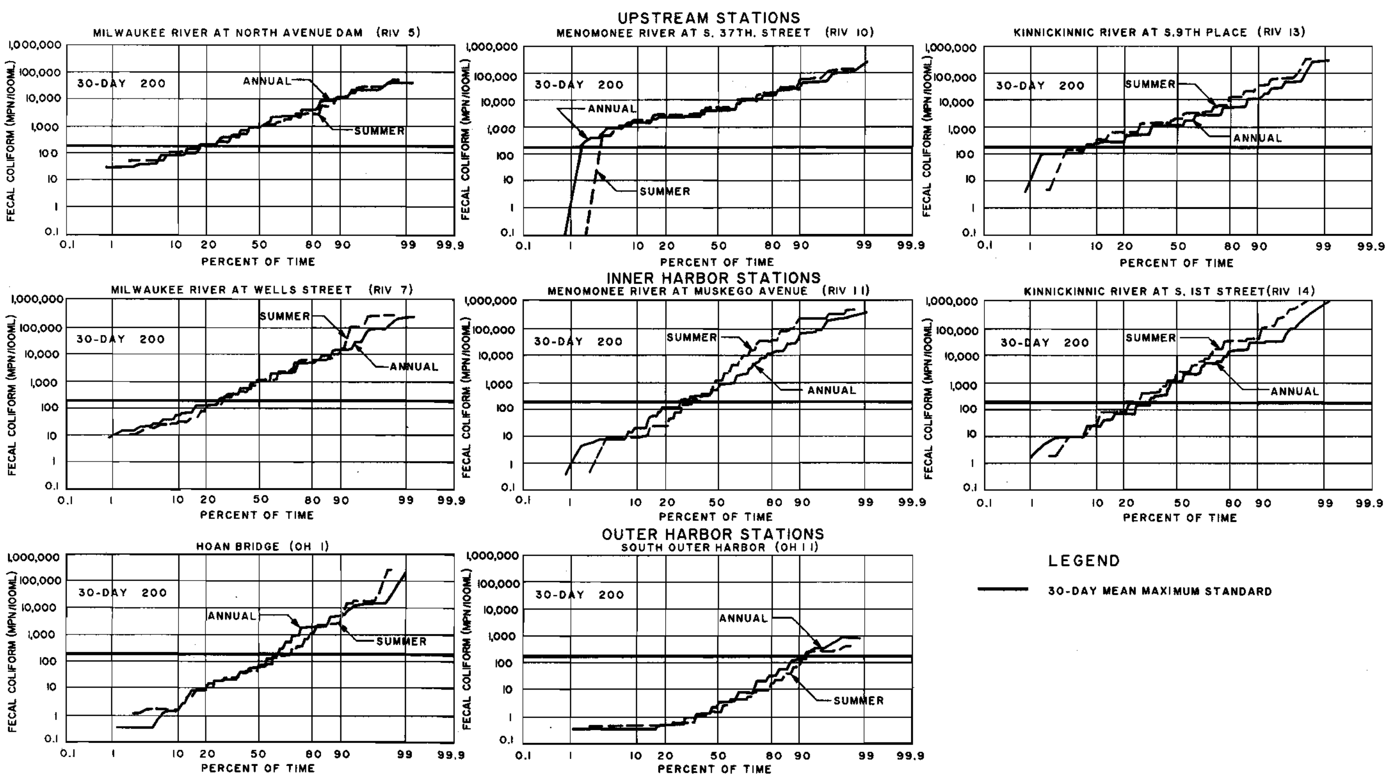
DISSOLVED OXYGEN PROBABILITY PLOTS FOR ANNUAL AND SUMMER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 71

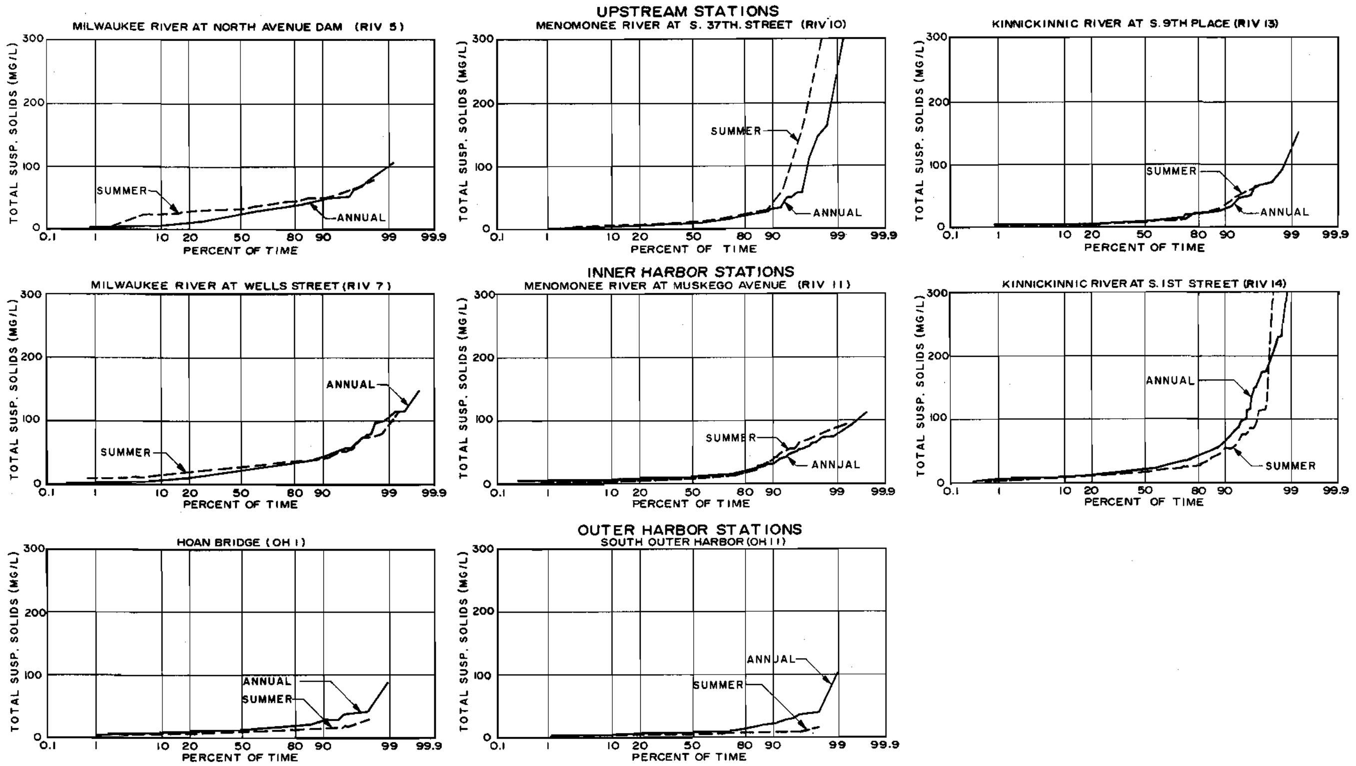
FECAL COLIFORM PROBABILITY PLOTS FOR ANNUAL AND SUMMER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 72

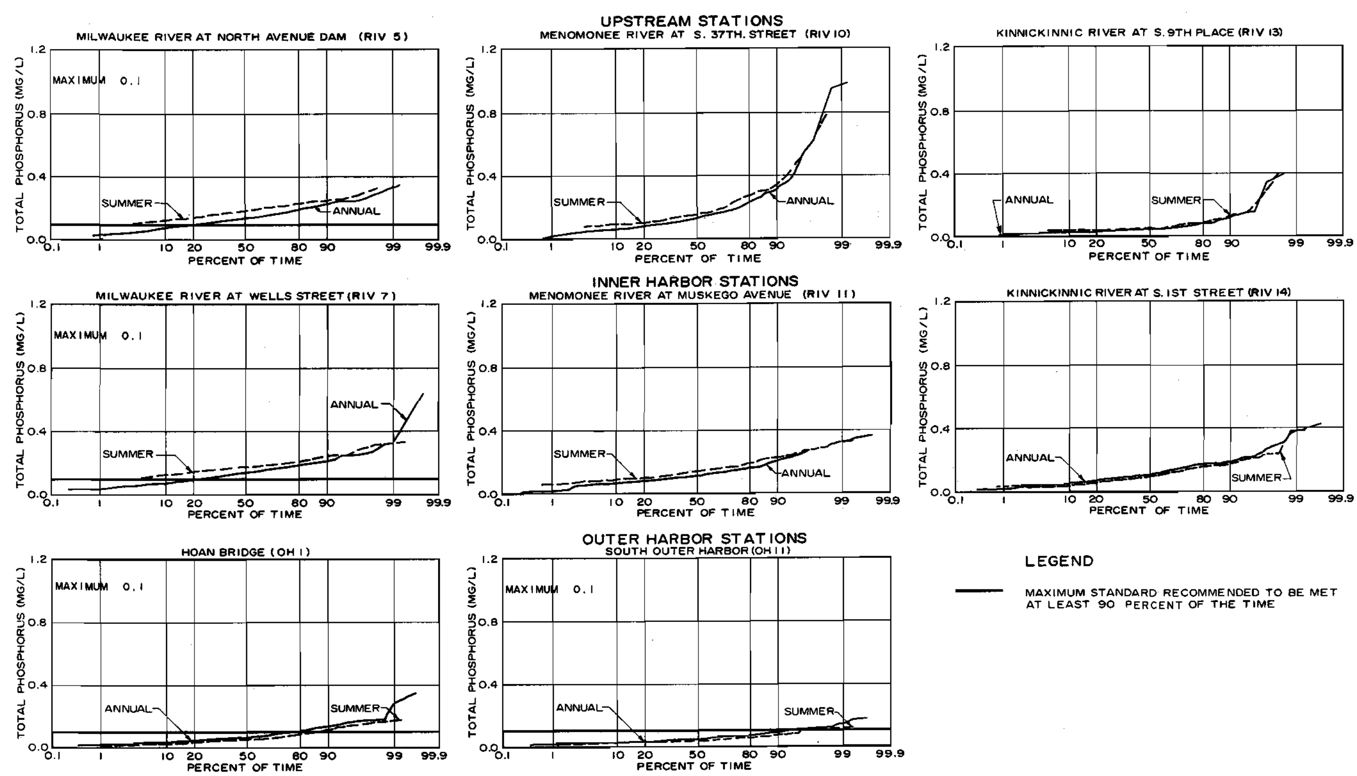
TOTAL SUSPENDED SOLIDS PROBABILITY PLOTS FOR ANNUAL AND SUMMER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 73

TOTAL PHOSPHORUS PROBABILITY PLOTS FOR ANNUAL AND SUMMER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

aquatic weed and algae growths which could interfere with recreational uses of the Milwaukee River and outer harbor.

Ammonia Nitrogen: Mean annual ammonia nitrogen levels ranged from 0.14 to 0.66 mg/l, while mean summer levels ranged from 0.10 to 0.63 mg/l. As shown in Figure 74, overall, ammonia nitrogen levels during the summer were not consistently higher or lower than the levels measured during the remainder of the year. In the estuarine portions of all three rivers, the ammonia nitrogen levels were higher than the upstream levels during both the summer and annual periods, and generally the Menomonee River was found to have the highest mean concentrations of the three rivers. Ammonia nitrogen concentrations were higher in the outer harbor than in the upstream rivers or in the inner harbor. There is no recommended standard for ammonia nitrogen.

Un-ionized Ammonia Nitrogen: Mean annual un-ionized ammonia nitrogen levels ranged from 0.005 to 0.011 mg/l, while summer mean levels ranged from 0.006 to 0.015 mg/l. Mean un-ionized ammonia nitrogen levels were slightly higher during the summer period compared to the remainder of the year. In the Kinnickinnic River estuary, the un-ionized ammonia nitrogen levels were generally higher than the upstream levels. In the Milwaukee and Menomonee River estuaries, the un-ionized ammonia nitrogen levels were similar to the upstream levels. The acute and chronic toxic standards for un-ionized ammonia nitrogen recommended in Chapter II of Volume Two of this report are shown on the probability plots in Figure 75. The standards shown on the plots were calculated using the mean pH and water temperature levels measured under the baseline sampling program. The chronic standard, which is recommended to be met by the mean concentration measured over any 30-day period, was violated during two months at the Kinnickinnic River upstream station, and during one month at the south outer harbor station. The acute standard, which is recommended to be met at all times, was not violated at any of the stations shown in Figure 75. Violations of the acute standards were observed, although rarely, at other stations in the outer harbor. The violations of these standards may threaten the health and survival of fish and other aquatic organisms.

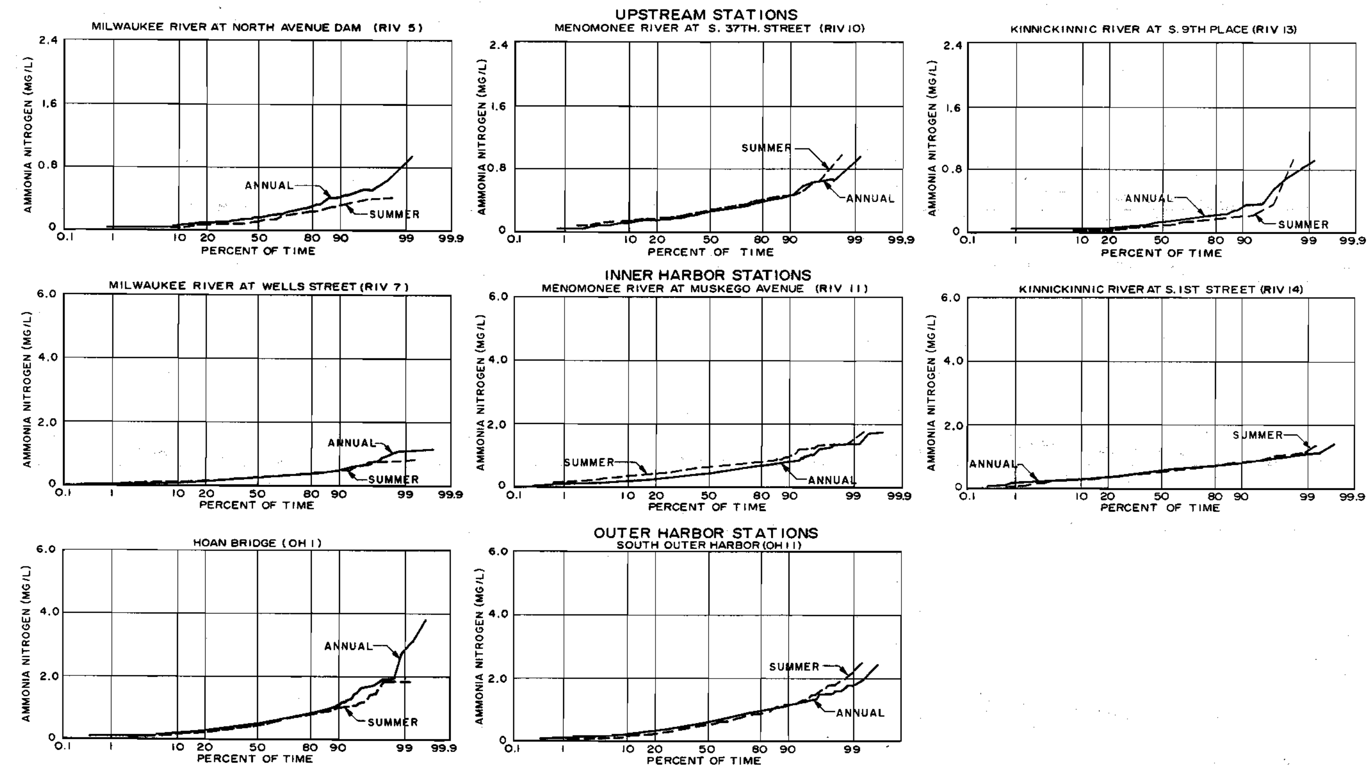
Volatile Suspended Solids: Mean annual volatile suspended solids levels ranged from 3 to 9 mg/l, while mean summer levels ranged from 2 to 13 mg/l. The concentrations of volatile suspended solids found during the summer were similar to those found during the remainder of the year, as shown in Figure 76. In general, the mean inner harbor levels were about the same as the upstream levels during both the summer and annual period except in the Kinnickinnic River estuary, where the volatile suspended solids levels were approximately double the upstream levels during both time periods. The highest levels of volatile suspended solids were generally found in the Milwaukee River. Based on the annual mean concentrations at the sampling stations set forth in Table 61, the volatile suspended solids concentrations represented from 23 to 38 percent of the total suspended solids concentrations. The relative portion of the total suspended solids concentration which was volatile in the summer was slightly higher—ranging from 27 to 50 percent. There is no recommended standard for volatile suspended solids.

Biochemical Oxygen Demand (BOD_5): Mean annual BOD_5 levels ranged from 3.1 to 5.1 mg/l, while mean summer levels ranged from 3.1 to 4.7 mg/l. The concentrations of BOD_5 found during the summer were similar to those found during the remainder of the year, except that in the Milwaukee River, as shown in Figure 77, the summer concentrations were generally higher than the annual concentrations. The upstream levels in all three rivers were generally slightly higher than the inner harbor levels on both an annual and summer basis. Since BOD_5 levels were not measured at the outer harbor stations at the Hoan Bridge and the south outer harbor, Figure 77 instead shows the probability plots for the main harbor entrance breakwater and central outer harbor sampling stations. There is no recommended standard for biochemical oxygen demand.

Chlorophyll-a: Mean annual chlorophyll-a levels ranged from 6.7 to 42.4 micrograms per liter (μg/l), while mean summer levels ranged from 9.2 to 85.9 μg/l. The summer chlorophyll-a levels were higher than the levels measured during the remainder of the year, although, as shown in Figure 78, the summer levels are only slightly higher than the annual levels at the Menomonee and Kinnickinnic River upstream stations and at the outer harbor stations. During both the annual and summer periods, the mean concentrations of chlorophyll-a at the Menomonee and Kinnickinnic River estuary stations were slightly higher than at the upstream stations on those rivers. However, within the Milwaukee River estuary, the mean

Figure 74

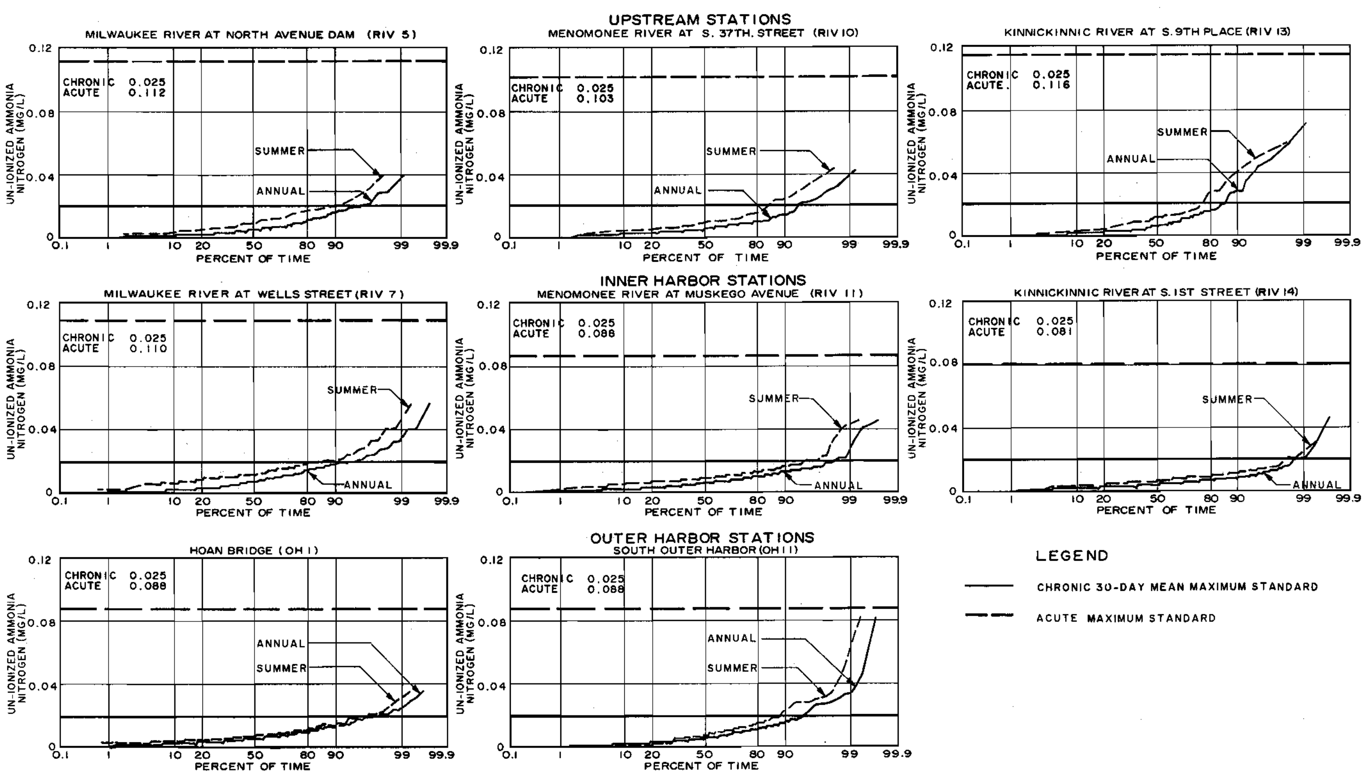
AMMONIA NITROGEN PROBABILITY PLOTS FOR ANNUAL AND SUMMER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 75

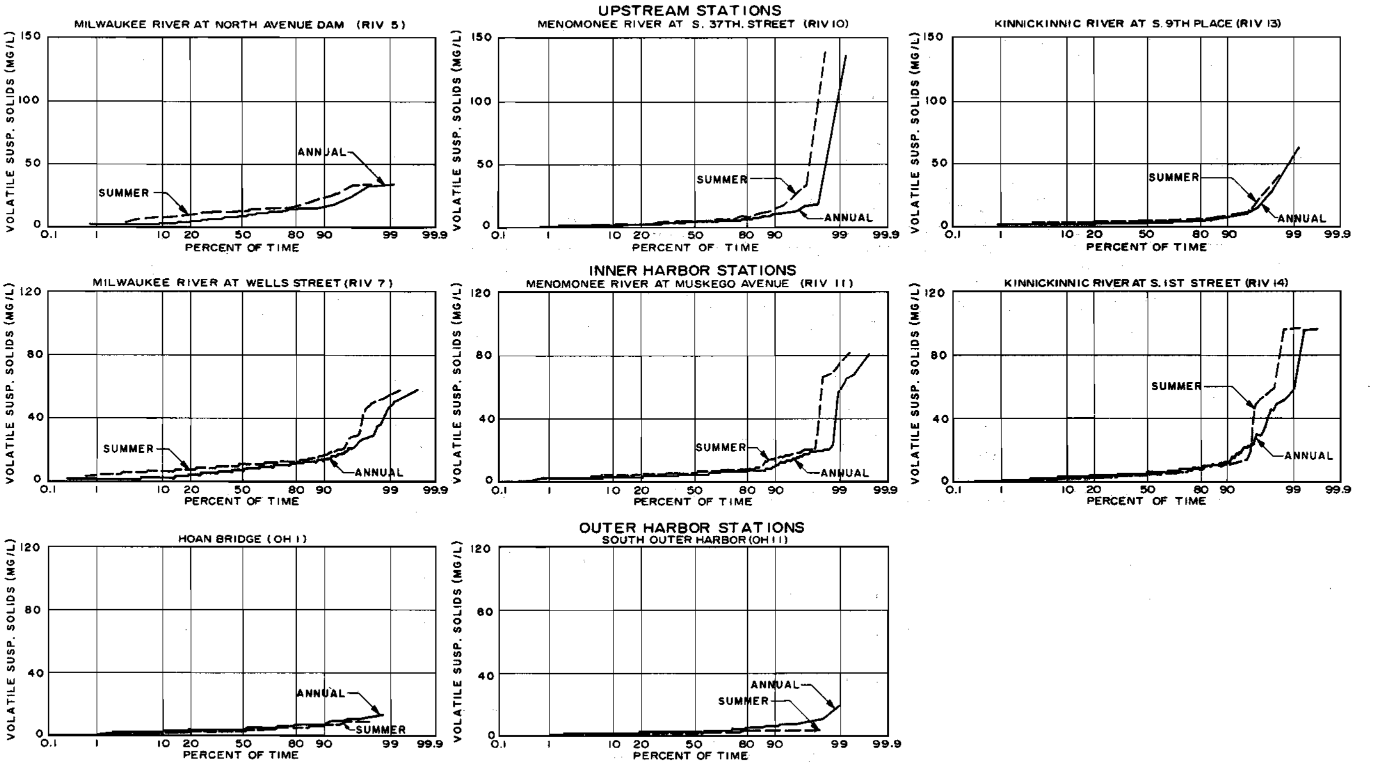
UN-IONIZED AMMONIA NITROGEN PROBABILITY PLOTS FOR ANNUAL AND SUMMER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 76

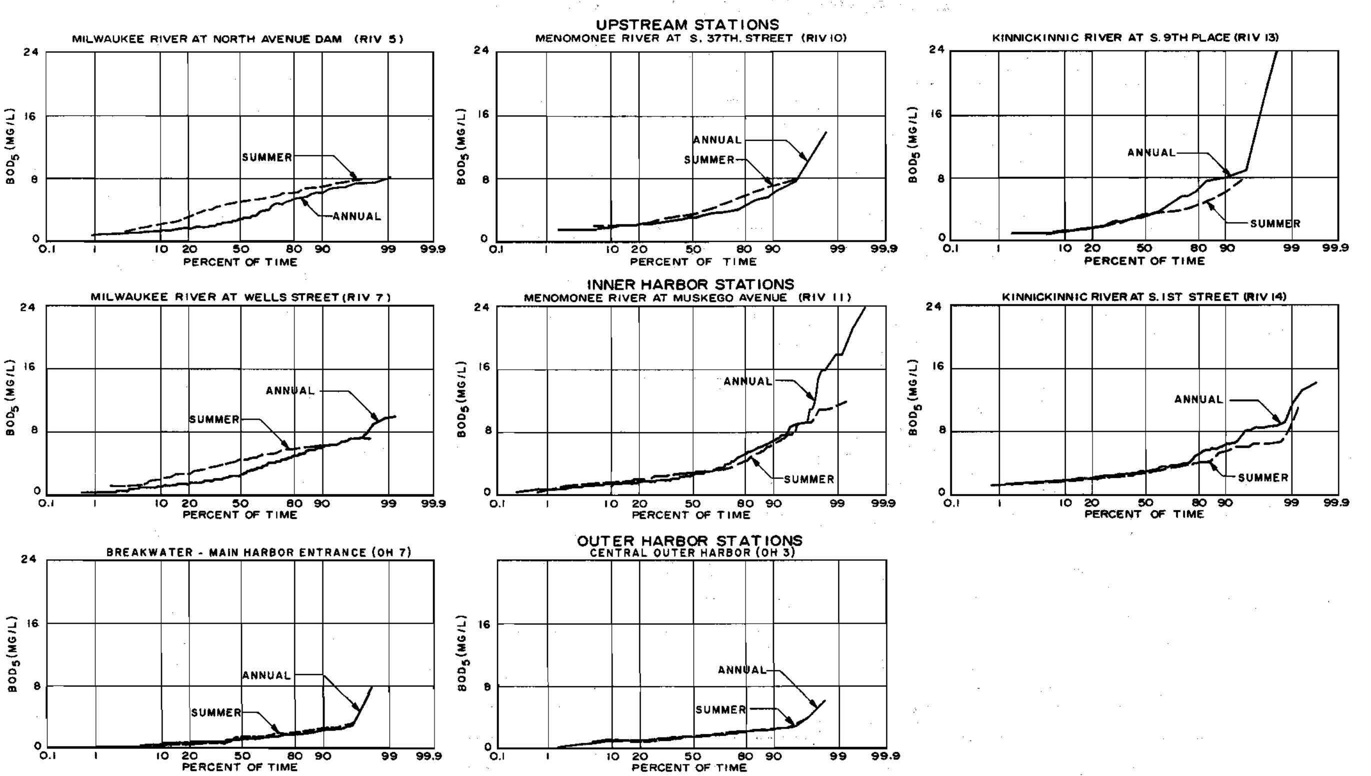
VOLATILE SUSPENDED SOLIDS PROBABILITY PLOTS FOR ANNUAL AND SUMMER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 77

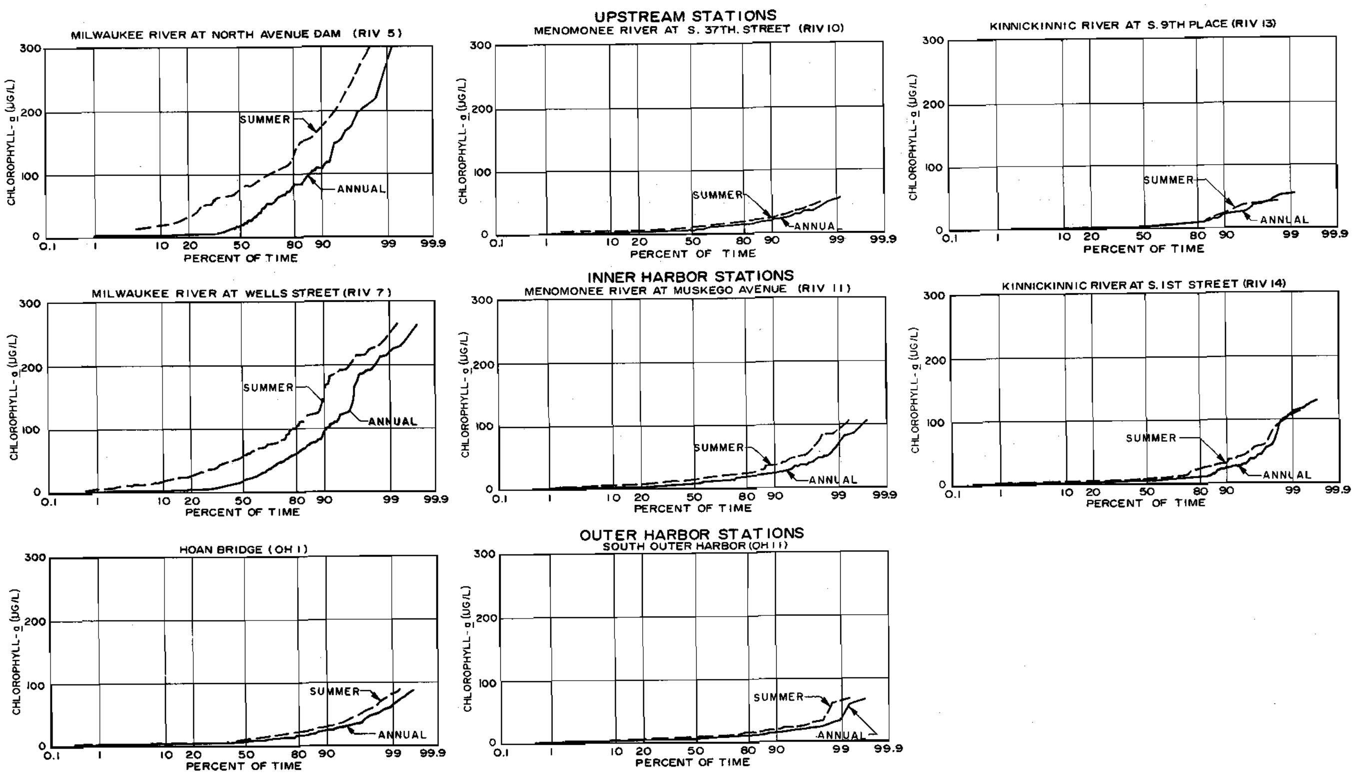
BIOCHEMICAL OXYGEN DEMAND PROBABILITY PLOTS FOR ANNUAL AND SUMMER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 78

CHLOROPHYLL-a PROBABILITY PLOTS FOR ANNUAL AND SUMMER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

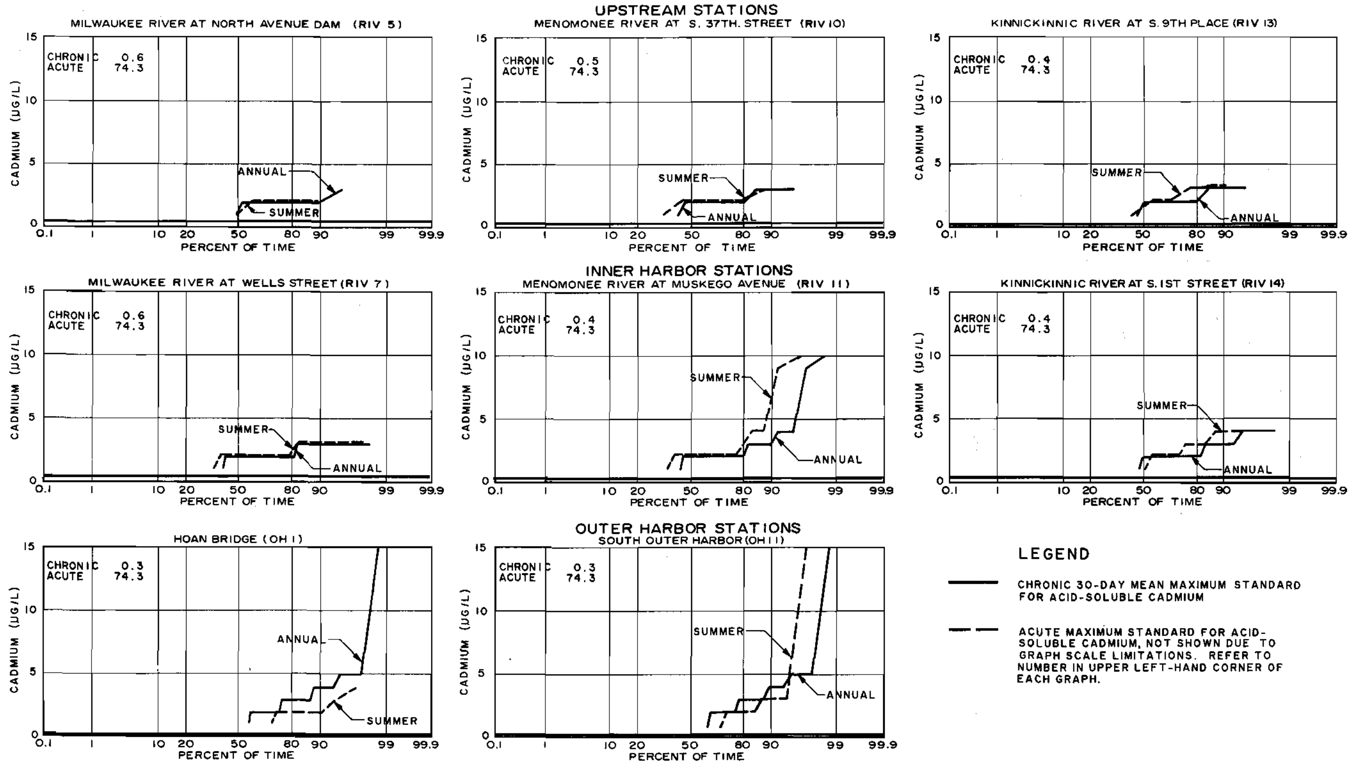
concentration was lower than the mean upstream concentration. The Milwaukee River levels were higher than the Menomonee River and Kinnickinnic River levels, or the outer harbor levels. There is no recommended standard for chlorophyll-a.

Cadmium: Mean annual total cadmium levels measured above the detection level of 1.0 µg/l ranged from 1.5 to 13.8 µg/l, while mean summer levels ranged from 2.5 to 4.0 µg/l. Generally, the summer levels of cadmium were similar to the levels measured during the remainder of the year. Cadmium concentrations at the upstream, inner harbor, and outer harbor stations were also similar with the exception of at the outer harbor station at Hoan Bridge, where a few very high levels were measured. The acute and chronic toxic standards for acid-soluble cadmium recommended in Chapter II of Volume Two of this report are shown on the probability plots in Figure 79. The chronic standards were calculated using the mean hardness levels measured under the baseline sampling program. The chronic standards for acid-soluble cadmium, which are recommended to be met by the mean concentration measured over any 30-day period, ranged from 0.3 to 0.6 µg/l. Since the laboratory detection limit for cadmium was 1.0 µg/l, it was not possible to determine if those total cadmium measurements shown as 1.0 µg/l or less were higher than the chronic standards for acid-soluble cadmium. However, as shown in Figure 79, from 20 to 60 percent of the total cadmium levels measured exceeded 1.0 µg/l and, therefore, were higher than the chronic standards. Since the measurements were of total cadmium and the standards are established for acid-soluble cadmium, the exceedance of the standards does not necessarily indicate that toxic conditions existed.

Copper: Mean annual total copper levels ranged from 6.4 to 22.7 µg/l, while mean summer levels ranged from 2.8 to 7.9 µg/l. Although some relatively high copper levels were measured occasionally, as shown in Figure 80, the summer levels of copper appear to be similar to the levels measured during the remainder of the year. Copper concentrations at the upstream, inner harbor, and outer harbor stations were also similar. The acute and chronic toxic standards for acid-soluble copper recommended in Chapter II of Volume Two of this report are shown on the probability plots in Figure 80. The acute and chronic standards were

Figure 79

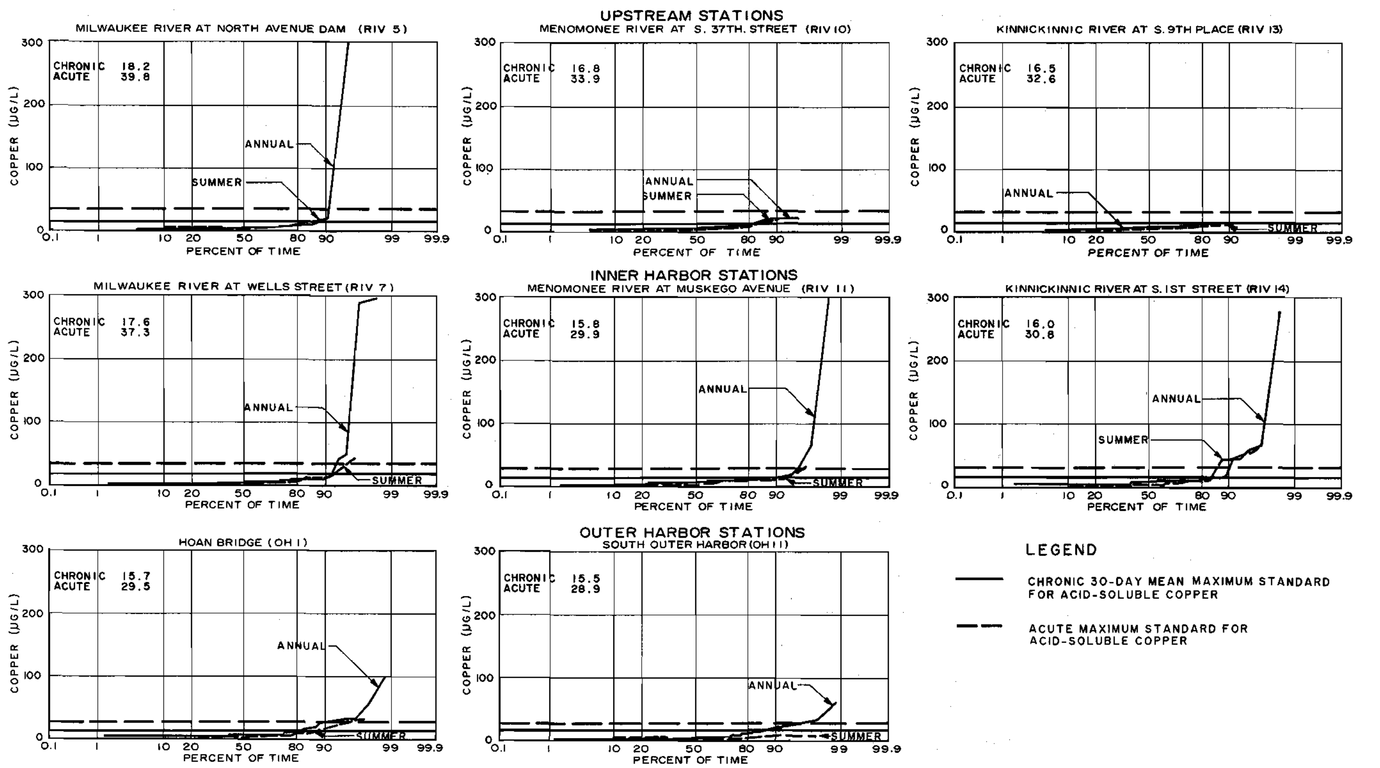
CADMIUM PROBABILITY PLOTS FOR ANNUAL AND SUMMER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 80

COPPER PROBABILITY PLOTS FOR ANNUAL AND SUMMER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

calculated using the mean hardness levels measured under the baseline sampling program. Over the three-year sampling period, the chronic standards for acid-soluble copper, which are recommended to be met by the mean concentration measured over any 30-day period, were violated during one month at the Milwaukee River upstream, Menomonee River upstream, and Menomonee River estuary stations; during two months at the Milwaukee and Kinnickinnic River estuary stations; and during three months at each outer harbor station. In addition, as shown in Figure 80, one total copper sample measured at the Milwaukee River upstream station, and at each inner harbor station, violated the acute standards for acid-soluble copper. Since the measurements were of total copper and the standards are established for acid-soluble copper, the exceedance of the standards does not necessarily indicate that toxic conditions existed.

Lead: Mean annual total lead levels ranged from 41.1 to 63.1 µg/l, while mean summer levels ranged from 33.5 to 72.1 µg/l. In general, concentrations of lead were lower during the summer than during the remainder of the year, as shown in Figure 81. In both the summer and annual probability plots, the lead concentrations in the Milwaukee and Menomonee River estuary and upstream stations were similar. In the Kinnickinnic River estuary station, however, the concentrations of lead were higher than at the upstream station, especially during the summer months. The acute and chronic toxic standards for acid-soluble lead recommended in Chapter II of Volume Two of this report are shown on the probability plots in Figure 81. The acute and chronic standards were calculated using the mean hardness levels measured under the baseline sampling program. Neither the chronic standards for acid-soluble lead, which are recommended to be met by the mean concentration measured over any 30-day period, nor the acute standards, which are recommended to be met at all times, were violated at any of the stations shown in Figure 81, based on total lead measurements. Although a few individual total lead measurements exceeded the chronic standards for acid-soluble lead, no monthly means exceeded the standard. Since the total lead measurements met the standards established for acid-soluble lead, it can be concluded that lead was not present in the water column in high enough levels to have toxic effects.

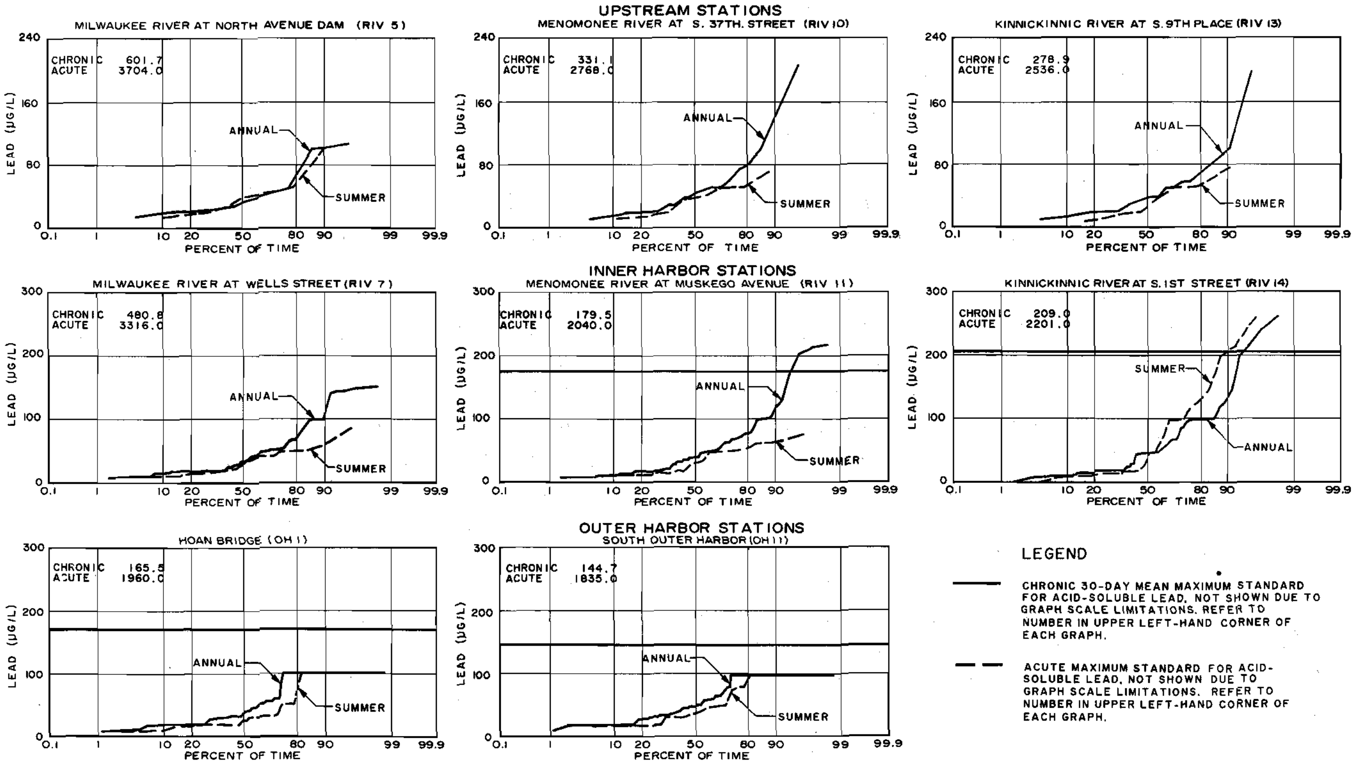
Zinc: Mean annual total zinc levels ranged from 7.7 to 26.7 µg/l, while mean summer levels ranged from 4.6 to 16.8 µg/l. In general, concentrations of zinc were lower during the summer than during the remainder of the year, as shown in Figure 82, except in the Milwaukee River, where summer and annual levels were about the same. Concentrations at the upstream stations were generally similar to those in the inner harbor, although the Kinnickinnic River generally had higher levels than did the Milwaukee or Menomonee Rivers. The lowest concentrations of zinc were found in the outer harbor. The acute and chronic toxic standards for acid-soluble zinc recommended in Chapter II of Volume Two of this report are shown on the probability plots in Figure 82. The acute standards were calculated using the mean hardness levels measured under the baseline sampling program. Neither the chronic standard for acid-soluble zinc, which is recommended to be met by the mean concentration measured over any 30-day period, nor the acute standards, which are recommended to be met at all times, were violated at any of the stations shown in Figure 82, based on total zinc measurements. Since the total zinc measurements met the standards established for acid-soluble zinc, it can be concluded that zinc was not present in the water column in high enough levels to have toxic effects.

Wet- and Dry-Weather Data: One of the objectives of the Milwaukee Harbor estuary study was to assess the impact of wet weather conditions and combined sewer overflow loads on estuary water quality conditions. Since the weekly baseline sampling was conducted during all weather conditions, the data represent a statistically unbiased sampling of both wet- and dry-weather conditions. The baseline data were divided into wet-weather data and dry-weather data to allow the analysis of the relative effects of rainfall events on receiving water quality. This section compares the wet-weather and dry-weather conditions. A more detailed analysis of water quality conditions during surveyed major runoff events is provided in a following section. For the purposes of this analysis, a sample was considered to be a wet-weather sample if at least one-tenth of one inch of precipitation fell on the sampling date, or within the three days preceding the sampling date. The three-day wet-weather impact period was selected based on an analysis by HydroQual, Inc., which indicated that the maximum difference between wet-weather and dry-weather data occurred when a three-day impact period was used to define wet-weather data.

Summaries of the concentrations of selected water quality indicators measured during wet-weather conditions and during dry-weather conditions are set forth in Tables 62 and 63, respectively. These

Figure 81

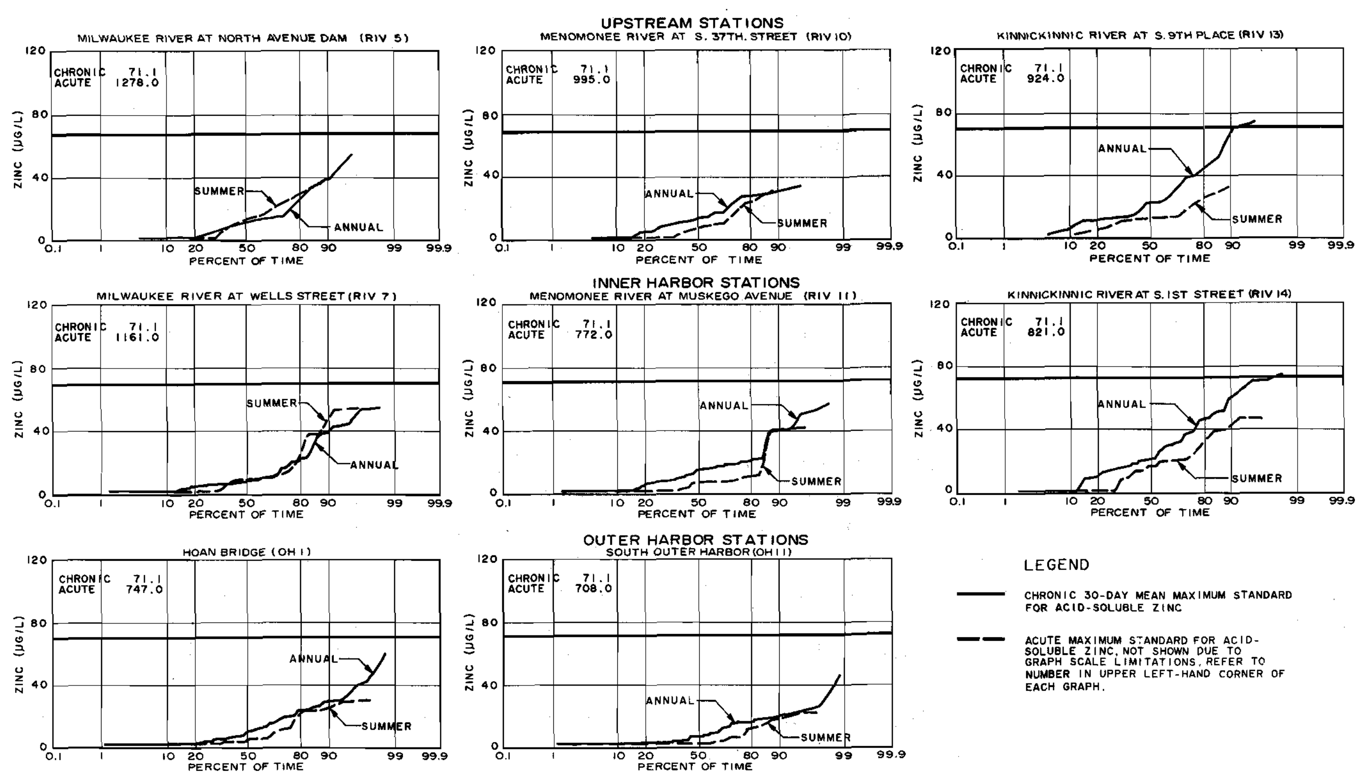
LEAD PROBABILITY PLOTS FOR ANNUAL AND SUMMER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 82

ZINC PROBABILITY PLOTS FOR ANNUAL AND SUMMER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Table 62

SUMMARY OF BASELINE WATER QUALITY DATA AT SELECTED STATIONS: WET WEATHER 1981-1983

Sampling Station	Statistical Variable	Dissolved Oxygen (mg/l)	Fecal Coliform (MPN/100ml)	Total Suspended Solids (mg/l)	Total Phosphorus (mg/l)	Ammonia Nitrogen (mg/l)	Un-ionized Ammonia Nitrogen (mg/l)	Volatile Suspended Solids (mg/l)	BOD_5 (mg/l)	Chlorophyll-a (µg/l)	Cadmium[a] (µg/l)	Copper (µg/l)	Lead (µg/l)	Zinc (µg/l)
Upstream Stations														
Milwaukee River at North Avenue Dam (RIV-5)	Number of Samples	75	80	80	79	82	74	76	69	80	9	9	9	9
	Minimum	3.5	30	1.0	0.03	0.02	0.000	1.0	0.8	0.7	2.0	1.0	9.5	9.5
	Mean	10.0	6,100	26.0	0.15	0.19	0.007	9.0	3.4	44.2	2.0	3.8	45.2	21.4
	Maximum	20.0	43,000	106.0	0.34	0.67	0.040	31.0	7.4	329.9	2.0	8.0	100.0	54.3
	Standard Deviation	3.0	9,800	18.0	0.06	0.14	0.007	6.0	1.8	57.6	0.0	2.3	25.6	15.6
Menomonee River at S. 37th Street (RIV-10)	Number of Samples	65	73	73	72	75	67	70	33	71	4	9	9	9
	Minimum	5.3	230	1.0	0.02	0.02	0.000	1.0	1.4	1.4	2.0	2.0	20.0	0.2
	Mean	10.5	14,000	25.0	0.15	0.24	0.005	7.0	3.9	10.6	2.3	6.4	63.1	15.4
	Maximum	17.0	240,000	341.0	0.57	0.91	0.028	136.0	14.0	57.6	3.0	19.0	207.0	29.7
	Standard Deviation	3.1	32,000	47.0	0.11	0.15	0.05	16.0	2.5	9.9	0.5	5.0	59.3	10.1
Kinnickinnic River at S. 9th Place (RIV-13)	Number of Samples	67	71	71	73	75	66	69	30	72	4	9	9	9
	Minimum	2.0	3	2.0	0.01	0.02	0.001	1.0	0.8	0.3	2.0	2.0	10.0	12.2
	Mean	14.5	12,000	16.0	0.07	0.15	0.010	6.0	6.5	6.4	2.0	6.6	62.0	31.4
	Maximum	20.0	240,000	149.0	0.40	0.90	0.058	63.0	76.5	43.9	2.0	15.0	202.0	72.4
	Standard Deviation	3.8	40,000	23.0	0.08	0.16	0.013	9.0	5.7	6.7	0.0	3.7	58.3	19.1
Inner Harbor Stations														
Milwaukee River at Wells Street (RIV-7)	Number of Samples	223	78	234	233	237	224	222	100	233	14	27	27	27
	Minimum	1.2	40	1.0	0.03	0.02	0.000	1.0	0.3	0.4	2.0	1.0	10.0	3.5
	Mean	8.8	18,000	26.0	0.16	0.26	0.009	9.0	3.3	39.7	2.4	5.6	57.7	17.6
	Maximum	17.8	240,000	148.0	0.65	1.12	0.057	57.0	10.0	265.1	3.0	16.0	154.0	52.8
	Standard Deviation	3.5	43,000	19.0	0.07	0.20	0.007	7.0	2.1	51.9	0.5	4.0	43.0	14.7
Menomonee River at Muskego Avenue (RIV-11)	Number of Samples	203	72	220	219	221	203	213	203	218	13	27	27	27
	Minimum	0.0	3	3.0	0.01	0.06	0.001	0.0	0.6	0.6	2.0	2.0	9.0	4.4
	Mean	5.1	36,000	18.0	0.13	0.50	0.007	6.0	4.1	10.1	2.3	6.9	67.1	20.5
	Maximum	16.0	430,000	95.0	0.36	1.73	0.046	81.0	26.0	105.6	3.0	14.0	218.0	55.9
	Standard Deviation	4.4	79,000	17.0	0.06	0.31	0.006	9.0	3.6	12.5	0.6	3.5	59.5	15.8
Kinnickinnic River at S. 1st Street (RIV-14)	Number of Samples	194	67	193	193	195	190	188	185	189	11	24	24	24
	Minimum	0.0	9	5.0	0.02	0.19	0.000	1.0	1.2	0.8	2.0	1.0	9.0	8.2
	Mean	5.6	40,000	45.0	0.13	0.53	0.005	10.0	3.9	7.1	2.5	11.1	82.9	36.0
	Maximum	15.4	930,000	480.0	0.43	1.42	0.020	97.0	14.0	39.3	4.0	57.0	265.0	74.2
	Standard Deviation	4.1	130,000	67.0	0.07	0.20	0.003	13.0	2.1	7.1	0.8	14.5	75.1	22.0
Outer Harbor Stations														
Hoan Bridge[b] (OH-1)	Number of Samples	167	53	57	162	160	160	54	31	164	15	39	39	39
	Minimum	3.8	3	4.0	0.02	0.08	0.000	1.0	0.1	1.7	2.0	1.0	9.0	0.5
	Mean	8.3	8,700	14.0	0.09	0.53	0.006	4.0	1.3	11.3	3.2	8.4	64.9	10.6
	Maximum	14.8	240,000	83.0	0.31	3.84	0.023	12.0	2.7	88.9	5.0	97.0	100.0	41.0
	Standard Deviation	2.2	33,000	12.0	0.05	0.45	0.004	2.0	0.6	12.4	1.1	16.3	34.9	10.1
South Outer Harbor[b] (OH-11)	Number of Samples	168	55	56	161	166	106	55	32	165	13	38	38	38
	Minimum	3.9	3	1.0	0.01	0.03	0.000	0.0	0.1	0.7	2.0	1.0	19.0	0.4
	Mean	9.6	200	11.0	0.05	0.59	0.007	3.0	1.4	5.9	3.1	7.9	68.8	7.7
	Maximum	14.4	2,300	100.0	0.17	1.58	0.029	19.0	2.6	23.3	5.0	62.0	100.0	45.0
	Standard Deviation	1.7	500	15.0	0.03	0.32	0.006	3.0	0.6	4.1	1.3	13.0	31.7	9.1

[a] *The cadmium statistics exclude measurements of 1.0 µg/l, which was the laboratory detection limit, or less.*

[b] *Concentrations of BOD_5 were not measured at stations OH-1 and OH-11. Therefore, concentrations of BOD_5 measured at OH-7, located at the main harbor entrance, are presented for OH-1, and concentrations of BOD_5 measured at OH-3, located in the central outer harbor, are presented for OH-11.*

Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

statistical summaries for 13 selected water quality indicators are presented for the previously identified three upstream sampling stations, three inner harbor sampling stations, and two outer harbor sampling stations. Probability plots of the selected water quality indicators, which represent the overall impact of wet-weather and dry-weather conditions over the three-year sampling period, are set forth in Figures 83 through 95. The water quality standards are also shown on the probability plots.

Concentrations of most water quality indicators were higher during wet-weather conditions than during dry-weather conditions, indicative of pollutants discharged by nonpoint sources and

Table 63

SUMMARY OF BASELINE WATER QUALITY DATA AT SELECTED STATIONS: DRY WEATHER 1981-1983

Sampling Station	Statistical Variable	Dissolved Oxygen (mg/l)	Fecal Coliform (MPN/100ml)	Total Suspended Solids (mg/l)	Total Phosphorus (mg/l)	Ammonia Nitrogen (mg/l)	Un-ionized Ammonia Nitrogen (mg/l)	Volatile Suspended Solids (mg/l)	BOD_5 (mg/l)	Chlorophyll-a (μg/l)	Cadmium[a] (μg/l)	Copper (μg/l)	Lead (μg/l)	Zinc (μg/l)
Upstream Stations														
Milwaukee River at	Number of Samples	54	56	53	56	57	54	53	51	57	6	12	12	12
North Avenue Dam	Minimum	4.8	30	1.0	0.04	0.02	0.000	1.0	0.9	1.0	2.0	1.0	12.0	0.4
(RIV-5)	Mean	10.2	1,600	22.0	0.13	0.15	0.006	9.0	3.3	39.8	2.2	36.8	38.1	7.6
	Maximum	14.3	23,000	85.0	0.25	0.90	0.021	33.0	8.0	196.4	3.0	413.0	105.0	33.5
	Standard Deviation	2.8	3,200	16.0	0.06	0.16	0.005	7.0	1.9	49.1	0.4	118.6	31.5	10.2
Menomonee River	Number of Samples	50	51	52	54	54	51	51	26	54	7	11	11	11
at S. 37th Street	Minimum	5.0	0	1.0	0.01	0.02	0.001	0.0	1.4	0.8	2.0	1.0	12.0	0.5
(RIV-10)	Mean	11.6	9,900	8.0	0.19	0.23	0.008	4.0	2.9	10.1	2.3	6.4	48.2	13.0
	Maximum	18.0	93,000	30.0	0.98	0.93	0.041	16.0	6.8	32.3	3.0	19.0	142.0	33.7
	Standard Deviation	2.7	17,000	6.0	0.20	0.16	0.008	3.0	1.1	9.3	0.5	5.9	38.6	10.9
Kinnickinnic River	Number of Samples	50	49	53	53	54	51	52	25	52	6	11	11	11
at S. 9th Place	Minimum	2.0	90	2.0	0.01	0.02	0.001	1.0	1.1	0.4	2.0	1.0	12.0	1.0
(RIV-13)	Mean	15.7	1,700	9.0	0.05	0.12	0.011	3.0	3.3	11.2	2.5	6.6	37.7	20.8
	Maximum	20.0	9,300	67.0	0.34	0.68	0.071	10.0	7.8	56.4	3.0	13.0	84.0	67.9
	Standard Deviation	3.2	100	10.0	0.05	0.13	0.013	2.0	1.8	12.9	0.5	4.4	25.1	20.4
Inner Harbor Stations														
Milwaukee River	Number of Samples	162	54	158	171	170	161	157	71	171	20	33	33	33
at Wells Street	Minimum	1.3	70	1.0	0.03	0.02	0.000	1.0	0.4	0.4	2.0	1.0	12.0	0.4
(RIV-7)	Mean	9.1	3,700	20.0	0.13	0.23	0.008	8.0	3.1	27.6	2.2	29.7	40.9	7.8
	Maximum	14.6	43,000	115.0	0.25	1.08	0.033	45.0	7.7	125.2	3.0	478.0	151.0	54.0
	Standard Deviation	3.7	7,300	18.0	0.05	0.17	0.007	7.0	1.9	32.2	0.4	95.1	34.1	11.4
Menomonee River	Number of Samples	147	51	154	159	155	146	151	155	158	20	33	33	33
at Muskego Avenue	Minimum	0.0	30	4.0	0.01	0.02	0.000	1.0	0.4	0.8	2.0	1.0	12.0	0.0
(RIV-11)	Mean	5.5	4,700	12.0	0.11	0.41	0.007	5.0	2.6	9.9	3.2	16.8	45.8	10.3
	Maximum	12.4	93,000	114.0	0.31	1.07	0.022	23.0	9.4	64.8	10.0	302.0	170.0	36.9
	Standard Deviation	3.8	14,000	11.0	0.05	0.21	0.004	4.0	1.6	11.8	2.3	52.4	37.7	8.7
Kinnickinnic River	Number of Samples	129	48	132	137	138	132	131	135	135	17	32	32	32
at S. 1st Street	Minimum	0.0	30	2.0	0.01	0.05	0.000	1.0	1.3	0.4	2.0	1.0	1.0	0.5
(RIV-14)	Mean	4.8	2,600	21.0	0.12	0.56	0.006	6.0	3.1	13.9	2.4	13.6	48.3	19.7
	Maximum	11.1	43,000	84.0	0.35	1.12	0.047	24.0	8.4	132.9	4.0	275.0	150.0	50.5
	Standard Deviation	3.4	6,700	14.0	0.05	0.23	0.005	3.0	1.5	24.7	0.6	48.9	40.1	14.8
Outer Harbor Stations														
Hoan Bridge[b]	Number of Samples	117	35	35	115	115	115	34	25	117	18	38	39	39
(OH-1)	Minimum	3.6	3	2.0	0.02	0.12	0.001	0.0	0.4	1.3	2.0	1.0	10.0	0.5
	Mean	8.2	1,000	9.0	0.07	0.69	0.007	3.0	1.6	9.8	54.8	8.3	35.6	12.4
	Maximum	14.5	23,000	26.0	0.35	2.75	0.035	10.0	8.1	55.4	942.0	51.0	100.0	59.0
	Standard Deviation	2.2	4,000	5.0	0.04	0.48	0.006	2.0	1.5	10.0	221.4	11.4	22.8	12.5
South Outer Harbor[b]	Number of Samples	117	35	38	116	117	117	37	25	117	16	39	39	39
(OH-11)	Minimum	3.8	3	2.0	0.01	0.08	0.000	1.0	0.8	1.3	2.0	1.0	9.0	0.3
	Mean	9.5	90	6.0	0.05	0.75	0.009	3.0	1.7	7.7	3.7	6.5	43.9	7.7
	Maximum	15.1	1,500	21.0	0.14	2.44	0.082	9.0	6.2	65.7	17.0	22.0	100.0	21.0
	Standard Deviation	1.8	300	4.0	0.02	0.43	0.010	2.0	1.1	9.3	3.6	6.5	25.1	100.0

[a] *The cadmium statistics exclude measurements of 1.0 μg/l, which was the laboratory detection limit, or less.*

[b] *Concentrations of BOD_5 were not measured at stations OH-1 and OH-11. Therefore, concentrations of BOD_5 measured at OH-7, located at the main harbor entrance, are presented for OH-1, and concentrations of BOD_5 measured at OH-3, located in the central outer harbor, are presented for OH-11.*

Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

combined sewer overflows. Those pollutants that had higher concentrations during wet-weather conditions were fecal coliform, total suspended solids, total phosphorus, volatile suspended solids, BOD_5, lead, and zinc.

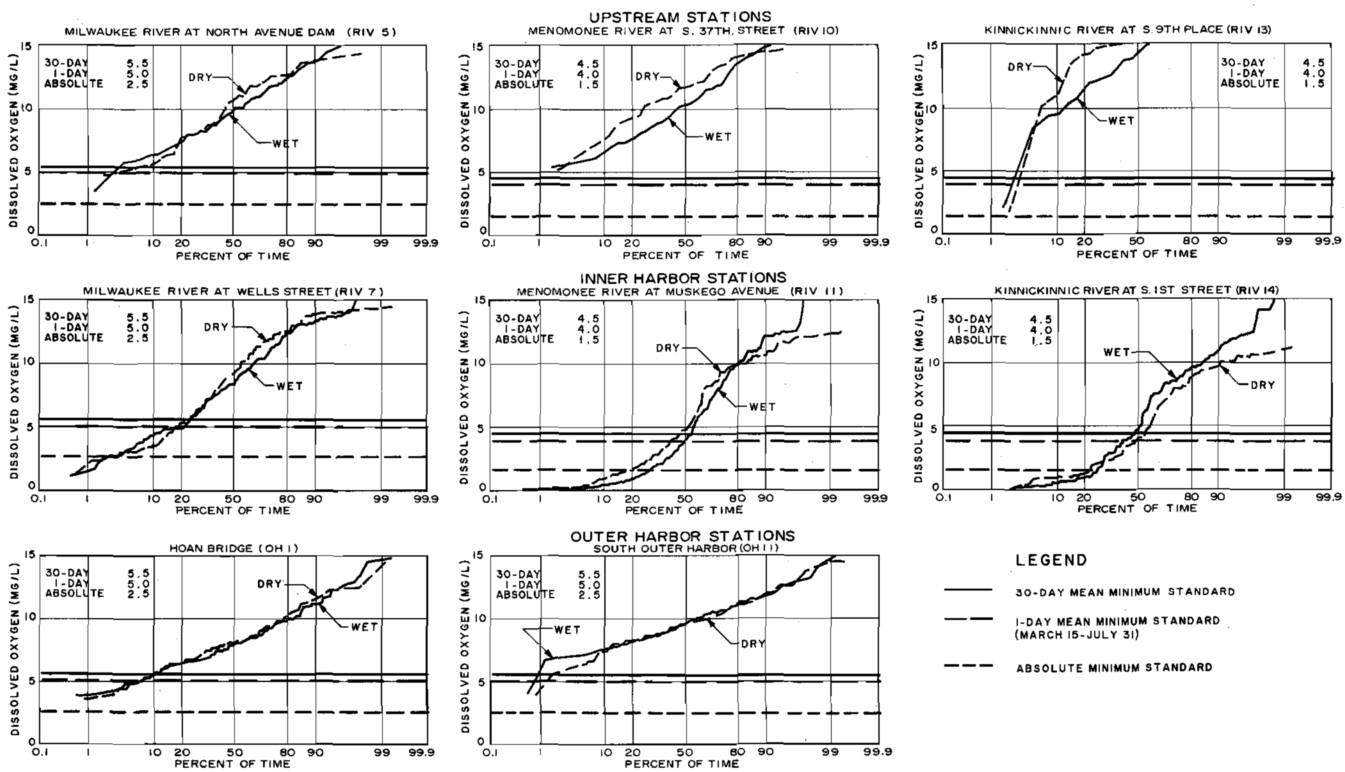
The difference between wet-weather and dry-weather concentrations was greatest for fecal coliform levels, as shown in Figure 84. The very high fecal coliform levels observed within the inner harbor may be attributed to combined sewer overflows.

Concentrations of the metals lead and zinc increased during wet-weather conditions, with lead increasing the most. Concentrations of cadmium and copper, however, were generally lower during wet weather. This suggests that point sources may be more significant than nonpoint sources and combined sewer overflows with respect to cadmium and copper concentrations.

The concentrations of ammonia nitrogen and un-ionized ammonia nitrogen were generally similar during dry-weather and wet-weather conditions,

Figure 83

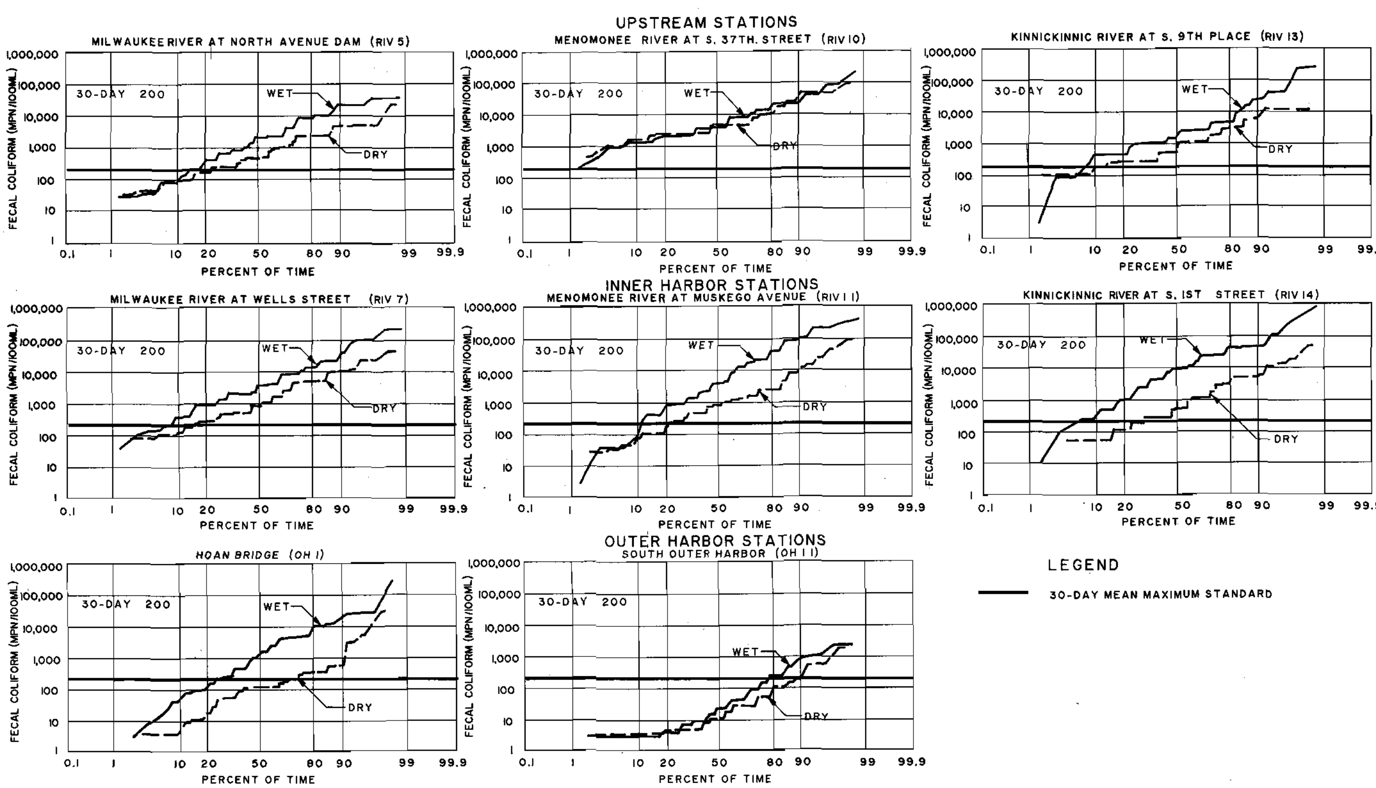
DISSOLVED OXYGEN PROBABILITY PLOTS FOR WET-WEATHER AND DRY-WEATHER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 84

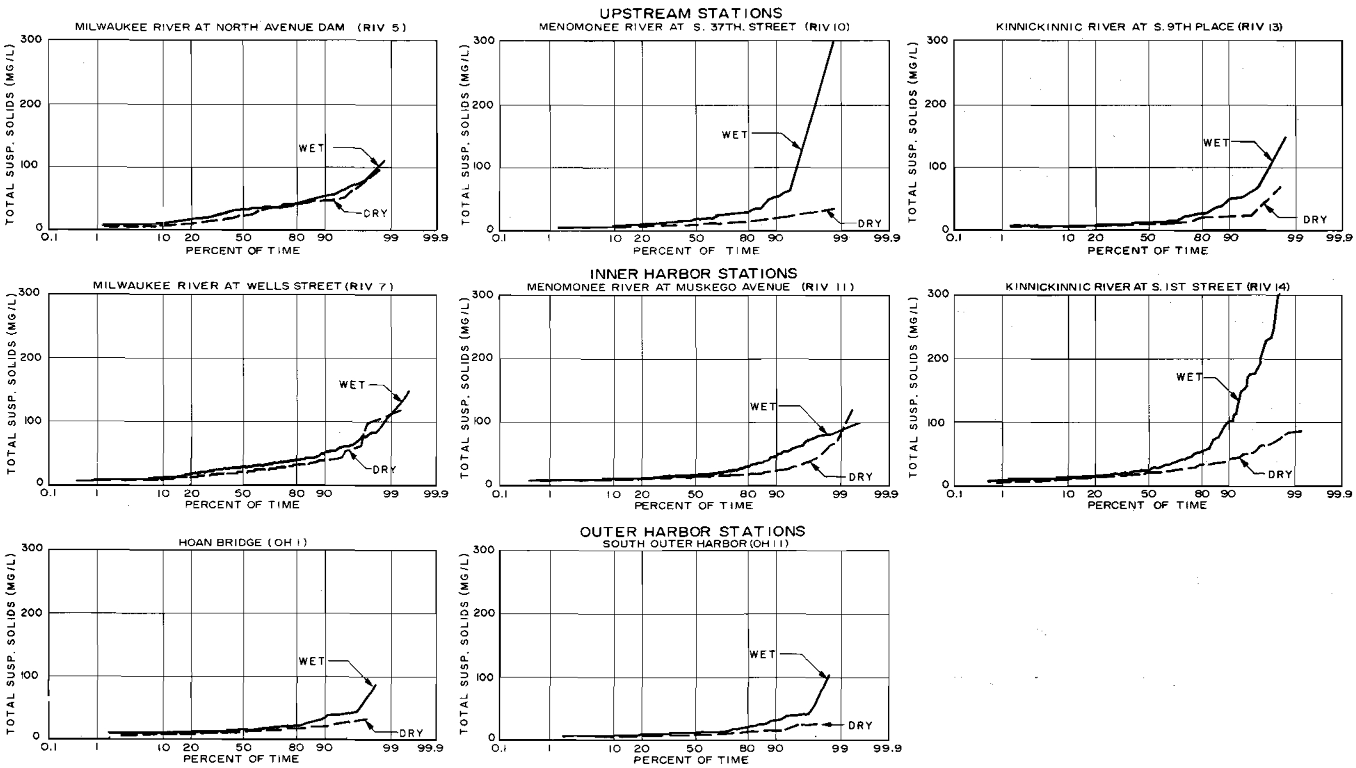
FECAL COLIFORM PROBABILITY PLOTS FOR WET-WEATHER AND DRY-WEATHER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 85

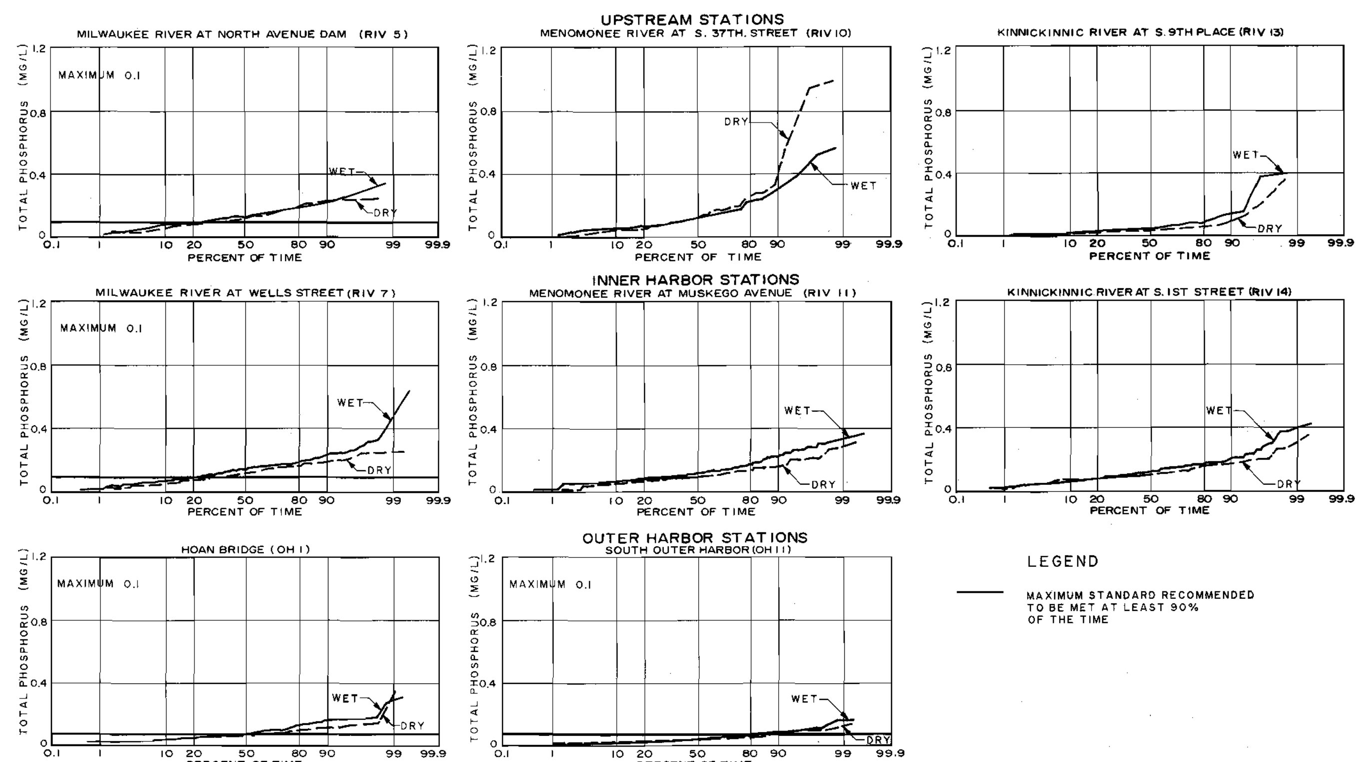
TOTAL SUSPENDED SOLIDS PROBABILITY PLOTS FOR WET-WEATHER AND DRY-WEATHER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 86

TOTAL PHOSPHORUS PROBABILITY PLOTS FOR WET-WEATHER AND DRY-WEATHER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

except that within the outer harbor ammonia nitrogen concentrations were generally higher during dry weather, as shown in Figure 87, a condition attributable to the large discharge of ammonia nitrogen into the outer harbor from the Jones Island wastewater treatment plant, and less dilution with river water during these dry-weather periods. However, as shown in Figure 88, the dry weather un-ionized ammonia nitrogen concentrations in the outer harbor were not substantially higher than the wet-weather concentrations because of the effects of temperature and pH. During those times when higher levels of ammonia nitrogen occurred within the outer harbor, the pH and temperature levels were slightly lower during dry-weather conditions than during wet-weather conditions. At lower pH and temperature levels, the portion of total ammonia which is in the un-ionized form is reduced. Hence, the higher levels of ammonia nitrogen in the outer harbor during dry weather did not result, overall, in higher levels of un-ionized ammonia nitrogen.

The baseline data indicate that wet-weather conditions have a modest effect on dissolved oxygen levels, as shown in Figure 83. In the upstream and estuarine portions of the Milwaukee and Menomonee Rivers, as well as in the upstream portion of the Kinnickinnic River, dissolved oxygen levels are generally slightly higher during dry-weather conditions. The Kinnickinnic River estuary levels are similar under wet- and dry-weather conditions. Within the outer harbor, the dry-weather dissolved oxygen levels appear to be slightly lower than the wet-weather levels.

The water quality monitoring program data suggest that wet-weather conditions in general, and combined sewer overflow events in particular, generally do not cause severe depressions in the dissolved oxygen levels within the estuary. Critical low dissolved oxygen levels are generally associated with summer low flow and high temperature conditions, and during this period of the year, wet-weather events tend to raise, rather than lower, dissolved oxygen levels at estuary stations. As shown in the probability plots in Figure 83, very low levels of dissolved oxygen occur more frequently during dry-weather conditions in the Milwaukee River and in the outer harbor.

Analysis of suspended solids concentrations during combined sewer overflow events by HydroQual, Inc., indicated that the immediate oxygen demand associated with sediment scouring which occurs during combined sewer overflow events is insufficient to cause severely depressed dissolved oxygen levels at inner harbor stations. HydroQual conducted a detailed analysis of an observed decline in dissolved oxygen levels in the Milwaukee River estuary at St. Paul Avenue during a storm event on August 10, 1983. The analysis suggested that the observed decline was not due to immediate oxygen demand associated with sediment scouring, but rather to reduced photosynthetic production of oxygen by algae. This may have been caused by less light availability because of cloud cover and the increased turbidity of the water, or by the toxic effects of substances such as metals contributed by the combined sewer overflows and nonpoint sources.

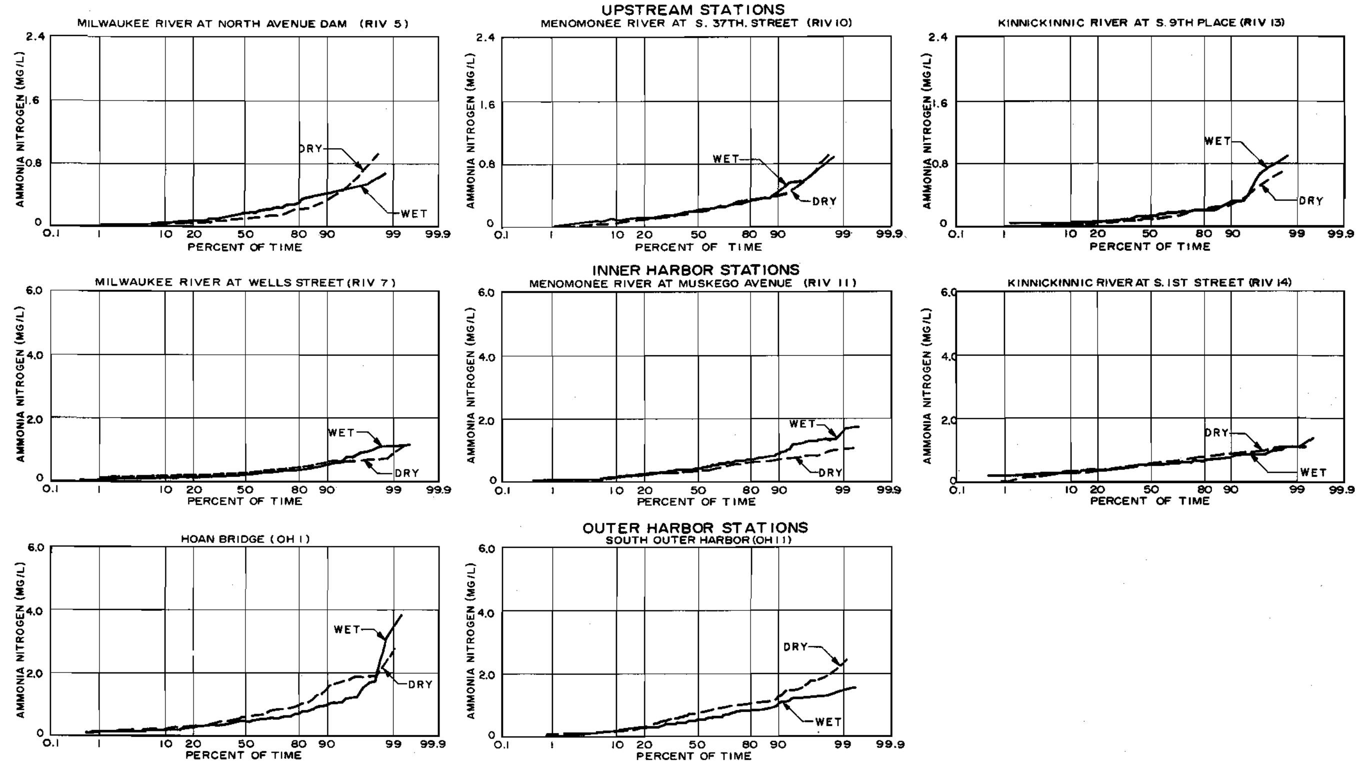
Inner harbor chlorophyll-a levels during wet-weather periods are largely determined by upstream levels of chlorophyll-a, rather than by combined sewer overflows and direct nonpoint source discharges. In the Milwaukee River, where upstream chlorophyll-a levels are relatively high, levels within the Milwaukee River estuary generally increase during wet weather conditions, as shown in Figure 91, as the upstream chlorophyll-a is flushed into the harbor. In the Kinnickinnic and Menomonee River estuaries, where upstream levels of chlorophyll-a are relatively low, the dry-weather levels of chlorophyll-a appear to be slightly higher than the wet-weather levels. Within the outer harbor, wet-weather levels of chlorophyll-a are similar to dry-weather levels.

Temporal Variations in Baseline Data: The baseline water quality data were examined on a time-variable basis to help analyze the general variability of the data and to determine if seasonal or longer-term trends were evident. Concentration versus time plots of 13 water quality indicators for the three-year sampling program at the representative sampling stations are presented herein. Overall the plots indicated that, although concentrations of many indicators varied substantially, there was no obvious long-term trend in the data over the three-year sampling period.

Concentration versus time plots for dissolved oxygen and chlorophyll-a are shown in Figure 96. The dissolved oxygen levels were generally highest in the winter and lowest in the summer at all stations. Essentially, all of the extremely low levels of dissolved oxygen which may impair the health and survival of fish and aquatic life occurred in the summer. The seasonal trend in dissolved oxygen levels was least evident in the Kinnickinnic River at S. 9th Place, where high levels of dissolved oxygen

Figure 87

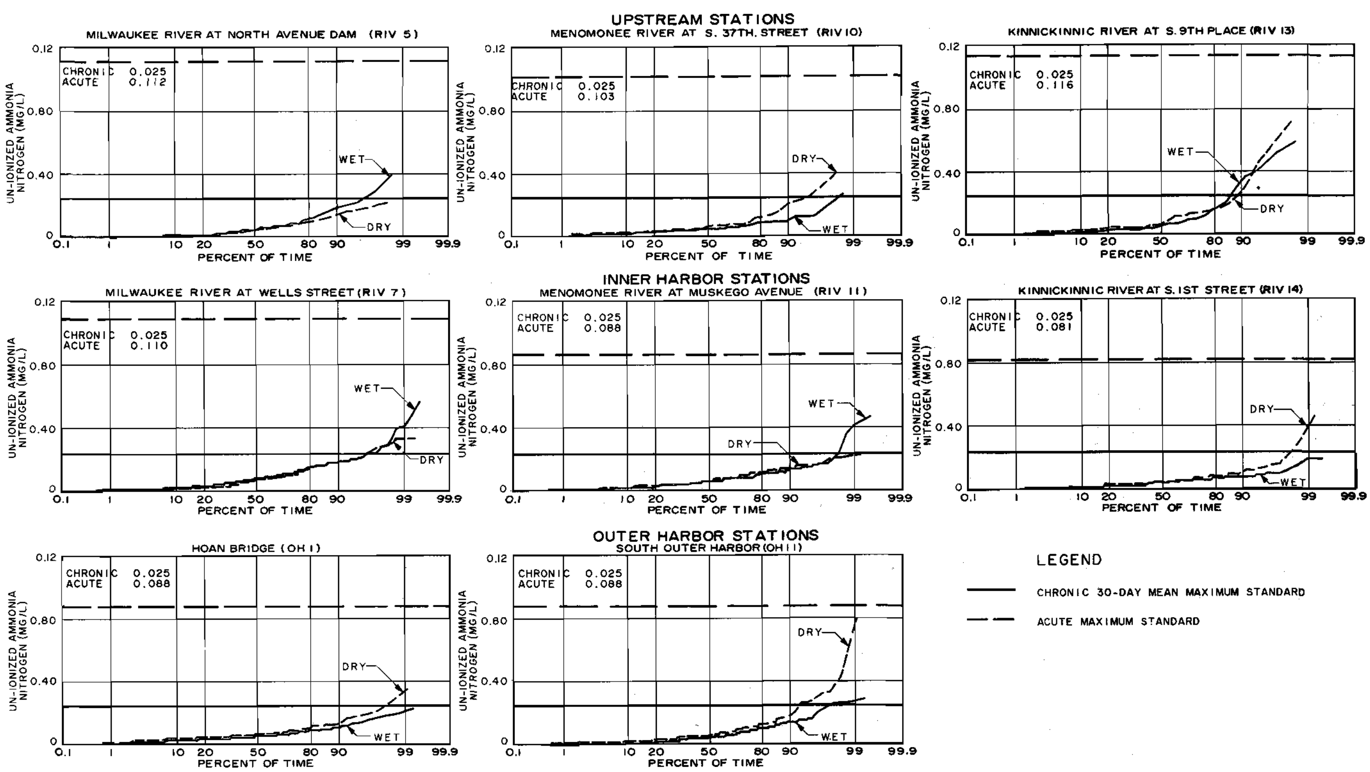
AMMONIA NITROGEN PROBABILITY PLOTS FOR WET-WEATHER AND DRY-WEATHER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 88

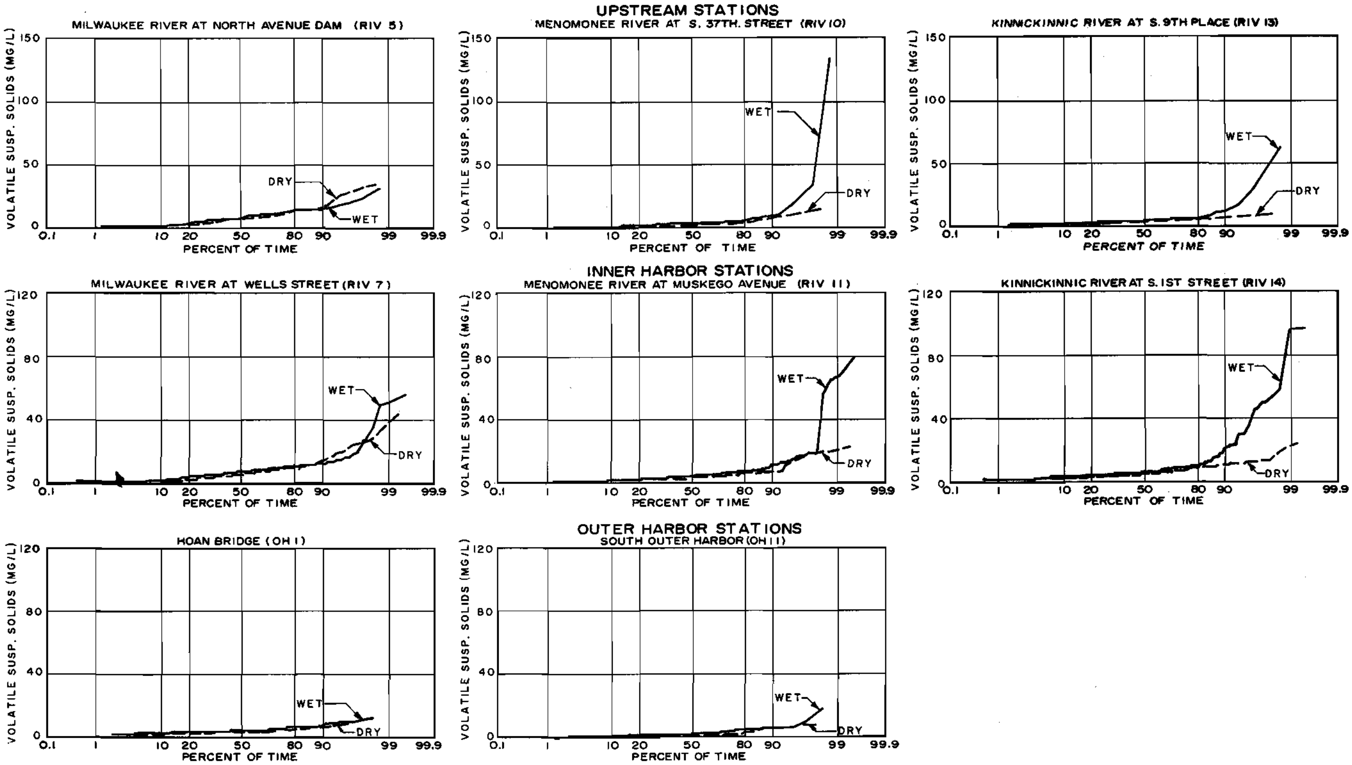
UN-IONIZED AMMONIA NITROGEN PROBABILITY PLOTS FOR WET-WEATHER AND DRY-WEATHER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 89

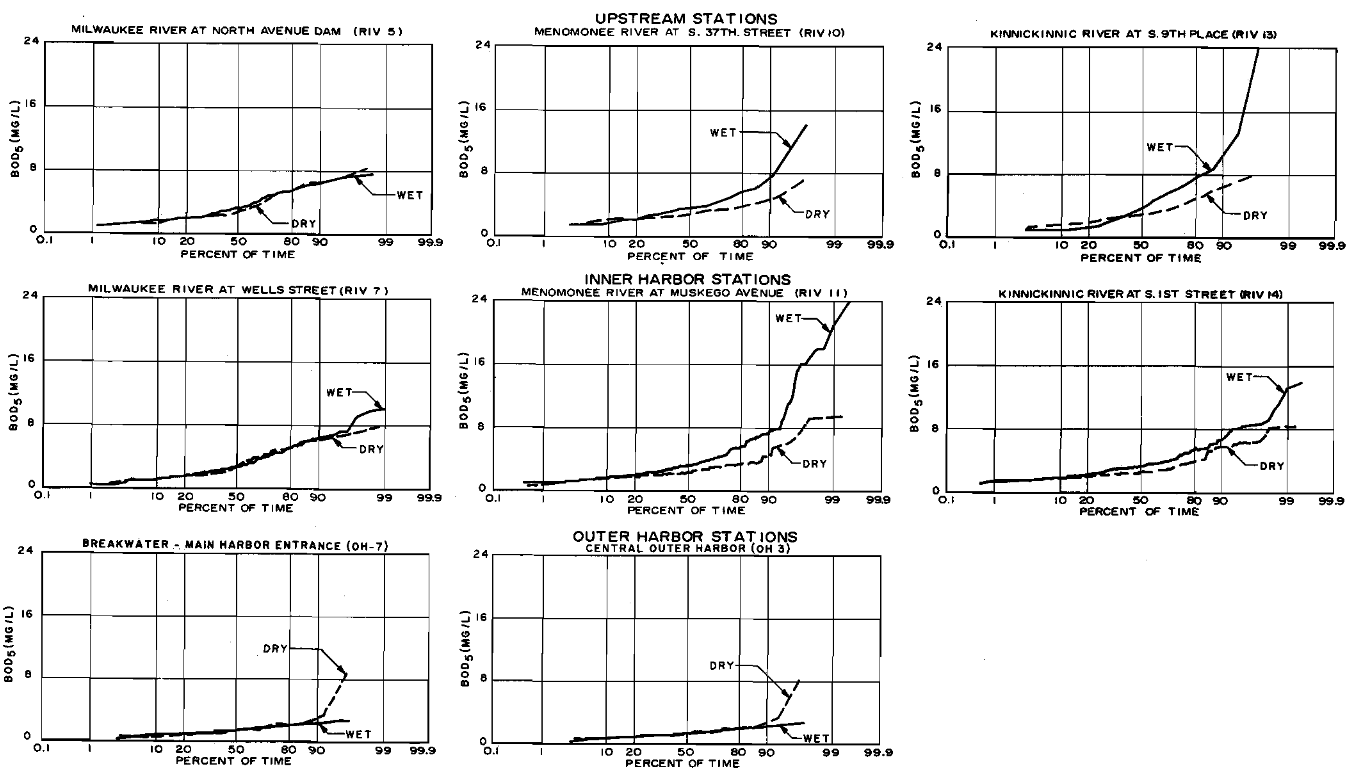
VOLATILE SUSPENDED SOLIDS PROBABILITY PLOTS FOR WET-WEATHER AND DRY-WEATHER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 90

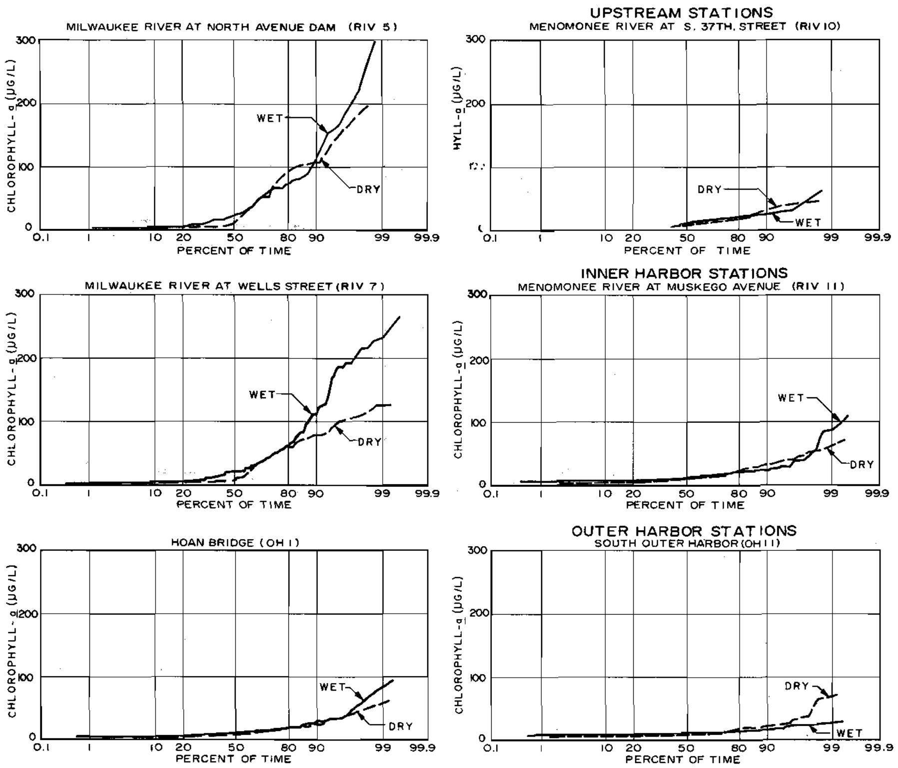
BIOCHEMICAL OXYGEN DEMAND PROBABILITY PLOTS FOR WET-WEATHER AND DRY-WEATHER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 91

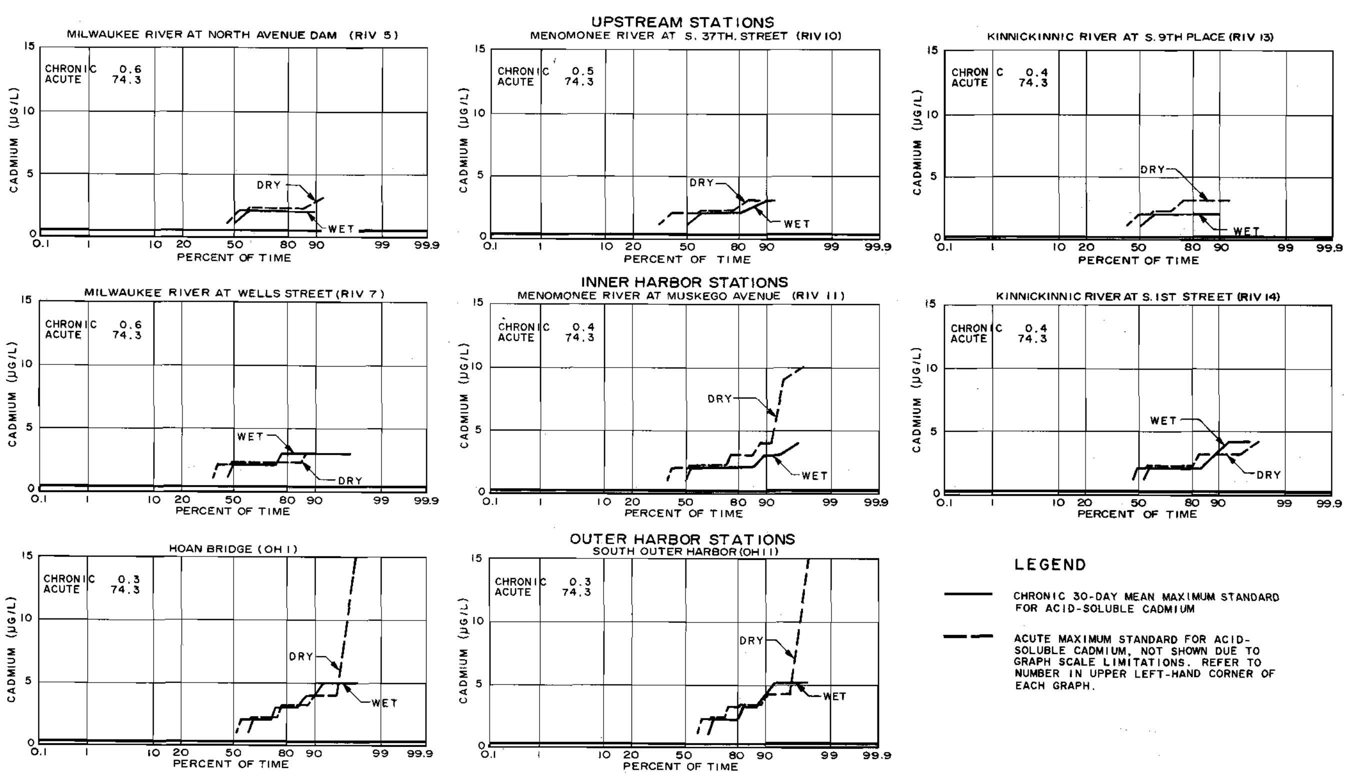
CHLOROPHYLL-a PROBABILITY PLOTS FOR WET-WEATHER AND DRY-WEATHER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 92

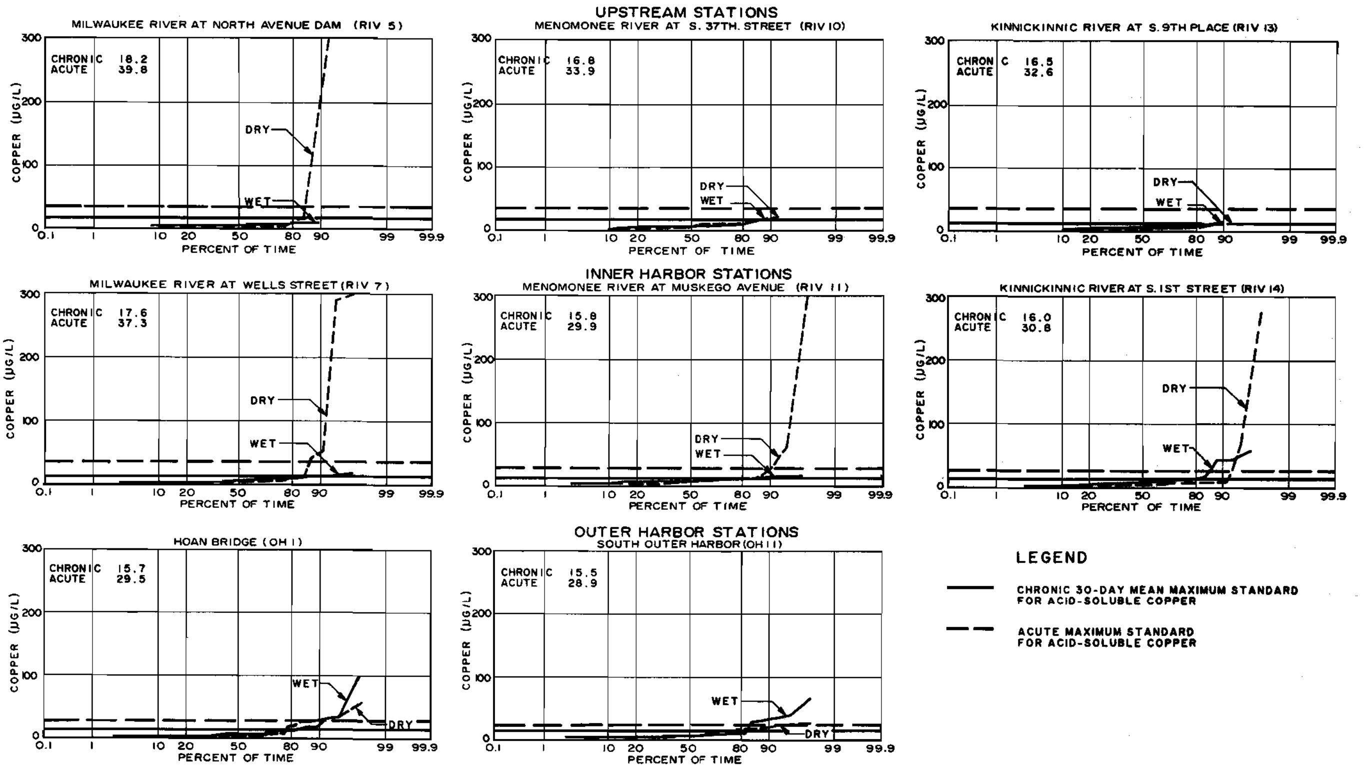
CADMIUM PROBABILITY PLOTS FOR WET-WEATHER AND DRY-WEATHER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 93

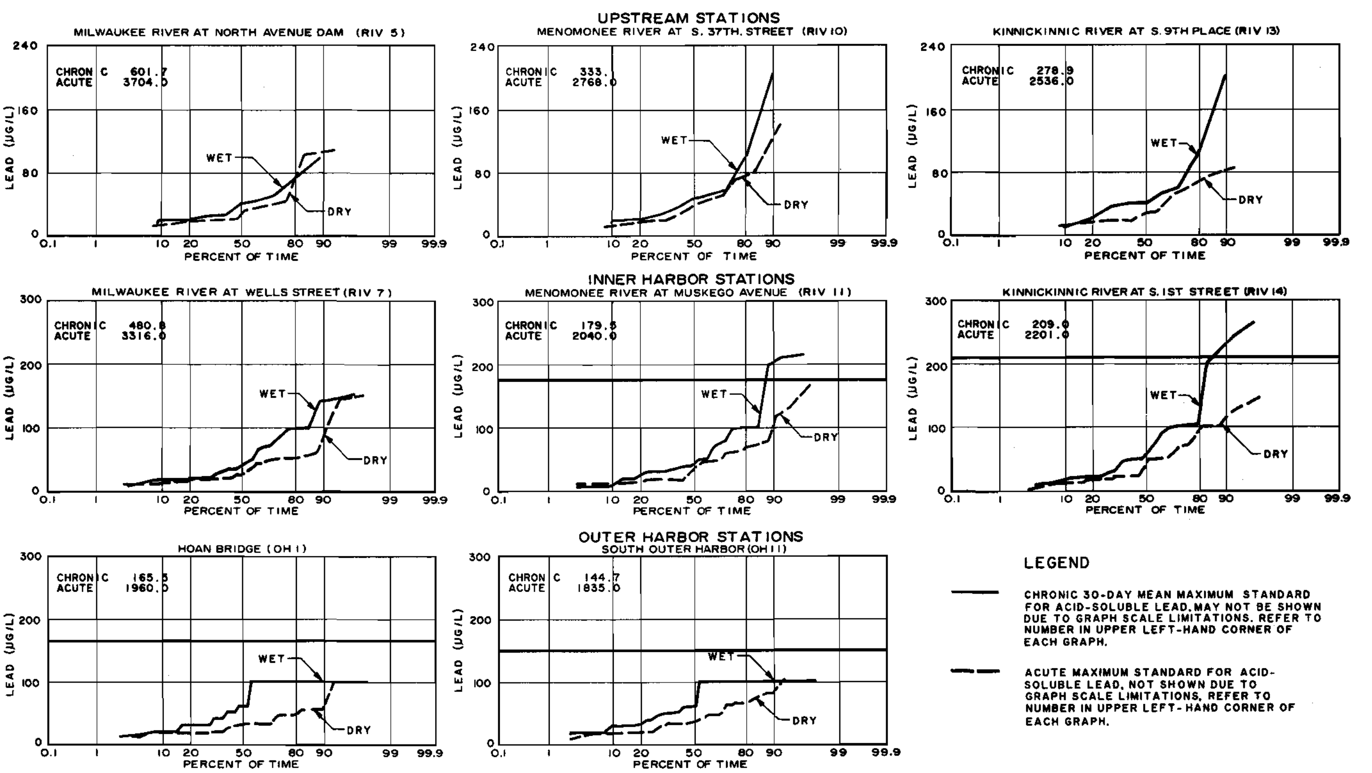
COPPER PROBABILITY PLOTS FOR WET-WEATHER AND DRY-WEATHER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 94

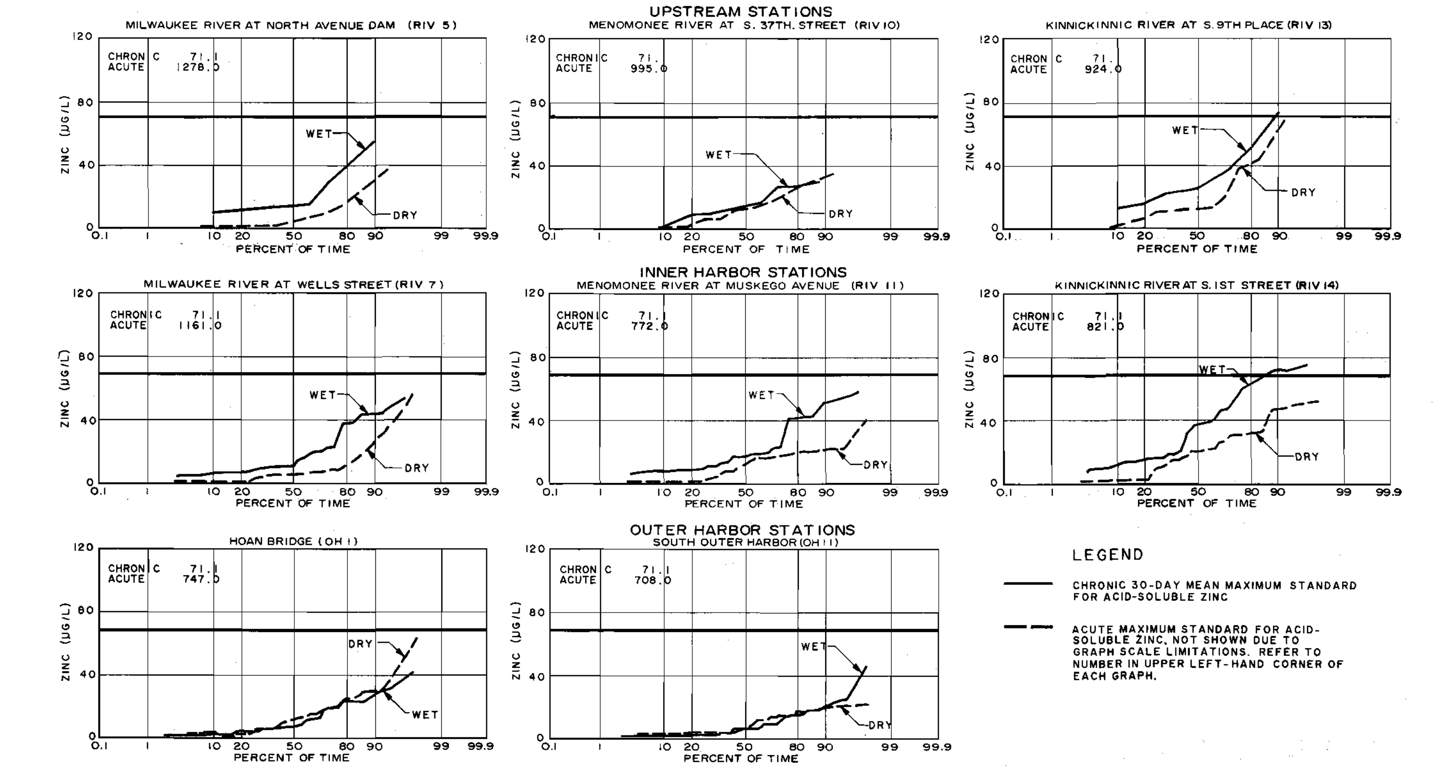
LEAD PROBABILITY PLOTS FOR WET-WEATHER AND DRY-WEATHER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 95

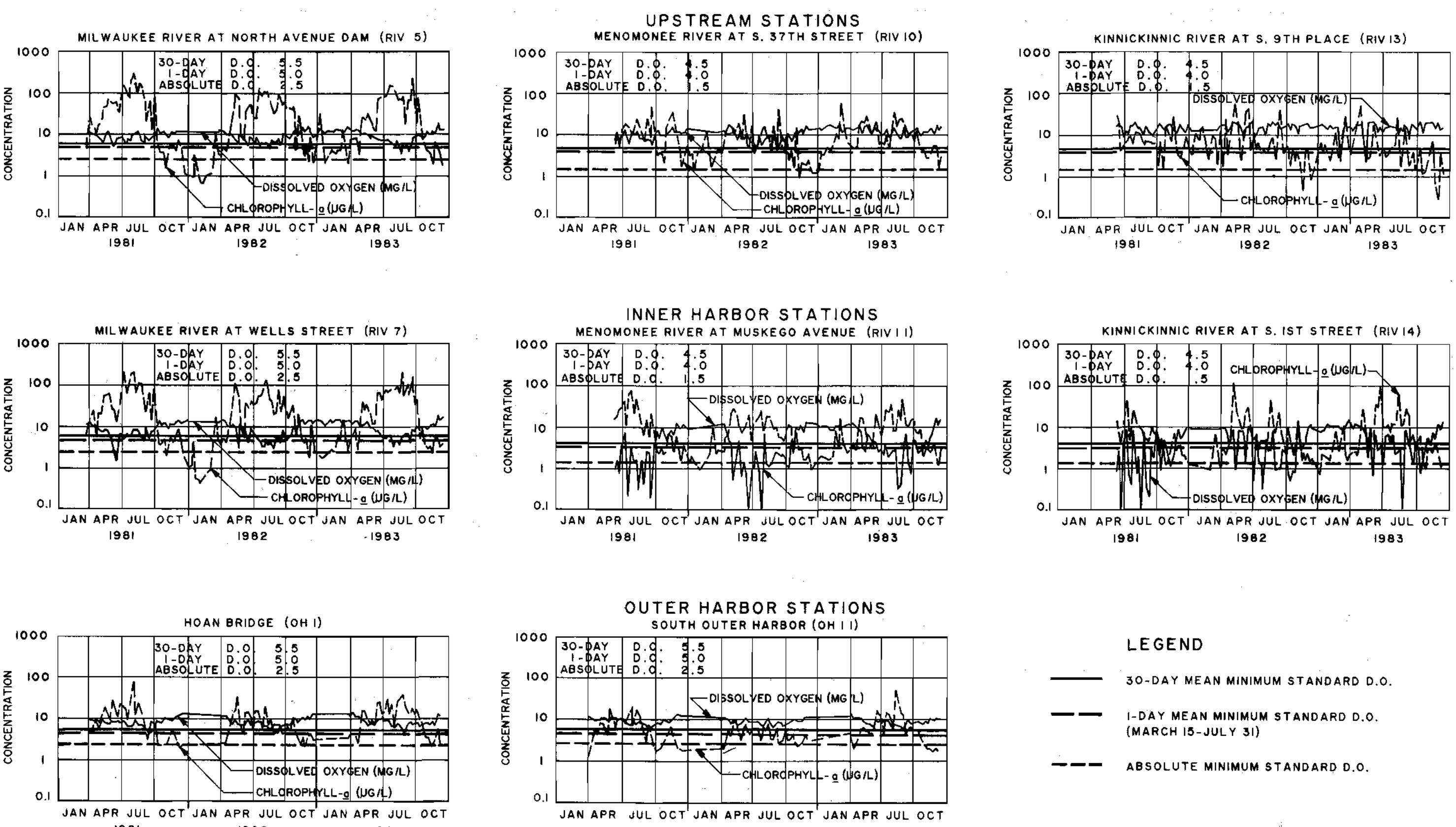
ZINC PROBABILITY PLOTS FOR WET-WEATHER AND DRY-WEATHER BASELINE CONDITIONS: 1981-1983



Source: SEWRPC.

Figure 96

CONCENTRATION VERSUS TIME PLOTS FOR DISSOLVED OXYGEN AND CHLOROPHYLL-a: 1981-1983



Source: SEWRPC.

were consistently found. Chlorophyll-a levels were highest in the summer and lowest in the winter. The Milwaukee River stations showed the greatest seasonal differences in chlorophyll-a, and the Kinnickinnic River stations the least.

Concentration versus time plots for fecal coliform and biochemical oxygen demand are shown in Figure 97. The fecal coliform levels are extremely variable over several orders of magnitude. No seasonal trends in fecal coliform levels, however, were evident from the plots. The biochemical oxygen demand plots also showed no apparent seasonal trends.

Concentration versus time plots for total suspended solids and volatile suspended solids are shown in Figure 98. Both total and volatile suspended solids appeared to be higher in the summer and lower in the winter in the Milwaukee River stations, due, in part, to the relatively higher agal levels in the Milwaukee River during the summer. The Menomonee River, Kinnickinnic River, and outer harbor stations did not show a seasonal trend in total or volatile suspended solids concentrations.

Concentration versus time plots for cadmium and copper are shown in Figure 100, while plots for lead and zinc are shown in Figure 101. The plots for all of the metals are quite variable, indicating that many of the sources of metals to these surface waters may be intermittent and sporadic. There were no obvious seasonal trends in any of the metal plots.

Concentration versus time plots for total phosphorus, ammonia nitrogen, and un-ionized ammonia nitrogen are shown in Figure 99. For both total phosphorus and ammonia nitrogen, a slight seasonal trend is apparent at the Milwaukee River stations, with the summer levels being slightly higher than the winter levels. That seasonal trend is less apparent at the remaining stations. The seasonal trend was even more pronounced for un-ionized ammonia nitrogen, again with the summer values being generally higher. At higher water temperatures and levels of pH, which are most likely to occur in summer, the portion of the total ammonia nitrogen which is in the un-ionized form increases.

Supplemental Dissolved Metals Data: The recommended water quality standards for metals set forth in Chapter II of Volume Two of this report are expressed in terms of acid-soluble concentrations of metals. Although acid-soluble metal concentrations were not measured under the Milwaukee Harbor estuary study, concentrations of dissolved metals were measured by the Wisconsin Electric Power Company within the inner harbor.[1] Although the measurement of dissolved metals is different from the measurement of acid-soluble metals, the dissolved concentrations are nevertheless useful in determining the toxicity of water samples.[2] If the dissolved metal concentrations violate the standards for acid-soluble metals, it can be concluded that toxic conditions exist. If the dissolved metal concentrations satisfy the standards, however, it cannot necessarily be concluded that toxic conditions do not exist.

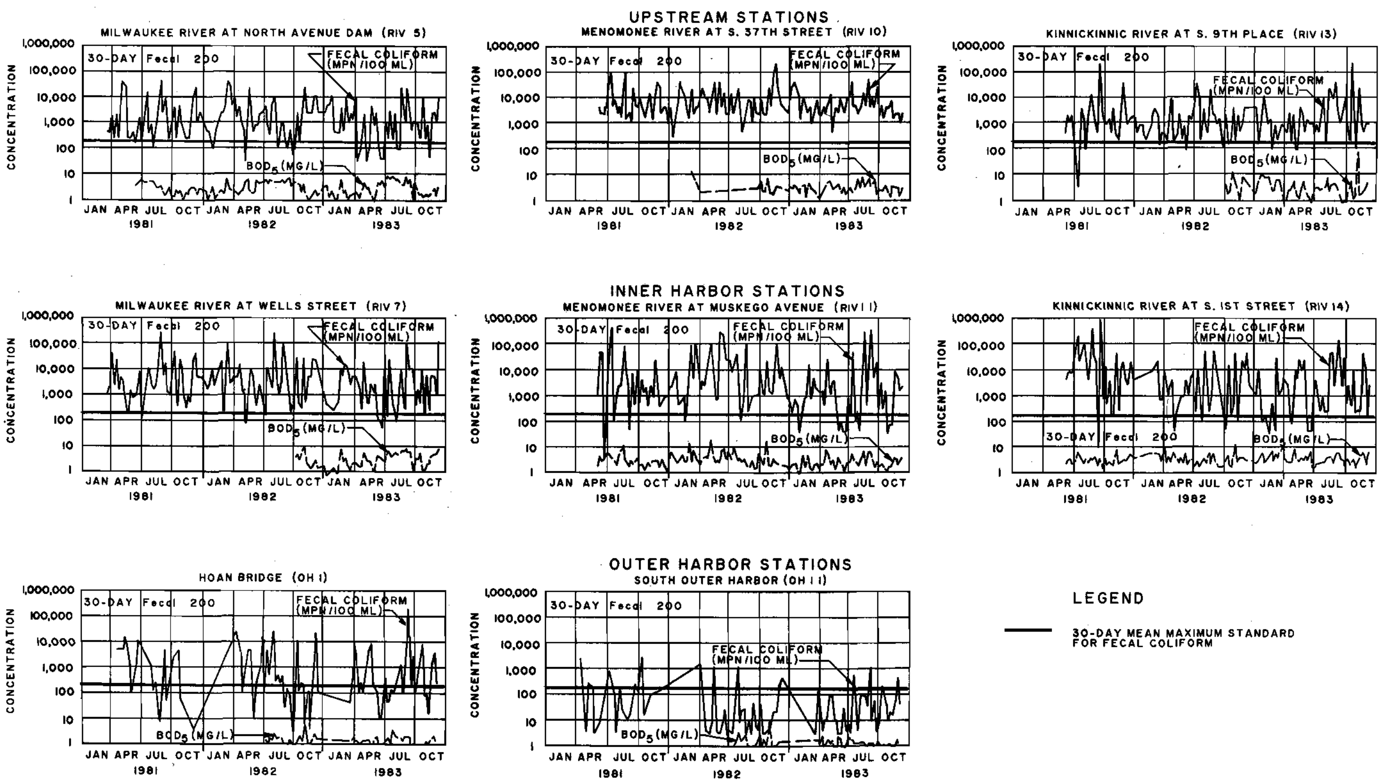
Dissolved metal concentrations measured at four stations on the Milwaukee River, two stations on the Menomonee River, and one station on the South Menomonee Canal are summarized in Table 64. The recommended acute and chronic toxic standards for acid-soluble metals are also shown in the table. A comparison of the dissolved metal concentrations to the toxic standards indicates that one sample in the Milwaukee River and one sample in the Menomonee River violated the chronic toxic standard for cadmium, and 15 of the 19 total samples violated the chronic toxic standard for mercury. No other standards were violated. This review of available metals data in the inner harbor suggests that chronic toxic conditions may exist because of elevated concentrations of some metals in the water, but that acute toxic conditions probably seldom occur.

[1] *CDM/Limnetics Environmental Consultants, Aquatic Studies at Valley, Commerce Street, and Wells Street Power Plants, prepared for the Wisconsin Electric Power Company, 1976.*

[2] *Water samples are prepared for the measurement of acid-soluble concentrations of metals by first acidifying the sample, which releases some of the metals weakly bound to sediment particles, and then filtering the sample to remove the particulates. Acid-soluble metal concentrations thus include dissolved metals and metals which were weakly bound to sediment particles. Water samples are prepared for the measurement of dissolved concentrations of metals by first filtering the sample to remove particulates. The sample is then acidified to keep the remaining metals dissolved. Dissolved metal concentrations therefore do not include metals weakly bound to sediment particles. For any given sample, the acid-soluble metal concentrations will always be equal to, or greater than, the dissolved metal concentrations.*

Figure 97

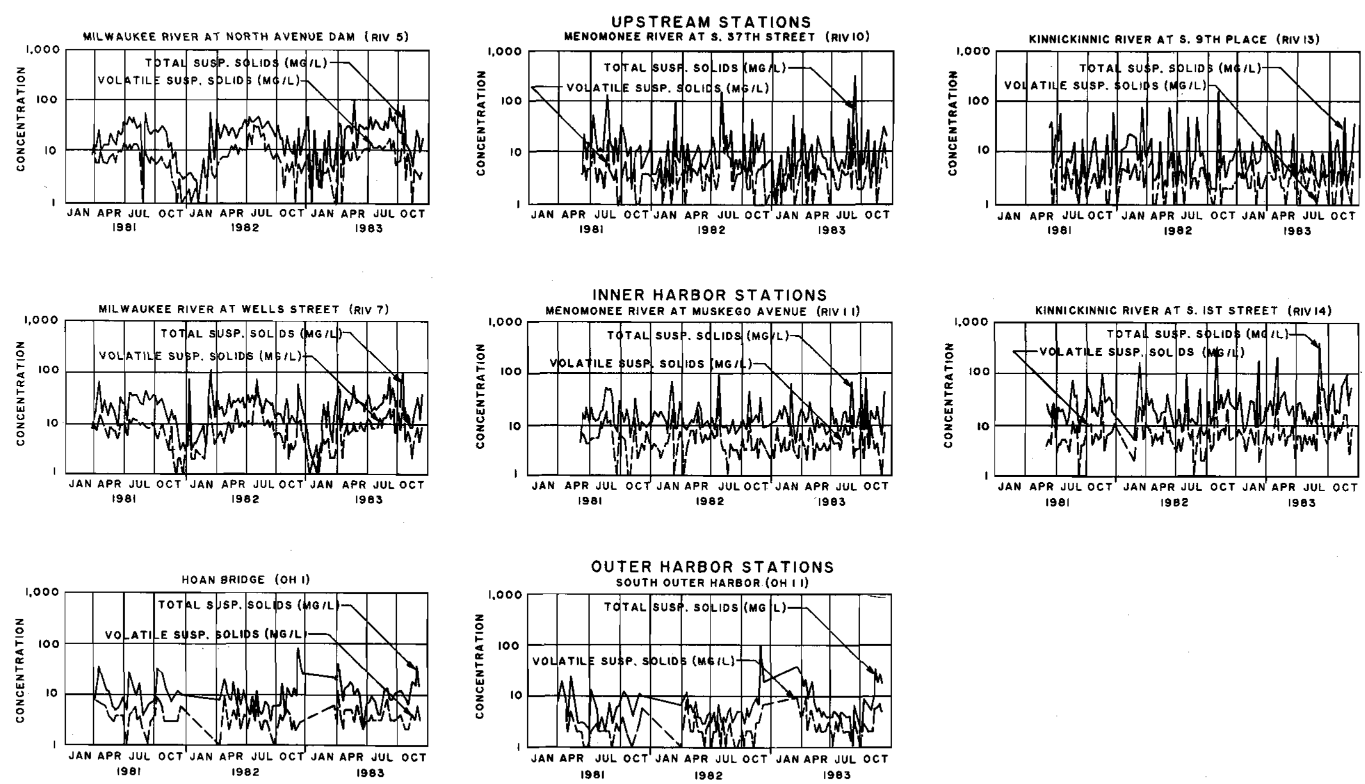
CONCENTRATION VERSUS TIME PLOTS FOR FECAL COLIFORM AND BOD_5: 1981-1983



Source: SEWRPC.

Figure 98

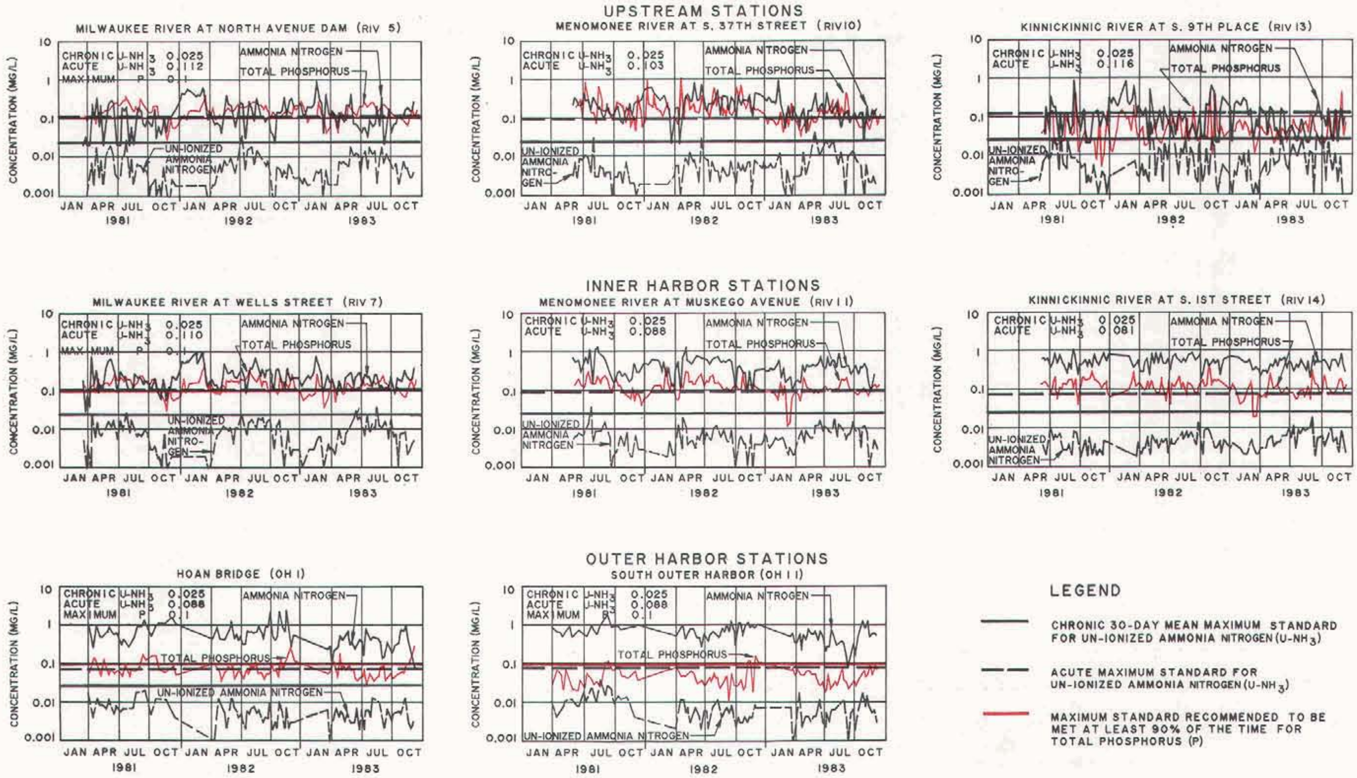
CONCENTRATION VERSUS TIME PLOTS FOR TOTAL SUSPENDED SOLIDS AND VOLATILE SUSPENDED SOLIDS: 1981-1983



Source: SEWRPC.

Figure 99

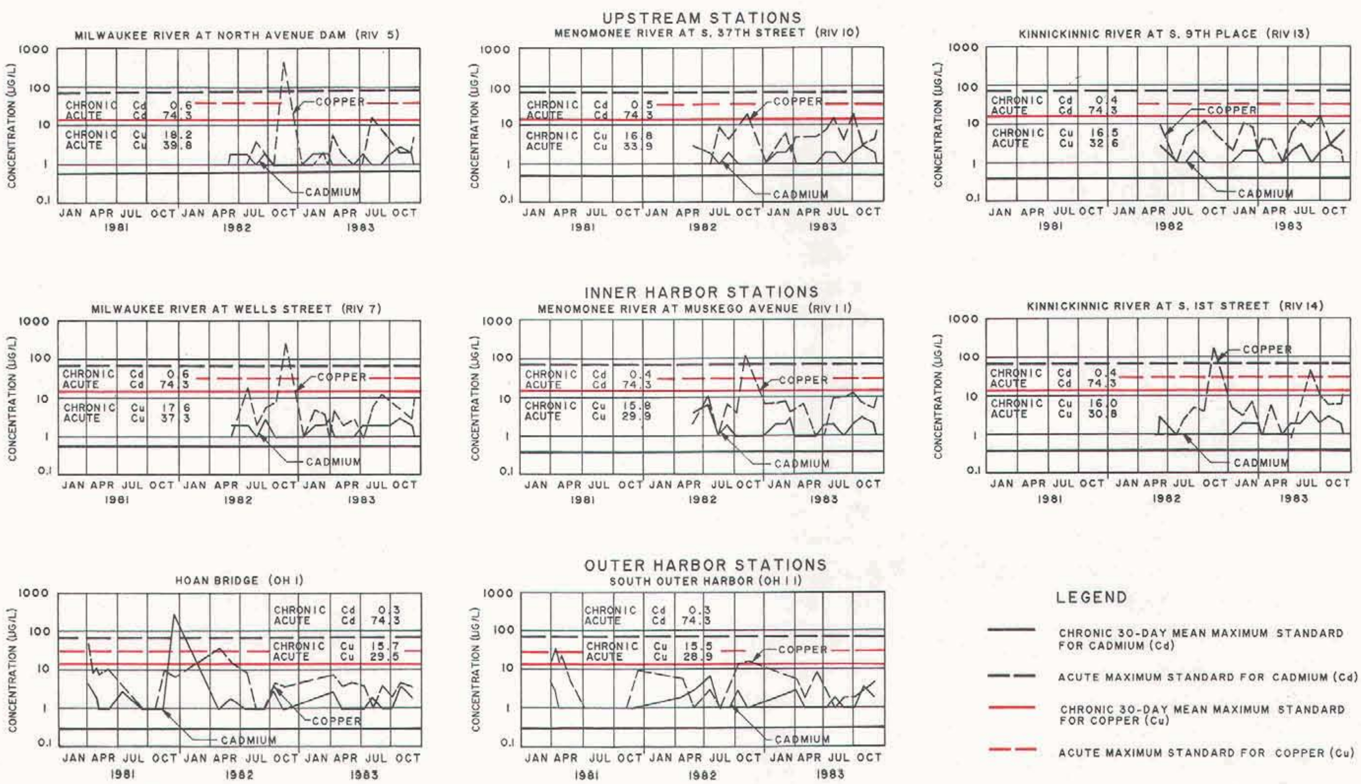
CONCENTRATION VERSUS TIME PLOTS FOR TOTAL PHOSPHORUS, AMMONIA NITROGEN, AND UN-IONIZED AMMONIA NITROGEN: 1981-1983



Source: SEWRPC.

Figure 100

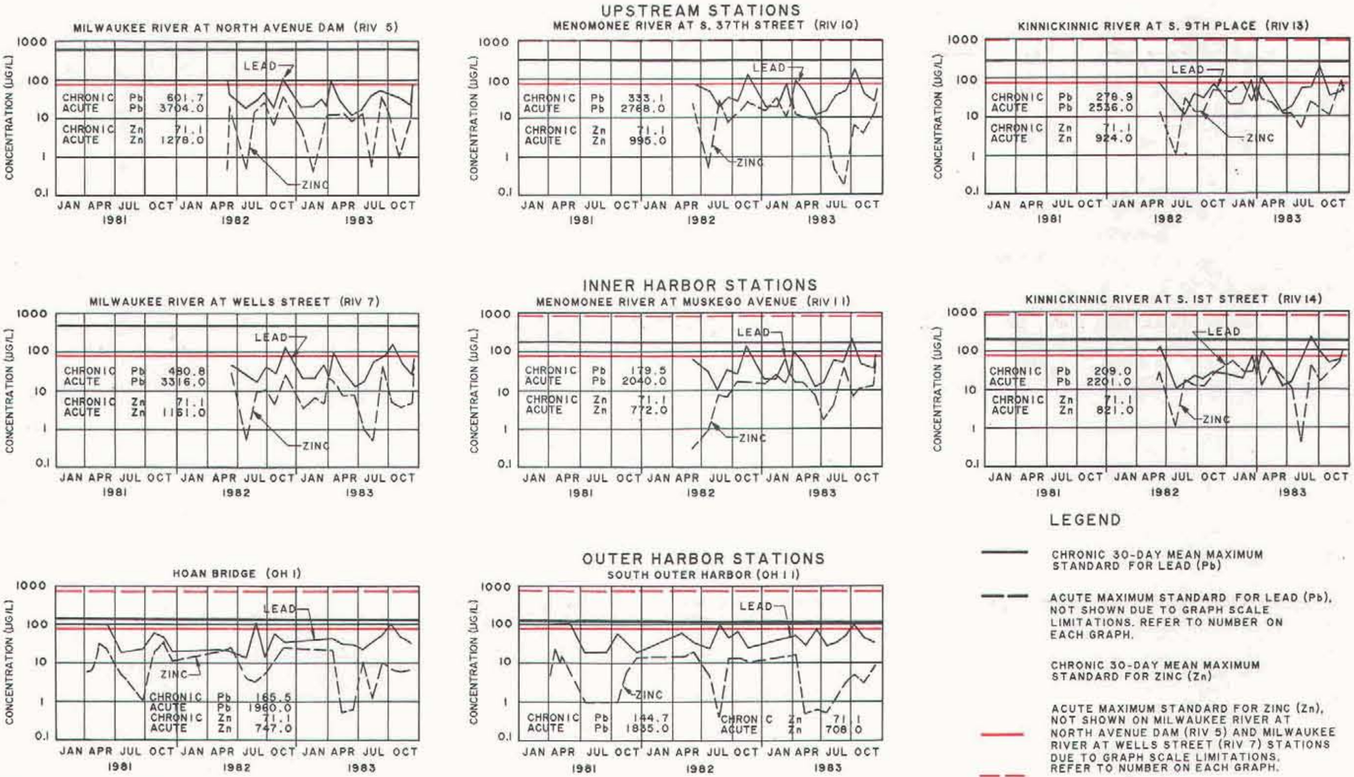
CONCENTRATION VERSUS TIME PLOTS FOR CADMIUM AND COPPER: 1981-1983



Source: SEWRPC.

Figure 101

CONCENTRATION VERSUS TIME PLOTS FOR LEAD AND ZINC: 1981-1983



Source: SEWRPC.

Water Quality Runoff Event Conditions

Until recently, water quality sampling and monitoring were most often conducted during dry-weather, low-flow periods such as might be expected in July, August, and September. This practice reflected a stage in the development of the state-of-the-art of water quality management when continuous and relatively uniform discharges from point sources—primarily municipal sewage treatment plant and industrial wastewater outfalls—were the dominant sources of pollution and, in effect, the only sources addressed in pollution abatement efforts. The impact of these kinds of "point" sources of pollutants on streamwater quality was most critical when streamflows were lowest. In the last decade, significant progress has been made in the control of major point sources of pollution. Consequently, substances carried into the streams by land surface runoff, particularly during major rainfall or snowmelt runoff events, are becoming increasingly important in terms of their impacts on water quality. That direct runoff moves from the land surface to the surface waters by overland routes, such as drainage swales and street and highway ditches and gutters, or by the underground storm sewer system and combined sewer system.

As previously mentioned, the surface water quality sampling program conducted under this study included an "event-related" component. Five intensive synoptic runoff event sampling surveys were conducted by the U. S. Geological Survey, the Milwaukee Metropolitan Sewerage District, and the Regional Planning Commission during the monitoring program. These events occurred in the months of April 1983, September 1983, October 1983, February 1984, and August 1984. A more detailed description of the runoff event sampling program, including the locations of sampling stations, water quality indicators, and field sampling methods used, is set forth in Chapter IV of this volume.

The types and the amount of runoff and pollutant washoff generated during a storm event are greatly affected by the amount of rainfall, as well as the season in which the event occurs. The storm events surveyed were chosen to represent a range of rainfall conditions which result in combined sewer overflows. All of the events selected, therefore, had a sufficient rainfall intensity—at least 0.1 to 0.2 inch per hour—to cause an overflow of the combined sewer system. In addition, the events

Table 64

DISSOLVED METAL CONCENTRATIONS IN THE INNER HARBOR: 1976

Dissolved Metal	Milwaukee River											
	Acute Toxic Standard	Chronic Toxic Standard	Cherry Street			Park Freeway			Kilbourn Avenue			Wells Street
			Jan. 20	March 9	May 1	Jan. 20	March 9	May 1	Jan. 20	March 9	May 1	March 9
Cadmium (μg/l)	74.3	0.6	0.2	0.5	<0.1	0.2	0.6	0.1	0.3	0.6	0.2	0.7
Copper (μg/l)	37.3	17.6	5	5	2	6	4	3	6	4	3	4
Hexavalent Chromium (μg/l)	108.2	17.8	6	<5	<5	7	<5	<5	10	<5	<5	<5
Lead (μg/l)	3,316	481	4	1	<1	1	<1	<1	2	<1	<1	6
Mercury (μg/l)	2.22	0.2	0.5	0.8	0.3	<0.2	0.7	0.4	1.1	0.4	0.3	1.6
Nickel (μg/l)	3,955	272	5	12	<5	5	7	12	5	17	<5	12
Zinc (μg/l)	1,161	71.1	15	4	5	15	12	8	23	5	8	1

Dissolved Metal	Menomonee River								South Menomonee Canal				
	Acute Toxic Standard	Chronic Toxic Standard	Confluence with Burnham Canal			S. 16th Street			Acute Toxic Standard	Chronic Toxic Standard	WEPCo Outfall		
			Jan. 21	March 9	May 1	Jan. 21	March 9	May 1			Jan. 21	March 9	May 1
Cadmium (μg/l)	74.3	0.4	0.4	0.2	0.1	1.1	0.3	<0.1	74.3	0.4	0.2	0.3	0.2
Copper (μg/l)	29.9	15.8	9	3	4	10	4	3	29.9	15.8	10	3	4
Hexavalent Chromium (μg/l)	108.2	17.8	14	<5	<5	<5	<5	<5	108.2	17.8	5	<5	<5
Lead (μg/l)	2,040	180	2	1	<1	1	<1	<1	2,040	180	1	6	<1
Mercury (μg/l)	2.22	0.2	2.0	0.3	0.2	1.5	1.4	0.4	2.22	0.2	0.4	0.2	0.2
Nickel (μg/l)	3,955	272	7	12	5	13	8	6	3,955	272	7	9	5
Zinc (μg/l)	772	71.1	35	34	6	69	30	8	772	71.1	27	39	11

NOTE: The acute toxic and chronic toxic standards apply to acid-soluble metals but are presented herein to allow comparison to dissolved metal concentrations. Standards may vary by river because they are a function of the hardness of the water.

Source: CDM/Limnetics Environmental Consultants.

were selected to cover a range of seasonal conditions. Thus, one spring event, two summer events, one fall event, and one late winter event were surveyed. Significant variations were found in the total amount of precipitation that occurred at different sampling station locations in the estuary area during these storm events. Based on rainfall data provided by the City of Milwaukee Bureau of Engineers at seven rain gage stations located within the Milwaukee Harbor estuary direct drainage area, the total amount of precipitation which occurred during the storm events ranged from approximately 0.4 to 0.7 inch in the September 1983 runoff event, to approximately 1.6 to 2.4 inches in the April 1983 runoff event.

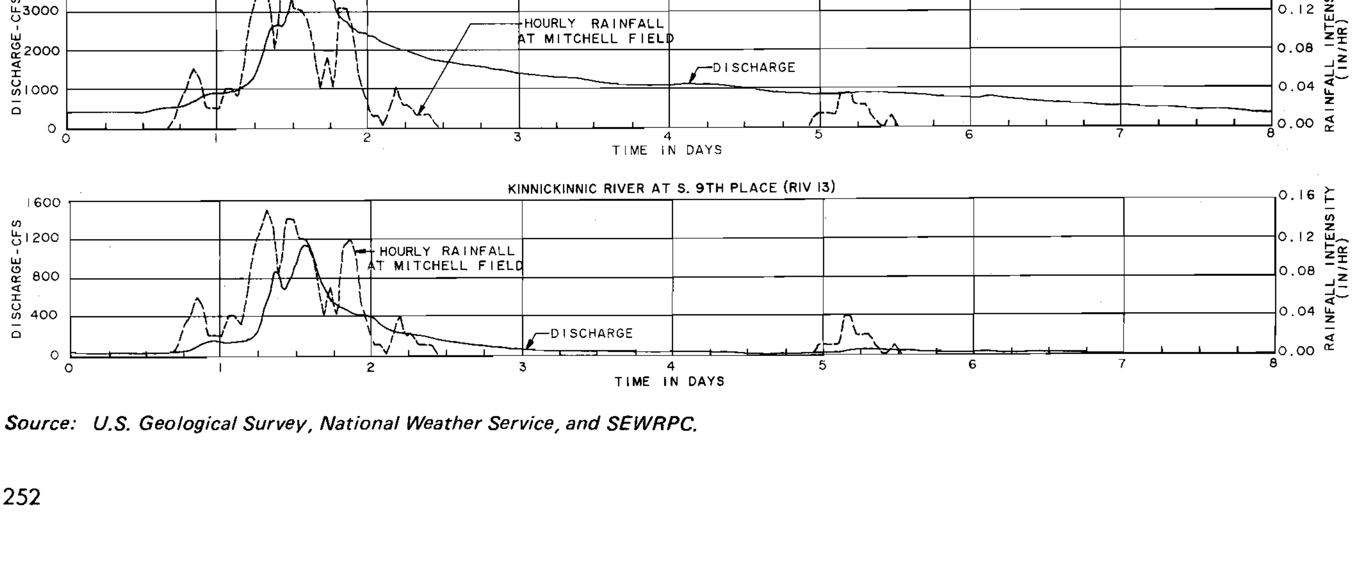
As already noted, the season of the year also affects the type and amount of pollutant loadings during major runoff events. Therefore, the storm events surveyed were chosen to characterize seasonal changes. More specifically, surveys of snowmelt runoff events provide data on the washoff of pollutant loads which have accumulated over the winter months and are flushed from the land surface; surveys of the first major spring rainfall runoff event provide data on the washoff of pollutant loads which have accumulated in, and are flushed from, separate sewers, combined sewers, and the land surface; surveys of summer thunderstorm events provide data on pollutant loads flushed from the land surface by brief but intense rainfall events; and a fall rainfall runoff event provides data on the effect of defoliage of deciduous trees and attendant increased pollutant loads. The runoff event sampling was conducted at the 10 riverine stations, nine inner harbor stations, 10 outer harbor stations, and five near-shore Lake Michigan stations which were also sampled in the baseline sampling program. In all, approximately 2,370 water quality samples were collected and analyzed under the runoff sampling program.

The following describes the findings of these surveys, including a statistical analysis of the concentrations of selected water quality indicators found at various sampling stations; a description of the spatial water quality variations in the upstream, inner harbor, and outer harbor stations; an illustration of temporal variations in the water quality conditions at selected sampling stations; an evaluation of the receiving water quality conditions relative to the recommended water use objectives and supporting standards set forth in Chapter II of Volume Two of this report; and a description of the type and amount of pollutant loadings being transported into the estuarine systems by the Milwaukee, Menomonee, and Kinnickinnic Rivers.

April 1-8, 1983 Runoff Event: The first intensive runoff event was sampled in April 1983. The total amount of rainfall that occurred in the Milwaukee Harbor estuary direct drainage area during this runoff event ranged from 1.60 inches to 2.35 inches. The total duration of the rainfall was approximately 36 hours. Figure 102 illustrates the precipitation pattern that occurred at General Mitchell Field during the monitoring period in relationship to measured flows at the three river stations located just upstream of the inner harbor. During the eight-day monitoring period, the upstream stations were sampled on a depth-integrated basis between nine and 13 times, the inner harbor stations were sampled at three depths between six and 13 times, and the outer harbor stations were sampled at three depths between three and five times.

Figure 102

DISCHARGE AND RAINFALL MEASUREMENTS AT STATIONS JUST UPSTREAM OF THE INNER HARBOR: APRIL 1-8, 1983



Source: U.S. Geological Survey, National Weather Service, and SEWRPC.

A summary of the concentrations of selected water quality indicators found at three representative upstream stations, three representative inner harbor stations, and two representative outer harbor stations is presented in Table 65. Based on these representative stations, the findings of the water quality monitoring during the April event are discussed below.

Table 65

SUMMARY OF RUNOFF EVENT WATER QUALITY DATA AT SELECTED STATIONS: APRIL 1-8, 1983

Sampling Station	Statistical Variable	Dissolved Oxygen (mg/l)	Fecal Coliform (MPN/100ml)	Total Suspended Solids (mg/l)	Total Phosphorus (mg/l)	Ammonia Nitrogen (mg/l)	Un-ionized Ammonia Nitrogen (mg/l)	Volatile Suspended Solids (mg/l)	BOD_5 (mg/l)
Upstream Stations									
Milwaukee River at North Avenue Dam (RIV-5)	Number of Samples	12	13	12	13	13	13	12	12
	Minimum	12.2	200	14	0.06	0.06	0.002	3	1.7
	Mean	12.8	5,900	65	0.14	0.18	0.050	11	2.6
	Maximum	14.1	24,000	234	0.36	1.07	0.539	34	4.4
	Standard Deviation	0.5	8,500	63	0.08	0.27	0.159	8	0.8
Menomonee River at S. 37th Street (RIV-10)	Number of Samples	13	12	13	13	13	13	13	12
	Minimum	11.8	400	16	0.06	0.05	0.000	2	1.1
	Mean	12.5	3,900	98	0.13	0.14	0.003	16	3.4
	Maximum	13.4	11,000	352	0.41	0.35	0.006	42	9.3
	Standard Deviation	0.5	3,400	100	0.10	0.09	0.002	14	2.9
Kinnickinnic River at S. 9th Place (RIV-13)	Number of Samples	10	9	11	11	11	11	11	10
	Minimum	9.4	100	12	0.04	0.09	0.000	4	1.1
	Mean	11.6	9,300	214	0.33	0.27	0.003	22	5.0
	Maximum	13.6	24,000	854	1.39	0.88	0.010	63	12.0
	Standard Deviation	1.3	9,200	287	0.50	0.21	0.003	20	3.4
Inner Harbor Stations									
Milwaukee River at Wells Street (RIV-7)	Number of Samples	39	13	39	39	39	39	39	28
	Minimum	10.2	200	10	0.06	0.06	0.000	1	1.2
	Mean	11.2	15,000	63	0.15	0.16	0.005	12	3.5
	Maximum	12.7	93,000	259	0.43	0.58	0.047	42	8.7
	Standard Deviation	0.5	25,000	58	0.09	0.12	0.008	9	1.7
Menomonee River at Muskego Avenue (RIV-11)	Number of Samples	36	12	39	39	39	39	39	26
	Minimum	9.9	900	7	0.06	0.05	0.001	2	0.4
	Mean	11.1	9,400	46	0.07	0.22	0.003	8	4.4
	Maximum	12.8	46,000	184	0.08	0.85	0.013	29	8.8
	Standard Deviation	0.9	12,000	47	0.01	0.19	0.002	6	2.5
Kinnickinnic River at S. 1st Street (RIV-14)	Number of Samples	39	11	42	42	42	42	42	31
	Minimum	6.9	400	14	0.02	0.09	0.000	3	0.8
	Mean	10.3	26,000	129	0.21	0.32	0.013	16	4.7
	Maximum	13.5	110,000	776	1.37	1.20	0.176	74	26.0
	Standard Deviation	1.9	32,000	203	0.31	0.17	0.031	17	4.7
Outer Harbor Stations									
Hoan Bridge[a] (OH-1)	Number of Samples	15	5	5	15	15	15	5	5
	Minimum	10.5	400	14	0.07	0.07	0.000	4	0.6
	Mean	12.6	5,500	30	0.10	0.12	0.001	8	1.6
	Maximum	14.8	11,000	56	0.12	0.25	0.002	12	2.5
	Standard Deviation	1.2	4,500	18	0.02	0.06	0.001	4	0.7
South Outer Harbor[a] (OH-11)	Number of Samples	15	5	5	15	15	15	5	5
	Minimum	11.0	<100	8	0.04	0.25	0.000	4	2.0
	Mean	12.5	300	22	0.06	0.34	0.003	5	2.4
	Maximum	14.4	900	38	0.09	0.50	0.008	8	3.3
	Standard Deviation	1.0	400	11	0.01	0.07	0.003	2	0.6

[a]*Concentrations of BOD_5 were not measured at stations OH-1 and OH-11. Therefore, concentrations of BOD_5 measured at OH-7, located at the main harbor entrance, are presented for OH-1, and concentrations of BOD_5 measured at OH-3, located in the central outer harbor, are presented for OH-11.*

Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

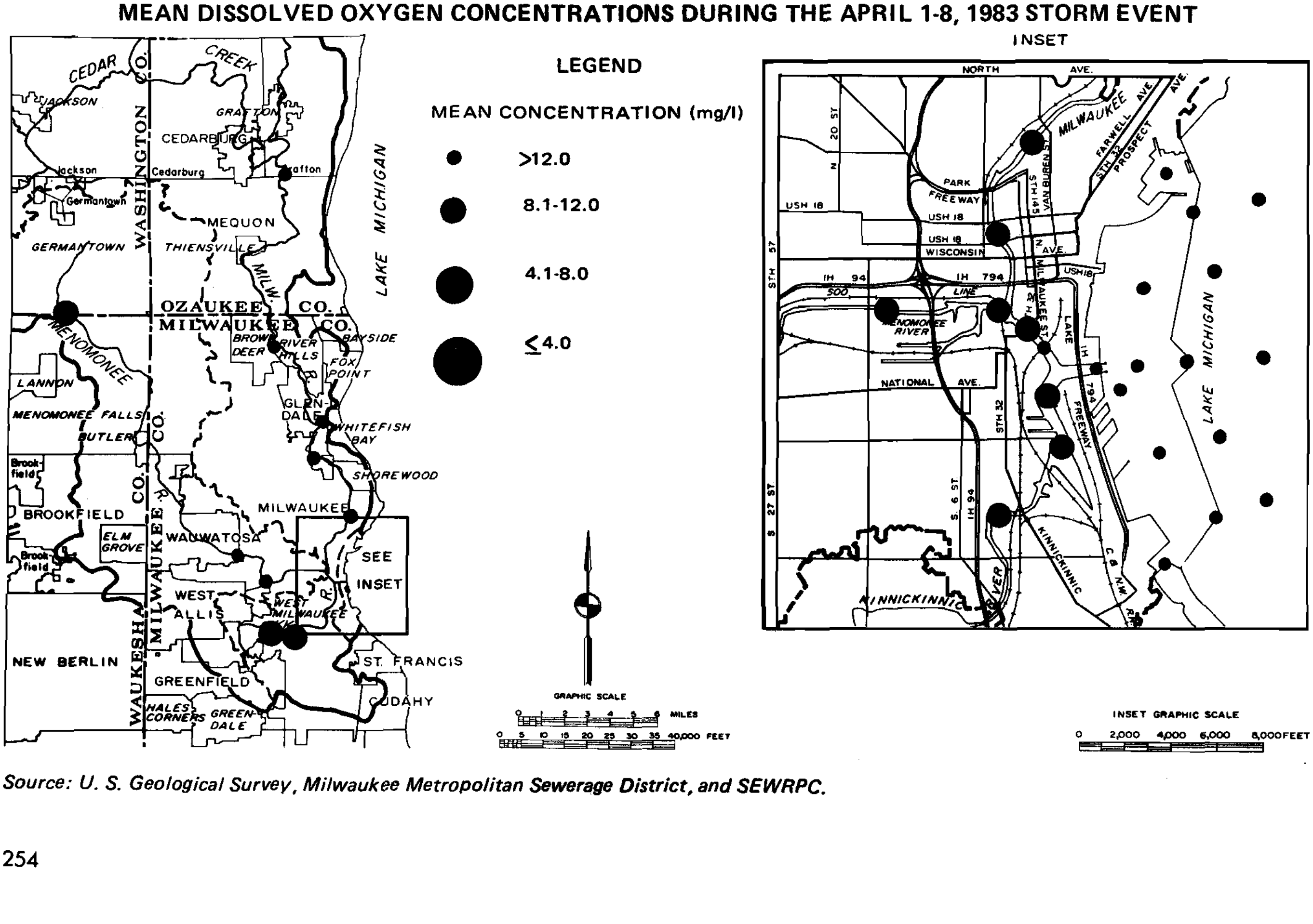
Dissolved oxygen levels were relatively high at all stations, with values ranging from 6.9 to 14.8 mg/l. Spatial variations in dissolved oxygen levels are shown on Map 58, and temporal variations which occurred during the event sampling program are presented in Figure 103. In all three rivers, the dissolved oxygen concentrations at the upstream stations, with means ranging from 11.6 to 12.8 mg/l, were slightly higher than the concentrations at the inner harbor stations, with means ranging from 10.3 to 11.2 mg/l. At both the estuary and upstream stations, the Kinnickinnic River dissolved oxygen concentrations were slightly lower than the concentrations in the Menomonee and Milwaukee Rivers. The dissolved oxygen concentrations were relatively high in the outer harbor, with the mean levels ranging from 12.5 to 12.6 mg/l. As shown in Figure 103, during the event, the dissolved oxygen levels either remained constant or declined slightly. Within the inner and outer harbors, there were no significant differences between the dissolved oxygen levels at the three sample depths.

Fecal coliform levels ranged from fewer than 100 to 110,000 MPN/100 ml. Spatial variations in fecal coliform levels are shown on Map 59 and temporal variations which occurred during the event sampling program are presented in Figure 104. In all three rivers, the fecal coliform levels at the inner harbor stations, with means ranging from 9,400 to 26,000 MPN/100 ml, were at least twice as high as the levels at the upstream stations, with means ranging from 3,900 to 9,300 MPN/100 ml. At both the estuary and upstream stations, the Kinnickinnic River fecal coliform levels were generally higher than the levels in the Menomonee and Milwaukee Rivers. Mean fecal coliform levels at the representative outer harbor stations ranged from 300 to 5,500 MPN/100 ml. As shown in Figure 104, the fecal coliform levels generally exhibited a "first flush" effect, especially in the inner harbor, in that peak fecal coliform concentrations were reached shortly after the event began.

Total suspended solids concentrations ranged from 7 to 854 mg/l. Spatial variations in suspended solids concentrations are shown on Map 60, and temporal variations are presented in Figure 105. In all three rivers, the suspended solids concentrations in the upstream reaches, with means ranging from 65 to 214 mg/l, were slightly higher than the concentrations within the inner harbor—with means

Map 58

MEAN DISSOLVED OXYGEN CONCENTRATIONS DURING THE APRIL 1-8, 1983 STORM EVENT



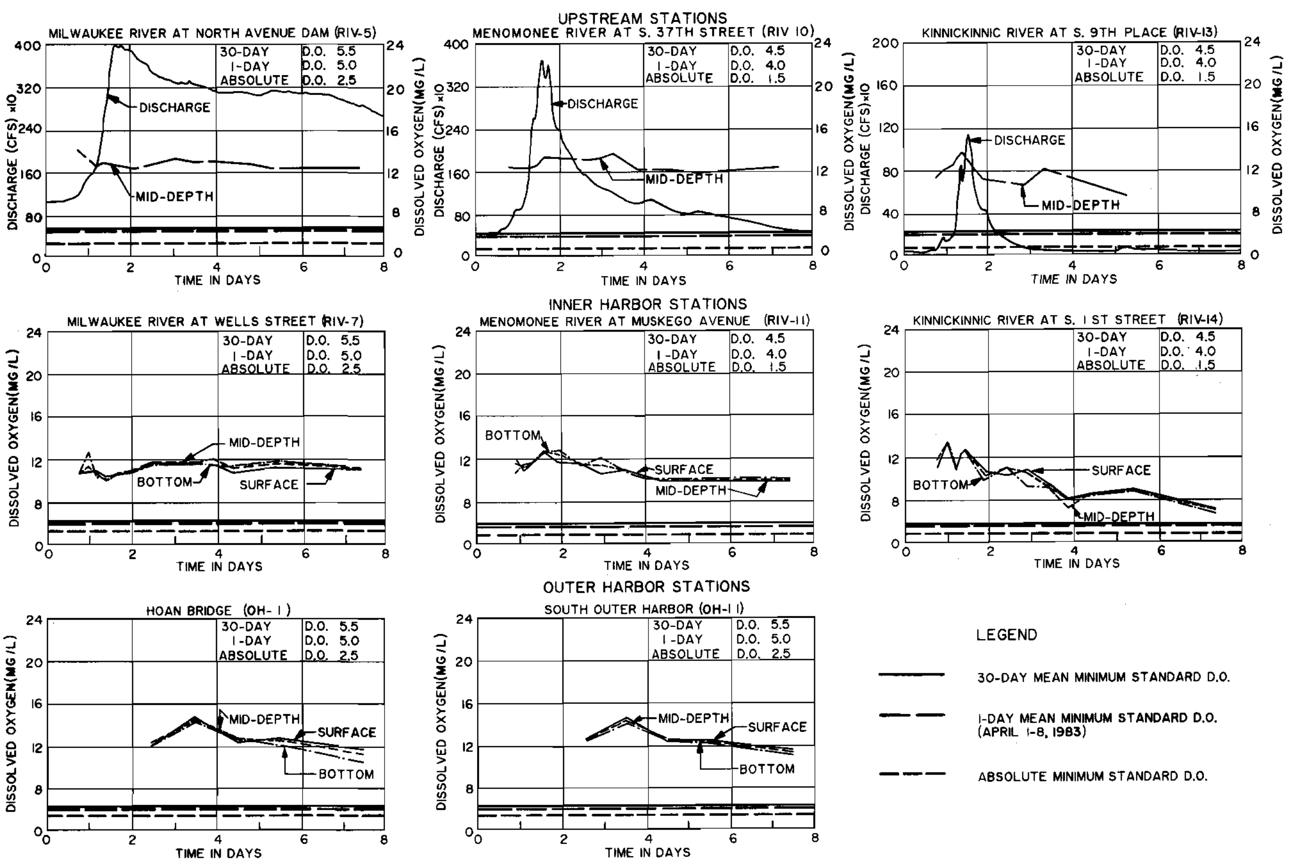
Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

ranging from 46 to 129 mg/l. At both the estuary and upstream stations, the Kinnickinnic River suspended solids concentrations were higher than in the Milwaukee and Menomonee Rivers. Total suspended solids concentrations were lowest in the outer harbor, with means ranging from 22 to 30 mg/l. As shown in Figure 105, the suspended solids concentrations also exhibited a "first flush" effect within both the upstream reaches and the inner harbor. Within the inner harbor, there was little significant difference between the suspended solids concentrations at the three sample depths, except that within the Milwaukee and Kinnickinnic River estuaries, the peak concentrations were highest in the bottom layer of water.

Total phosphorus concentrations ranged from 0.02 to 1.39 mg/l. Spatial variations in total phosphorus concentrations are shown on Map 61, and temporal variations are presented in Figure 106. In the Menomonee and Kinnickinnic River estuaries, the mean total phosphorus concentrations—ranging from 0.07 to 0.21 mg/l—were lower than the mean concentrations measured in the upstream reaches, which ranged from 0.13 to 0.33 mg/l. In the Milwaukee River estuary, however, the mean concentration of total phosphorus was about the same as in the upstream reach—about 0.15 mg/l. The Kinnickinnic River estuary and upstream reaches had mean total phosphorus concentrations that were 40 to 150 percent higher than those present in the Menomonee and Milwaukee Rivers. Mean total phosphorus concentrations in the outer harbor ranged from 0.06 to 0.10 mg/l, or slightly lower than the levels found in the inner harbor. As shown in Figure 106, total phosphorus concentrations also exhibited a "first flush" effect in both the upstream and inner harbor stations. After this "first flush," the total phosphorus concentrations quickly returned to near-background levels. As with suspended solids, the peak phosphorus concentrations in the Milwaukee and Kinnickinnic River estuary stations were highest in the bottom layer of water. In the Menomonee River, there was no difference between the phosphorus concentrations measured at the three sample depths.

Figure 103

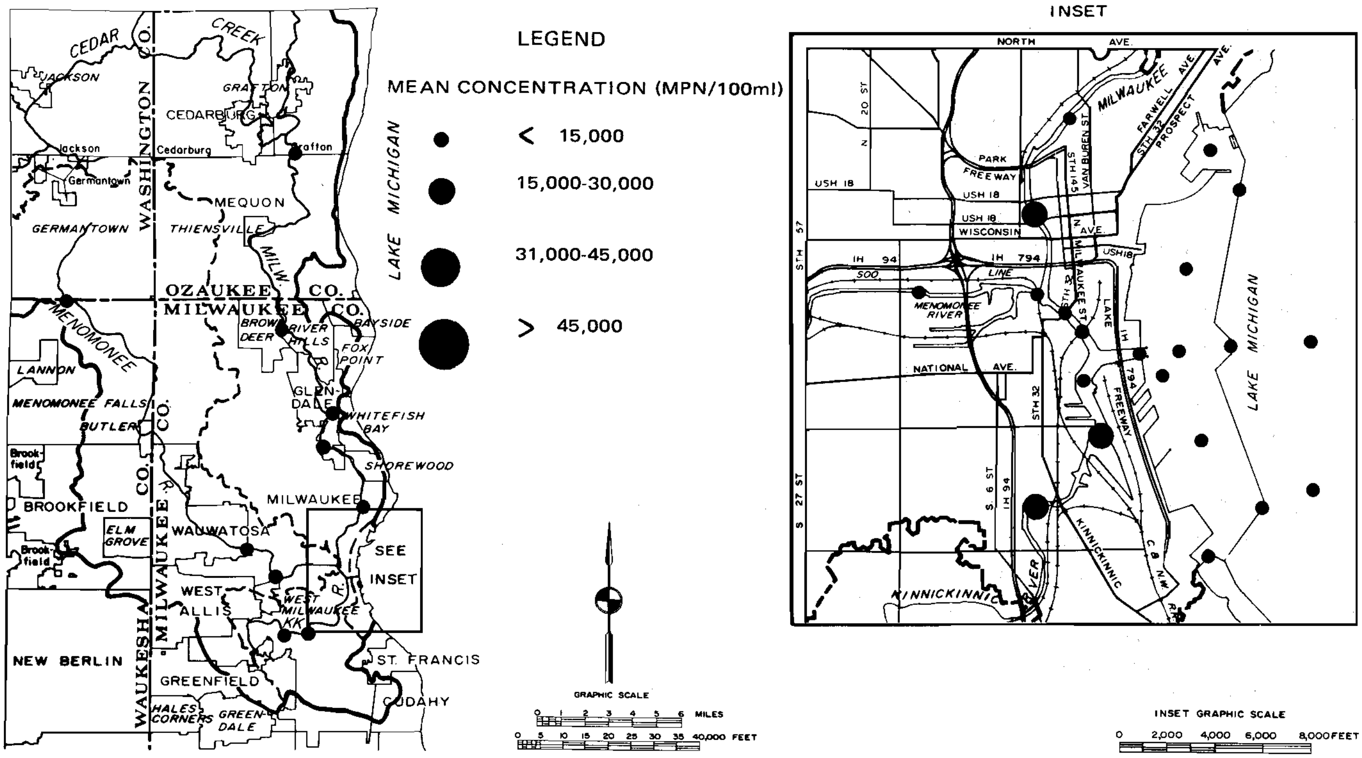
CONCENTRATION VERSUS TIME PLOTS FOR DISSOLVED OXYGEN: APRIL 1-8, 1983



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 59

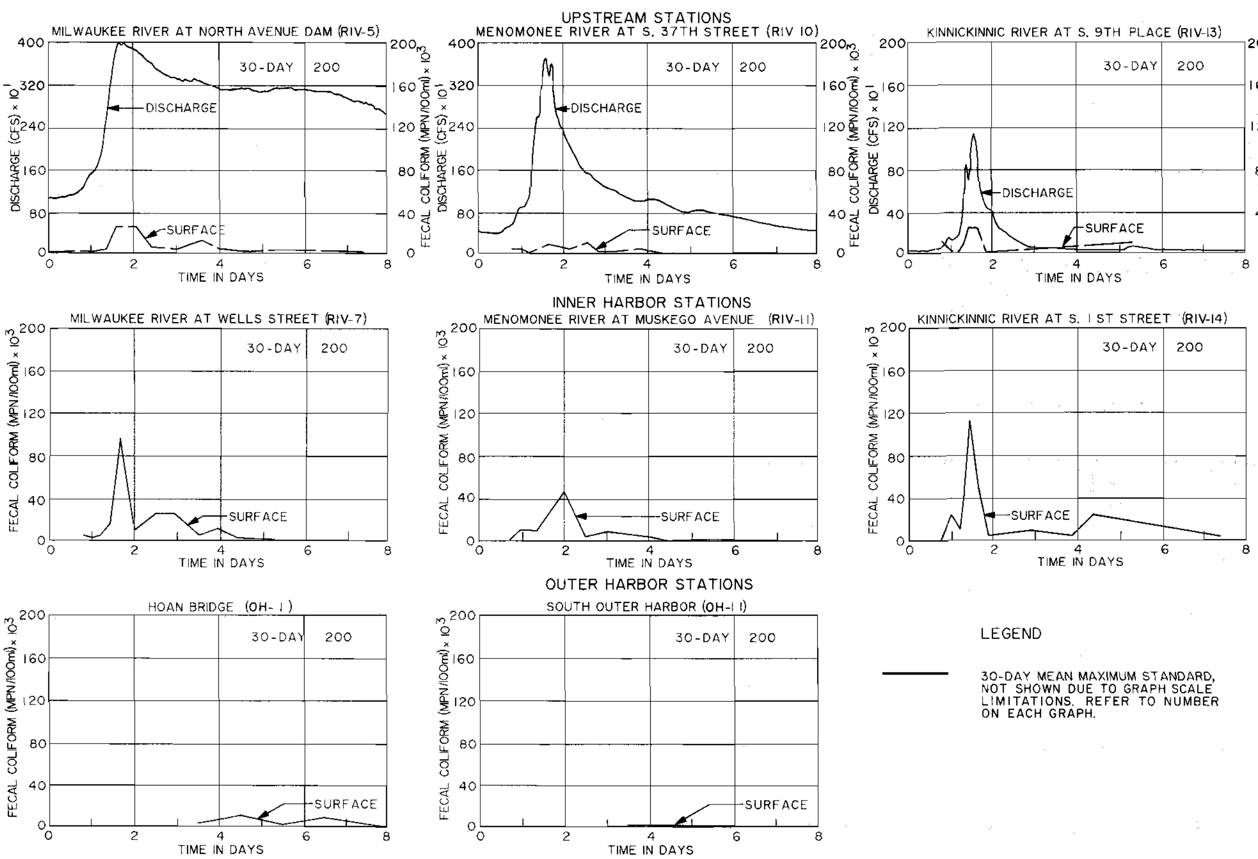
MEAN FECAL COLIFORM CONCENTRATIONS DURING THE APRIL 1-8, 1983 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 104

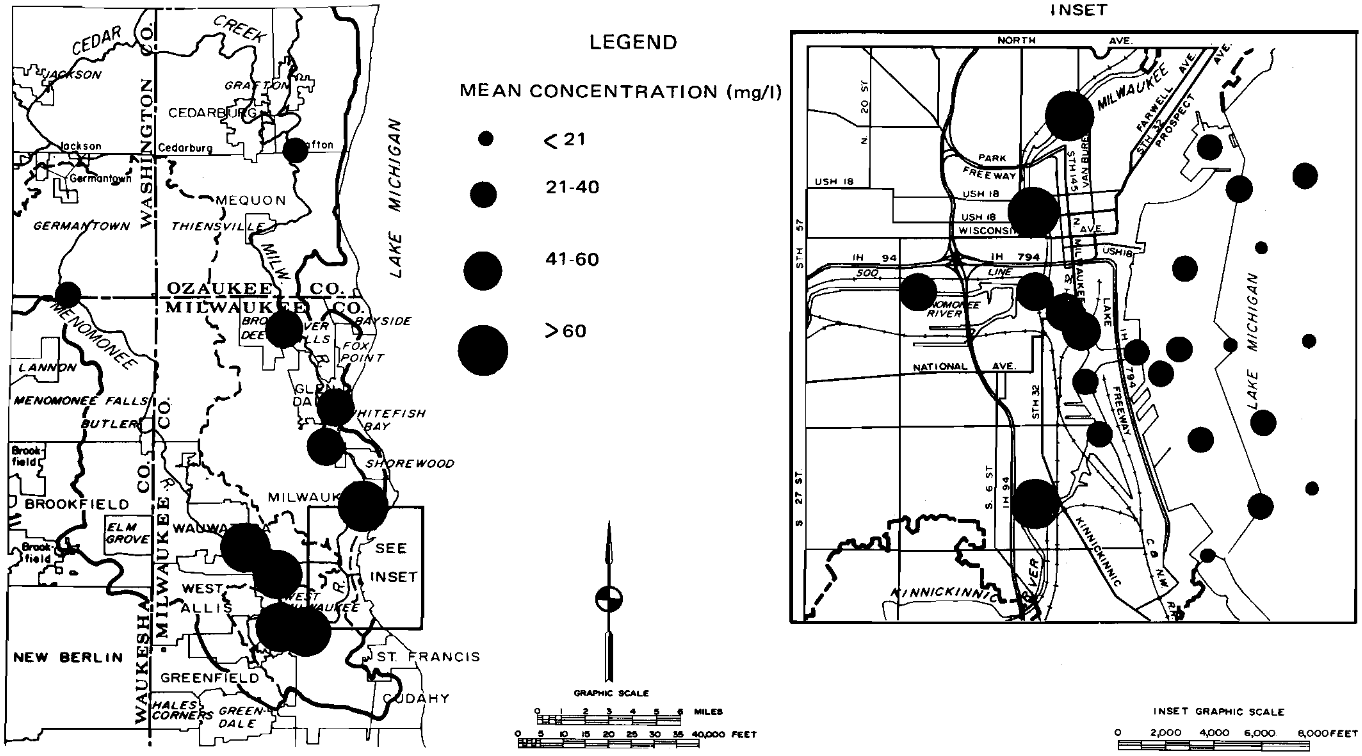
CONCENTRATION VERSUS TIME PLOTS FOR FECAL COLIFORM: APRIL 1-8, 1983



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 60

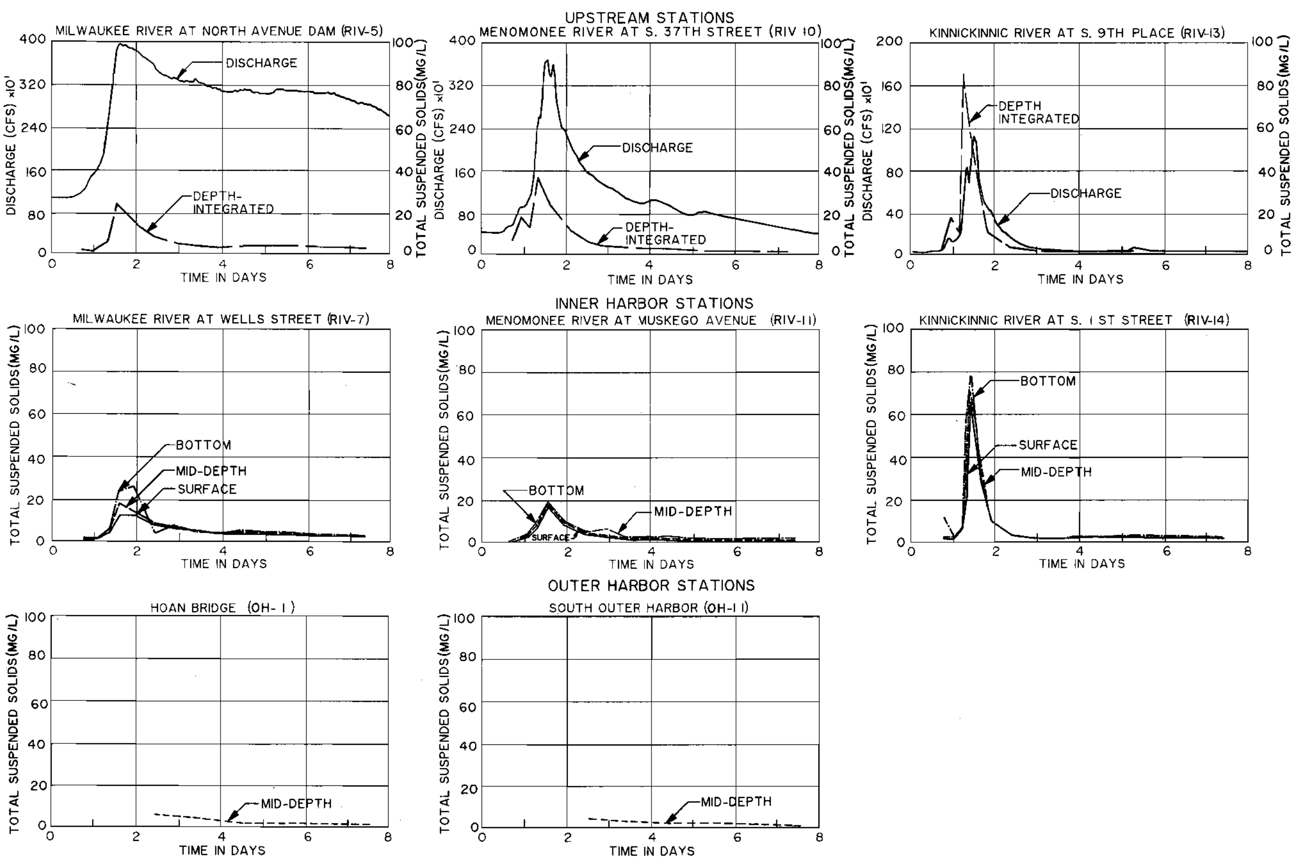
MEAN TOTAL SUSPENDED SOLIDS CONCENTRATION DURING THE APRIL 1-8, 1983 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 105

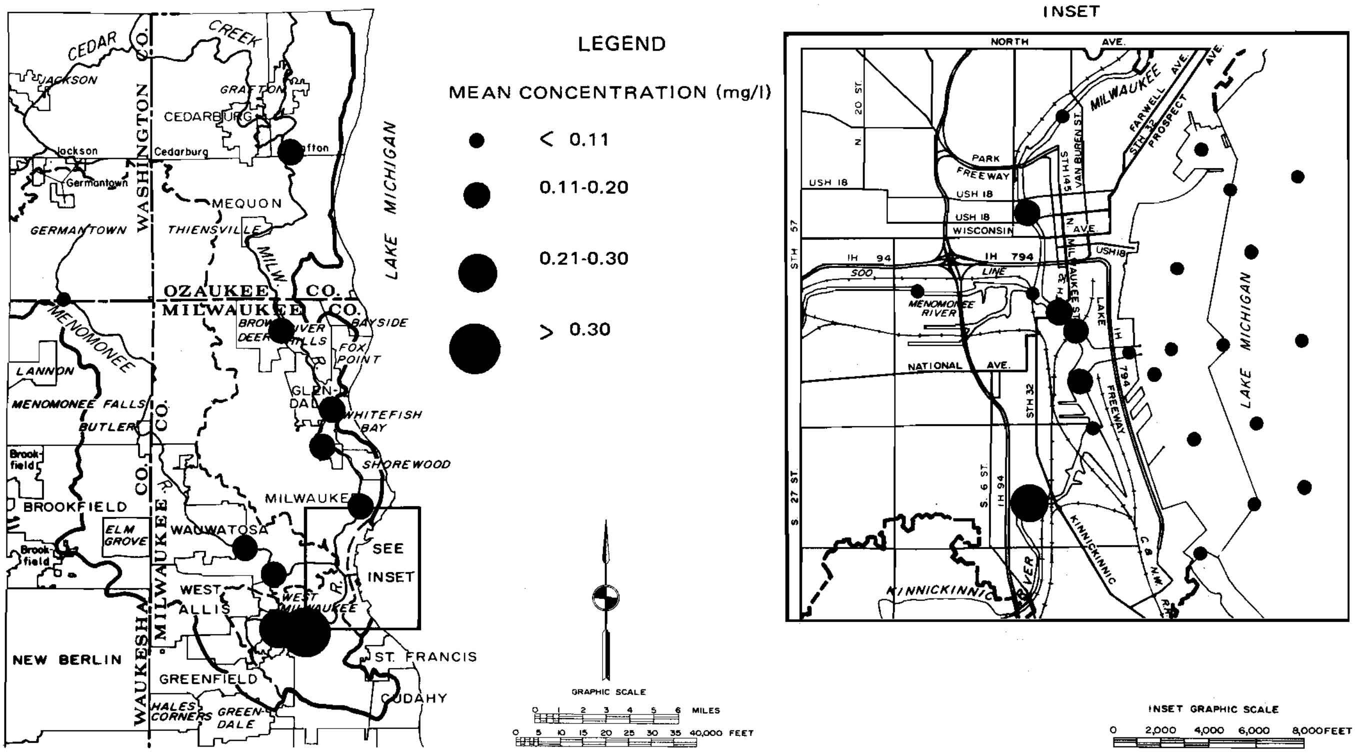
CONCENTRATION VERSUS TIME PLOTS FOR TOTAL SUSPENDED SOLIDS: APRIL 1-8, 1983



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 61

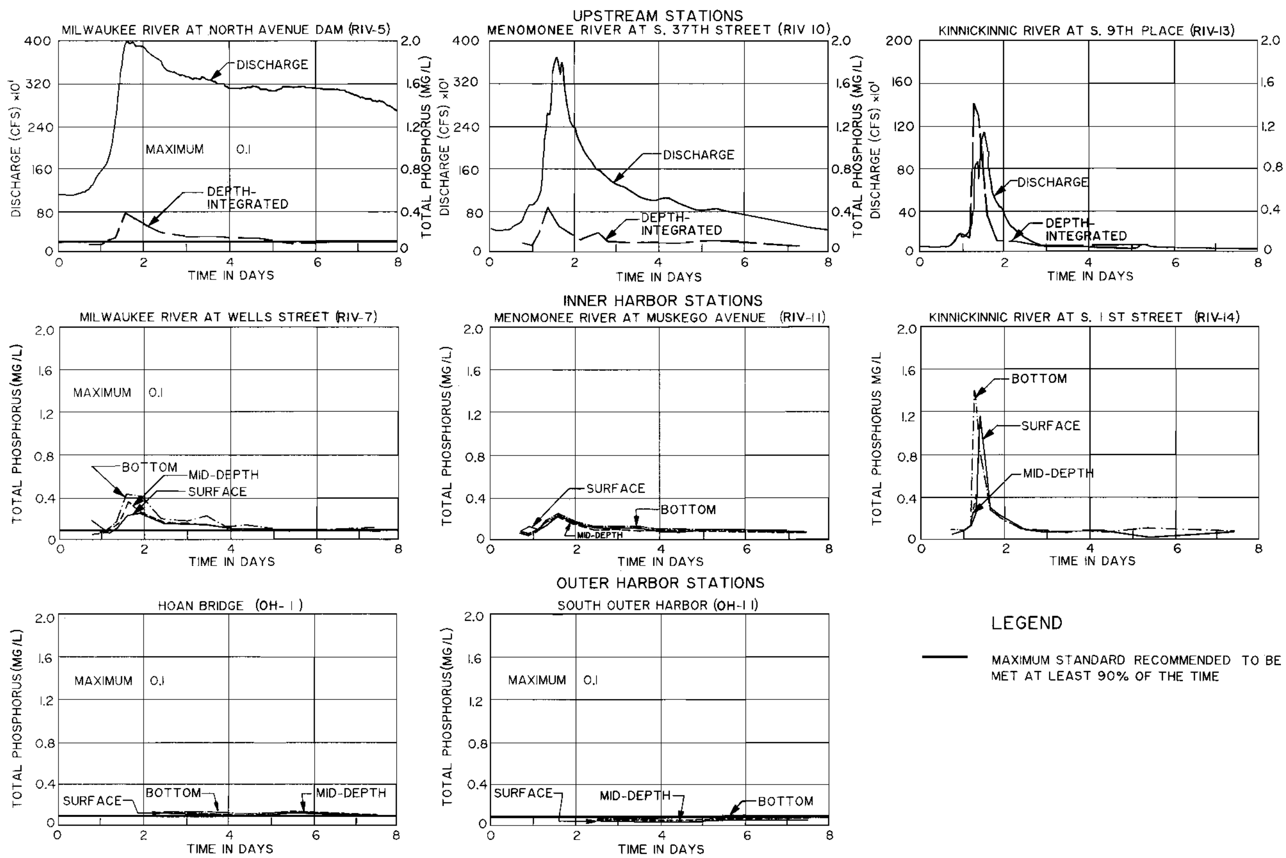
MEAN TOTAL PHOSPHORUS CONCENTRATIONS DURING THE APRIL 1-8, 1983 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 106

CONCENTRATION VERSUS TIME PLOTS FOR TOTAL PHOSPHORUS: APRIL 1-8, 1983



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Ammonia nitrogen concentrations ranged from 0.05 to 1.20 mg/l. The mean concentrations measured at the upstream stations—ranging from 0.14 to 0.27 mg/l—were similar to those measured at the inner harbor stations, which ranged from 0.16 to 0.32 mg/l. The outer harbor exhibited mean ammonia nitrogen concentrations ranging from 0.12 to 0.34 mg/l.

Un-ionized ammonia nitrogen concentrations ranged from 0 to 0.539 mg/l. The mean concentrations measured at the upstream stations ranged from 0.003 to 0.05 mg/l, and at the inner harbor stations, from 0.003 to 0.013 mg/l. Un-ionized ammonia nitrogen concentrations were lowest in the outer harbor, with means ranging from 0.001 to 0.003 mg/l.

Volatile suspended solids concentrations ranged from 1 to 74 mg/l. The mean concentrations measured at the Kinnickinnic and Menomonee River estuary stations—ranging from 8 to 14 mg/l—were lower than those measured at the upstream stations—ranging from 16 to 22 mg/l. Within the Milwaukee River estuary, the concentrations of volatile suspended solids were about the same as the upstream concentrations, with a mean of about 12 mg/l. In both the upstream and estuary reaches, the Kinnickinnic River had higher mean and maximum volatile suspended solids concentrations than did the Menomonee and Milwaukee Rivers. Based on mean concentrations within the upstream and estuary reaches of the three rivers, the volatile suspended solids represented from 10 to 19 percent of the total suspended solids concentration. The relative portion of the total suspended solids load which was volatile was higher in the outer harbor—ranging from 23 to 27 percent. Concentrations of volatile suspended solids, however, were lower in the outer harbor than in the rivers, with means ranging from 5 to 8 mg/l.

Biochemical oxygen demand (BOD_5) concentrations ranged from 0.4 to 26.0 mg/l. The mean concentrations of BOD_5 measured at the upstream stations—ranging from 2.6 to 5.0 mg/l—were similar to the mean concentrations measured at the inner harbor stations, which ranged from 3.5 to 4.7 mg/l. At both the upstream and estuary portions of the Kinnickinnic River, the mean concentrations measured—ranging from 4.7 to 5.0 mg/l—were slightly higher than in the Milwaukee and Menomonee Rivers, where the means ranged from 2.6 to 4.4 mg/l. BOD_5 measurements were lowest in the outer harbor, with means ranging from 1.8 to 2.4 mg/l.

<u>September 10-14, 1983 Runoff Event</u>: The second intensive runoff event was sampled in September 1983. The total amount of rainfall that occurred in the Milwaukee Harbor estuary direct drainage area during this event ranged from 0.36 inch to 0.71 inch. The total duration of the rainfall was approximately 35 hours. Figure 107 illustrates the precipitation pattern that occurred at General Mitchell Field during the monitoring period in relationship to measured flows at the three river stations located just upstream of the inner harbor. During the five-day monitoring period, the upstream stations were sampled on a depth-integrated basis between four and 13 times, the inner harbor stations were sampled at three depths between four and 14 times, and the outer harbor stations were sampled at three depths either three or four times.

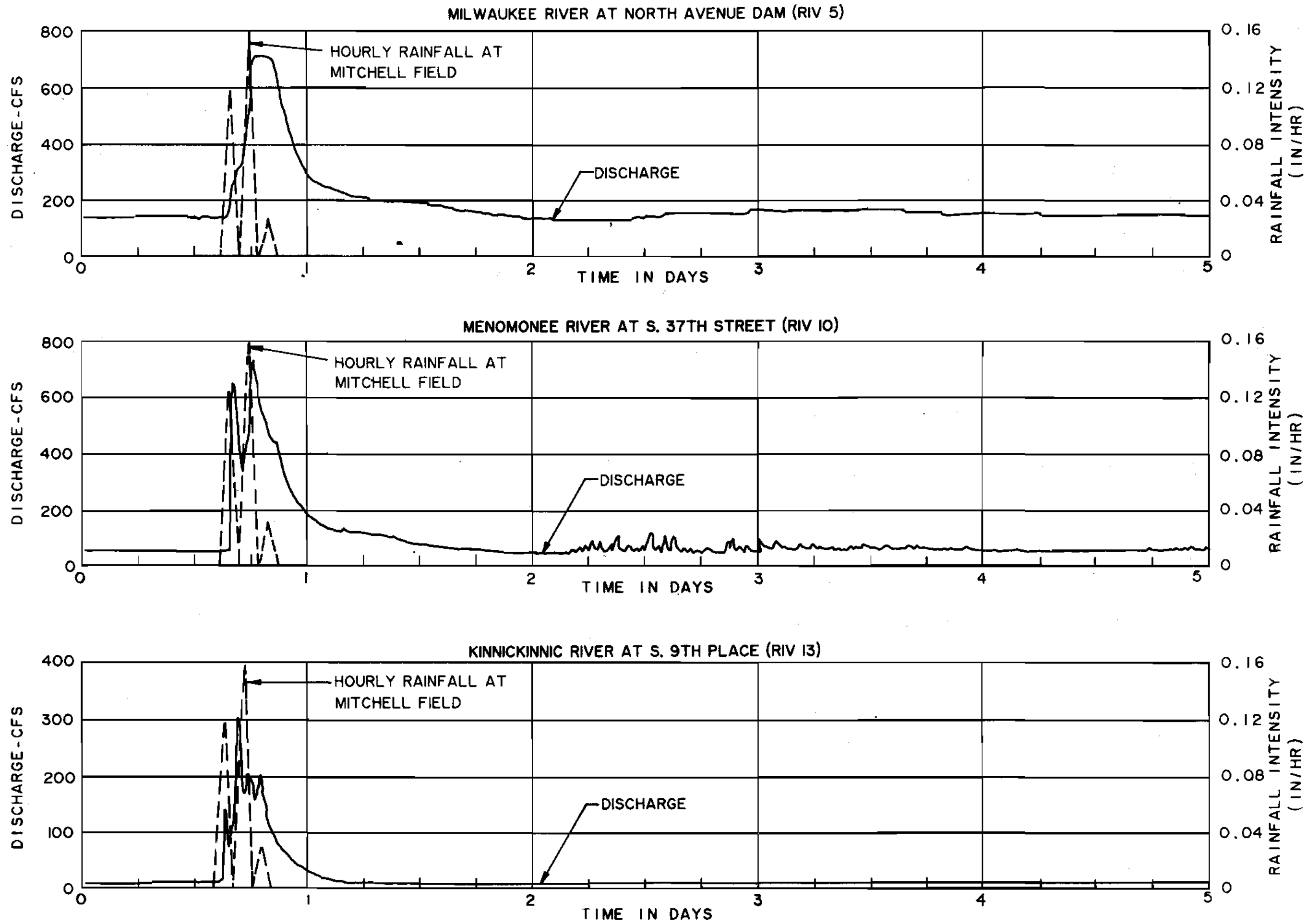
A summary of the concentrations of selected water quality indicators at three representative upstream stations, three representative inner harbor stations, and two representative outer harbor stations is presented in Table 66. Based on these representative stations, the results of the water quality monitoring during the September event are discussed below.

Dissolved oxygen levels were extremely variable at all stations, with values ranging from 0.1 to 13.8 mg/l. Spatial variations in dissolved oxygen levels are shown on Map 62, and the temporal variations which occurred during the event sampling program are presented in Figure 108. The dissolved oxygen concentrations at the upstream stations and the outer harbor stations were similar, with means ranging from 7.3 to 9.5 mg/l, and from 7.9 to 9.5 mg/l, respectively; however, at the inner harbor stations the dissolved oxygen concentrations were considerably lower, with means ranging from 2.0 to 4.5 mg/l. As shown in Figure 108, during the event, the upstream and inner harbor stations exhibited diurnal fluctuations in dissolved oxygen levels, with the most pronounced fluctuations found in the Kinnickinnic River at S. 9th Place. Within the inner and outer harbors, there was no significant difference between the dissolved oxygen levels at the three sample depths.

Fecal coliform levels ranged from fewer than 100 to 240,000 MPN/100 ml. Spatial variations in fecal coliform levels are shown on Map 63, and the temporal variations which occurred during the event sampling program are presented in Figure 109. In all three rivers, the fecal coliform

Figure 107

DISCHARGE AND RAINFALL MEASUREMENTS AT STATIONS JUST UPSTREAM OF THE INNER HARBOR: SEPTEMBER 10-14, 1983



Source: U.S. Geological Survey, National Weather Service, and SEWRPC.

levels at the inner harbor stations, with means ranging from 11,000 to 95,000 MPN/100 ml, were 47 to 132 percent higher than the levels at the upstream stations, with means ranging from 7,500 to 44,000 MPN/ 100 ml. At both the estuary and upstream stations, the Menomonee River fecal coliform levels were generally higher than the levels in the Milwaukee and Kinnickinnic Rivers. Mean fecal coliform levels at the representative outer harbor stations ranged from 200 to 60,700 MPN/ 100 ml. As shown in Figure 109, the fecal coliform levels generally exhibited a "first flush" effect, especially in the inner harbor, in that peak fecal coliform concentrations were reached shortly after the event began.

Total suspended solids concentrations ranged from 1 to 261 mg/l. The spatial variations in suspended solids concentrations are shown on Map 64, and the temporal variations are presented in Figure 110. The mean total suspended solids concentrations in the Milwaukee and Menomonee River estuary reaches—ranging from 16 to 29 mg/l—were lower than the mean concentrations measured in the upstream reaches, which ranged from 42 to 53 mg/l. The mean concentration in the Kinnickinnic River estuary—48 mg/l—was over twice as high as the concentration at the upstream station—18 mg/l. Total suspended solids concentrations were lowest in the outer harbor, with means ranging from 4 to 8 mg/l.

Table 66

SUMMARY OF RUNOFF EVENT WATER QUALITY DATA AT SELECTED STATIONS: SEPTEMBER 10-14,1983

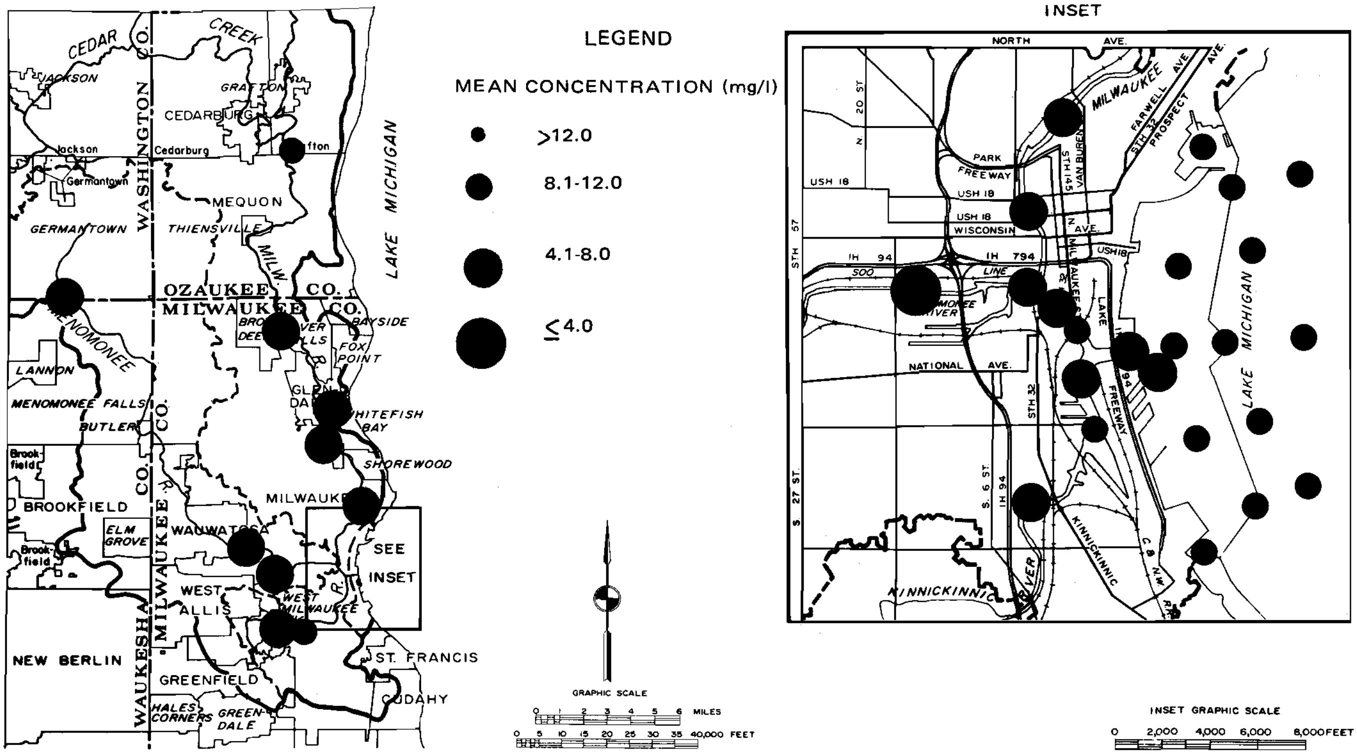
Sampling Station	Statistical Variable	Dissolved Oxygen (mg/l)	Fecal Coliform (MPN/100ml)	Total Suspended Solids (mg/l)	Total Phosphorus (mg/l)	Ammonia Nitrogen (mg/l)	Un-ionized Ammonia Nitrogen (mg/l)	Volatile Suspended Solids (mg/l)	BOD_5 (mg/l)	Chlorophyll-a (μg/l)
Upstream Stations										
Milwaukee River at North Avenue Dam (RIV-5)	Number of Samples	13	12	12	13	13	13	13	13	13
	Minimum	4.0	200	28	0.13	0.02	0.001	6	4.3	54.8
	Mean	7.3	7,500	42	0.16	0.05	0.010	12	5.4	73.6
	Maximum	9.3	24,000	87	0.22	0.10	0.025	16	7.6	100.4
	Standard Deviation	1.5	8,400	15	0.03	0.02	0.007	3	1.1	12.8
Menomonee River at S. 37th Street (RIV-10)	Number of Samples	12	12	12	12	12	12	11	12	12
	Minimum	6.4	900	3	0.04	0.03	0.001	1	1.4	5.1
	Mean	7.8	44,000	53	0.18	0.14	0.006	9	7.0	12.5
	Maximum	9.6	240,000	232	1.08	0.47	0.029	49	30.0	43.7
	Standard Deviation	1.2	70,000	83	0.30	0.13	0.009	14	7.9	11.5
Kinnickinnic River at S. 9th Place (RIV-13)	Number of Samples	11	10	10	11	11	11	10	11	11
	Minimum	6.8	200	1	0.02	0.03	0.001	1	0.8	1.3
	Mean	9.5	37,000	18	0.37	0.31	0.010	4	7.7	10.6
	Maximum	13.8	240,000	96	3.09	1.61	0.047	18	38.0	46.7
	Standard Deviation	2.9	74,000	30	0.91	0.49	0.014	5	10.7	16.2
Inner Harbor Stations										
Milwaukee River at Wells Street (RIV-7)	Number of Samples	36	12	36	36	36	36	35	27	36
	Minimum	0.4	900	16	0.11	0.04	0.001	5	1.5	32.0
	Mean	4.1	11,000	29	0.14	0.18	0.011	11	5.0	62.5
	Maximum	7.3	46,000	48	0.19	0.43	0.072	15	10.0	93.6
	Standard Deviation	1.1	14,000	8	0.02	0.10	0.013	2	1.8	13.0
Menomonee River at Muskego Avenue (RIV-11)	Number of Samples	39	13	39	39	39	39	39	26	39
	Minimum	0.1	200	4	0.06	0.24	0.002	1	1.6	5.4
	Mean	2.0	95,000	16	0.11	0.42	0.006	6	6.4	12.3
	Maximum	8.5	240,000	71	0.30	1.19	0.028	19	24.0	40.8
	Standard Deviation	1.7	110,000	12	0.53	0.19	0.005	4	6.0	6.2
Kinnickinnic River at S. 1st Street (RIV-14)	Number of Samples	42	13	41	42	42	42	41	28	41
	Minimum	0.5	900	7	0.03	0.05	0.001	1	1.0	2.0
	Mean	4.5	86,000	48	0.19	0.37	0.008	12	5.9	7.0
	Maximum	9.3	240,000	261	1.61	1.02	0.040	137	23.0	21.6
	Standard Deviation	2.5	98,000	48	0.29	0.23	0.009	21	5.0	5.3
Outer Harbor Stations										
Hoan Bridge[a] (OH-1)	Number of Samples	12	4	4	12	12	12	4	3	12
	Minimum	6.6	200	6	0.02	0.10	0.001	3	1.4	6.0
	Mean	7.9	61,000	8	0.04	0.32	0.005	3	3.9	15.1
	Maximum	8.7	240,000	10	0.06	0.75	0.015	4	8.5	26.5
	Standard Deviation	0.7	12,000	2	0.01	0.22	0.005	1	4.0	7.7
South Outer Harbor[a] (OH-11)	Number of Samples	12	4	4	12	12	12	4	3	12
	Minimum	8.0	<100	1	0.02	0.03	0.000	1	1.4	4.5
	Mean	9.5	200	4	0.02	0.14	0.003	2	2.3	10.4
	Maximum	11.5	400	7	0.03	0.21	0.011	4	3.4	18.1
	Standard Deviation	1.1	200	2	0.01	0.06	0.003	2	1.0	3.9

[a] *Concentrations of BOD_5 were not measured at stations OH-1 and OH-11. Therefore, concentrations of BOD_5 measured at OH-7, located at the main harbor entrance, are presented for OH-1, and concentrations of BOD_5 measured at OH-3, located in the central outer harbor, are presented for OH-11.*

Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 62

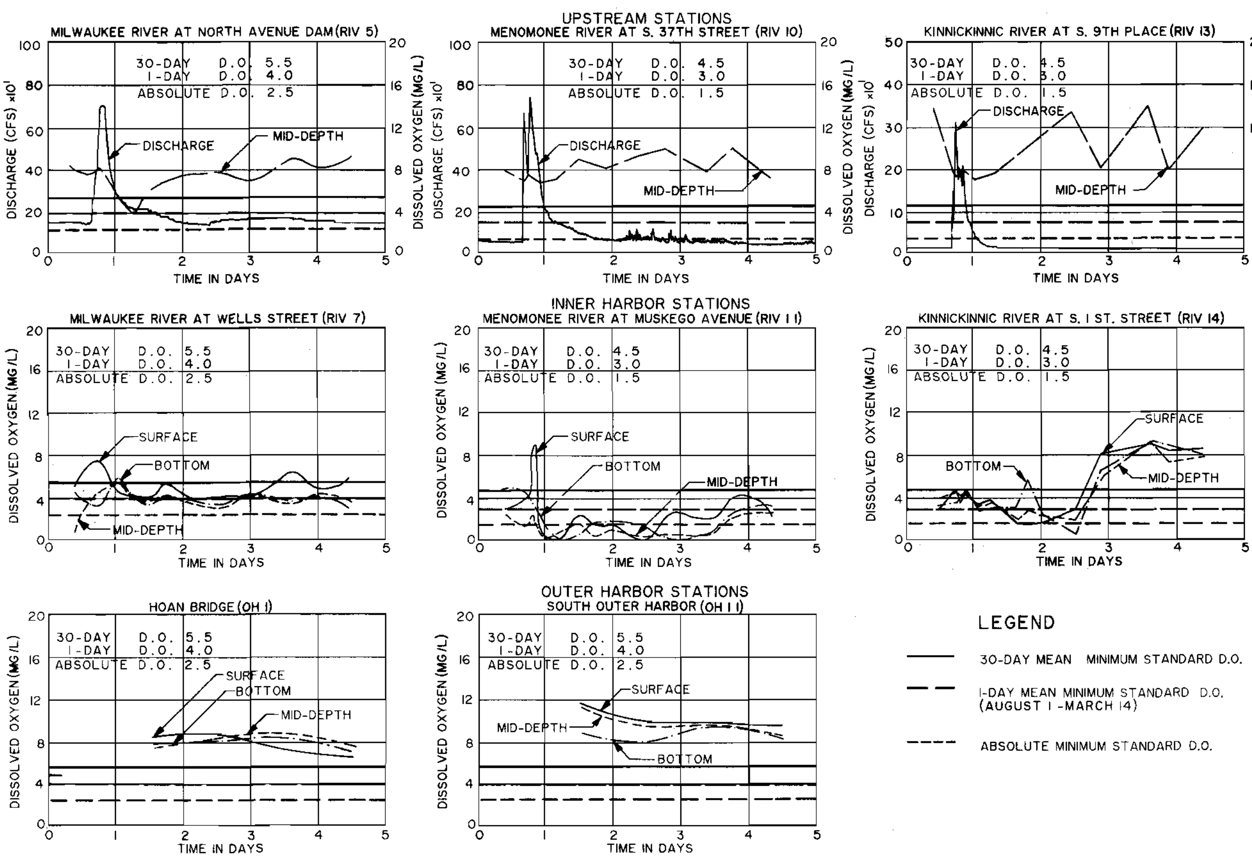
MEAN DISSOLVED OXYGEN CONCENTRATIONS DURING THE SEPTEMBER 10-14, 1983 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 108

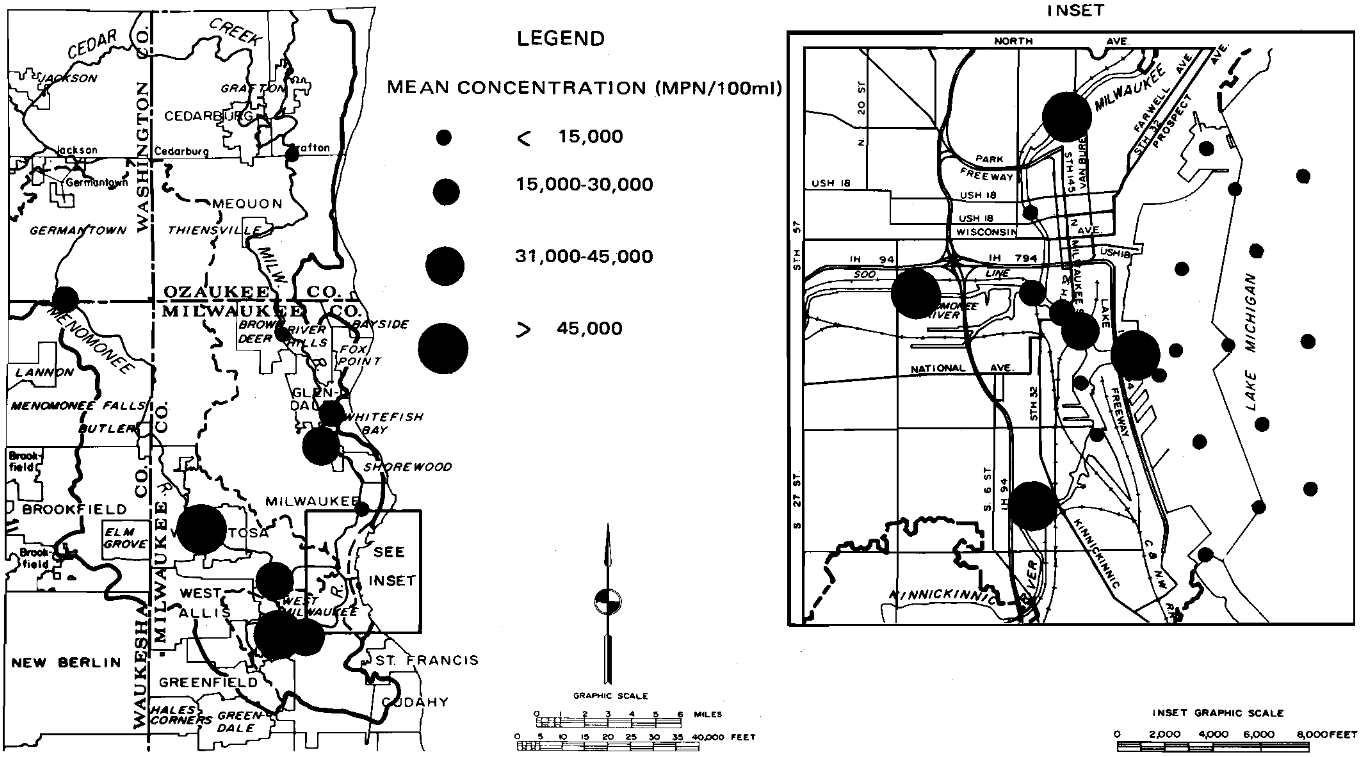
CONCENTRATION VERSUS TIME PLOTS FOR DISSOLVED OXYGEN: SEPTEMBER 10-14, 1983



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 63

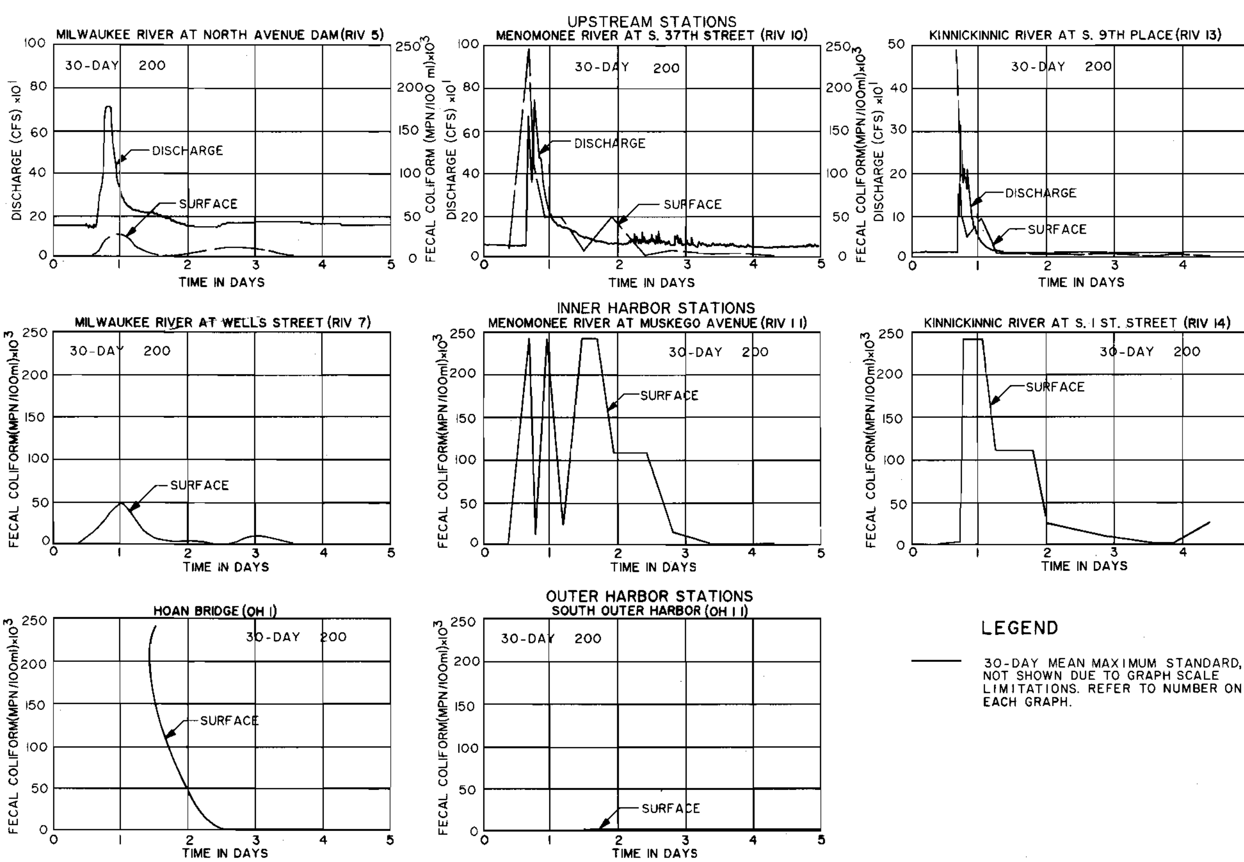
MEAN FECAL COLIFORM CONCENTRATIONS DURING THE SEPTEMBER 10-14, 1983 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 109

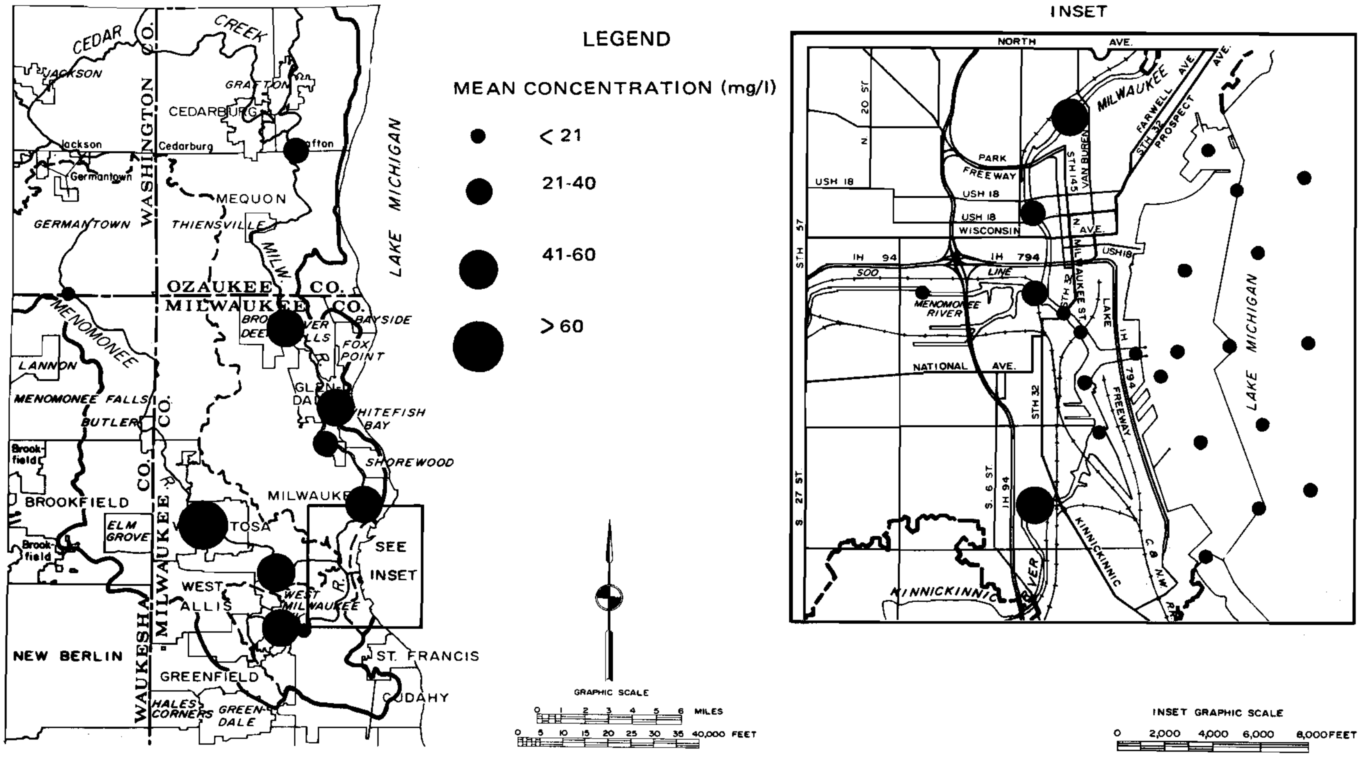
CONCENTRATION VERSUS TIME PLOTS FOR FECAL COLIFORM: SEPTEMBER 10-14, 1983



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 64

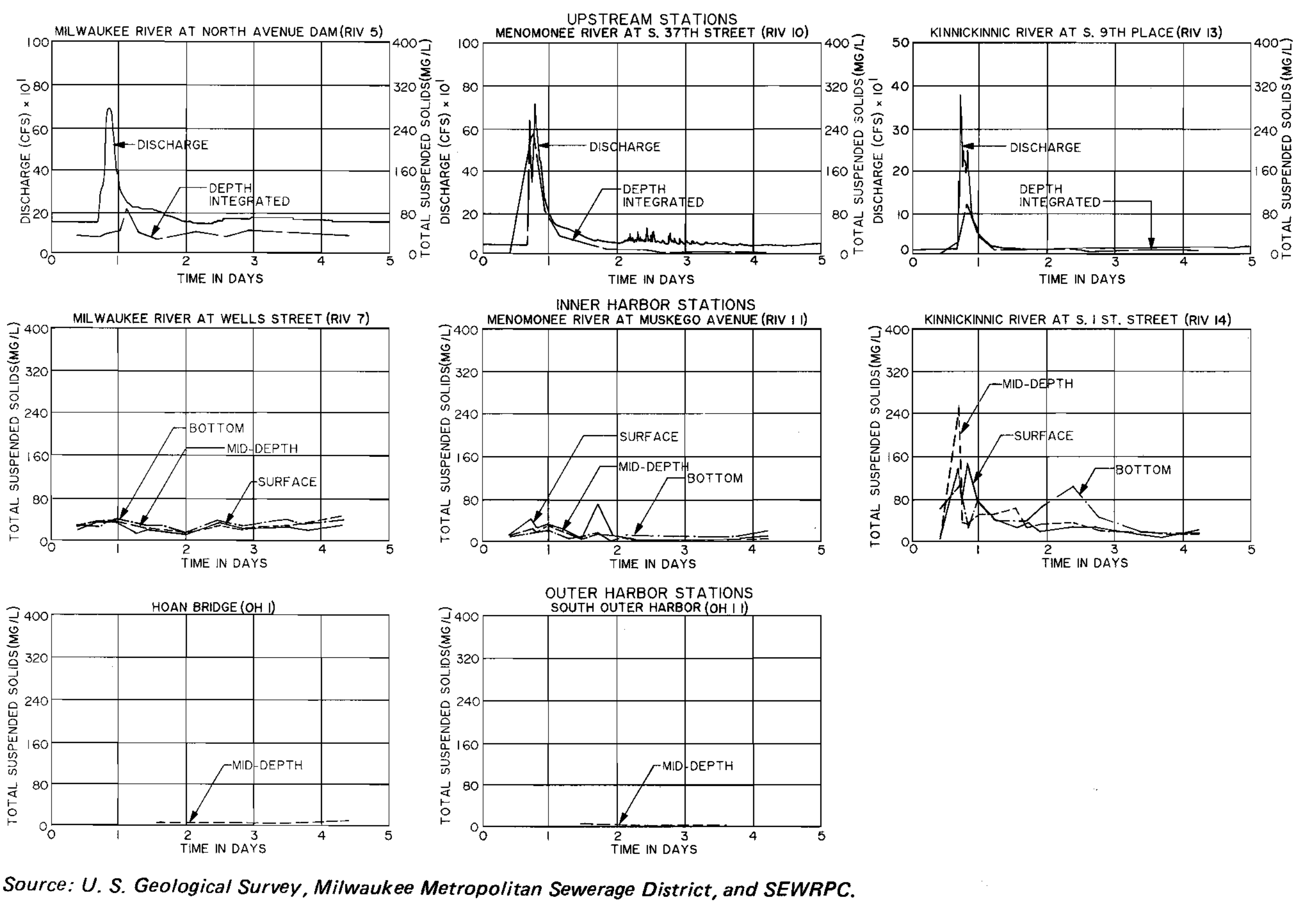
MEAN TOTAL SUSPENDED SOLIDS CONCENTRATIONS DURING THE SEPTEMBER 10-14, 1983 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 110

CONCENTRATION VERSUS TIME PLOTS FOR TOTAL SUSPENDED SOLIDS: SEPTEMBER 10-14, 1983



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Total phosphorus concentrations ranged from 0.02 to 3.09 mg/l. The spatial variations in total phosphorus concentrations are shown on Map 65, and the temporal variations are presented in Figure 111. In all three rivers, the mean total phosphorus concentrations at the upstream stations—ranging from 0.16 to 0.37 mg/l—were higher than the concentrations at the inner harbor stations, which ranged from 0.11 to 0.19 mg/l. At both the estuary and upstream stations, the Kinnickinnic River total phosphorus concentrations were higher than the concentrations in the Menomonee and Milwaukee Rivers. The total phosphorus concentrations were relatively low in the outer harbor, with the mean levels ranging from 0.02 to 0.04 mg/l. As shown in Figure 111, total phosphorus concentrations in the Milwaukee and Menomonee River estuary and upstream stations exhibited a "first flush" effect. Within the inner harbor, there is little significant difference between the total phosphorus concentrations at the three sample depths, except within the Kinnickinnic River estuary.

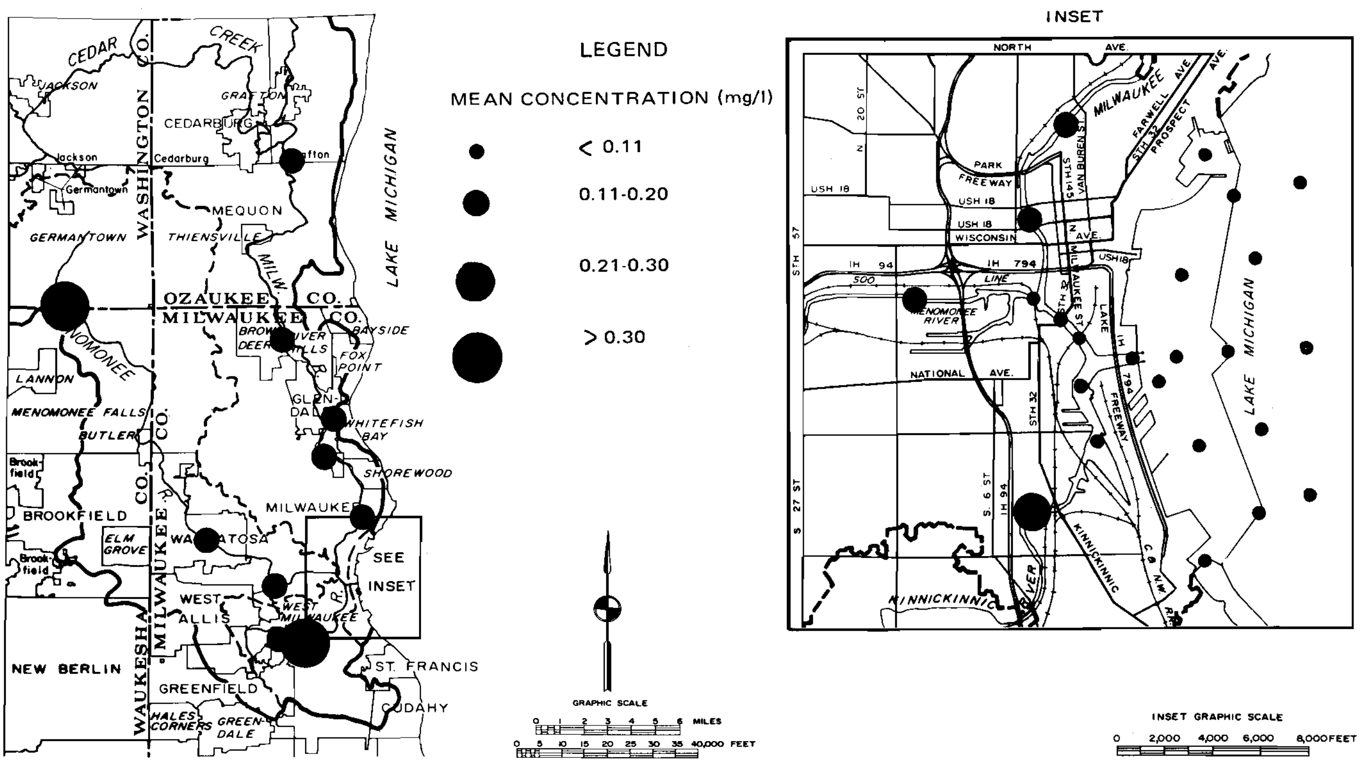
Ammonia nitrogen concentrations ranged from 0.02 to 1.61 mg/l. In all three rivers, the mean concentrations measured at the upstream stations—ranging from 0.05 to 0.31 mg/l—were lower than those measured at the inner harbor stations, which ranged from 0.18 to 0.42 mg/l. The outer harbor exhibited relatively high ammonia nitrogen concentrations, with means ranging from 0.14 to 0.32 mg/l.

Un-ionized ammonia nitrogen concentrations ranged from 0 to 0.072 mg/l. The mean concentrations measured at the upstream stations, which ranged from 0.006 to 0.010 mg/l, were about the same as the mean concentrations measured at the inner harbor stations, which ranged from 0.006 to 0.011 mg/l. Un-ionized ammonia nitrogen concentrations were lowest in the outer harbor, with means ranging from 0.003 to 0.005 mg/l.

Volatile suspended solids concentrations ranged from 1 to 137 mg/l. The mean concentrations at

Map 65

MEAN TOTAL PHOSPHORUS CONCENTRATIONS DURING THE SEPTEMBER 10-14, 1983 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

the upstream stations of the Milwaukee and Menomonee Rivers—ranging from 9 to 12 mg/l—were slightly higher than those measured at the Milwaukee and Menomonee River estuary stations, which ranged from 6 to 11 mg/l. Within the Kinnickinnic River, the mean upstream concentration of volatile suspended solids, 4 mg/l, was one-third the mean Kinnickinnic River estuary concentration of 12 mg/l. Based on mean concentrations in the upstream and inner harbor reaches of the three rivers, volatile suspended solids represented 7 to 38 percent of the total suspended solids concentration. The relative portion of the total suspended solids load which was volatile was slightly higher in the outer harbor—ranging from 38 to 50 percent. Concentrations of volatile suspended solids, however, were lower in the outer harbor than in the rivers, with means ranging from 2 to 3 mg/l.

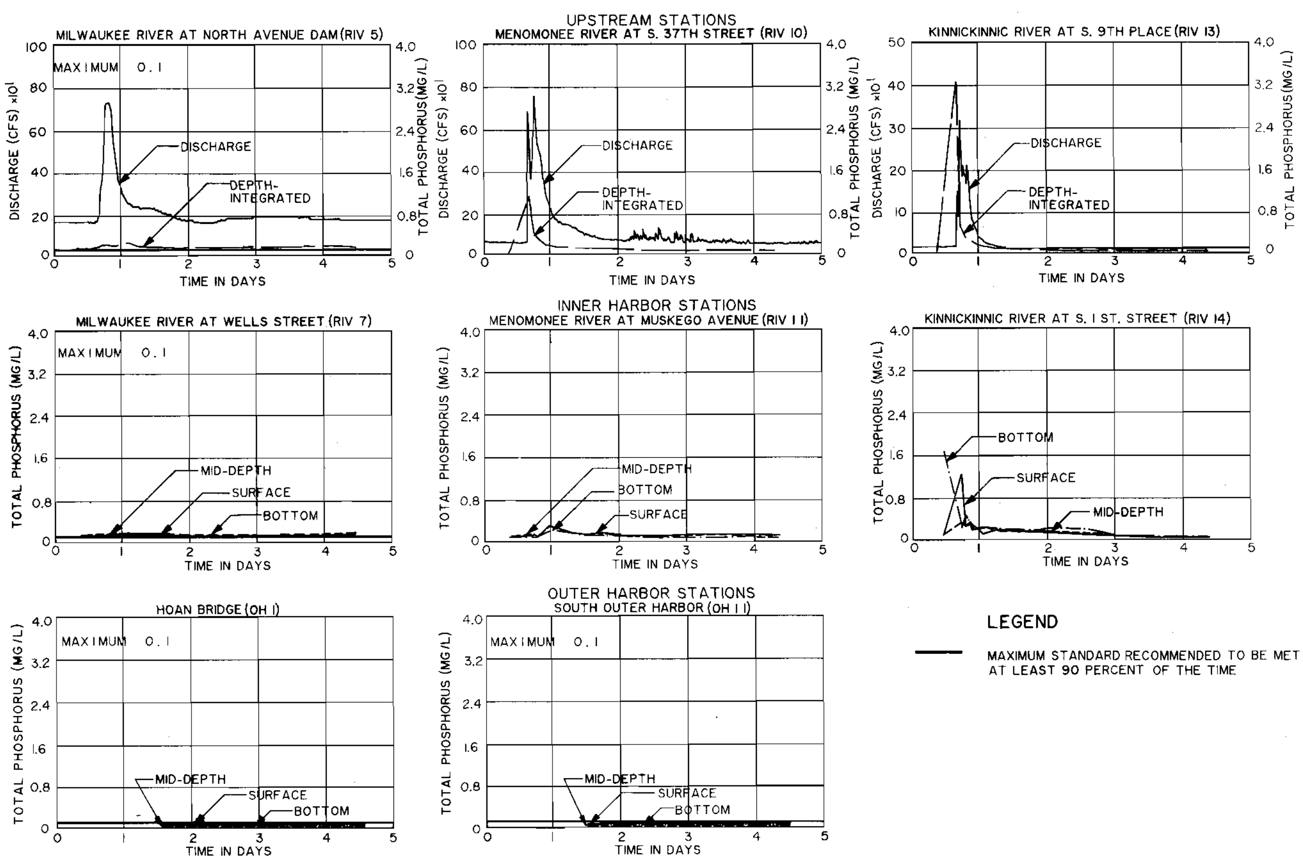
Biochemical oxygen demand (BOD_5) concentrations ranged from 0.8 to 38.0 mg/l. In all three rivers, the mean concentrations of BOD_5 measured at the upstream stations—ranging from 5.4 to 7.7 mg/l—were slightly higher than the mean concentrations measured at the inner harbor stations, which ranged from 5.0 to 6.4 mg/l. BOD_5 measurements were lowest in the outer harbor, with means ranging from 2.3 to 3.9 mg/l.

Chlorophyll-a concentrations ranged from 1.3 to 100.4 µg/l. In all three rivers, the mean concentrations of chlorophyll-a measured at the upstream stations—ranging from 10.6 to 73.6 µg/l—were higher than the mean concentrations at the inner harbor stations, which ranged from 7.4 to 62.5 µg/l. At both the upstream and estuary reaches, the mean concentrations measured in the Milwaukee River—ranging from 62.5 to 73.6 µg/l—were substantially higher than the concentrations in the Menomonee and Kinnickinnic Rivers, where the means ranged from 7.4 to 12.5 µg/l. Mean chlorophyll-a levels at the representative outer harbor stations ranged from 10.4 to 15.1 µg/l.

October 11-15, 1983 Runoff Event: The third intensive runoff event was sampled in October 1983. The total amount of rainfall that occurred in the Milwaukee Harbor estuary direct drainage area during this event ranged from 0.45 inch to

Figure 111

CONCENTRATION VERSUS TIME PLOTS FOR TOTAL PHOSPHORUS: SEPTEMBER 10-14, 1983



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

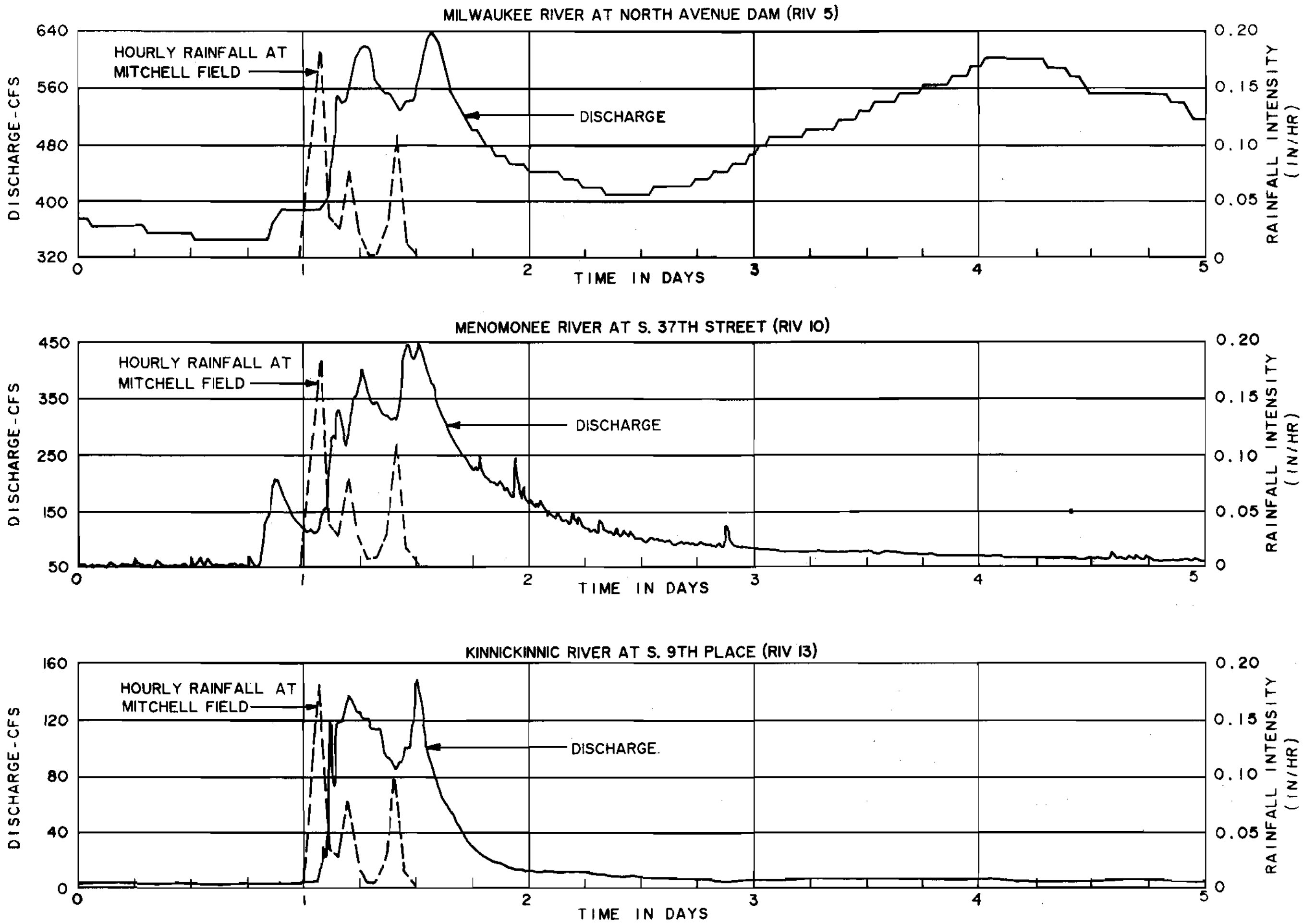
0.83 inch. The total duration of the rainfall was approximately 10 hours. Figure 112 illustrates the precipitation pattern that occurred at General Mitchell Field during the monitoring period in relationship to measured flows at the three river stations located just upstream of the inner harbor. During the five-day monitoring period, the upstream stations were sampled on a depth-integrated basis between five and 12 times, the inner harbor stations were sampled at three depths between four and 12 times, and the outer harbor stations were sampled at three depths four times.

A summary of the concentrations of selected water quality indicators at the representative stations is presented in Table 67. Based on these representative stations, the results of the water quality monitoring during the October event are discussed below.

Dissolved oxygen levels were found to be highly variable at all stations, with values ranging from 0.2 to 17.4 mg/l. The spatial variations in dissolved oxygen levels are shown on Map 66, and the temporal variations that occurred during the event sampling program are presented in Figure 113. In all three rivers, the dissolved oxygen concentrations at the upstream stations, with means ranging from 8.6 to 9.7 mg/l, were higher than the concentrations at the inner harbor stations—with means ranging from 2.5 to 9.0 mg/l. At both the estuary and upstream stations, the Menomonee River dissolved oxygen concentrations were slightly lower than the concentrations in the Milwaukee and Kinnickinnic Rivers. The dissolved oxygen concentrations in the outer harbor stations ranged from 7.9 to 9.3 mg/l. As shown in Figure 113, the dissolved oxygen concentrations in the upstream and inner harbor stations generally

Figure 112

DISCHARGE AND RAINFALL MEASUREMENTS AT STATIONS JUST UPSTREAM OF THE INNER HARBOR: OCTOBER 11-15, 1983



Source: U.S. Geological Survey, National Weather Service, and SEWRPC.

Table 67

SUMMARY OF RUNOFF EVENT WATER QUALITY DATA AT SELECTED STATIONS: OCTOBER 11-15, 1983

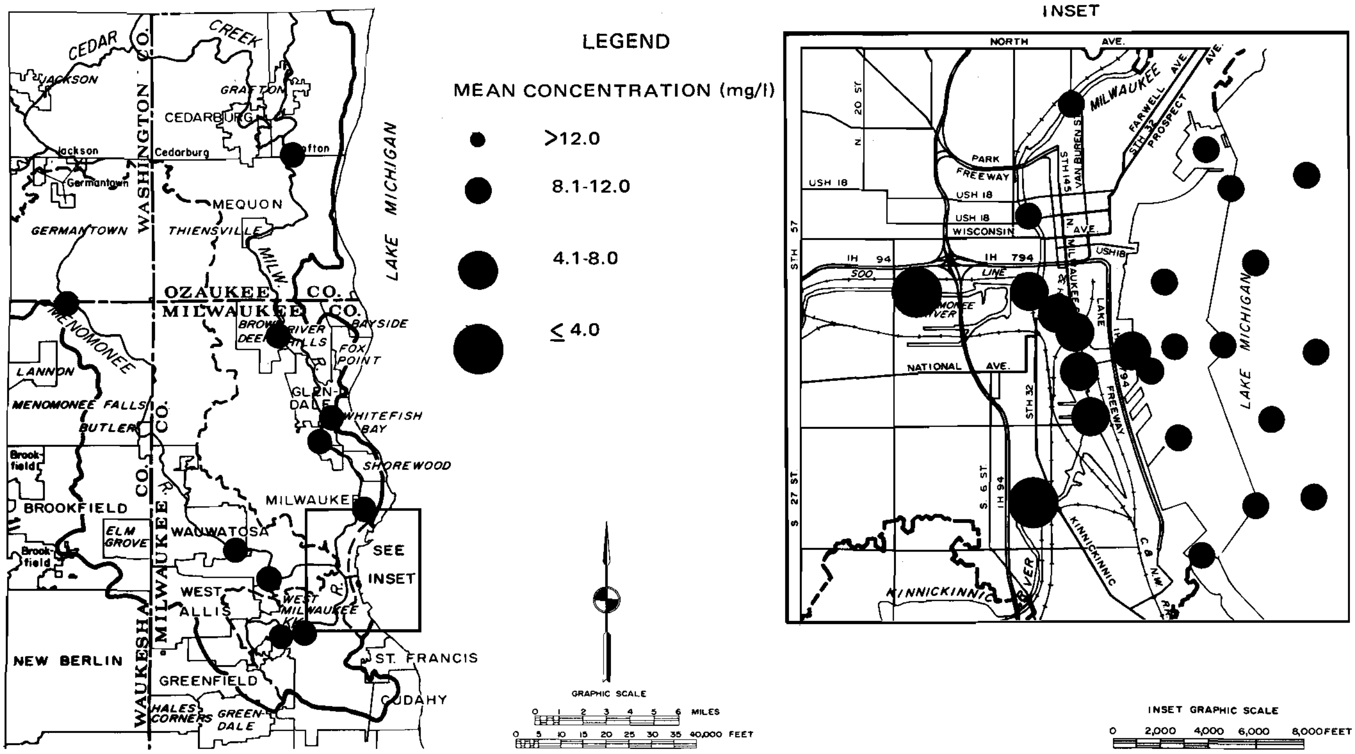
Sampling Station	Statistical Variable	Dissolved Oxygen (mg/l)	Fecal Coliform (MPN/100ml)	Total Suspended Solids (mg/l)	Total Phosphorus (mg/l)	Ammonia Nitrogen (mg/l)	Un-ionized Ammonia Nitrogen (mg/l)	Volatile Suspended Solids (mg/l)	BOD_5 (mg/l)	Chlorophyll-a (µg/l)
Upstream Stations										
Milwaukee River at North Avenue Dam (RIV-5)	Number of Samples	10	8	9	9	9	9	9	9	9
	Minimum	8.8	400	12	0.09	0.04	0.010	4	1.8	4.5
	Mean	9.7	24,000	23	0.10	0.06	0.018	6	2.7	11.5
	Maximum	10.7	110,000	33	0.13	0.08	0.023	8	3.6	15.9
	Standard Deviation	0.6	38,000	7	0.01	0.02	0.007	1	0.7	3.2
Menomonee River at S. 37th Street (RIV-10)	Number of Samples	12	11	11	11	11	11	11	11	11
	Minimum	6.7	900	5	0.06	0.05	0.005	2	1.8	4.9
	Mean	8.6	24,000	45	0.13	0.08	0.009	10	6.3	11.2
	Maximum	10.6	110,000	90	0.22	0.19	0.012	21	16.0	19.4
	Standard Deviation	1.2	33,000	31	0.06	0.05	0.004	7	4.5	4.9
Kinnickinnic River at S. 9th Place (RIV-13)	Number of Samples	11	10	9	10	10	10	9	10	8
	Minimum	5.4	200	2	0.02	0.02	0.001	1	1.4	1.2
	Mean	9.5	12,000	31	0.07	0.07	0.009	7	5.9	5.2
	Maximum	17.4	46,000	95	0.20	0.16	0.028	20	16.0	21.1
	Standard Deviation	3.4	16,000	34	0.06	0.05	0.009	7	5.2	6.8
Inner Harbor Stations										
Milwaukee River at Wells Street (RIV-7)	Number of Samples	27	8	24	24	24	24	24	16	24
	Minimum	7.8	1,500	12	0.01	0.07	0.001	3	2.1	5.8
	Mean	9.0	8,500	22	0.10	0.14	0.008	6	4.7	13.6
	Maximum	11.0	24,000	34	0.15	0.31	0.023	8	8.1	18.5
	Standard Deviation	0.9	10,000	5	0.03	0.07	0.007	1	1.7	2.9
Menomonee River at Muskego Avenue (RIV-11)	Number of Samples	36	10	33	32	32	32	33	22	32
	Minimum	0.2	900	5	0.07	0.06	0.000	3	1.7	4.4
	Mean	2.5	53,000	14	0.10	0.24	0.003	6	5.1	7.6
	Maximum	4.7	110,000	27	0.18	0.48	0.012	12	16.0	11.3
	Standard Deviation	1.2	50,000	5	0.03	0.10	0.003	2	3.2	2.0
Kinnickinnic River at S. 1st Street (RIV-14)	Number of Samples	33	10	30	30	30	30	29	29	30
	Minimum	0.4	700	19	0.10	0.27	0.001	4	1.8	1.3
	Mean	3.0	84,000	40	0.16	0.36	0.027	8	5.3	3.4
	Maximum	7.1	240,000	151	0.39	0.59	0.102	26	10.0	7.1
	Standard Deviation	2.0	95,000	26	0.06	0.08	0.031	4	2.6	1.5
Outer Harbor Stations										
Hoan Bridge[a] (OH-1)	Number of Samples	12	4	3	12	12	12	3	4	12
	Minimum	5.5	900	7	0.04	0.13	0.001	3	0.7	2.4
	Mean	7.9	6,000	9	0.05	0.29	0.003	3	1.0	7.2
	Maximum	10.0	23,000	11	0.07	0.44	0.004	4	1.4	16.5
	Standard Deviation	1.4	11,000	2	0.01	0.08	0.001	1	0.3	3.6
South Outer Harbor[a] (OH-11)	Number of Samples	12	4	4	12	12	12	4	4	12
	Minimum	7.7	200	5	0.03	0.24	0.000	2	0.8	4.0
	Mean	9.3	500	6	0.03	0.31	0.001	2	1.2	6.1
	Maximum	10.2	900	7	0.04	0.38	0.001	3	1.6	7.4
	Standard Deviation	0.7	300	1.2	0.003	0.05	0.000	1	0.3	1.1

[a] *Concentrations of BOD_5 were not measured at stations OH-1 and OH-11. Therefore, concentrations of BOD_5 measured at OH-7, located at the main harbor entrance, are presented for OH-1, and concentrations of BOD_5 measured at OH-3, located in the central outer harbor, are presented for OH-11.*

Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 66

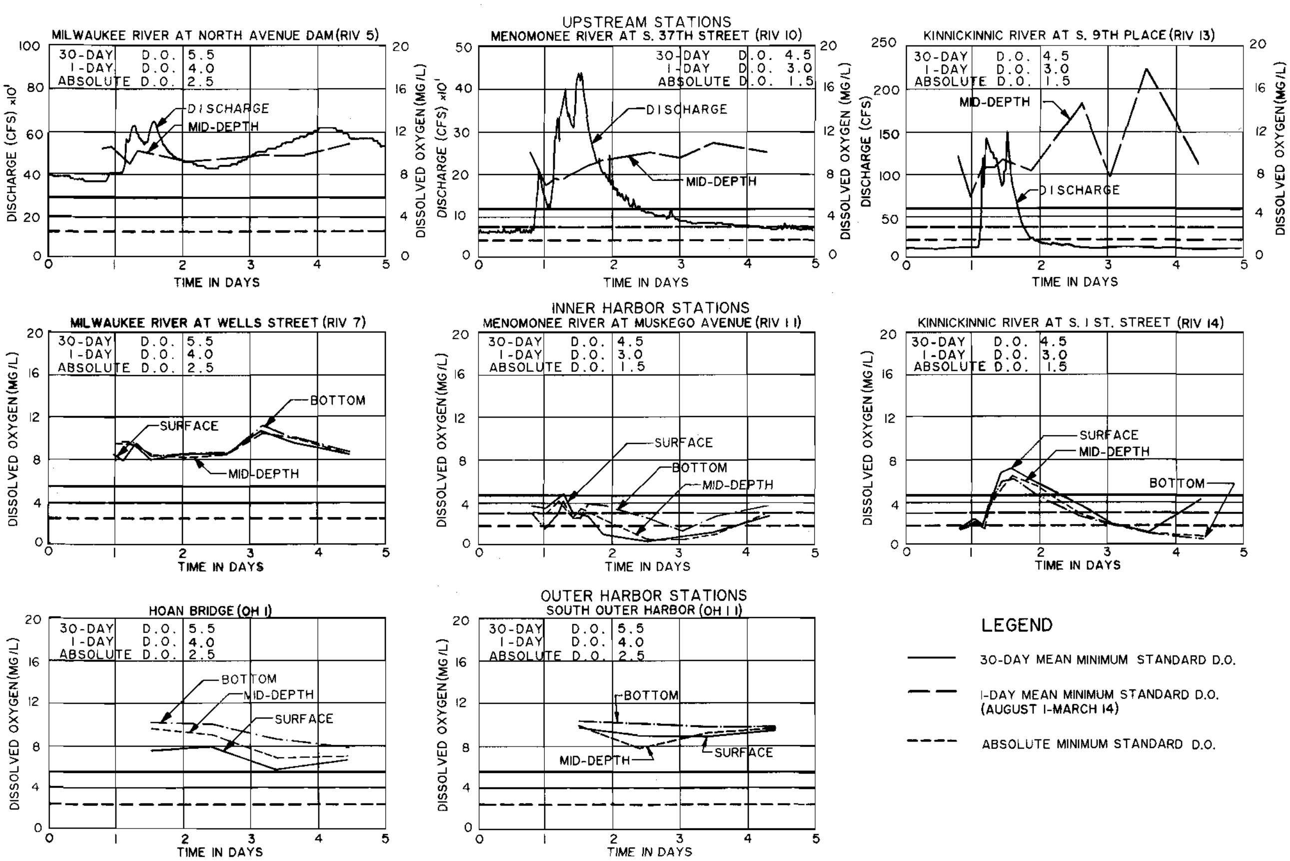
MEAN DISSOLVED OXYGEN CONCENTRATIONS DURING THE OCTOBER 11-15, 1983 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 113

CONCENTRATION VERSUS TIME PLOTS FOR DISSOLVED OXYGEN: OCTOBER 11-15, 1983



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

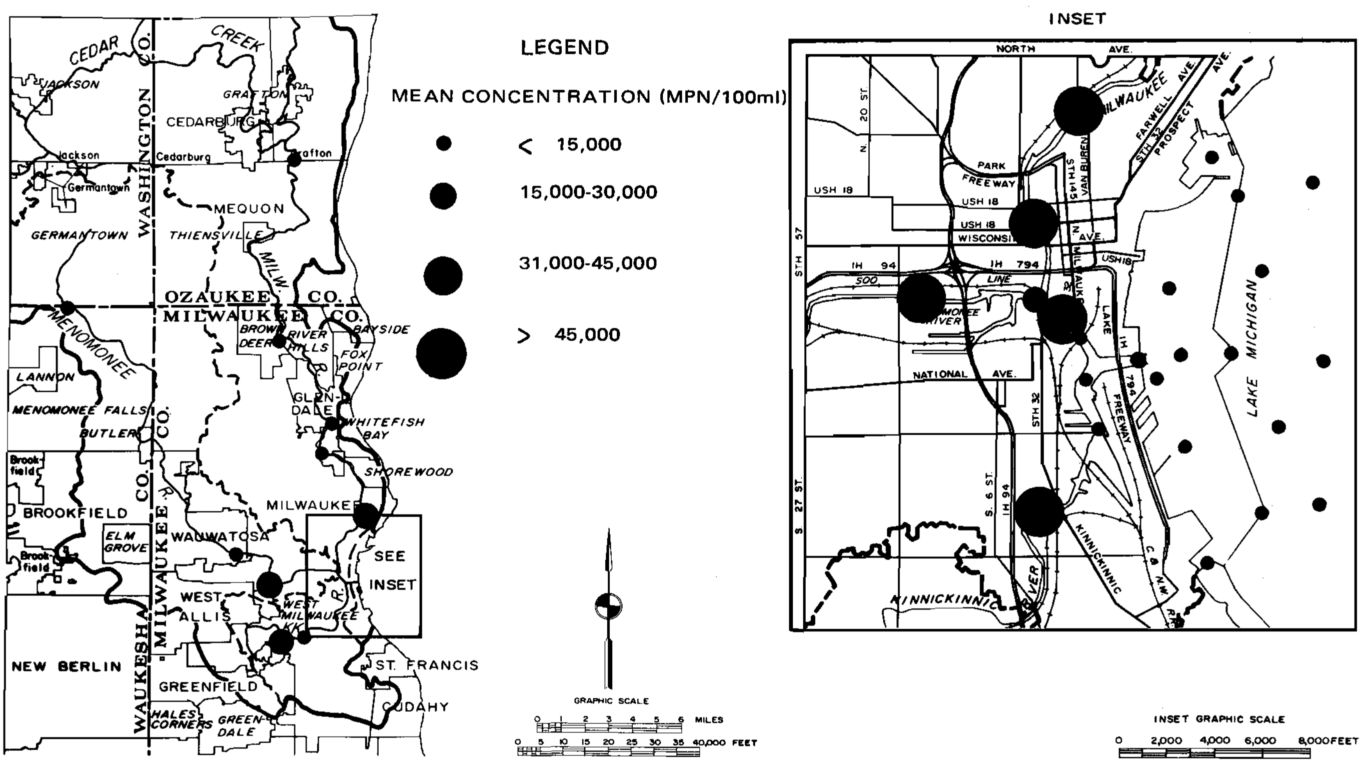
declined at the start of the event, and exhibited diurnal fluctuations, with the most pronounced fluctuations found in the Kinnickinnic River at S. 9th Place. Within the inner and outer harbors there was no significant difference between the dissolved oxygen levels at the three sample depths.

Fecal coliform levels ranged from 200 to 240,000 MPN/100 ml. The spatial variations in fecal coliform levels are shown on Map 67, and the temporal variations which occurred during the event are presented in Figure 114. The mean fecal coliform concentrations in the Menomonee and Kinnickinnic River estuary stations—ranging from 53,000 to 84,000 MPN/100 ml—were at least twice as high as the levels at the upstream stations, where means ranged from 12,000 to 24,000 MPN/100 ml. In the Milwaukee River estuary station, however, the mean concentration—8,500 MPN/100 ml—was nearly three times lower than the upstream mean fecal coliform concentration of 24,000 MPN/100 ml. Mean fecal coliform levels at the representative outer harbor stations were lowest, with means ranging from 500 to 6,800 MPN/100 ml. As shown in Figure 114, the fecal coliform levels in the upstream stations generally exhibited a "first flush" effect in that peak fecal coliform concentrations were reached shortly after the event began.

Total suspended solids concentrations ranged from 2 to 151 mg/l. The spatial variations in suspended solids concentrations are shown on Map 68, and the temporal variations are presented in Figure 115. In the Milwaukee and Menomonee Rivers, the mean total suspended solids concentrations in the upstream reaches—ranging from 23 to 45 mg/l—were higher than the mean concentrations measured in the Milwaukee and Menomonee River estuaries, which ranged from 14 to 22 mg/l. In the Kinnickinnic River, however, the mean concentration in the upstream station—31 mg/l—was slightly lower than concentration in the estuary station—40 mg/l. Total suspended solids concentrations were lowest in the outer harbor, with means ranging from 6 to 9 mg/l.

Map 67

MEAN FECAL COLIFORM CONCENTRATIONS DURING THE OCTOBER 11-15, 1983 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Total phosphorus concentrations ranged from 0.01 to 0.39 mg/l. The spatial variations in total phosphorus concentrations are shown on Map 69, and the temporal variations are presented in Figure 116. In all three rivers, the mean total phosphorus concentrations in the upstream stations—ranging from 0.07 to 0.13 mg/l—were about the same as the concentrations in the inner harbor, which ranged from 0.10 to 0.16 mg/l. Total phosphorus concentrations were lowest in the outer harbor, with means ranging from 0.03 to 0.05 mg/l.

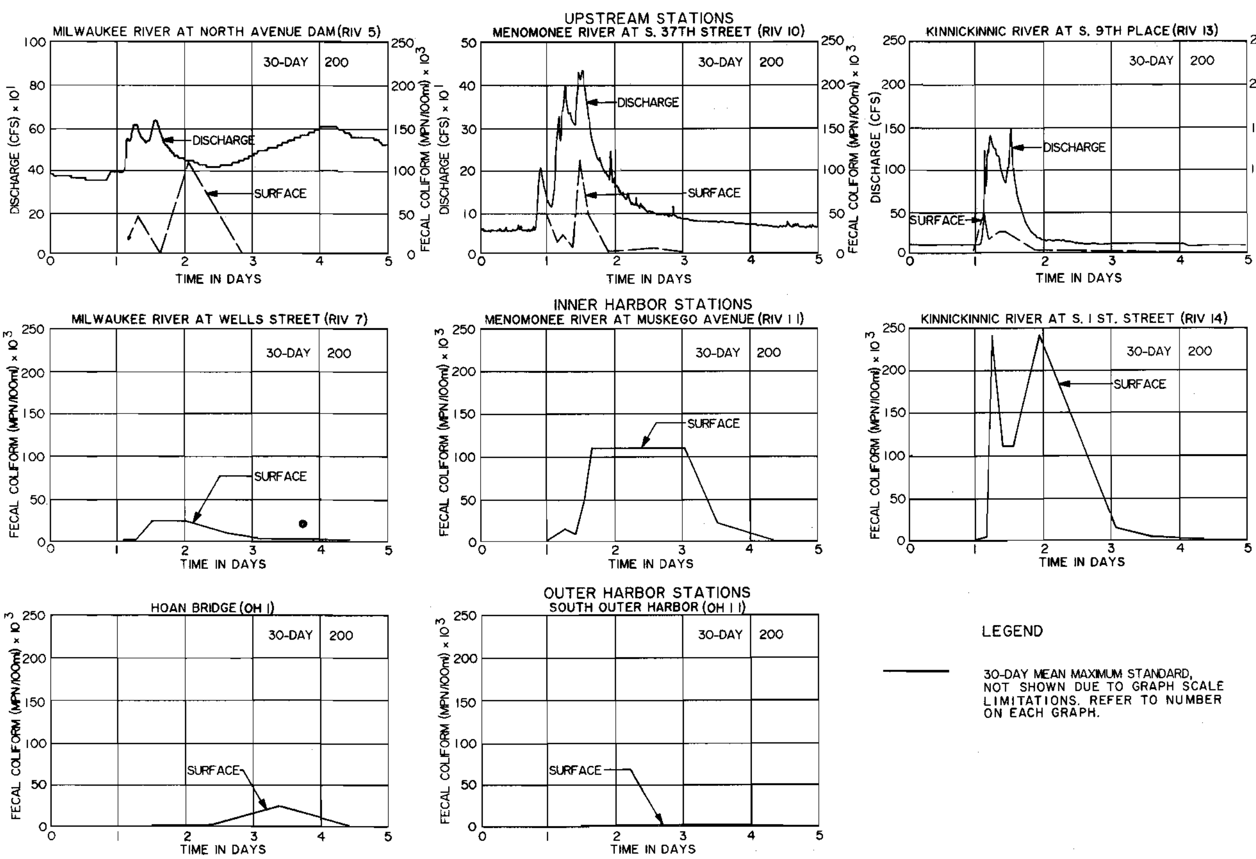
Ammonia nitrogen concentrations ranged from 0.02 to 0.59 mg/l. The mean concentrations measured at the upstream stations—ranging from 0.06 to 0.08 mg/l—were consistently lower than those measured at the inner harbor stations, which ranged from 0.14 to 0.36 mg/l. The outer harbor exhibited relatively high ammonia nitrogen concentrations, with means ranging from 0.29 to 0.31 mg/l.

Un-ionized ammonia nitrogen concentrations ranged from 0 to 0.102 mg/l. The mean concentrations measured at the upstream stations ranged from 0.009 to 0.018 mg/l, while the mean concentrations measured at the inner harbor stations ranged from 0.003 to 0.027 mg/l. Un-ionized ammonia nitrogen concentrations were lowest in the outer harbor, with means ranging from 0.001 to 0.003 mg/l.

Volatile suspended solids concentrations ranged from 1 to 26 mg/l. In all three rivers, the mean volatile suspended solids concentrations at the upstream stations—ranging from 6 to 10 mg/l—were about the same as the concentrations in the inner harbor, which ranged from 6 to 8 mg/l. Based on mean concentrations within the upstream and inner harbor reaches of the three rivers, volatile suspended solids represented about 20 to 43 percent of the total suspended solids concentration. Approximately 33 percent of the total suspended

Figure 114

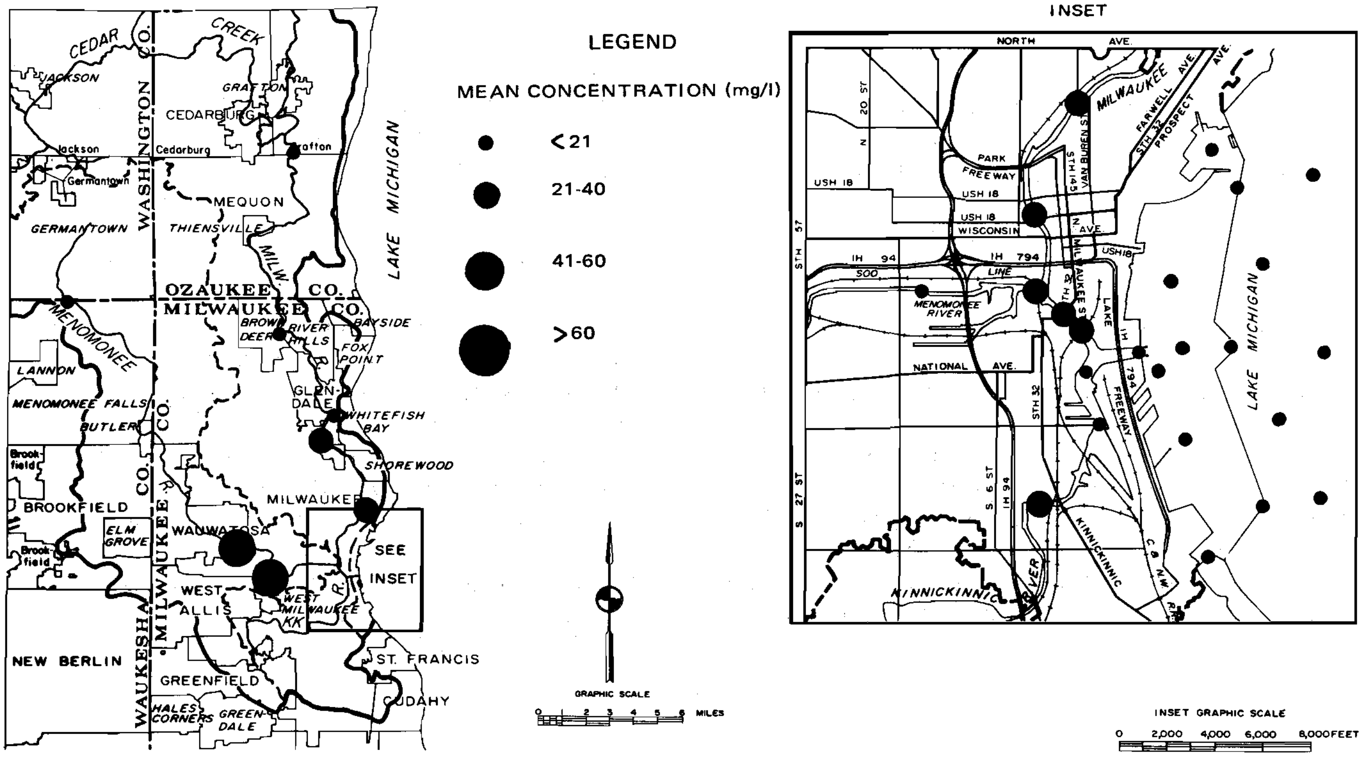
CONCENTRATION VERSUS TIME PLOTS FOR FECAL COLIFORM: OCTOBER 11-15, 1983



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 68

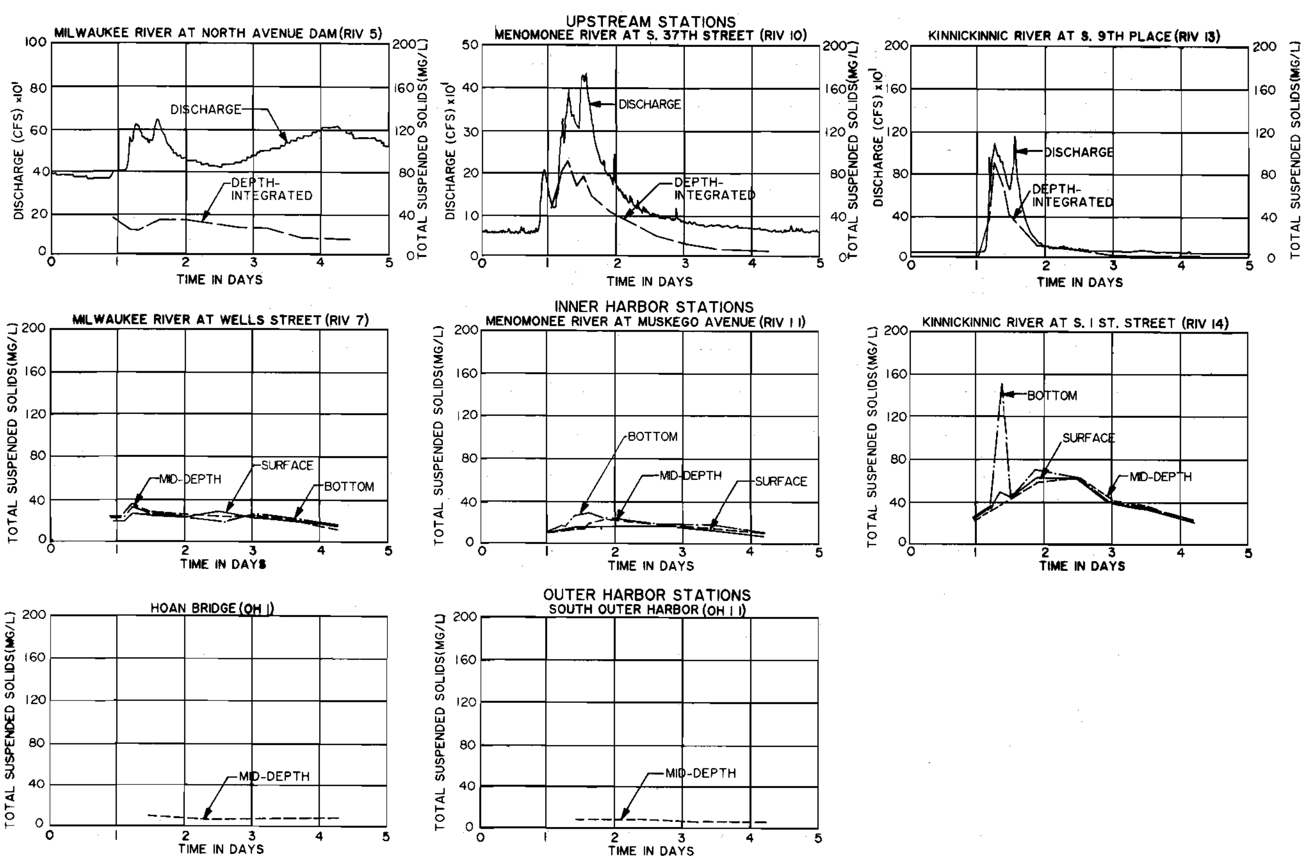
MEAN TOTAL SUSPENDED SOLIDS CONCENTRATIONS DURING THE OCTOBER 11-15, 1983 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 115

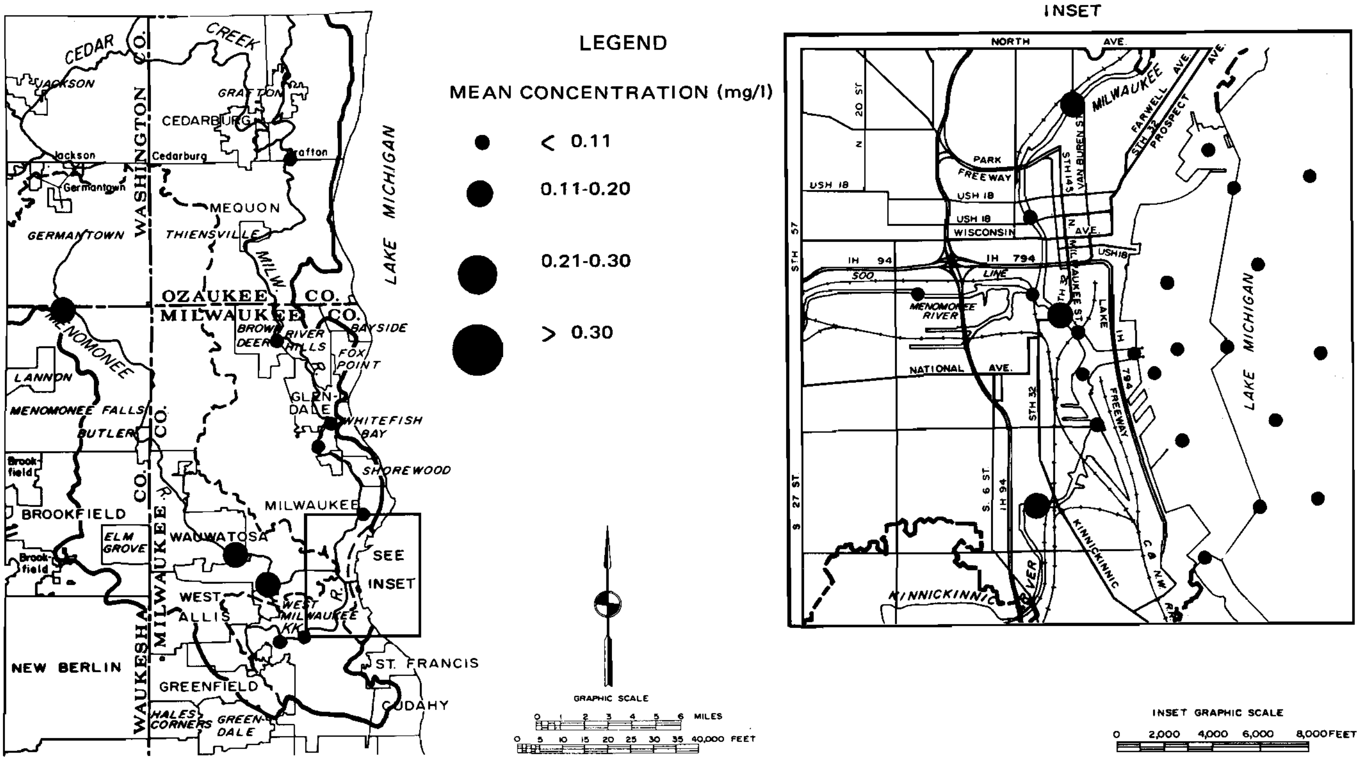
CONCENTRATION VERSUS TIME PLOTS FOR TOTAL SUSPENDED SOLIDS: OCTOBER 11-15, 1983



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 69

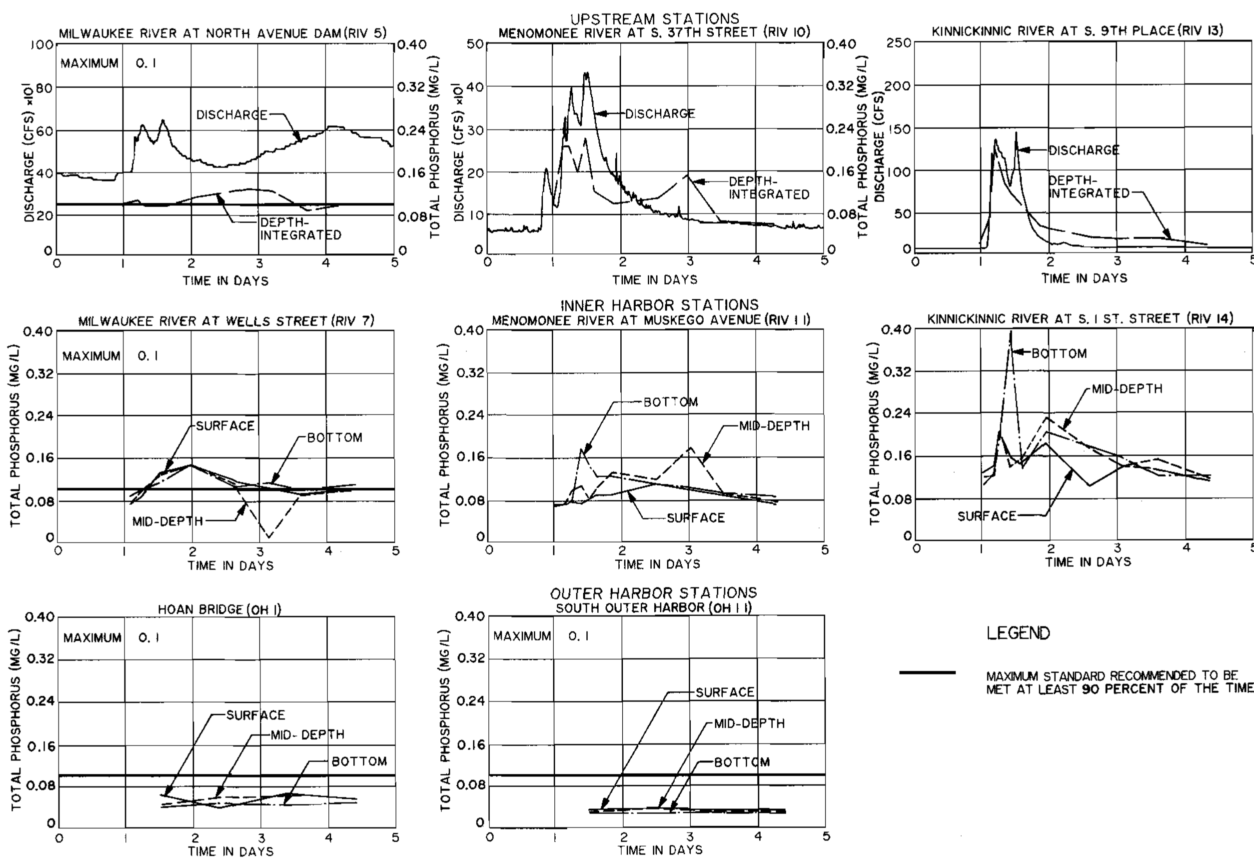
MEAN TOTAL PHOSPHORUS CONCENTRATIONS DURING THE OCTOBER 11-15, 1983 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 116

CONCENTRATION VERSUS TIME PLOTS FOR TOTAL PHOSPHORUS: OCTOBER11-15, 1983



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

solids load in the outer harbor was volatile. Concentrations of volatile suspended solids, however, were lower in the outer harbor than in the rivers, with means ranging from 2 to 3 mg/l.

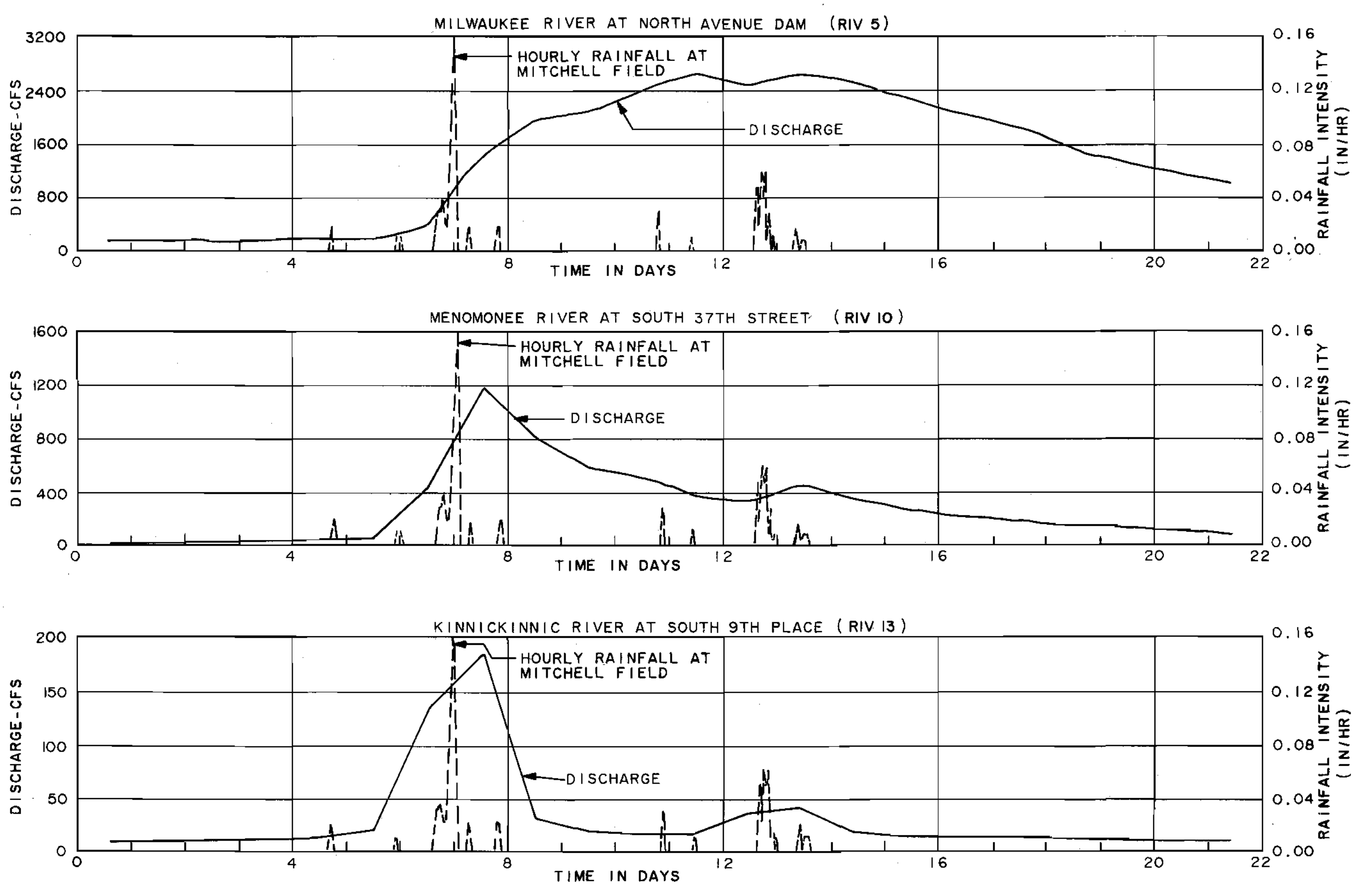
Biochemical oxygen demand (BOD_5) concentrations ranged from 0.7 to 16.0 mg/l. The mean concentrations at the upstream stations of the Menomonee and Kinnickinnic Rivers—ranging from 5.9 to 6.3 mg/l—were higher than those measured at the Menomonee and Kinnickinnic River estuary stations, where means ranged from 5.1 to 5.3 mg/l. Within the Milwaukee River, the mean concentration of biochemical oxygen demand of 4.7 mg/l measured within the estuary was higher than the concentration at the upstream station of 2.7 mg/l. BOD_5 measurements were lowest in the outer harbor, with means ranging from 1.0 to 1.2 mg/l.

Chlorophyll-a concentrations ranged from 1.2 to 21.1 µg/l. The mean concentrations at the upstream stations of the Menomonee and Kinnickinnic Rivers—ranging from 5.2 to 11.2 µg/l—were higher than those measured at the Menomonee and Kinnickinnic River estuary stations—ranging from 3.4 to 7.6 µg/l. However, within the Milwaukee River, the mean concentration of 13.6 µg/l measured within the estuary was higher than the concentration at the upstream station of 11.5 µg/l. At both the estuary and upstream stations, the Milwaukee River chlorophyll-a mean concentrations were higher than the concentrations in the Menomonee and Kinnickinnic Rivers. Mean chlorophyll-a levels at representative outer harbor stations ranged from 6.1 to 7.2 µg/l.

February 6-27, 1984 Runoff Event: The fourth intensive runoff event, a snowmelt event, was sampled in February 1984. The total amount of snow on the ground in the Milwaukee area during this event was approximately four inches, as recorded at General Mitchell Field. In addition, a total of 1.08 inches of rainfall occurred during this time period. Figure 117 illustrates the precipitation pattern that occurred at General Mitchell Field during the monitoring period in relationship to measured flows at the three river stations located

Figure 117

DISCHARGE AND RAINFALL MEASUREMENTS AT STATIONS JUST UPSTREAM OF THE INNER HARBOR: FEBRUARY 6-17, 1984



Source: U.S. Geological Survey, National Weather Service, and SEWRPC.

just upstream of the inner harbor. Temperatures reached a maximum of 62°F at General Mitchell Field at the time of the runoff event, and averaged in the mid-thirties. During the 22-day monitoring period, the upstream stations were sampled on a depth-integrated basis seven times, and the inner harbor stations were sampled at three depths between four and seven times. The outer harbor stations were not sampled during this event because of ice conditions.

A summary of the concentrations of selected water quality indicators at the representative stations is presented in Table 68. Based on these representative stations, the results of the water quality monitoring during the February event are discussed below.

Dissolved oxygen levels ranged from 1.1 to 17.3 mg/l. The spatial variations in dissolved oxygen levels are shown on Map 70, and the temporal variations which occurred during the event sampling program are presented in Figure 118. In all three rivers, the dissolved oxygen concentrations at the upstream stations, with means ranging from 12.8 to 13.5 mg/l, were higher than the concentrations at the inner harbor stations, with means ranging from 10.0 to 12.9 mg/l. As shown in Figure 118, the dissolved oxygen concentrations generally increased with flow except within the Kinnickinnic River at S. 9th Place. Within the inner harbor, there was no significant difference between dissolved oxygen levels at the three depths sampled.

Fecal coliform levels ranged from 100 to 93,000 MPN/100 ml. The spatial variations in fecal coliform levels are shown on Map 71, and the temporal variations which occurred during the event sampling program are presented in Figure 119. The mean fecal coliform concentrations in the Milwaukee and Menomonee River estuaries—ranging from 4,500 to 17,000 MPN/100 ml—were approximately three times higher than the concentrations at the upstream stations, which ranged from 1,600 to 5,000 MPN/100 ml. In the Kinnickinnic River,

Table 68

SUMMARY OF RUNOFF EVENT WATER QUALITY DATA AT SELECTED STATIONS: FEBRUARY 6-27, 1984

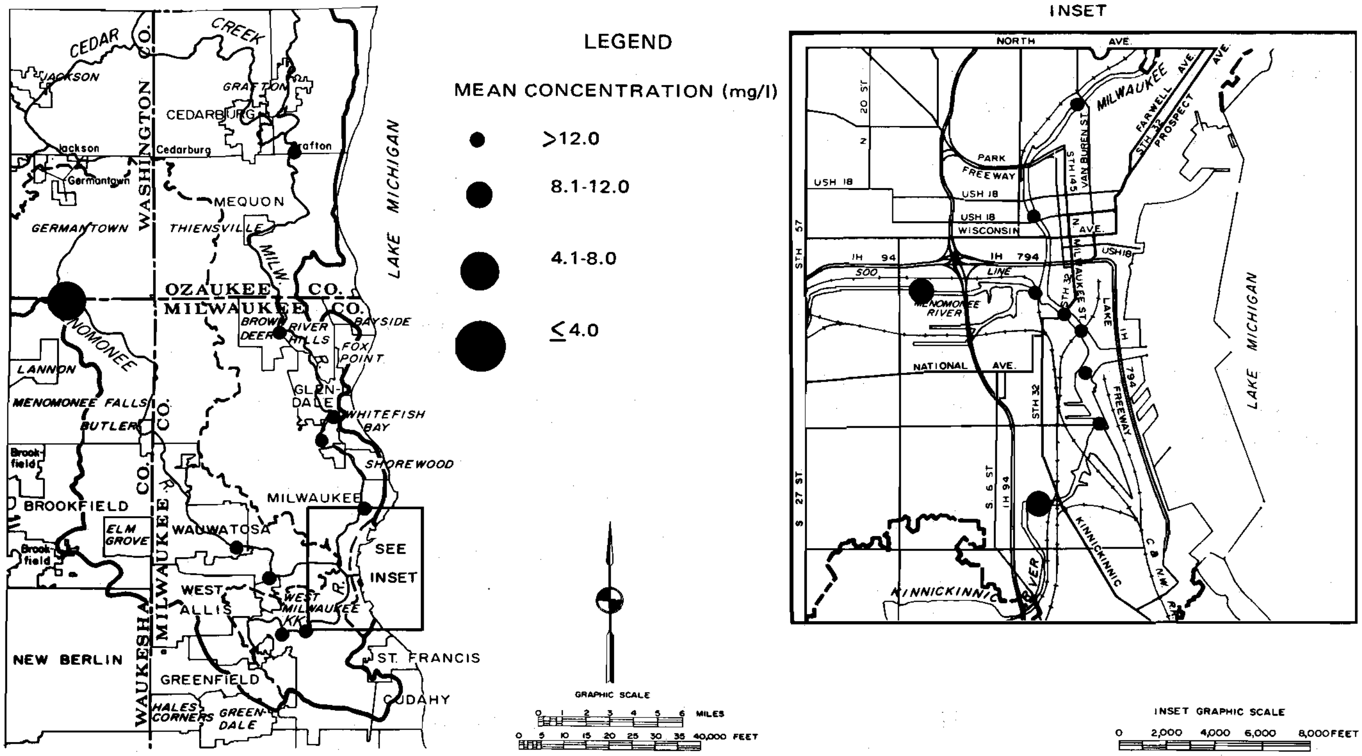
Sampling Station[a]	Statistical Variable	Dissolved Oxygen (mg/l)	Fecal Coliform (MPN/100ml)	Total Suspended Solids (mg/l)	Total Phosphorus (mg/l)	Ammonia Nitrogen (mg/l)	Un-ionized Ammonia Nitrogen (mg/l)	Volatile Suspended Solids (mg/l)	BOD_5 (mg/l)	Chlorophyll-a (μg/l)	Cadmium (μg/l)	Copper (μg/l)	Lead (μg/l)	Zinc (μg/l)
Upstream Stations														
Milwaukee River at North Avenue Dam (RIV-5)	Number of Samples	7	6	7	7	7	7	7	7	7	1	1	1	1
	Minimum	10.6	200	4	0.11	0.08	0.001	2	1.4	0.6	--	--	--	--
	Mean	13.0	5,000	68	0.49	0.37	0.002	13	4.7	11.0	2.0	5.0	15.0	2.9
	Maximum	14.4	21,000	168	1.71	0.60	0.003	27	8.2	5.5	--	--	--	--
	Standard Deviation	1.4	8,000	59	0.57	0.19	0.001	10	2.7	3.6	--	--	--	--
Menomonee River at S. 37th Street (RIV-10)	Number of Samples	7	6	7	7	7	7	7	7	6	1	1	1	1
	Minimum	12.8	900	4	0.06	0.14	0.001	1	1.8	1.5	--	--	--	--
	Mean	13.5	1,600	32	0.16	0.27	0.003	6	4.0	2.9	3.0	12.0	8.0	19.6
	Maximum	15.0	2,300	91	0.30	0.37	0.005	15	8.3	7.6	--	--	--	--
	Standard Deviation	0.8	600	31	0.10	0.10	0.001	5.7	2.0	2.3	--	--	--	--
Kinnickinnic River at S. 9th Place (RIV-13)	Number of Samples	7	6	7	7	7	7	7	7	6	1	1	1	1
	Minimum	10.4	200	2	0.06	0.06	0.002	1	2.9	0.5	--	--	--	--
	Mean	12.8	7,800	21	0.20	0.18	0.005	5	6.9	3.1	2.0	20.0	42.0	92.6
	Maximum	17.3	43,000	79	0.74	0.35	0.009	13	11.0	13.2	--	--	--	--
	Standard Deviation	2.5	17,300	27	0.24	0.12	0.003	4.7	2.8	5.0	--	--	--	--
Inner Harbor Stations														
Milwaukee River at Wells Street (RIV-7)	Number of Samples	19	6	19	19	19	19	19	19	16	1	1	1	1
	Minimum	11.5	200	4	0.14	0.09	0.001	2	1.5	0.5	--	--	--	--
	Mean	12.9	17,000	64	0.32	0.40	0.003	14	6.5	6.2	2.0	8.0	15.0	7.1
	Maximum	14.3	93,000	134	0.55	0.61	0.006	32	11.0	8.4	--	--	--	--
	Standard Deviation	0.9	37,000	38	0.14	0.18	0.001	9	3.0	2.2	--	--	--	--
Menomonee River at Muskego Avenue (RIV-11)	Number of Samples	21	6	21	21	21	21	21	18	18	1	1	1	1
	Minimum	1.1	400	3	0.09	0.09	0.001	1	1.8	0.7	--	--	--	--
	Mean	10.5	4,500	32	0.18	0.33	0.005	7	4.4	3.1	2.0	12.0	22.3	15.3
	Maximum	13.4	9,300	112	0.30	0.69	0.017	18	8.0	10.6	--	--	--	--
	Standard Deviation	3.6	3,900	34	0.07	0.15	0.004	5.5	2.1	3.2	--	--	--	--
Kinnickinnic River at S. 1st Street (RIV-14)	Number of Samples	21	6	21	21	21	21	21	18	18	1	1	1	1
	Minimum	8.8	<100	5	0.04	0.35	0.001	1	1.7	1.2	--	--	--	--
	Mean	10.0	1,300	54	0.19	0.43	0.003	9	5.3	1.8	2.0	11.0	28.7	7.5
	Maximum	12.0	2,300	236	0.36	0.57	0.006	34	9.2	3.4	--	--	--	--
	Standard Deviation	1.0	1,130	70	0.09	0.06	0.001	9.9	2.8	0.6	--	--	--	--

[a] *The outer harbor was not sampled during this event.*

Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 70

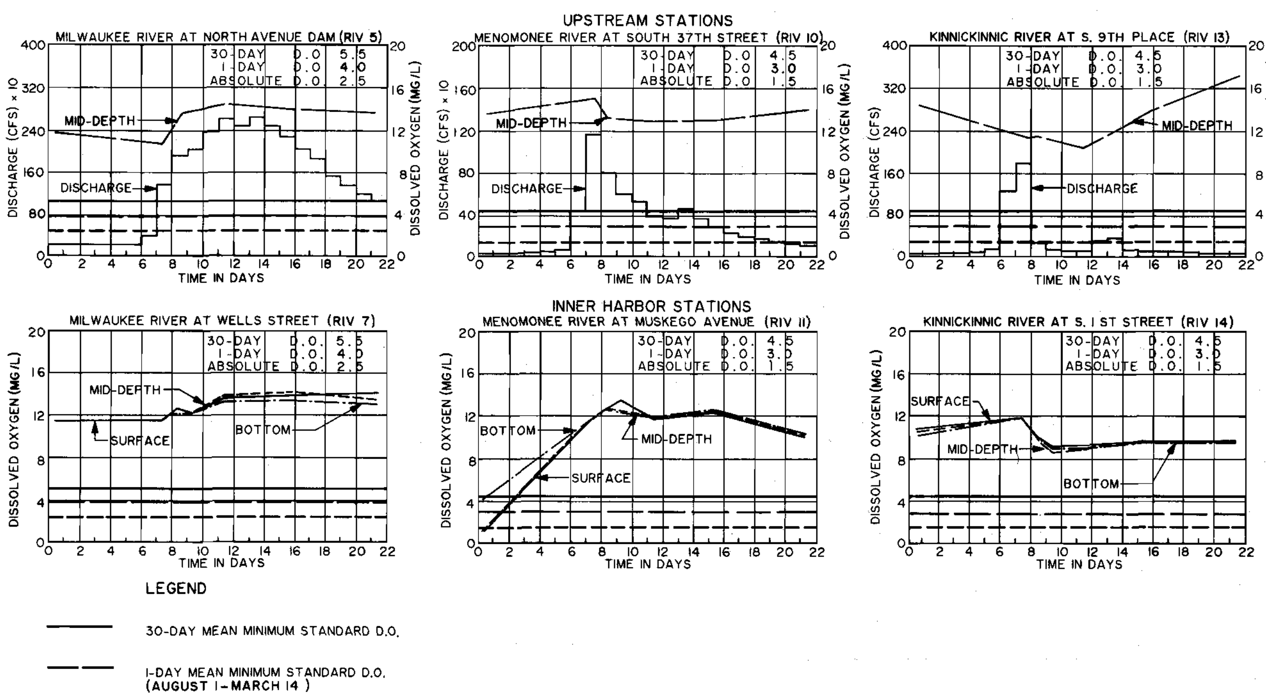
MEAN DISSOLVED OXYGEN CONCENTRATIONS DURING THE FEBRUARY 6-27, 1984 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 118

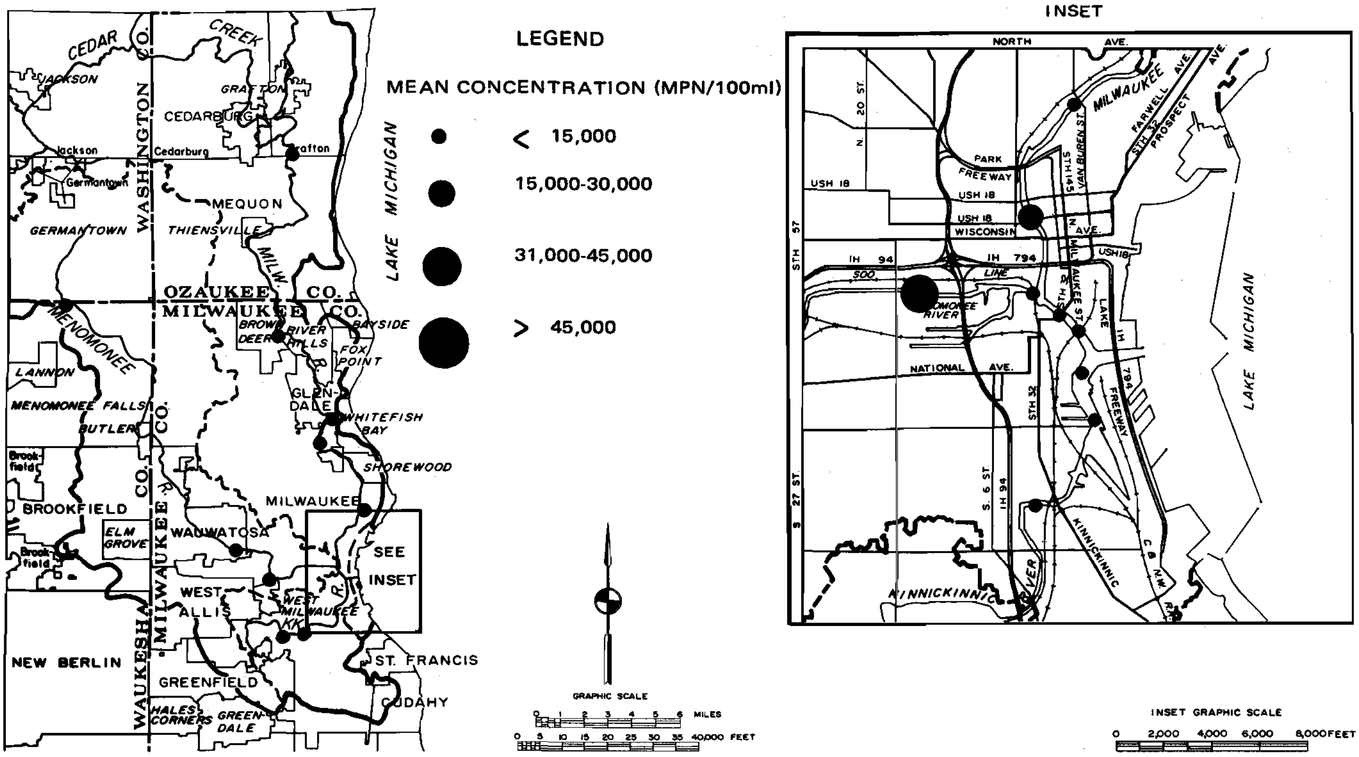
CONCENTRATION VERSUS TIME PLOTS FOR DISSOLVED OXYGEN: FEBRUARY 6-27, 1984



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 71

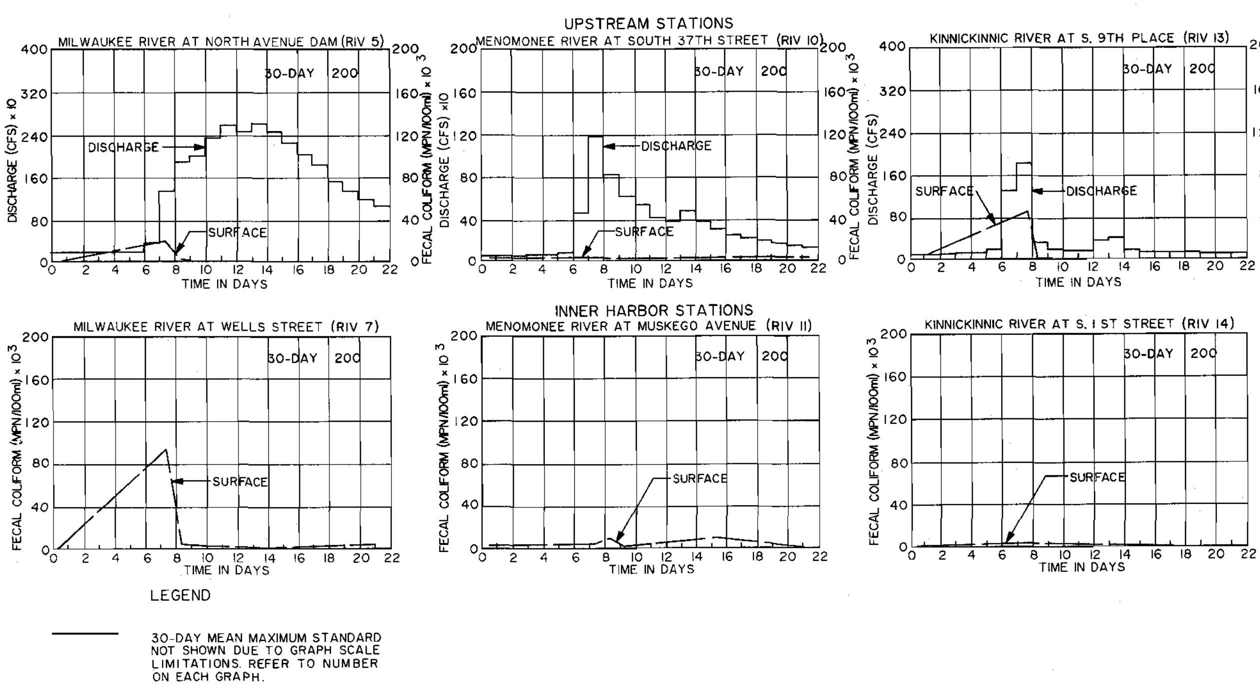
MEAN FECAL COLIFORM CONCENTRATIONS DURING THE FEBRUARY 6-27, 1984 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 119

CONCENTRATION VERSUS TIME PLOTS FOR FECAL COLIFORM: FEBRUARY 6-27, 1984



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

however, the mean concentration at the upstream station of 7,800 MPN/100 ml was six times higher than the concentration at the Kinnickinnic River estuary station of 1,300 MPN/100 ml. As shown in Figure 119, the fecal coliform levels either remained constant throughout the event or exhibited a "first flush" effect and then quickly returned to the initial levels.

Total suspended solids concentrations ranged from 2 to 236 mg/l. The spatial variations in suspended solids concentrations are shown on Map 72, and the temporal variations are presented in Figure 120. In the Milwaukee and Menomonee Rivers, the mean total suspended solids concentrations in the upstream reaches—ranging from 32 to 68 mg/l—were about the same as the concentrations at the inner harbor stations, where means ranged from 32 to 64 mg/l. In the Kinnickinnic River estuary, however, the mean concentration of 54 mg/l was higher than the concentration at the upstream station of 21 mg/l. At both the estuary and upstream stations, the Milwaukee River mean suspended solids concentrations were higher than the concentrations in the Menomonee and Kinnickinnic Rivers. As shown in Figure 120, the suspended solids concentrations at the three sample depths showed no significant differences.

Total phosphorus concentrations ranged from 0.04 to 1.71 mg/l. The spatial variations in total phosphorus concentrations are shown on Map 73, and the temporal variations are presented in Figure 121. At the Menomonee and Kinnickinnic River estuary stations, the mean total phosphorus concentrations—ranging from 0.18 to 0.19 mg/l—were about the same as the concentrations at the upstream stations, where means ranged from 0.16 to 0.20 mg/l. At the Milwaukee River estuary station, however, the mean concentration of 0.32 mg/l was lower than the concentration at the upstream station of 0.49 mg/l. At both the estuary and upstream stations, the Milwaukee River mean and maximum total phosphorus concentrations were higher than the concentrations in the Menomonee and Kinnickinnic Rivers. As shown in Figure 121, total phosphorus concentrations exhibited the "first flush" effect at the Milwaukee and Menomonee River estuary and upstream stations, and at the Kinnickinnic River estuary station. After this "first flush," the total phosphorus concentrations quickly returned to near-background levels. At the upstream station of the Kinnickinnic River, the highest concentrations of total phosphorus were reached prior to the start of the event. Within the inner harbor stations, there was no significant difference between the total phosphorus concentrations at the three sample depths.

Ammonia nitrogen concentrations ranged from 0.06 to 0.69 mg/l. Within all three rivers, the mean concentrations measured at the upstream stations—ranging from 0.18 to 0.37 mg/l—were lower than those measured at the inner harbor stations, which ranged from 0.33 to 0.43 mg/l.

Un-ionized ammonia nitrogen concentrations ranged from 0.001 to 0.017 mg/l. The mean concentrations measured at the upstream stations, which ranged from 0.002 to 0.005 mg/l, were about the same as the mean concentrations measured at the inner harbor stations, which ranged from 0.003 to 0.006 mg/l.

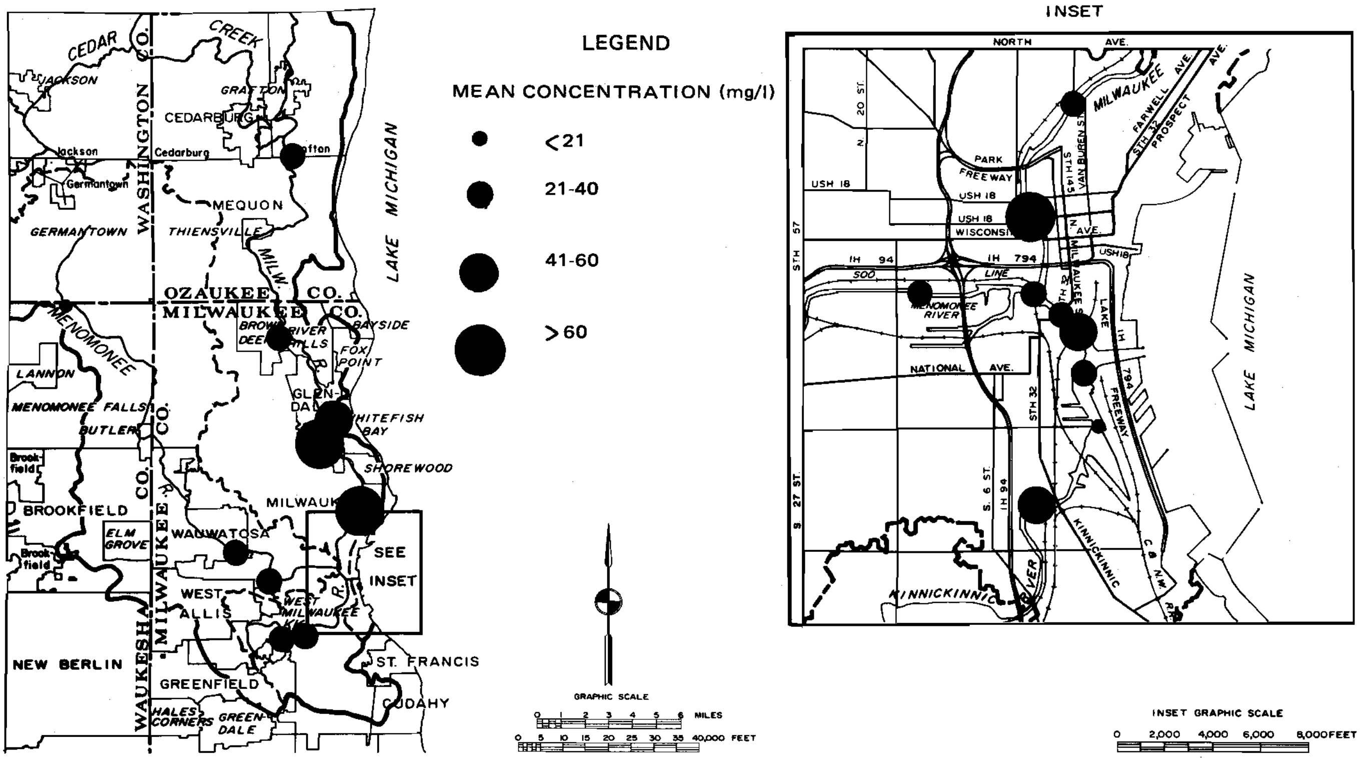
Volatile suspended solids concentrations ranged from 1 to 34 mg/l. In all three rivers, the volatile suspended solids concentrations at the inner harbor stations, with means ranging from 7 to 14 mg/l, were slightly higher than the concentrations at the upstream stations, with means ranging from 5 to 13 mg/l. In both the estuary and upstream reaches, the Milwaukee River mean volatile suspended solids concentrations were higher than the concentrations in the Menomonee and Kinnickinnic Rivers. Based on mean concentrations within the upstream and inner harbor reaches of the three rivers, volatile suspended solids represented about 17 to 24 percent of the total suspended solids concentration.

Biochemical oxygen demand (BOD_5) concentrations ranged from 1.4 to 11.0 mg/l. The mean BOD_5 concentrations in the Milwaukee and Menomonee River estuary stations—ranging from 4.4 to 6.5 mg/l—were higher than concentrations at the upstream stations, where means ranged from 4.0 to 4.7 mg/l. In the Kinnickinnic River estuary, however, the mean concentration—5.3 mg/l—was lower than the concentration at the upstream station of 6.9 mg/l.

Chlorophyll-a concentrations ranged from 0.5 to 13.2 µg/l. In the Milwaukee and Kinnickinnic Rivers, the mean chlorophyll-a concentrations at the upstream reaches—ranging from 3.1 to 11.0 µg/l—were slightly higher than the concentrations at the Milwaukee and Kinnickinnic River estuary stations, where means ranged from 1.8 to 6.2 µg/l. In the Menomonee River, however, the mean

Map 72

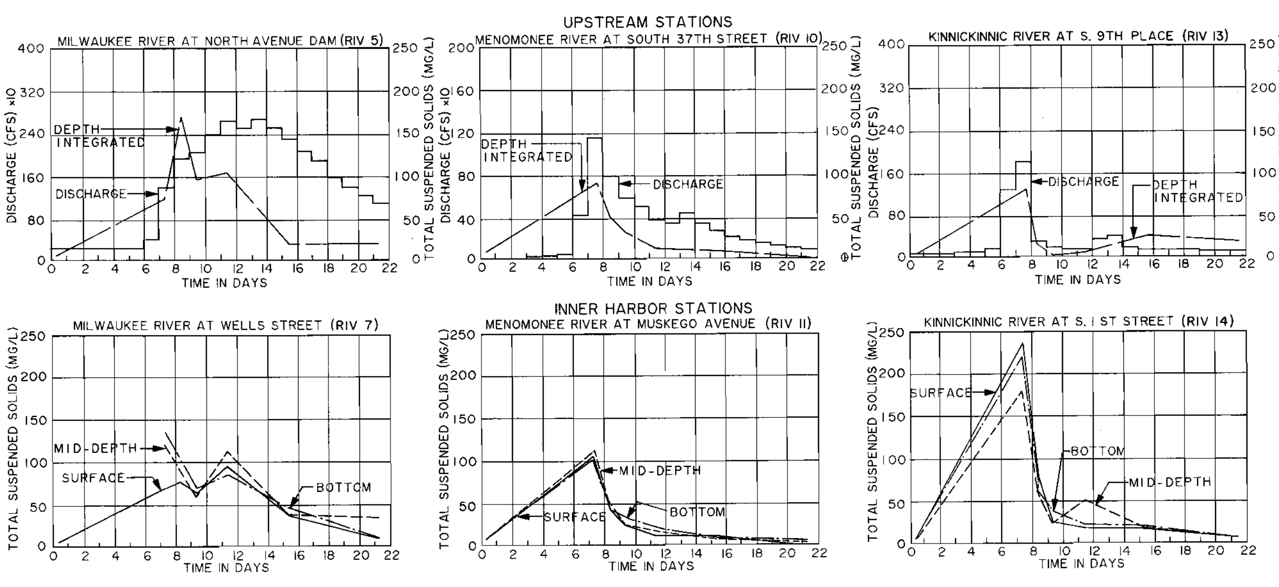
MEAN TOTAL SUSPENDED SOLIDS CONCENTRATIONS DURING THE FEBRUARY 6-27, 1984 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 120

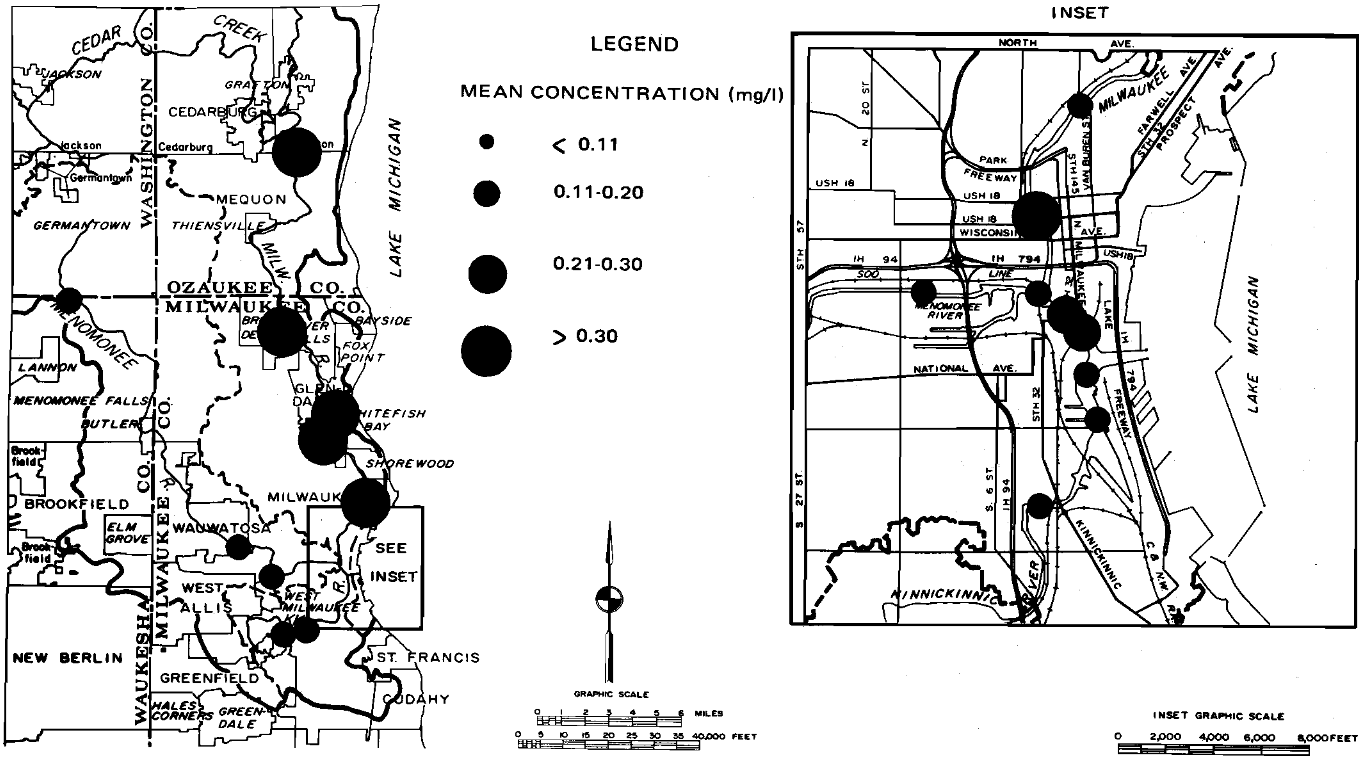
CONCENTRATION VERSUS TIME PLOTS FOR TOTAL SUSPENDED SOLIDS: FEBRUARY 6-27, 1984



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 73

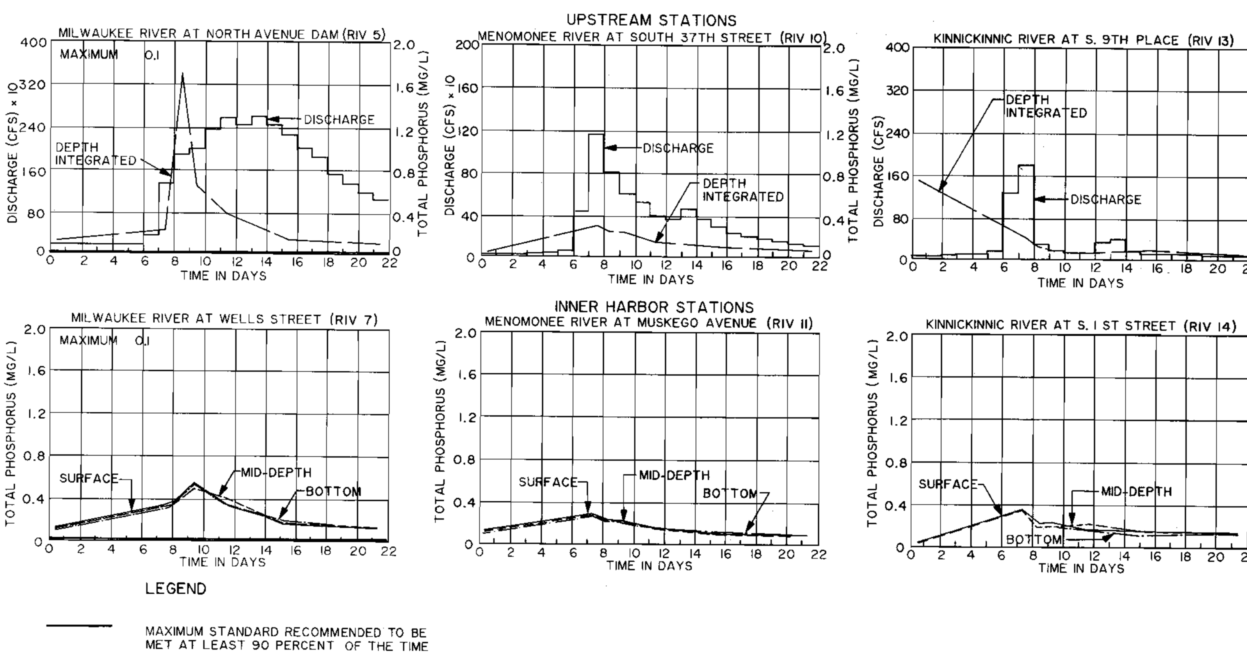
MEAN TOTAL PHOSPHORUS CONCENTRATIONS DURING THE FEBRUARY 6-27, 1984 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 121

CONCENTRATION VERSUS TIME PLOTS FOR TOTAL PHOSPHORUS: FEBRUARY 6-27, 1984



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

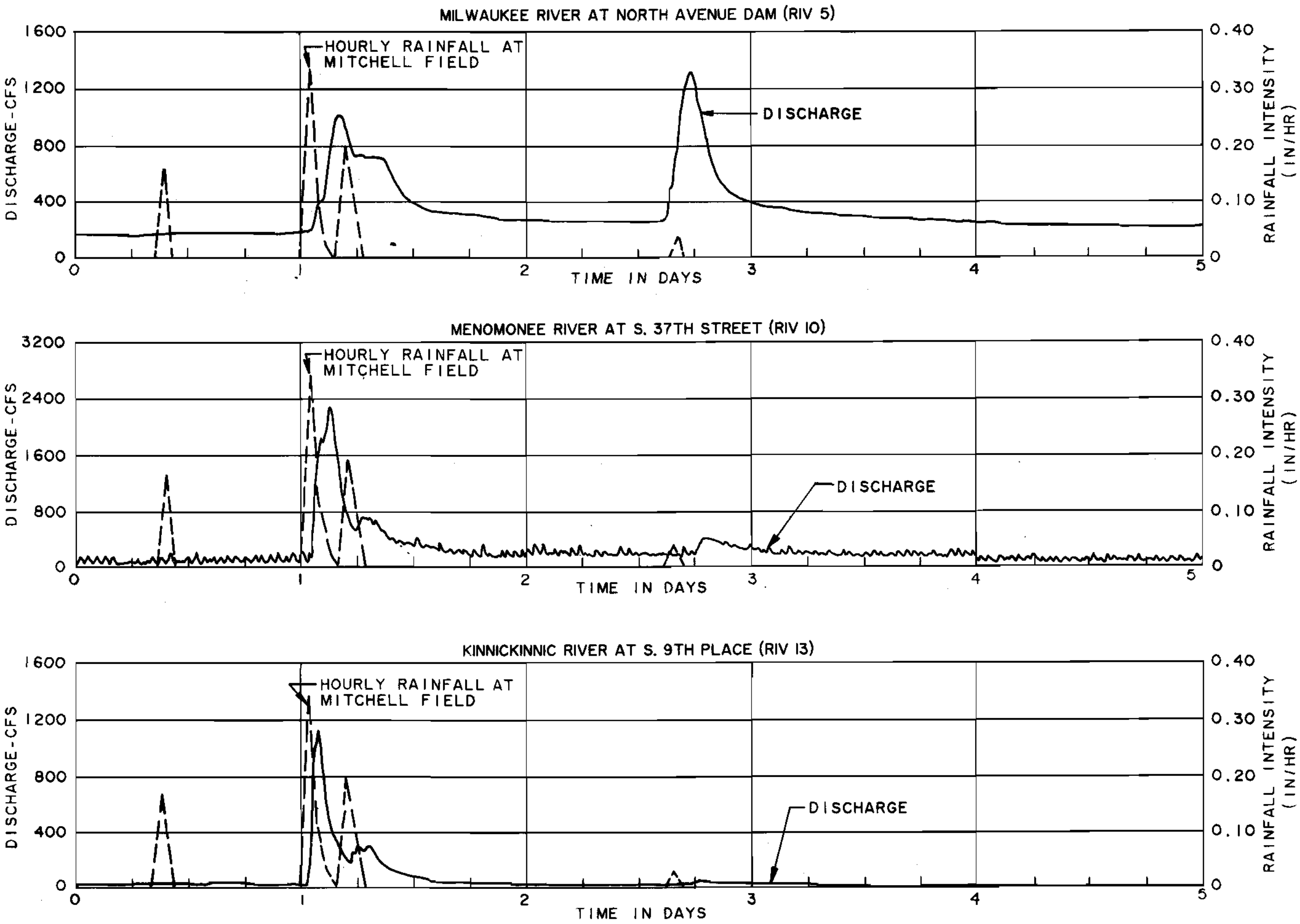
concentration at the upstream station was about the same as at the Menomonee River estuary station—about 3.0 μg/l. At both the estuary and upstream stations, the Milwaukee River mean concentrations measured—ranging from 6.2 to 11.0 μg/l—were higher than the concentrations in the Menomonee and Kinnickinnic Rivers, where the means ranged from 1.8 to 3.1 μg/l.

During this event, a number of samples were taken at each station and analyzed for metals content. In all three rivers, the cadmium concentrations were relatively the same at the upstream and inner harbor stations, with values ranging from 2.0 to 3.0 μg/l. Copper concentrations ranged from 5 to 20 μg/l, with the highest value found in the upstream reach of the Kinnickinnic River. Lead concentrations at both the Kinnickinnic River estuary and upstream stations—ranging from 29 to 42 μg/l—were higher than at the Milwaukee and Menomonee River sampling stations, where concentrations ranged from 8 to 22 μg/l. Zinc concentrations within the upstream reaches of the Menomonee and Kinnickinnic Rivers—ranging from 19.6 to 92.6 μg/l—were higher than the concentrations in the Menomonee and Kinnickinnic River estuaries, which ranged from 7.5 to 15.3 μg/l. In the Milwaukee River estuary station, however, the mean zinc concentration of 7.1 μg/l was greater than the concentration in the upstream reach of 2.9 μg/l.

August 7-11, 1984 Runoff Event: The fifth intensive runoff storm event was sampled in August 1984. The total amount of rainfall that occurred in the Milwaukee Harbor estuary direct drainage area during this event ranged from 0.74 inch to 1.58 inch. The total duration of the rainfall was approximately five and one-half hours. Figure 122 illustrates the precipitation pattern that occurred

Figure 122

DISCHARGE AND RAINFALL MEASUREMENTS AT STATIONS JUST UPSTREAM OF THE INNER HARBOR: AUGUST 7-11, 1984



Source: U.S. Geological Survey, National Weather Service, and SEWRPC.

at General Mitchell Field during the monitoring period in relationship to measured flows of the three river stations located just upstream of the inner harbor. During the five-day monitoring period, the upstream stations were sampled on a depth-integrated basis between three and 13 times, the inner harbor stations were sampled at three depths between five and 16 times, and the outer harbor stations were sampled at three depths between three and five times.

A summary of the concentrations of selected water quality indicators at the representative stations is presented in Table 69. Based on these

Table 69

SUMMARY OF RUNOFF EVENT WATER QUALITY DATA AT SELECTED STATIONS: AUGUST 7-11, 1984

Sampling Station	Statistical Variable	Dissolved Oxygen (mg/l)	Fecal Coliform (MPN/100ml)	Total Suspended Solids (mg/l)	Total Phosphorus (mg/l)	Ammonia Nitrogen (mg/l)	Un-ionized Ammonia Nitrogen (mg/l)	Volatile Suspended Solids (mg/l)	BOD_5 (mg/l)	Chlorophyll-a (μg/l)
Upstream Stations										
Milwaukee River at North Avenue Dam (RIV-5)	Number of Samples	15	12	15	17	17	17	15	15	14
	Minimum	4.2	<100	21	0.07	0.04	0.040	10	3.0	35.3
	Mean	6.8	27,000	39	0.15	0.10	0.018	14	4.7	80.6
	Maximum	12.8	110,000	54	0.23	0.56	0.092	22	6.3	160.2
	Standard Deviation	2.5	39,000	10	0.05	0.12	0.024	3	1.1	37.1
Menomonee River at S. 37th Street (RIV-10)	Number of Samples	13	9	13	13	13	13	13	13	13
	Minimum	6.3	900	4	0.07	0.06	0.001	1	1.0	5.3
	Mean	7.4	15,000	94	0.18	0.21	0.008	17	4.4	12.1
	Maximum	8.6	46,000	385	0.53	0.68	0.024	58	15.0	51.9
	Standard Deviation	0.6	14,000	128	0.13	0.18	0.007	17	3.6	12.3
Kinnickinnic River at S. 9th Place (RIV-13)	Number of Samples	12	11	12	16	16	16	12	12	12
	Minimum	6.2	<100	3	0.07	0.05	0.002	1	2.4	1.5
	Mean	8.9	16,000	94	0.39	0.28	0.025	16	4.8	5.4
	Maximum	14.9	46,000	602	2.00	0.76	0.077	90	8.3	13.8
	Standard Deviation	2.5	17,000	171	0.50	0.21	0.024	26	2.1	3.8
Inner Harbor Stations										
Milwaukee River at Wells Street (RIV-7)	Number of Samples	42	13	42	42	42	42	42	42	42
	Minimum	<0.1	200	1	0.11	0.03	0.001	1	4.0	13.8
	Mean	2.2	52,000	26	0.16	0.10	0.013	11	7.2	42.0
	Maximum	10.6	240,000	58	0.23	0.30	0.096	24	9.0	108.9
	Standard Deviation	2.4	66,000	14	0.03	0.62	0.019	5	1.5	24.9
Menomonee River at Muskego Avenue (RIV-11)	Number of Samples	42	12	42	42	42	42	42	42	42
	Minimum	0.2	<100	2	0.08	0.10	0.001	1	1.0	4.4
	Mean	1.9	110,000	23	0.13	0.32	0.010	7	4.9	8.5
	Maximum	6.4	240,000	175	0.32	0.76	0.027	29	9.3	43.2
	Standard Deviation	1.8	120,000	32	0.04	0.16	0.007	6	2.4	6.0
Kinnickinnic River at S. 1st Street (RIV-14)	Number of Samples	48	16	48	48	47	47	48	32	48
	Minimum	0.7	<100	6	0.10	0.41	0.003	1	2.1	2.0
	Mean	3.2	48,000	184	0.33	0.59	0.095	29	6.1	13.4
	Maximum	6.8	240,000	2,280	3.61	1.22	0.431	354	33.0	210.1
	Standard Deviation	2.0	69,000	482	0.69	0.15	0.141	69	7.1	34.7
Outer Harbor Stations										
Hoan Bridge[a] (OH-1)	Number of Samples	15	5	5	15	15	15	15	4	15
	Minimum	1.5	1,500	6	0.03	0.09	0.000	3	1.4	8.2
	Mean	7.4	8,200	11	0.06	0.18	0.001	4	2.2	14.1
	Maximum	10.5	24,000	13	0.09	0.31	0.003	7	4.4	34.5
	Standard Deviation	2.6	9,300	3	0.19	0.06	0.001	2	0.5	6.9
South Outer Harbor[a] (OH-11)	Number of Samples	15	5	5	15	15	15	5	5	15
	Minimum	8.8	<100	4	0.01	0.09	0.000	1	1.2	4.5
	Mean	10.1	1,100	5	0.04	0.20	0.003	3	2.2	11.3
	Maximum	11.9	2,400	7	0.05	0.36	0.009	5	3.0	17.6
	Standard Deviation	0.8	1,200	1	0.01	0.09	0.002	2	0.8	4.1

[a] *Concentrations of BOD_5 were not measured at stations OH-1 and OH-11. Therefore, concentrations of BOD_5 measured at OH-7, located at the main harbor entrance, are presented for OH-1, and concentrations of BOD_5 measured at OH-3, located in the central outer harbor, are presented for OH-11.*

Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

representative stations, the results of the water quality monitoring during the August event are discussed below.

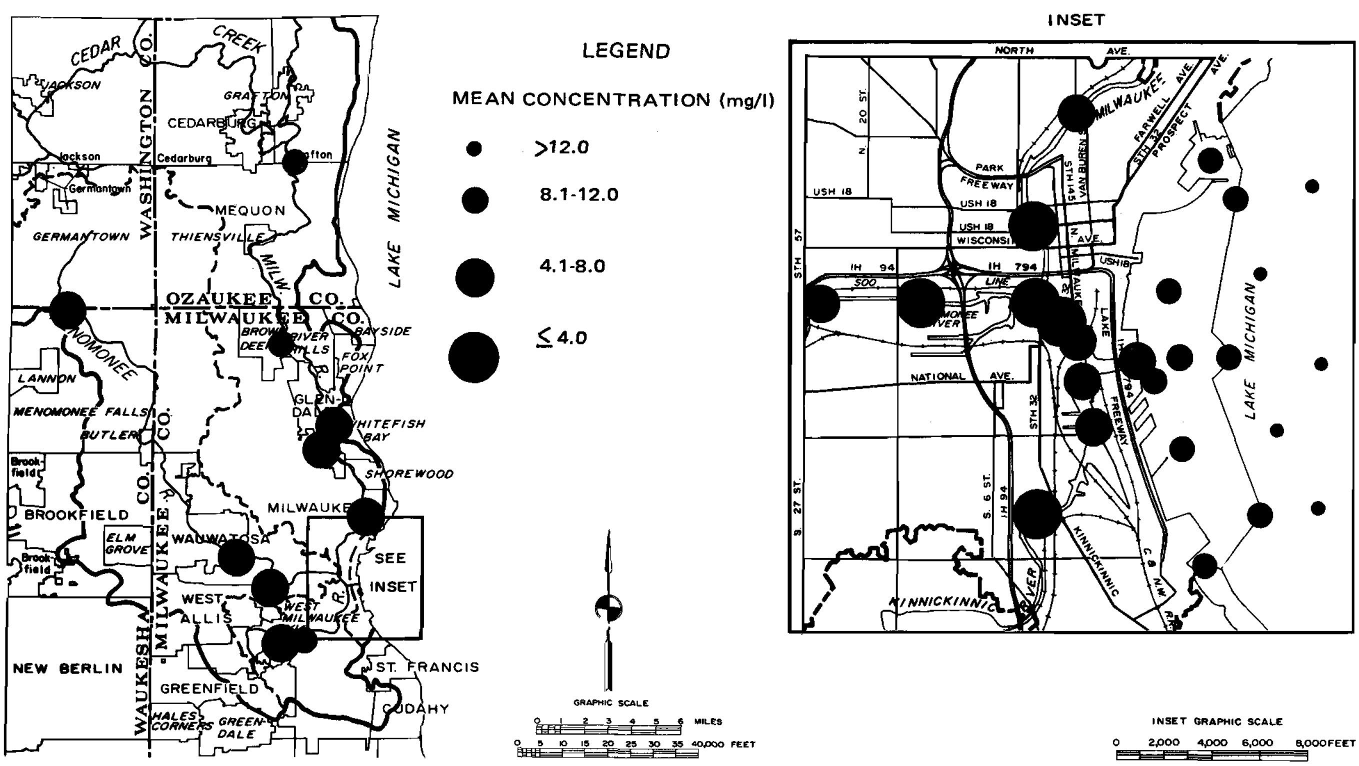
Dissolved oxygen concentrations ranged from less than 0.1 to 14.9 mg/l. The spatial variations in dissolved oxygen levels are shown on Map 74, and the temporal variations which occurred during the event sampling program are presented in Figure 123. In all three rivers, the dissolved oxygen concentrations at the upstream stations, with means ranging from 6.8 to 8.9 mg/l, were higher than the concentrations at the inner harbor stations, where means ranged from 1.9 to 3.2 mg/l. The mean dissolved oxygen concentrations in the outer harbor ranged from 7.4 to 10.1 mg/l. As shown in Figure 123, the dissolved oxygen concentrations in the upstream reach of the Milwaukee River and the estuarine portions of the Menomonee and Kinnickinnic Rivers increased at the start of the event, while the concentrations at the Milwaukee River estuary and other upstream stations decreased. During the event, the upstream and inner harbor stations exhibited diurnal fluctuations in dissolved oxygen levels.

Fecal coliform levels ranged from 100 to 240,000 MPN/100 ml. The spatial variations in fecal coliform levels are shown on Map 75, and the temporal variations which occurred during the event sampling program are presented in Figure 124. In all three rivers, the fecal coliform levels at the inner harbor stations, with means ranging from 48,000 to 110,000 MPN/100 ml, were higher than the levels at the upstream stations, where means ranged from 16,000 to 27,000 MPN/100 ml. Mean fecal coliform levels at the representative outer harbor stations were lower, with values ranging from 1,100 to 8,200 MPN/100 ml. As shown in Figure 124, the fecal coliform levels generally exhibited a "first flush" effect, especially in the inner harbor, in that peak fecal coliform concentrations were reached shortly after the event began.

Total suspended solids concentrations ranged from 7 to 2,280 mg/l. The spatial variations in suspended solids concentrations are shown on Map 76, and the temporal variations are presented in Figure 125. In the Milwaukee and Menomonee Rivers, the suspended solids concentrations in the upstream reaches, with means ranging from 39 to

Map 74

MEAN DISSOLVED OXYGEN CONCENTRATIONS DURING THE AUGUST 7-11, 1984 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

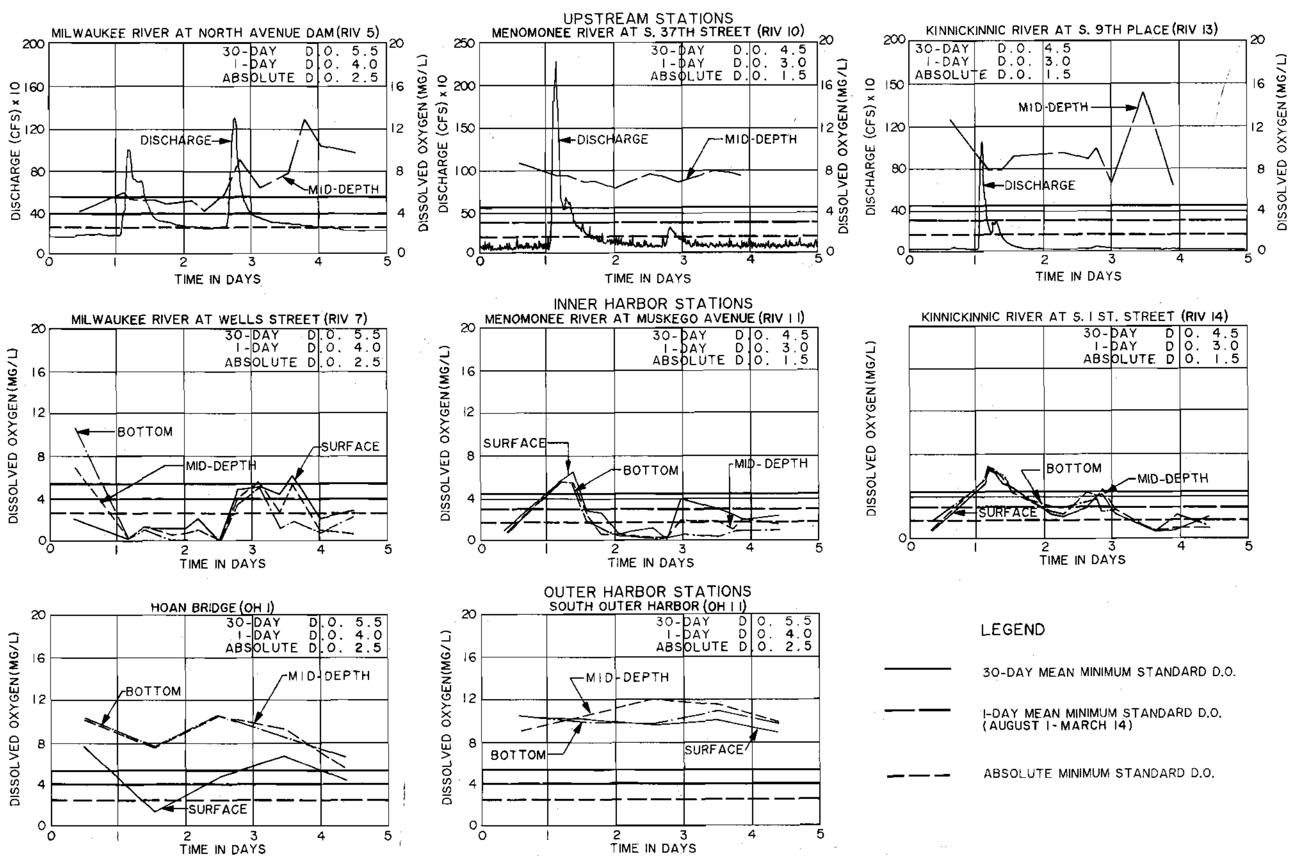
94 mg/l, were higher than the concentrations within the estuarine portions of the rivers, where means ranged from 23 to 26 mg/l. In the Kinnickinnic River estuary, however, the suspended solids concentration of 184 mg/l was nearly double that at the upstream station of 94 mg/l.

At both the upstream and inner harbor stations, the mean suspended solids concentrations in the Kinnickinnic River were equal to or higher than those in the Milwaukee and Menomonee Rivers. Total suspended solids concentrations were lowest in the outer harbor, with means ranging from 5 to 11 mg/l. As shown in Figure 125, the suspended solids concentrations either remained constant or exhibited a "first flush" effect within the upstream reaches and the inner harbor. Within the inner harbor, there is little significant difference between the suspended solids concentrations at the three sample depths, except that within the Menomonee and Kinnickinnic River estuaries, the peak concentrations were highest in the bottom layer of water.

Total phosphorus concentrations ranged from 0.01 to 3.61 mg/l. The spatial variations in total phosphorus concentrations are shown on Map 77, and the temporal variations are presented in Figure 126. In the Menomonee and Kinnickinnic Rivers, the mean total phosphorus concentrations in the upstream reaches—ranging from 0.18 to 0.39 mg/l—were higher than the mean concentrations measured in the inner harbor, which ranged from 0.13 to 0.33 mg/l. In the Milwaukee River, however, the mean concentration in the upstream station was about the same as in the Milwaukee River estuary station—about 0.16 mg/l. The mean total phosphorus concentrations in the Kinnickinnic River were substantially higher than those present in the Menomonee and Milwaukee Rivers in both the upstream and estuary reaches. Mean total phosphorus concentrations in the outer harbor ranged from 0.03 to 0.04 mg/l, which are lower than the levels found in the inner harbor. As shown in Figure 126, total phosphorus concentrations either remained constant or exhibited a "first

Figure 123

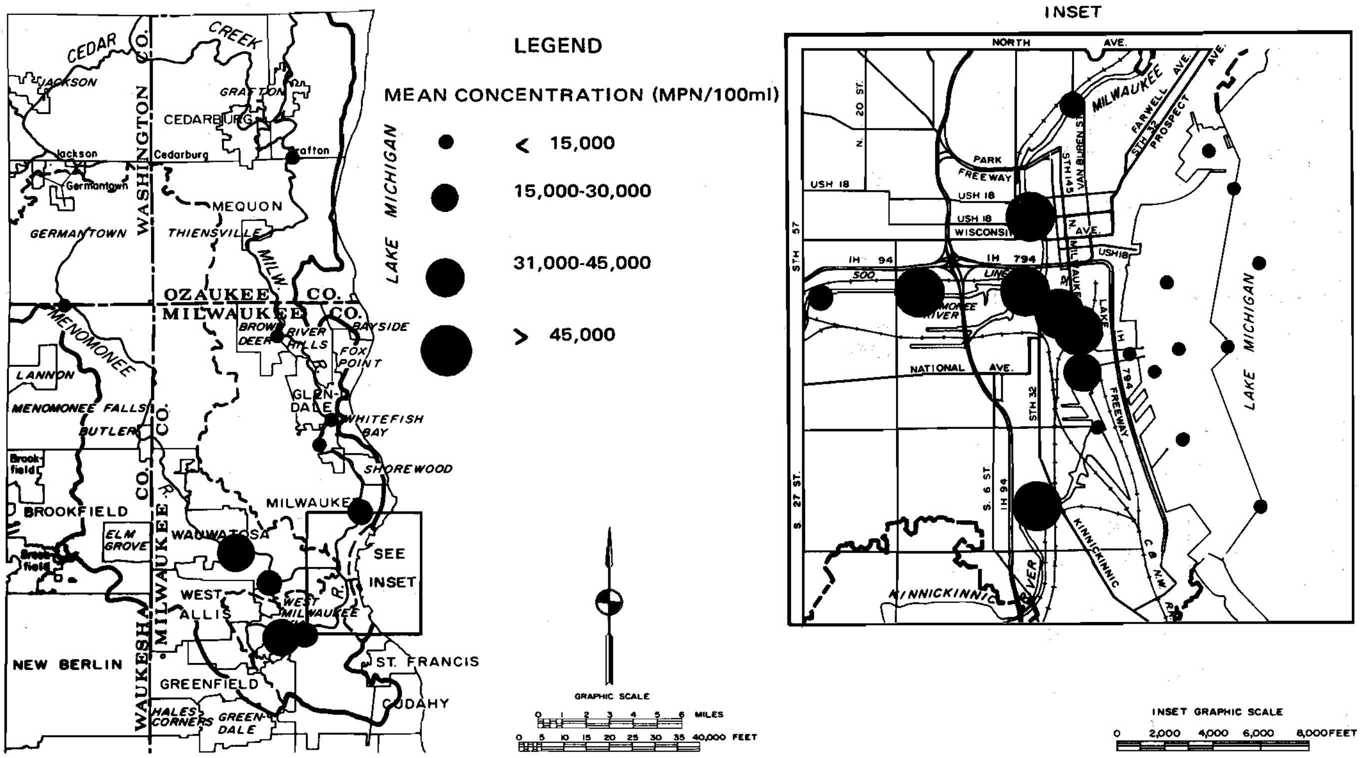
CONCENTRATION VERSUS TIME PLOTS FOR DISSOLVED OXYGEN: AUGUST 7-11, 1984



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 75

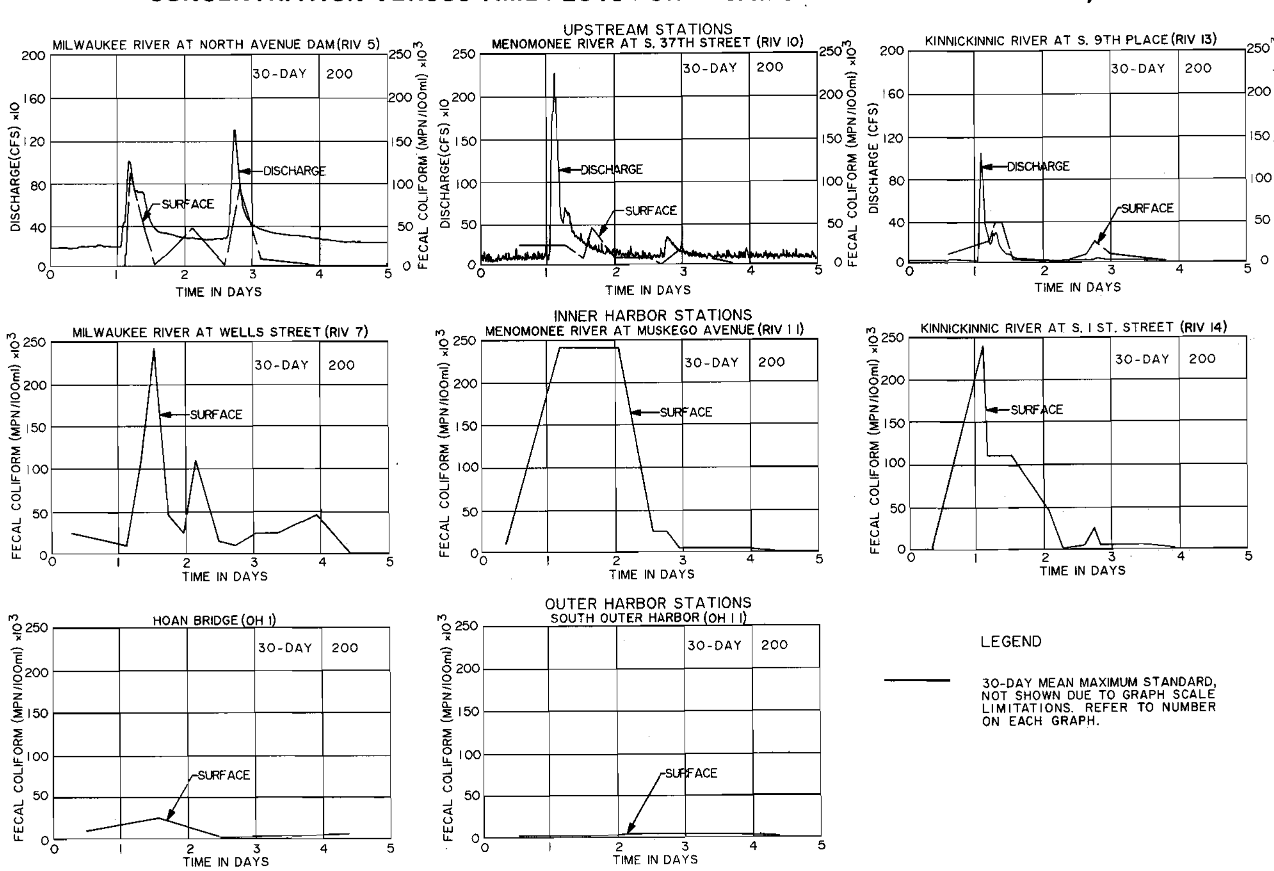
MEAN FECAL COLIFORM CONCENTRATIONS DURING THE AUGUST 7-11, 1984 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 124

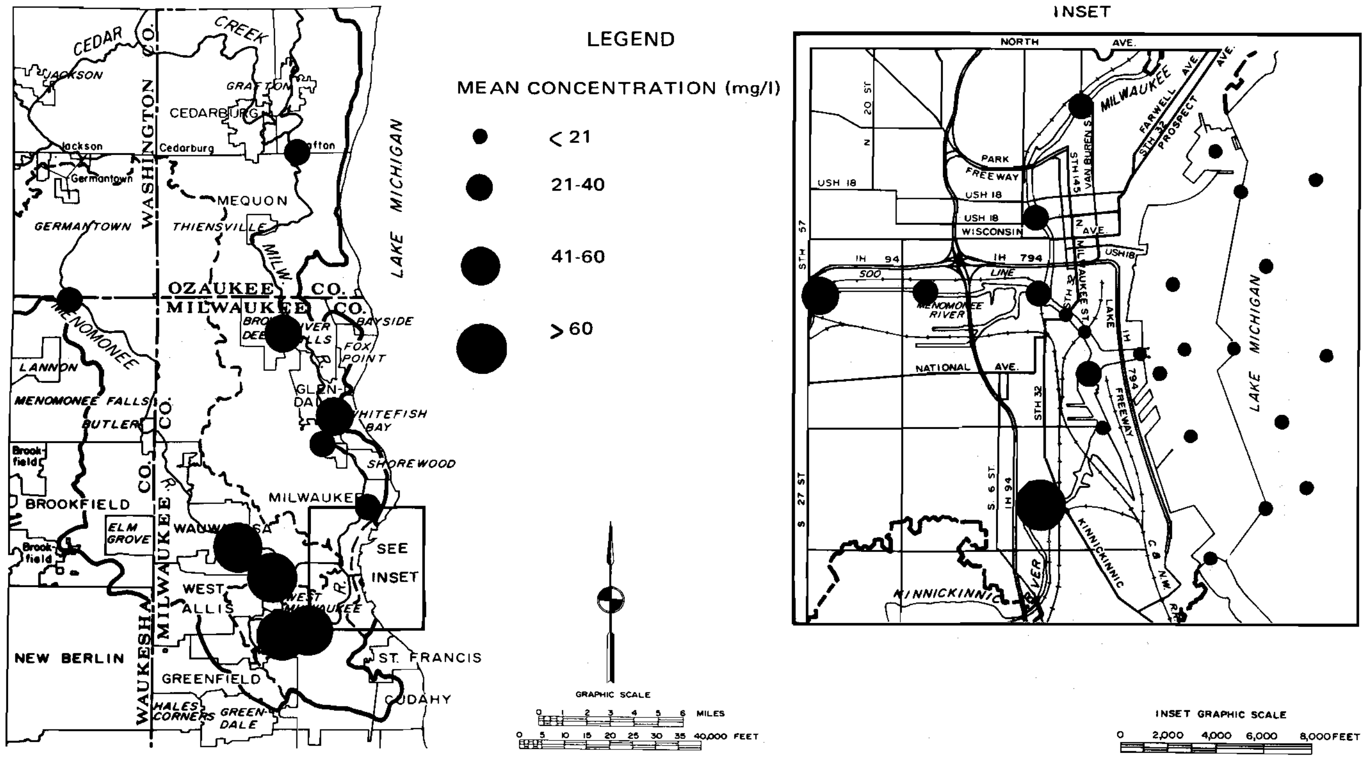
CONCENTRATION VERSUS TIME PLOTS FOR FECAL COLIFORM: AUGUST 7-11, 1984



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 76

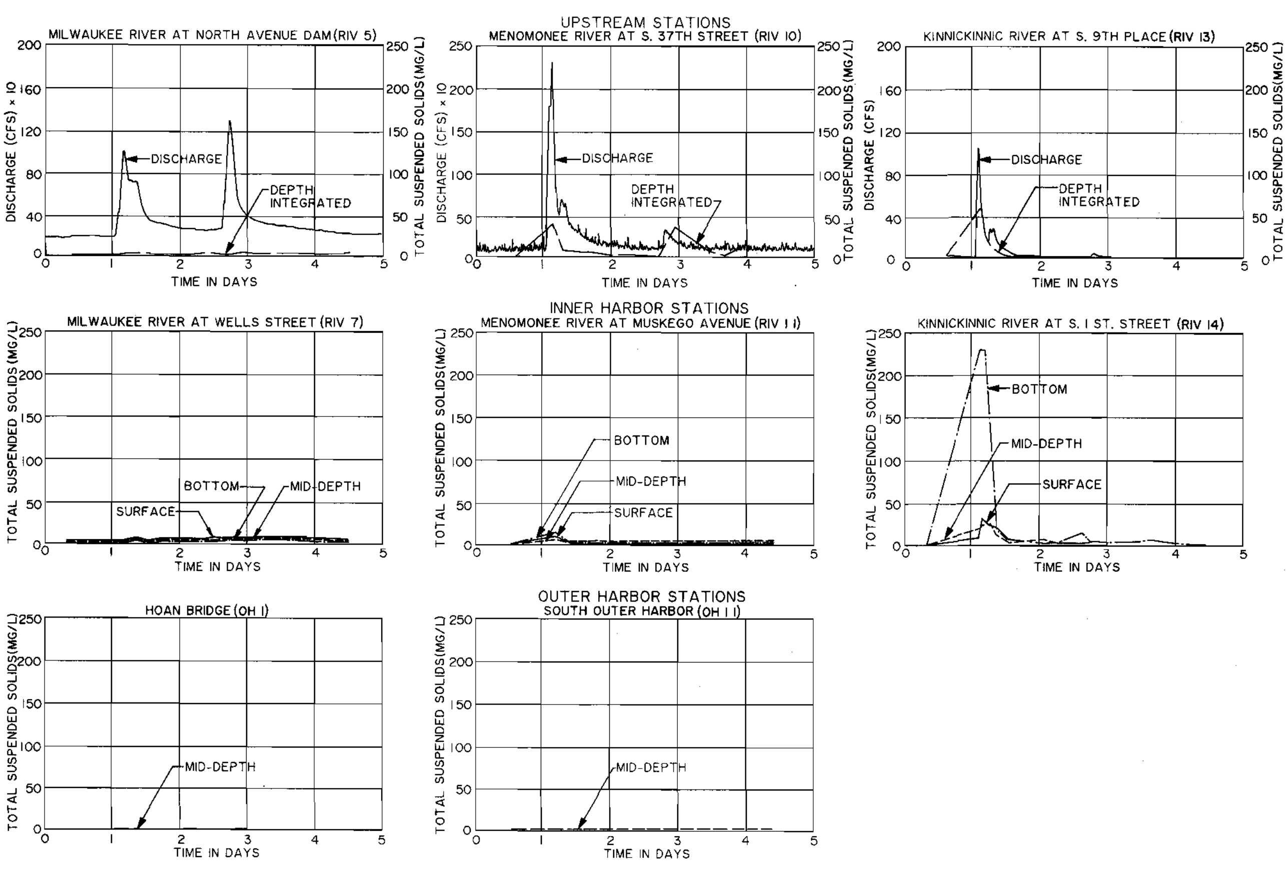
MEAN TOTAL SOLIDS CONCENTRATIONS DURING THE AUGUST 7-11, 1984 STORM EVENT



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Figure 125

CONCENTRATION VERSUS TIME PLOTS FOR TOTAL SUSPENDED SOLIDS: AUGUST 7-11, 1984



Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Map 77

MEAN TOTAL PHOSPHORUS CONCENTRATIONS DURING THE AUGUST 7-11, 1984 STORM EVENT

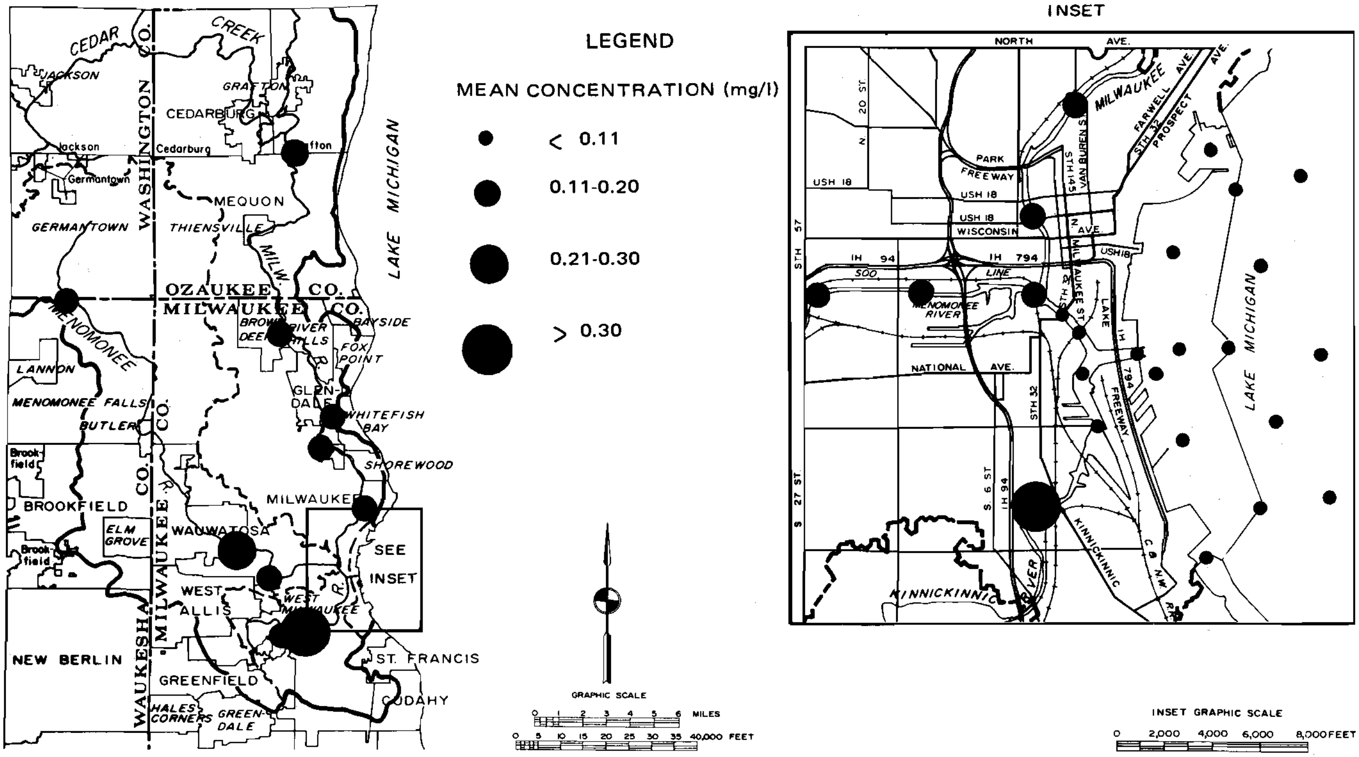
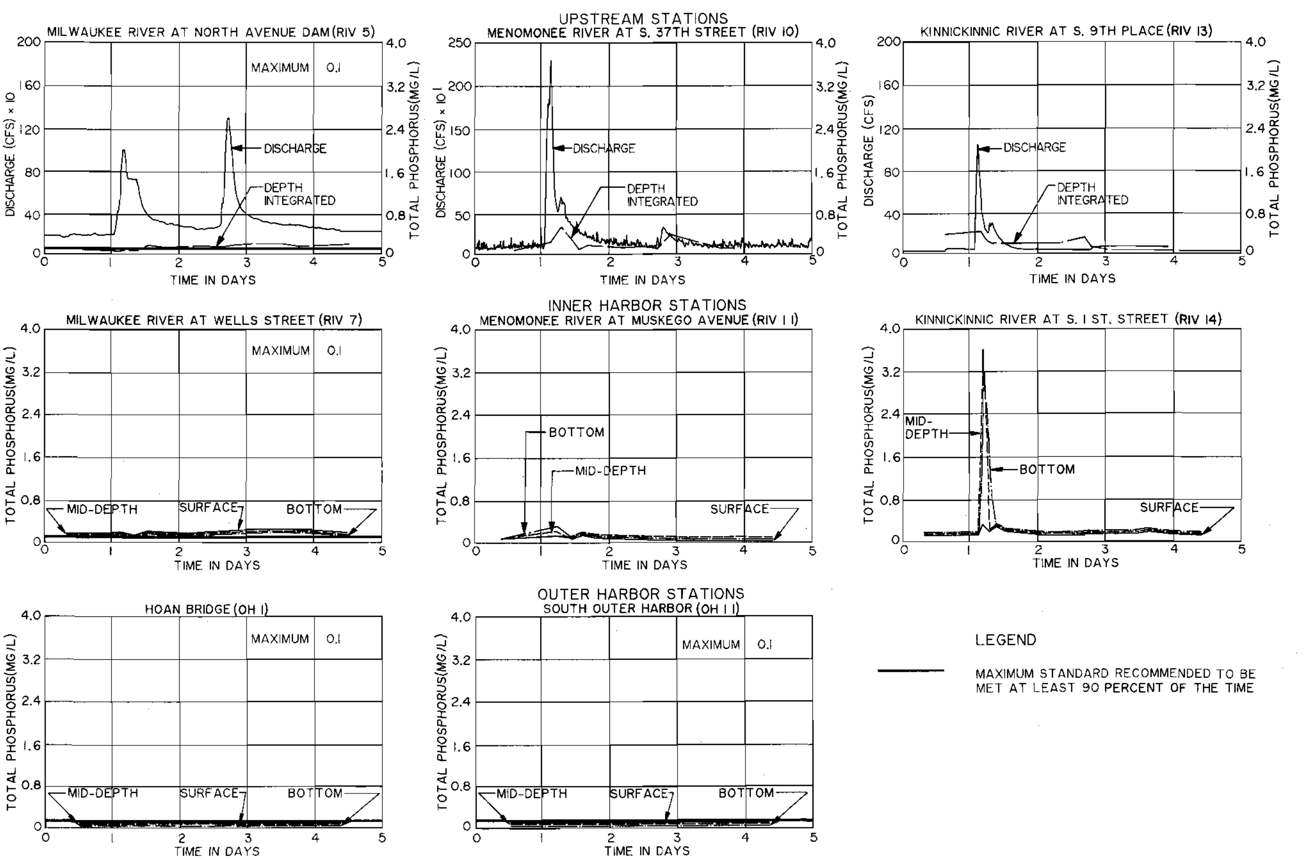


Figure 126

CONCENTRATION VERSUS TIME PLOTS FOR TOTAL PHOSPHORUS: AUGUST 7-11, 1984



flush" effect at both the upstream and inner harbor stations. After this "first flush," the total phosphorus concentrations quickly returned to near-background levels. As with suspended solids, the peak phosphorus concentrations in the Menomonee and Kinnickinnic River estuaries were highest in the bottom layer of water. In the Milwaukee River estuary, there was no difference between the phosphorus concentrations measured at the three sample depths.

Ammonia nitrogen concentrations ranged from 0.03 to 1.22 mg/l. In the Menomonee and Kinnickinnic Rivers, the mean concentrations in the upstream reaches—ranging from 0.21 to 0.28 mg/l—were lower than the mean concentrations measured in the estuarine portions of the Menomonee and Kinnickinnic Rivers, which ranged from 0.32 to 0.59 mg/l. At the Milwaukee River estuary and upstream stations, however, the mean concentrations were about the same—approximately 0.10 mg/l. At both the estuary and upstream stations, the Kinnickinnic River mean concentrations were higher than the concentrations in the Milwaukee and Menomonee Rivers. Mean ammonia nitrogen concentrations at the representative outer harbor stations ranged from 0.18 to 0.20 mg/l.

Un-ionized ammonia nitrogen concentrations ranged from 0 to 0.431 mg/l. The mean concentrations measured at the upstream stations ranged from 0.008 to 0.025 mg/l, while the mean concentrations measured at the inner harbor stations ranged from 0.010 to 0.095 mg/l. At both the estuary and upstream stations, the Kinnickinnic River mean concentrations were higher than the concentrations in the Milwaukee and Menomonee Rivers. Un-ionized ammonia nitrogen concentrations were lowest in the outer harbor, with means ranging from 0.001 to 0.003 mg/l.

Volatile suspended solids concentrations ranged from 1 to 354 mg/l. The mean concentrations at the upstream stations of the Milwaukee and Menomonee Rivers—ranging from 14 to 17 mg/l—were higher than those measured at the inner harbor stations, where means ranged from 7 to 11 mg/l. Within the Kinnickinnic River estuary, the mean concentration of volatile suspended solids—29 mg/l—was higher than the upstream concentration of 16 mg/l. Based on the mean concentrations in the upstream and estuarine portions of the three rivers, volatile suspended solids represented from 16 to 42 percent of the total suspended solids concentration. The relative portion of the total suspended solids level which was volatile was higher in the outer harbor—ranging from 36 to 60 percent. The concentrations of volatile suspended solids, however, were lower in the outer harbor than in the rivers, with means ranging from 3 to 4 mg/l.

Biochemical oxygen demand (BOD_5) concentrations ranged from 1.0 to 33.0 mg/l. In all three rivers, the BOD_5 concentrations in the inner harbor, with means ranging from 4.9 to 7.2 mg/l, were slightly higher than the concentrations in the upstream reaches, where means ranged from 4.4 to 4.8 mg/l. BOD_5 measurements were lowest in the outer harbor during this event, with mean values of about 2.2 mg/l.

Chlorophyll-a concentrations ranged from 1.5 to 210.1 µg/l. The mean concentrations at the upstream stations of the Milwaukee and Menomonee Rivers—ranging from 12.1 to 80.6 µg/l—were higher than those measured at the Milwaukee and Menomonee River estuary stations, where means ranged from 8.5 to 42.0 µg/l. Within the Kinnickinnic River, however, the upstream concentration of 5.4 µg/l was less than the Kinnickinnic River estuary concentration of 13.4 µg/l. At both the estuary and upstream stations, the Milwaukee River mean concentrations—ranging from 42.0 to 80.6 µg/l—were substantially higher than in the Menomonee and Kinnickinnic Rivers, where the means ranged from 5.4 to 13.4 µg/l. Mean chlorophyll-a levels at representative outer harbor stations ranged from 11.3 to 14.1 µg/l.

Summary of Findings of Synoptic Runoff Events

During the course of the harbor estuary study, a total of five intensive runoff events were surveyed. The amount of runoff and the resultant pollutant loads which occurred during each of the events were found to be affected by the amount and the duration of the rainfall, as well as the season of the year in which the event occurred. The spring rainfall event in April 1983, had the largest rainfall, ranging from 1.6 to 2.4 inches over a 36-hour period. A more intense rainfall occurred, however, in the summer event in August, 1984, with precipitation ranging from 0.74 inch to 1.58 inches over a five-and-one-half-hour period. Mean daily flows were highest during the April 1983 event in all three rivers. High flows also occurred during the February 1984 event. The monitoring periods during each of the five events lasted a minimum of five days, and ranged up to 22 days for the runoff event in February 1984. During each of the monitoring periods, the upstream stations were sampled in a depth-integrated basis, from three to 14 times, the inner harbor stations were sampled at three depths from four to 14 times, and the outer harbor and near-shore Lake Michigan stations were sampled at three depths from three to five times.

A summary of the mean concentrations of selected water quality indicators for each event is presented in Table 70 for three representative upstream stations, three representative inner harbor stations,

Table 70

SUMMARY OF THE MEAN CONCENTRATIONS OF WATER QUALITY INDICATORS AT SELECTED STATIONS DURING THE RUNOFF EVENTS

Sampling Station	Runoff Event	Dissolved Oxygen (mg/l)	Fecal Coliform (MPN/100ml)	Total Suspended Solids (mg/l)	Total Phosphorus (mg/l)	Ammonia Nitrogen (mg/l)	Un-ionized Ammonia Nitrogen (mg/l)	Volatile Suspended Solids (mg/l)	BOD_5 (mg/l)	Chlorophyll-a (μg/l)
Upstream Stations										
Milwaukee River at North Avenue Dam (RIV-5)	April 1-8, 1983	12.8	5,900	65	0.14	0.18	0.050	11	2.6	- -
	September 10-14, 1983	7.3	7,500	42	0.16	0.05	0.010	12	5.4	73.6
	October 11-15, 1983	9.7	24,000	23	0.10	0.06	0.018	6	2.7	11.5
	February 6-27, 1984	13.0	5,000	68	0.49	0.37	0.002	13	4.7	11.0
	August 7-11, 1984	6.8	27,000	39	0.15	0.10	0.018	14	4.7	80.6
Menomonee River at S. 37th Street (RIV-10)	April 1-8, 1983	12.5	3,900	98	0.13	0.14	0.003	16	3.4	- -
	September 10-14, 1983	7.8	44,000	53	0.18	0.14	0.006	9	7.0	12.5
	October 11-15, 1983	8.6	24,000	45	0.13	0.08	0.009	10	6.3	11.2
	February 6-27, 1984	13.5	1,600	32	0.16	0.27	0.003	6	4.0	2.9
	August 7-11, 1984	7.4	15,000	94	0.18	0.21	0.008	17	4.4	12.1
Kinnickinnic River at S. 9th Place (RIV-13)	April 1-8, 1983	11.6	9,300	214	0.33	0.27	0.003	22	5.0	- -
	September 10-14, 1983	9.5	37,000	18	0.37	0.31	0.010	4	7.7	10.6
	October 11-15, 1983	9.5	12,000	31	0.07	0.07	0.009	7	5.9	5.2
	February 6-27, 1984	12.8	7,800	21	0.20	0.18	0.005	5	6.9	3.1
	August 7-11, 1984	8.9	16,000	94	0.39	0.28	0.025	16	4.8	5.4
Inner Harbor Stations										
Milwaukee River at Wells Street (RIV-7)	April 1-8, 1983	11.2	15,000	63	0.15	0.16	0.005	12	3.5	- -
	September 10-14, 1983	4.1	11,000	29	0.14	0.18	0.011	11	5.0	62.5
	October 11-15, 1983	9.0	8,500	22	0.10	0.14	0.008	6	4.7	13.6
	February 6-27, 1984	12.9	17,000	64	0.32	0.40	0.003	14	6.5	6.2
	August 7-11, 1984	2.2	52,000	26	0.16	0.10	0.013	11	7.2	42.0
Menomonee River at Muskego Avenue (RIV-11)	April 1-8, 1983	11.1	9,400	46	0.07	0.22	0.003	8	4.4	- -
	September 10-14, 1983	2.0	95,000	16	0.11	0.42	0.006	6	6.4	12.3
	October 11-15, 1983	2.5	53,000	14	0.10	0.24	0.003	6	5.1	7.6
	February 6-27, 1984	10.5	4,500	32	0.18	0.33	0.005	7	4.4	3.1
	August 7-11, 1984	1.9	110,000	23	0.13	0.32	0.010	7	4.9	8.5
Kinnickinnic River at S. 1st Street (RIV-14)	April 1-8, 1983	10.3	26,000	129	0.21	0.32	0.013	16	4.7	- -
	September 10-14, 1983	4.5	86,000	48	0.19	0.37	0.008	12	5.9	7.4
	October 11-15, 1983	3.0	84,000	40	0.16	0.36	0.027	8	5.3	3.4
	February 6-27, 1984	10.0	1,300	54	0.19	0.43	0.003	9	5.3	1.8
	August 7-11, 1984	3.2	48,000	184	0.33	0.59	0.095	29	6.1	13.4
Outer Harbor Stations										
Hoan Bridge[a] (OH-1)	April 1-8, 1983	12.6	5,500	30	0.10	0.12	0.001	8	1.8	- -
	September 10-14, 1983	7.9	61,000	8	0.04	0.32	0.005	3	3.9	15.1
	October 11-15, 1983	7.9	7,000	9	0.05	0.29	0.003	3	1.0	7.2
	August 7-11, 1984	7.4	8,200	11	0.06	0.18	0.001	4	2.2	14.1
South Outer Harbor[a] (OH-11)	April 1-8, 1983	12.5	300	22	0.06	0.34	0.003	5	2.4	- -
	September 10-14, 1983	9.5	200	4	0.02	0.14	0.003	2	2.3	10.4
	October 11-15, 1983	9.3	500	6	0.03	0.31	0.001	2	1.2	6.1
	August 7-11, 1984	10.1	1,100	5	0.04	0.20	0.003	3	2.2	11.3

[a] *Concentrations of BOD_5 at stations OH-1 and OH-11 were not measured. Therefore, concentrations of BOD_5 measured at OH-7, located at the main harbor entrance, are presented for OH-1, and concentrations of BOD_5 measured at OH-3, located in the central outer harbor, are presented for OH-11.*

Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

and two representative outer harbor stations. Table 71 presents the total pollutant loadings to the inner harbor for each event, and Table 72 presents the corresponding unit-area loadings.

The following discussion of the water quality monitoring during the runoff events is based on the representative stations and includes a comparison, for each of the selected water quality indicators, of the concentrations, total loadings, and unit-area loadings. Where applicable, the relationship of the water quality indicators to the recommended water use objectives and water quality standards as set forth in Chapter II of Volume Two of this report is also discussed.

Table 71

TOTAL POLLUTANT LOADINGS FOR SAMPLED RUNOFF EVENTS AT RIVER STATIONS JUST UPSTREAM OF THE INNER HARBOR

Sampling Station	Runoff Event	Mean Daily Flow (cfs)	Fecal Coliform (number x 10^6)	Total Suspended Solids (pounds)	Total Phosphorus (pounds)	Ammonia Nitrogen (pounds)	Un-ionized Ammonia Nitrogen (pounds)	Volatile Suspended Solids (pounds)	BOD_5 (pounds)	Chlorophyll-a (pounds)
Milwaukee River at North Avenue Dam (RIV-5)	April 1-8, 1983	2,840	2,640,000	7,120,500	15,800	13,500	3,700	1,322,600	275,900	- -
	September 10-14, 1983	190	138,000	202,200	800	300	70	58,600	29,500	400
	October 11-15, 1983	480	592,000	361,600	1,300	800	200	101,000	42,100	100
	February 6-27, 1984	1,390	1,520,000	8,779,500	55,000	52,400	300	1,887,200	667,900	800
	August 7-11, 1984	300	787,000	346,000	1,400	1,100	100	121,900	44,400	700
Menomonee River at S. 37th Street (RIV-10)	April 1-8, 1983	1,050	750,000	4,308,400	6,200	6,900	200	702,100	141,600	- -
	September 10-14, 1983	50	476,000	151,300	400	400	40	30,800	17,300	40
	October 11-15, 1983	100	1,230,000	118,600	400	200	30	25,400	16,100	40
	February 6-27, 1984	300	261,000	1,260,100	6,300	9,300	100	235,700	150,000	100
	August 7-11, 1984	140	361,000	602,600	1,000	1,300	100	105,900	30,800	80
Kinnickinnic River at S. 9th Place (RIV-13)	April 1-8, 1983	110	188,000	1,204,800	1,700	1,100	30	114,800	17,700	- -
	September 10-14, 1983	20	1,930,000	15,000	100	200	50	3,200	3,500	10
	October 11-15, 1983	20	28,000	19,300	40	40	20	4,200	3,200	10
	February 6-27, 1984	30	224,000	121,700	600	700	20	23,900	23,600	10
	August 7-11, 1984	10	94,000	249,300	400	300	100	39,400	5,300	10

Source: SEWRPC.

Table 72

UNIT-AREA POLLUTANT LOADINGS FOR SAMPLED RUNOFF EVENTS AT RIVER STATIONS JUST UPSTREAM OF THE INNER HARBOR

Sampling Station	Tributary Drainage Area (square miles)	Runoff Event	Mean Daily Flow (cfs)	Fecal Coliform (number/ square mile x 10^6)	Total Suspended Solids (pounds/ square mile)	Total Phosphorus (pounds/ square mile)	Ammonia Nitrogen (pounds/ square mile)	Un-ionized Ammonia Nitrogen (pounds/ square mile)	Volatile Suspended Solids (pounds/ square mile)	BOD_5 (pounds/ square mile)	Chlorophyll-a (pounds/ square mile)
Milwaukee River at North Avenue Dam (RIV-5)	702	April 1-8, 1983	2,840	3,760	10,100	20	20	5	1,900	390	- -
		September 10-14, 1983	190	200	290	1	<1	<1	80	40	<1
		October 11-15, 1983	480	840	520	2	1	<1	140	60	<1
		February 6-27, 1984	1,390	2,160	12,510	80	70	<1	2,690	950	1
		August 7-11, 1984	300	1,120	490	2	2	<1	170	60	1
Menomonee River at S. 37th Street (RIV-10)	134	April 1-8, 1983	1,050	5,600	32,150	50	50	1	5,240	1,060	- -
		September 10-14, 1983	50	3,550	1,130	3	3	<1	230	130	<1
		October 11-15, 1983	100	9,180	880	3	1	<1	190	120	<1
		February 6-27, 1984	300	1,950	9,400	50	70	1	1,760	1,120	1
		August 7-11, 1984	140	2,690	4,500	7	10	1	790	230	1
Kinnickinnic River at S. 9th Place (RIV-13)	20.2	April 1-8, 1983	110	9,310	59,640	80	50	1	5,680	880	- -
		September 10-14, 1983	20	95,540	740	5	10	2	160	170	<1
		October 11-15, 1983	20	1,390	960	2	2	1	210	160	<1
		February 6-27, 1984	30	11,090	6,020	30	30	1	1,180	1,170	<1
		August 7-11, 1984	10	4,650	12,340	20	10	5	1,950	260	<1

Source: SEWRPC.

During the five events, the concentrations of dissolved oxygen varied widely, with values ranging from less than 0.1 mg/l up to 17.4 mg/l. As shown in Table 70, the lowest mean dissolved oxygen concentrations were found in the warmer months of September and October, while the highest concentrations were found in the colder months of February and April. In all cases, the mean dissolved oxygen concentrations found at the upstream stations, ranging from 6.8 to 13.5 mg/l, were higher than those found at the inner harbor stations, where values ranged from 1.9 to 12.9 mg/l. Instream diurnal changes in dissolved oxygen concentrations were found to be more pronounced during the summer and fall events. Within the inner harbor, the variations in dissolved oxygen concentrations with depth were lowest during the events of February and April. A comparison to the recommended water use objectives and supporting water quality standards set forth in Chapter II of Volume Two of this report indicated that water quality conditions in all three rivers within the inner harbor violated all dissolved oxygen standards during both of the summer events, as shown in Table 73. In addition, conditions in the Kinnickinnic River estuary station were found to violate all dissolved oxygen standards during the October event, and conditions in the Menomonee River estuary station were found to violate all dissolved oxygen standards during the October event and the one-day and absolute dissolved oxygen standards during the February event. The absolute recommended standard was also violated at one station in the outer harbor during the August event. No measurements of dissolved oxygen were collected in the outer harbor during the February event.

Fecal coliform levels during the five events were found to range from less than 100 to 240,000 MPN/100 ml. Generally, the highest fecal coliform concentrations were found during the August and September events, and the lowest concentrations during the February event. The mean fecal coliform levels in the inner harbor stations were found to range from 1,300 to 110,000 MPN/100 ml, usually at least twice the level found at upstream stations, with means ranging from 1,600 to 44,000 MPN/100 ml. The outer harbor stations generally exhibited the lowest fecal coliform concentrations, with means ranging from 200 to 61,000 MPN/100 ml. Fecal coliform levels were not measured in the outer harbor during the February event. During all five events sampled, the fecal coliform levels generally exhibited a "first flush" effect, which was most evident within the inner harbor stations. Total loadings calculated for the upstream stations during events were highest during the April event

Table 73

RECOMMENDED DISSOLVED OXYGEN STANDARDS VIOLATED DURING RUNOFF EVENTS

	Runoff Event															
	April 1983				September 1983			October 1983			February 1984			August 1984		
Sampling Station	30-Day[a]	7-Day	1-Day	Absolute	30-Day[a]	1-Day	Absolute	30-Day[a]	1-Day	Absolute	30-Day[a]	1-Day	Absolute	30-Day[a]	1-Day	Absolute
Upstream Stations																
Milwaukee River at North Avenue Dam (RIV-5)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Menomonee River at S. 37th Street (RIV-10)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Kinnickinnic River at S. 9th Place (RIV-13)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Inner Harbor Stations																
Milwaukee River at Wells Street (RIV-7)	--	--	--	--	X	X	X	--	--	--	--	--	--	X	X	X
Menomonee River at Muskego Avenue (RIV-11)	--	--	--	--	X	X	X	X	X	X	--		X	X	X	X
Kinnickinnic River at S. 1st Street (RIV-14)	--	--	--	--	X	X	X	X	X	X	--	--	--	X	X	X
Outer Harbor Stations																
Hoan Bridge (OH-1)	--	--	--	--	--	--	--	--	--	--	NA	NA	NA	--	--	X
South Outer Harbor (OH-11)	--	--	--	--	--	--	--	--	--	--	NA	NA	NA	--	--	--

NOTES: X - Standard violated, NA - Not Applicable. Dissolved oxygen was not measured in the outer harbor during the February event.

[a]The recommended 30-day mean dissolved oxygen standards were compared to the mean dissolved oxygen level measured over the entire storm event, even though the duration of each event was fewer than 30 days.

Source: SEWRPC.

for the Milwaukee River, during the October event for the Menomonee River, and during the September event for the Kinnickinnic River. Unit-area loadings for fecal coliform during the events were generally highest in the Kinnickinnic River watershed. Fecal coliform levels exceeded the recommended standards at all stations between 20 and 100 percent of the time during the five runoff events surveyed.

During the five events, total suspended solids concentrations were found to range from 1 to 2,280 mg/l. Generally, the highest levels of total suspended solids occurred during the February and April events, reflecting the runoff of pollutant loads accumulated over the winter months. Within the Milwaukee and Menomonee Rivers, the mean total suspended solids concentrations at the upstream stations were found to range from 23 to 98 mg/l, higher than at the Milwaukee and Menomonee estuary stations, where values ranged from 14 to 64 mg/l. Within the Kinnickinnic River estuary station, however, the mean concentrations ranged from 40 to 184 mg/l, generally higher than at the upstream station, where values ranged from 18 to 214 mg/l. The Kinnickinnic River estuary levels of total suspended solids were consistently higher than concentrations at the Milwaukee and Menomonee River estuary stations. The outer harbor stations generally had the lowest total suspended solids concentrations, with means ranging from 5 to 30 mg/l. Total suspended solids concentrations were not measured in the outer harbor during the February event. The suspended solids concentrations during the events exhibited a "first flush" effect within the upstream reaches and the inner harbor. Within the inner harbor, little difference was found between the suspended solids concentrations at the three depths sampled, except that in some cases the peak concentrations at the three sample depths were highest in the bottom layer of water. Loadings of total suspended solids calculated for the upstream stations were highest during the April event for the Menomonee and Kinnickinnic Rivers, and during the February event for the Milwaukee River. Overall, the total loadings were highest in the Milwaukee River except during the August event, when the total load to the Menomonee River was highest. Unit-area loadings were generally higher in the Kinnickinnic and Menomonee River watersheds than in the Milwaukee River watershed, with the exception of the February event.

Concentrations of total phosphorus were found to range from 0.01 to 3.61 mg/l during the five events surveyed. Generally, the highest mean concentrations of total phosphorus occurred during the February event for the Milwaukee River, and during the August event for the Menomonee and Kinnickinnic Rivers. Within the Menomonee and Kinnickinnic Rivers, the mean total phosphorus concentrations at the upstream stations, ranging from 0.07 to 0.39 mg/l, were generally slightly higher than at the Menomonee and Kinnickinnic River estuary stations, where values ranged from 0.07 to 0.33 mg/l. At the Milwaukee River estuary station, however, the mean concentrations during each event were about the same as at the upstream stations, with values ranging from 0.10 to 0.49 mg/l. The outer harbor stations generally had the lowest total phosphorus concentrations, with means ranging from 0.02 to 0.10 mg/l. Total phosphorus concentrations were not measured in the outer harbor during the February event. The total phosphorus concentrations within the upstream and inner harbor stations either remained constant throughout the event or peaked shortly after the event began and then quickly returned to near-background levels. As with suspended solids, the peak phosphorus concentrations in the inner harbor stations were, in some cases, highest in the bottom layer of water. Loadings calculated for the upstream stations were highest during the February event for the Milwaukee and Menomonee Rivers, and during the April event for the Kinnickinnic River. The total loadings were highest in the Milwaukee River during all events. Unit-area loadings in the Kinnickinnic River watershed were approximately 70 to 900 percent higher than loadings in the Milwaukee or Menomonee River during the summer events. During the February event, however, the highest unit-area loading of total phosphorus was in the Milwaukee River. The recommended phosphorus standard applies to the Milwaukee River and to the outer harbor. During the events, from 44 to 100 percent of the phosphorus samples were found to violate the recommended standard.

During the runoff events surveyed, the concentrations of ammonia nitrogen were found to range from 0.02 to 1.61 mg/l. Generally, higher concentrations occurred during the February snowmelt event. Within all three rivers, mean concentrations of ammonia nitrogen in the inner harbor, ranging from 0.10 to 0.59 mg/l, were usually slightly higher than concentrations at the upstream stations, with values ranging from 0.05 to 0.37 mg/l. The mean ammonia nitrogen concentrations were generally higher in the Kinnickinnic River than in the Milwaukee or Menomonee Rivers. The outer harbor ammonia nitrogen concentrations were relatively high in most cases—with means ranging from 0.12 to 0.34 mg/l. Ammonia nitrogen concentrations were not measured in the outer harbor during the February event. Loadings calculated from the upstream stations, like the total phosphorus loadings, were found to be highest during the February event for the Milwaukee and Menomonee Rivers, and during the April event for the Kinnickinnic River. The total loadings of ammonia nitrogen were found to be highest in the Menomonee River for the September and August events, and in the Milwaukee River for the remaining events. Generally, the highest unit-area loadings were found in the Menomonee and Kinnickinnic River watersheds.

Un-ionized ammonia nitrogen concentrations were found to range from 0 to 0.539 mg/l. Generally, the highest mean concentrations were found during the August event. In most cases, the mean un-ionized ammonia concentration at the upstream stations, ranging from 0.002 to 0.050 mg/l, were about the same as at the inner harbor stations, where levels ranged from 0.003 to 0.095 mg/l. The mean concentrations of un-ionized ammonia nitrogen were lowest in the outer harbor, where values ranged from 0.001 to 0.005 mg/l. Un-ionized ammonia nitrogen concentrations were not measured in the outer harbor during the February event. Total loadings calculated for the upstream stations were generally highest within the Milwaukee River. Unit-area loadings for un-ionized ammonia nitrogen were generally higher in the Kinnickinnic River watershed than in the Milwaukee and Menomonee River watersheds except during the April event, when the Milwaukee River watershed had the highest unit-area loadings. With respect to the recommended water quality standards, un-ionized ammonia nitrogen levels were found to occasionally exceed the chronic toxicity standards, although the exceedances during the runoff events do not necessarily indicate that the standard was violated because the duration of exceedance was fewer than 30 days. The measured concentrations of un-ionized ammonia nitrogen never exceeded the recommended acute toxic standards during the runoff events.

Volatile suspended solids concentrations during all the events were found to range from 1 to 354 mg/l. Generally, the highest mean concentrations were recorded during the events with the greatest amount of rainfall—April and August. In most cases, the mean volatile suspended solid concentrations at the upstream stations, ranging from 4 to 22 mg/l, were about the same as the concentrations at the inner harbor stations, where levels ranged from 6 to 29 mg/l. The concentrations of volatile suspended solids at the upstream stations were similar in all three rivers. The Kinnickinnic River estuary, however, had higher concentrations than did the Menomonee and Milwaukee River estuaries. Based on mean concentrations, volatile suspended solids represented the greatest proportion of total suspended solids during the October event for the upstream and inner harbor reaches of the three rivers. Compared to the river stations, the relative proportion of the total suspended solids load which was volatile was generally higher in all the events in the outer harbor. The actual outer harbor concentrations of volatile suspended solids—ranging from 2 to 8 mg/l—however, were lower than the concentrations in the rivers. Volatile suspended solids concentrations were not measured in the outer harbor during the February event. Total loadings of volatile suspended solids calculated for the upstream stations were, like suspended solids, highest during the April event for the Menomonee and Kinnickinnic Rivers, and during the February event for the Milwaukee River. Overall, the total loadings were highest in the Milwaukee River during the events. Unit-area loadings were approximately 40 to 1,000 percent higher in the Kinnickinnic and Menomonee River watersheds than in the Milwaukee River watershed except during the February event, when the Milwaukee River watershed had unit-area loadings approximately 30 to 130 percent higher than the loadings in the Kinnickinnic or Menomonee River watersheds.

Biochemical oxygen demand (BOD_5) concentrations were found to range from 0.4 to 38.0 mg/l during the runoff events surveyed. Generally, the highest mean concentrations were found during the September and August events. In most cases, the mean BOD_5 concentrations at the upstream stations, ranging from 2.6 to 7.7 mg/l, were about the same as the concentrations at the inner harbor stations, where values ranged from 3.5 to 7.2 mg/l. The mean concentrations of BOD_5 in the inner harbor stations were similar in all three rivers. At the upstream reaches, however, the Kinnickinnic River had higher concentrations than did the Menomonee and Milwaukee Rivers. BOD_5 concentrations were not measured in the outer harbor during the February event. Total loadings of BOD_5 calculated for the upstream stations were highest during the February event for all three rivers. During the five events, the total BOD_5 load within the Milwaukee River was consistently the highest; however, unit-area loadings during the events were approximately 20 to 330 percent higher in the Kinnickinnic and Menomonee River watersheds than in the Milwaukee River watershed.

During the runoff events, the concentrations of chlorophyll-a were found to range from 0.5 to 210.0 µg/l. Generally, the highest mean concentrations were recorded during the September and August events. In most cases, the mean chlorophyll-a concentrations at the upstream stations, with values ranging from 3.1 to 80.6 µg/l, were higher than the concentrations at the inner harbor stations, where they ranged from 1.8 to 62.5 µg/l. The Milwaukee River mean chlorophyll-a concentrations were up to three times higher than those found in the Menomonee and Kinnickinnic Rivers during the October and February events, and were between two and 14 times higher during the September and August events. No chlorophyll-a samples were taken during the April or February events at the outer harbor stations. The mean concentrations of chlorophyll-a within the outer harbor during the three events sampled ranged from 6.1 to 15.1 µg/l. Total loadings of chlorophyll-a calculated for the upstream stations were highest in the Milwaukee River. Unit-area loadings were equivalent to, or less than, one pound per square mile during all runoff events.

During the February event, a single sample was taken at each station and analyzed for total metal content. The chronic toxic standards for acid-soluble cadmium, copper, and lead, and the acute toxic standards for acid-soluble cadmium, copper, lead, and zinc, were calculated using the mean hardness levels measured under the baseline sampling program. The single measurement of total cadmium at all the representative stations, and of total copper and total zinc at the upstream station of the Kinnickinnic River, exceeded the chronic standards for acid-soluble metals. Since it is recommended that the chronic standards be met by the mean concentration measured over any 30-day period, the violation by a single measurement does not necessarily indicate chronic toxic conditions. Furthermore, since the measurements were of total metals and the standards are established for acid-soluble metals, the violation of the standards is not necessarily indicated. No acute standards were violated at any of the sampling stations. Loadings were not calculated for any of the metals because of the single measurement taken.

Special Water Quality Studies

As part of the Milwaukee Harbor estuary study, three special water quality studies were conducted to provide data needed for an understanding of existing conditions. These studies dealt with the impacts of operating the flushing tunnels in the Milwaukee and Kinnickinnic Rivers; the runoff pollutant loadings from industrial areas in the direct drainage area of the estuary; and the impacts of pollutants in groundwater inflow to the estuary. The results of these studies are described below.

Water Quality Effects of the Milwaukee River and Kinnickinnic River Flushing Tunnels: During low-flow and low-dissolved oxygen periods, the flows in the Milwaukee and Kinnickinnic River estuaries are augmented by water pumped from the outer harbor into the rivers through flushing tunnels. The flushing tunnels are operated and maintained by the Milwaukee Metropolitan Sewerage District.[3] The Milwaukee flushing tunnel discharges into the river just downstream of the North Avenue dam. The Kinnickinnic flushing tunnel discharges into the river just downstream of S. Chase Avenue. The capacity of the Milwaukee flushing tunnel is about 600 cubic feet per second (cfs), upgraded in the summer of 1985 from a previous capacity of 400 cfs; while the Kinnickinnic flushing tunnel has a capacity of about 350 cfs. The period of operation of the flushing tunnels is presented in Table 74 for the years 1982 through 1984.

Table 74

OPERATION OF THE MILWAUKEE RIVER AND KINNICKINNIC RIVER FLUSHING TUNNELS: 1982-1984

Year	Hours of Flushing Tunnel Operation	
	Milwaukee River	Kinnickinnic River
1982	224	569
1983	112	389
1984	164	278
Total	500	1,236

Source: Milwaukee Metropolitan Sewerage District.

[3] *The Milwaukee River flushing tunnel was constructed by the City of Milwaukee in 1888. The responsibility for the operation and maintenance of the tunnel was transferred to the Milwaukee Metropolitan Sewerage District in 1964. The Kinnickinnic River flushing tunnel was constructed by the City of Milwaukee in 1907. The responsibility for the operation and maintenance of the tunnel was transferred to the Milwaukee Metropolitan Sewerage District in 1980.*

The effect of the flushing tunnel discharges on the water quality of the inner harbor was studied over the period September 10 through 24, 1984. The effects of the tunnels on dissolved oxygen concentrations in the rivers are described below. From September 10 through September 24, the flow of the Milwaukee River at the North Avenue dam, just upstream of the Milwaukee tunnel, ranged from about 191 to 334 cfs, and the flow of the Kinnickinnic River at S. 9th Place, just upstream of the Kinnickinnic tunnel, ranged from about 6 to 28 cfs. Upstream dissolved oxygen concentrations ranged from 5.9 to 10.8 mg/l in the Milwaukee River at the North Avenue dam, and from 4.4 to 19.9 mg/l in the Kinnickinnic River at S. 9th Place. Plots of the measured flows and dissolved oxygen concentrations over the flushing tunnel study period at stations just upstream of the Milwaukee and Kinnickinnic flushing tunnels are shown in Figure 127. From 8:00 a.m. September 11 through 12:00 p.m. on September 15, each flushing tunnel was operated continuously.

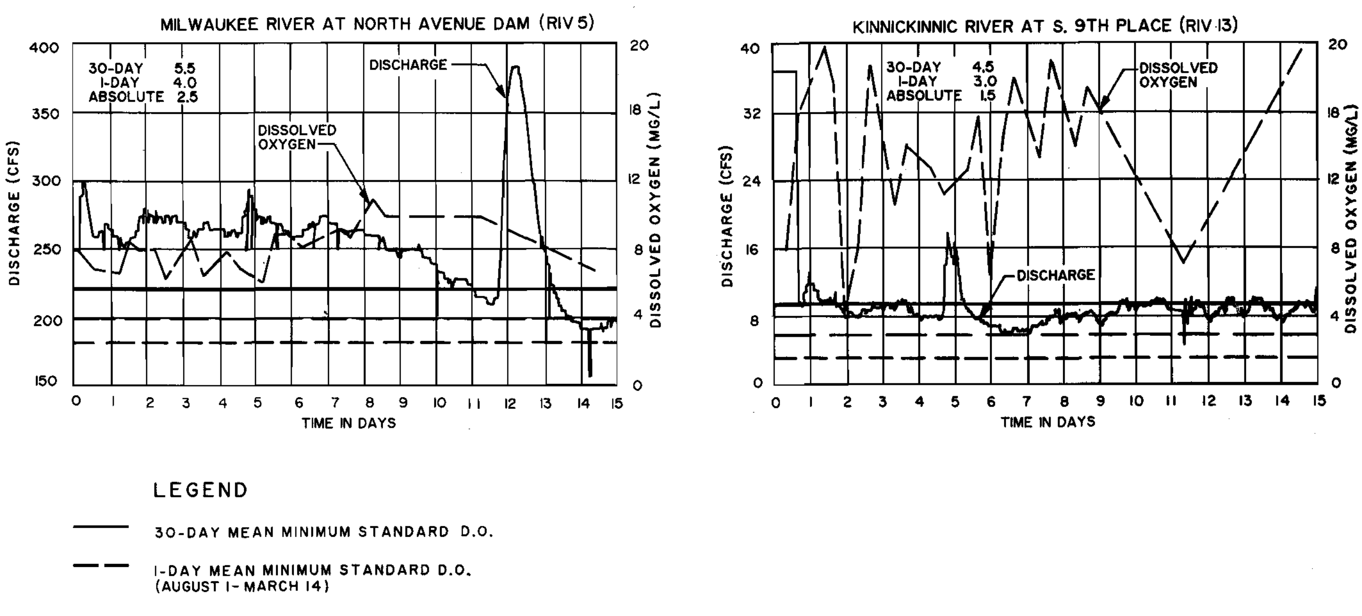
Analyses conducted using the results of the flushing tunnel study as well as other studies conducted by the Milwaukee Metropolitan Sewerage District staff indicated that operation of the tunnels can substantially increase dissolved oxygen levels at some river stations. This increase is the primary water quality benefit of the tunnel operation. The flushing also slightly reduces the concentration of some pollutants, transports accumulated floating debris from the inner harbor, and reduces foul odors from the water.

Figure 128 shows the effect of the tunnel operation on the dissolved oxygen concentrations of the Milwaukee River estuary. At Juneau Avenue, the Chicago & North Western railroad bridge, Kilbourn Avenue, and Walnut Street, the improvement in dissolved oxygen levels when the tunnel began operation on September 11 was not very apparent because the levels were relatively high—generally from 5 to 8 mg/l—before the tunnel began operating. Throughout the flushing tunnel study period, the dissolved oxygen levels at these Milwaukee River stations remained quite high—usually exceeding 5 mg/l. At Broadway Street, the dissolved oxygen levels dropped to very low levels at the start of the tunnel operation, and then rose to about 4 mg/l. None of the Milwaukee River sampling stations exhibited a substantial decline in dissolved oxygen levels immediately after the flushing tunnel operation ceased on September 15, partly because, as shown in Figure 128, the dissolved oxygen levels at the North Avenue dam, just

Figure 127

DISCHARGE AND DISSOLVED OXYGEN MEASUREMENTS AT STATIONS JUST UPSTREAM OF THE MILWAUKEE AND KINNICKINNIC RIVER FLUSHING TUNNELS: SEPTEMBER 10-24, 1984

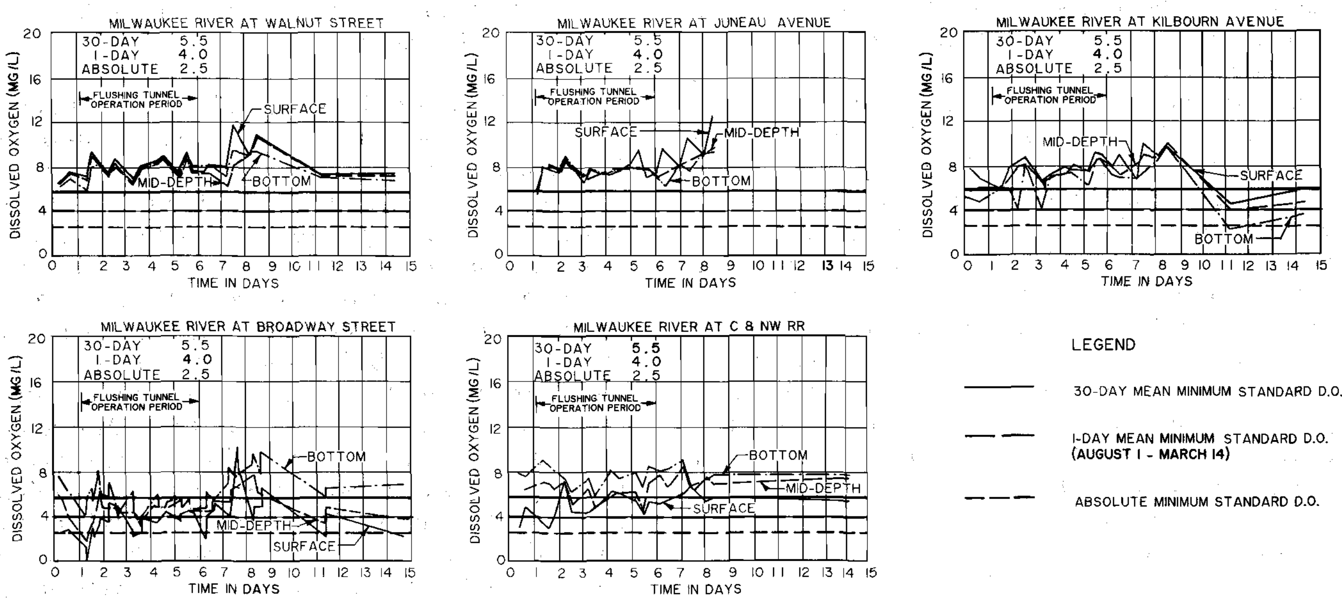
UPSTREAM STATIONS



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Figure 128

EFFECT OF THE FLUSHING TUNNEL ON DISSOLVED OXYGEN CONCENTRATION IN THE MILWAUKEE RIVER: SEPTEMBER 10-24, 1984



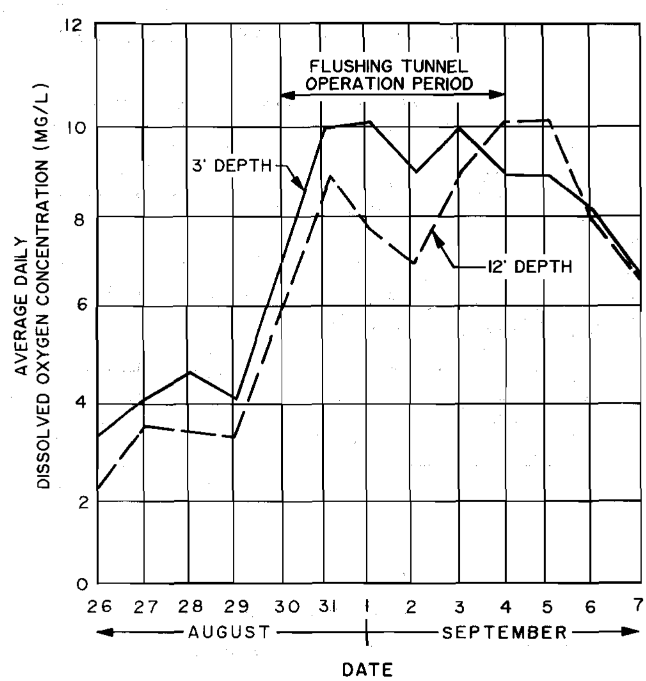
Source: U. S. Geological Survey, Milwaukee Metropolitan Sewerage District, and SEWRPC.

upstream of the inner harbor, were about 1.4 mg/l higher from September 16 through 24 than from September 10 through 16, and perhaps partly because algal concentrations had been reduced dramatically by flushing, thereby resulting in significantly less oxygen consumption by algal respiration. It may be anticipated that, at the upgraded capacity of 600 cfs, the Milwaukee flushing tunnel will have a greater impact on the dissolved oxygen levels in the Milwaukee River estuary than was indicated in the survey.

A similar study of the Milwaukee River was conducted by the Milwaukee Metropolitan Sewerage District from August 26 to September 7, 1982. During that study, the flow of the Milwaukee River at the North Avenue dam ranged from just under 100 cfs to 300 cfs. At the start of operation of the flushing tunnel, the river flow rate was 177 cfs. Dissolved oxygen measurements were made during the study at the continuous monitor at St. Paul Avenue about 3.5 miles downstream of the flushing tunnel. Dissolved oxygen measurements at two depths—3 and 12 feet below the water surface—during this study period are shown in Figure 129. The data show that a significant increase in dissolved oxygen—from about 4 mg/l up to a range of 7 to 10 mg/l—occurred following start-up of the flushing tunnel on August 30. The elevated levels of dissolved oxygen were maintained for the duration of the flushing tunnel operation.

Figure 129

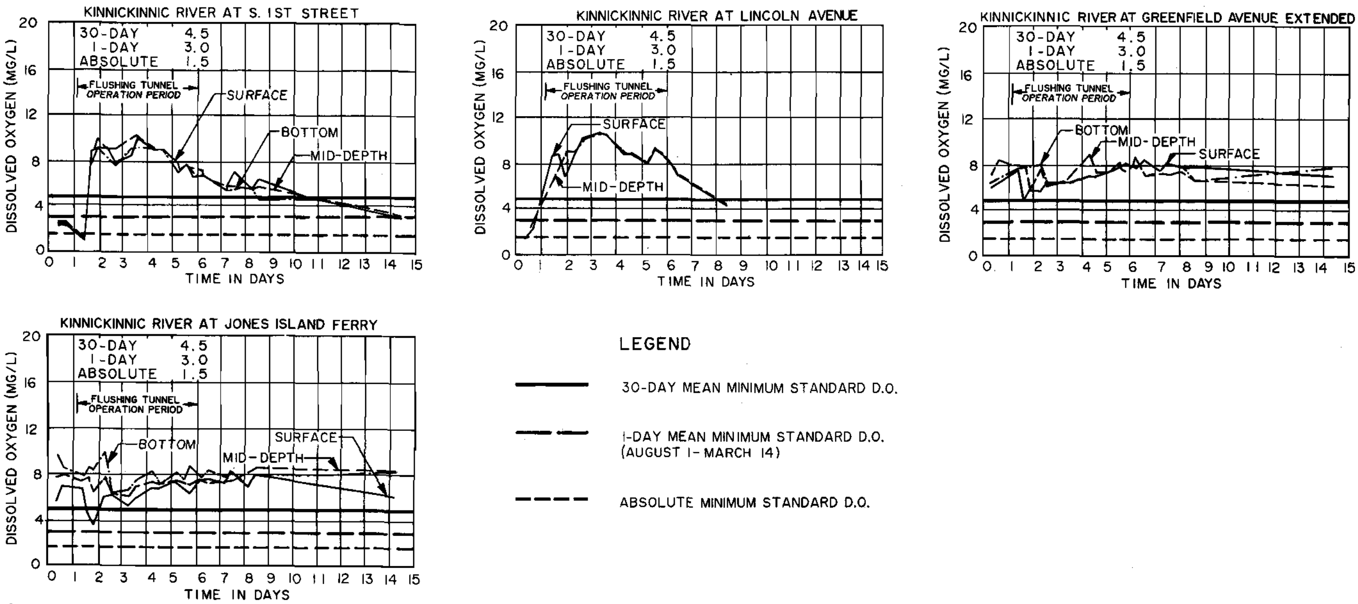
EFFECT OF THE FLUSHING TUNNEL ON DISSOLVED OXYGEN CONCENTRATION IN THE MILWAUKEE RIVER AT ST. PAUL AVENUE: AUGUST 26-SEPTEMBER 7, 1982



Source: Milwaukee Metropolitan Sewerage District.

Figure 130

EFFECT OF THE FLUSHING TUNNEL ON DISSOLVED OXYGEN CONCENTRATION IN THE KINNICKINNIC RIVER: SEPTEMBER 10-24, 1984



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

During the 1982 period of flushing tunnel operation, the movement of floating debris out of the inner harbor was reported to be quite evident within 12 hours after pump start-up, with most flotsam moving down river to the mouth of the river. Within 48 hours of flushing tunnel start-up, the Milwaukee River system was essentially clear of debris. This flushing action on floating debris was quickly canceled, however. Within 24 hours after the operation of the flushing tunnel ceased, debris—much of which was observed to be the same material as had been accumulated in the system prior to flushing tunnel operation start-up—was forced back up river by the action of the lake on the system.

Figure 130 shows the effect of the September 11 through 15, 1984, operation of the Kinnickinnic flushing tunnel on the dissolved oxygen concentrations of the Kinnickinnic River. The flushing tunnel quickly and substantially increased the dissolved oxygen concentrations at S. 1st Street, increasing from about 2.5 mg/l on September 10 to about 8 to 9 mg/l late on September 11. Following the cessation of the Kinnickinnic tunnel operation on September 15, the dissolved oxygen levels declined steadily to a low of about 3.0 mg/l on September 24. The flushing tunnel had a similar effect on dissolved oxygen levels at the Lincoln Avenue station. At the more downstream Kinnickinnic River stations—at E. Greenfield Avenue extended and at the Jones Island Ferry—the flushing tunnel had little noticeable effect on dissolved oxygen levels. Primarily because of the influx of Lake Michigan water, the dissolved oxygen levels were relatively high on September 10 prior to the operation of the tunnel. The dissolved oxygen levels at these stations remained relatively high throughout the study period.

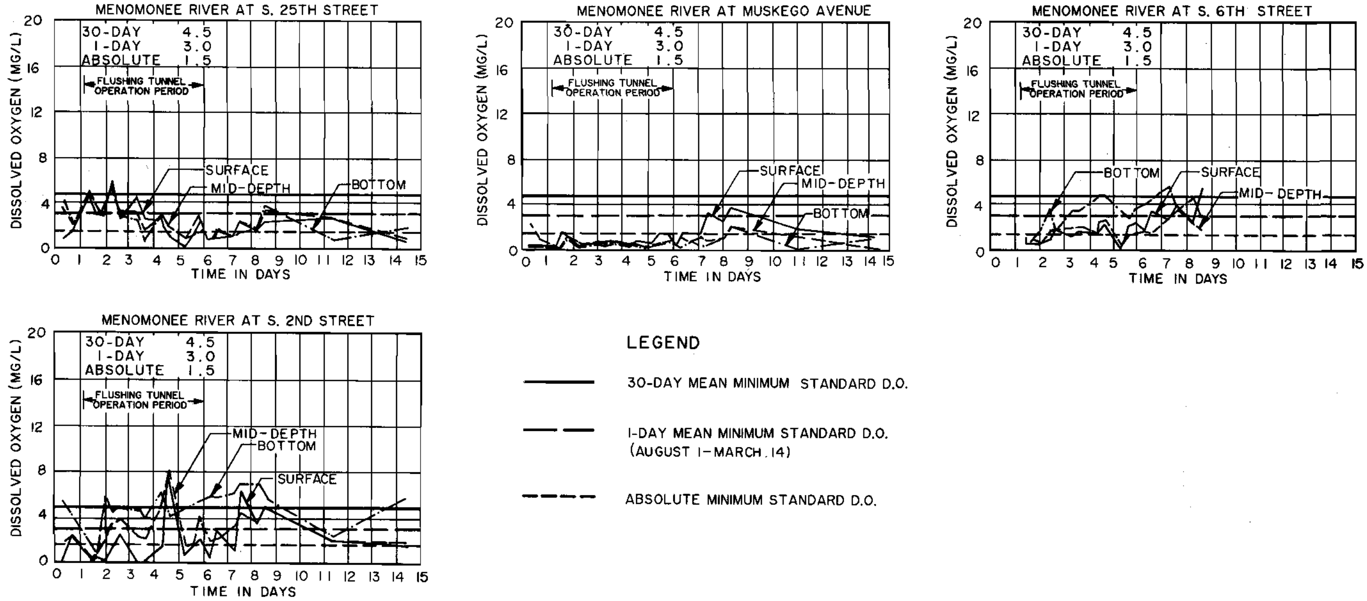
As shown in Figure 131, the operation of the Milwaukee and Kinnickinnic flushing tunnels from September 11 through 15, 1984, had an apparent minor effect on the dissolved oxygen concentrations in the Menomonee River. Dissolved oxygen levels, particularly in the bottom water layer, may have been slightly increased at S. 2nd Street and S. 6th Street owing to operation of the tunnels. Surface and middle layer concentrations of dissolved oxygen at these stations, however, generally remained below 4 mg/l. Farther upstream at Muskego Avenue and at S. 25th Street, the tunnels had no apparent effect on dissolved oxygen levels.

Runoff from Directly Tributary Industrial Areas: Two stormwater runoff quality surveys were conducted to determine the type, concentration, and loadings of pollutants being discharged from industrial areas immediately adjacent and directly tributary to the inner harbor.[4] Stormwater runoff

[4] *L. B. House, Milwaukee Harbor Estuary Shoreland Runoff Study, U. S. Geological Survey, June 1985.*

Figure 131

EFFECT OF THE MILWAUKEE AND KINNICKINNIC RIVER FLUSHING TUNNELS ON DISSOLVED OXYGEN CONCENTRATION IN THE MENOMONEE RIVER: SEPTEMBER 10-24, 1984



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

samples were collected on August 30, 1984, and on September 24 and 25, 1984. The sampling was conducted at eight stations, as shown on Map 78 and described in Table 75. Of the eight stations, five are located on the Menomonee River portion of the estuary and three along the Kinnickinnic River portion of the estuary. Stormwater runoff from coal, salt, and scrap iron storage areas, as well as from general industrial use areas, was sampled.

During the August 30, 1984, storm event, a total of 0.91 inch of rain fell over a one-hour period. During the September 24-25, 1984, storm event, a total of 1.33 inches of rain fell over a 15-hour period, with a maximum rainfall intensity of 0.52 inch/hour.

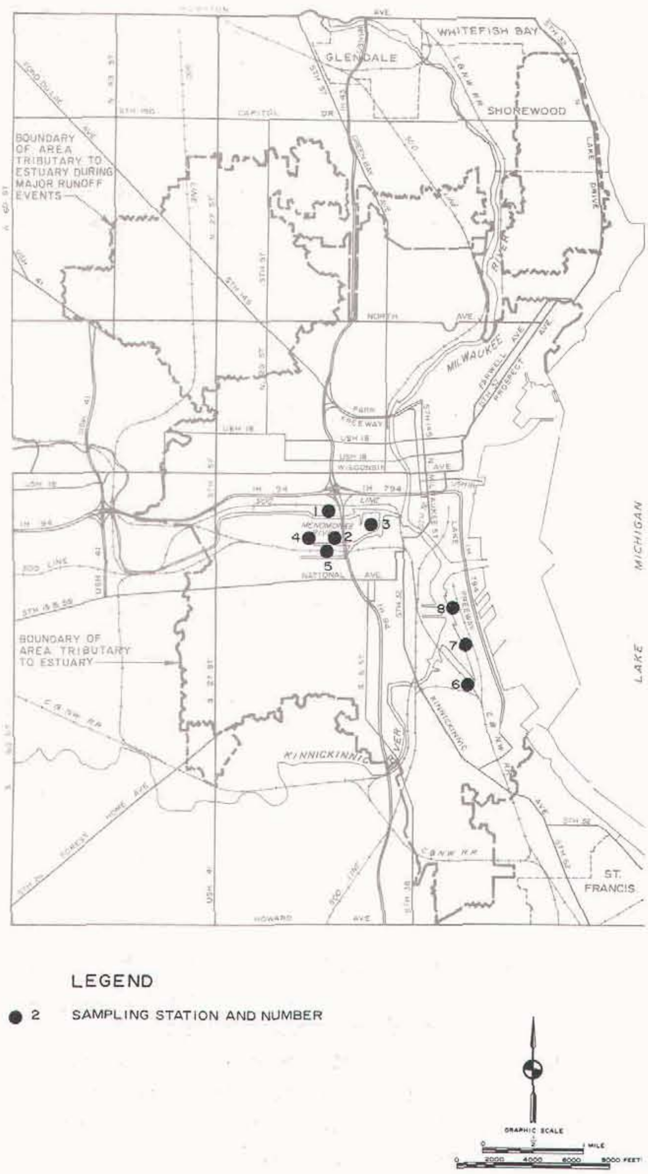
A summary of the water quality data collected during the two runoff events is set forth in Table 76. The samples were analyzed for a total of 32 water quality indicators. Concentrations of several toxic metal and organic substances were detected in the surface runoff, although the concentrations of organic substances were very low.

A pollutant loading analysis was conducted for arsenic, chromium, lead, mercury, and phenols because relatively high levels of the substances were measured, and because these substances are representative of the types of pollutants found in the runoff. Annual pollutant loadings to the inner harbor were estimated using the Hydrological Simulation Program-Fortran (HSPF) model for 1981, 1982, and January through September 1983. The model was used to simulate runoff from salt, coal, and scrap iron storage areas and from general industrial areas. The total acreage of these storage areas was measured from Commission 1 inch equals 100 feet scale topographic maps of the study area. Storage-area type was determined by field inspection.

An average contaminant concentration was determined for each type of storage station using the data from the runoff sample analysis. Annual pollutant loadings to the estuary were estimated using the annual runoff volume from each type of storage area and the average concentration for each pollutant. In estimating the loadings from each type of facility, the area adjacent to each storage pile which appeared to be saturated with material as well as the storage pile itself was considered. Loads from each type of storage area were then summed for each pollutant to determine the total load to the inner harbor from the industrial areas directly tributary to the Menomonee and Kinnickinnic River portions of the estuary.

Map 78

SAMPLING STATION LOCATIONS USED IN THE DIRECTLY TRIBUTARY INDUSTRIAL SITE RUNOFF SURVEYS: 1984



Water quality sampling for the directly tributary industrial site runoff surveys was conducted at eight stations, of which five were located along the Menomonee River estuary, and three along the Kinnickinnic River estuary. Stormwater runoff from coal, salt, and scrap iron storage areas, as well as from industrial areas, was sampled. Unit-area loading rates were calculated for arsenic, chromium, lead, mercury, and phenols.

Source: U. S. Geological Survey.

A summary of the annual loading estimates to the inner harbor from directly tributary industrial areas is set forth in Table 77. The simulated 1982 loadings were approximately 20 to 40 percent higher than the 1981 loadings. Mean annual lead loadings to the inner harbor from the Menomonee and Kinnickinnic Rivers were estimated to total 14,200 pounds (see Table 123). The annual lead loading from directly tributary industrial areas of from 900 to 1,200 pounds therefore represents from 6 to 8 percent of the total river loading of lead to the Menomonee and Kinnickinnic River portions of the estuary.

The sources of the loadings of arsenic, chromium, lead, mercury, and phenols from directly tributary industrial areas are illustrated in Figure 132. The "other industrial area" category accounts for the majority of the loadings of all pollutants analyzed, except mercury. Scrap iron storage stations contribute about 80 percent of the mercury loadings. For arsenic, lead, and phenols, the scrap iron storage stations constitute the second largest source. Salt storage areas constitute the second largest source of chromium loadings, and other industrial areas constitute the second largest source of mercury loadings.

Unit-area pollutant loading rates, expressed in pounds per acre, are set forth in Table 78. Annual unit-area loading rates ranged from 0.0046 to 0.0897 pound per acre for arsenic; from 0.0029 to 0.70 pound per acre for chromium; from 0.98 pound to 6.41 pounds per acre for lead; from 0.0007 to 0.0212 pound per acre for mercury; and from 0.0102 to 0.13 pound per acre for phenols. Coal storage areas had the highest unit-area loadings of arsenic; salt storage stations had the highest unit-area loadings of chromium and lead; and scrap iron storage stations had the highest unit-area loadings of mercury and phenols.

Menomonee River Industrial Valley Groundwater Study: A groundwater study was conducted to estimate the type and quantity of pollutants entering the Menomonee River estuary from potentially polluted groundwater from the industrial valley.[5] The sampling period extended from November 30, 1982, through January 4, 1984. Water levels were measured weekly or biweekly at six observation wells in the Menomonee Valley at locations shown on Map 79. In addition, groundwater samples were collected at each of the six

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[5] *L. B. House, Menomonee River Industrial Valley Groundwater Study, U. S. Geological Survey, August 1985.*

Table 75

DESCRIPTION OF INDUSTRIAL SITE SAMPLING STATIONS

Station Number	Description
1	Menomonee River salt pile—Station is located adjacent to the Menomonee River on the north side between 16th and 25th Streets, east of the Schwerman Trucking Company lot. Samples were collected from overland flow.
2	Wisconsin Electric Power Company coal pile—Station is located adjacent to the South Menomonee Canal on the north side, to the east of S. 11th Street. Samples were collected from a storm drain leading to the canal.
3	Morton Salt Company storage pile—Station is located at east end of Canal Street adjacent to the Burnham Canal. Samples were collected from overland flow.
4	Cargill railroad yard—Station is located adjacent to South Menomonee Canal, on the south side. Samples were collected from buried container in overland flow path to canal.
5	Miller Compressing Company scrap iron yard—Station is located adjacent to the Burnham Canal on the north side. Sample collected from storm drain.
6	Kinnickinnic River turning basin scrap iron yard—Station is located at the south end of the basin on the west side. Samples were collected from ponded areas adjacent to scrap iron piles.
7	Kinnickinnic River turning basin salt pile—Station is located on east side of basin near U. S. Steel Corporation warehouse. Samples were collected from overland flow.
8	Milwaukee heavy lift dock—Station is located adjacent to Kinnickinnic turning basin on east side at north end. Samples were collected from storm drain.

Source: U. S. Geological Survey.

observation wells. These samples were collected four times—once each in the months of February, May, July, and September of 1983.

The reach of the Menomonee River included in this study extends from the S. 25th Street bridge downstream to the N. 2nd Street bridge, and is approximately 9,000 feet long. This study reach was selected because of the potential groundwater contamination from the industrial areas present. Calculations were then made to estimate groundwater inflow to the Menomonee River during the study period and the associated total pollutant load flowing into the Menomonee River estuary using groundwater and river levels along with groundwater pollutant concentrations. Annual loads for 1983 were also estimated for selected inorganic contaminants.

Continuously recorded water-level data for the Menomonee River were obtained from the City of Milwaukee Department of Public Works. Manual measurements of the water levels at each observation well were made weekly except during the winter, when biweekly measurements were made. The daily average maximum and minimum recorded river elevations during the monitoring period were 581.85 and 580.10 feet, respectively, National Geodetic Vertical Datum (NGVD), or mean sea level datum. The maximum water table elevation measured was 583.13 feet NGVD for well number 4 on April 6, 1983. The minimum water table elevation measured was 577.93 feet NGVD for well number 3 on February 9, 1983. A comparative plot of the water levels of the paired observation wells and the Menomonee River is shown in Figure 133. As shown in Figure 133, there is no constant groundwater flow gradient to the river, except at well number 2. A major groundwater inflow to the river is therefore not expected. The data in Figure 133 were used to simulate total discharge to the river from each riverbank section. The results are shown in Table 79 for the 1983 water year.

Table 76

WATER QUALITY DATA COLLECTED AT DIRECTLY TRIBUTARY INDUSTRIAL STATIONS: AUGUST 30 AND SEPTEMBER 25, 1984

Indicator	Sample Stations and Date																
	1		2		3		4		5		6		7		8		
	Aug. 30	Sept. 25	Aug. 30	Sept. 25	Aug. 30	Sept. 25	Aug. 30	Sept. 25	Aug. 30	Sept. 25	Aug. 30	Sept. 25	Aug. 30	Sept. 25	Aug. 30	Sept. 25	Mean
Aldrin (μg/l)	<0.010	--	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	--[a]	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Arsenic (μg/l)	--	3	--	7	--	3	--	3	--[a]	4	--	2	--	4	--	1	3
Barium (μg/l)	<100	400	100	200	100	200	300	400	--[a]	400	<100	200	200	400	<100	200	200
Beryllium (μg/l)	<10	10	<10	<10	90	<10	<10	<10	--[a]	<10	<10	<10	10	<10	<10	<10	10
Calcium (mg/l)	83	130	41	85	1,100	720	1	380	--[a]	81	17	17	110	420	18	38	216
Chlordane (μg/l)	<0.10	--	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	--[a]	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Chromium (μg/l)	40	40	10	20	170	180	100	60	--[a]	70	20	50	60	210	20	20	70
Cobalt (μg/l)	210	110	< 50	480	4,500	1,800	270	140	--[a]	500	<50	390	1,400	2,000	<50	260	800
Copper (μg/l)	50	40	420	90	470	330	510	290	--[a]	600	40	120	120	220	30	60	230
DDD (μg/l)	<0.010	--	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	--[a]	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
DDE (μg/l)	<0.010	--	<0.010	<0.010	<0.010	<0.010	0.0160	<0.010	--[a]	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.011
DDT (μg/l)	<0.010	--	<0.010	<0.010	<0.010	<0.010	0.020	<0.010	--[a]	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Dieldrin (μg/l)	<0.010	--	<0.010	<0.010	<0.010	0.020	<0.010	0.020	--[a]	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Endosulfan (μg/l)	<0.010	--	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	--[a]	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Endrin (μg/l)	<0.010	--	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	--[a]	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Heptachlor (μg/l)	<0.010	--	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	--[a]	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Heptachlor Epoxide (μg/l)	<0.010	--	<0.010	<0.010	<0.010	0.020	<0.010	<0.010	--[a]	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Iron (μg/l)	6,700	11,000	23,000	9,300	7,900	4,900	54,000	26,000	--[a]	24,000	6,300	53,000	3,900	14,000	3,300	2,700	16,700
Lead (μg/l)	200	400	300	85	2,200	1,500	1,200	700	--[a]	1,700	<80	300	700	1,400	85	49	721
Lindane (μg/l)	<0.010	--	<0.010	<0.010	<0.010	<0.010	<0.010	0.010	--[a]	<0.010	<0.010	<0.010	<0.010	0.010	<0.010	0.010	<0.010
Lithium (μg/l)	10	20	60	30	90	40	40	10	--[a]	50	10	10	10	10	<10	10	30
Magnesium (mg/l)	19	38	13	28	140	75	360	150	--[a]	16	6	6	19	110	6	13	67
Manganese (μg/l)	260	490	360	180	280	260	1,400	770	--[a]	480	210	580	240	470	190	280	430
Mercury (μg/l)	0.7	0.2	0.6	0.3	0.9	1.0	0.3	0.2	--[a]	7	0.10	0.50	0.60	1.6	0.10	0.30	1.0
Methoxychlor (μg/l)	<0.01	--	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	--[a]	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Mirex (μg/l)	<0.01	--	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	--[a]	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Molybdenum (μg/l)	1	--	31	--	29	--	29	--	--[a]	--	330	--	31	--	3	--	65
Napthalenes, Polychlor (μg/l)	<0.10	--	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	--[a]	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
PCB's (μg/l)	<0.10	--	<0.10	<0.10	<0.10	<0.10	0.30	<0.10	--[a]	<0.10	<0.10	<0.10	0.60	<0.10	<0.10	<0.10	0.06
Perthane (μg/l)	<0.10	--	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	--[a]	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Phenols (μg/l)	<1	4	<1	2	<1	3	<1	2	--[a]	39	19	9	160	1	8	24	18
Toxaphene (μg/l)	<1	--	7	<1	<1	<1	<1	<1	--[a]	<1	4	<1	<1	<1	<1	<1	1

[a] *No data, insufficient runoff.*

Source: U. S. Geological Survey.

Table 77

ESTIMATED ANNUAL POLLUTANT LOADINGS OF LEAD, PHENOLS, CHROMIUM, MERCURY, AND ARSENIC TO THE INNER HARBOR FROM DIRECTLY TRIBUTARY INDUSTRIAL AREAS: 1981-1983

Pollutant	Estimated Loading (pounds)		
	1981	1982	1983[a]
Lead.	856	1,205	817
Phenols	17.5	22.0	16.3
Chromium	50.8	65.8	49.1
Mercury.	1.6	1.9	1.4
Arsenic	2.7	3.4	2.6

[a]*From January 1 through September 30, 1983. About 82 percent of annual loading typically occurs from January through September.*

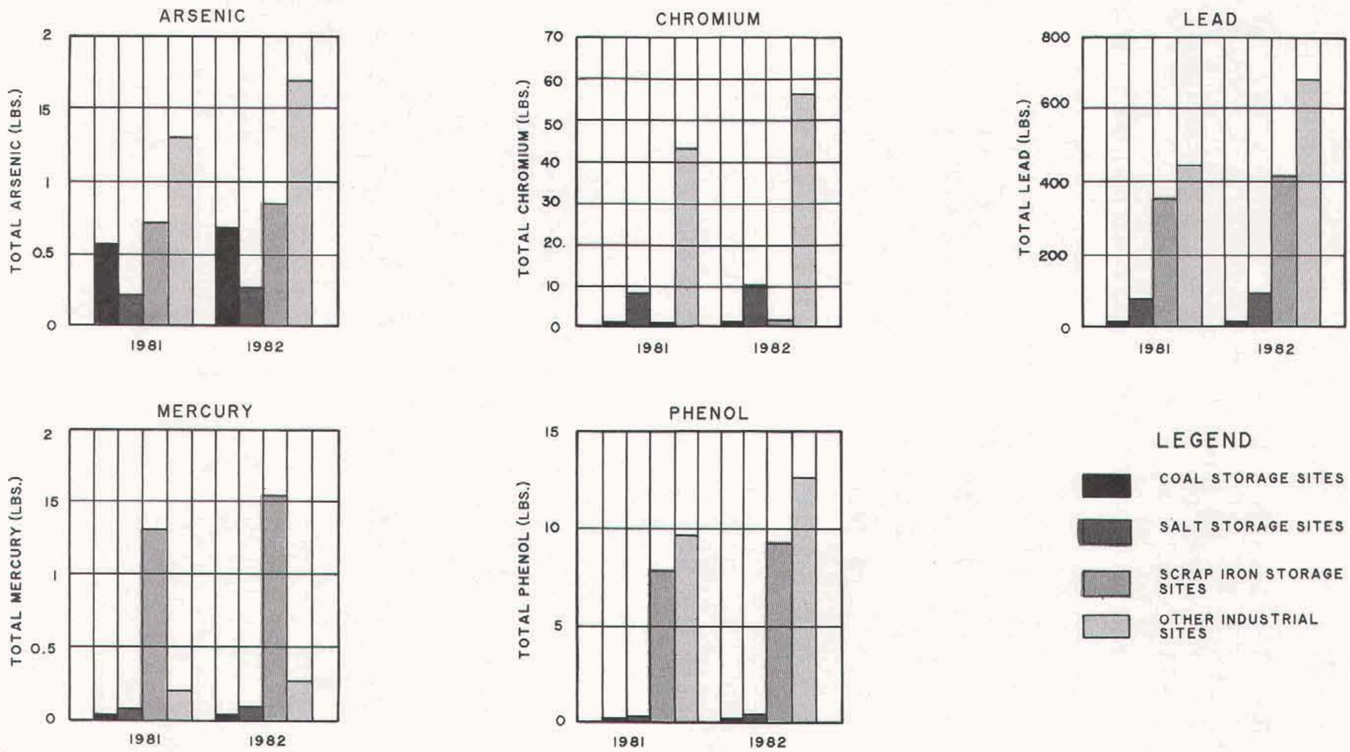
Source: U. S. Geological Survey.

Figure 134 illustrates the groundwater contributions associated with the observation wells. The groundwater inflow associated with well number 2 accounts for 75 percent of the total inflow. The inflow associated with well number 5 is 14 percent of the total groundwater inflow to the Menomonee River within the study limits. The total annual groundwater inflow of 275,025 cubic feet represents a continuous flow rate of only 0.0087 cubic feet per second, or 5,620 gallons per day.

The six observation wells were sampled in February 1983 for dissolved organo-chloride contaminants and total phenols. No organo-chloride concentrations were found above detection limits with the exception of one dieldrin concentration in well number 3, which was found to have the minimum detectable level of 0.01 μg/l. The only phenol concentration found above the detection limit was a concentration of 22 μg/l found in well number 1. This concentration was assumed to be due to local contamination from a railroad bed infiltration and therefore would probably not be indicative of the

Figure 132

SOURCES OF POLLUTANTS FROM DIRECTLY TRIBUTARY INDUSTRIAL AREAS TO THE MENOMONEE AND KINNICKINNIC PORTIONS OF THE ESTUARY: 1981-1982



Source: U. S. Geological Survey.

Table 78

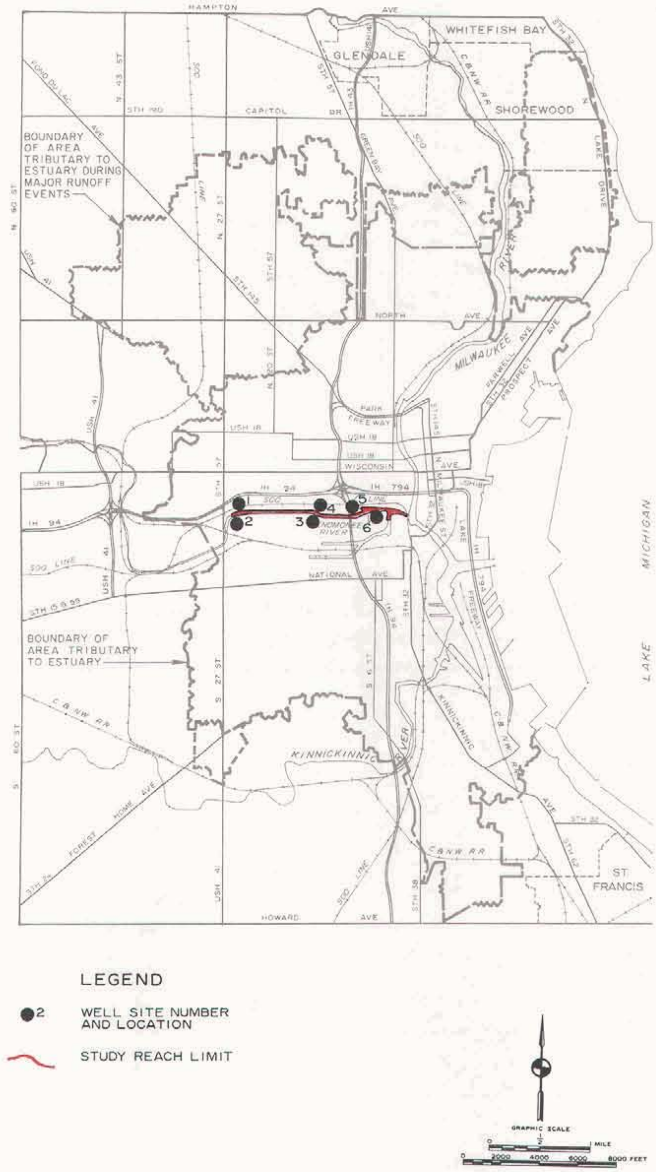
ESTIMATED UNIT-AREA POLLUTANT LOADING RATES FOR DIRECTLY TRIBUTARY INDUSTRIAL AREAS

Source Area	1981 Pounds/Acre	1982 Pounds/Acre	Average Pounds/Acre
Coal Storage Areas			
Arsenic.	0.0742	0.0897	0.0820
Chromium	0.0768	0.0929	0.0848
Lead	0.98	1.19	1.08
Mercury	0.0023	0.0028	0.0026
Phenols.	0.0102	0.0123	0.0112
Salt Storage Areas			
Arsenic.	0.0149	0.0181	0.0165
Chromium	0.58	0.70	0.64
Lead	5.30	6.41	5.86
Mercury	0.0041	0.0050	0.0046
Phenols.	0.0132	0.0160	0.0146
Scrap Iron Storage Areas			
Arsenic.	0.0096	0.0113	0.0104
Chromium	0.0029	0.0034	0.0032
Lead	4.81	5.67	5.42
Mercury	0.0180	0.0212	0.0196
Phenols.	0.11	0.13	0.12
Other Industrial Areas			
Arsenic.	0.0046	0.0060	0.0053
Chromium	0.15	0.20	0.18
Lead	1.58	2.55	2.06
Mercury	0.0007	0.0009	0.0008
Phenols.	0.0349	0.0457	0.0403

Source: U. S. Geological Survey.

Map 79

LOCATION OF WELL SITES AND STUDY REACH LIMITS FOR THE MENOMONEE RIVER INDUSTRIAL VALLEY GROUNDWATER STUDY



Water levels were measured weekly or biweekly at six observation wells in the Menomonee Valley. In addition, groundwater samples were collected at each of the six observation wells and analyzed for pollutant concentrations. Based on the data, annual pollutant loadings to the estuary from groundwater were calculated for 18 water quality indicators.

Source: U. S. Geological Survey.

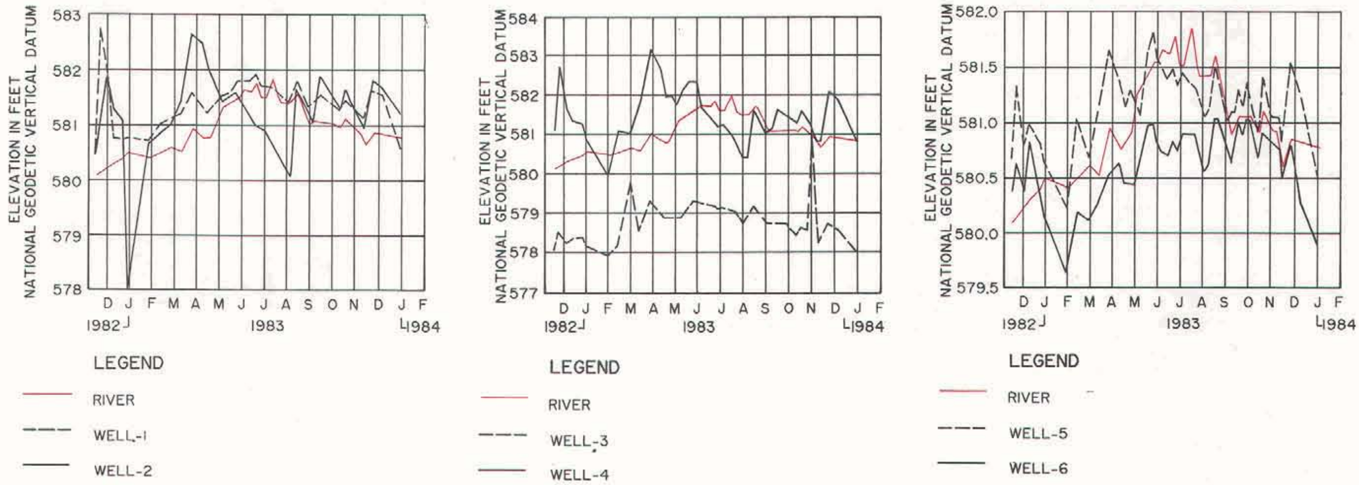
larger area represented by the well. No further sampling for organo-chlorides or phenol compounds was undertaken.

The six observation wells were sampled for dissolved inorganic contaminant concentrations in May, July, and September 1983. The results of the sampling surveys are set forth in Table 80. Of particular importance are the results of the analysis of well number 2, which represents 75 percent of the estimated groundwater inflow to the Menomonee River. A review of all six well sample analysis results indicates that the concentration values for most constituents are higher for well number 2 than for the other wells.

Pollutant loads for the 1983 water year October 1, 1982-September 30, 1983, were calculated using the July and September average contaminant concentrations for well number 2 and the total groundwater inflow volume from all areas. This approach is reasonable because well number 2 represents 75 percent of the total inflow volume as previously estimated. This approach also tends to give maximum load estimates because the contaminant concentrations found for well number 2

Figure 133

COMPARISON OF THE MENOMONEE RIVER STAGE VERSUS
THE WATER LEVELS AT THE SIX OBSERVATION WELLS: 1983



Source: U. S. Geological Survey.

Table 79

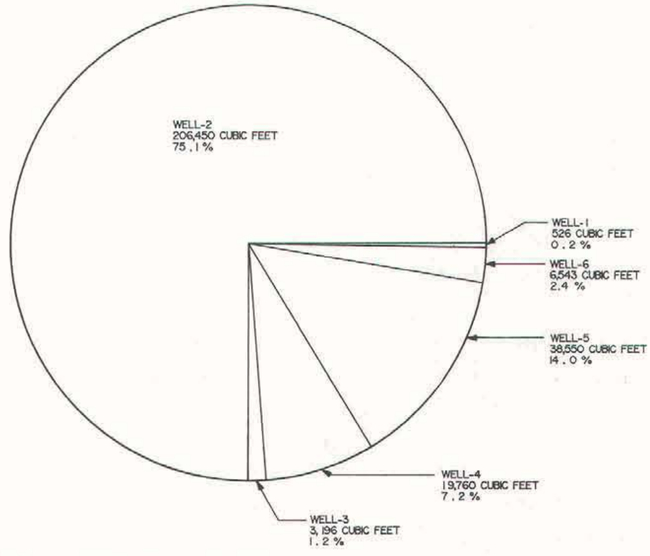
GROUNDWATER INFLOW TO THE MENOMONEE
RIVER ESTUARY BY RIVER SECTION: 1983

Well Number Located in River Section:	Inflow in Cubic Feet	Percent of Total
1	526	0.2
2	206,450	75.0
3	3,196	1.2
4	19,760	7.2
5	38,550	14.0
6	6,543	2.4
Total	275,025	100.0

Source: U. S. Geological Survey.

Figure 134

COMPARISON OF GROUNDWATER INFLOW
CONTRIBUTIONS OF OBSERVATION WELLS: 1983



Source: U. S. Geological Survey.

tended to be higher than for the other five wells. Load estimates computed for each water quality indicator are presented in Table 81. The loading values per foot of river length were computed using a reach length of 9,000 feet, and assume inflow from both sides of the river channel.

There appears to be some contamination of the estuary by groundwater containing salt. The estimated loading of chloride to the Menomonee River estuary was 60,600 pounds, and the estimated load of sodium was 52,900 pounds. All six observation wells showed significant sodium and chloride concentrations, although well number 2 had particularly high concentrations. Observation wells numbers 5 and 6 displayed even higher salt concentrations in the July samples. The groundwater loadings of the pollutants chloride, cadmium, chromium, iron, phosphorus, lead, and zinc, as shown in Table 81, represent less than 0.2 percent of the total loadings to the Menomonee River estuary. Groundwater in the Menomonee Valley industrial area is therefore not a significant source of pollutants to the Menomonee River.

Table 80

GROUNDWATER QUALITY DATA MEASURED IN THE MENOMONEE RIVER INDUSTRIAL VALLEY: 1983

Indicator[a]	May 11						July 22						September 29					
	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6
Aluminum	0.07	0.12	0.10	0.11	0.10	0.11	0.56	0.82	0.68	0.76	0.67	0.73	0.52	0.85	0.73	0.70	0.65	0.72
Antimony	0.002	0.009	0.005	0.006	0.004	0.006	0.038	0.078	0.058	0.061	0.048	0.064	--	--	--	--	--	--
Arsenic	0.010	0.024	0.017	0.020	0.015	0.020	0.062	0.094	0.082	0.087	0.070	0.090	--	--	--	--	--	--
Barium	0.014	0.018	0.034	0.056	0.022	0.042	0.250	0.180	0.370	0.540	0.190	0.390	0.17	0.18	0.35	0.44	0.22	0.39
Beryllium	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0011	0.0016	0.0022	0.0020	0.0015	0.0051	--	--	--	--	--	--
Boron	0.11	0.19	0.10	0.12	0.16	0.07	0.43	1.00	0.44	0.39	0.31	0.22	0.42	1.10	0.43	0.37	0.20	0.200
Cadmium	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.006	0.011	0.006	0.006	0.005	0.006	0.002	0.005	0.004	0.004	0.004	0.004
Calcium	93	51	16	61	16	50	160	250	230	260	270	250	68	210	250	250	250	250
Chloride	89	5,960	876	1,070	397	290	7,200	3,290	4,000	3,230	> 10,000	>10,000	63.4	3,930	807	786	433	328
Chromium	0.002	0.004	0.003	0.003	0.002	0.003	0.016	0.022	0.020	0.019	0.017	0.023	0.006	0.011	0.009	0.008	0.008	0.009
Cobalt	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	0.003	0.008	0.006	0.006	0.005	0.007	--	--	--	--	--	--
Copper	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Iron	<2.1	3.1	2.8	3.5	2.7	7.9	7.8	8.6	14.0	13.0	10.0	25.0	7.3	8.4	12.0	12.0	8.0	21.0
Lead	0.005	0.018	0.006	0.011	0.007	0.010	0.052	0.130	0.091	0.097	0.072	0.097	0.023	0.086	0.063	0.060	0.045	0.071
Lithium	0.0025	0.0110	0.0068	0.0043	0.0047	0.0039	0.0260	0.0890	0.0640	0.0380	0.0430	0.0360	--	--	--	--	--	--
Magnesium	8	15	12	13	11	12	83	120	110	120	98	100	70	120	110	110	90	110
Manganese	0.083	0.150	0.090	0.090	0.160	0.190	0.500	0.720	0.540	0.490	0.880	1.100	0.460	0.690	0.480	0.430	0.680	1.000
Mercury	0.081	0.17	0.13	0.15	0.12	0.14	--	--	--	--	--	--	--	--	--	--	--	--
Molybdenum . .	<0.002	0.002	<0.002	<0.002	<0.002	<0.002	0.090	0.017	0.014	0.014	0.011	0.014	--	--	--	--	--	--
Nickel	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	0.016	0.024	0.028	0.019	0.015	0.022	0.006	0.016	0.012	0.012	0.008	0.013
Phosphorus . . .	0.060	0.38	0.30	0.17	0.47	0.49	0.26	1.70	2.10	0.68	2.20	2.20	0.24	1.60	1.90	0.67	2.20	2.00
Potassium	3.9	21	31	23	15	30	8.5	17	30	24	15	32	3.7	18	29	17	13	32
Selenium	0.007	0.025	0.014	0.018	0.012	0.015	0.041	0.091	0.056	0.061	0.058	0.070	0.014	0.056	0.038	0.038	0.032	0.057
Silicon	--	--	--	--	--	--	1.6	2.3	2.0	0.96	2.2	2.5	--	--	--	--	--	--
Silver	0.034	0.550	0.150	0.370	0.083	0.200	0.002	0.009	0.005	0.005	0.004	0.004	--	--	--	--	--	--
Sodium	9.2	370	48	54	34	16	250	3,600	730	810	510	260	39	2,700	380	290	280	140
Strontium	0.68	0.27	0.071	0.042	0.1400	0.0970	5.4000	2.5000	0.6900	0.3900	1.3000	0.8600	6.600	2.300	6.700	3.200	1.100	0.910
Tin	0.003	0.008	0.005	0.005	0.004	0.006	0.038	0.060	0.052	0.053	0.048	0.056	--	--	--	--	--	--
Titanium	0.010	0.067	0.024	0.045	0.017	0.028	0.120	0.350	0.210	0.220	0.160	0.160	--	--	--	--	--	--
Vanadium	0.004	0.019	0.010	0.014	0.008	0.014	0.008	0.016	0.012	0.013	0.010	0.016	--	--	--	--	--	--
Zinc	0.0018	0.0017	0.0120	0.0012	0.0012	0.0021	0.0100	0.0180	0.3100	<0.0010	<0.0010	<0.0010	0.020	0.016	0.250	0.005	0.003	0.009

[a]All data expressed in mg/l.

Source: U. S. Geological Survey.

Table 81

GROUNDWATER POLLUTANT LOADINGS TO THE MENOMONEE RIVER ESTUARY: 1983

Pollutant	Load (pounds)	Load per Length of River (pounds/1,000 feet)
Chloride	60,000	6,700
Aluminum	13.9	1.54
Barium	3.0	0.33
Boron	17.6	1.96
Calcium	3,860	430
Cadmium	0.13	0.014
Chromium	0.29	0.032
Iron	143	15.9
Potassium	290	32.2
Magnesium	2,000	220
Manganese	11.8	5.35
Sodium	52,900	5,900
Nickel	0.33	0.037
Phosphorus	27.8	3.09
Lead	1.81	0.20
Selenium	1.24	0.14
Strontium	40.4	0.45
Zinc	0.29	0.03

Source: U. S. Geological Survey.

SEDIMENT QUALITY CONDITIONS AND SEDIMENT-WATER INTERACTIONS

As indicated in Chapter IV of this volume, sediment quality was evaluated as part of the Milwaukee Harbor estuary study at 15 stations, six located in the upstream reaches and nine located within the inner harbor. Approximately 1,500 sediment samples were taken during the period 1982 through 1983. The evaluation involved the collection and analysis of sediment core samples, interstitial water chemistry, gas production measurements, sediment oxygen demand measurements, and sediment trap data. The results of previous field observations of sediment characteristics and studies of the concentrations of organic toxic substances in sediments were also reviewed and the findings summarized herein. The discussion below summarizes the results of 3,055 measurements of organic toxic substances in the sediments taken from 1975 through 1985 for the upstream river reaches, the inner harbor, and the outer harbor.

Sediment Observations

Field observations were made on sediment samples as they were collected from the inner and outer harbors during a 1980 investigation of sediment contamination by the U. S. Environmental Protection Agency.[6] Sediments in the Milwaukee River upstream of St. Paul Avenue were described as mud or muddy sand with organic detritus, having an earthy odor. Sediments in the vicinity of St. Paul Avenue were described as having an oily odor. Sediments at the confluence of the Milwaukee River and Menomonee River were gray clay, indicating a scoured area. Sediments in the Menomonee River, the South Menomonee Canal, and the Burnham Canal were described as black mud over gray clay, having a disagreeable hydrocarbon odor. Sediments in the Kinnickinnic River upstream of Kinnickinnic Avenue were described as mud with an earthy odor, while sediments farther downstream were described as having oily and hydrocarbon odors. Sediments in the Milwaukee River downstream of the confluence with the Menomonee and Kinnickinnic Rivers were described as dark gray to black mud with an earthy odor. Hard gray clay was found at a sample station in the outer harbor, indicating a scoured area. Sediments in the outer harbor to the Jones Island sewage treatment plant were found to have a stale odor.

A study of fingernail clams (Sphaeriidae) conducted in 1973 in the outer harbor and in portions of the inner harbor also evaluated the bottom sediment characteristics.[7] Of the total of 99 sediment samples collected in the outer harbor, 67 samples were identified as either silt, clayey silt, or sandy silt, and 11 samples were identified as loam. Loam contains similar portions of sand, silt, and clay. The remaining 21 samples were identified as either sand or silty sand. The distribution of the primary sediment texture classes is illustrated on Map 80. The sandy substrate areas were primarily found in the inner harbor at the confluence of the Kinnickinnic River and the Milwaukee River, and in the outer harbor in the northwest and southwest shore areas, just north of the mouth of the inner harbor, and near some breakwater openings to Lake Michigan. The loamy substrate areas were primarily found at the mouth of the inner harbor, and adjacent to the sandy substrate areas. The remaining substrates found in the outer harbor were silty substrates, as shown on the map. Nearly all the sediments sampled were poorly sorted, possessing a

[6] *A. G. Kizlaukas, "Report on an Investigation of Sediment Contamination, the Milwaukee Estuary, Wisconsin, Sampled July 29-31, 1980," Remedial Programs Staff, Great Lakes National Program Office, U. S. Environmental Protection Agency, October 1982.*

[7] *P. J. Emmling, "Factors Affecting the Distribution of Sphaeriidae (Mollusca: Pelecypoda) in the Milwaukee Harbor, Lake Michigan," Master of Science Thesis, University of Wisconsin-Milwaukee, 1976.*

wide range of particle sizes. Poorly sorted sediments are generally found in areas exhibiting variable currents or turbulence during deposition.

Map 81 shows the detailed distribution of sand found within the outer harbor. The highest percentages of sand were found within the bottom sediments closer to the shore, particularly in the northwest and southwest corners of the outer harbor, as well as within the central harbor opening to Lake Michigan. The 1973 study concluded that the sand near the shore was not depositional, but rather represented conditions present prior to the construction of the outer harbor breakwater.[8] Since these areas are relatively shallow, silt and clay transported by the rivers into the outer harbor and deposited in these areas are probably resuspended by surface waves and deposited in deeper areas. These sandy areas are also located a sizable distance from the mouth of the inner harbor. High percentages of sand found within the inner harbor were attributed to scouring, deposition from industrial and transportation-related sources, and other localized factors.

The organic content of the bottom sediment, which often produces the odors described above, was also studied.[9] The organic content of the 99 sediment samples collected within the outer harbor and adjacent inner harbor ranged from 1.5 to 23.6 percent by weight, with a mean of 10 percent. Map 81 illustrates the distribution of the percentage of organic matter within the bottom sediments. The highest organic percentages were found within the outer harbor near the mouth of the inner harbor and near the discharge outfall from the Jones Island wastewater treatment plant. Generally, the highest levels of organic matter were found to be associated with silt-size particles. Little organic deposition occurred in the sandy substrate areas, and, because of greater substrate permeability which increased dissolved oxygen input into the sediments, that organic matter which was deposited was more efficiently decomposed and washed away. Substrate areas with a high clay content were heavily scoured, which also removed the organic matter.

Sediment Chemistry

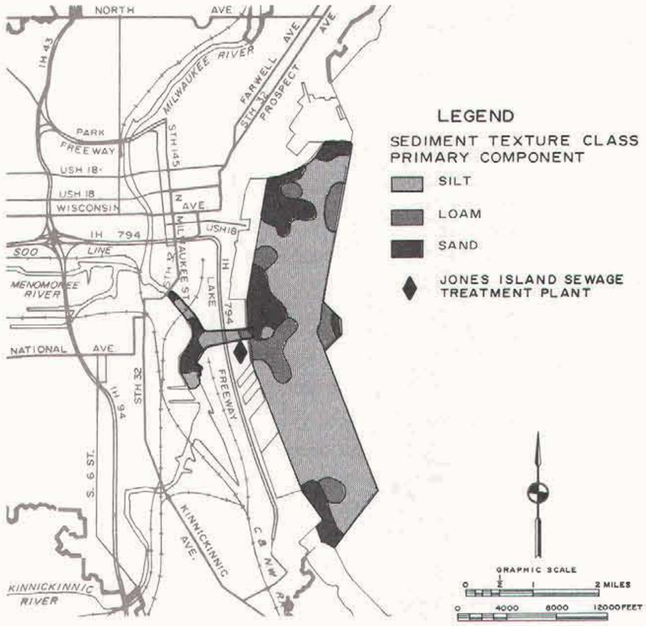
In 1982 and 1983, sediment cores were collected at the 15 upstream and inner harbor stations as a part of the harbor estuary study and subsampled at 0.5-inch (1-centimeter) increments for the first 2.5 inches (six centimeters), and at one-inch (2.5-centimeter) increments below that for a total

[8] *Ibid.*

[9] *Ibid.*

Map 80

DISTRIBUTION OF BOTTOM SEDIMENT TEXTURE CLASSES IN THE OUTER HARBOR AND A PORTION OF THE INNER HARBOR: 1973



Bottom sediment textures in the outer harbor and in a portion of the inner harbor were identified during a 1976 study of fingernail clams. Of the total of 99 sediment samples collected from the outer harbor, 67 were identified as primarily silt, 21 as primarily sand, and 11 as primarily loam. The bottom sediments of that portion of the inner harbor studied consisted primarily of silt, although significant amounts of sand were also observed.

Source: P. J. Emmling, "Factors Affecting the Distribution of Sphaeriidae (Mollusca: Pelecypoda) in the Milwaukee Harbor, Lake Michigan," Master of Science Thesis, University of Wisconsin-Milwaukee, 1976; and SEWRPC.

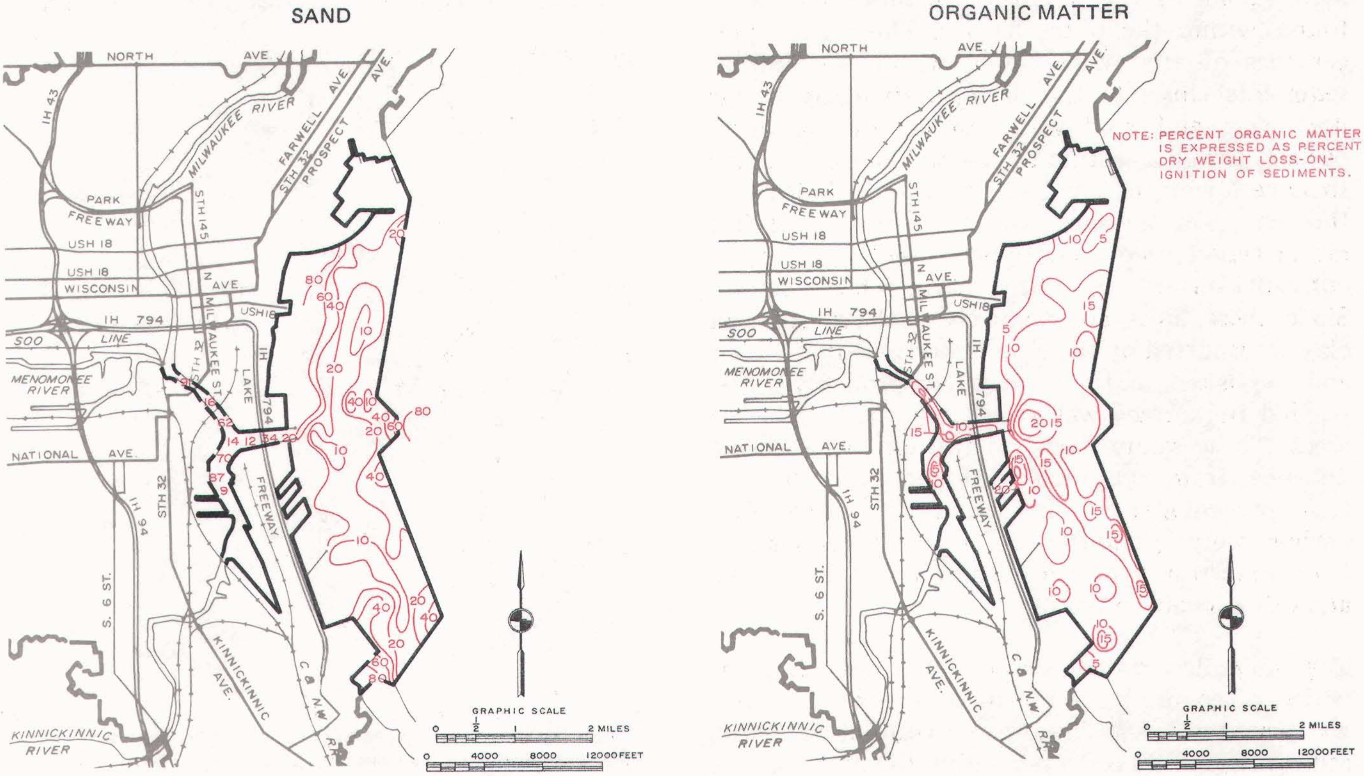
of 10 subsamples. Vertical profiles were plotted using core data to determine trends in the vertical distribution of various indicators. At each depth, the mean plus or minus one standard deviation is plotted.

The 1983 vertical sediment profiles at six representative sample stations for 11 quality indicators are set forth in Figures 135 through 145. The vertical profiles are relatively uniform and exhibit significant variability. No consistent trends in sediment chemistry with depth were evident, and the sediments at most stations appear to be well mixed.

A statistical summary of the 1982-1983 sediment core measurements at the upstream and inner harbor stations is presented in Table 82. In general, the inner harbor sediments have a lower percentage of total solids than do the upstream sediments, and are therefore more flocculent. The inner harbor sediments have a higher organic content

Map 81

DISTRIBUTION OF THE PERCENT SAND AND ORGANIC MATTER IN THE BOTTOM SEDIMENTS OF THE OUTER HARBOR AND A PORTION OF THE INNER HARBOR: 1973

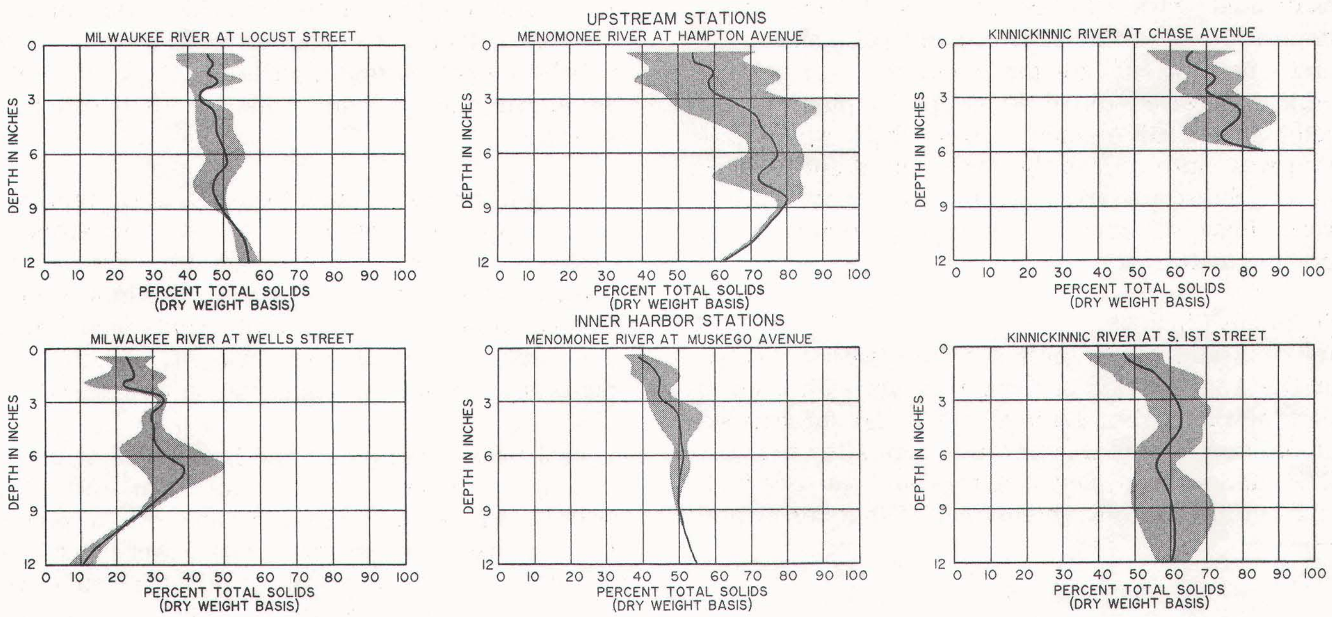


The sand and organic matter content of the bottom sediments of the outer harbor was surveyed in a 1976 study. As shown on the map on the left above, the highest percentages of the sand in the bottom sediments were found closer to shore, especially in the northwestern and southwestern extremities of the outer harbor, as well as near the central harbor opening to Lake Michigan. The sandy sediments found near the shore were not depositional. Rather, the initial mixed deposits of sand, silt, and clay in the shoreland areas are washed out and redeposited in the deeper water areas. The organic content of the bottom sediments ranged from 1.5 to 23.6 percent by weight, with a mean of about 10 percent. As shown on the map on the right, organic contents exceeding 20 percent were found near the inner harbor entrance and the Jones Island wastewater treatment plant outfall. The highest organic contents were found in the areas with silt deposits, as shown on Map 80.

Source: P. J. Emmling, "Factors Affecting the Distribution of Sphaeriidae (Mollusca: Pelecypoda) in the Milwaukee Harbor, Lake Michigan," Master of Science Thesis, University of Wisconsin-Milwaukee, 1976.

Figure 135

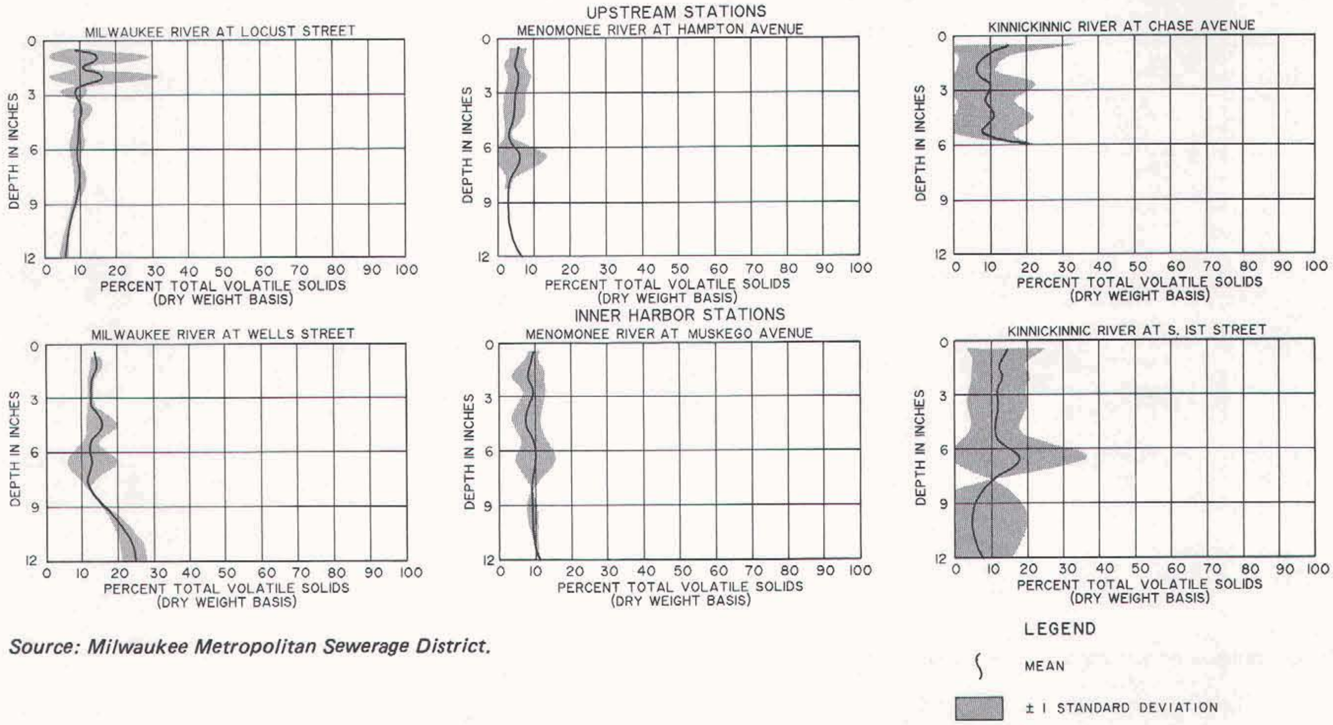
VERTICAL PROFILES OF TOTALS SOLIDS IN SEDIMENT CORES: 1983



Source: Milwaukee Metropolitan Sewerage District.

Figure 136

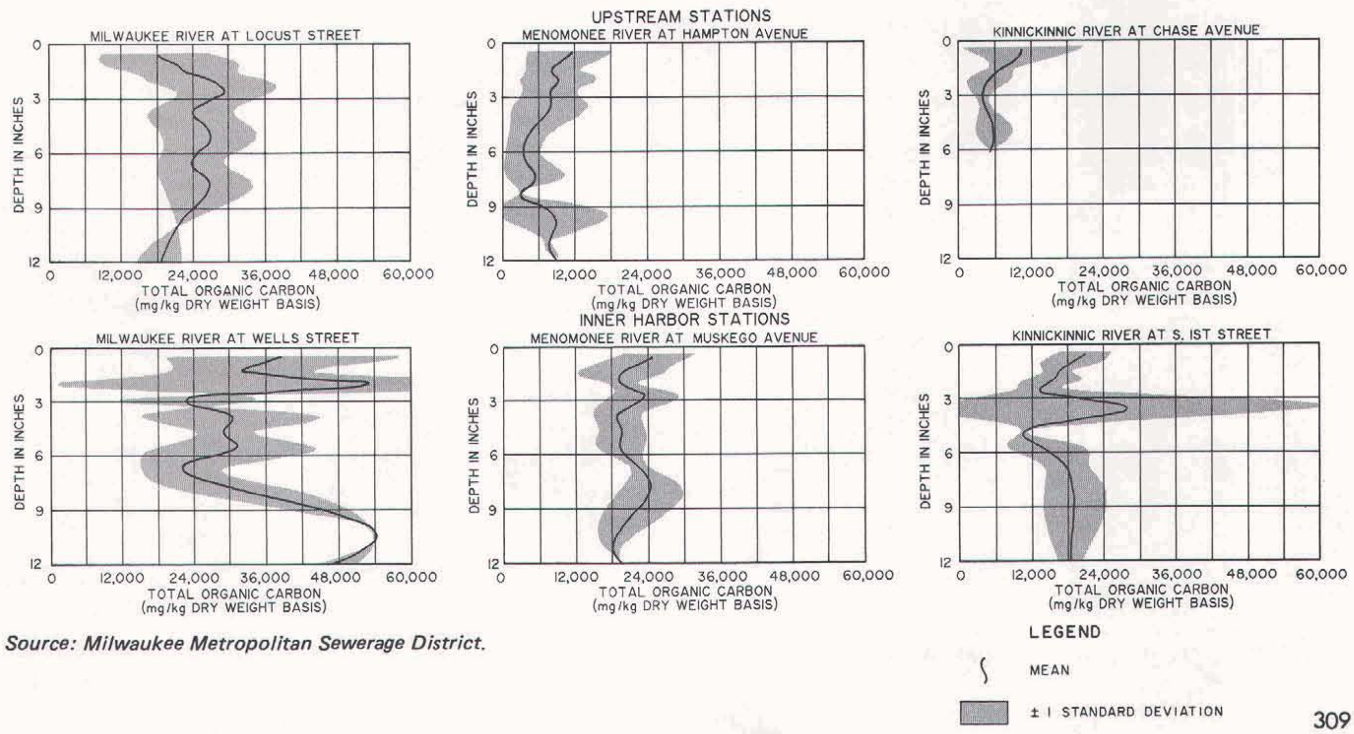
VERTICAL PROFILES OF TOTAL VOLATILE SOLIDS IN SEDIMENT CORES: 1983



Source: Milwaukee Metropolitan Sewerage District.

Figure 137

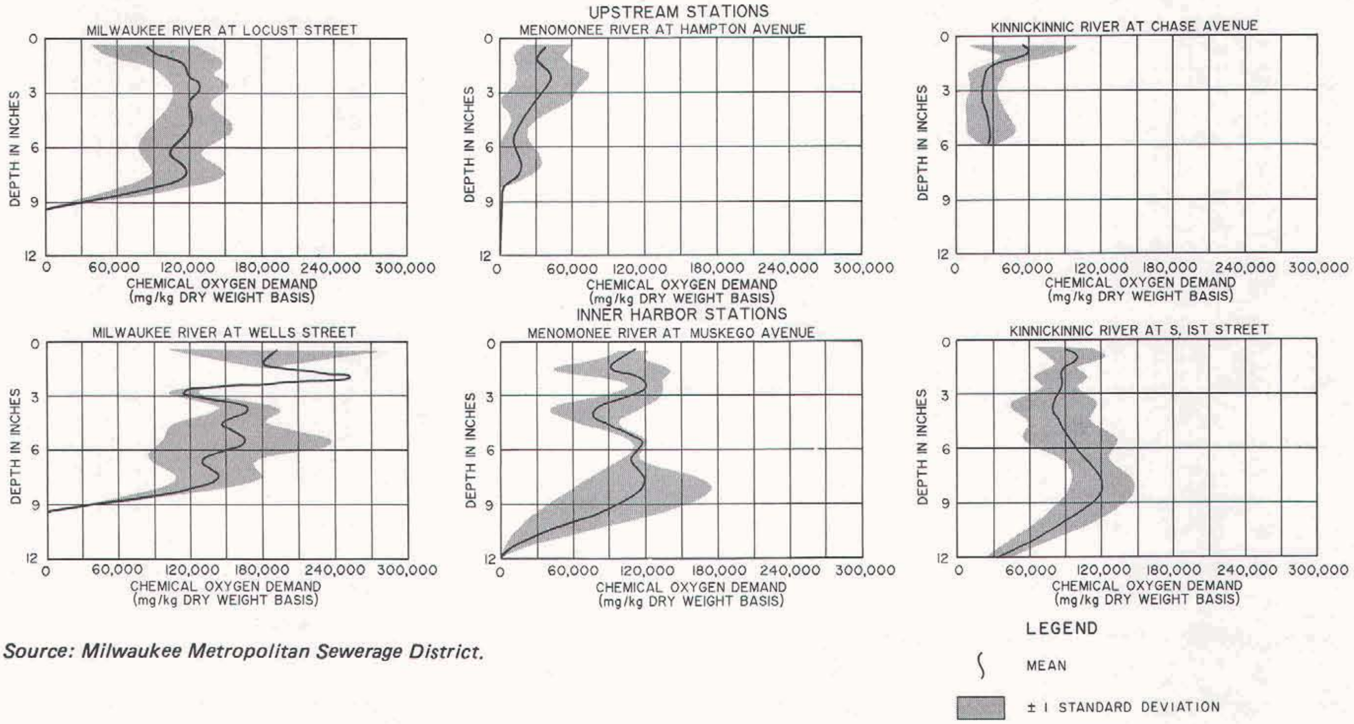
VERTICAL PROFILES OF TOTAL ORGANIC CARBON IN SEDIMENT CORES: 1983



Source: Milwaukee Metropolitan Sewerage District.

Figure 138

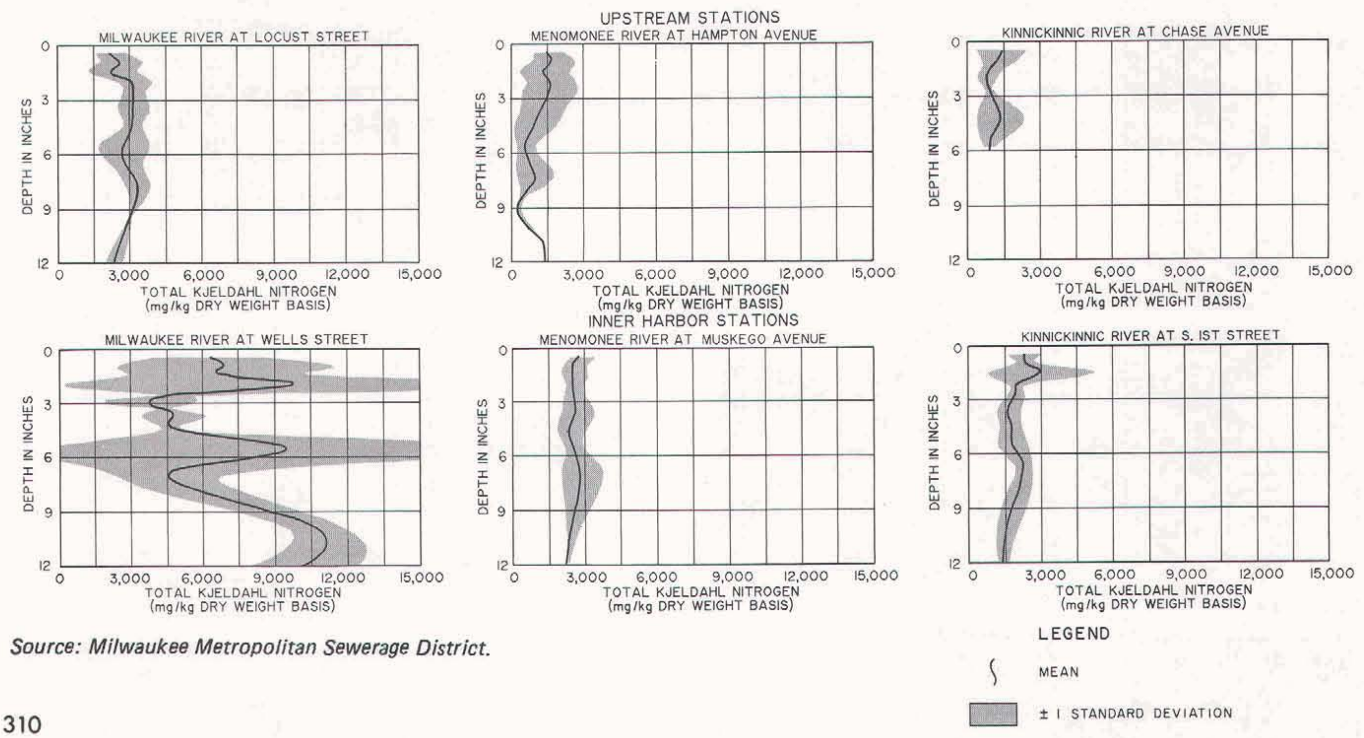
VERTICAL PROFILES OF CHEMICAL OXYGEN DEMAND IN SEDIMENT CORES: 1983



Source: Milwaukee Metropolitan Sewerage District.

Figure 139

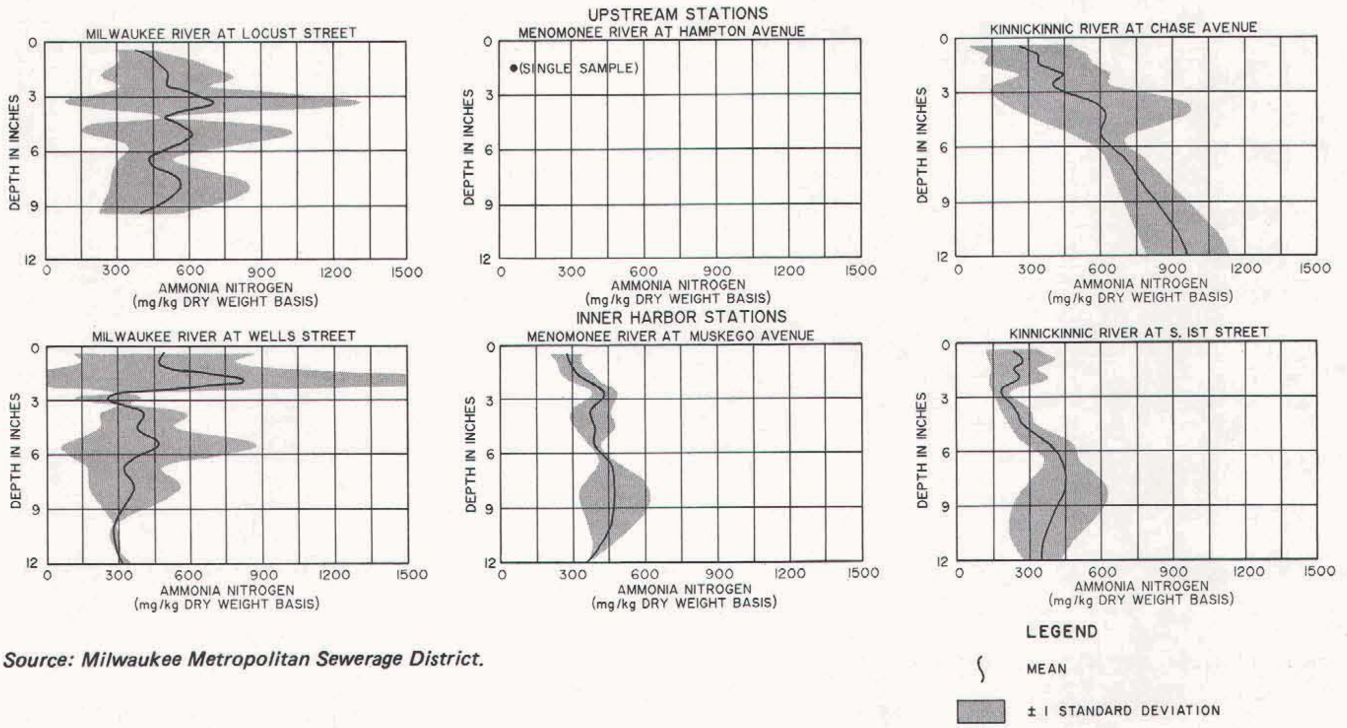
VERTICAL PROFILES OF TOTAL KJELDAHL NITROGEN IN SEDIMENT CORES: 1983



Source: Milwaukee Metropolitan Sewerage District.

Figure 140

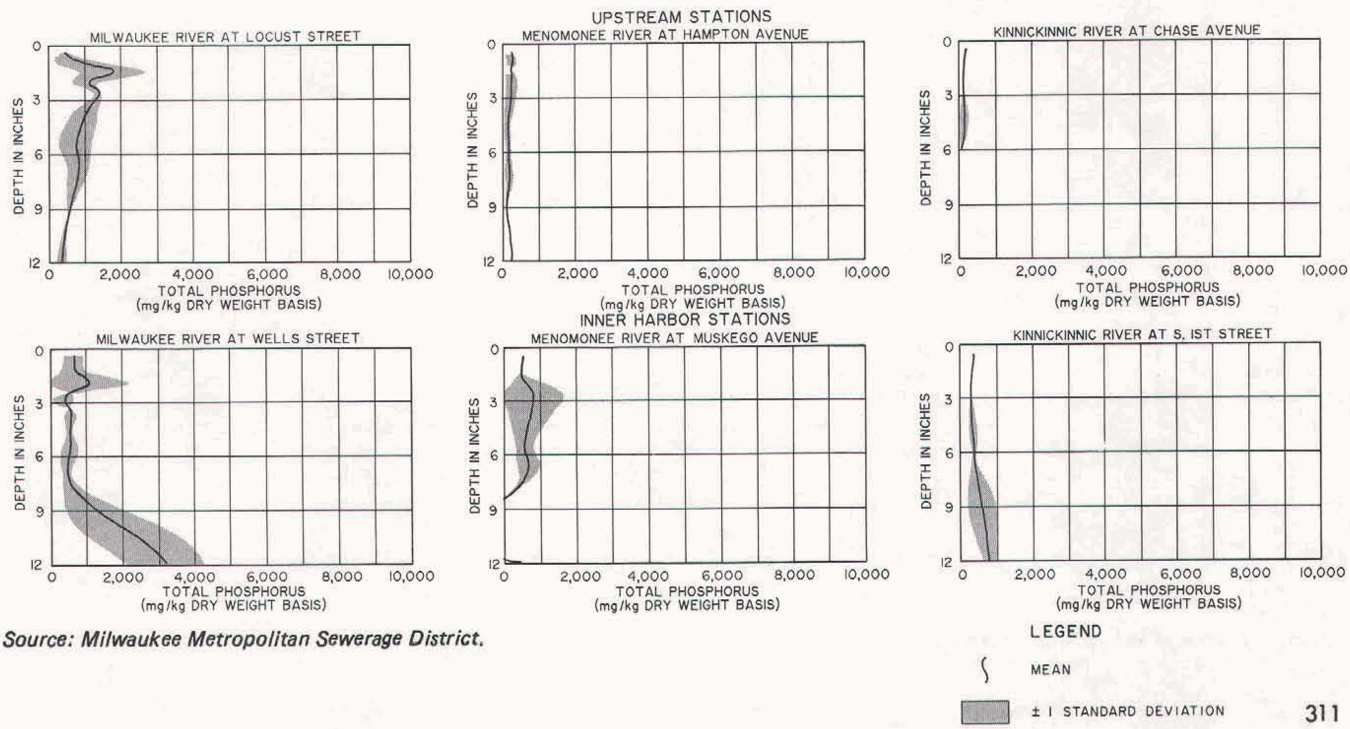
VERTICAL PROFILES OF AMMONIA NITROGEN IN SEDIMENT CORES: 1983



Source: Milwaukee Metropolitan Sewerage District.

Figure 141

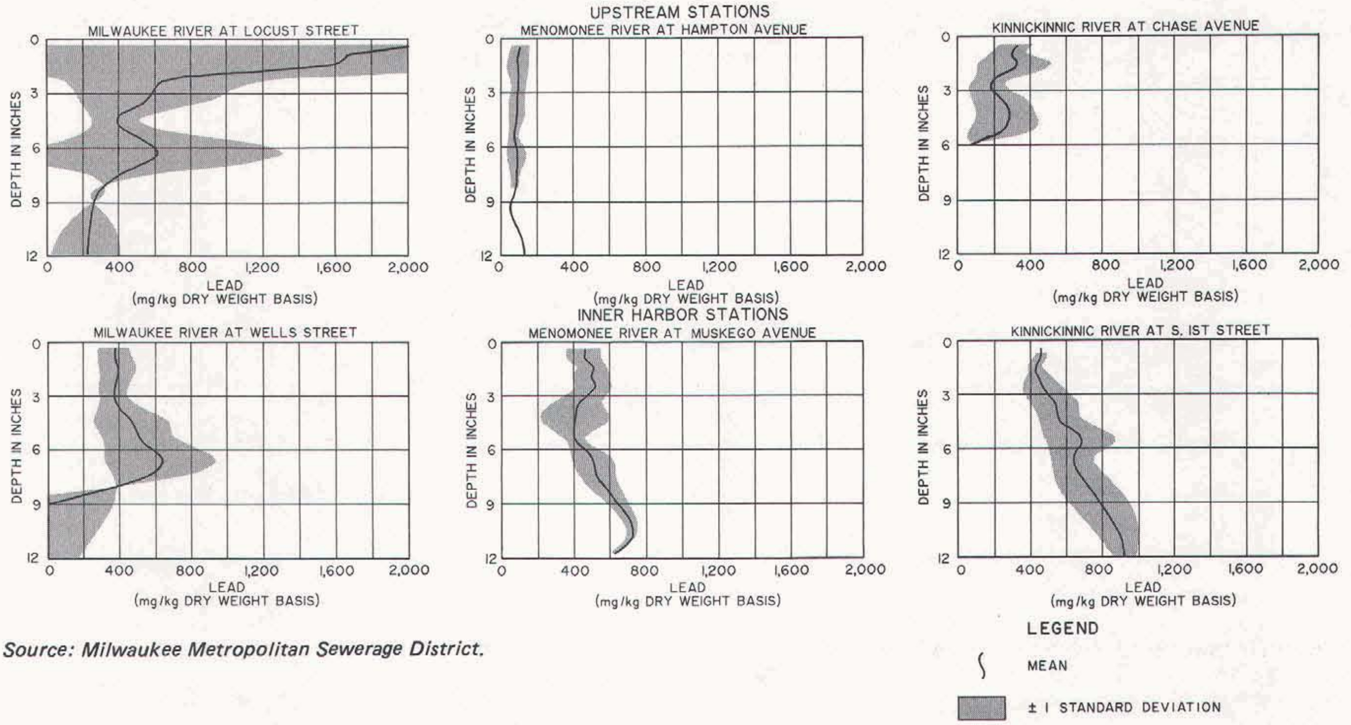
VERTICAL PROFILES OF TOTAL PHOSPHORUS IN SEDIMENT CORES: 1983



Source: Milwaukee Metropolitan Sewerage District.

Figure 142

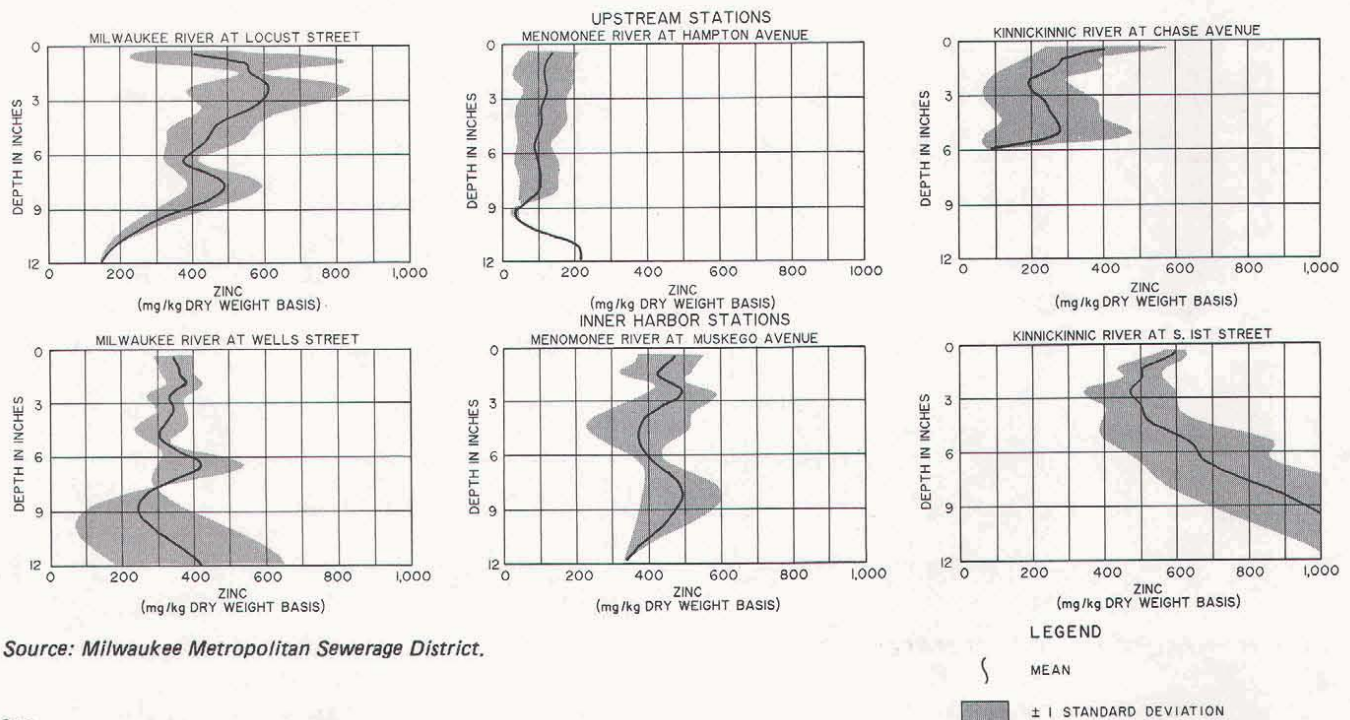
VERTICAL PROFILES OF LEAD IN SEDIMENT CORES: 1983



Source: Milwaukee Metropolitan Sewerage District.

Figure 143

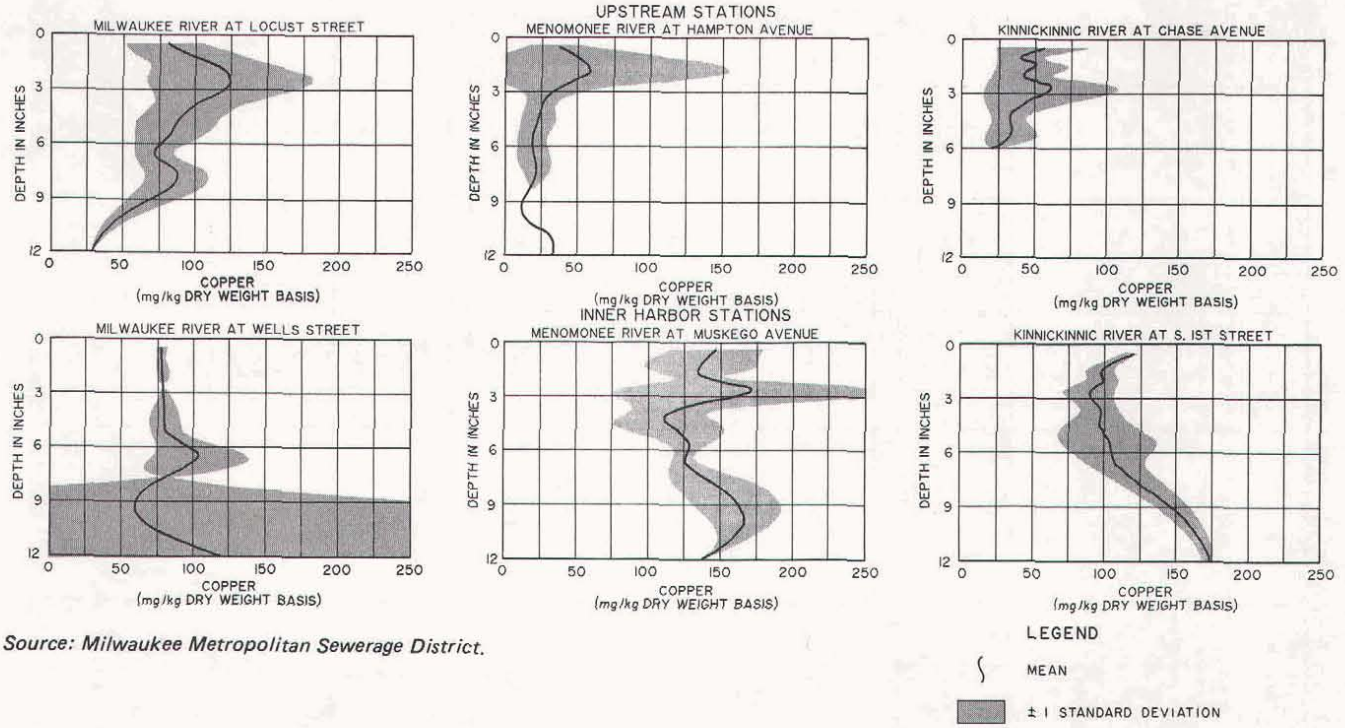
VERTICAL PROFILES OF ZINC IN SEDIMENT CORES: 1983



Source: Milwaukee Metropolitan Sewerage District.

Figure 144

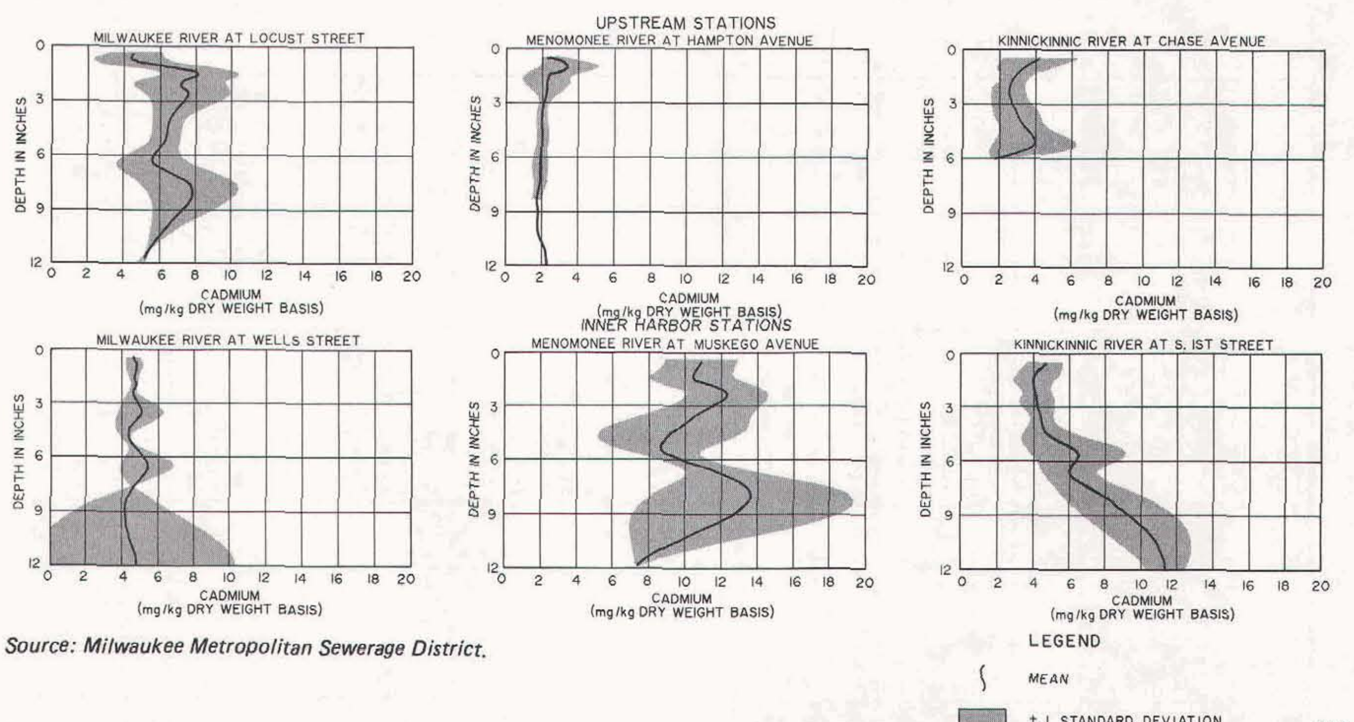
VERTICAL PROFILES OF COPPER IN SEDIMENT CORES: 1983



Source: Milwaukee Metropolitan Sewerage District.

Figure 145

VERTICAL PROFILES OF CADMIUM IN SEDIMENT CORES: 1983



Source: Milwaukee Metropolitan Sewerage District.

Table 82

CHEMICAL ANALYSIS OF SEDIMENT CORE SAMPLES: 1982-1983

Sampling Station	Statistical Variable	Total Solids (percent wet weight)	Total Volatile Solids (percent dry weight)	Total Organic Carbon (mg/kg dry weight)	Chemical Oxygen Demand (mg/kg dry weight)	Total Kjeldahl Nitrogen (mg/kg dry weight)	Ammonia Nitrogen (mg/kg dry weight)	Total Phosphorus (mg/kg dry weight)	Lead (mg/kg dry weight)	Zinc (mg/kg dry weight)	Copper (mg/kg dry weight)	Cadmium (mg/kg dry weight)
Upstream Stations												
Milwaukee River at Hampton Avenue	Number of Samples	101	81	101	95	101	101	81	79	79	79	79
	Minimum	39	0.8	600	3,100	500	10	100	20	20	6	1.1
	Mean	69	6.3	10,900	50,700	1,500	130	580	160	190	49	3.1
	Maximum	89	21.2	29,900	173,000	6,900	480	2,020	470	690	208	9.8
	Standard Deviation	12	4.2	8,000	43,800	1,200	120	490	120	170	45	1.8
Milwaukee River at Locust Street	Number of Samples	121	121	121	109	121	121	121	122	122	122	122
	Minimum	33	5.3	7,600	25,900	800	60	20	180	200	41	2.7
	Mean	46	11.5	24,200	129,200	3,000	510	990	840	510	100	6.7
	Maximum	66	43.0	41,700	231,000	8,600	940	3,380	8,950	1,020	202	11.8
	Standard Deviation	6	4.9	6,800	38,400	1,200	230	580	1,350	140	31	1.9
Menomonee River at Hampton Avenue	Number of Samples	114	94	114	104	114	114	103	93	93	93	93
	Minimum	33	1.0	200	1,900	100	10	10	40	31	0	0.9
	Mean	69	4.8	6,600	32,200	1,100	110	330	100	124	40	2.3
	Maximum	88	22.6	20,300	113,000	3,100	400	1,090	250	243	220	5.3
	Standard Deviation	14	3.2	4,700	24,400	700	80	250	40	60	30	0.7
Menomonee River at Hawley Road	Number of Samples	33	27	33	33	33	33	30	27	27	27	27
	Minimum	42	1.4	700	4,100	50	10	80	60	64	10	1.2
	Mean	70	3.3	3,700	24,600	700	60	210	120	114	20	1.9
	Maximum	82	7.1	10,100	77,200	2,300	220	690	260	254	60	3.2
	Standard Deviation	10	1.9	2,600	18,600	600	60	160	50	43	10	0.5
Kinnickinnic River at Wilson Park Creek	Number of Samples	34	28	34	34	34	34	31	31	31	31	31
	Minimum	23	1.1	900	3,900	200	10	30	80	75	10	1.2
	Mean	67	7.2	6,200	30,800	900	50	270	170	187	30	2.2
	Maximum	88	24.5	26,000	169,000	2,600	300	1,340	290	950	80	3.4
	Standard Deviation	16	6.3	6,100	33,300	600	10	260	60	158	20	0.6
Kinnickinnic River at Chase Avenue	Number of Samples	104	70	104	100	104	104	83	95	95	95	95
	Minimum	28	1.4	200	1,000	100	10	70	50	73	20	1.5
	Mean	68	6.9	7,800	42,100	1,300	140	380	590	370	60	5.6
	Maximum	88	43.0	35,300	213,000	4,500	570	1,920	3,430	2,258	130	62.4
	Standard Deviation	14	7.6	7,200	41,200	900	120	360	680	285	30	7.7
Inner Harbor Stations												
Milwaukee River at Walnut Street	Number of Samples	117	117	117	99	117	117	117	95	95	95	95
	Minimum	21	6.0	10,500	70,200	2,100	80	280	250	240	56	4.2
	Mean	36	11.9	25,700	144,900	4,600	530	890	420	350	86	5.3
	Maximum	67	21.2	62,600	259,000	15,400	1,500	2,830	2,120	570	127	6.8
	Standard Deviation	6	2.2	7,900	29,700	2,200	290	540	230	50	11	0.6
Milwaukee River at Wells Street	Number of Samples	126	104	125	110	126	126	106	104	104	104	104
	Minimum	5	5.4	9,400	55,400	2,200	100	280	220	150	56	2.3
	Mean	33	13.6	30,600	171,900	6,700	520	910	560	380	107	5.6
	Maximum	59	32.2	146,000	732,000	38,300	2,600	3,790	3,430	780	543	14.5
	Standard Deviation	9	3.2	14,600	72,700	5,000	350	630	390	100	59	1.9

Table 82 (continued)

Sampling Station	Statistical Variable	Total Solids (percent wet weight)	Total Volatile Solids (percent dry weight)	Total Organic Carbon (mg/kg dry weight)	Chemical Oxygen Demand (mg/kg dry weight)	Total Kjeldahl Nitrogen (mg/kg dry weight)	Ammonia Nitrogen (mg/kg dry weight)	Total Phosphorus (mg/kg dry weight)	Lead (mg/kg dry weight)	Zinc (mg/kg dry weight)	Copper (mg/kg dry weight)	Cadmium (mg/kg dry weight)
Inner Harbor Stations (continued)												
Milwaukee River at St. Paul Avenue	Number of Samples	118	108	116	102	118	118	108	120	120	120	120
	Minimum	23	6.5	17,200	76,900	2,500	220	420	290	230	58	3.6
	Mean	34	12.2	27,700	150,400	5,300	480	970	420	370	98	5.8
	Maximum	56	17.1	40,800	219,000	16,800	1,700	2,100	650	870	135	14.7
	Standard Deviation	6	1.6	5,600	20,100	2,900	200	520	90	60	15	1.1
Milwaukee River at Broadway Street	Number of Samples	39	17	39	39	39	39	16	19	19	19	19
	Minimum	33	1.0	90	900	130	30	170	90	50	14	2.0
	Mean	51	6.7	18,500	102,200	2,900	230	310	720	220	73	3.7
	Maximum	86	11.9	32,500	194,000	6,700	460	640	4,910	400	149	6.1
	Standard Deviation	16	4.0	10,500	55,800	1,700	120	170	1,090	110	41	1.4
Milwaukee River at C&NW Railway	Number of Samples	129	106	129	112	129	129	102	116	116	116	116
	Minimum	18	0.5	12,100	42,000	1,600	90	230	90	60	20	2.2
	Mean	37	11.4	27,900	142,500	4,100	430	800	390	430	106	8.2
	Maximum	58	18.4	68,800	230,000	8,100	2,270	2,980	1,080	980	148	13.6
	Standard Deviation	8	2.4	7,900	31,300	1,200	220	470	140	130	18	1.9
Menomonee River near Falk dam (at N. 25th Street)	Number of Samples	108	96	108	93	108	108	98	98	98	98	98
	Minimum	14	1.0	1,300	1,800	200	10	120	70	63	17	1.8
	Mean	45	13.8	27,400	158,800	4,200	750	870	370	430	150	16.2
	Maximum	94	49.7	82,900	480,000	27,100	5,350	10,100	610	779	270	50.9
	Standard Deviation	21	11.1	21,000	124,400	3,500	720	1,310	140	201	60	12.9
Menomonee River at Muskego Avenue	Number of Samples	112	90	100	100	111	111	90	102	102	102	102
	Minimum	25	0.3	10,500	24,600	1,300	200	270	210	220	70	4.2
	Mean	47	11.8	23,300	121,500	3,100	410	710	510	453	140	11.9
	Maximum	60	90.0	41,000	194,000	7,900	780	2,350	1,230	678	330	20.6
	Standard Deviation	7	12.1	5,800	31,500	1,300	120	410	150	96	30	3.6
Kinnickinnic River at S. 1st Street	Number of Samples	126	117	125	110	120	126	116	106	106	106	105
	Minimum	38	4.7	6,600	36,200	700	130	180	320	272	50	2.0
	Mean	55	10.9	19,400	115,200	2,300	340	660	580	640	120	6.6
	Maximum	79	51.2	85,700	164,000	6,800	720	3,030	1,010	1,358	160	11.4
	Standard Deviation	7	6.5	7,700	30,600	700	150	550	170	205	20	2.3
Kinnickinnic River at Greenfield Avenue (extended)	Number of Samples	127	127	127	109	127	127	125	118	118	118	118
	Minimum	27	6.0	8,200	81,000	1,300	90	180	250	331	80	6.6
	Mean	43	11.5	23,700	143,200	3,100	360	1,160	380	528	120	9.9
	Maximum	100	25.4	37,000	218,000	5,000	690	4,760	540	860	190	15.8
	Standard Deviation	8	2.1	5,000	28,100	600	130	1,000	50	83	10	1.6

Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

than do the upstream sediments, as expressed by higher concentrations of total volatile solids, total organic carbon, and chemical oxygen demand. The inner harbor sediments also have higher concentrations of total phosphorus, ammonia nitrogen, and total Kjeldahl nitrogen, and of lead, zinc, cadmium, and copper.

Maps 82 through 92 show the spatial variation in the mean sediment concentrations of 11 quality indicators. The maps show that the pollutant concentrations found were generally higher at the inner harbor stations than at the upstream stations.

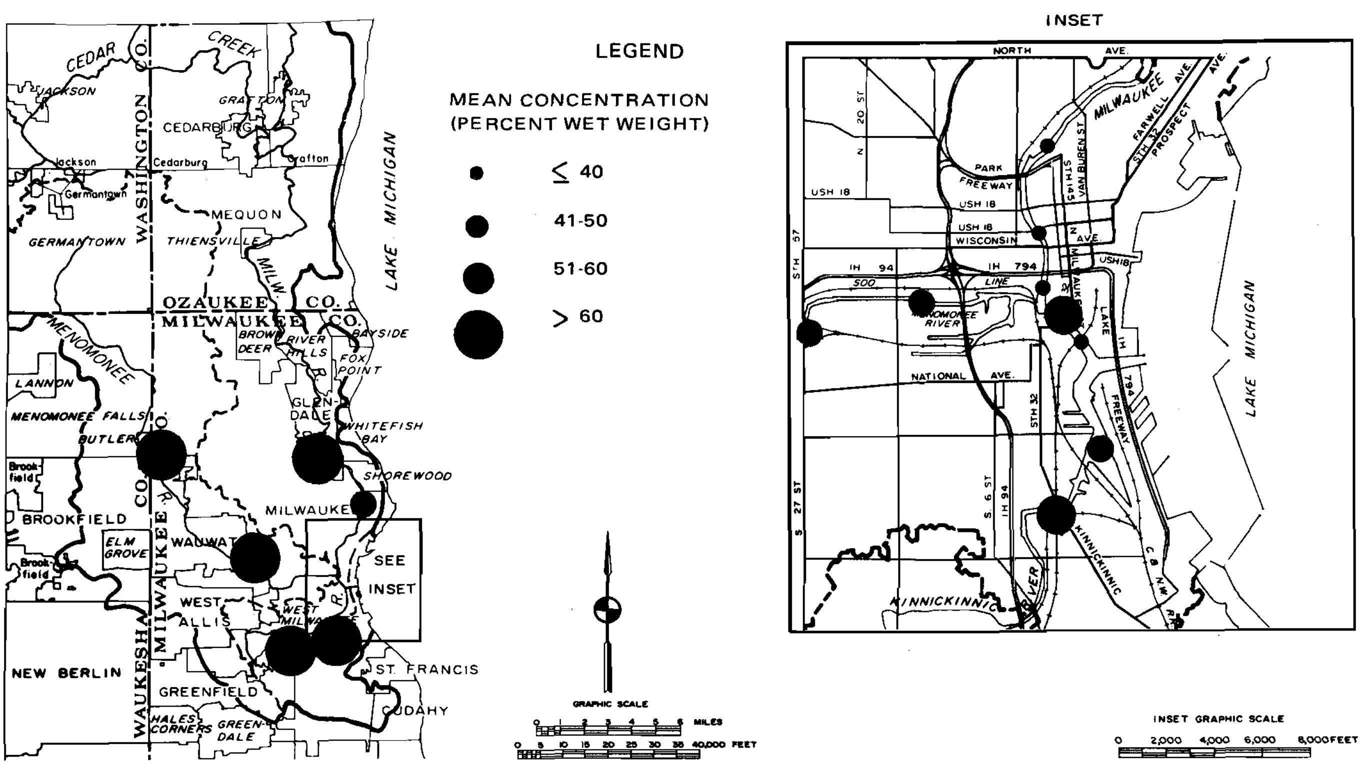
A summary of sediment concentrations of 117 organic toxic substances measured over the period 1975 through 1985 is set forth in Table 83. The locations of the sampling stations for organic toxic substances and metals are shown on Map 93. Mean concentrations of PCB's found in the bottom sediments are shown on Map 94. The concentrations of PCB's found in the sediments were highly variable, indicating that the sources of PCB contamination often have primarily localized effects.

Sediment quality guidelines established by the U. S. Environmental Protection Agency (EPA) for Great Lakes harbor sediments are set forth in Table 84. The guidelines can be used to classify sediments as nonpolluted, moderately polluted, or heavily polluted. A comparison of selected observed mean sediment core chemistry data set forth in Tables 82 and 83 to the EPA sediment quality guidelines is presented in Table 85. As shown in the table, the upstream sediments, except at Locust Street for the Milwaukee River, are generally moderately polluted with respect to most indicators. All upstream sediments, however, are heavily polluted with lead. The sediments in the Milwaukee River at Locust Street, within the North Avenue impoundment, were similar in quality to the sediments at the inner harbor stations, and may be classified as heavily polluted with respect to all indicators.

All inner harbor sediments were classified as heavily polluted. The least polluted inner harbor sediments were found at Broadway Street on the Milwaukee River, where the total phosphorus concentrations were representative of nonpolluted conditions, and the total volatile solids concentrations of moderately polluted conditions. The cadmium concentrations at Walnut Street, Wells Street, St. Paul Avenue, and Broadway Street on the Milwaukee River were not indicative of heavily polluted conditions. The average bottom sediments in the inner harbor were rated as heavily polluted for all sediment quality indicators except PCB's,

Map 82

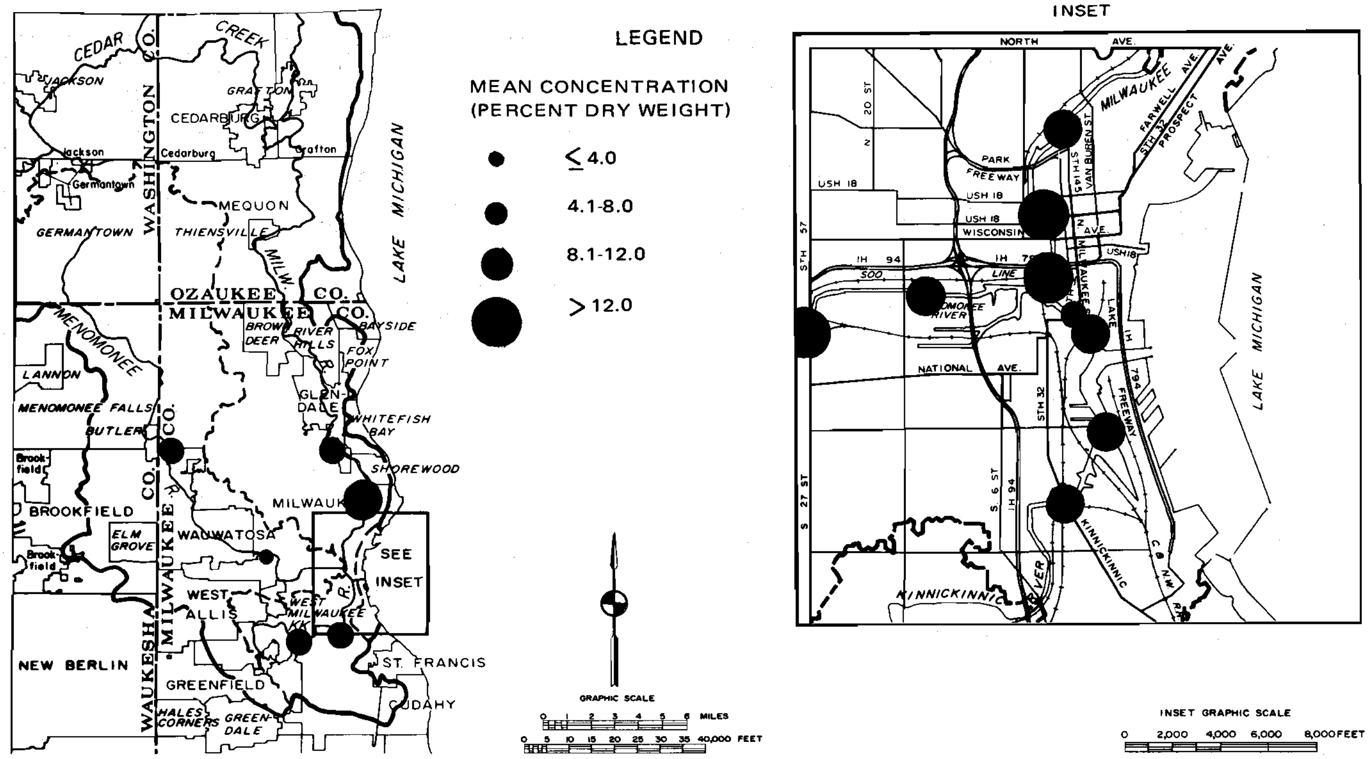
MEAN CONCENTRATIONS OF TOTAL SOLIDS IN THE BOTTOM SEDIMENTS: 1982-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Map 83

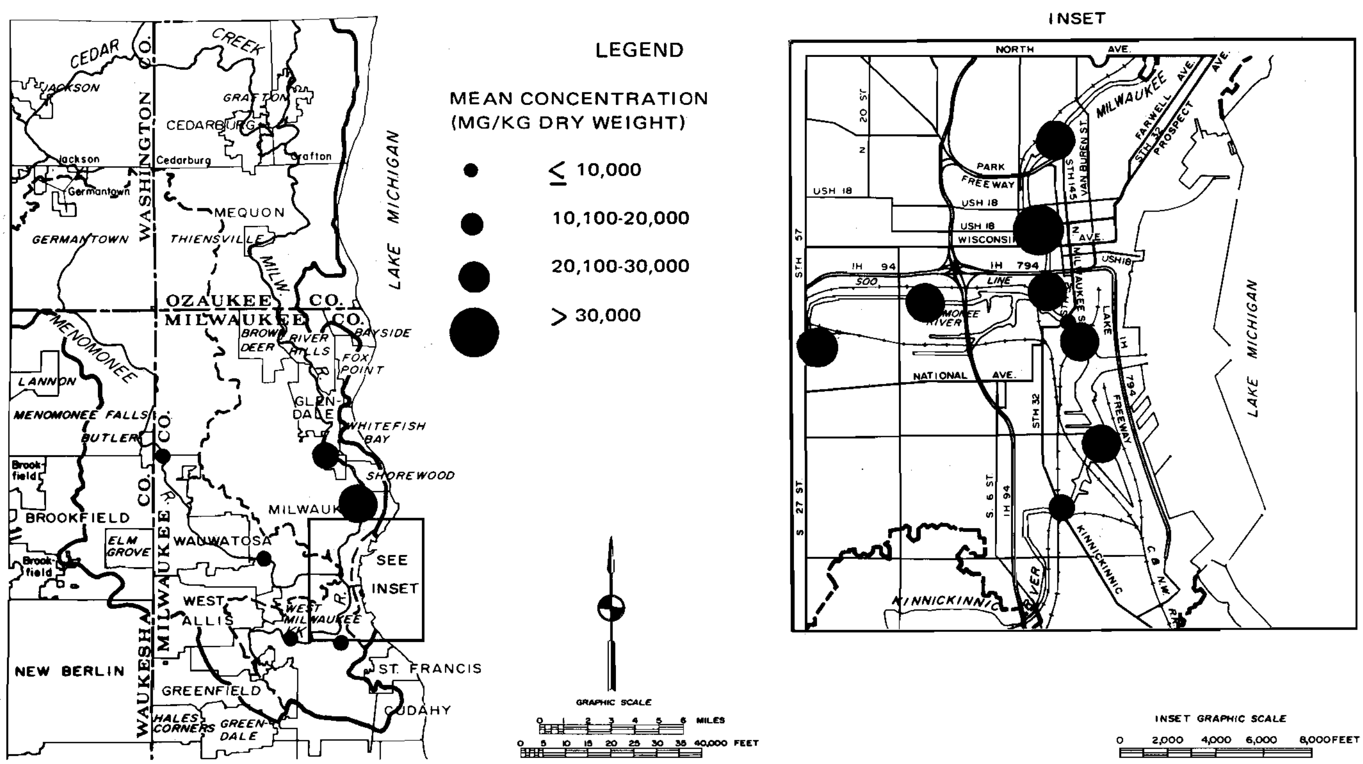
MEAN CONCENTRATIONS OF TOTAL VOLATILE SOLIDS IN THE BOTTOM SEDIMENTS: 1982-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Map 84

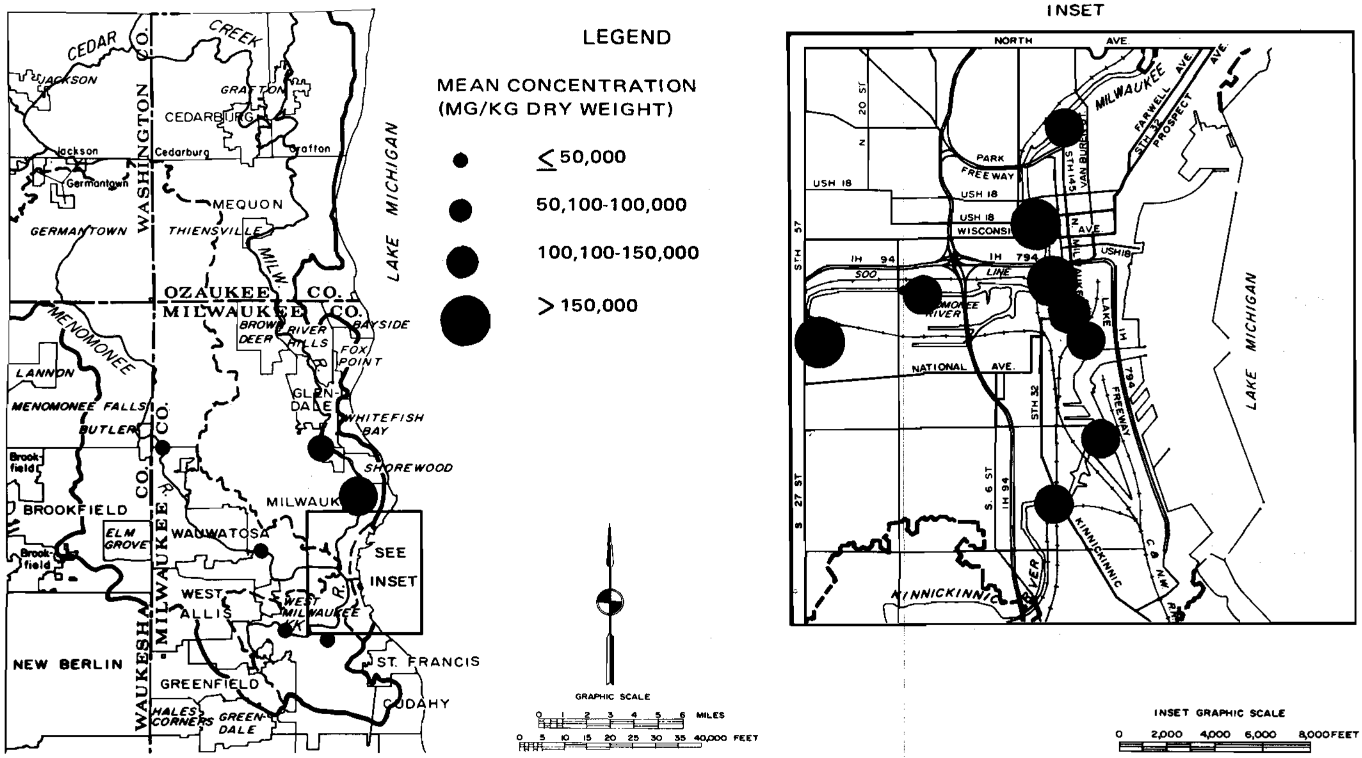
MEAN CONCENTRATIONS OF TOTAL ORGANIC CARBON IN THE BOTTOM SEDIMENTS: 1982-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Map 85

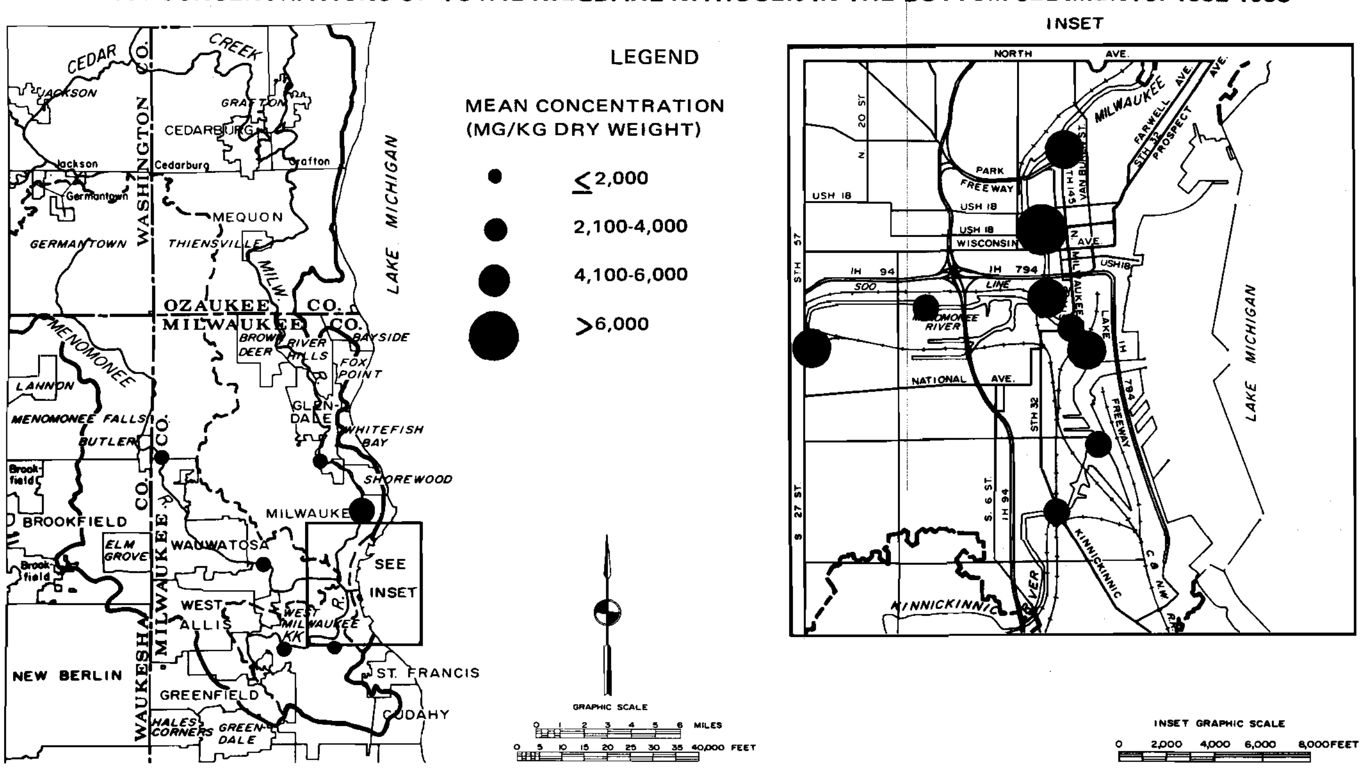
MEAN CONCENTRATIONS OF CHEMICAL OXYGEN DEMAND IN THE BOTTOM SEDIMENTS:1982-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Map 86

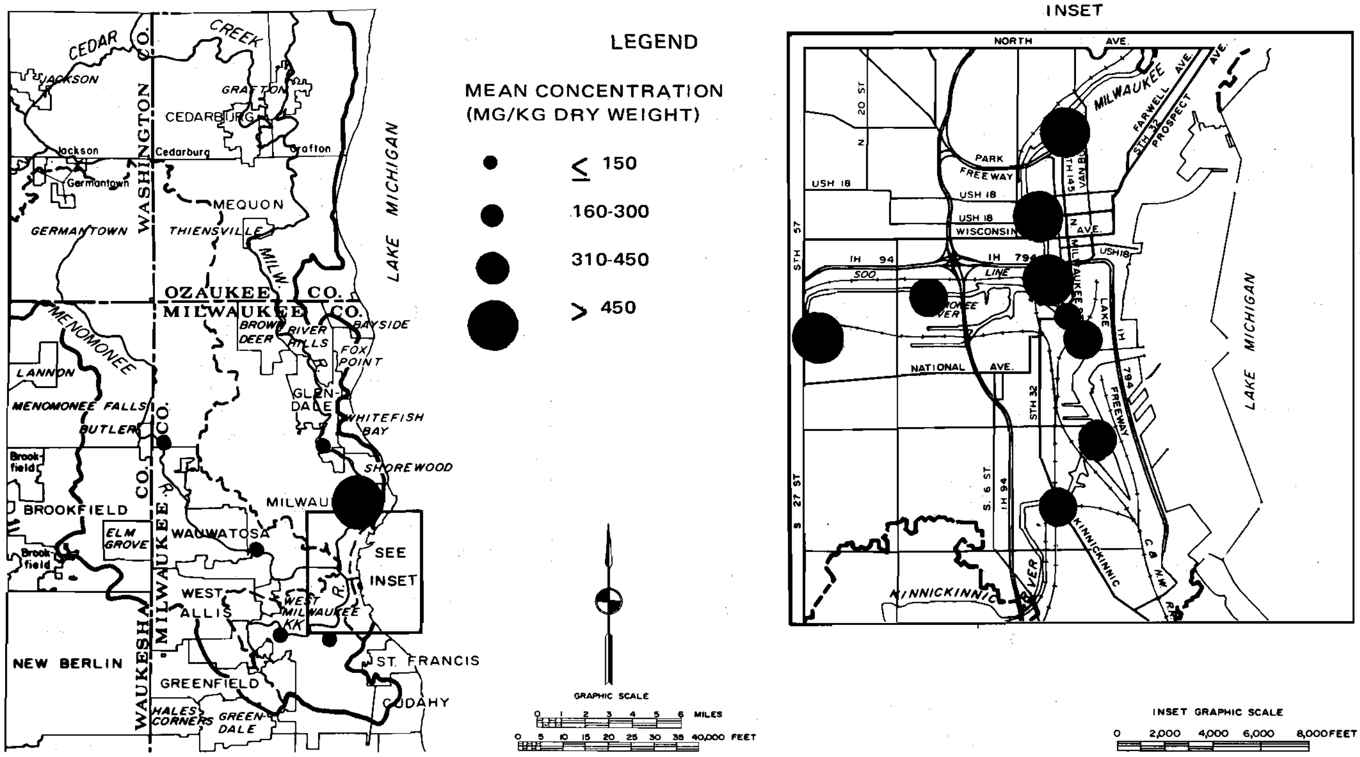
MEAN CONCENTRATIONS OF TOTAL KJELDAHL NITROGEN IN THE BOTTOM SEDIMENTS: 1982-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Map 87

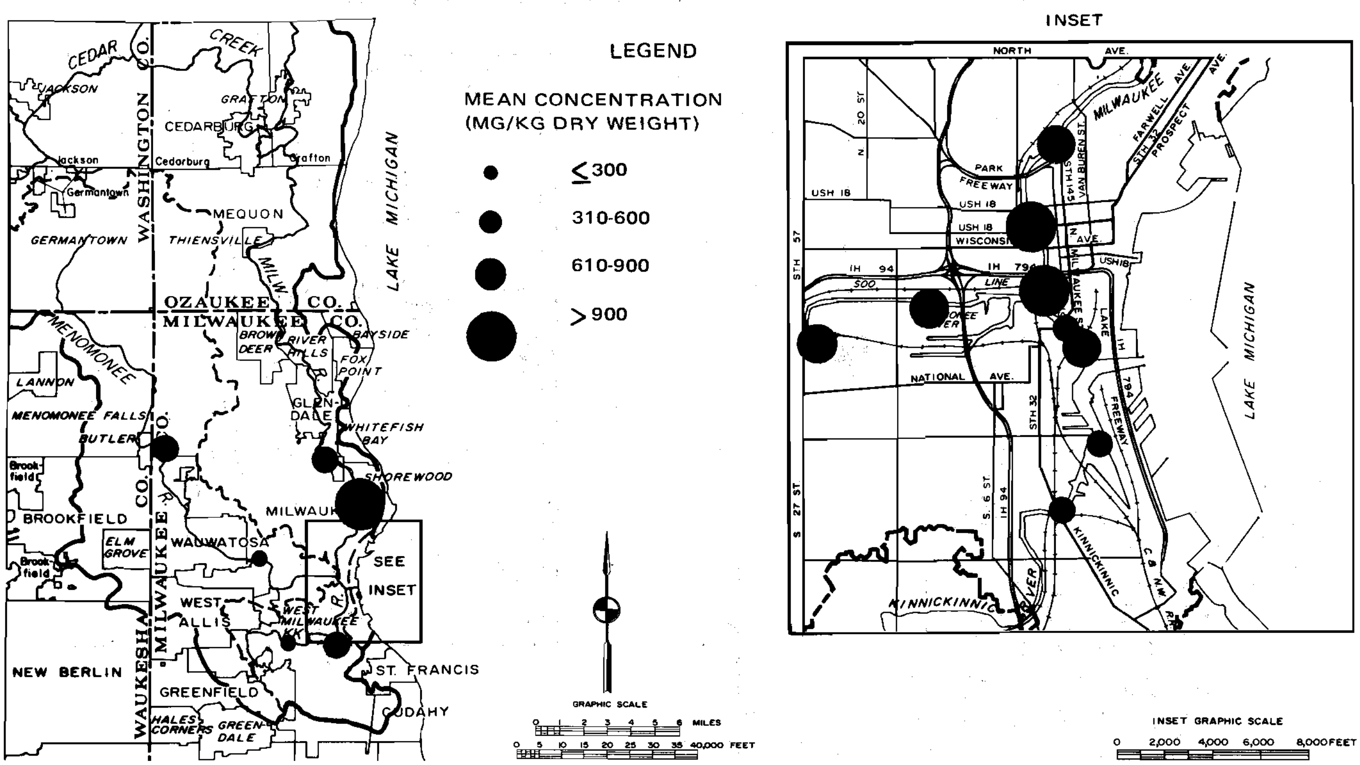
MEAN CONCENTRATIONS OF AMMONIA NITROGEN IN THE BOTTOM SEDIMENTS: 1982-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Map 88

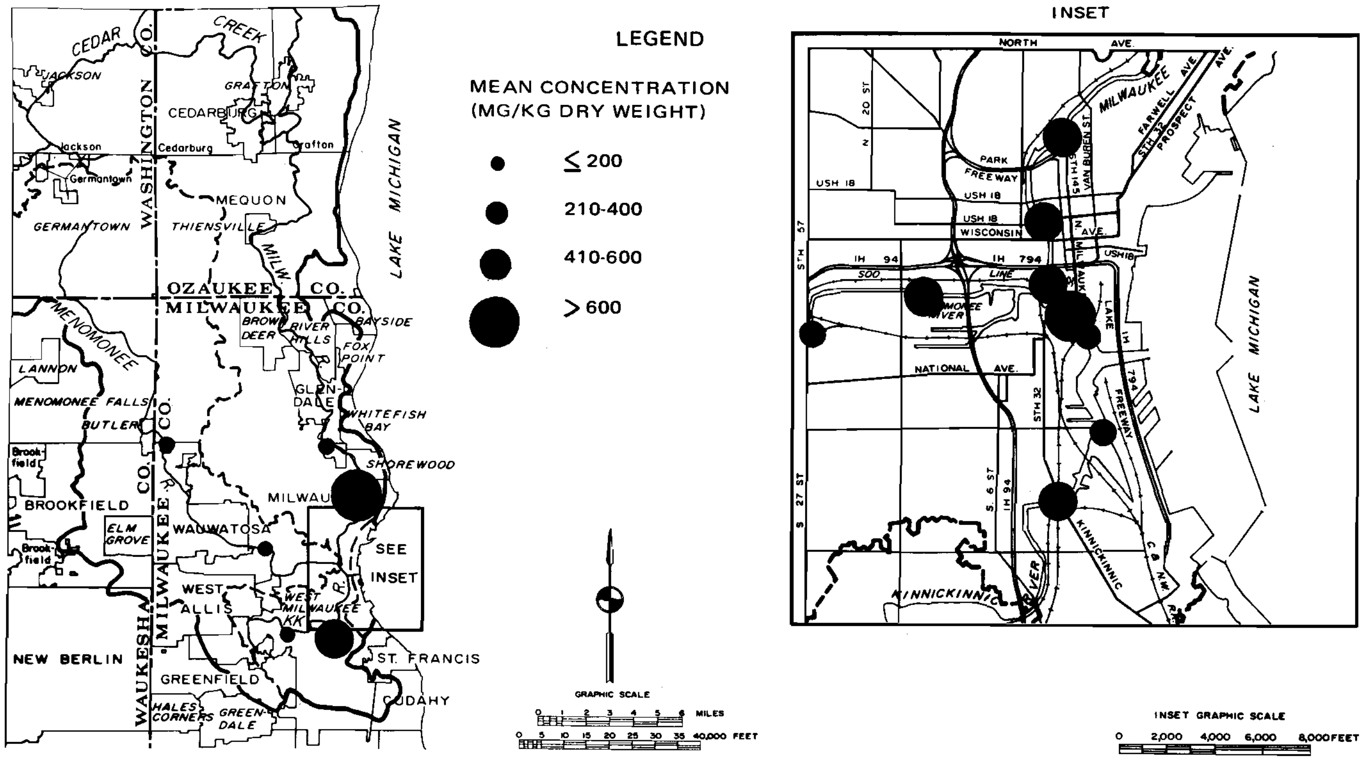
MEAN CONCENTRATIONS OF TOTAL PHOSPHORUS IN THE BOTTOM SEDIMENTS: 1982-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Map 89

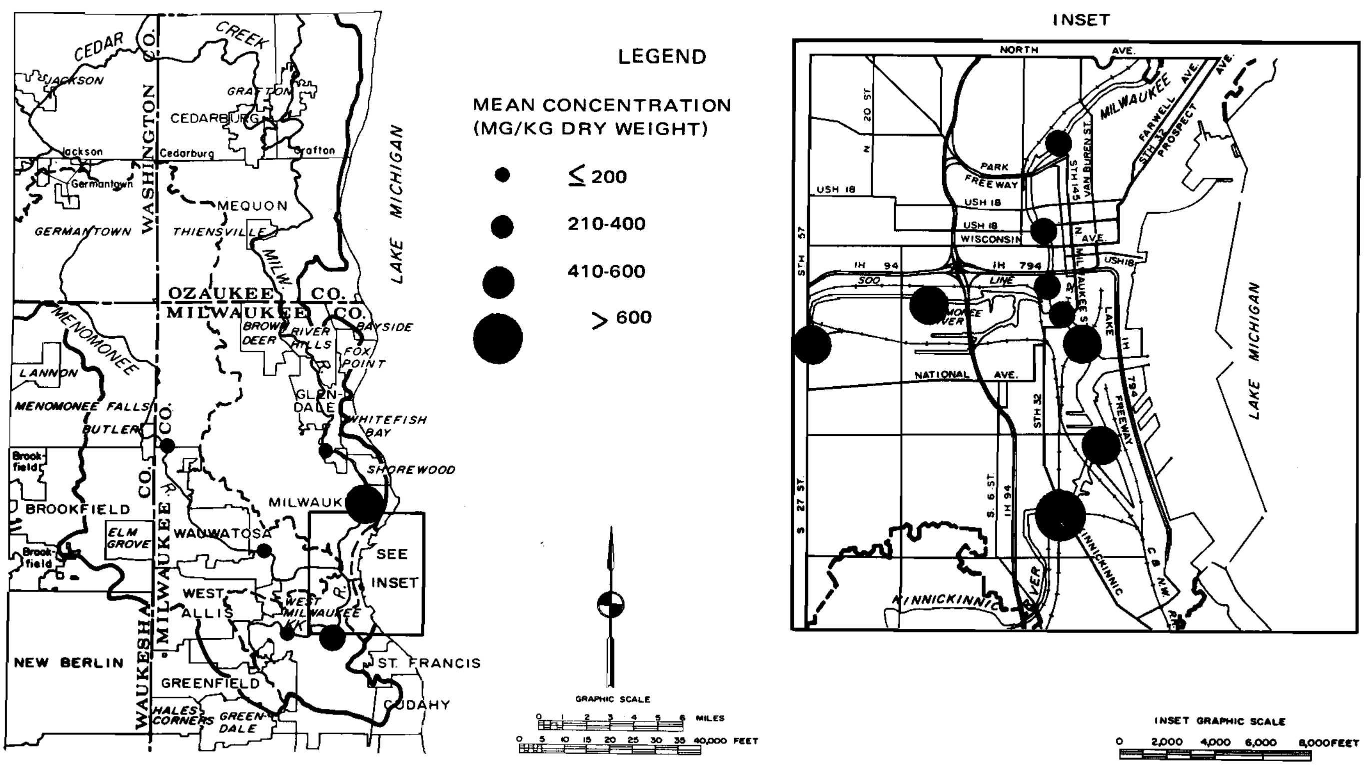
MEAN CONCENTRATIONS OF LEAD IN THE BOTTOM SEDIMENTS: 1982-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Map 90

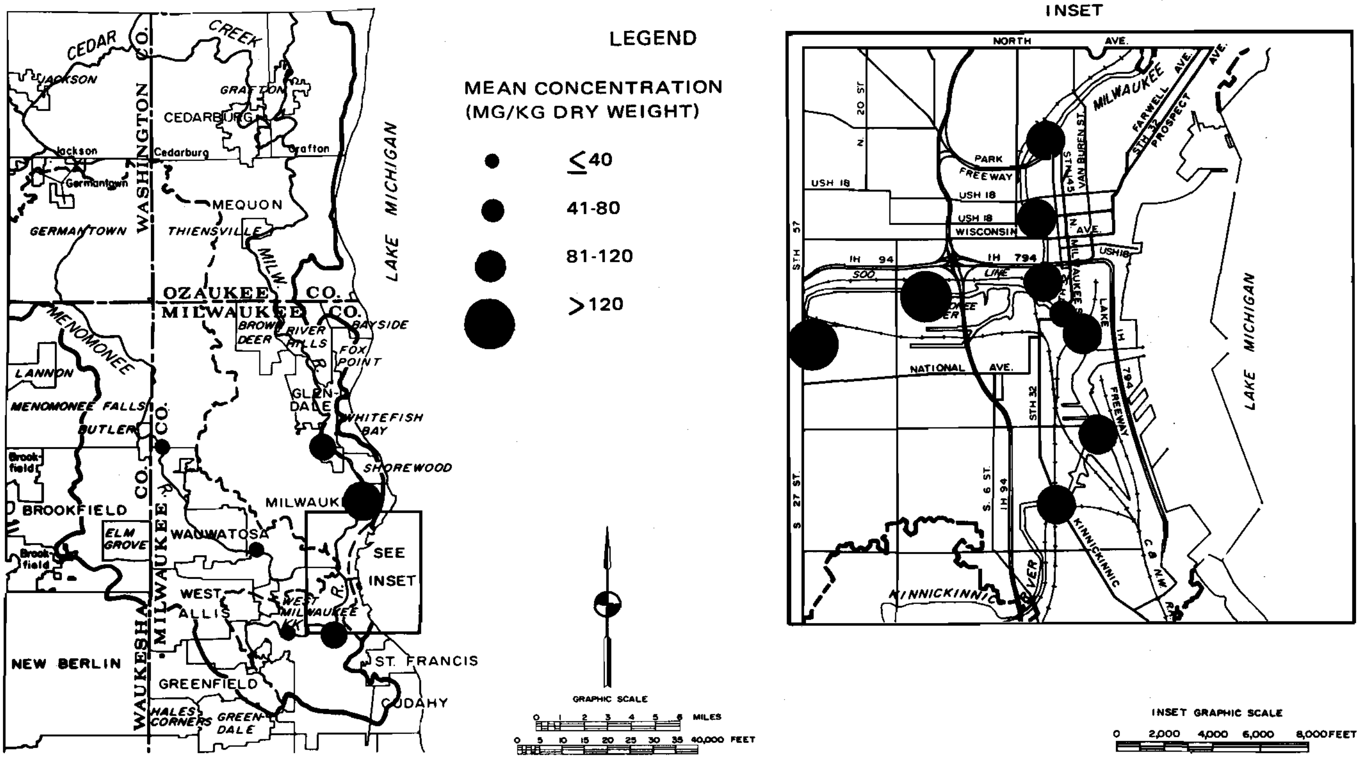
MEAN CONCENTRATIONS OF ZINC IN THE BOTTOM SEDIMENTS: 1982-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Map 91

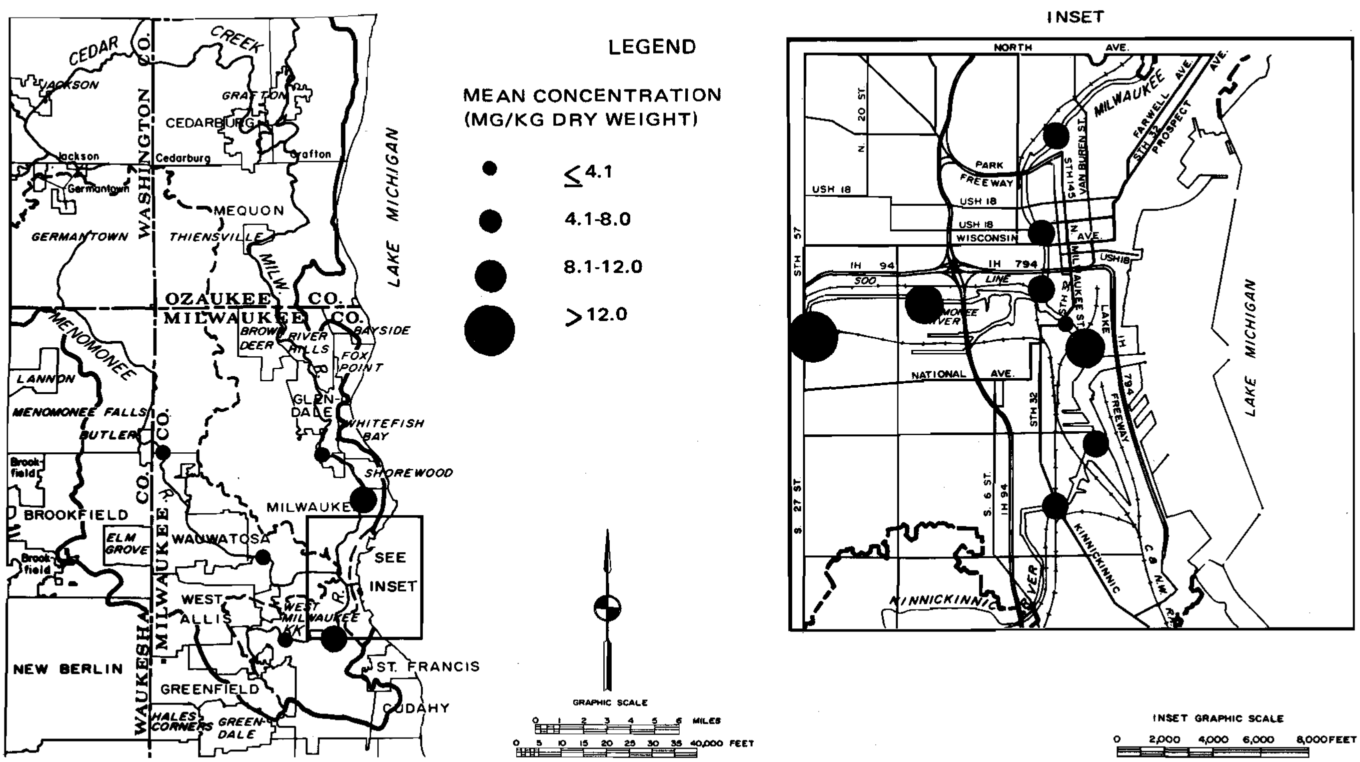
MEAN CONCENTRATIONS OF COPPER IN THE BOTTOM SEDIMENTS: 1982-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Map 92

MEAN CONCENTRATIONS OF CADMIUM IN THE BOTTOM SEDIMENTS: 1982-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Table 83

SUMMARY OF CONCENTRATIONS OF ORGANIC TOXIC SUBSTANCES IN THE BOTTOM SEDIMENTS: 1975-1985

Organic Substance	Upstream									Inner Harbor									Outer Harbor		
	Milwaukee River			Menomonee River			Kinnickinnic River			Milwaukee River			Menomonee River			Kinnickinnic River					
	Number of Samples	Minimum (mg/kg dry weight)	Maximum (mg/kg dry weight)	Number of Samples	Minimum (mg/kg dry weight)	Maximum (mg/kg dry weight)	Number of Samples	Minimum (mg/kg dry weight)	Maximum (mg/kg dry weight)	Number of Samples	Minimum (mg/kg dry weight)	Maximum (mg/kg dry weight)	Number of Samples	Minimum (mg/kg dry weight)	Maximum (mg/kg dry weight)	Number of Samples	Minimum (mg/kg dry weight)	Maximum (mg/kg dry weight)	Number of Samples	Minimum (mg/kg dry weight)	Maximum (mg/kg dry weight)
Alpha-BHC	2	<0.10	<0.10	--	--	--	--	--	--	11	<0.01	<1.0	23	<0.01	<1.0	18	<0.01	<1.0	9	<0.01	0.02
Acenaphthene	2	<0.10	3.9	--	--	--	--	--	--	6	<0.5	2.58	13	0.21	11.9	12	<0.5	4.01	6	<0.0025	<0.5
Acenaphthylene	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.5	0.56	13	<0.5	1.69	7	0.11	4.34	6	<0.0025	<0.5
Acrolein	2	<1.0	<1.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Acrylonitrile	2	<1.0	<1.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Aldrin	2	<0.10	<0.10	--	--	--	--	--	--	10	<0.01	<1.0	23	<0.01	0.07	17	<0.01	0.07	8	<0.01	0.06
Anthracene/Phenanthrene	--	--	--	--	--	--	--	--	--	6	<0.5	36.2	13	1.39	63.9	7	5.41	34.9	6	<0.0025	0.5
Benzene	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Benzidine	2	<0.10	<0.10	--	--	--	--	--	--	6	<2.0	<2.0	13	<2.0	<2.0	7	<2.0	<2.0	6	0.0025	<2.0
Benzo(a) Anthracene/ Chrysene	2	<0.10	70.0	--	--	--	--	--	--	6	5.4	82.9	13	2.05	117.0	7	9.4	76.0	6	0.0025	11.0
Benzo(a) Pyrene	2	<0.10	<0.10	--	--	--	--	--	--	6	5.42	22.4	13	1.12	35.4	7	2.23	41.3	5	0.0015	17.0
3, 4 Benzofluoranthene/ Benzo(k) Fluoranthene	2	<0.10	110.0	--	--	--	--	--	--	6	<0.5	37.4	13	2.44	40.9	7	3.32	50.9	6	0.0025	<0.5
Benzo(ghi) Perylene	2	<0.25	<0.25	--	--	--	--	--	--	6	<0.5	8.64	13	0.54	14.5	7	1.11	22.3	6	<0.5	0.001
Beta-BHC	2	<0.10	<0.10	--	--	--	--	--	--	11	<0.01	<1.0	23	<0.01	<1.0	16	<0.01	<1.0	9	<0.01	<0.1
Bis(2-chloroethyl) Ether	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
Bis(2-chloroethoxy) Methane	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	4	<0.1	<0.1
Bis(2-chloroisopropyl) Ether	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
Bis-(2-ethylhexyl) Phthalate	2	2.2	6.3	--	--	--	--	--	--	6	1.56	16.7	13	0.22	41.3	9	<0.1	<11.0	6	0.006	43.0
Bromoform	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Bromomethane	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
4-Bromophenyl Phenyl Ether	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	4	<0.1	<0.1
Butyl Benzyl Phthalate	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	0.55	13	<0.1	1.65	7	<0.1	0.97	6	<0.0025	<0.1
Carbon Tetrachloride	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Chlordane	18	<0.01	0.16	4	<0.01	<0.01	6	<0.01	0.01	15	< .01	<1.0	27	<0.01	<1.0	19	<0.01	<0.01	11	<0.01	0.44
Chlorobenzene	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Chloroethane	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2-Chloroethylvinyl Ether	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Chloroform	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Chloromethane	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2-Chloronaphthalene	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2	<0.0025	<0.0025
2-Chlorophenol	--	--	--	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.1	<1.25
4-Chlorophenyl Phenyl Ether	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
Chrysene	2	<0.10	70.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2	0.0025	0.004
Cyanide	2	<0.10	<0.10	--	--	--	--	--	--	18	0.2	1.3	31	0.2	11.5	27	0.2	36.7	10	<2.0	5.88
DDD	18	<0.01	0.21	4	0.01	0.56	6	<0.01	0.09	13	<0.01	0.5	24	<0.01	1.0	21	<0.01	0.5	9	<0.01	<1.0
DDE	18	<0.01	0.03	4	<0.01	0.02	6	<0.01	0.05	16	<0.01	0.1	24	<0.01	1.0	18	<0.01	<1.0	9	<0.01	0.33
DDT	18	<0.01	0.02	4	<0.01	1.7	6	<0.01	0.04	15	<0.01	0.1	24	<0.01	1.7	24	<0.01	0.1	9	<0.01	<1.0
Delta-BHC	2	<0.10	<0.10	--	--	--	--	--	--	9	<0.01	<0.12	23	<0.01	1.0	16	<0.01	<1.0	9	<0.01	0.12
Dibenzo(a,h) Anthracene	2	<0.25	<0.25	--	--	--	--	--	--	6	<0.5	6.25	13	1.33	11.4	7	0.7	20.6	6	<0.001	<0.5
Dibromochloromethane	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
1,3-Dichlorobenzene	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
1,4-Dichlorobenzene	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
1,2-Dichlorobenzene	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
3,3-Dichlorobenzidine	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
1,1-Dichloroethane	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
1,2-Dichloroethane	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
1,1-Dichloroethene	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
trans-1,2-Dichloroethene	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Dichloromethane	--	--	--	--	--	--	--	--	--	1	30.0	30.0	--	--	--	--	--	--	--	--	--
2,4-Dichlorophenol	--	--	--	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.1	<1.25
1,2-Dichloropropane	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
cis-1,3-Dichloropropene	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
trans-1,3-Dichloropropene	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Dieldrin	10	<0.01	<0.10	2	0.01	0.01	3	<0.01	<0.01	12	<0.01	<0.1	25	<0.01	<1.0	18	<0.01	<0.1	12	<0.005	0.01
Diethyl Phthalate	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	1.34	13	<0.1	8.6	7	<0.1	0.53	6	<0.0025	1.5
2,4-Dimethylphenol	--	--	--	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.1	<1.25
Dimethyl Phthalate	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
4,6-Dinitro-o-cresol	--	--	--	--	--	--	--	--	--	6	<0.2	<0.2	13	<0.2	<0.2	7	<0.2	<0.2	4	<0.2	<0.2
2,4-Dinitrophenol	--	--	--	--	--	--	--	--	--	6	<1.0	<1.0	13	<1.0	<1.0	7	<1.0	<1.0	6	<1.0	<5.0

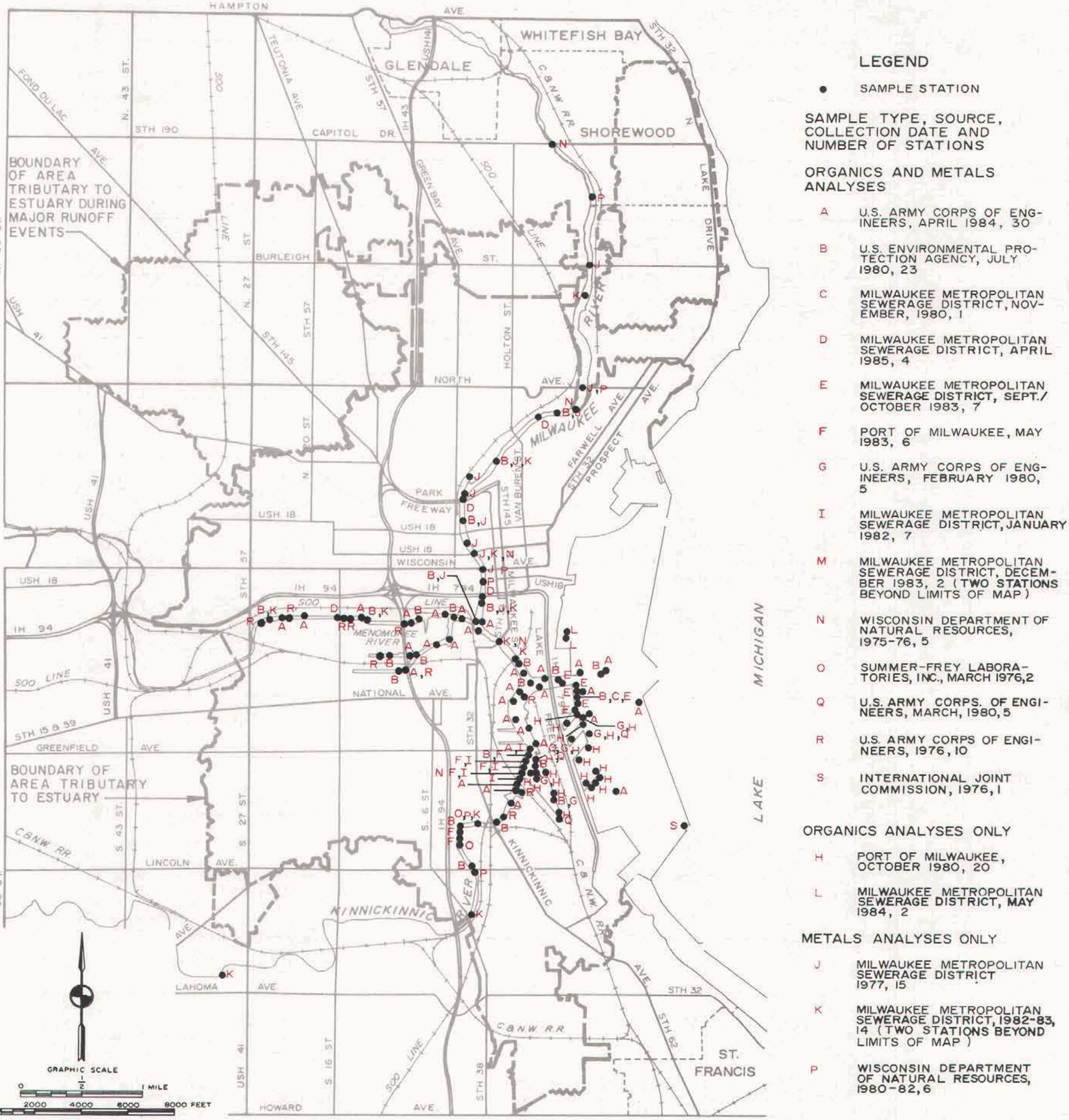
Table 83 (continued)

Organic Substance	Upstream: Milwaukee River Number of Samples	Upstream: Milwaukee River Minimum (mg/kg dry weight)	Upstream: Milwaukee River Maximum (mg/kg dry weight)	Upstream: Menomonee River Number of Samples	Upstream: Menomonee River Minimum (mg/kg dry weight)	Upstream: Menomonee River Maximum (mg/kg dry weight)	Upstream: Kinnickinnic River Number of Samples	Upstream: Kinnickinnic River Minimum (mg/kg dry weight)	Upstream: Kinnickinnic River Maximum (mg/kg dry weight)	Inner Harbor: Milwaukee River Number of Samples	Inner Harbor: Milwaukee River Minimum (mg/kg dry weight)	Inner Harbor: Milwaukee River Maximum (mg/kg dry weight)	Inner Harbor: Menomonee River Number of Samples	Inner Harbor: Menomonee River Minimum (mg/kg dry weight)	Inner Harbor: Menomonee River Maximum (mg/kg dry weight)	Inner Harbor: Kinnickinnic River Number of Samples	Inner Harbor: Kinnickinnic River Minimum (mg/kg dry weight)	Inner Harbor: Kinnickinnic River Maximum (mg/kg dry weight)	Outer Harbor Number of Samples	Outer Harbor Minimum (mg/kg dry weight)	Outer Harbor Maximum (mg/kg dry weight)
2,4-Dinitrotoluene	2	<0.10	<0.10	--	--	--	--	--	--	7	<0.2	0.41	13	<0.2	<0.2	7	<0.2	<0.2	6	<0.0025	4.3
2,6-Dinitrololuene	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
Di-n-butyl Phthalate	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	0.85	13	<0.1	2.1	7	<0.1	0.36	6	<0.0025	1.2
Di-n-Octyl Phthalate	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	0.26	13	<0.1	0.32	7	<0.1	0.52	6	<0.0025	<0.1
1,2-Diphenylhydrazine	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
Endosulfan I	2	<0.10	<0.10	--	--	--	--	--	--	11	<0.01	<0.1	23	<0.01	<1.0	16	<0.01	<0.1	9	<0.01	<0.1
Endosulfan II	2	<0.10	<0.10	--	--	--	--	--	--	11	<0.01	<0.1	23	<0.01	<1.0	16	<0.01	<0.1	9	<0.01	<0.1
Endosulfan Sulfate	2	<0.10	<0.10	--	--	--	--	--	--	5	<0.1	<0.1	10	<0.1	<1.0	9	<0.1	<1.0	7	<0.005	<0.1
Endrin	2	<0.10	<0.10	--	--	--	--	--	--	46	0.001	0.02	26	<0.004	0.001	7	<0.02	<0.02	11	<0.005	0.03
Endrin Aldehyde	2	<0.10	<0.10	--	--	--	--	--	--	5	<0.1	<0.1	10	<0.1	<1.0	9	<0.1	<0.1	7	<0.005	<0.1
Ethyl Benzene	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Fluorene	2	<0.10	13.0	--	--	--	--	--	--	6	<0.5	2.64	13	0.25	4.58	7	0.48	2.98	3	<0.0025	0.9
Fluoroanthene	2	0.29	41.0	--	--	--	--	--	--	6	6.0	64.7	13	2.65	84.6	9	6.0	66.9	6	<0.0025	13.0
Gamma-BHC	2	<0.10	<0.10	--	--	--	--	--	--	9	<0.01	0.03	23	<0.01	<1.0	16	<0.01	<1.0	9	<0.1	0.06
Heptachlor	2	<0.10	<0.10	--	--	--	--	--	--	9	<0.01	0.25	23	<0.01	<1.0	18	<0.01	0.25	10	<0.1	1.10
Heptachlor Epoxide	2	<0.10	<0.10	--	--	--	--	--	--	21	<0.01	<1.0	23	<0.01	0.04	16	<0.01	<1.0	10	<0.01	<1.0
Hexachlorobenzene	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
Hexachlorobutadiene	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
Hexachloroethane	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
Hexachlorocyclo-pentadiene	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
Indeno(1,2,3-cd) Pyrene	2	<0.25	<0.25	--	--	--	--	--	--	6	1.8	8.96	13	1.32	14.2	7	1.19	21.8	6	0.001	3.5
Isophorone	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
2-Methyl-4, 6-Dinitrophenol	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2	<5.0	<5.0
Methylene Chloride	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Naphthalene	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.5	2.09	1	<0.5	1.80	1	<0.5	24.3	6	<0.0025	<0.5
Nitrobenzene	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
2-Nitrophenol	--	--	--	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.1	<1.25
4-Nitrophenol	--	--	--	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.1	<1.25
n-Nitrosodimethylamine	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.1	<0.1
n-Nitrosodi-n-propylamine	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
N-nitrosodiphenylamine	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	1	0.6	0.6	2	<0.0025	0.0025
Parachlorometa Cresol	--	--	--	--	--	--	--	--	--	6	<0.1	<0.1	13	0.1	<0.1	7	<0.1	<0.1	4	<0.1	<0.1
Polychlorinated Biphenyls (PCB's)	16	<0.10	345.0	2	0.1	1.3	7	0.11	11.0	62	<0.0001	40.53	46	<0.08	17.0	139	<0.07	73.3	184	<0.1	68.2
Aroclor 1016	2	<0.10	<0.10	--	--	--	--	--	--	16	<0.01	<0.01	21	<0.01	<0.01	16	<0.01	<0.01	4	<0.01	<0.01
Aroclor 1221	2	<0.10	<0.10	--	--	--	--	--	--	16	<0.01	<0.01	21	<0.01	<0.01	16	<0.01	1.0	4	<0.01	<0.01
Aroclor 1232	2	<0.10	<0.10	--	--	--	--	--	--	16	<0.01	<0.01	21	<0.01	<0.01	16	<0.01	1.0	4	<0.01	<0.01
Aroclor 1242	2	<0.10	<0.10	--	--	--	--	--	--	56	<0.01	31.7	35	<0.01	17.0	101	<0.01	40.6	145	<0.01	68.2
Aroclor 1248	2	<0.10	3.4	--	--	--	--	--	--	21	0.04	32.0	30	0.60	8.5	28	<0.01	11.09	23	0.14	33.0
Aroclor 1254	2	<0.10	<0.10	--	--	--	--	--	--	59	<0.01	7.49	38	<0.01	3.6	40	<0.01	11.3	44	<0.2	15.3
Aroclor 1260	2	<0.10	<0.10	--	--	--	--	--	--	47	<0.01	2.29	34	<0.01	<2.0	57	<0.01	8.11	74	<0.01	8.11
Polychlorinated Dibenzodioxins	--	--	--	--	--	--	--	--	--	12	0.000013	0.009900	--	--	--	--	--	--	10	0.00143	0.01140
Polychlorinated Dibenzo-furans	2	<1.0	<1.0	--	--	--	--	--	--	13	0.000005	0.000920	--	--	--	--	--	--	10	0.00036	0.00187
Pentachlorophenol	--	--	--	--	--	--	--	--	--	6	0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.1	4.6
Phenanthrene	2	<0.10	100	--	--	--	--	--	--	--	--	--	--	--	--	2	1.6	1.8	5	<0.0025	3.3
Phenols	2	<0.330	<0.425	--	--	--	--	--	--	18	<0.06	1.56	31	<0.03	3.51	27	<0.09	1.72	13	0.9	2.63
Pyrene	2	0.21	79.0	--	--	--	--	--	--	6	6.5	48.9	13	1.83	88.0	7	7.96	48.1	6	<0.0025	13.0
2,3,7,8-Tetrachlorodi-benzo-p-dioxin	2	<1.0	<1.0	--	--	--	--	--	--	7	<0.000008	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	4	<0.1	<0.1
1,1,2,2-Tetrachloroethane	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Tetrachloroethene	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
1,2,4-Trichlorobenzene	2	<0.10	<0.10	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.0025	<0.1
1,1,1-Trichloroethane	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
1,1,2-Trichloroethane	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Trichlorofluoromethane	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2,4,6-Trichlorophenol	--	--	--	--	--	--	--	--	--	6	<0.1	<0.1	13	<0.1	<0.1	7	<0.1	<0.1	6	<0.1	<1.25
Toluene	2	<0.10	<0.10	--	--	--	--	--	--	1	6.0	6.0	--	--	--	--	--	--	--	--	--
Trichloroethene	2	<0.10	<0.10	--	--	--	--	--	--	1	1.0	1.0	--	--	--	--	--	--	--	--	--
Toxaphene	2	<0.10	<0.10	--	--	--	--	--	--	10	<0.01	<10.0	22	<0.01	<10.0	7	<0.01	2.1	10	<0.01	<10.0
Vinyl Chloride	2	<0.10	<0.10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Source: U. S. Environmental Protection Agency, U. S. Army Corps of Engineers, Milwaukee Metropolitan Sewerage District, Port of Milwaukee, and SEWRPC.

Map 93

SEDIMENT SAMPLING STATIONS FOR ORGANIC TOXIC SUBSTANCES AND METALS: 1975-1985

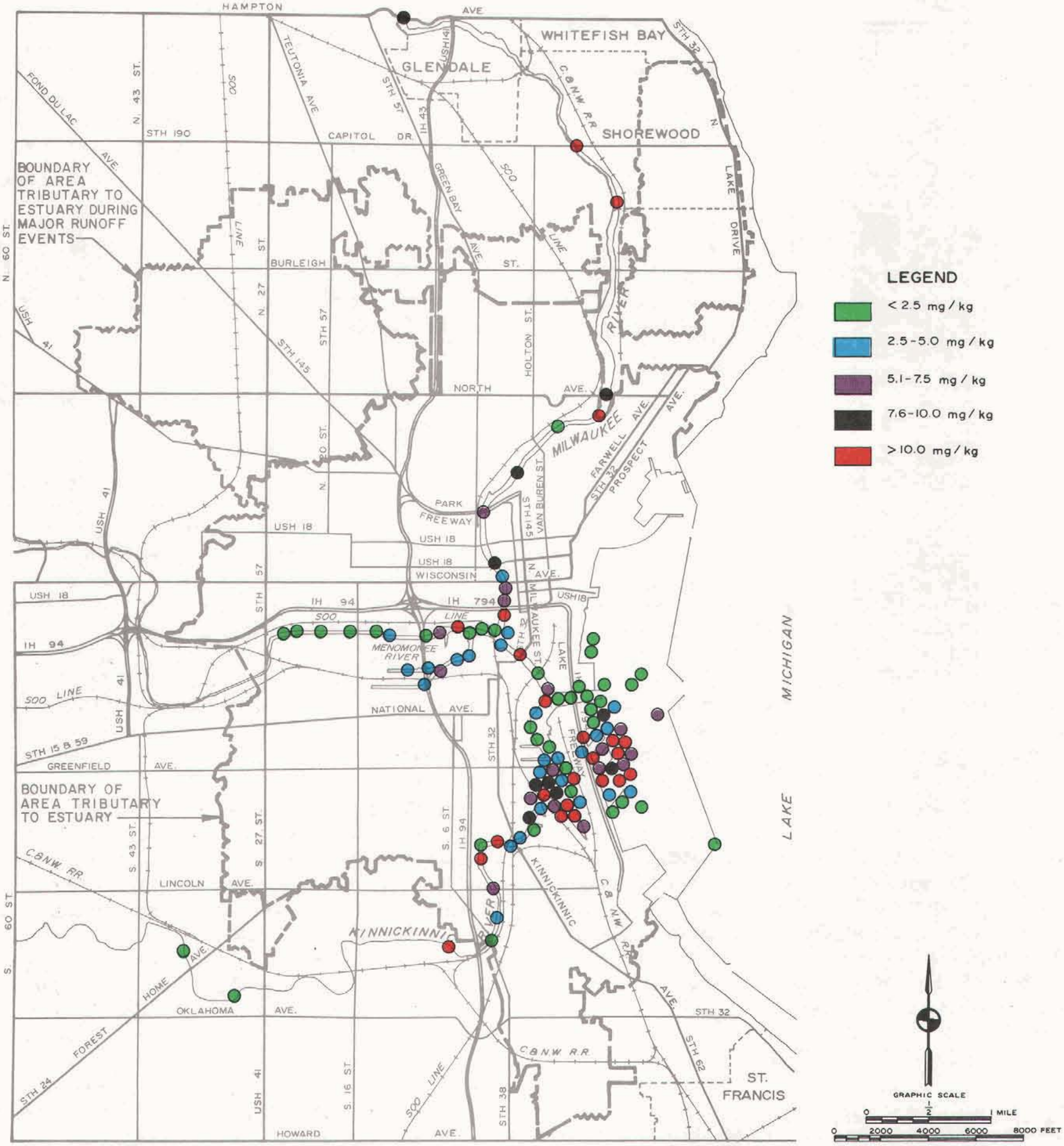


Sediment samples taken at a total of 108 stations were analyzed for both organic toxic substances and metals; samples taken at 28 stations were analyzed for only organic toxic substances; and samples taken at 29 stations were analyzed for only metals. The specific sources of these data are set forth in Appendix B. The data for organic toxic substances collected at these stations are summarized in Table 83.

Source: U. S. Environmental Protection Agency, U. S. Army Corps of Engineers, Milwaukee Metropolitan Sewerage District, Port of Milwaukee, and SEWRPC.

Map 94

MEAN CONCENTRATIONS OF PCB'S IN THE BOTTOM SEDIMENTS: 1975-1985



Concentrations of polychlorinated biphenols(PCB's) in the bottom sediments of the inner and outer harbors were measured at 112 stations over the period of 1975 through 1985. The concentrations of PCB's found in the sediments were highly variable, indicating that the sources of PCB contamination often have highly localized effects.

Source: U. S. Environmental Protection Agency, U. S. Army Corps of Engineers, Milwaukee Metropolitan Sewerage District, Port of Milwaukee, and SEWRPC.

Table 84

U. S. EPA SEDIMENT QUALITY GUIDELINES FOR GREAT LAKES HARBOR SEDIMENTS

Indicator	Sediment Quality Classification[a]		
	Nonpolluted	Moderately Polluted	Heavily Polluted
Volatile Solids (percent)	<5	5 - 8	>8
Chemical Oxygen Demand	<40,000	40,000 - 80,000	>80,000
Total Kjeldahl Nitrogen	<1,000	1,000 - 2,000	>2,000
Total Phosphorus	<420	420 - 650	>650
Ammonia Nitrogen	<75	75 - 200	>200
Oil and Grease	<1,000	1,000 - 2,000	>2,000
Lead	<40	40 - 60	>60
Zinc	<90	90 - 200	>200
Iron	<17,000	17,000 - 25,000	>25,000
Nickel	<20	20 - 50	>50
Manganese	<300	300 - 500	>500
Cadmium	--[b]	--[b]	>6
Arsenic	<3	3 - 8	>8
Chromium	<25	25 - 75	>75
Copper	<25	25 - 50	>50
Barium	<20	20 - 60	>60
Cyanide	<0.10	0.10 - 0.25	>0.25
Mercury	--[b]	--[b]	>1
Total PCB's	--[b]	--[b]	>10

[a] *All units in mg/kg unless otherwise noted.*

[b] *Lower limits not established.*

Source: U. S. Environmental Protection Agency, Guidelines for the Pollution Classification of Great Lakes Harbor Sediments, April 1977.

which were variable but generally less than the 10 milligrams per kilogram (mg/kg) guideline for heavily polluted classification.

A summary of selected sediment quality conditions in the outer harbor measured over the period 1980 through 1984 is set forth in Table 86, along with a comparison of the data to the EPA sediment quality guidelines. As shown in the table, the outer harbor sediments are generally heavily polluted with respect to most indicators. However, concentrations of volatile solids, chemical oxygen demand, and total Kjeldahl nitrogen, which were indicative of heavy pollution in the inner harbor, were indicative of moderate pollution in the outer harbor. PCB concentrations within the outer harbor were generally greater than within the inner harbor, and exceeded the 10 mg/kg guideline for a heavily polluted classification.

Sediment-Water Interactions

When organic matter decomposes in the bottom sediments under anaerobic conditions, reduced end-products are released to the sediment pore water and subsequently transported across the sediment-water interface via diffusion and gas ebullition. This relatively slow process of decomposition and stabilization of organic material is referred to as diagenesis. The associated material fluxes can be significant in water bodies, and must be quantified if a meaningful assessment of the water quality of the inner harbor and outer harbor is to be made.

Estimation of Particulate Organic Carbon Loads to the Estuary: The rate of release of decomposition end-products from sediments is a function of the antecedent history of deposition. Previously deposited refractory material which has stabilized for a period of six months to a year or longer continues to slowly decompose and release a portion of the total diagenetic flux from the sediment. As such, the total diagenesis represents the integrated effect of the decomposition of sedimentary organic material that has stabilized to varying degrees.

An average annual basis was, therefore, used to assess the relative magnitudes of combined sewer overflow and upstream loadings on the Milwaukee River estuary. Estimates of particulate organic carbon loadings from combined sewer overflows were based on the estimated volume of combined sewer overflow entering the estuary in conjunction with a particulate organic carbon concentration determined by analyses of lab samples of Jones Island wastewater treatment plant wet-weather influent. Upstream particulate organic carbon loadings were calculated from an analysis of the baseline sampling data, and reduced by the estimated upstream combined sewer overflow loadings to determine the particulate organic carbon loadings from detritus and algae, as described below.

Determination of the total volume of combined sewer overflow from both upstream and direct discharges to the inner harbor was based on detailed land use information compiled by the Regional Planning Commission for each of the drainage areas tributary to the combined sewer outfalls. The land use information was used to determine the proportion of each drainage area in impervious surface. A modified version of the STORM model was then used to calculate the annual combined sewer overflow volume. The quality of combined sewer overflow discharges was estimated using grab samples of influent to the Jones Island wastewater treatment plant during wet-weather conditions.

Upstream particulate organic carbon loadings, which include combined sewer overflow discharges upstream of the inner harbor, were estimated from log-probability plots of volatile suspended solids loads computed using the 1981 through 1983 baseline sampling data and average daily river flows.

Table 85

COMPARISON OF MEAN SEDIMENT CORE CHEMISTRY TO U. S. ENVIRONMENTAL PROTECTION AGENCY SEDIMENT QUALITY GUIDELINES IN THE UPSTREAM AND INNER HARBOR STATIONS

Sampling Station	Total Volatile Solids	Chemical Oxygen Demand	Total Kjeldahl Nitrogen	Ammonia Nitrogen	Total Phosphorus	Lead	Zinc	Copper	Cadmium	Arsenic	PCB's[a]	Overall Sediment Quality
Upstream Stations												
Milwaukee River												
At Hampton Avenue	M	M	M	N	M	H	M	M	--[b]	--	--[d]	M
At Locust Street	H	H	H	H	H	H	H	H	H	--	H	H
Menomonee River												
At Hampton Avenue	N	N	M	M	N	H	M	M	--[b]	--	--[d]	M
At Hawley Road	N	N	N	N	N	H	M	N	--[b]	--	--[d]	M
Kinnickinnic River												
At Wilson Park Avenue	M	N	N	N	N	H	M	M	--[b]	--	--[d]	M
At Chase Avenue	M	M	M	M	N	H	H	H	--[b]	--	--[d]	M
Average-Upstream	M	M	M	M	M	H	H	M	--[b]	--[c]	--[d]	M
Inner Harbor Stations												
Milwaukee River												
At Walnut River	H	H	H	H	H	H	H	H	--[b]	H	--[d]	H
At Wells Street	H	H	H	H	H	H	H	H	--[b]	H	--[d]	H
At St. Paul Avenue	H	H	H	H	H	H	H	H	--[b]	H	H	H
At Broadway Street	M	H	H	H	N	H	H	H	--[b]	H	H	H
At C&NW Railway Bridge	H	H	H	H	H	H	H	H	H	H	--[d]	H
Menomonee River												
At Falk Corporation Dam	H	H	H	H	H	H	H	H	H	H	--[d]	H
At Muskego Avenue	H	H	H	H	H	H	H	H	H	H	--[d]	H
Kinnickinnic River												
At S. 1st Street	H	H	H	H	H	H	H	H	H	H	H	H
Average-Inner Harbor	H	H	H	H	H	H	H	H	H	H	--[d]	H

NOTE: H - Heavily polluted
M - Moderately polluted
N - Nonpolluted

[a] *Comparison provided using data from nearest location if sample not available at specified sampling station.*

[b] *These sediments were not heavily polluted with cadmium. The EPA has not established moderately polluted or nonpolluted criteria for cadmium.*

[c] *No upstream sediment samples were analyzed for arsenic.*

[d] *These sediments were not heavily polluted with PCB's. The EPA has not established moderately polluted or nonpolluted criteria for PCB's.*

Source: SEWRPC.

The volatile suspended solids were converted to particulate organic carbon using an assumed carbon content of 40 percent within the volatile suspended solids. Table 87 summarizes average annual inner harbor particulate organic carbon loadings from upstream and direct sources to each river. Overall, combined sewer overflow inputs account for 60, 72, and 93 percent of the particulate organic carbon loadings to the estuarine portions of the Milwaukee, Menomonee, and Kinnickinnic Rivers, respectively. Combined sewer overflows account for two-thirds of the total particulate organic carbon loading to the inner harbor. These data indicate that combined sewer overflows are the primary source of organic material loadings to the inner harbor.

Table 86

COMPARISON OF SEDIMENT QUALITY CONDITIONS TO U. S. ENVIRONMENTAL PROTECTION AGENCY SEDIMENT QUALITY GUIDELINES IN THE OUTER HARBOR: 1980-1984

Sediment Quality Indicator	Number of Samples	Minimum (mg/kg)	Mean (mg/kg)	Maximum (mg/kg)	EPA Sediment Quality Classification[a]
Volatile Solids (percent)	11	2	6	17	M
Chemical Oxygen Demand	14	6,800	48,900	74,000	M
Total Kjeldahl Nitrogen	12	313	1,100	23,200	M
Total Phosphorus	9	320	2,260	8,250	H
Ammonia Nitrogen	9	90	270	460	H
Lead	14	20	140	410	H
Zinc	14	80	450	1,950	H
Cadmium	11	4	18	74	H
Arsenic	15	2.4	11.3	45.2	H
Copper	11	22	90	293	H
Total PCB's	133	<0.10	10.7	73.3	H

NOTE: H - Heavily polluted
M - Moderately polluted
N - Nonpolluted

[a] *Based on mean concentrations.*

Source: U. S. Environmental Protection Agency, U. S. Army Corps of Engineers, Milwaukee Metropolitan Sewerage District, and SEWRPC.

Table 87

AVERAGE ANNUAL CARBON BALANCE LOADING ESTIMATES TO THE INNER HARBOR: 1981-1983

River	Particulate Organic Carbon Loading (1,000 pounds/day)								
	Upstream								
	Non-CSO	Percent of Total	CSO	Percent of Total	Direct CSO to Inner Harbor	Percent of Total	Total CSO	Percent of Total	Total Loading
Milwaukee	5.95	40	3.97	27	4.86	33	8.83	60	14.78
Menomonee	1.85	28	1.33	21	3.34	51	4.67	72	6.52
Kinnickinnic	0.23	7	0.45	13	2.82	80	3.27	93	3.50
Total	8.03	32	5.75	23	11.02	44	16.77	67	24.80

NOTE: CSO - Combined Sewer Overflow.

Source: HydroQual, Inc.

The relative magnitude of upstream carbon sources—primarily in the form of algae and detritus—is, however, an important consideration when examining ways in which to reduce particulate organic carbon loadings. Table 88 presents the relative contribution of particulate organic carbon loadings to each of the rivers from combined sewer overflows, and from algal and detrital sources. A carbon to chlorophyll ratio of 40 was used to convert chlorophyll-a loadings to carbon loadings. The table indicates that algae account for about 39 percent of the particulate organic carbon loading to the Milwaukee River, 12 percent to the Menomonee River, and 6 percent to the Kinnickinnic River. However, as described below, consideration must also be given to the portion of algal carbon which settles from the water column.

Table 88

RELATIVE CONTRIBUTION OF UPSTREAM PARTICULATE ORGANIC CARBON SOURCES TO THE INNER HARBOR

River	Relative Contribution (percent)		
	Combined Sewer Overflow	Algae	Detritus
Milwaukee	39	39	22
Menomonee	43	12	45
Kinnickinnic. . . .	66	6	28
Total	42	31	27

Source: HydroQual, Inc.

Particle Settling and the Analysis of Sediment Trap Data: Once particulate matter enters the estuary it can either settle from the water column or be transported through the system to the outer harbor and Lake Michigan. Sediment trap data from four inner harbor and three upstream river stations were used to measure gross particle settling rates. The total suspended solids flux and the particle settling velocities summarized in Table 89 are based upon a statistical analysis of sediment trap accumulations. Short-term sedimentation rates were calculated using sediment trap analyses and solids balance analyses conducted by the Milwaukee Metropolitan Sewerage District and HydroQual, Inc. The estimated short-term sedimentation rates are compared to long-term sedimentation rates estimated by the Regional Planning Commission using the sounding records from the U. S. Army Corps of Engineers shown in Figure 146. As shown in the figure, the short-term sedimentation rate estimates range from 0 to 50 inches per year, while the long-term rates range from 0 to 43 inches per year. The long-term sedimentation rate analysis also indicated that some stations experienced a net loss of sediment.

If resuspension of sediments occurs, net sedimentation is reduced, and, hence, the short-term estimates represent an upper bound on inner harbor sedimentation rates during the period of record. Studies conducted in August 1983 indicate that an average of 0.10 inch of sediment, at most, could have been resuspended during a one-week period. If surficial material were actually resuspended more than once, the depth of material interacting with the water column would be even less. Additionally, since a portion of the accumulated material can be attributed to combined sewer overflow and upstream sources, even less can be attributed to scour of in-place sediments. A review of the correlation between rainfall and trap accumulation data suggested that a significant portion of accumulated material may, in fact, be accounted for by material from exogenous sources, rather than resuspended inner harbor sediments.

Particle settling rates were assigned to each of the carbon sources in the diagenesis model in order to quantify the importance of sedimentation. Quiescent settling tests performed with sediment solids from two inner harbor stations indicated that 90 percent of the sedimentary material in the inner harbor settled at a velocity greater than 33 feet per day. Sediment trap tests conducted by the Milwaukee Metropolitan Sewerage District indicated median settling velocities of 33 to 60 feet per day at four inner harbor stations. In order to compute organic carbon loadings to the bottom sediments, combined sewer overflow particles were assigned a median settling velocity of 33 feet per day.[10] A typical literature value of 0.3 foot per day was assigned to algae and detritus.[11] Hence, several order-of-magnitude differences in settling rates for combined sewer overflow solids and for algal and detritus solids were indicated.

[10] *U. S. Environmental Protection Agency, Revised Section 301(H) Technical Support Document, November 1982.*

[11] *Tetra Tech, Inc., Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling, NTISPB-290 938, December 1978.*

Table 89

SUMMARY OF 1983 SEDIMENT TRAP SUSPENDED SOLIDS DATA

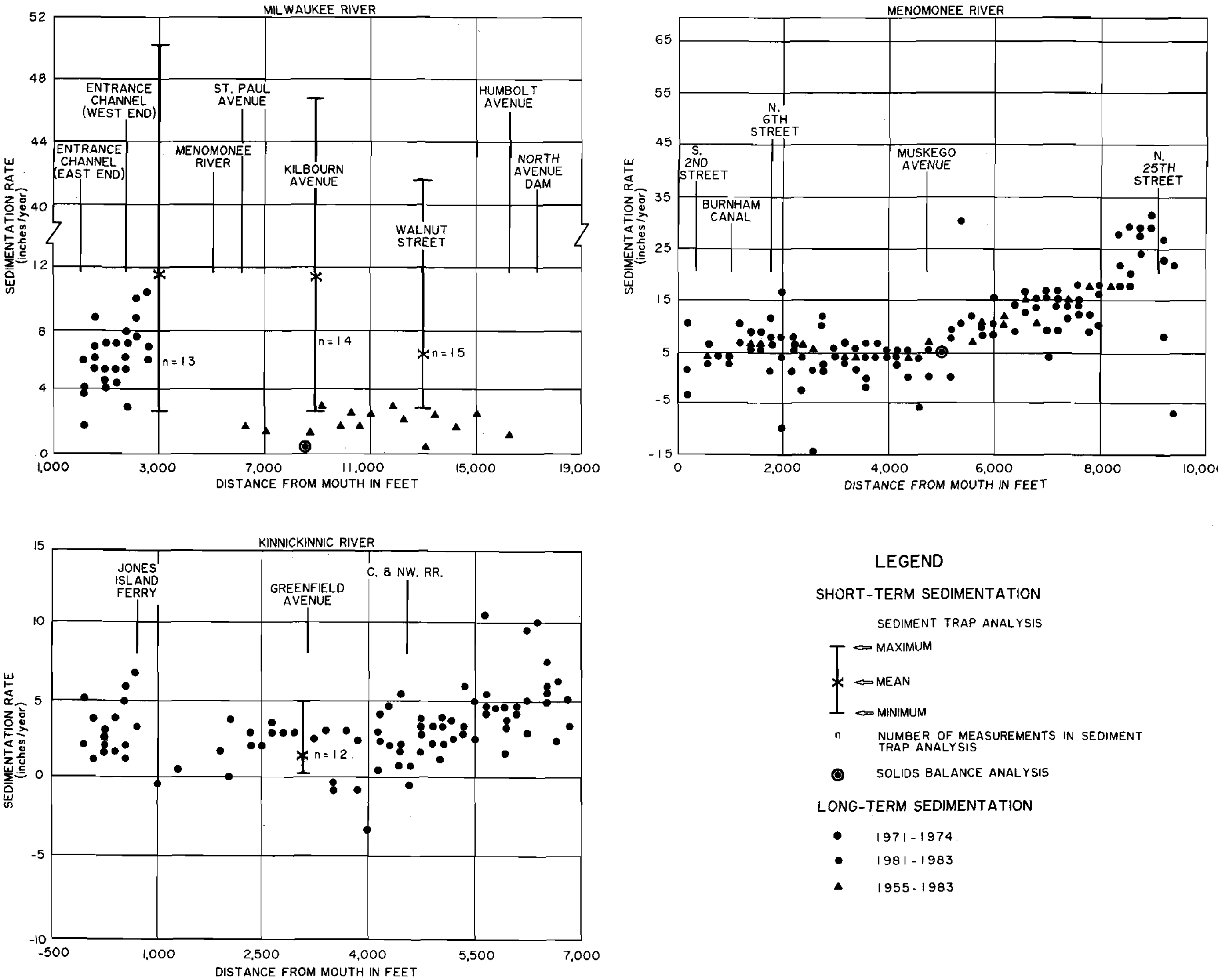
Sampling Station	Total Suspended Solids Flux			Particle Settling Velocity	
	Number of Samples	Mean (grams/ meter^2/day)	Coefficient of Variation	Mean (feet/day)	Coefficient of Variation
Upstream Stations					
Milwaukee River					
At Hampton Avenue	14	380	1.14	49.8	1.14
At Locust Street	14	819	0.93	133.8	1.46
Menomonee River					
At Hampton Avenue	14	430	1.03	199.3	1.15
Inner Harbor Stations					
Milwaukee River					
At Walnut Street	15	218	0.44	42.3	0.82
At Wells Street (north of)	13	384	0.80	70.2	0.77
At C&NW Railway Bridge	13	391	0.90	74.8	0.78
Kinnickinnic River					
At Greenfield Avenue Extended	12	114	0.56	47.5	0.86

Source: Milwaukee Metropolitan Sewerage District and HydroQual, Inc.

Particle-specific characteristics are not the only factors affecting the rate at which particles settle from a water body. Hydrodynamic forces also affect the net rate of transport of particulate material from the water column to the sediment. Long-term average sedimentation rates in the inner harbor were reviewed to obtain a quantitative indication of areas where conditions in the harbor were conducive to particle settling. Figure 147 illustrates the spatial variation of net sedimentation in the inner harbor. These rates were determined by the Regional Planning Commission from an analysis of U. S. Army Corps of Engineers dredging records and sounding data. Average rates denoted by the solid lines were assigned in the diagenesis model, as discussed in Chapter VII. The Milwaukee River estuary reach upstream of the Menomonee River shown in the top panel in the figure has the lowest average annual sedimentation rate within the inner harbor, about 1.8 inches per year, based on the analysis of sounding data from 1955 through 1983. This relatively low rate may reflect the higher advective velocities in the Milwaukee River estuary in comparison to the rest of the inner harbor. The Menomonee River estuary and the downstream reach of the Milwaukee River estuary, shown in the middle panel of Figure 147, exhibited much higher net sedimentation rates than did the upper Milwaukee River estuary. The highest sedimentation rates in the inner harbor were observed in the Menomonee River at N. 25th Street—as high as 43 inches per year at one cross-section, and averaging almost 20 inches per year for about 0.3 mile downstream of N. 25th Street. Net sedimentation decreased to between 4 and 6 inches per year in the Menomonee River at Muskego Avenue and was only slightly higher in the reach of the Milwaukee River downstream of the confluence with the Menomonee River. The spatial variation of sedimentation rates in the Kinnickinnic River estuary is similar to that in the Menomonee River estuary, although maximum rates in upstream reaches are less than 50 percent of those in the Menomonee River. Downstream reaches of the Kinnickinnic River estuary in the vicinity of the turning basin and the lower harbor area had sedimentation rates of about 4 inches per year. The spatial average sedimentation rate within the inner harbor, including the estuarine reaches of all three rivers, was about 4.5 inches per year.

Figure 146

COMPARISON OF ESTIMATED SHORT-TERM SEDIMENTATION RATES TO OBSERVED LONG-TERM SEDIMENTATION RATES



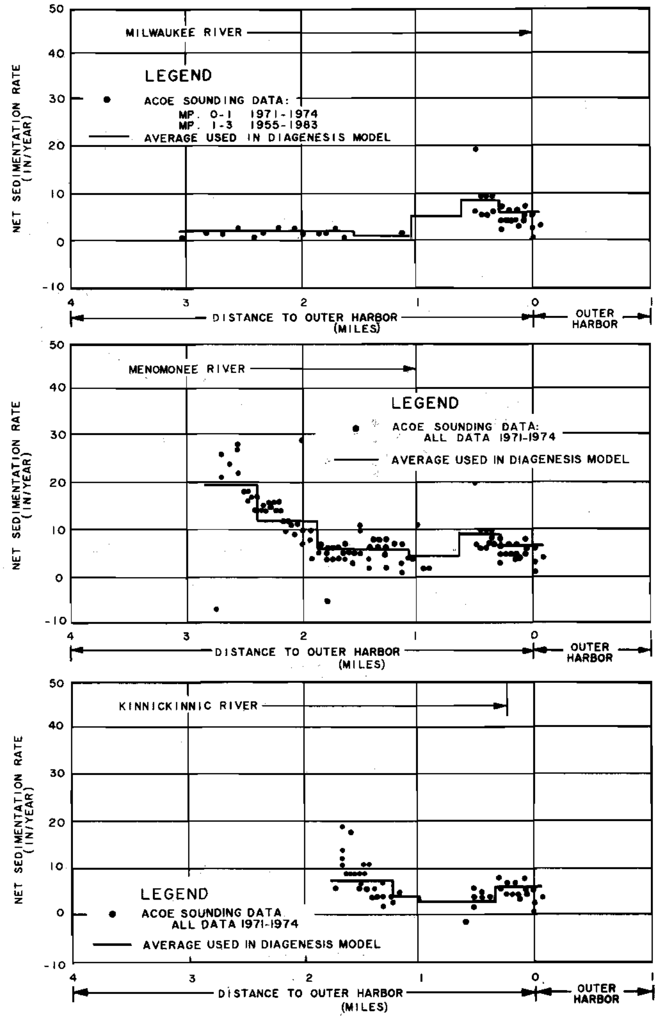
Source: HydroQual, Inc., and SEWRPC.

The variation of sedimentation rates in the estuary suggests that upstream dredged reaches of the Menomonee and Kinnickinnic Rivers are conducive to particle settling, while the upstream reach of the Milwaukee River is relatively less amenable to removal of solids from the water column. In the Menomonee and Kinnickinnic Rivers, relatively low upstream flows enter a dredged region which induces a rapid decrease in velocity, promoting the rapid rate of deposition of the suspended load. Large combined sewer overflow loads also contribute significantly to the suspended solids inputs to these areas.

Sediment Diagenesis Experiment: Just as particle settling rates control the downward flux of particulate organic carbon to the sediments, the kinetics of sediment diagenesis control the release of the products of decomposition to the pore water and the subsequent transfer upward through the sediment-water interface to the overlying water column. Laboratory studies were performed by the Milwaukee Metropolitan Sewerage District to define the rates of stabilization of sediment samples from upstream, inner harbor, and outer harbor stations, and to determine the fraction of sediment organic material available for decomposition.

Figure 147

INNER HARBOR NET SEDIMENTATION RATES



Source: HydroQual, Inc., and SEWRPC.

The sediment diagenetic experiment was conducted on sediment samples obtained from five stations in the inner harbor. Characteristics of each of these samples are summarized in Table 90. The sediment water was analyzed to determine the net release of sediment decomposition end products under anaerobic conditions. The volume of gas generated by the sediments was also monitored throughout the course of the experiment, which was continued for a period of approximately one year. The gas generation rates and water chemistry measurements provided an estimate of the mass of carbon and nitrogen released by the anaerobically decomposing sediments. These data were then analyzed to determine the requisite coefficients needed in the diagenesis model.

The diagenesis experiment data showed a relatively high and sharply decreasing rate of release of total Kjeldahl nitrogen and total organic carbon from the sediment to the water during the first 25 to 50 days, followed by a markedly slower and gradually decreasing rate of release during the remainder of the experiment. This result suggests the presence of a highly reactive, or labile, fraction within the sediments which decomposed within the first 25 to 50 days, and a refractory fraction within the sediments which decomposed at a much slower rate throughout the duration of the experiment. An inert fraction within the sediments which degrades at a negligibly slow rate was also identified in the experiment.

The results of a least squares regression analysis of the inner harbor sediment samples are summarized in Table 91. The analysis, performed on the basis of both total organic carbon and total Kjeldahl

Table 90

DIAGENESIS EXPERIMENT SEDIMENT SAMPLES

River	Sample Location	Total Solids (percent wet weight)	Total Volatile Solids (percent dry weight)	Bulk Specific Gravity[a]	Immediate Oxygen Demand (mg/kg dry weight)	Chemical Oxygen Demand (mg/kg dry weight)	Total Kjeldahl Nitrogen (mg/kg dry weight)	Ammonia Nitrogen (mg/kg dry weight)	Total Phosphorus (mg/kg dry weight)	Total Organic Carbon (mg/kg dry weight)	Total Inorganic Carbon (mg/kg dry weight)
Milwaukee . . .	Walnut Street	30.9	13.1	1.250	734	151,400	7,590	471	597	23,620	28,940
Milwaukee . . .	St. Paul Avenue	30.9	12.0	1.266	594	139,400	4,632	300	588	25,940	37,260
Milwaukee . . .	C&NW Railway Bridge	33.5	11.5	1.302	656	122,200	4,004	315	892	26,340	30,900
Menomonee . .	N. 25th Street	56.6	10.0	1.492	426	83,540	2,006	412	534	17,820	17,380
Kinnickinnic. .	S. 1st Street	52.7	7.9	1.452	348	88,440	3,562	1,264	505	12,760	22,640

[a]Ratio of the density of the sediments to the density of water.

Source: Milwaukee Metropolitan Sewerage District and HydroQual, Inc.

Table 91

DECOMPOSITION COMPONENT OF SEDIMENTS BASED ON A REGRESSION ANALYSIS OF THE DIAGENESIS EXPERIMENT DATA

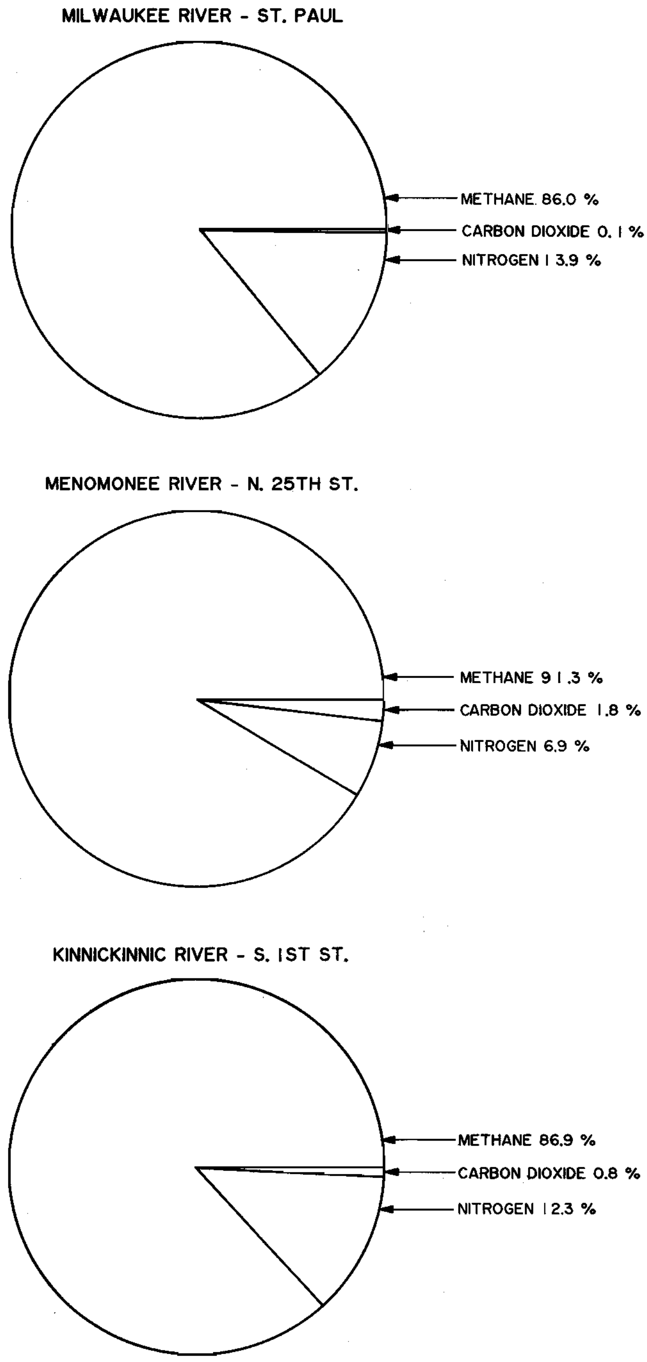
River	Sample Location	Indicator[a]	Decomposition Component (percent)		
				Reactive	
			Inert	Labile	Refractory
Milwaukee . . .	Walnut Street	TKN	83	5	12
		TC	70	9	21
Milwaukee . . .	St. Paul Avenue	TKN	72	8	20
		TC	70	8	22
Milwaukee . . .	C&NW Railway Bridge	TKN	80	7	13
		TC	82	8	10
Menomonee . .	N. 25th Street	TKN	72	4	24
		TC	72	5	23
Kinnickinnic. .	S. 1st Street	TKN	79	3	18
		TC	95	1	4

[a] *TKN - Total Kjeldahl Nitrogen*
TC - Total Carbon

Source: HydroQual, Inc.

Figure 148

MEAN CONCENTRATION OF GAS RELEASED FROM THE BOTTOM SEDIMENTS IN THE INNER HARBOR: 1982-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

nitrogen, shows the proportion of the decomposition component which is inert, labile (rapidly reactive), and refractory (slowly reactive). The labile fractions of the reactive material, or that portion of the organic material which decomposed at a relatively rapid rate, varied from 1 to 9 percent of the total concentration of organic material in the sediment. The results were similar for carbon and nitrogen. The data indicated that the labile reactive fraction was a relatively small part of the total concentration of organic material in the sediment—generally less than 10 percent—although it accounted for about 90 percent of the initial release of organic material from the sediment at the start of the experiment. The refractory fractions of the reactive material, or that portion of the organic material which decomposed at a relatively slow rate, varied from 4 to 24 percent of the total organic material. Most of the organic material—from 70 to 95 percent—therefore, was inert, and decomposed at a negligible rate.

The gas released by the bottom sediments in the inner harbor was found to be composed primarily of methane, as shown in Figure 148. The predominance of methane gas suggests that oxidation of dissolved methane is a major source of sediment oxygen demand, although the presence of nitrogen gas indicates that ammonia oxidation via nitrification-denitrification also contributes to the sediment oxygen demand. The oxidation of dissolved methane exerts an oxygen demand under aerobic conditions in the water column; during anaerobic conditions in the water column, the methane diffuses into the water column and exerts its oxygen demand at a later time as carbonaceous biochemical oxygen demand. The remaining methane produced by sediment diagenesis processes escapes as a gas flux as was measured by the gas collection device used in this study. Gas release rates in excess of 132,000 milliliters per square meter per day ($ml/m^2/day$) were observed at N. 25th Street on the Menomonee River. In the Milwaukee River, gas release rates were always less than 6,400 $ml/m^2/day$, while in the Kinnickinnic River, gas release rates were always less than 5,700 $ml/m^2/$ day. The highest rates of gas production occurred in the summer months when sediment and water temperatures were highest. No hydrogen sulfide was detected in any of the gas samples, and very little carbon dioxide was observed.

The consumption of dissolved oxygen by sediment reactions is an important factor affecting dissolved oxygen levels in the inner harbor. The primary reaction that results in sediment oxygen demand is the bacterial decomposition of particulate sedimentary organic matter. This reaction, referred to as the diagenesis reaction, liberates carbon and nitrogen, and their associated potential oxygen demand, to the interstitial water of the sediment. These dissolved constituents diffuse to the sediment-water interface, where they undergo oxidation. Sediment oxygen demand measurements from the inner harbor in 1982 and 1983 ranged from 0.59 to 5.22 grams of oxygen per square meter per day ($gO_2/m^2/day$), with the highest demand measured at N. 25th Street on the Menomonee River. The median sediment oxygen demand level was less than 2 $gO_2/m^2/day$.

BIOLOGICAL CONDITIONS

This section describes and evaluates the existing biological conditions within the Milwaukee Harbor estuary waters, providing needed information on the resident biological communities which have adapted to the existing habitats, water quality conditions, and other limiting factors; indicating the overall ecological health and stability of the water bodies; and providing data needed to determine desired and attainable water use objectives. The existing biological conditions of the estuary waters are addressed, as are some of the factors which affect these biological conditions. These factors include the physical habitat of the surface water systems, and conditions which impair or prevent the achievement of desired water use objectives.

For the estuarine portions of the Milwaukee, Menomonee, and Kinnickinnic Rivers, and for the outer harbor, the existing biota—fish, benthic invertebrates, zooplankton, and algae—are described. Bacteria, however, are addressed in the water quality sections. Habitat characteristics, including stream bank erosion and slope failure, stream bank vegetative protection, stream channelization and lining, stream channel capacity, bottom scouring and deposition, bottom substrate, water depth, riffles and pools, and low-flow discharges, are described and evaluated. Those water quality-related or habitat factors which impair the establishment of desired biological communities are discussed.

The fishery surveys summarized below were conducted by the Wisconsin Department of Natural Resources (DNR) as part of the Milwaukee Harbor estuary study. Other biological surveys and an evaluation of aquatic habitats were conducted by the DNR as part of a 1984 review of water use objectives and water quality standards, and as a part of a 1976 "Milwaukee County Basins Assessment Report." Aquatic studies prepared for the Wisconsin Electric Power Company by CDM/ Limnetics Environmental Consultants of Milwaukee, Wisconsin, and for the U. S. Army Engineer District, Detroit, by Limno-Tech, Inc., of Ann Arbor, Michigan, are also summarized. Chlorophyll-a and nutrient measurements made under the estuary study baseline water quality sampling program are included in an analysis of algal growth dynamics.

Milwaukee River

Biological data for the Milwaukee River estuary were available from the Wisconsin Department of Natural Resources (DNR), CDM/Limnetics Environmental Consultants, and Limno-Tech, Inc. Data on fishery resources were set forth in the unpublished report entitled, "Lower Milwaukee River Classification," December 1984, prepared by the DNR. That report also included an evaluation of the aquatic habitat, and of the factors impairing the survival of desired biological organisms. Algal data collected by the DNR were set forth in the biological chapter of the "Milwaukee County Basins Assessment Report." Data on algae and zooplankton are set forth in Aquatic Studies at Valley, Commerce Street, and Wells Street Power Plants, 1976, prepared by CDM/Limnetics, Environmental Consultants of Milwaukee, Wisconsin, for the Wisconsin Electric Power Company. Data on benthic macroinvertebrates are set forth in Field Methodology and Results for Milwaukee Harbor, Kinnickinnic River and Menomonee River prepared by Limno-Tech, Inc., for the U. S. Army Engineer District, Detroit, June 1984. Chlorophyll-a levels were measured as part of the Milwaukee Harbor estuary study.

Fish: Extensive fishery surveys were conducted in the Milwaukee River downstream of the North Avenue dam by the DNR in 1983 as part of the Milwaukee Harbor estuary study. The tolerance level, type, and number of fish collected during these surveys are set forth in Table 92. Thirty-five species of fish were captured within the Milwaukee River downstream of the North Avenue dam during the 1983 surveys, of which 10, or 29 percent, were rated as intolerant of pollution, 17, or 48 percent, were rated as tolerant, and eight, or 23 percent, were rated as very tolerant of pollution. The most abundant fish caught were carp and white sucker, followed by redhorse, alewife, bluegill, rainbow trout, black crappie, black bullhead, rock bass, and goldfish. Unusual fish species captured include the bloater chub and grass carp. The bloater chub normally inhabits deep coldwater lakes and is seldom found in rivers. The grass carp was the first occurrence in Wisconsin in streams which provide direct access to Lake Michigan. Most rainbow trout were caught in May and June, and their size indicated that they were recently stocked. All of the coho and chinook salmon were caught in October during their fall migration.

Fish recapture studies indicated that there is little movement of fish between the Milwaukee River estuary and the other inner harbor reaches or the outer harbor. Seven of the nine white sucker, and 11 of the 12 black bullhead, recaptured in the Milwaukee River were originally caught in the Milwaukee River, and the remaining two white suckers and one black bullhead were originally caught in the Kinnickinnic River. Of the two recaptured pumpkinseed, one was originally caught in the Milwaukee River while the other was originally caught in the South Shore Harbor. All of the redhorse, rock bass, black crappie, white crappie, bluegill, green sunfish, and brown bullhead recaptured in the Milwaukee River were originally caught in the Milwaukee River.

Concentrations were measured of 14 toxic organic substances and three metals in the tissue of fish taken from the Milwaukee River estuary from July 1980 through August 1983, and of 11 toxic organic substances and five metals in the tissue of fish taken from the upstream reaches of the Milwaukee River from May 1970 through July 1983. The results of the fish tissue toxic surveys are set forth in Tables 93 and 94. The presence of toxic substances in fish tissue may, in some instances, pose a health threat to humans consuming the fish.

Polychlorinated biphenyl (PCB) concentrations in the tissue of fish taken from the Milwaukee River estuary were higher than those found in the tissue of fish taken from the Menomonee and Kinnickinnic Rivers, or from the outer harbor, and also higher than those found in the tissue of fish taken from the upstream reaches of the Milwaukee River. The PCB concentrations in the tissue of fish taken from the Milwaukee River estuary ranged from

Table 92

TOLERANCE LEVEL, TYPE, AND NUMBER OF FISH COLLECTED DURING THE MILWAUKEE HARBOR ESTUARY FISH SURVEY IN THE MILWAUKEE RIVER ESTUARY: 1983

Tolerance Level	Species	Number	Percent of Subtotal	Percent of Total
Intolerant	Bloater Chub	1	0.2	< 0.1
	Brook Trout	9	1.5	0.3
	Brown Trout	8	1.3	0.3
	Chinook Salmon	20	3.3	0.7
	Coho Salmon	2	0.3	0.1
	Lake Trout	1	0.2	< 0.1
	Rainbow Trout	202	33.3	7.6
	Redhorse	342	56.4	12.8
	Spottail Shiner	15	2.5	0.6
	Trout Perch	6	1.0	0.2
	Subtotal	606	100.0	22.6
Tolerant	Alewife	290	21.0	10.8
	Black Crappie	175	12.7	6.5
	Bluegill	211	15.2	7.9
	Channel Catfish	10	0.7	0.4
	Flathead Catfish	1	0.1	< 0.1
	Gizzard Shad	55	4.0	2.1
	Largemouth Bass	2	0.1	0.1
	Northern Pike	18	1.3	0.7
	Pumpkinseed-Green Sunfish	1	0.1	< 0.1
	Pumpkinseed	31	2.2	1.2
	Rainbow Smelt	5	0.4	0.2
	Rock Bass	120	8.7	4.5
	Smallmouth Bass	24	1.7	0.9
	Walleye	11	0.8	0.4
	White Crappie	20	1.4	0.7
	White Sucker	402	29.1	15.0
	Yellow Perch	7	0.5	0.3
	Subtotal	1,383	100.0	51.7
Very Tolerant	Black Bullhead	152	22.1	5.7
	Bowfin	1	0.2	< 0.1
	Brown Bullhead	3	0.4	0.1
	Carp	404	58.8	15.1
	Goldfish	108	15.7	4.1
	Grass Carp	1	0.2	< 0.1
	Green Sunfish	17	2.4	0.7
	Yellow Bullhead	1	0.2	< 0.1
	Subtotal	687	100.0	25.7
	Total	2,676	--	100.0

Source: Wisconsin Department of Natural Resources and SEWRPC.

Table 93

CONCENTRATIONS OF TOXIC ORGANIC SUBSTANCES AND METALS IN THE TISSUE OF FISH IN THE MILWAUKEE RIVER ESTUARY: 1980-1983

Toxic Substance	Carp			Northern Redhorse			Northern Pike			Bluegill			White Sucker			Gizzard Shad		
	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean
Dates of Sampling	August 2, 1983 to August 8, 1983			July 2, 1980 to August 8, 1983			August 10, 1983			August 5, 1983			August 10, 1983			August 8, 1983		
Organics																		
PCB's	3	7.9-52.0	26.6	2	2.7-6.9	4.8	1	--	16.0	1	--	9.1	1	--	15.0	1	--	13.0
Aldrin	1	--	<0.3	--	--	--	1	--	<0.1	1	--	<0.1	1	--	<0.02	--	--	--
Dieldrin	1	--	0.07	1	--	<0.02	1	--	0.05	1	--	<0.02	1	--	<0.02	--	--	--
Endrin	1	--	<0.02	--	--	--	1	--	<0.02	1	--	<0.02	1	--	<0.02	--	--	--
DDT	1	--	0.70	1	--	0.19	1	--	0.62	1	--	0.34	1	--	0.39	--	--	--
DDE	--	--	--	1	--	0.09	--	--	--	--	--	--	--	--	--	--	--	--
PP-DDD	--	--	--	1	--	0.10	--	--	--	--	--	--	--	--	--	--	--	--
Chlordane	1	--	0.06	1	--	<0.05	1	--	0.06	1	--	<0.05	1	--	<0.05	--	--	--
Hexachlorobenzene	1	--	<0.05	--	--	--	1	--	<0.05	1	--	<0.05	1	--	<0.05	--	--	--
Hexachlorocyclohexane	1	--	<0.01	--	--	--	1	--	<0.01	1	--	<0.01	1	--	<0.01	--	--	--
Heptachlor	1	--	<0.05	--	--	--	--	--	--	1	--	<0.05	1	--	<0.05	--	--	--
Methoxychlor	1	--	<0.05	--	--	--	1	--	<0.05	1	--	<0.05	1	--	<0.05	--	--	--
Pentachloroanisol	1	--	<0.05	--	--	--	--	--	--	1	--	<0.05	1	--	0.05	--	--	--
Toxaphene	1	--	1.0	--	--	--	--	--	--	1	--	<1.0	1	--	<1.0	--	--	--
Metals																		
Chromium	1	--	<0.5	--	--	--	1	--	<0.5	1	--	<0.5	1	--	<0.5	--	--	--
Copper	1	--	2.0	--	--	--	1	--	1.4	1	--	1.5	1	--	1.6	--	--	--
Mercury	1	--	0.04	--	--	--	1	--	0.09	1	--	0.09	1	--	0.04	--	--	--

NOTE: All concentrations are in parts per million.

Source: Wisconsin Department of Natural Resources.

2.7 parts per million (ppm) in a northern redhorse captured on July 9, 1981, to 52 ppm in a carp captured on August 8, 1983. The PCB concentrations in the tissue of fish taken from upstream stations on the Milwaukee River ranged from 0.21 ppm in a rock bass captured in July 1980, in a white sucker captured in June 1981, and in a black bullhead captured in July 1981, to 49 ppm in a carp captured on July 1, 1980. Because the levels of PCB's in the tissue of fish taken from the Milwaukee River often exceeded the health standard of a maximum fish tissue concentration of 2 ppm established by the U. S. Food and Drug Administration, the DNR has issued a health advisory for persons consuming fish taken from the Milwaukee River downstream of Cedar Creek, as well as from the remainder of the inner harbor and from the outer harbor. That health advisory, as of April 1985, suggested that pregnant women, nursing mothers, women who wish to bear children, and children not consume redhorse, rock bass, and smallmouth bass under 13 inches in length, and that no one consume carp or northern pike. Perch were noted as posing the lowest health risk to consumers.

Concentrations of the pesticide DDT (dichloro-diphenyl-trichloro-ethane) in the tissue of fish taken from the Milwaukee River estuary ranged from 0.19 ppm in a northern redhorse captured on July 2, 1980, to 0.70 ppm in a carp captured on August 2, 1983. The DDT concentration in the tissue of fish taken from upstream stations on the Milwaukee River ranged from less than 0.05 ppm in a northern redhorse captured on July 9, 1981, to 1.36 ppm in a goldfish also captured on July 9, 1981. The U. S. Food and Drug Administration health standard for DDT concentrations in fish tissue is a maximum of 5 ppm.

Concentrations of several metals in fish tissues were also measured. Within the Milwaukee River estuary, concentrations of chromium were found to be below the minimum level of detection, as shown in Table 93. Copper concentrations were found to range from 1.4 ppm in a northern pike captured on August 10, 1983, to 2.0 ppm in a carp captured on August 2, 1983. Mercury concentrations were found to range from 0.04 ppm in a white sucker captured on August 10, 1983 and in a carp captured on August 2, 1983, to 0.09 ppm

Table 94

CONCENTRATIONS OF TOXIC ORGANIC SUBSTANCED AND METALS IN THE TISSUE OF FISH IN THE MILWAUKEE RIVER-UPSTREAM REACHES: 1970-1983[a]

Toxic Substance	Carp			Northern Redhorse			Smallmouth Bass			Brown Trout		
	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean
Dates of Sampling	July 8, 1970 to July 9, 1981			August 15, 1978 to July 22, 1981			July 9, 1979 to June 30, 1982			July 9, 1979		
Organics												
PCB's	28	0.39-49.0	15.3	21	0.26-14.0	4.0	6	0.35-26.0	5.7	1	--	8.6
Dieldrin	9	0.02-0.05	0.03	1	--	0.04	1	--	0.05	1	--	0.02
DDT	4	0.05-0.64	0.40	4	<0.05-0.24	0.14	1	--	1.25	1	--	0.08
PP-DDE	16	0.05-0.58	0.33	12	0.06-0.34	0.12	2	0.12-1.0	0.56	--	--	--
OP-DDD	--	--	--	--	--	--	1	--	0.07	--	--	--
PP-DDD	16	0.05-0.58	0.23	6	0.06-0.27	0.12	2	0.05-0.25	0.15	1	--	0.08
Chlordane	4	0.05-0.23	0.12	2	0.04-0.05	0.04	--	--	--	--	--	--
Metals												
Copper	7	0.8-1.5	1.3	2	0.08-1.8	1.3	1	--	1.3	1	--	3.2
Lead	4	0.05-0.3	0.34	--	--	--	--	--	--	--	--	--
Mercury	7	0.02-0.15	0.10	2	0.02-0.07	0.05	1	--	0.25	1	--	0.04
Zinc	1	--	10.6	--	--	--	--	--	--	--	--	--

Toxic Substance	Northern Pike			Goldfish			White Sucker			Largemouth Bass			Walleye		
	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean
Dates of Sampling	July 8, 1970 to July 9, 1979			July 9, 1970 to July 9, 1981			July 8, 1970 to July 30, 1980			July 2, 1980			July 2, 1980		
Organics															
PCB's	2	5.0-21.0	13.0	1	--	42.0	3	0.21-1.0	0.58	1	--	3.4	1	--	21.0
Dieldrin	1	--	0.08	--	--	--	--	--	--	--	--	--	--	--	--
DDT	1	--	1.08	1	--	1.36	--	--	--	1	--	0.20	1	--	0.39
PP-DDE	2	0.06-0.76	0.40	1	--	0.63	2	0.05-0.08	0.06	1	--	0.11	1	--	0.27
PP-DDD	1	--	0.32	1	--	0.73	--	--	--	1	--	0.09	1	--	0.12
Chlordane	1	--	0.10	--	--	--	--	--	--	--	--	--	--	--	--
Hexachlorobenzene	1	--	0.01	--	--	--	--	--	--	--	--	--	--	--	--
Hexachlorocyclohexane	1	--	0.01	--	--	--	--	--	--	--	--	--	--	--	--
Metals															
Arsenic	--	--	--	1	--	0.10	--	--	--	--	--	--	--	--	--
Lead	2	0.05-0.06	0.06	--	--	--	--	--	--	--	--	--	--	--	--
Mercury	1	--	0.19	3	0.11-0.18	0.15	--	--	--	--	--	--	--	--	--
Zinc	1	--	4.2	1	--	18.3	2	4.7-4.8	4.8	--	--	--	--	--	--

Toxic Substance	Gizzard Shad			Rock Bass			Black Bullhead			Turtle			Miscellaneous Species		
	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean
Dates of Sampling	June 30, 1982			July 1, 1980 to July 22, 1981			June 30, 1981 to July 1, 1981			July 11, 1983			May 20, 1970		
Organics															
PCB's	1	--	17.0	11	0.21-5.1	1.55	2	0.21-0.37	0.29	--	--	--	--	--	--
Dieldrin	--	--	--	1	--	0.02	--	--	--	--	--	--	--	--	--
DDT	--	--	--	1	--	0.23	--	--	--	--	--	--	--	--	--
PP-DDE	--	--	--	4	0.05-0.14	0.09	--	--	--	--	--	--	--	--	--
PP-DDD	--	--	--	1	--	0.09	--	--	--	--	--	--	--	--	--
2,3,7,8–Tetrachloro-dibenzo-P-dioxin	--	--	--	--	--	--	--	--	--	1	--	0.20	--	--	--
2,3,7,8–Tetrachloro-dibenzo-P-furan	--	--	--	--	--	--	--	--	--	1	--	0.11	--	--	--
Metals															
Mercury	--	--	--	--	--	--	--	--	--	--	--	--	3	0.11-0.35	0.23

NOTE: All concentrations are in parts per million.

[a] *Includes one sample from the tissue of a turtle.*

Source: Wisconsin Department of Natural Resources.

in a northern pike captured on August 5, 1983. Within the upstream portion of the Milwaukee River, copper concentrations in fish tissue were found to range from 0.8 ppm in a carp captured on August 5, 1978, to 3.2 ppm in a brown trout captured on July 9, 1979. Mercury concentrations were found to range from 0.02 ppm in a carp captured on August 10, 1978 and in a northern redhorse captured on August 15, 1978, to 0.35 ppm in a miscellaneous species captured on May 20, 1970. Lead concentrations were found to range from 0.05 ppm to 0.30 ppm in carp captured on July 8 and July 9, 1970, respectively. Zinc concentrations were found to range from 4.2 ppm in a northern pike captured on July 8, 1970, to 18.3 ppm in a goldfish captured on July 9, 1970. The U. S. Food and Drug Administration health standard for mercury concentrations in fish tissue is a maximum of 1 ppm.

Benthic Macroinvertebrates: In 1984 a total of 18 species of benthic macroinvertebrates were identified at three stations in the Milwaukee River estuary.[12] The locations of the sampling stations are shown on Map 95, and the species are listed in Table 95. Oligochaetes were always found to compose over 87 percent of the total benthic fauna present. Limnodrilus species were generally the most abundant organisms sampled. Many of the oligochaete species found are normally associated with organically enriched habitats. All of the species identified were rated as tolerant of pollution. In addition, the Wisconsin Department of Natural Resources reported that the soft mucky substrates, anaerobic sediments, and in-place pollutants present within the Milwaukee River downstream of the North Avenue dam would support only benthic organisms very tolerant of pollution.[13]

Algae: Phytoplankton were surveyed during January, March, and May of 1976 in the Milwaukee River estuary.[14] Table 96 lists the type and rela-

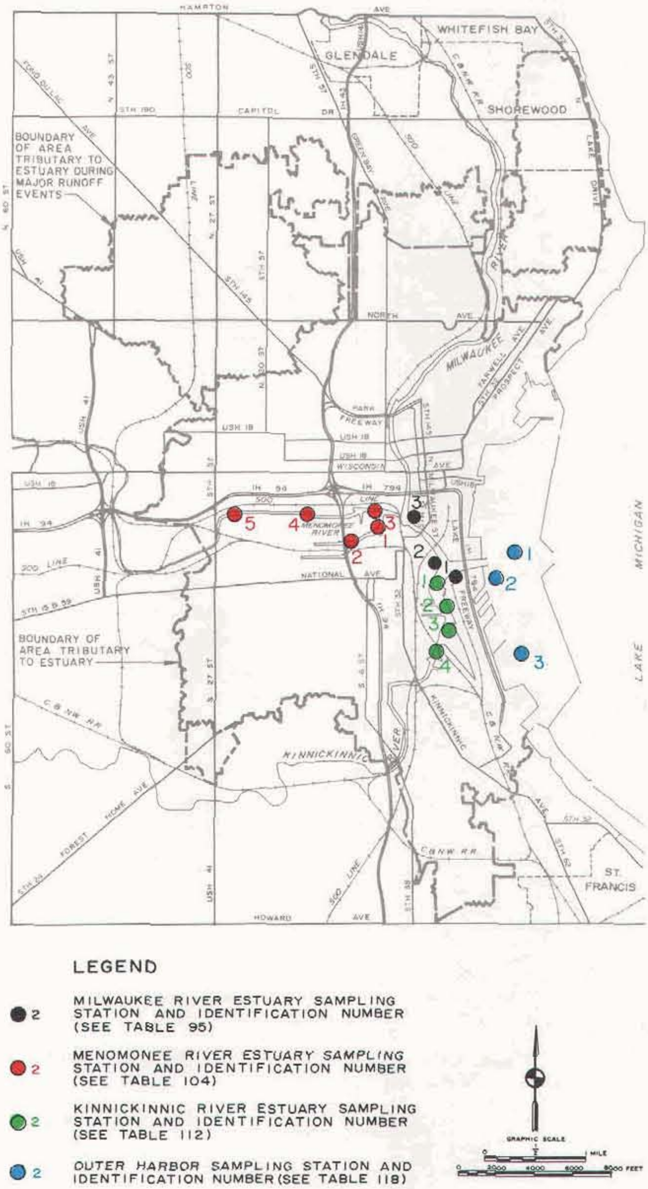
[12] *Limno-Tech, Inc., Field Methodology and Results for Milwaukee Harbor, Kinnickinnic River and Menomonee River, prepared for the U. S. Army Engineer District, Detroit, June 1984.*

[13] *Wisconsin Department of Natural Resources, "Lower Milwaukee River Classification," December 1984.*

[14] *CDM/Limnetics Environmental Consultants, Aquatic Studies at Valley, Commerce Street, and Wells Street Power Plants, prepared for the Wisconsin Electric Power Company, 1976.*

Map 95

LOCATION OF BENTHIC MACROINVERTEBRATE SAMPLING STATIONS WITHIN THE MILWAUKEE, MENOMONEE, AND KINNICKINNIC RIVER ESTUARIES AND OUTER HARBOR: 1984



During a 1984 survey, a total of 18 species of benthic macroinvertebrates were indentified at three stations in the Milwaukee River estuary; a total of 17 species of benthic macroinvertebrates were identified at five stations in the Menomonee River estuary; and a total of 18 species of benthic macroinvertebrates were identified at four stations in the Kinnickinnic River estuary. A total of 21 species of benthic macroinvertebrates were idenified in 1984 at three stations in the outer harbor. All of the species identified were rated as pollution tolerant.

Source: Limno-Tech, Inc.

tive abundance of the algae within the Milwaukee River during this sampling period. Figure 149 illustrates the seasonal changes in the various types of algae at a representative station. As shown in the figure, the total number of algae was about three times higher in May than in January, and the diatoms (Bacillariophytes) were the most dominant algal type in January and May, whereas the green algae (Chlorophytes) were dominant in March. While the sampling period did not include the summer months, it is probable that the green algae (Chlorophytes) and blue-green algae (Cyanophytes) are dominant during the summer.

Planktonic and periphytic diatoms were identified and quantified in the Milwaukee River at Wells Street by the Wisconsin Department of Natural Resources over the period 1975 to 1976.[15] Planktonic diatom genera identified in October 1975 are listed in Table 97. Tabellaria and Cyclotella were the most common genera sampled in the Milwaukee River at Wells Street. Periphytic diatom genera identified in July 1975 and in May 1976 are set forth in Table 98. Achnanthes and Rhoicosphenia were the most numerous periphytic algae in July 1975, while Navicula and Nitzschia were dominant in May 1976. Navicula and Nitzschia are indicative of nutrient-enriched conditions, and are pollution tolerant. Some genera are listed in both Tables 97 and 98 because the algae may exist in both planktonic and periphytic forms.

Chlorophyll-a, an indicator of algal biomass, was measured in the Milwaukee River over the period 1981 through 1983 as part of the Milwaukee Harbor estuary study. A statistical summary of the observed chlorophyll-a levels at four stations within the Milwaukee River estuary is set forth in Table 99. The table summarizes annual levels—measured over the entire year—and summer levels—measured during June, July, and August. The mean annual concentrations of chlorophyll-a were found to range from 15.2 µg/l at the C&NW Railway bridge to 50.5 µg/l at Walnut Street. The mean summer concentrations of chlorophyll-a were found to be from 32 to 71 percent higher than the annual means and to range from 20.1 µg/l at the C&NW bridge to 84.0 µg/l at Walnut Street. The maximum concentration of chlorophyll-a of 359.4 µg/l was measured on July 27, 1981, at Walnut Street. Maximum summer, mean summer, and

[15] *Wisconsin Department of Natural Resources, "Milwaukee County Basins Assessment Report," 1976.*

Table 95

BENTHIC MACROINVERTEBRATES IDENTIFIED WITHIN THE MILWAUKEE RIVER ESTUARY: 1984

Species	Population Density (number/feet^2) Sampling Station[a] 1	2	3
Class Oligochaeta[b]			
Aulodrilus pluriseta	--	--	$\geq$ 4
Limnodrilus cervix	$\geq$ 40	$\geq$ 68	$\geq$104
Limnodrilus hoffmeisteri	$\geq$220	$\geq$384	$\geq$436
Limnodrilus maumeensis	$\geq$ 4	--	--
Limnodrilus udekemianus	$\geq$ 20	$\geq$ 36	$\geq$ 32
Quistadrilus multisetosus	$\geq$300	$\geq$ 44	$\geq$152
Tubifex tubifex	$\geq$180	$\geq$228	$\geq$112
Unidentified Immature Oligochaeta with Capilliform Chaeta	$\geq$ 32	$\geq$ 48	$\geq$ 16
Unidentified Immature Oligochaeta without Capilliform Chaeta	$\geq$ 52	$\geq$ 80	$\geq$ 16
Total	$\geq$848	$\geq$888	$\geq$872
Class Insecta			
Chironomus sp	4	--	--
Procladius sp	--	4	--
Total	4	4	--
Class Gastropoda			
Bithynia tentaculata	12	--	--
Valvata sincera	4	--	--
Total	16	--	--
Class Pelecypoda			
Sphaerium sp	--	4	--
Total	--	4	--
Class Crustacea			
Ascellus sp	80	--	--
Gammarus sp	4	--	--
Total	84	--	--
Class Hirudinea			
Helobdella stagnalis	12	--	--
Total	12	--	--
Class Tubellaria			
Tubellaria sp	8	--	--
Total	8	--	--

[a] *Sampling station locations are shown on Map 95.*

[b] *Because the number of Oligochaetes was very high within each sample, only a limited number of individuals was counted to provide a representative distribution of species.*

Source: Limno-Tech, Inc.

Table 96

TYPE AND ABUNDANCE OF PHYTOPLANKTON SURVEYED WITHIN THE MILWAUKEE RIVER ESTUARY: 1976[a]

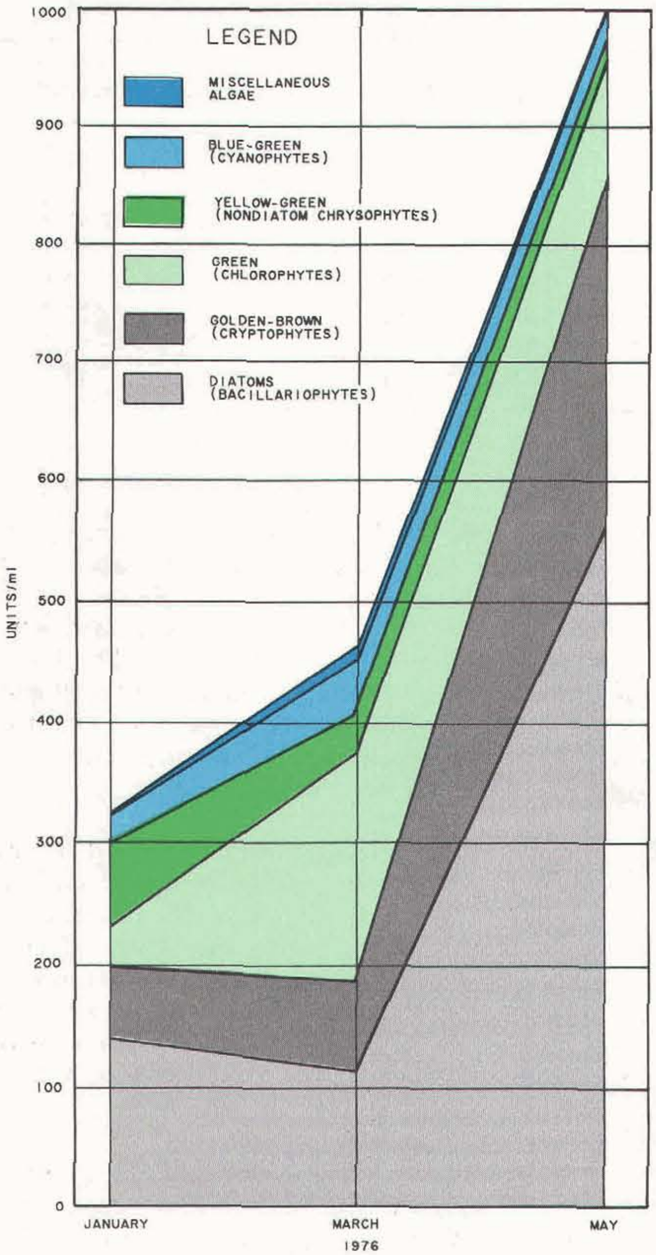
Species	January 20						March 9								May 1					
	Cherry Street		Park Freeway		Kilbourn Avenue		Cherry Street		Park Freeway		Kilbourn Avenue		Wells Street		Cherry Street		Park Freeway		Kilbourn Avenue	
	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent
Chlorophyta	34	9.5	44	9.7	54	15.0	191	40.1	196	43.8	212	36.9	258	47.5	109	10.5	111	13.5	92	12.9
Chlamydomonas spp	--	--	--	--	--	--	166	34.8	161	35.9	180	31.3	229	42.2	52	5.0	69	8.4	59	8.3
Unidentified Chlorophytes	34	9.5	44	9.7	54	15.0	25	5.3	35	7.9	32	5.6	29	5.3	57	5.5	42	5.1	33	4.6
Euglenophyta	1	0.3	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7	0.9	2	0.3
Pyrrhophyta	--	--	--	--	1	0.3	8	1.7	10	2.2	13	2.3	13	2.4	2	0.2	2	0.2	3	0.4
Cryptophyta	58	16.2	86	19.11	81	22.4	74	15.6	76	17.0	87	15.2	78	14.4	277	26.7	237	28.9	185	25.9
Chroomonas spp.	41	11.4	67	14.9	63	17.4	45	9.5	47	10.5	53	9.2	60	11.0	186	17.9	149	18.2	108	15.1
Cryptomonas spp	--	--	--	--	--	--	29	6.1	29	6.5	26	4.5	10	1.8	79	7.6	86	10.5	65	9.1
Unidentified Cryptophytes	17	4.8	19	4.2	18	5.0	--	--	--	--	7	1.5	8	1.6	12	1.2	2	0.2	12	1.7
Chrysophyceae	67	18.7	97	21.7	73	20.2	29	6.1	19	4.2	35	6.1	30	5.5	16	1.5	42	5.1	38	5.3
Erkenia spp.	18	5.0	20	4.5	27	7.5	26	5.5	15	3.3	35	6.1	25	4.6	7	0.7	8	1.0	1	0.1
Stelexomonas dicotoma	15	4.2	36	8.0	17	4.7	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Aulomonas purdyi.	34	9.5	41	9.2	29	8.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Unidentified Chrysophytes	--	--	--	--	--	--	3	0.6	4	0.8	--	--	5	0.9	9	0.9	34	4.1	37	5.2
Diatomaceae	139	38.7	146	32.6	96	26.6	111	23.3	118	26.3	160	27.9	122	22.5	558	53.7	373	45.5	354	49.5
Centrales spp.	24	6.6	34	7.6	37	10.2	--	--	--	--	--	--	--	--	202	19.4	106	12.9	87	12.2
Cyclotella spp	39	10.9	25	5.6	9	2.5	--	--	--	--	--	--	--	--	131	12.6	121	14.8	165	23.1
Stephanodiscus astraea	--	--	--	--	--	--	--	--	--	--	--	--	--	--	66	6.4	19	2.3	16	2.2
Fragilaria pinnata	--	--	--	--	--	--	21	4.4	38	8.5	42	7.3	33	6.1	--	--	--	--	--	--
Unidentified Diatoms	76	21.2	87	19.4	50	13.9	90	18.9	80	17.8	118	20.6	89	16.4	159	15.3	127	15.5	86	12.0
Cyanophyta	23	6.4	45	10.2	29	8.0	22	4.6	9	2.0	34	5.9	22	4.0	20	1.9	31	3.8	25	3.5
Unidentified Phytoplankton	37	10.2	30	6.7	27	7.5	41	8.6	20	4.5	33	5.7	20	3.7	57	5.5	17	2.1	16	2.2
Total Phytoplankton	359	100.0	448	100.0	361	100.0	476	100.0	448	100.0	574	100.0	543	100.0	1,039	100.0	820	100.0	715	100.0

[a]*All means are expressed as organisms per cubic meter.*

Source: CDM/Limnetics Environmental Consultants.

Figure 149

PHYTOPLANKTON SURVEYED IN THE MILWAUKEE RIVER AT CHERRY STREET: 1976



Source: CDM/Limnetics Environmental Consultants.

mean annual chlorophyll-a levels are plotted on Figure 150. Peak chlorophyll-a levels were reached at Walnut Street and decreased substantially at the downstream stations.

Plots of chlorophyll-a, inorganic nitrogen, and soluble phosphorus versus time at four stations within the Milwaukee River estuary over the period

Table 97

TYPE AND RELATIVE ABUNDANCE OF PLANKTONIC DIATOM GENERA SAMPLED IN THE MILWAUKEE RIVER AT WELLS STREET: OCTOBER 1975

Genera	Relative Abundance (percent)
Cocconeis	4
Nitzschia	8
Cyclotella	24
Fragilaria	16
Rhoicosphenia	4
Gomphonema	8
Amphora	4
Tabellaria	32
Total	100

Source: Wisconsin Department of Natural Resources.

Table 98

TYPE AND RELATIVE ABUNDANCE OF PERIPHYTIC GENERA SAMPLED IN THE MILWAUKEE RIVER AT WELLS STREET: 1975-1976

Genera	Relative Abundance (percent)	
	July 1975	May 1976
Cocconeis	4	1
Achnanthes	51	3
Nitzchia	3	30
Cyclotella	1	1
Fragilaria	2	4
Navicula	<1	37
Rhoicosphenia	19	1
Gomphonema	12	2
Amphora	1	<1
Diatoma	2	<1
Melosira	3	3
Synedra	2	5
Surirella	0	13
Total	100	100

Source: Wisconsin Department of Natural Resources.

Table 99

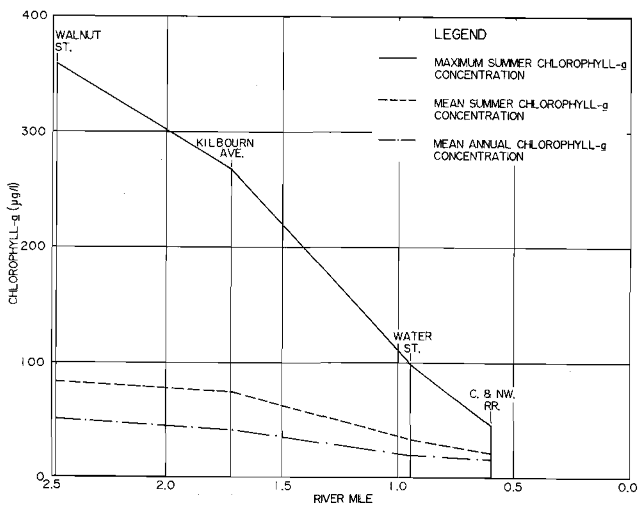
SUMMARY OF CHLOROPHYLL-a CONCENTRATIONS WITHIN THE MILWAUKEE RIVER ESTUARY: 1981-1983

Sampling Station	Period	Number of Samples	Chlorophyll-a (μg/l) Minimum	Mean	Maximum	Standard Deviation
Walnut Street	Annual	96	0.6	50.5	359.4	55.6
	Summer	48	11.8	84.0	359.4	58.7
Kilbourn Avenue.	Annual	103	0.5	41.1	265.1	46.2
	Summer	49	12.3	70.2	265.1	49.0
Water Street.	Annual	103	0.6	19.7	97.2	20.1
	Summer	49	6.8	32.3	97.2	21.3
C&NW Railway Bridge	Annual	32	2.2	15.2	45.2	11.1
	Summer	20	4.4	20.1	45.2	11.1

Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Figure 150

MAXIMUM SUMMER, MEAN SUMMER, AND MEAN ANNUAL CHLOROPHYLL-a LEVELS WITHIN THE MILWAUKEE RIVER ESTUARY: 1981-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

1981 through 1983 are shown in Figure 151. Although not conclusive, the plots indicate that algal growth levels may be limited by nitrogen, rather than by phosphorus. Inorganic nitrogen levels tended to decline when chlorophyll-a levels increased to high levels, whereas soluble phosphorus levels tended to remain relatively constant. At other stream locations, and perhaps even at the four stations shown on Figure 151 during certain conditions, phosphorus, rather than nitrogen, may limit aquatic plant growth. Previous studies have indicated that algal and macrophyte growth in many—if not most—streams in southeastern Wisconsin is primarily controlled by phosphorus.[16] Furthermore, even if nitrogen levels currently limit algal growths, future reductions in phosphorus levels achieved by the implementation of upstream point and nonpoint source pollution control measures could result in phosphorus, rather than nitrogen, becoming the limiting nutrient.

Zooplankton: Zooplankton were surveyed during January, March, and May of 1976 at four stations within the Milwaukee River.[17] Table 100 lists the species, number, and relative abundance of zooplankton collected during the surveys. As shown in the table, rotifers were the dominant type of zooplankton collected at all stations. The relative abundance of copepods was greatest during March.

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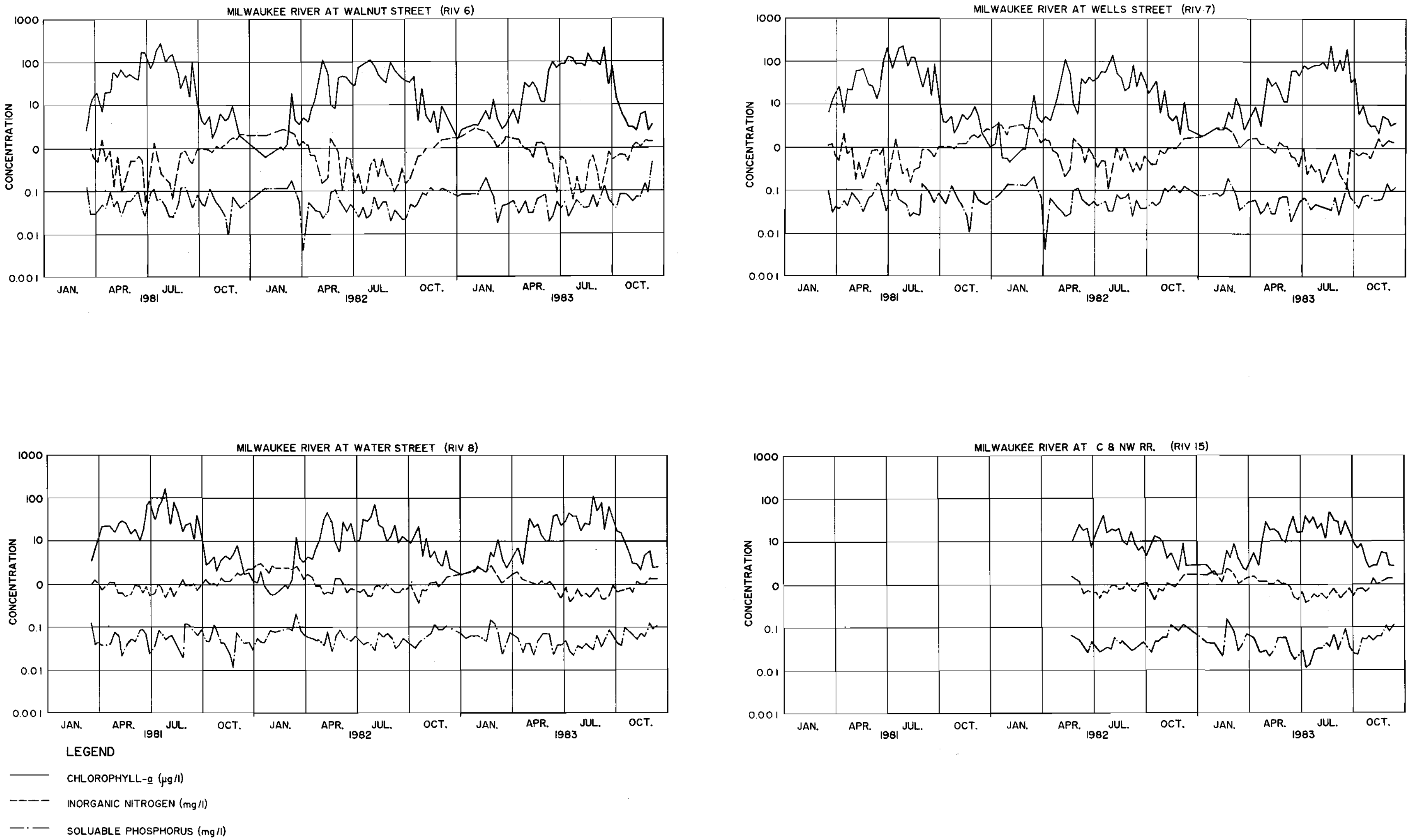
[16] *See Bureau of Water Resources Management, Wisconsin Department of Natural Resources, Impacts of Phosphorus on Streams, April 1984; SEWRPC Planning Report No. 30, A Regional Water Quality Management Plan for Southeastern Wisconsin: 2000, 1979; and D. Kendziorski, "Evaluation of a Water Quality Standard for Total Phosphorus in Flowing Streams in Southeastern Wisconsin," SEWRPC Technical Record, Vol. 4, No. 2, 1981.*

[17] *CDM/Limnetics Environmental Consultants, Aquatic Studies at Valley, Commerce Street, and Wells Street Power Plants, prepared for the Wisconsin Electric Power Company, 1976.*

Figure 151

CHLOROPHYLL-a, INORGANIC NITROGEN, AND SOLUBLE PHOSPHORUS CONCENTRATIONS WITHIN THE MILWAUKEE RIVER ESTUARY: 1981-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Table 100

TYPE AND ABUNDANCE OF ZOOPLANKTON SURVEYED WITHIN THE MILWAUKEE RIVER ESTUARY: 1976[a]

Species	January 20						March 9								May 1					
	Cherry Street		Park Freeway		Kilbourn Avenue		Cherry Street		Park Freeway		Kilbourn Avenue		Wells Street		Cherry Street		Park Freeway		Kilbourn Avenue	
	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent
Rotifera																				
Keratella spp	60	2.6	180	6.2	280	5.2	400	7.9	200	3.8	467	8.2	500	8.4	2,933	45.8	3,267	47.6	2,900	38.9
Pleurotrocha spp.	587	25.0	360	12.3	560	10.4	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Polyarthra spp	--	--	--	--	--	--	100	2.0	133	2.5	467	8.2	100	1.7	--	--	--	--	--	--
Synchaeta spp	927	39.5	1,800	61.8	3,733	69.1	867	17.1	1,233	23.4	1,833	32.4	1,267	21.4	1,170	18.3	1,320	19.2	1,507	20.2
Bdelloidea spp	160	6.8	147	5.0	313	5.8	1,567	30.9	1,900	36.1	1,200	21.2	2,167	36.5	874	13.7	1,320	19.2	1,120	15.0
Filinia longiseta	180	7.7	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Notholca spp.	--	--	--	--	--	--	--	--	--	--	--	--	--	--	563	8.8	120	1.8	533	7.1
Cladocera	13	0.5	7	0.2	7	0.1	233	4.6	133	2.5	267	4.7	167	2.8	--	--	53	0.8	93	1.2
Copepoda																				
Calanoida	67	2.8	107	3.7	73	1.4	--	--	--	--	33	0.6	--	--	--	--	--	--	--	--
Cyclopoida	140	6.0	113	3.9	113	2.1	167	3.3	333	6.3	33	0.6	233	3.9	104	1.6	120	1.7	147	2.0
Harpacticoida	--	--	--	--	--	--	33	0.6	33	0.7	--	--	67	1.1	--	--	27	0.4	--	--
Unidentified Copepods	213	9.1	200	6.9	320	5.9	1,700	33.6	1,300	24.7	1,367	24.1	1,433	24.2	756	11.8	640	9.3	1,160	15.6
Total Zooplankton	2,347	100.0	2,914	100.0	5,399	100.0	5,067	100.0	5,265	100.0	5,667	100.0	5,934	100.0	6,400	100.0	6,867	100.0	7,460	100.0

[a] *All means are expressed as organisms per cubic meter.*

Source: CDM/Limnetics Environmental Consultants.

Habitat Evaluation: The aquatic habitat in the Milwaukee River estuary was evaluated by the DNR and Regional Planning Commission using the stream system habitat evaluation system developed by Ball.[18] Ball's habitat evaluation system was modified, however, to be more applicable to an estuarine environment. The habitat rating for the reach of the Milwaukee River extending from Lake Michigan to the North Avenue dam is set forth in Table 101.[19] Overall, the evaluation concluded that this portion of the Milwaukee River provided fair habitat for aquatic organisms.

The ratings for the individual habitat characteristics ranged from excellent to poor. In general, the water depth characteristics and discharge and stream bank erosion characteristics were rated as providing excellent and good habitat, respectively, whereas the stream bottom characteristics were rated as providing poor habitat.

Specifically, it was observed that the stream banks were stabilized and little erosion was occurring. A survey of the channel of the Milwaukee River indicated adequate channel capacity to accommodate peak flows and suitable average water depths. These conditions provide good to excellent habitat for aquatic life.

The surveys indicated that extensive stream channelization and bank lining are present, that the lower reaches downstream of Buffalo Street are dredged to maintain navigation, that the river bottom has been affected by severe scouring and deposition, that there is an absence of desired gravel and rubble substrate on the channel bottom, and that the bottom sediments contain toxic metals and organic substances. These conditions provide poor habitat for aquatic life.

Impairing Factors: The DNR evaluation identified the following primary factors as currently limiting the populations of desired fish and other aquatic life within the Milwaukee River estuary:[20] 1) pollutant loadings from combined sewer overflows, urban stormwater runoff, and industrial spills and discharges; 2) toxic substances in the water and in the bottom sediments; and 3) severe scouring and deposition within the river channel.

The DNR evaluation also reported that the impoundments on the Milwaukee River, including the North Avenue dam impoundment located immediately upstream of the Milwaukee River estuary, accumulate sediments and toxic substances, and prevent fish migration and fish access

[18] *Joseph R. Ball, "Stream Classification Guidelines for Wisconsin," Wisconsin Department of Natural Resources Technical Bulletin, 1982.*

[19] *Wisconsin Department of Natural Resources, "Lower Milwaukee River Classification," December 1984.*

[20] *Ibid.*

Table 101

AQUATIC HABITAT RATING FOR THE MILWAUKEE RIVER ESTUARY: 1984

Habitat Characteristic	Rating for Support of Aquatic Life	Description of Habitat Characteristic
Stream Channelization and Bank Lining	Poor	Lower reaches are periodically dredged for maintenance of navigation. Nearly all banks are lined with steel or concrete. Linings do not provide adequate cover or substrate for aquatic life
Stream Bank Erosion	Good	Although the stream banks are not vegetated, there is little observed, or potential for, bank failure because the banks are lined with steel or concrete
Bank Channel Capacity	Good	Ample bank channel capacity exists to accommodate peak flows
Bottom Scouring and Deposition	Poor	Most of the stream bottom is affected by scouring or deposition
Bottom Substrate	Poor	Only a small portion of the channel bottom is composed of desired gravel and rubble substrate. Bottom sediments contain toxic metals and organic substances
Average Water Depth	Excellent	Adequate water depths are present to support year-round residence of fish and aquatic life

Source: Wisconsin Department of Natural Resources and SEWRPC.

to desirable spawning grounds, thereby adversely affecting aquatic life in the stream reaches adjacent to the impoundments.

Menomonee River

Biological data for the Menomonee River estuary were available from the Wisconsin Department of Natural Resources, from CDM/Limnetics Environmental Consultants, and from Limno-Tech, Inc. Data on fishery resources are set forth in the unpublished report entitled, "Menomonee River Classification," July 1985, prepared by the DNR. The report also included an evaluation of the aquatic habitat, and of the factors limiting the populations of desired biological organisms. Data on algae and zooplankton were set forth in Aquatic Studies at Valley, Commerce Street, and Wells Street Power Plants, 1976, prepared by CDM/Limnetics Environmental Consultants for the Wisconsin Electric Power Company. Data on benthic macroinvertebrates are set forth in Field Methodology and Results for Milwaukee Harbor, Kinnickinnic River and Menomonee River prepared by Limno-Tech, Inc., of Ann Arbor, Michigan, for the U. S. Army Engineer District, Detroit, June 1984. Chlorophyll-a and nutrient levels were measured as part of the Milwaukee Harbor estuary study.

Fish: Extensive fishery surveys were conducted in the Menomonee River downstream of the Falk Corporation dam by the DNR in 1983 as part of the Milwaukee Harbor estuary study. The tolerance level, type, and number of fish collected during these surveys are set forth in Table 102. Twenty species of fish were captured within the Menomonee River downstream of the Falk Corporation dam during the 1983 surveys, of which four, or 20 percent, were rated as intolerant of pollution, 10, or 50 percent, were rated as tolerant of pollution, and six or 30 percent, were rated as very tolerant of pollution. The most abundant fish caught were carp, followed by white sucker, rainbow trout, green sunfish, black bullhead, alewife, and bluegill. Redhorse were noticeably absent, in contrast to the Milwaukee River, as were walleye and catfish. Most rainbow trout were caught in the spring, but some were caught in July.

Table 102

TOLERANCE LEVEL, TYPE, AND NUMBER OF FISH COLLECTED DURING THE MILWAUKEE HARBOR ESTUARY FISH SURVEY IN THE MENOMONEE RIVER ESTUARY: 1983

Tolerance Level	Species	Number	Percent of Subtotal	Percent of Total
Intolerant	Brook Trout	1	1.6	0.2
	Brown Trout	1	1.6	0.2
	Rainbow Trout	57	93.5	13.3
	Spottail Shiner	2	3.3	0.5
	Subtotal	61	100.0	14.2
Tolerant	Alewife	20	13.7	4.7
	Black Crappie	1	0.7	0.2
	Bluegill	19	13.0	4.4
	Emerald Shiner	1	0.7	0.2
	Gizzard Shad	7	4.8	1.6
	Northern Pike	1	0.7	0.2
	Pumpkinseed	6	4.1	1.4
	Pumpkinseed-Green Sunfish	5	3.4	1.2
	White Sucker	78	53.4	18.2
	Yellow Perch	8	5.5	1.9
	Subtotal	146	100.0	34.0
Very Tolerant	Black Bullhead	30	13.5	7.0
	Brown Bullhead	1	0.5	0.2
	Carp	151	68.0	35.2
	Carp-Green Sunfish	2	0.9	0.5
	Goldfish	1	0.5	0.2
	Green Sunfish	37	16.6	8.0
	Subtotal	222	100.0	51.8
	Total	429	--	100.0

Source: Wisconsin Department of Natural Resources.

Fish recapture studies indicated that there is little movement of fish between the Menomonee River estuary and the other inner harbor reaches or the outer harbor. The white sucker, carp, green sunfish, and black bullhead recaptured in the Menomonee River were originally caught in the Menomonee River. One bluegill recaptured in the Menomonee River was originally caught in the Milwaukee River.

Concentrations of 16 toxic organic substances and three metals were measured in the tissue of fish taken from the Menomonee River estuary from July 1979 through August 1983. No data were available for the upstream reaches of the Menomonee River. The results of the fish tissue toxic surveys are set forth in Table 103. The presence of toxic substances in fish tissue may, in some instances, pose a health threat to humans consuming the fish.

Polychlorinated biphenyl (PCB) concentrations in the tissue of fish taken from the Menomonee River were lower than those found in the tissue of fish taken from the Milwaukee and Kinnickinnic Rivers, but higher than those found in the tissue of fish taken from the outer harbor. The PCB concentrations in the tissue of fish taken from the Menomonee River estuary ranged from 1.2 ppm in a white sucker captured on August 2, 1983, to 88 ppm in a carp captured in July 1979. Because the levels of PCB's in the tissue of fish taken from the Menomonee River often exceeded the health standard of a maximum fish tissue concentration of 2 ppm established by the U. S. Food and Drug Administration, the DNR has issued a health advisory for persons consuming fish from the Menomonee River estuary, as well as from the remainder of the inner harbor, and from the outer harbor. That health advisory, as of April 1985, suggested that pregnant women, nursing mothers, women who wish to bear children, and children not consume redhorse, rock bass, and smallmouth bass under 13 inches in length, and that no one consume carp or northern pike. Perch were noted as posing the lowest health risk to consumers.

Levels of the pesticide DDT (dichloro-diphenyl-trichloro-ethane) found in the tissue of fish taken from the Menomonee River ranged from less than 0.23 ppm in a white sucker captured on August 2, 1983, to 2.98 ppm in a carp captured in July 1979. The U. S. Food and Drug Administration health standard for DDT in fish tissue is a maximum of 5 ppm.

The concentrations of several metals in fish tissues were also measured by the DNR. Concentrations of chromium were found to be below the minimum level of detection, as shown in Table 103. Copper concentrations ranged from 1.2 ppm in a carp captured on July 9, 1979, to 2 ppm in a goldfish also captured on July 9, 1979. Mercury concentrations ranged from 0.03 ppm in a carp and in a goldfish captured on July 9, 1979, to 0.10 ppm in a carp also captured on July 9, 1979. The U. S. Food and Drug Administration health standard for mercury concentrations in fish tissue is a maximum of 1 ppm.

Benthic Macroinvertebrates: In 1984 a total of 17 species of benthic macroinvertebrates were identified at five stations in the Menomonee estuary.[21]

[21] *Limno-Tech, Inc., Field Methodology and Results for Milwaukee Harbor, Kinnickinnic River and Menomonee River, prepared for the U. S. Army Engineer District, Detroit, June 1984.*

Table 103

CONCENTRATIONS OF TOXIC ORGANIC SUBSTANCES AND METALS IN THE TISSUE OF FISH IN THE MENOMONEE RIVER ESTUARY: 1979-1983

Toxic Substance	Carp			White Sucker			Bluegill			Goldfish		
	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean
Dates of Sampling	July 9, 1979 to August 10, 1983			August 2, 1983			August 2, 1983			July 9, 1979		
Organics												
PCB's	3	9.3-88.0	36.4	1	--	1.2	1	--	3.5	1	--	21.0
Aldrin	1	--	<0.15	1	--	<0.05	1	--	<0.05	--	--	--
Dieldrin	3	<0.02-0.06	0.03	1	--	<0.02	1	--	<0.02	1	--	0.02
Endrin	1	--	<0.02	1	--	<0.02	1	--	<0.02	--	--	--
DDT	3	0.08-2.98	1.62	1	--	0.23	1	--	1.30	1	--	1.28
DDE	2	0.35-1.3	0.82	--	--	--	--	--	--	1	--	0.28
OP-DDD	2	0.09-0.23	0.16	--	--	--	--	--	--	1	--	0.13
PP-DDD	2	0.36-1.4	0.88	--	--	--	--	--	--	1	--	0.87
Chlordane	3	<0.05-0.29	0.07	1	--	<0.05	1	--	<0.05	1	--	0.05
Hexachlorobenzene	2	--	<0.01	1	--	<0.05	1	--	<0.05	--	--	--
Hexachlorocyclohexane	1	--	<0.01	1	--	<0.01	1	--	<0.01	--	--	--
Methoxychlor	1	--	<0.05	1	--	<0.05	1	--	<0.05	--	--	--
Heptachlor	1	--	<0.05	1	--	<0.05	1	--	<0.05	--	--	--
Pentachloroanisol	1	--	<0.05	1	--	<0.05	1	--	<0.05	--	--	--
Toxaphene	1	--	<1.0	1	--	<1.0	1	--	<1.0	--	--	--
T-Nonachlor	2	0.05	0.05	--	--	--	--	--	--	--	--	--
Metals												
Chromium	1	--	<0.5	1	--	<0.5	1	--	<0.5	--	--	--
Copper	3	1.2-1.8	1.5	1	--	1.4	1	--	1.3	1	--	2.0
Mercury	3	0.03-0.10	0.06	1	--	0.04	1	--	0.06	1	--	0.03

NOTE: All concentrations are in parts per million.

Source: Wisconsin Department of Natural Resources.

The locations of the sampling stations are shown on Map 95, and the species are listed in Table 104. Oligochaetes always were found to compose over 92 percent of the total benthic fauna present. Limnodrilus species were found to be the most abundant organisms. Many of the oligochaete species found are associated with organically enriched habitats. All of the species identified were rated as tolerant of pollution.

Algae: Phytoplankton were surveyed during January, March, and May of 1976 at three stations in the Menomonee River estuary.[22] Table 105 lists the type and relative abundance of the algae within the Menomonee River during this sampling period. Figure 152 illustrates the seasonal changes in the various types of algae in the Menomonee River at S. 16th Street. As shown in the figure, the total number of algae was about three and one-half times higher in May than in January, and the green algae (Chlorophytes) were the most dominant algal type in all three months sampled. While the sampling period did not include the summer months, it is probable that the green algae (Chlorophytes) and blue-green algae (Cyanophytes) would be dominant during the summer.

Chlorophyll-a, an indicator of algal biomass, was measured in the Menomonee River over the period 1981 through 1983 as part of the Milwaukee Harbor estuary study. A statistical summary of

[22] *Ibid.*

Table 104

BENTHIC MACROINVERTEBRATES INDENTIFIED WITHIN THE MENOMONEE RIVER ESTUARY: 1984

Species	Population Density (number/feet²) Sampling Station[a] 1	2	3	4	5
Class Oligochaeta[b]					
Ilyodrilus templetoni	--	--	--	--	≥ 8
Limnodrilus cervix	≥228	≥224	≥124	≥268	≥ 24
Limnodrilus claparedianus	--	--	--	≥ 12	--
Limnodrilus hoffmeisteri	≥340	≥168	≥476	≥252	≥356
Limnodrilus udekemianus	≥ 4	≥ 20	≥ 4	--	≥252
Lumbricillus sp	--	--	--	--	≥ 40
Potamothrix moldaviensis	--	--	≥ 4	--	--
Quistadrilus multisetosus	≥136	≥156	≥128	≥ 72	--
Tubifex tubifex	≥132	≥ 40	≥108	≥196	≥ 92
Unidentified Immature Oligochaeta with Capilliform Chaeta	≥ 8	≥ 12	≥ 12	≥ 44	≥ 20
Unidentified Immature Oligochaeta without Capilliform Chaeta	≥ 20	≥228	≥ 12	≥ 52	≥ 96
Total	≥868	≥848	≥868	≥896	≥888
Class Insecta					
Ceratoposonidae pupae	--	--	--	--	4
Chironomidae pupae	--	--	--	--	4
Total	--	--	--	--	8
Class Gastropoda					
Valvata sincera	44	--	12	--	--
Total	44	--	12	--	--
Class Pelecypoda					
Sphaerium sp	12	--	--	--	--
Total	12	--	--	--	--
Class Hirudinea					
Helobdella stagnalis	--	--	--	--	4
Total	--	--	--	--	4
Class Tubellaria					
Tubellaria sp	16	--	--	--	--
Total	16	--	--	--	--

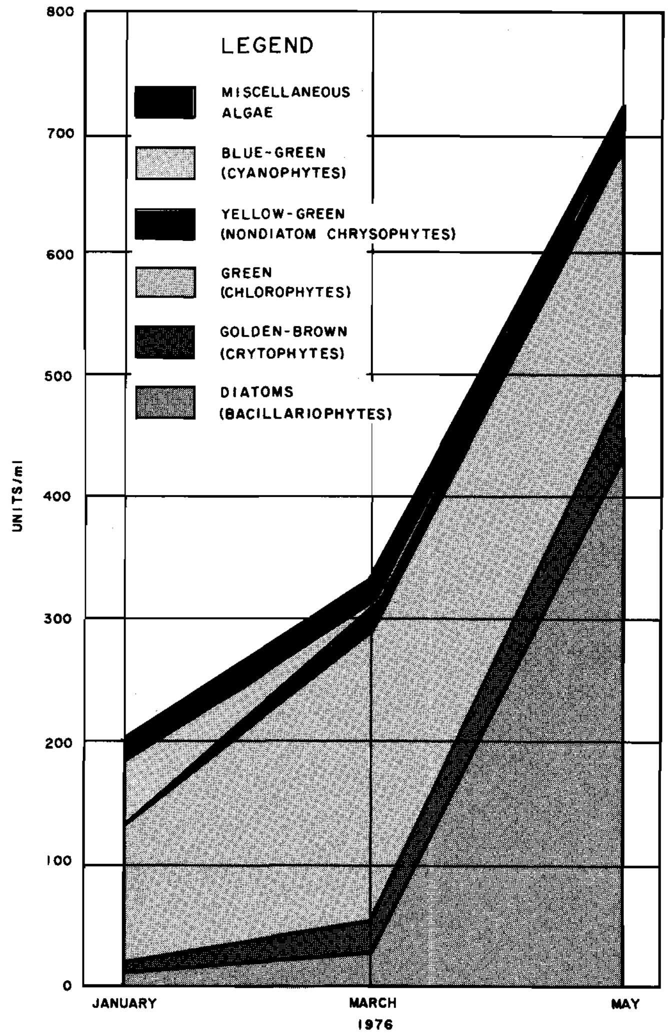
[a]*Sampling station locations are shown on Map 95.*

[b]*Because the number of Oligochaetes was very high within each sample, only a limited number of individuals was counted to provide a representative distribution of species.*

Source: Limno-Tech, Inc.

Figure 152

PHYTOPLANKTON SURVEYED IN THE MENOMONEE RIVER AT S. 16TH STREET: 1976



Source: CDM/Limnetics Environmental Consultants.

the observed chlorophyll-a levels at two stations within the Menomonee River estuary is set forth in Table 106. The table summarizes annual levels—measured over the entire year—and summer levels—measured during June, July, and August. The mean annual concentrations of chlorophyll-a were found to range from 12.5 µg/l at Muskego Avenue to 16.8 µg/l at S. 2nd Street. The mean summer concentrations of chlorophyll-a were found to be about 5 to 53 percent higher than the annual means, and to range from 17.7 µg/l at S. 2nd Street to 19.1 µg/l at Muskego Avenue. The maximum concentration of chlorophyll-a of 105.6 µg/l was measured on July 27, 1981, at Muskego Avenue. Maximum summer, mean summer, and mean annual chlorophyll-a levels are plotted on Figure 153. Peak chlorophyll-a levels were generally reached at Muskego Avenue and decreased downstream.

Plots of chlorophyll-a, inorganic nitrogen, and soluble phosphorus versus time at the two stations on the Menomonee River over the period 1981 through 1983 are shown in Figure 154. The plots

Table 105

TYPE AND ABUNDANCE OF PHYTOPLANKTON SURVEYED WITHIN THE MENOMONEE RIVER ESTUARY: 1976[a]

Species	January 21						March 9						May 1					
	Station 1		Station 2		Station 3		Station 1		Station 2		Station 3		Station 1		Station 2		Station 3	
	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent
Chlorophyta	61	45.2	64	38.8	111	55.5	412	85.8	394	78.6	237	72.3	1,025	65.0	125	23.4	198	28.1
Chlamydomonas spp . .	6	4.4	8	4.8	94	47.0	406	84.6	383	76.4	233	71.1	1,001	63.5	99	18.5	188	26.7
Gloeocystis spp	10	7.4	14	8.5	7	3.5	--	--	--	--	--	--	--	--	--	--	--	--
Ankistrodesmus falcatus	9	6.7	7	4.2	1	0.5	--	--	--	--	--	--	--	--	--	--	--	--
Scenedesmus quadricauda.	19	14.1	17	10.4	1	0.5	--	--	--	--	--	--	--	--	--	--	--	--
Unidentified Chlorophytes.	17	12.6	18	10.9	8	4.0	6	1.2	11	2.2	4	1.2	24	1.5	26	4.9	10	14
Euglenophyta	--	--	--	--	--	--	--	--	--	--	--	--	6	0.4	7	1.3	6	0.9
Pyrrhophyta	1	0.7	1	0.6	--	--	7	1.5	7	1.4	5	1.5	1	0.1	--	--	--	--
Cryptophyta.	7	5.2	10	6.1	8	4.0	15	3.1	20	4.0	27	8.2	106	6.7	110	20.6	64	9.1
Chroomonas spp.	--	--	--	--	--	--	5	1.0	7	1.4	16	4.9	74	4.7	79	14.8	34	4.8
Cryptomonas spp	--	--	--	--	--	--	--	--	--	--	--	--	28	1.8	31	5.8	30	4.3
Unidentified Cryptophytes.	7	5.2	10	6.1	8	4.0	10	2.0	13	2.6	11	3.3	4	0.2	--	--	--	--
Chrysophyceae	2	1.5	3	1.8	1	0.5	7	1.5	16	3.2	15	4.6	19	1.2	22	4.1	22	3.1
Diatomaceae.	38	28.2	47	28.5	10	5.0	31	6.4	22	4.4	25	7.6	375	23.8	255	47.7	411	58.4
Centrales spp.	10	7.4	8	4.9	3	1.5	--	--	--	--	--	--	190	12	77	14.4	234	33.3
Cyclotella spp	10	7.4	6	3.6	--	--	--	--	--	--	--	--	151	9.6	134	25.1	146	20.7
Fragilaria pinnata	6	4.4	9	5.5	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Unidentified Diatoms. .	12	9.0	24	14.5	7	3.5	31	6.4	22	4.4	25	7.6	34	2.2	44	8.2	31	4.4
Cyanophyta	11	8.1	18	10.9	55	27.5	--	--	1	0.2	3	0.9	33	2.1	12	2.2	--	--
Chroococcus spp.	6	4.4	15	9.1	51	25.5	--	--	--	--	--	--	--	--	--	--	--	--
Unidentified Cyanophytes	5	3.7	3	1.8	4	2.0	--	--	1	0.2	3	0.9	33	2.1	12	2.2	--	--
Unidentified Phytoplankton	15	11.1	22	13.3	15	7.5	8	1.7	41	8.2	16	4.9	12	0.7	4	0.7	3	0.4
Total Phytoplankton	135	100.0	165	100.0	200	100.0	480	100.0	501	100.0	328	100.0	1,577	100.0	535	100.0	704	100.0

Station 1: South Menomonee Canal at WEPCo outfall
Station 2: Confluence of Burnham Canal and Menomonee River
Station 3: Menomonee River at S. 16th Street

[a] *All means are expressed as units per milliliter.*

Source: CDM/Limnetics Environmental Consultants.

Table 106

SUMMARY OF CHLOROPHYLL-a CONCENTRATIONS WITHIN THE MENOMONEE RIVER ESTUARY: 1981-1983

Sampling Station	Period	Number of Samples	Chlorophyll-a (µg/l)			
			Minimum	Mean	Maximum	Standard Deviation
Muskego Avenue	Annual	94	0.6	12.5	105.6	15.7
	Summer	50	3.6	19.1	105.6	18.2
S. 2nd Street	Annual	26	2.5	16.8	46.2	9.1
	Summer	24	2.6	17.7	46.2	8.9

Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

do not provide a clear indication as to whether nitrogen or phosphorus levels limit the growth of algae in the Menomonee River.

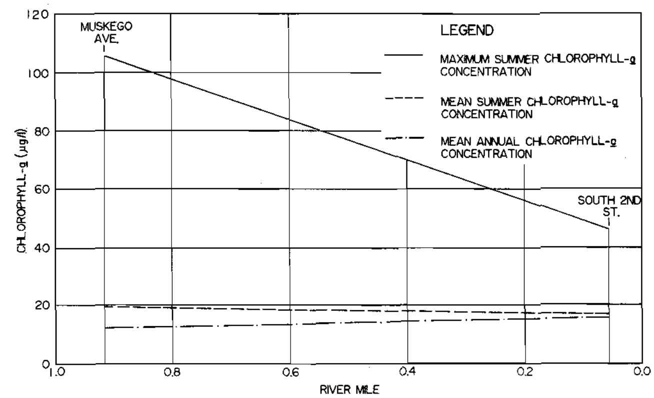
Zooplankton: Zooplankton were surveyed during January, March, and May of 1976 at three stations in the Menomonee River estuary.[23] Table 107 lists the species, number, and relative abundance of zooplankton collected during the surveys. As shown in the table, rotifers were the dominant type of zooplankton collected at all stations, except during January at the South Burnham Canal station when copepods were dominant.

Habitat Evaluation: The aquatic habitat in the Menomonee River estuary was evaluated by the DNR and Regional Planning Commission using

[23] *Ibid.*

Figure 153

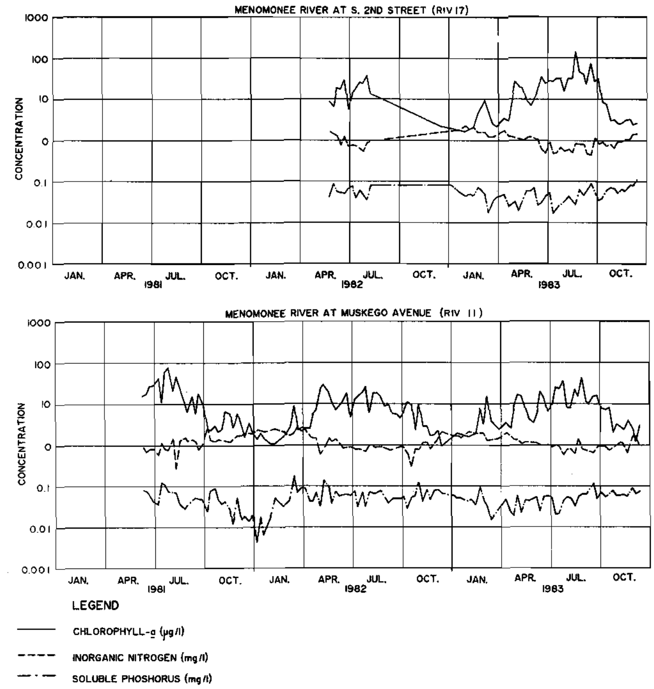
MAXIMUM SUMMER, MEAN SUMMER, AND MEAN ANNUAL CHLOROPHYLL-a LEVELS WITHIN THE MENOMONEE RIVER ESTUARY: 1981-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Figure 154

CHLOROPHYLL-a, INORGANIC NITROGEN, AND SOLUBLE PHOSPHORUS CONCENTRATIONS WITHIN THE MENOMONEE RIVER ESTUARY: 1981-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

the stream system habitat evaluation system developed by Ball.[24] Ball's habitat evaluation system was modified, however, to be more applicable to an estuarine environment. The habitat rating for the reach of the Menomonee River extending from Lake Michigan to the Falk Corporation dam is set forth in Table 108.[25] Overall, the evaluation concluded that this portion of the Menomonee River provided fair habitat for aquatic organisms.

The ratings for the individual habitat characteristics ranged from excellent to poor. In general, the water depth characteristics and discharge and stream bank erosion characteristics were rated as providing excellent and good habitat, respectively, whereas the stream bottom characteristics were rated as providing poor habitat.

Specifically, it was observed that the stream banks were stabilized and little erosion was occurring. A survey of the channel of the Menomonee River indicated adequate channel capacity to accommodate peak flows and suitable average water depths. These conditions provide good to excellent habitat for aquatic life.

The surveys indicated that extensive stream channelization and bank lining are present, that the harbor was periodically dredged to maintain navigation, that the river bottom was affected by severe scouring and deposition, that there was an absence of desired gravel and rubble substrate on the channel bottom, and that the bottom sediments contained toxic metals and organic substances. These conditions provide poor habitat for aquatic life.

Impairing Factors: The DNR identified the following primary factors as currently limiting the populations of desired fish and other aquatic life within the Menomonee River estuary: [26] 1) pollutant loadings from combined sewer overflows, urban stormwater runoff, and industrial spills and discharges; 2) toxic substances in the water and in the bottom sediments; and 3) severe scouring and deposition within the river channel.

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[24] *Joseph R. Ball, "Stream Classification Guidelines for Wisconsin," Wisconsin Department of Natural Resources Technical Bulletin, 1982.*

[25] *Wisconsin Department of Natural Resources, "Menomonee River Classification," July 1985.*

[26] *Ibid.*

Table 107

TYPE AND ABUNDANCE OF ZOOPLANKTON SURVEYED WITHIN THE MENOMONEE RIVER ESTUARY: 1976[a]

Species	January 21						March 9						May 1					
	Station 1		Station 2		Station 3		Station 1		Station 2		Station 3		Station 1		Station 2		Station 3	
	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent	Mean	Percent
Rotifera																		
Keratella spp. . .	--	--	--	--	--	--	6,634	25.1	1,467	14.3	103	1.8	7,496	8.1	3,873	13.2	4,060	10.7
Polyarthra spp. .	--	--	--	--	--	--	2,061	7.8	148	1.4	153	2.7	--	--	--	--	--	--
Synchaeta spp. .	419	0.8	716	7.2	147	1.1	2,400	9.5	5,244	51.1	3,582	63.4	3,363	3.6	2,380	8.1	4,200	11.1
Filinia longiseta .	12,722	24.9	1,649	16.6	453	3.4	--	--	--	--	--	--	31,213	33.6	5,460	18.6	3,967	10.5
Bdelloidea spp. .	5,691	11.1	4,027	40.4	7,640	57.2	3,861	14.6	1,630	15.9	739	13.1	15,733	16.9	8,073	27.5	12,647	33.5
Cladocera	84	0.2	14	0.1	--	--	1,852	7.0	593	5.8	148	2.6	1,852	2.0	233	0.8	280	0.8
Copepoda																		
Calanoida.	405	0.8	54	0.5	67	0.5	--	--	--	--	--	--	--	--	47	0.2	47	0.1
Cyclopoida. . . .	4,479	8.7	514	5.2	2,173	16.3	1,036	3.9	104	1.0	93	1.7	1,911	2.1	840	2.9	1,400	3.7
Harpacticoida . .	--	--	--	--	--	--	--	--	15	0.2	41	0.7	104	0.1	--	--	47	0.1
Unidentified Copepods. . . .	27,392	53.5	2,987	30.0	2,880	21.5	8,551	32.5	1,052	10.3	791	14.0	31,273	33.6	8,400	28.7	11,153	29.5
Total Zooplankton	51,192	100.0	9,961	100.0	13,360	100.0	26,395	100.0	10,253	100.0	5,650	100.0	92,945	100.0	29,306	100.0	37,801	100.0

Station 1: South Menomonee Canal at WEPCo outfall
Station 2: Confluence of Burnham Canal and Menomonee River
Station 3: Menomonee River at S. 16th Street

[a] *All means are expressed as units per milliliter.*

Source: CDM/Limnetics Environmental Consultants.

Table 108

AQUATIC HABITAT RATING FOR THE MENOMONEE RIVER ESTUARY: 1984

Habitat Characteristic	Rating for Support of Aquatic Life	Description of Habitat Characteristic
Stream Channelization and Bank Lining	Poor	Harbor is periodically dredged for maintenance of navigation and the entire harbor is channelized. Banks are lined with steel or concrete. Linings do not provide adequate cover or substrate for aquatic life
Stream Bank Erosion	Good	Although the stream banks are not vegetated, there is little observed, or potential for, bank failure because the banks are lined with steel or concrete
Bank Channel Capacity	Good	Ample bank channel capacity exists to accommodate peak flows
Bottom Scouring and Deposition	Poor	Most of the stream bottom is affected by scouring or deposition
Bottom Substrate	Poor	Only a small portion of the channel bottom is composed of desired gravel and rubble substrate. Bottom sediments contain toxic metals and organic substances
Average Water Depth	Excellent	Adequate water depths are present to support year-round residence of fish and other aquatic life

Source: Wisconsin Department of Natural Resources and SEWRPC.

Kinnickinnic River

Biological data for the Kinnickinnic River estuary were available from the Wisconsin Department of Natural Resources. Data on fishery resources were set forth in the unpublished report entitled, "Kinnickinnic River Classification," November 1984, prepared by the DNR. That report also included an evaluation of the aquatic habitat, and of the factors impairing the survival of desired biological organisms. Algal data collected by the DNR are set forth in the "Milwaukee County Basins Assessment Report," 1976. There were no zooplankton data available for the Kinnickinnic River estuary. Data on benthic macroinvertebrates are set forth in Field Methodology and Results for Milwaukee Harbor, Kinnickinnic River and Menomonee River prepared by Limno-Tech, Inc., of Ann Arbor, Michigan, for the U. S. Army Engineer District, Detroit, June 1984. Chlorophyll-a levels were measured as part of the Milwaukee Harbor estuary study.

Fish: Extensive fishery surveys were conducted in the Kinnickinnic River downstream of Chase Avenue by the DNR in 1983 as part of the Milwaukee Harbor estuary study. The tolerance level, type, and number of fish collected during these surveys are set forth in Table 109. Twenty-three species of fish were captured within the Kinnickinnic River downstream of Chase Avenue during the 1983 surveys, of which six, or 26 percent, were rated as intolerant of pollution, 12, or 52 percent, were rated as tolerant of pollution, and five, or 22 percent, were rated as very tolerant of pollution. The most abundant fish caught were white sucker, followed by black bullhead, rainbow trout, and carp. Three species of minnows were caught: the golden shiner, the spottail shiner, and the common shiner. Most rainbow trout were caught in May and June.

Fish recapture studies indicated that there is little movement of fish between the Kinnickinnic River estuary and the other inner harbor reaches or the outer harbor. Four of the six white sucker and the two black bullhead recaptured in the Kinnickinnic River were originally caught in the Kinnickinnic River. The remaining two white sucker were originally caught in the Milwaukee River and the South Shore Harbor.

Concentrations of 16 toxic organic substances and three metals were measured in the tissue of fish taken from the Kinnickinnic River estuary from September 1977 through August 1983, and of nine toxic organic substances and three metals in the tissue of fish taken from the upstream reaches of the Kinnickinnic River from September 1977 through September 1980. The results of the fish tissue toxic surveys are set forth in Tables 110 and 111. The presence of toxic substances in fish tissue may, in some instances, pose a health threat to humans consuming the fish.

Polychlorinated biphenyl (PCB) concentrations in the tissue of fish taken from the Kinnickinnic River estuary were generally higher than those in the tissue of fish taken from the Menomonee River and in the outer harbor, but lower than those in the tissue of fish found in the Milwaukee River. The PCB concentrations within the tissue of fish taken from the Kinnickinnic River estuary were

Table 109

TOLERANCE LEVEL, TYPE, AND NUMBER OF FISH COLLECTED DURING THE MILWAUKEE HARBOR ESTUARY FISH SURVEY IN THE KINNICKINNIC RIVER ESTUARY: 1983

Tolerance Level	Species	Number	Percent of Subtotal	Percent of Total
Intolerant	Brook Trout	2	2.1	0.4
	Brown Trout	2	2.1	0.4
	Chinook Salmon	2	2.1	0.4
	Coho Salmon	10	10.4	1.8
	Rainbow Trout	78	81.2	14.4
	Spottail Shiner	2	2.1	0.4
	Subtotal	96	100.0	17.8
Tolerant	Alewife	19	6.7	3.5
	Black Crappie	7	2.5	1.3
	Bluegill	9	3.2	1.7
	Common Shiner	2	0.7	0.4
	Gizzard Shad	2	0.7	0.4
	Golden Shiner	5	1.8	0.9
	Largemouth Bass	1	0.3	0.2
	Northern Pike	8	2.8	1.5
	Pumpkinseed	5	1.8	0.9
	Rock Bass	1	0.3	0.2
	White Sucker	225	78.9	41.7
	Yellow Perch	1	0.3	0.2
	Subtotal	285	100.0	52.8
Very Tolerant	Black Bullhead	82	51.6	15.2
	Carp	70	44.0	13.0
	Goldfish	3	1.9	0.5
	Goldfish-Carp	1	0.6	0.2
	Green Sunfish	3	1.9	0.5
	Subtotal	159	100.0	29.4
	Total	540	--	100.0

Source: Wisconsin Department of Natural Resources.

Table 110

CONCENTRATIONS OF TOXIC ORGANIC SUBSTANCES AND METALS IN THE TISSUE OF FISH IN THE KINNICKINNIC RIVER ESTUARY: 1980-1983

Toxic Substance	Carp			White Sucker			Bluegill			Goldfish			Northern Redhorse		
	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean
Dates of Sampling	July 2, 1980 to August 8, 1983			August 12, 1983			August 16, 1983			July 8, 1981			July 2, 1980		
Organics															
PCB's	5	4.1-34.0	17.6	1	--	6.2	1	--	6.2	1	--	21.0	1	--	2.7
Aldrin	1	--	< 0.40	1	--	<0.10	1	--	<0.05	--	--	--	--	--	--
Dieldrin	4	0.02-0.15	0.07	1	--	<0.02	1	--	0.02	1	--	0.03	1	--	0.04
Endrin	1	--	< 0.02	1	--	<0.02	1	--	<0.02	--	--	--	--	--	--
DDT	2	1.43-1.65	1.54	1	--	0.22	1	--	1.18	--	--	--	1	--	0.17
PP-DDE	4	0.08-1.3	0.53	--	--	--	--	--	--	1	--	0.63	1	--	0.12
OP-DDD	1	--	0.11	--	--	--	--	--	--	1	--	0.05	--	--	--
PP-DDD	4	0.14-0.94	0.40	--	--	--	--	--	--	1	--	0.05	1	--	0.05
Chlordane	3	0.05-0.43	0.18	1	--	<0.05	1	--	<0.05	--	--	--	1	--	<0.05
Hexachlorobenzene	2	<0.05-0.05	0.02	1	--	<0.05	1	--	<0.05	--	--	--	--	--	--
Hexachlorocyclohexane	1	--	<0.01	1	--	<0.01	1	--	<0.01	--	--	--	--	--	--
Heptachlor	1	--	<0.05	1	--	<0.05	1	--	<0.05	--	--	--	--	--	--
Methoxychlor	1	--	<0.05	1	--	<0.05	1	--	<0.05	--	--	--	--	--	--
Pentachloroanisol	1	--	<0.05	1	--	<0.05	1	--	<0.05	--	--	--	--	--	--
Toxaphene	1	--	<1.0	1	--	<1.0	1	--	<1.0	--	--	--	--	--	--
T-Nonachlor	2	0.04-0.05	0.04	--	--	--	--	--	--	--	--	--	--	--	--
Metals															
Chromium	1	--	<0.5	1	--	<0.5	1	--	<0.5	--	--	--	--	--	--
Copper	3	1.6-2.6	2.2	1	--	1.6	1	--	1.3	--	--	--	--	--	--
Mercury	2	0.04-0.1	0.07	1	--	0.03	1	--	0.05	1	--	0.18	--	--	--

NOTE: All concentrations are in parts per million.

Source: Wisconsin Department of Natural Resources.

also higher than those in the tissue of fish taken from the upstream reaches of the Kinnickinnic River. The PCB concentrations in the tissue of fish taken from the Kinnickinnic River estuary ranged from 2.7 ppm in a northern redhorse captured on July 2, 1980, to 34 ppm in a carp captured on July 2, 1980. The PCB concentrations in the tissue of fish taken from upstream reaches ranged from 2.6 ppm in a northern pike captured on September 17, 1980, to 18 ppm in a goldfish captured on August 15, 1978. Because the levels of PCB's in the tissue of fish taken from the Kinnickinnic River often exceeded the health standard of a maximum fish tissue concentration of 2 ppm established by the U. S. Food and Drug Administration, the DNR has issued a health advisory for persons consuming fish taken from the Kinnickinnic River estuary, as well as from the remainder of the inner harbor, and from the outer harbor. That health advisory, as of April 1985, suggested that pregnant women, nursing mothers, women who wish to bear children, and children not consume redhorse, rock bass, and smallmouth bass under 13 inches in length, and that no one consume carp or northern pike. Perch were noted as posing the lowest health risk to consumers.

Levels of the pesticide DDT (dichloro-diphenyl-trichloro-ethane) in the tissue of fish taken from the Kinnickinnic River estuary ranged from 0.12 ppm in a northern redhorse captured on July 2, 1980, to 1.65 ppm in a carp captured on August 8, 1983. The DDT concentration in the upstream portion of the Kinnickinnic River ranged from less than

Table 111

CONCENTRATIONS OF TOXIC ORGANIC SUBSTANCES AND METALS IN THE TISSUE OF FISH IN THE KINNICKINNIC RIVER UPSTREAM REACHES: 1977-1980

Toxic Substance	Carp			White Sucker			Goldfish			Northern Pike			Rainbow Trout		
	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean
Dates of Sampling	September 15, 1977 to September 17, 1980			September 17, 1980			August 15, 1978 to July 9, 1979			September 17, 1980			September 15, 1977 to November 10, 1977		
Organics															
PCB's	6	4.2-17.0	10.5	1	--	20.0	5	12.0-18.0	16.4	1	--	2.6	3	5.7-7.4	6.3
Dieldrin	2	0.12-0.23	0.18	--	--	--	2	0.03	0.03	--	--	--	2	0.01-0.09	0.05
Endrin	1	--	0.02	--	--	--	--	--	--	--	--	--	--	--	--
DDT	4	<0.01-2.11	1.22	1	--	1.07	3	0.22-1.02	0.74	1	--	0.14	1	--	1.9
PP-DDE	3	0.32-1.6	0.86	1	--	0.88	2	0.3-0.57	0.43	1	--	0.68	2	1.0-1.9	1.4
PP-DDD	3	0.2-0.51	0.35	1	--	0.19	3	0.22-0.68	0.45	1	--	0.06	1	--	0.20
Chlordane	2	0.2-0.61	0.40	--	--	--	3	0.16-0.19	0.18	--	--	--	--	--	--
Hexachlorobenzene	1	--	0.05	--	--	--	--	--	--	--	--	--	--	--	--
Hexachlorocyclohexane	1	--	0.03	--	--	--	--	--	--	--	--	--	--	--	--
Metals															
Chromium	1	--	0.5	1	--	0.8	--	--	--	--	--	--	--	--	--
Copper	5	1.8-3.7	2.5	1	--	5.0	2	1.3-1.5	1.4	1	--	2.3	2	0.09-0.9	0.50
Mercury	4	0.02-0.16	0.08	1	--	0.03	2	0.01-0.03	0.02	1	--	0.21	1	--	0.14

NOTE: All concentrations are in parts per million.

Source: Wisconsin Department of Natural Resources.

0.01 ppm in a carp captured on September 15, 1977, to 2.11 ppm in a carp captured on July 9, 1979. The U. S. Food and Drug Administration health standard for DDT in fish tissue is a maximum of 5 ppm.

Concentrations of several metals in the tissue of fish were also measured by the DNR. Concentrations of chromium within the Kinnickinnic River estuary were below the minimum level of detection, as shown in Table 110. Copper concentrations ranged from 1.3 ppm in a bluegill captured on August 16, 1983, to 2.6 ppm in a carp captured on August 8, 1983. Mercury concentrations ranged from 0.03 ppm in a white sucker captured on August 12, 1983, to 0.18 ppm in a goldfish captured on July 8, 1981. Within the upstream portion of the Kinnickinnic River, chromium concentrations ranged from 0.5 ppm in a carp captured on September 17, 1980, to 0.8 ppm in a white sucker also captured on September 17, 1980. Copper concentrations ranged from 0.09 ppm in a rainbow trout captured on September 15, 1977, to 5 ppm in a white sucker captured on September 17, 1980. Mercury concentrations ranged from 0.01 ppm in a goldfish captured on August 15, 1978, to 0.21 ppm in a northern pike captured on September 17, 1980. The U. S. Food and Drug Administration health standard for mercury concentrations in fish tissue is a maximum of 1 ppm.

Benthic Macroinvertebrates: In 1984, a total of 18 species of benthic macroinvertebrates were identified at four stations in the Kinnickinnic River estuary.[27] The locations of the sampling stations are shown on Map 95, and the species are listed in Table 112. Oligochaetes always were found to compose over 63 percent of the total benthic fauna present. Limnodrilus species were generally found to be the most abundant organism. All of the species identified were rated as tolerant of pollution. In addition, the Wisconsin Department of Natural Resources reported that the soft mucky substrates, anaerobic sediments, and in-place

[27] *Limno-Tech, Inc., Field Methology and Results for Milwaukee Harbor, Kinnickinnic River and Menomonee River, prepared for the U. S. Army Engineer District, Detroit, June 1984.*

Table 112

BENTHIC MACROINVERTEBRATES IDENTIFIED WITHIN THE KINNICKINNIC RIVER ESTUARY: 1984

Species	Population Density (number/feet²) Sampling Station[a] 1	2	3	4
Class Oligochaeta[b]				
Aulodrilus pluriseta	≥ 4	- -	- -	- -
Ilyodrilus templetoni	≥ 8	≥224	≥ 60	≥ 32
Limnodrilus cervix	≥ 24	≥ 60	≥ 40	≥ 8
Limnodrilus hoffmeisteri	≥216	≥240	≥364	≥440
Limnodrilus udekemianus	- -	≥ 4	≥ 16	≥ 4
Potamothrix moldaviensis	≥ 68	- -	- -	- -
Quistadrilus multisetosus	≥248	≥128	≥212	≥236
Tubifex tubifex	≥ 88	≥120	≥ 68	≥128
Unidentified Immature Oligochaeta with Capilliform Chaeta	≥ 44	≥ 44	≥ 36	≥ 12
Unidentified Immature Oligochaeta without Capilliform Chaeta	≥156	≥ 20	≥ 28	≥ 8
Total	≥856	≥840	≥824	≥868
Class Insecta				
Procladius sp	8	8	- -	28
Total	8	8	- -	28
Class Gastropoda				
Bithynia tentaculata	104	- -	- -	64
Valvata sincera	16	32	8	248
Total	120	32	8	312
Class Pelecypoda				
Pisidium sp	12	- -	4	12
Sphaerium sp	24	32	12	156
Total	36	32	16	168
Class Crustacea				
Asellus sp	- -	8	- -	- -
Total	- -	8	- -	- -
Class Hirudinea				
Helobdella stagnalis	8	- -	- -	- -
Hirudinea sp	8	- -	- -	- -
Total	16	- -	- -	- -

[a] *Sampling station locations are shown on Map 95.*

[b] *Because the number of Oligochaetes was very high within each sample, only a limited number of individuals was counted to provide a representative distribution of species.*

Source: Limno-Tech, Inc.

pollutants present within the Kinnickinnic River downstream of Chase Avenue would support only benthic organisms very tolerant of pollution.

Algae: Periphytic diatoms were identified and quantified in the Kinnickinnic River just upstream of the inner harbor by the Wisconsin Department of Natural Resources over the period 1975 to 1976.[28] Periphytic diatom genera identified from July 1975 to May 1976 are set forth in Table 113. Surirella and Gomphonema were the most common genera sampled.

Table 113

TYPE AND ABUNDANCE OF PERIPHYTIC GENERA SAMPLED IN THE KINNICKINNIC RIVER AT S. 6TH STREET: 1975-1976

Genera	Relative Abundance (percent) July 1975	October 1975	May 1976
Achnanthes	- -	- -	1
Gomphonema	89	- -	5
Fragilaria	10	- -	- -
Nitzschia	< 1	10	3
Navicula	- -	17	1
Cocconeis	< 1	- -	- -
Surirella	- -	63	90
Synedra	- -	- -	< 1
Pinnularia	- -	9	- -
Cyclotella	- -	1	- -
Total	100	100	100

Source: Wisconsin Department of Natural Resources.

Chlorophyll-a, an indicator of algal biomass, was measured in the Kinnickinnic River over the period 1981 through 1983 as part of the Milwaukee Harbor estuary study. A statistical summary of the observed chlorophyll-a levels at three stations on the Kinnickinnic River estuary is set forth in Table 114. The table summarizes annual levels—measured over the entire year—and summer levels—measured during June, July, and August. The mean annual concentrations of chlorophyll-a ranged from 9.1 μg/l at S. 1st Street to 12.9 μg/l at the Jones Island Ferry. The mean summer concentrations of chlorophyll-a were about 14 to 41 percent higher than the annual means and ranged from 10.4 μg/l at S. 1st Street to 18.2 μg/l at the Jones Island Ferry. The maximum concentration of chlorophyll-a of 119.3 μg/l was measured on May 4, 1982, at S. 1st Street. Maximum summer, mean summer, and mean annual chlorophyll-a levels are plotted on Figure 155. Peak summer chlorophyll-a levels were reached at Jones Island Ferry.

[28] *Wisconsin Department of Natural Resources, "Milwaukee County Basins Assessment Report," 1976.*

Table 114

SUMMARY OF CHLOROPHYLL-a CONCENTRATIONS WITHIN THE KINNICKINNIC RIVER ESTUARY: 1981-1983

Sampling Station	Period	Number of Samples	Chlorophyll-a (μg/l) Minimum	Mean	Maximum	Standard Deviation
S. 1st Street	Annual	88	0.9	9.1	119.3	15.0
	Summer	50	2.0	10.4	52.8	10.6
E. Greenfield Avenue	Annual	33	0.7	11.2	47.4	12.5
(extended)	Summer	21	1.9	15.7	47.4	13.6
Jones Island Ferry	Annual	33	1.6	12.9	62.7	13.2
	Summer	21	1.6	18.2	62.7	14.0

Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

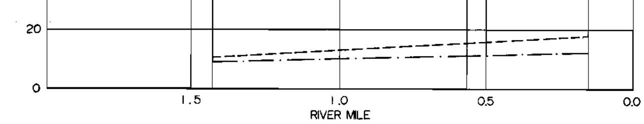
Plots of chlorophyll-a, inorganic nitrogen, and soluble phosphorus at three stations on the Kinnickinnic River over the period 1981 through 1983 are shown in Figure 156. The plots do not provide a clear indication as to whether nitrogen or phosphorus is limiting algal growth in the Kinnickinnic River.

Habitat Evaluation: The aquatic habitat in the Kinnickinnic River estuary was evaluated by the DNR and the Regional Planning Commission using the stream system habitat evaluation system developed by Ball.[29] Ball's habitat evaluation was, however, modified to be more applicable to an estuarine environment. The habitat rating for the reach of the Kinnickinnic River extending from Chase Avenue to the confluence with the Milwaukee River is set forth in Table 115. Overall, the evaluation concluded that this portion of the Kinnickinnic River provided fair habitat for aquatic organisms.

The ratings for the individual habitat characteristics ranged from excellent to poor. In general, the water depth characteristics and the discharge and some stream bank erosion characteristics were rated as providing excellent and good habitat, respectively; some stream banks were rated as providing fair habitat; and the stream bottom characteristics were rated as providing poor habitat.

Figure 155

MAXIMUM SUMMER, MEAN SUMMER, AND MEAN ANNUAL CHLOROPHYLL-a LEVELS IN THE KINNICKINNIC RIVER ESTUARY: 1981-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

Specifically, it was observed that, downstream of Becher Street, the stream banks were stabilized and little erosion was occurring. A survey of the channel of the Kinnickinnic River indicated adequate channel capacity to accommodate peak flows and suitable average water depths. These conditions provide good to excellent habitat for aquatic life.

Upstream of Becher Street, some stream banks were not lined and were partially vegetated with trees and shrubs. Some slumping and scouring of the banks was observed. These conditions provide fair habitat for aquatic life.

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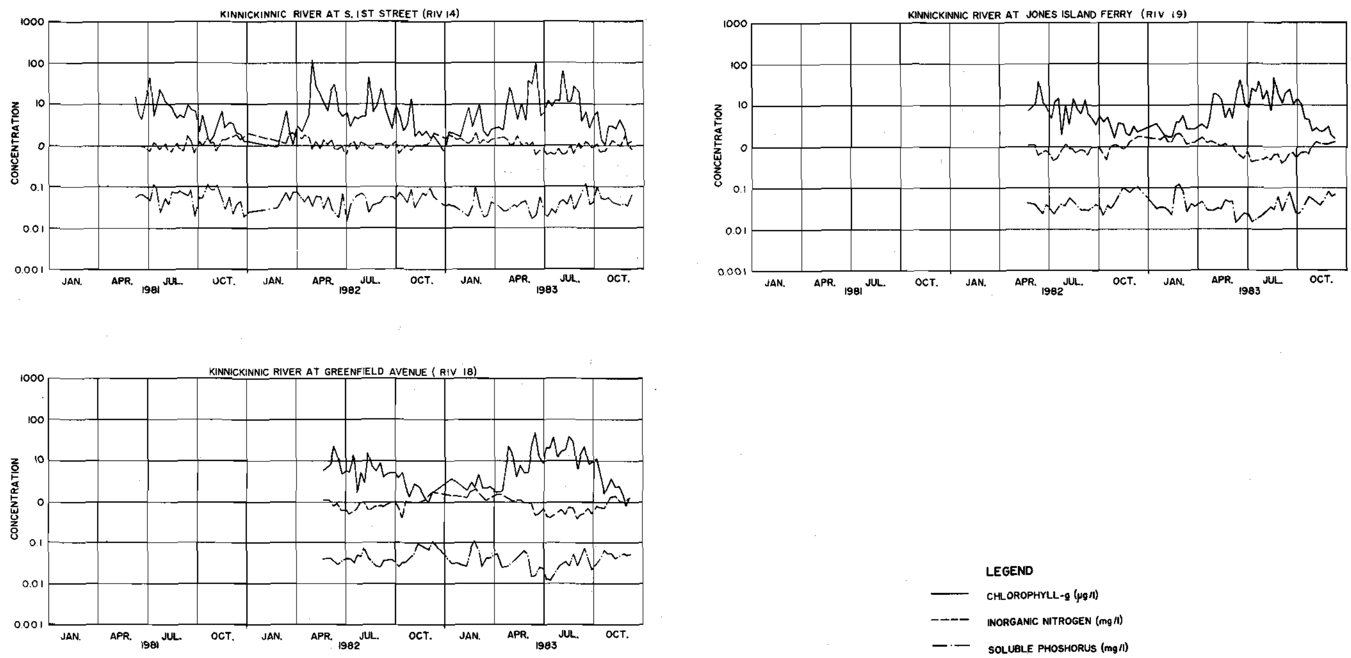
[29] *Joseph R. Ball, "Stream Classification Guidelines for Wisconsin," Wisconsin Department of Natural Resources Technical Bulletin, 1982.*

Figure 156

CHLOROPHYLL-a, INORGANIC NITROGEN, AND SOLUBLE PHOSPHORUS CONCENTRATIONS WITHIN THE KINNICKINNIC RIVER ESTUARY: 1981-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

The surveys indicated that extensive stream channelization and bank lining are present—especially downstream of Becher Street, that the river bottom was affected by severe scouring and deposition, that there was an absence of desired gravel and rubble substrate on the channel bottom, and that the bottom sediments contained toxic metals and organic substances. These conditions provide poor habitat for aquatic life.

Impairing Factors: The DNR identified the following primary factors as currently limiting the populations of desired fish and other aquatic life within the Kinnickinnic River estuary: 1) pollutant loadings from combined sewer overflows, sanitary bypasses, urban stormwater runoff, and industrial spills and discharges; and 2) toxic substances in the water and in the bottom sediments.[30]

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[30] *Wisconsin Department of Natural Resources, "Kinnickinnic River Classification," November 1984.*

Outer Harbor

Biological data for the outer harbor were available from the Wisconsin Department of Natural Resources (DNR) and from the Milwaukee Metropolitan Sewerage District (MMSD). Data on fishery resources were set forth in the report entitled, Milwaukee Harbor Estuary Fish Survey and Toxic Substance Evaluation, January 1984, prepared by the DNR. A summary of data on algae and zooplankton is set forth in MMSD Summary Support Data File Environmental Assessment, Volume 1-B, August 1980. Data on benthic macroinvertebrates are set forth in Field Methodology and Results for Milwaukee Harbor, Kinnickinnic River and Menomonee River, prepared by Limno-Tech, Inc., of Ann Arbor, Michigan, for the U. S. Army Engineer District, Detroit, June 1984. Chlorophyll-a and nutrient levels were measured as part of the Milwaukee Harbor estuary study.

Fish: Extensive fishery surveys were conducted in the outer harbor by the DNR in 1983 as part of the Milwaukee Harbor estuary study. The tolerance

Table 115

AQUATIC HABITAT RATING FOR THE KINNICKINNIC RIVER ESTUARY: 1984

Habitat Characteristic	Rating for Support of Aquatic Life	Description of Habitat Characteristic
Stream Channelization and Bank Lining	Poor	Most of harbor is periodically dredged for maintenance of navigation and the entire harbor is channelized. Banks are lined with steel or concrete. Linings do not provide adequate cover or substrate for aquatic life
Stream Bank Erosion—Upstream of Becher Street	Fair	Those banks that are not lined are partially vegetated with trees and shrubs. Overhanging stream bank vegetation provides cover for fish and other aquatic life. Some slumping and scouring of the banks is present
Stream Bank Erosion—Downstream of Becher Street	Good	Although the stream banks are not vegetated, there is little observed, or potential for, bank failure because the banks are lined with steel or concrete
Bank Channel Capacity	Good	Ample bank channel capacity exists to accommodate peak flows
Bottom Scouring and Deposition	Poor	Most of the stream bottom is affected by scouring or deposition
Bottom Substrate	Poor	Only a small portion of the channel bottom is composed of desired gravel and rubble substrate. Bottom sediments contain toxic metals and organic substances
Average Water Depth	Excellent	Adequate water depths are present to support year-round residence of fish and other aquatic life

Source: Wisconsin Department of Natural Resources and SEWRPC.

level, type, and number of fish collected during these surveys are set forth in Table 116. Thirty species of fish were captured within the outer harbor during the 1983 surveys of which 13, or 43 percent, were rated as intolerant of pollution, 14, or 47 percent, were rated as tolerant of pollution, and three, or 10 percent, were rated as very tolerant of pollution. The most abundant fish caught were yellow perch, followed by white sucker, alewife, rainbow trout, rainbow smelt, brown trout, and lake trout. Yellow perch, with a wide size range, were more abundant in the outer harbor than in the inner harbor. Panfish, large and smallmouth bass, and bullhead were noticeably lacking or low in numbers in the outer harbor when compared to the inner harbor.

Fish recapture studies indicated that there is little movement of fish between the outer harbor and the inner harbor reaches. Thirty-five of the 51 white sucker recaptured in the outer harbor, or 68 percent, were originally caught in the outer harbor. Of the remaining 16 white sucker, 13 were originally caught in the South Shore Harbor, two in the Milwaukee River, and one in the Kinnickinnic River. Of seven recaptured redhorse, five were originally caught in the outer harbor, while the remaining two were originally caught in the Milwaukee River and the South Shore Harbor.

Concentrations of 12 toxic organic substances and four metals were measured in the tissue of fish taken from the outer harbor in May 1970 and in

Table 116

TOLERANCE LEVEL, TYPE, AND NUMBER OF FISH COLLECTED DURING THE MILWAUKEE HARBOR ESTUARY FISH SURVEY IN THE OUTER HARBOR: 1983

Tolerance Level	Species	Number	Percent of Subtotal	Percent of Total
Intolerant	Bloater Chub	9	0.5	0.1
	Brook Trout	114	6.8	0.9
	Brown Trout	381	22.7	2.9
	Chinook Salmon	59	3.5	0.4
	Coho Salmon	21	1.2	0.1
	Lake Trout	230	13.7	1.7
	Lake Whitefish	48	2.8	0.4
	Longnose Dace	1	0.1	< 0.1
	Rainbow Trout	573	34.1	4.4
	Redhorse	77	4.6	0.6
	Sculpin	66	3.9	0.5
	Spottail Shiner	23	1.4	0.2
	Trout-Perch	79	4.7	0.6
	Subtotal	1,681	100.0	12.8
Tolerant	Alewife	1,719	15.1	13.1
	Black Crappie	3	< 0.1	< 0.1
	Bluegill	1	< 0.1	< 0.1
	Gizzard Shad	11	0.1	0.1
	Golden Shiner	7	0.1	0.1
	Lake Chub	1	< 0.1	< 0.1
	Longnose Sucker	6	0.1	0.1
	Northern Pike	10	0.1	0.1
	Rainbow Smelt	494	4.3	3.8
	Rock Bass	3	< 0.1	< 0.1
	Walleye	1	< 0.1	< 0.1
	White Crappie	1	< 0.1	< 0.1
	White Sucker	3,435	30.1	26.2
	Yellow Perch	5,713	50.1	43.6
	Subtotal	11,405	100.0	87.1
Very Tolerant	Carp	11	68.8	0.1
	Goldfish	2	12.5	< 0.1
	Green Sunfish	3	18.7	< 0.1
	Subtotal	16	100.0	0.1
	Total	13,102	--	100.0

Source: Wisconsin Department of Natural Resources.

August 1983. The results of the fish tissue toxic surveys are set forth in Table 117. The presence of toxic substances in fish tissue may, in some instances, pose a health threat to humans consuming the fish.

Polychlorinated biphenyl (PCB) concentrations in the tissue of fish taken from the outer harbor were generally lower than those in the tissue of fish found in the three rivers. The PCB concentrations ranged from 1.1 ppm in an alewife captured on August 2, 1983, to 4.2 ppm in a white sucker also captured on August 2, 1983. The U. S. Food and Drug Administration health standard for PCB's in fish tissue is a maximum of 2 ppm. Because the levels of PCB's in the tissue of some fish taken from the outer harbor have exceeded this health standard, the DNR has issued a health advisory for persons consuming fish from the outer harbor. That health advisory, as of April 1985, suggested that women and children not consume redhorse, rock bass, and smallmouth bass under 13 inches in length, and that no one consume carp or northern pike. Perch were noted as posing the lowest health risk to consumers.

Levels of the pesticide DDT (dichloro-diphenyl-trichloro-ethane) in the tissue of fish taken from the outer harbor ranged from 0.17 ppm in an alewife and white sucker captured on August 23, 1983, to 0.84 ppm in a brown trout captured on August 4, 1983. The U. S. Food and Drug Administration health standard for DDT in the tissue of fish is a maximum of 5 ppm.

Fish tissue concentrations of several metals were also measured by the DNR. Concentrations of chromium in the tissue of fish were below the minimum level of detection with the exception of a level of 0.42 ppm measured in a white sucker captured on May 20, 1970, as set forth in Table 117. Copper concentrations ranged from 1.2 ppm in a yellow perch captured on August 2, 1983, to 1.9 ppm in brown trout captured on August 4, 1983 and August 24, 1983. Mercury concentrations in the tissue of fish ranged from 0.03 ppm in an alewife captured on August 23, 1983, and in white sucker captured on August 2, 1983 and August 23, 1983, to 0.22 ppm in miscellaneous species captured on May 20, 1970. Zinc concentrations in the tissue of fish ranged from 4.6 ppm in a coho salmon captured on May 20, 1970, to 6.9 ppm in a white sucker also captured on May 20, 1970. The U. S. Food and Drug Administration health standard for mercury concentrations in the tissue of fish is a maximum of 1 ppm.

Benthic Macroinvertebrates: In 1984, a total of 21 species of benthic macroinvertebrates were identified at three stations in the outer harbor.[31] The locations of the sampling stations are shown on Map 95, and the species are listed in Table 118. Oligochaetes always were found to compose over 87 percent of the total benthic fauna present. The

[31] *Limno-Tech, Inc., Field Methodology and Results for Milwaukee Harbor, Kinnickinnic River and Menomonee River, prepared for the U. S. Army Engineer District, Detroit, June 1984.*

Table 117

CONCENTRATIONS OF TOXIC ORGANIC SUBSTANCES AND METALS IN THE TISSUE OF FISH IN THE OUTER HARBOR: 1970-1983

Toxic Substance	Alewive			White Sucker			Yellow Perch			Brown Trout			Coho Salmon			Miscellaneous Species		
	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean	Number of Samples	Range	Mean
Dates of Sampling	August 2, 1983 to August 23, 1983			May 20, 1970 to August 23, 1983			August 2, 1983 to August 23, 1983			August 4, 1983 to August 24, 1983			May 20, 1970			May 20, 1970		
Organics																		
PCB's	2	1.1-2.9	2.0	2	3.4-4.2	3.8	2	2.2-2.7	2.4	2	2.7-3.8	3.2	--	--	--	--	--	--
Aldrin	2	<0.05	<0.05	2	<0.05	<0.05	2	<0.05	<0.05	2	<0.05	<0.05	--	--	--	--	--	--
Dieldrin	2	0.04-0.06	0.05	2	<0.02	<0.02	2	0.3-0.05	0.04	2	0.15-0.17	0.16	--	--	--	--	--	--
Endrin	2	<0.02	<0.02	2	<0.02	<0.02	2	<0.02	<0.02	2	<0.02	<0.02	--	--	--	--	--	--
DDT	2	0.17-0.29	0.23	2	0.17-0.18	0.18	2	0.21-0.28	0.24	2	0.70-0.84	0.77	--	--	--	--	--	--
Chlordane	2	0.05-0.05	0.02	2	<0.05	<0.05	2	<0.05	<0.05	2	0.10-0.17	0.14	--	--	--	--	--	--
Hexachlorobenzene	2	<0.01	<0.01	2	<0.05	<0.05	2	<0.05	<0.05	2	<0.05	<0.05	--	--	--	--	--	--
Hexachlorocyclohexane	2	<0.01	<0.01	2	<0.01	<0.01	2	<0.01	<0.01	2	<0.01	<0.01	--	--	--	--	--	--
Heptachlor	2	<0.05	<0.05	2	<0.05	<0.05	2	<0.05	<0.05	2	<0.05	<0.05	--	--	--	--	--	--
Methoxychlor	2	<0.05	<0.05	2	<0.05	<0.05	2	<0.05	<0.05	2	<0.05	<0.05	--	--	--	--	--	--
Pentachloroanisol	2	<0.05	<0.05	2	<0.05	<0.05	2	<0.05	<0.05	2	<0.05	<0.05	--	--	--	--	--	--
Toxaphene	2	<1.0	<1.0	2	<1.0	<1.0	2	<1.0	<1.0	2	<1.0	<1.0	--	--	--	--	--	--
Metals																		
Chromium	2	<0.5	<0.5	3	<0.5-0.42	0.14	2	<0.5	<0.5	2	<0.5	<0.5	--	--	--	--	--	--
Copper	2	1.7-1.8	1.8	2	1.4-1.5	1.4	2	1.2-1.4	1.3	2	1.9	1.9	--	--	--	--	--	--
Mercury	2	0.03-0.05	0.04	2	0.03	0.03	2	0.06-0.08	0.07	2	0.08-0.12	0.10	--	--	--	3	0.05-0.22	0.13
Zinc	--	--	--	1	--	6.9	--	--	--	--	--	--	1	--	4.6	--	--	--

NOTE: All concentrations are in parts per million.

Source: Wisconsin Department of Natural Resources.

most abundant species reported were Tubifex tubifex, Limnodrilus noffmeisteri, and Quistadrilus multisetosus. All of the species identified were rated as tolerant of pollution.

Algae: Periphytic algae were surveyed in 1965 on the outer harbor breakwater.[32] The results of the sampling indicated that the outer harbor was dominated by Ultothrix sp. and diatoms in the spring and fall, and by Cladophora glomerata in the summer. Of particular importance was the abundance of C. glomerata, which commonly exists in nutrient-enriched areas of the Great Lakes, and which had been reported to create nuisance conditions in Milwaukee since 1959. Phytoplankton diatom species commonly found in the outer harbor include Stephanodiscus tenuis, Fragilaria crotonensis, and Tabellaria flocculosa.[33]

[32] *Ibid.*

[33] *Ibid.*

Chlorophyll-a, an indicator of algal biomass, was measured in the outer harbor over the period 1981 through 1983 as part of the Milwaukee Harbor estuary study. A statistical summary of the observed chlorophyll-a levels at 10 stations in the outer harbor is set forth in Table 119. The location of these stations is shown on Map 96. The table summarizes annual levels—measured over the entire year—and summer levels—measured during June, July, and August. The mean annual concentrations of chlorophyll-a ranged from 5.6 µg/l to 20.9 µg/l. The mean summer concentrations of chlorophyll-a were generally higher than the annual means and ranged from 7.4 µg/l to 17.3 µg/l. The maximum concentration of chlorophyll-a of 89.0 µg/l was measured on July 30, 1981, at the mouth of the inner harbor. Plots of chlorophyll-a, inorganic nitrogen, and soluble phosphorus at four stations within the outer harbor over the period 1981 through 1983 are shown in Figure 157. The plots do not provide a clear indication as to whether nitrogen or phosphorus is limiting algal growths.

Table 118

BENTHIC MACROINVERTEBRATES IDENTIFIED WITHIN THE OUTER HARBOR: 1984

Species	Population Density (number/feet^2) Sampling Station[a] 1	2	3
Class Oligochaeta[b]			
Ilyodrilus templetoni	--	--	$\geq$ 4
Limnodrilus cervix	$\geq$ 24	$\geq$ 12	$\geq$12
Limnodrilus claparedianus	--	--	$\geq$ 4
Limnodrilus hoffmeisteri	$\geq$304	$\geq$256	$\geq$240
Limnodrilus udekemianus	--	$\geq$ 4	--
Lumbriculus sp	--	$\geq$ 24	--
Potamothrix moldaviensis	--	--	$\geq$ 72
Potamothrix vejdovskyi.	--	--	$\geq$ 20
Quistadrilus multisetosus	$\geq$ 16	$\geq$ 44	$\geq$300
Tubifex tubifex	$\geq$448	$\geq$420	$\geq$ 8
Unidentified Immature Oligochaeta with Capilliform Chaeta	$\geq$ 72	$\geq$ 20	$\geq$ 8
Unidentified Immature Oligochaeta without Capilliform Chaeta	$\geq$ 40	$\geq$ 56	$\geq$192
Total	$\geq$904	$\geq$836	$\geq$860
Class Insecta			
Chironomus sp.	4	--	12
Cryptochironomus sp	--	--	4
Procladius sp	8	--	16
Total	12	--	32
Class Gastropoda			
Bithynia tentaculata.	--	--	4
Valvata sincera	4	--	8
Total	4	--	12
Class Pelecypoda			
Pisidium sp	--	--	40
Sphaerium sp.	--	--	32
Total	--	--	72
Class Crustacea			
Asellus sp.	--	8	4
Total	--	8	4
Class Hirudinea			
Helobdella stagnalis	--	--	12
Total	--	--	12

[a] *Sampling station locations are shown on Map 95.*

[b] *Because the number of Oligochaetes was very high within each sample, only a limited number of individuals was counted to provide a representative distribution of species.*

Source: Limno-Tech, Inc.

Zooplankton: Zooplankton data summarized by the MMSD indicate that the outer harbor has a rotifer species composition and abundance that is similar to that reported for the enriched areas of the Great Lakes. Major species reported were Filinia longigeta, Keratella cochlearis, K. quadrata, Branchionus calyciflorus, Synchaeta stylata, and S. oblonga.[34] The relative abundance of rotifers was greatest during July.

Habitat Evaluation: The aquatic habitat in the outer harbor was evaluated by the DNR in 1984.[35] Overall, the DNR evaluation concluded that while the water quality of the outer harbor varies substantially because of the high rate of exchange of water between the outer harbor and Lake Michigan, and the large loadings of pollutants from the inner harbor and the Jones Island wastewater treatment plant, habitat conditions are generally satisfactory to maintain propagation of warmwater fish and other aquatic life.

The DNR evaluation concluded that the substrate and habitat of the outer harbor are not conducive to the maintenance of self-sustaining salmonid populations. Of the salmonid species indigenous to this part of Lake Michigan, only lake trout and brown trout have been documented as spawning successfully in Lake Michigan itself, and then only in the open lake environment on rocky, reef-like structures. Any other salmonid species which may be present naturally migrate up streams and require free-flowing areas with clean gravel substrates and cool water for successful reproduction. These required spawning areas are not present within the Milwaukee Harbor estuary.

Substrate characteristics and the habitat in some portions of the outer harbor were, however, found to be conducive to the successful propagation of warmwater sport fish and a variety of indigenous forage species. Desirable substrate areas found were comprised of sand and rubble and of macrophyte beds, both of which provide spawning substrate and cover for a variety of fish species and food organisms. Bottom scouring is rare within the outer harbor, and some substrates do not have

[34] *Ibid.*

[35] *Wisconsin Department of Natural Resources, "Review of Water Quality Standards for the Outer Harbor at Milwaukee and the Nearshore Waters of Lake Michigan," 1984.*

Table 119

SUMMARY OF CHLOROPHYLL-a CONCENTRATIONS WITHIN THE OUTER HARBOR: 1981-1983

Station	Period	Number of Samples	Chlorophyll-a (µg/l) Minimum	Mean	Maximum	Standard Deviation
OH-1	Annual	281	1.3	10.7	89.0	11.4
	Summer	137	1.6	14.6	89.0	13.9
OH-2	Annual	281	0.7	5.6	31.6	4.2
	Summer	138	1.2	7.4	31.6	4.9
OH-3	Annual	300	0.7	7.4	58.9	7.1
	Summer	147	1.6	10.0	58.9	8.8
OH-4	Annual	282	0.8	8.5	51.6	7.0
	Summer	138	2.2	10.8	38.0	6.8
OH-5	Annual	281	0.9	8.7	33.2	6.4
	Summer	137	0.9	9.7	33.2	6.8
OH-7	Annual	297	1.4	7.4	56.5	7.2
	Summer	123	1.4	9.4	56.5	9.2
OH-9	Annual	278	1.7	7.3	70.3	7.3
	Summer	138	1.7	10.0	70.3	9.5
OH-10	Annual	281	1.5	7.5	50.0	6.4
	Summer	138	1.5	10.1	50.0	8.0
OH-11	Annual	282	0.7	6.7	65.7	6.8
	Summer	138	1.3	9.2	65.7	8.7
OH-15	Annual	126	3.5	20.9	57.6	12.6
	Summer	47	3.5	17.3	37.6	8.0

Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

substantial accumulations of fine-grained organic material. Water depths in all portions of the outer harbor are, of course, adequate to provide year-round habitat for fish and other aquatic life.

Impairing Factors: The DNR evaluation identified the following primary factors as currently impairing the survival of desired fish and other aquatic life within the outer harbor: 1) pollutant loadings from point and nonpoint sources originating in the Milwaukee, Menomonee, and Kinnickinnic River watersheds, from the MMSD Jones Island wastewater treatment plant, from combined sewer overflows, and from a 45-acre confined disposal facility for harbor dredge spoils; and 2) sedimentation dominated by heavily polluted silt-clay material high in organic matter.

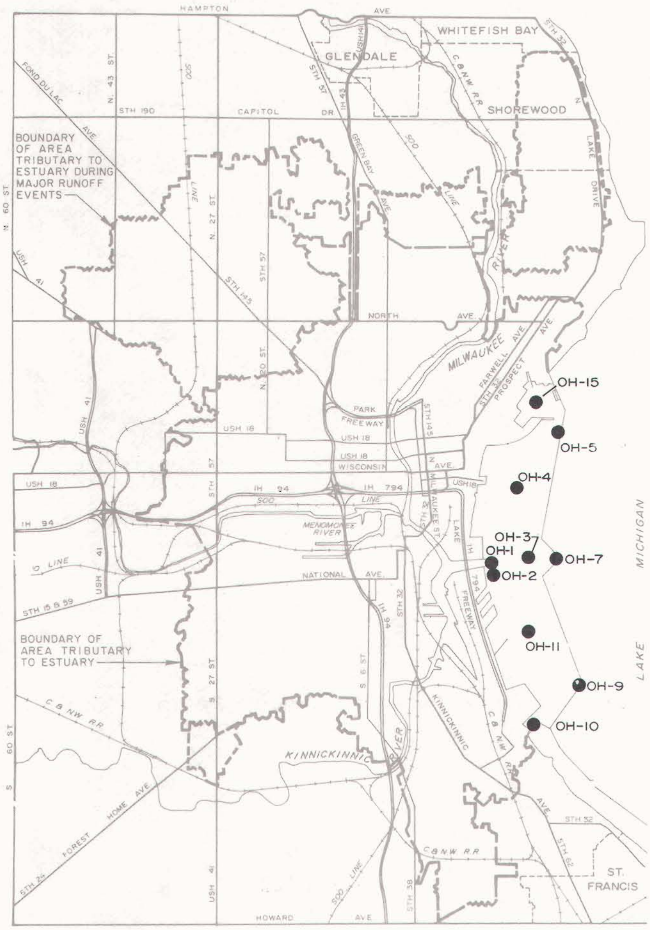
Faunal Toxicity Surveys

The findings of the water quality surveys conducted under the Milwaukee Harbor estuary study, as described herein, indicated that the waters contain certain substances—primarily metals and organic compounds—that in high enough concentrations may be toxic to aquatic life. To provide information on acute or chronic toxic conditions within the upstream river reaches, inner harbor, outer harbor, and Lake Michigan, a series of five toxicity surveys was conducted over the period August 20, 1984, through November 8, 1984.

During each survey, water samples were collected at the 16 stations shown on Map 97. Individuals of the zooplankton Ceriodaphnia affinis/dubia were then exposed to the water for a seven-day period

Map 96

LOCATION OF CHLOROPHYLL-a SAMPLING STATIONS IN THE OUTER HARBOR: 1981-1983



LEGEND

● OH-1 SAMPLING STATION AND DESIGNATION (SEE TABLE 119)

GRAPHIC SCALE

Chlorophyll-a, an indicator of algal biomass, was measured at 10 stations in the outer harbor over the period 1981 through 1983 as part of the Milwaukee Harbor estuary study. The chlorophyll-a levels ranged from 0.7 to 89 μg/l. The summer mean levels ranged from 7.4 to 17.3 μg/l.

Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

using a procedure described by Mount and Norberg of the U. S. Environmental Protection Agency.[36] The survival of adults and the reproduction of young Ceriodaphnia were recorded on the third, fifth, and seventh days of exposure to determine any acute or chronic toxic effects. Concurrently, water quality analyses were conducted on the water samples to measure the concentrations of the 29 elements listed in Table 120.

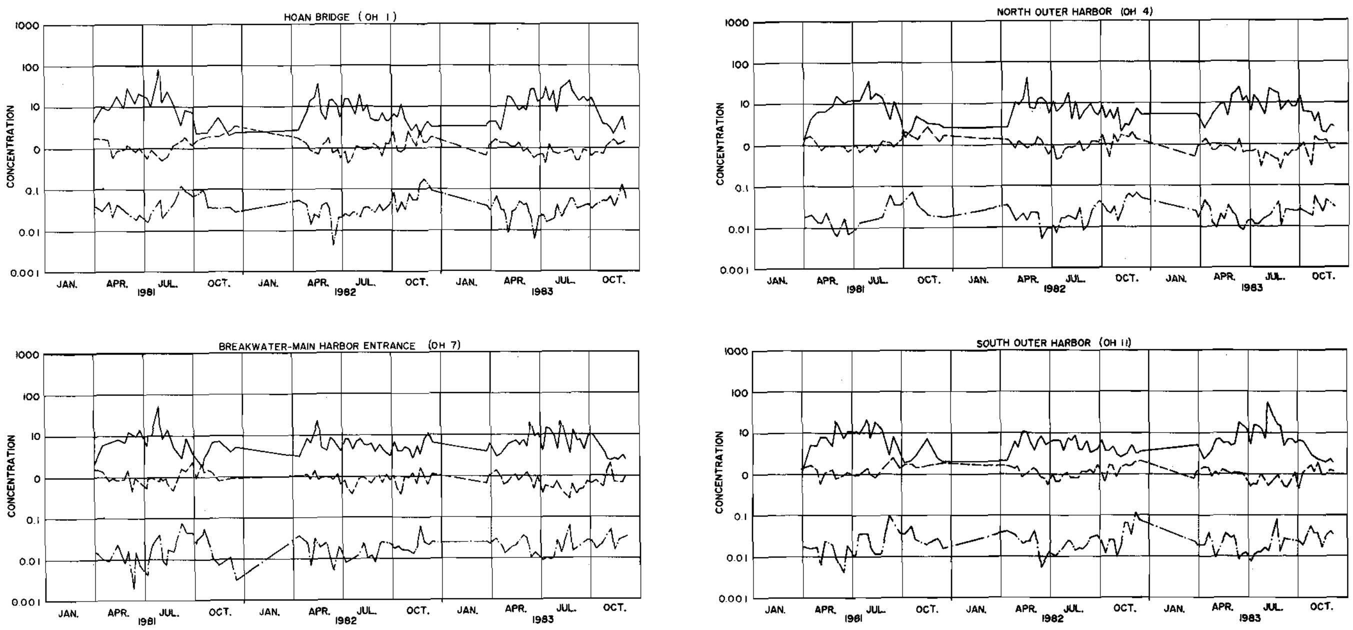
The results of the five Ceriodaphnia toxicity surveys are summarized in Table 121. The mean young produced ranged from 0 to 35.8 per adult over the seven-day testing periods. The percent survival of the adults over the seven-day testing periods ranged from 0 to 100 percent. Typically, nontoxic natural waters tested in the laboratory yield from 15 to 20 young produced per adult, with enriched nontoxic waters yielding significantly higher young produced and toxic waters yielding significantly lower.

Of the five surveys conducted, three were considered wet-weather surveys because significant rainfall occurred either on the day of sampling or within three days preceding the sampling day. Table 122 lists the rainfall data recorded at Mitchell Field and at Mount Mary College used to classify the surveys. Based on these data, the surveys of September 10, September 24, and October 8 were designated as wet-weather-event surveys, while the surveys of August 20 and November 8 were classified as dry-weather surveys. Mean production rates and survival rates at each station under wet-weather conditions are compared with those under dry-weather conditions in Table 121. Although the number of surveys conducted was limited, it appeared that young production under wet-weather conditions was significantly lower than production under dry-weather conditions in all three rivers, as well as in Lake Michigan at the sampling station located one mile east of the main harbor entrance. This is illustrated graphically in Figure 158, which plots reproduction and survival data by river mile. Survival of adults was not as significantly diminished under the wet-weather conditions for the Milwaukee and Kinnickinnic Rivers. The Menomonee River, however, showed a significantly higher mortality of adults under wet-weather conditions. The toxicity test results indicate that, as might be expected, chronic toxic conditions, which would affect reproduction, are more likely to occur during wet-weather conditions than during dry-weather conditions. Acute toxic conditions, which affect the survival of the adult Ceriodaphnia over a

[36] *D. I. Mount, and T. J. Norberg, "A Seven-Day Life-Cycle Cladoceran Toxicity Test," Environmental Toxicology and Chemistry, Vol. 3, No. 3, September 1984.*

Figure 157

CHLOROPHYLL-a, INORGANIC NITROGEN, AND SOLUBLE PHOSPHORUS CONCENTRATIONS IN SELECTED OUTER HARBOR STATIONS: 1981-1983



Source: Milwaukee Metropolitan Sewerage District and SEWRPC.

short time period, also appear to occur more often during wet, as compared to dry, weather conditions, especially in the Menomonee River.

POLLUTANT LOADINGS

Pollutant loadings to the inner harbor include both particulate pollutants, some of which settle to the bottom of the harbor, and dissolved pollutants. These loadings are important determinants of the water quality conditions in the inner harbor, as well as of the physical, biological, and chemical characteristics of the harbor bottom sediments. A portion of the pollutant loadings to the inner harbor is transported through the harbor into the outer harbor, and ultimately into Lake Michigan. Estimates of wet-weather and dry-weather loadings entering the inner harbor via the Milwaukee, Menomonee, and Kinnickinnic Rivers, of loadings from point source discharges both upstream of, and within, the inner harbor and outer harbor, and of loadings from combined sewer overflows were prepared under the Milwaukee Harbor estuary study. Loadings of particulate organic carbon into

Table 120

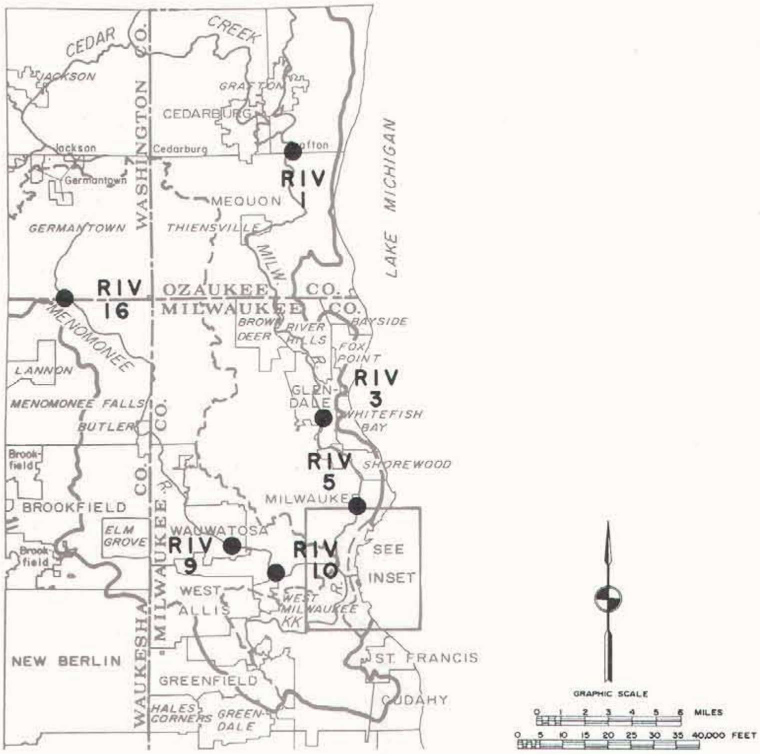
ELEMENTS MEASURED IN WATER SAMPLES COLLECTED FOR 7-DAY FAUNAL TOXICITY LEVELS FOR CERIODAPHNIA AFFINIS/DUBIA: 1984

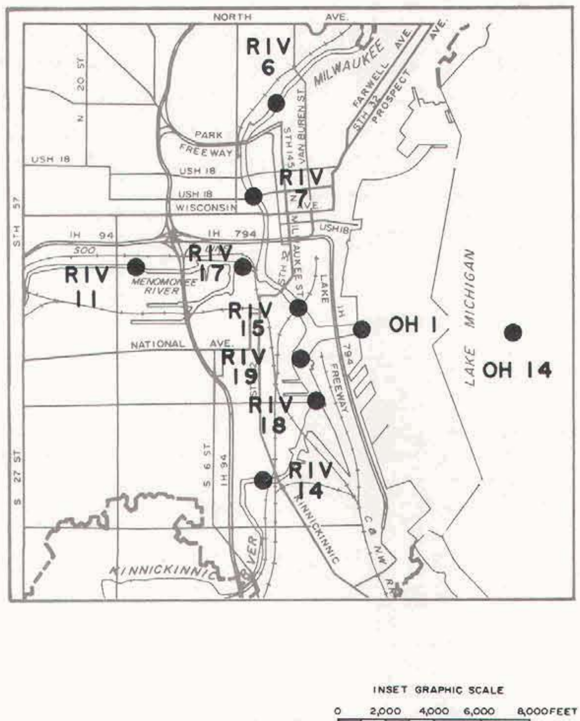
Aluminum	Manganese
Antimony	Molybdenum
Arsenic	Nickel
Barium	Phosphorus
Beryllium	Potassium
Boron	Selenium
Cadmium	Silicon
Calcium	Silver
Chromium	Sodium
Cobalt	Strontium
Copper	Thallium
Iron	Tin
Lead	Vanadium
Lithium	Zinc
Magnesium	

Source: Milwaukee Metropolitan Sewerage District.

Map 97

SAMPLING STATIONS FOR FAUNAL TOXICITY SURVEYS: 1984





A series of faunal toxicity surveys were conducted in 1984 to provide information on acute and chronic toxic conditions within the upstream river reaches, inner harbor, outer harbor, and Lake Michigan. During each survey, water samples were collected at 16 stations and used for bioassays conducted with Ceriodaphnia organisms. A concurrent water quality analysis was conducted.

Source: Milwaukee Metropolitan Sewerage District.

Table 121

RESULTS OF 7-DAY FAUNAL TOXICITY SURVEYS FOR CERIODAPHNIA AFFINIS/DUBIA: 1984[a]

		Mean Young Produced per Adult												Percent Adult Survival						
		8/20[c]		9/10[b]		9/24[b]		10/8[b]		11/8[c]										
Station	Station I.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Wet-Weather Mean	Dry-Weather Mean	8/20[c]	9/10[b]	9/24[b]	10/8[b]	11/8[c]	Wet-Weather Mean	Dry-Weather Mean
Milwaukee River																				
Pioneer Road	RIV01	22.1	7.58	8.5	5.25	11.0	6.13	10.6	6.55	17.4	3.94	10.0	19.8	90	90	100	90	100	93.3	95
Silver Spring Drive	RIV03	30.9	11.6	14.2	5.61	11.0	12.6	11.8	6.27	18.9	4.36	12.3	24.9	80	90	50	90	90	76.7	85
North Avenue Dam	RIV05	33.2	13.7	23.3	5.34	16.8	10.7	18.2	4.80	19.0	7.10	19.4	26.1	90	100	80	100	100	93.3	95
Walnut Street	RIV06	35.8	7.60	19.8	4.89	18.0	9.41	16.3	7.26	17.9	5.65	18.0	26.8	100	100	90	90	90	93.3	95
Wells Street	RIV07	34.8	6.89	24.1	8.76	12.2	9.58	21.7	8.55	17.3	4.36	19.3	26.0	100	90	50	100	100	80.0	100
C&NW Railway Bridge	RIV15	28.6	7.37	19.9	3.38	15.0	5.96	12.4	8.90	17.6	3.07	15.8	23.1	90	100	100	90	90	96.7	90
Mean	--	30.9	9.1	18.3	5.5	14.0	9.1	15.2	7.0	18.0	4.75	15.8	24.4	92	95	78	93	95	88.9	93
Menomonee River																				
County Line Road	RIV16	27.6	11.62	10.8	5.42	13.1	7.06	22.7	8.96	20.8	4.19	15.5	24.2	100	60	80	100	80	80.0	90
N. 70th Street	RIV09	29.2	13.6	0.0	0.0	16.3	10.6	16.9	4.91	18.6	4.36	11.1	23.9	80	0	80	90	90	56.7	85
Falk Dam	RIV10	20.6	11.6	9.9	4.65	18.8	10.3	12.3	3.37	18.9	5.49	13.7	19.8	80	0	70	100	90	56.7	85
Muskego Avenue	RIV11	27.4	7.34	17.1	9.13	19.4	14.4	14.2	8.03	17.5	5.16	16.9	22.4	100	80	70	90	100	80.0	100
S. 2nd Street	RIV17	27.6	9.23	21.8	5.53	21.2	9.41	15.7	8.31	14.2	2.58	19.6	22.8	90	100	90	100	80	96.7	85
Mean	--	26.5	10.7	11.92	4.9	17.8	10.4	16.4	6.7	18.0	4.36	15.4	22.6	90	48	78	96	88	74.0	89
Kinnickinnic River																				
S. 1st Street	RIV14	28.7	5.29	23.7	4.47	15.6	6.83	14.4	7.56	19.7	4.36	17.9	24.2	100	100	100	88	100	96.0	100
Greenfield Avenue	RIV18	28.3	9.41	15.0	5.75	14.2	6.05	10.8	6.70	22.4	4.68	13.3	25.4	90	90	90	90	100	90.0	95
Jones Island Ferry	RIV19	29.3	6.70	17.0	4.27	14.4	6.19	17.1	5.16	21.4	3.87	16.2	25.4	100	100	100	100	100	100.0	100
Mean	--	28.8	7.1	18.6	4.8	14.7	6.4	14.1	6.5	21.2	4.30	15.8	25.0	97	97	97	93	100	95.4	98
Outer Harbor	OH1	30.8	10.5	15.6	8.55	14.3	4.11	18.1	7.75	19.3	4.36	16.0	25.0	90	90	90	80	90	86.7	90
Lake Michigan	OH14	26.1	10.7	12.2	3.91	15.6	5.62	8.9	3.33	23.9	4.84	12.2	25.0	90	90	100	100	80	96.7	85
Mean	--	28.4	10.6	13.9	6.2	15.0	4.9	13.5	5.5	21.6	4.6	14.1	25.0	90	90	95	90	85	91.7	88

NOTE: S.D. - Standard Deviation.

[a] *All tests conducted by Engineering Science and Techology, Inc., Sparks, Maryland.*

[b] *Wet-weather sampling.*

[c] *Dry-weather sampling.*

Source: Milwaukee Metropolitan Sewerage District, HydroQual, Inc., and SEWRPC.

Table 122

PRECIPITATION AT MILWAUKEE MITCHELL FIELD AND AT MOUNT MARY COLLEGE THREE DAYS PRIOR TO AND ON DAY OF WATER SAMPLING FOR 7-DAY FAUNAL TOXICITY TEST FOR CERIODAPHNIA AFFINIS/DUBIA: 1984

Date	Mitchell Field (inch)	Mount Mary College (inch)	Wet or Dry Weather Survey
August 17	0	0	Dry
August 18	0	0	
August 19	0	0	
August 20	0	0	
September 7	0.12	0.23	Wet
September 8	0.04	0	
September 9	0	T	
September 10	0.04	0.06	
September 21	0	0	Wet
September 22	0.02	0	
September 23	0.03	0.02	
September 24	0.72	T	
October 5	0	T	Wet
October 6	0.03	0	
October 7	0.72	0.44	
October 8	0.02	0.04	
November 5	T	T	Dry
November 6	0	0	
November 7	T	0	
November 8	T	0.01	

NOTE: T - Trace.

Source: National Weather Service Monthly Summaries.

the bottom sediments of the inner harbor, along with sedimentation rates, are presented in the section of this chapter on sediment quality conditions and sediment-water interactions because these loadings are pertinent to the analysis of existing sediment quality conditions. Pollution loadings during five specific runoff events are presented in the section of this chapter on water quality-runoff event data to help characterize and compare these events.

Milwaukee, Menomonee, and Kinnickinnic Rivers Total Annual Loadings: Annual loadings of pollutants transported into the inner harbor via the Milwaukee, Menomonee, and Kinnickinnic Rivers were estimated using the 1981 through 1983 baseline water quality data collected during the study. The loadings were estimated for the Milwaukee River at the North Avenue dam, for the Menomonee River at S. 37th Street, and for the Kinnickinnic River at S. 9th Place, which were the first sampling stations located on each river upstream of the inner harbor.

Annual pollutant loadings were computed using the weekly baseline data collected at the above sampling stations and the instantaneous streamflow at the time of sampling. The flow and pollutant concentration were used to compute the instantaneous loading rate in amount per day. The annual loading rate was then computed for each pollutant for each station. To evaluate the accuracy of the annual mean loading rates and the resultant annual loads, a log-probability plot of the instantaneous loading rates was prepared for each pollutant for each station. The annual loading rates calculated with the baseline data were then adjusted as necessary to be consistent with loading rates calculated for the five storm runoff events surveyed.

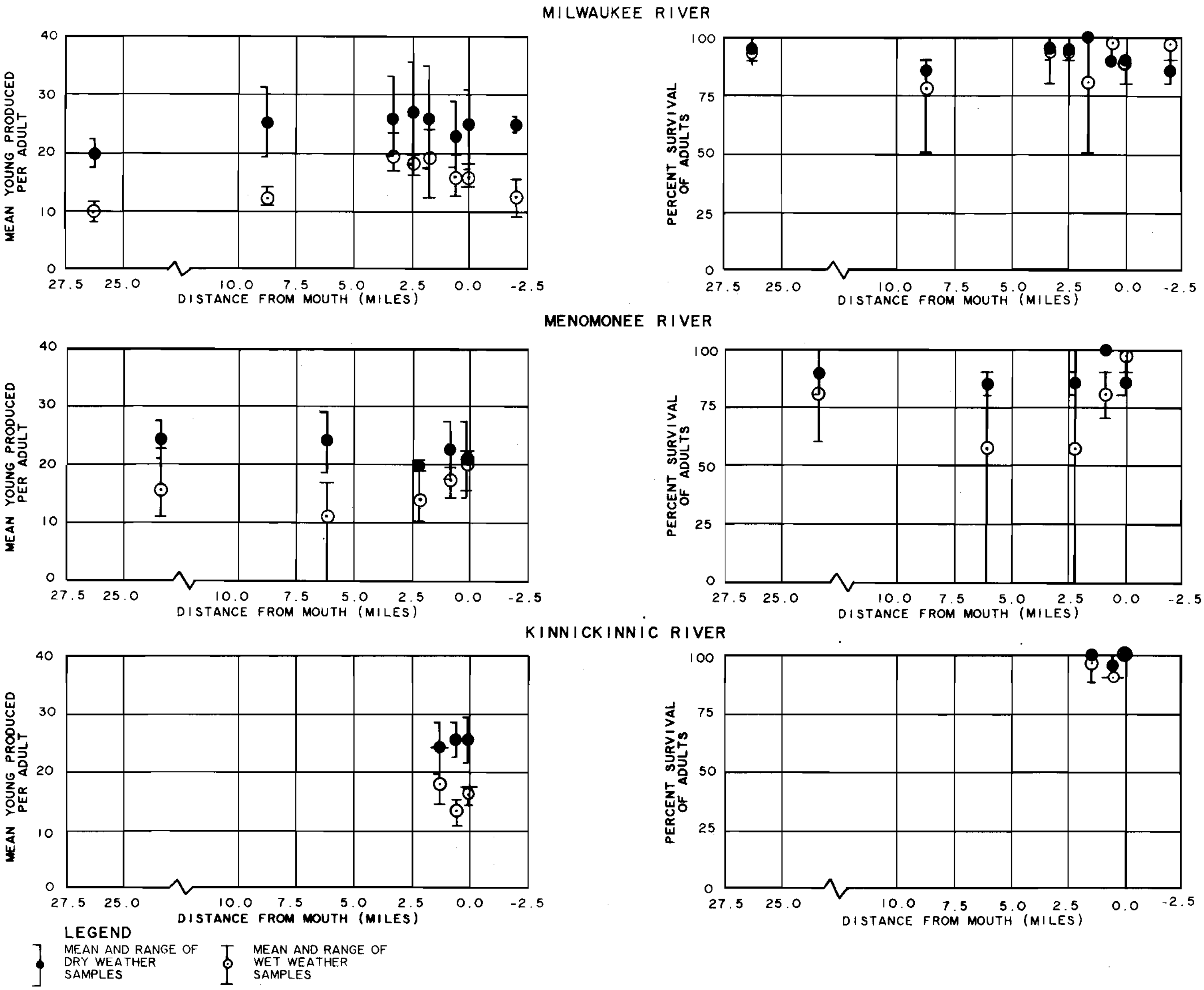
A summary of the estimated annual pollutant loadings to the inner harbor from the tributary rivers over the period 1981 through 1983 is set forth in Table 123. For the various water quality indicators shown in the table, the Milwaukee River contributes from 57 to 97 percent of the total river loadings; the Menomonee River contributes from 3 to 33 percent; and the Kinnickinnic River contributes from less than 1 to 19 percent.

For most pollutants, the 1982 and 1983 loadings were higher than the 1981 loadings. The 1982 loadings of total suspended solids, volatile suspended solids, fecal coliform, biochemical oxygen demand, chemical oxygen demand, total and soluble phosphorus, ammonia nitrogen, nitrate nitrogen, nitrite nitrogen, and copper were the highest for the three-year sampling period. The 1983 loadings of total organic and inorganic carbon, un-ionized ammonia nitrogen, chloride, cadmium, chromium, iron, lead, and zinc were the highest. The 1981 loadings were the highest only for total solids, total Kjeldahl nitrogen, and chlorophyll-a.

Since the baseline water quality analyses indicated no overall trend in concentrations of water quality indicators, the higher loadings estimated for 1982 and 1983 are probably due to increased runoff volumes and river flows. Table 124 sets forth precipitation and river flow data for 1981 through

Figure 158

WET-WEATHER AND DRY-WEATHER EFFECTS ON THE REPRODUCTION AND SURVIVAL OF CERIODAPHNIA AFFINIS: 1984



Source: HydroQual, Inc., and SEWRPC.

Milwaukee and Menomonee Rivers were highest in 1983, whereas the Kinnickinnic River flows were highest in 1982.

Wet-Weather and Dry-Weather Loadings: Table 125 separates the estimated annual pollutant loadings into wet-weather and dry-weather loadings. Wet-weather and dry-weather loading rates were calculated using the same procedure used to determine annual loadings. The wet-weather loading rates, in amount per day, were then multiplied by the number of days each year estimated to be affected by wet-weather conditions. Wet-weather conditions were assumed to exist if at least one-tenth of one inch of precipitation fell on a given day, or within the preceding three days. The dry-weather loading rates were then multiplied by the remaining days, which were assumed to be marked by dry-weather conditions.

Overall, approximately two-thirds of the total pollutant loadings carried by the three rivers into the inner harbor were contributed during wet-weather conditions. The relative contribution of the total river loadings generated during wet-weather conditions was remarkably similar for the different water quality indicators. For all indicators except chlorophyll-a, iron, and copper, the relative contribution of loadings during wet-weather conditions ranged from 61 to 76 percent. The wet-weather

Table 123

SUMMARY OF THE ESTIMATED ANNUAL POLLUTANT LOADINGS TO THE INNER HARBOR FROM THE MILWAUKEE, MENOMONEE, AND KINNICKINNIC RIVERS: 1981-1983[a]

Year	Station	Total Solids	Total Suspended Solids	Volatile Suspended Solids	Fecal Coliform	Biochemical Oxygen Demand	Chemical Oxygen Demand	Total Organic Carbon	Total Inorganic Carbon	Total Phosphorus	Soluble Phosphorus	Ammonia Nitrogen	Un-ionized Ammonia Nitrogen	Nitrate Nitrogen	Nitrite Nitrogen	Total Kjeldahl Nitrogen	Chlorophyll-a	Chlorides	Cadmium	Chromium	Copper	Iron	Lead	Zinc
1981	Milwaukee River at North Avenue Dam (RIV-5)	623,000	33,500	9,790	289.0	4,430	--	--	--	191	88	169.0	6.8	990.0	25.0	1,590.0	62.6	47,600	--	--	--	--	--	--
	Menomonee River at S. 37th Street (RIV-10)	89,300	6,230	1,070	229.0	--	--	--	--	31	13	32.8	0.7	212.0	5.7	143.0	15.0	9,260	--	--	--	--	--	--
	Kinnickinnic River at S. 9th Place (RIV-13)	17,700	709	220	29.6	--	--	--	--	2	2	5.4	0.3	17.8	1.1	22.3	0.2	1,720	--	--	--	--	--	--
	Total	730,000	40,439	11,080	547.6	4,430	--	--	--	224	103	207.2	7.8	1,219.8	31.8	1,755.3	64.3	58,580	--	--	--	--	--	--
1982	Milwaukee River at North Avenue Dam (RIV-5)	510,000	34,100	9,520	544.0	3,810	40,100	9,320	45,500	207	102	319.0	6.7	1,290.0	29.2	1,420.0	24.3	54,000	1.20	5.5	127.0	141	67.7	15.7
	Menomonee River at S. 37th Street (RIV-10)	147,000	11,300	4,920	203.0	2,940	5,960	126	729	54	28	58.1	0.9	315.0	7.6	230.0	1.8	30,800	0.10	0.9	0.6	33	5.8	1.5
	Kinnickinnic River at S. 9th Place (RIV-13)	27,100	2,640	564	6.39	869	3,370	446	1,300	7	3	9.0	0.3	26.7	1.2	40.9	0.3	5,700	0.03	1.4	0.1	7	0.8	0.4
	Total	684,100	48,040	15,004	753.4	7,619	49,430	11,026	54,090	268	133	386.1	7.9	1,631.7	38.0	1,690.9	26.4	90,500	1.33	7.8	127.7	180	74.3	17.6
1983	Milwaukee River at North Avenue Dam (RIV-5)	518,000	31,800	10,300	222.0	3,250	31,000	11,000	62,600	156	86	253.0	6.2	1,150.0	28.7	1,307.0	23.1	59,500	1.80	5.7	5.2	713	73.5	21.6
	Menomonee River at S. 37th Street (RIV-10)	177,000	11,100	1,980	76.7	935	6,580	2,330	12,700	33	17	51.1	1.9	224.0	7.7	263.0	3.3	32,900	0.50	2.2	1.9	136	20.1	4.3
	Kinnickinnic River at S. 9th Place (RIV-13)	20,800	309	97	9.31	125	687	181	1,160	2	1	2.8	0.2	14.7	0.8	21.5	0.2	5,040	0.05	0.2	0.2	13	1.6	1.0
	Total	715,800	43,209	12,377	308.1	4,310	38,267	13,511	76,460	191	104	306.9	8.3	1,388.7	37.2	1,591.5	26.6	97,440	2.35	8.1	7.3	862	95.2	26.9
Mean	Milwaukee River at North Avenue Dam (RIV-5)	550,000	33,100	9,870	352.0	3,830	35,500	10,160	54,000	185	92	247.0	6.6	1,140.0	27.6	1,440.0	36.7	53,700	1.50	5.6	66.1	427	70.6	18.6
	Menomonee River at S. 37th Street (RIV-10)	137,000	9,540	2,660	170.0	1,940	6,270	1,800	10,000	39	19	47.3	1.2	250.0	7.0	212.0	2.2	24,300	0.30	1.6	1.2	84	13.0	2.9
	Kinnickinnic River at S. 9th Place (RIV-13)	21,900	1,220	294	15.1	497	2,030	314	1,230	4	2	5.7	0.3	19.7	1.0	28.2	0.2	4,150	0.04	0.8	0.2	10	1.2	0.7
	Total	708,900	45,860	12,524	537.1	6,267	43,800	12,274	65,230	228	113	300.0	8.1	1,410.0	35.6	1,680.0	39.1	82,150	1.80	8.0	67.5	521	84.8	22.2

[a] *All loadings in 1,000 pounds except fecal coliform, in No. x 10^{14}.*

Source: SEWRPC.

Table 124

PRECIPITATION AND RIVER FLOW DATA: 1981-1983

Year	Precipitation[a] (inches)	River Flow and Watershed Runoff					
		Milwaukee River[b]		Menomonee River[c]		Kinnickinnic River[d]	
		Mean Flow (cfs)	Watershed Runoff (inches)	Mean Flow (cfs)	Watershed Runoff (inches)	Mean Flow (cfs)	Watershed Runoff (inches)
1981	33.88	532	10.58	105	11.64	25.9	17.22
1982	36.56	599	11.68	114	12.57	27.5	18.28
1983	37.47	605	11.80	119	13.14	23.1	15.52

[a]Precipitation measured in the City of Milwaukee at General Mitchell Field.

[b]Milwaukee River at Estabrook Park, City of Milwaukee.

[c]Menomonee River at N. 70th Street, City of Wauwatosa.

[d]Kinnickinnic River at S. 7th Street for 1981 and 1982, and at S. 11th Street for 1983, City of Milwaukee.

Source: National Weather Service, National Oceanic and Atmospheric Administration, and U. S. Geological Survey.

contribution of copper was 8 percent, of chlorophyll-a was 43 percent, and of iron was 83 percent. Dry-weather conditions accounted for the remaining 92 percent of the copper loading, 57 percent of the chlorophyll-a loading, 17 percent of the iron loading, and from 24 to 39 percent of the remaining loadings.

It should be noted that the wet-weather loadings represent total loadings from all sources estimated for all wet-weather-affected days. Over the three-year study period, about 55 percent of the days were marked by wet-weather conditions.

Unit-Area Loadings: The total annual pollutant loadings set forth in Table 123 were divided by the tributary drainage areas of the respective rivers to estimate unit-area loadings. The unit-area loadings, presented in pollutant amount per square mile of tributary drainage area, permit comparisons to be made of the relative contribution from each of the three tributary watersheds. The unit-area loadings are set forth in Table 126.

In general, the smaller watersheds may be expected to have higher unit-area pollutant loadings than the larger watersheds because the delivery efficiency of the smaller watersheds is higher since there is less opportunity for pollutants in the stream to be converted, trapped, or settled out. Similarly, more urbanized watersheds would tend to have higher pollutant unit-area loadings than would rural watersheds because the increased impervious area under urban conditions results in larger peak runoff flows and runoff volumes, and because more pollutants are often available for transport in urban areas. As shown in Table 126, however, these assumptions are not always correct.

The Kinnickinnic River, having the smallest and most urbanized watershed, generated the highest pollutant unit-area loadings of total solids, biochemical oxygen demand, chemical oxygen demand, total organic carbon, un-ionized ammonia nitrogen, chloride, chromium, and zinc. The Menomonee River watershed generated the highest unit-area loadings of total suspended solids, volatile suspended solids, fecal coliform, total and soluble phosphorus, nitrate and nitrite nitrogen, and iron. The Milwaukee River watershed, although being the largest and least urbanized, contributed the highest unit-area loadings of total inorganic carbon, total Kjeldahl nitrogen, chlorophyll-a, copper, and lead. The relatively high unit-area loadings of chlorophyll-a and total Kjeldahl nitrogen may be attributed to the higher levels of algae growing in

Table 125

ESTIMATED ANNUAL WET-WEATHER AND DRY-WEATHER POLLUTANT LOADINGS TO THE INNER HARBOR FROM THE MILWAUKEE, MENOMONEE, AND KINNICKINNIC RIVERS: 1981-1983

Period	Station	Total Solids		Total Suspended Solids		Volatile Suspended Solids		Fecal Coliform		Biochemical Oxygen Demand		Chemical Oxygen Demand		Total Organic Carbon	
		Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (No. $\times 10^{14}$)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total
Wet Weather	Milwaukee River at North Avenue Dam (RIV-5)	326,590,000	46	24,170,700	53	6,062,400	48	235.19	44	2,259,000	36	23,473,000	53	6,186,000	51
	Menomonee River at S. 37th Street (RIV-10)	96,130,000	14	9,333,400	20	2,443,100	20	100.90	19	1,896,000	30	5,156,000	12	1,390,000	11
	Kinnickinnic River at S. 9th Place (RIV-13)	15,510,000	2	1,224,900	3	258,400	2	53.22	10	540,000	9	2,068,000	5	281,000	2
	Total	438,220,000	62	34,732,100	76	8,763,900	70	389.26	73	4,695,000	75	30,697,000	70	7,857,000	64
Dry Weather	Milwaukee River at North Avenue Dam (RIV-5)	218,070,000	31	10,309,100	22	3,431,400	27	92.94	17	1,326,000	21	11,736,010	27	3,952,000	32
	Menomonee River at S. 37th Street (RIV-10)	45,940,000	6	716,500	2	294,600	2	53.62	10	218,000	3	1,224,000	3	417,000	3
	Kinnickinnic River at S. 9th Place (RIV-13)	6,660,000	1	102,300	0	34,200	1	1.25	0	28,000	1	141,000	0	48,000	1
	Total	270,660,000	38	11,127,900	24	3,760,100	30	147.81	27	1,572,000	25	13,101,000	30	4,417,000	36
Total	Milwaukee River at North Avenue Dam (RIV-5)	544,660,000	77	34,479,800	75	9,493,800	75	328.08	61	3,585,000	57	35,209,000	80	10,138,000	83
	Menomonee River at S. 37th Street (RIV-10)	142,070,000	20	10,049,900	22	2,737,700	22	154.52	29	2,114,000	33	6,380,000	15	1,807,000	14
	Kinnickinnic River at S. 9th Place (RIV-13)	22,170,000	3	1,327,200	3	292,600	3	54.47	10	568,000	10	2,209,000	5	329,000	3
	Total	708,900,000	100	45,860,000	100	12,524,000	100	537.10	100	6,267,000	100	43,800,000	100	12,274,000	100

Period	Station	Total Inorganic Carbon		Total Phosphorus		Soluble Phosphorus		Ammonia Nitrogen		Un-ionized Ammonia Nitrogen		Nitrate Nitrogen		Nitrite Nitrogen		Total Kjeldahl Nitrogen	
		Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total
Wet Weather	Milwaukee River at North Avenue Dam (RIV-5)	33,448,800	51	121,700	54	55,300	49	163,900	54	4,570	56	692,400	49	18,900	53	924,600	55
	Menomonee River at S. 37th Street (RIV-10)	7,472,200	11	28,800	13	12,400	11	31,900	11	620	8	186,300	13	5,600	16	161,700	10
	Kinnickinnic River at S. 9th Place (RIV-13)	963,400	2	3,200	1	1,600	1	4,500	2	210	3	15,600	1	800	2	22,200	1
	Total	41,884,300	64	153,700	68	69,300	61	200,300	67	5,400	67	894,300	63	25,300	71	1,108,500	66
Dry Weather	Milwaukee River at North Avenue Dam (RIV-5)	20,294,200	31	61,700	27	36,200	32	82,400	28	2,070	25	446,400	32	8,600	24	508,000	30
	Menomonee River at S. 37th Street (RIV-10)	2,733,600	4	11,900	5	7,200	7	16,200	5	550	7	65,200	5	1,500	4	56,800	3
	Kinnickinnic River at S. 9th Place (RIV-13)	317,900	1	400	0	200	0	1,100	<1	80	1	4,100	<1	200	1	6,700	1
	Total	23,345,700	36	74,000	32	43,600	39	99,700	33	2,700	33	515,700	37	10,300	29	571,600	34
Total	Milwaukee River at North Avenue Dam (RIV-5)	53,743,000	82	183,400	81	91,500	81	246,300	82	6,640	81	1,138,800	81	27,500	77	1,432,600	85
	Menomonee River at S. 37th Street (RIV-10)	10,205,800	15	40,700	18	19,600	18	48,100	16	1,170	15	251,500	18	7,100	20	218,500	13
	Kinnickinnic River at S. 9th Place (RIV-13)	1,281,300	3	3,600	1	1,800	1	5,600	2	290	4	19,700	1	1,000	3	28,900	2
	Total	65,230,000	100	227,700	100	112,900	100	300,000	100	8,100	100	1,410,000	100	35,600	100	1,680,000	100

Table 125 (continued)

Period	Station	Chlorophyll-a		Chlorides		Cadmium		Chromium		Copper		Iron		Lead		Zinc	
		Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total	Load (pounds)	Percent of Total
Wet Weather	Milwaukee River at North Avenue Dam (RIV-5)	15,500	40	33,675,100	41	830	46	3,800	48	4,200	6	365,000	70	43,200	51	11,200	51
	Menomonee River at S. 37th Street (RIV-10)	1,100	3	17,348,000	21	210	12	1,200	15	1,300	2	63,100	12	11,400	13	2,000	9
	Kinnickinnic River at. S. 9th Place (RIV-13)	60	< 1	2,836,900	3	20	1	100	1	100	< 1	6,100	1	900	1	400	2
	Total	16,660	43	53,860,000	65	1,060	59	5,100	64	5,600	8	434,200	83	55,500	65	13,700	62
Dry Weather	Milwaukee River at North Avenue Dam (RIV-5)	22,000	56	19,456,900	24	620	34	2,300	29	61,300	91	65,400	12	26,000	31	4,200	18
	Menomonee River at S. 37th Street (RIV-10)	400	1	7,459,600	9	100	6	500	6	500	1	18,700	4	2,900	3	600	3
	Kinnickinnic River at S. 9th Place (RIV-13)	40	< 1	1,373,500	2	20	1	100	1	100	< 1	2,700	1	400	1	3,800	17
	Total	22,440	57	28,290,000	35	740	41	2,900	36	61,900	92	86,800	17	29,300	35	8,500	8
Total	Milwaukee River at North Avenue Dam (RIV-5)	37,500	96	53,132,000	65	1,450	80	6,100	77	65,500	97	430,400	82	69,200	82	15,400	69
	Menomonee River at S. 37th Street (RIV-10)	1,500	4	24,807,600	30	310	18	1,700	21	1,800	3	81,800	16	14,300	16	2,600	12
	Kinnickinnic River at S. 9th Place (RIV-13)	100	< 1	4,210,400	5	40	2	200	2	200	< 1	8,800	2	1,300	2	4,200	19
	Total	39,100	100	82,150,000	100	1,800	100	8,000	100	67,500	100	521,000	100	84,800	100	22,200	100

Source: SEWRPC.

the Milwaukee River than in the other two rivers. These algal growths occasionally become particularly high within the impoundments on the Milwaukee River.

Point Sources of Pollution

As of 1985, the Wisconsin Department of Natural Resources reported that Wisconsin Pollutant Discharge Elimination System (WPDES) permits were issued to a total of 14 municipal wastewater treatment facilities and to 77 industrial wastewater dischargers which discharge to surface waters within the Milwaukee Harbor tributary drainage area. One of the municipal treatment facilities—the Milwaukee Metropolitan Sewerage District's Jones Island wastewater treatment plant—discharges effluent directly to the Milwaukee outer harbor. All of the remaining municipal treatment facilities discharge to surface waters upstream of the inner harbor. Table 127 summarizes the 1984 estimated pollutant loadings to surface waters from municipal and industrial wastewater dischargers based upon flow and pollutant concentration measurements contained within the DNR discharge monitoring reports. All of the municipal wastewater treatment facilities and 35 of the 77 industrial wastewater dischargers, or 45 percent, were required to submit discharge monitoring reports to the DNR. Of the industrial wastewater discharges listed in Table 127, 32, or 91 percent, discharge to surface waters upstream of the inner harbor, and three, or 9 percent, discharge directly to the inner harbor. The table excludes loadings discharged from the Jones Island wastewater treatment plant, which are presented separately in Table 128. The Jones Island wastewater treatment plant loadings were calculated from monitoring data provided by the Milwaukee Metropolitan Sewerage District.

Table 127 indicates that the overwhelming majority—generally over 99 percent—of the total point source pollutant loadings, excluding those from the Jones Island sewage treatment plant, are discharged upstream of the inner harbor. Pollutant loadings being discharged from point sources other than combined sewers directly into the inner harbor are relatively low.

Table 126

SUMMARY OF THE ESTIMATED POLLUTANT UNIT-AREA LOADINGS TO THE INNER HARBOR FROM THE MILWAUKEE, MENOMONEE, AND KINNICKINNIC RIVERS: 1981-1983[a]

Year	Station	Total Solids	Total Suspended Solids	Volatile Suspended Solids	Fecal Coliform	Biochemical Oxygen Demand	Chemical Oxygen Demand	Total Organic Carbon	Total Inorganic Carbon	Total Phosphorus	Soluble Phosphorus	Ammonia Nitrogen	Un-ionized Ammonia Nitrogen	Nitrate Nitrogen	Nitrite Nitrogen	Total Kjeldahl Nitrogen	Chlorophyll-a	Chlorides	Cadmium	Chromium	Copper	Iron	Lead	Zinc
1981	Milwaukee River at North Avenue Dam (RIV-5)	887,000	47,700	13,900	41	6,310	- -	- -	- -	272	125	241	10	1,410	36	2,260	89	67,800	- -	- -	- -	- -	- -	- -
	Menomonee River at S. 37th Street (RIV-10)	666,000	46,500	7,980	171	- -	- -	- -	- -	228	95	245	5	1,580	42	1,070	11	69,100	- -	- -	- -	- -	- -	- -
	Kinnickinnic River at S. 9th Place (RIV-13)	876,000	35,100	10,900	147	- -	- -	- -	- -	119	89	267	15	881	54	1,100	10	85,100	- -	- -	- -	- -	- -	- -
	Total[b]	853,000	47,200	12,900	64	- -	- -	- -	- -	262	120	242	9	1,425	37	2,050	75	68,400	- -	- -	- -	- -	- -	- -
1982	Milwaukee River at North Avenue Dam (RIV-5)	726,000	48,600	13,600	77	5,430	57,100	13,300	64,800	295	145	454	10	1,840	42	2,020	35	76,900	2	8	181	201	96	22
	Menomonee River at S. 37th Street (RIV-10)	1,100,000	84,300	36,700	151	21,900	44,500	9,400	54,400	402	207	434	7	2,350	57	1,720	13	230,000	1	7	4	243	43	11
	Kinnickinnic River at S. 9th Place (RIV-13)	1,340,000	131,000	27,900	32	43,000	167,000	22,100	64,400	347	134	446	15	1,320	59	2,020	15	282,000	1	69	5	327	40	20
	Total[b]	799,000	56,100	17,500	88	8,900	57,700	12,900	63,200	313	155	451	9	1,910	44	1,970	31	105,700	2	9	149	210	87	21
1983	Milwaukee River at North Avenue Dam (RIV-5)	738,000	45,300	14,700	32	4,630	44,200	15,700	89,200	222	123	360	9	1,640	41	1,860	33	84,800	3	8	7	1,020	105	31
	Menomonee River at S. 37th Street (RIV-10)	1,320,000	82,800	14,800	57	6,980	49,100	17,400	94,800	246	123	381	14	1,670	57	1,960	25	246,000	4	16	14	1,020	150	32
	Kinnickinnic River at S. 9th Place (RIV-13)	1,030,000	15,300	4,810	46	6,190	34,000	8,960	57,400	74	45	139	10	728	40	1,060	10	250,000	2	10	10	619	79	50
	Total[b]	836,000	50,500	14,500	36	5,030	45,000	15,780	89,300	222	121	358	10	1,620	43	1,860	31	113,800	3	9	9	1,010	110	31
Mean	Milwaukee River at North Avenue Dam (RIV-5)	783,000	50,000	14,100	50	5,460	50,600	14,500	76,900	260	130	350	9	1,620	39	2,050	52	76,500	2	8	94	608	100	26
	Menomonee River at S. 37th Street (RIV-10)	1,020,000	71,200	19,850	127	14,500	46,800	13,400	74,600	290	140	350	9	1,860	52	1,580	16	181,000	2	12	9	628	97	22
	Kinnickinnic River at S. 9th Place (RIV-13)	1,080,000	60,400	14,500	75	24,600	100,500	15,500	60,900	180	90	280	15	980	50	1,400	10	205,000	2	40	10	475	59	35
	Total[b]	828,000	53,600	14,000	63	7,320	51,200	14,340	76,190	266	132	350	9	1,650	42	1,960	46	95,900	2	9	79	610	100	26

[a] *All loadings in pounds per square mile except fecal coliform, in No. x 10^{12} per square mile.*

[b] *The total indicates the weighted average for the three areas listed above.*

Source: SEWRPC.

Table 127

SUMMARY OF ESTIMATED DISCHARGE AND POLLUTANT LOADINGS FROM MUNICIPAL AND INDUSTRIAL WASTEWATER DISCHARGES: 1984[a]

Watershed and Type of Facility	Name of Facility	Mean Reported Discharge (mgd)	Suspended Solids	Fecal Coliform (No. x 10^7 per year)	Total Phosphorus	Ammonia Nitrogen	Biochemical Oxygen Demand	Chemical Oxygen Demand	Dissolved Solids	Chlorine	Cadmium	Chromium	Cobalt	Lead	Zinc	Oil/Grease	Dichloro-ethylene	Methylene Chloride	Phenols	Tetra-chloroethane	Toulene	Trichloro-ethane
Kinnickinnic Industrial	Caterpillar Tractor Company	0.003	160	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	--	--	--	--
	Kurth Malting Corporation	0.430	--	--	--	--	--	--	--	700	--	--	--	--	--	--	--	--	--	--	--	--
	Rexworks, Inc.	0.020	160	--	--	--	--	--	--	--	--	--	--	--	--	180	--	--	--	--	--	--
	Union Oil Company of California	0.004	--	--	--	--	--	--	--	--	--	--	--	--	--	25	--	--	--	--	--	--
	Unit Drop Forge	0.054	2,380	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal	0.511	2,700	--	--	--	--	--	--	700	--	--	--	--	--	215	--	--	--	--	--	--
Menomonee Industrial	Amoco Oil Company	0.007	--	--	--	--	--	--	--	--	--	--	--	--	--	40	--	--	--	--	--	--
	Briggs & Stratton[b]	0.193	--	--	--	--	--	--	--	--	--	--	--	--	--	2,110	--	--	--	--	--	--
	Chicago, Milwaukee, St. Paul & Pacific Railroad	0.301	5,600	--	--	--	--	--	--	--	--	--	--	--	--	4,175	--	--	--	--	--	--
	Chicago & North Western Transportation Company	0.020	480	--	--	--	--	--	--	--	--	--	--	--	--	530	--	--	--	--	--	--
	Falk Corporation	0.981	71,300	--	--	--	--	--	--	--	--	--	--	--	--	6,775	--	--	--	--	--	--
	Harnischfeger Corporation	0.282	2,700	--	--	--	--	--	--	--	--	--	--	--	--	2,520	--	--	--	--	--	--
	Koopers Company/Thiem Corporation	0.091	1,860	--	--	--	760	--	--	--	--	--	--	--	--	860	--	--	--	--	--	--
	Miller Brewing Company	1.518	--	--	--	--	16,490	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Milwaukee Marble Company[b]	0.001	20	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Rexnord, Inc.-West Milwaukee Facility	0.132	1,100	--	--	--	--	--	--	--	--	--	9	--	--	1,160	--	--	--	--	--	--
	Stroh Die Casting Company, Inc.	0.009	120	--	--	--	5,000	--	--	--	--	--	--	--	--	825	--	--	--	--	--	--
	Union Oil Company of California	0.003	--	--	--	--	--	--	--	--	--	--	--	--	--	60	--	--	--	--	--	--
	United Parcel Service	0.11	1,720	--	40	--	1,620	--	--	--	--	--	--	--	--	2,300	--	--	--	--	--	--
	Veteran Administration Medical Center	0.004	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Waste Management of Wisconsin-Menomonee Falls	0.051	2,180	--	--	60	350	--	--	--	--	--	--	--	--	--	--	--	56	--	--	--
	Waste Management of Wisconsin-Omega Hills	0.103	5,550	--	--	--	1,590	6,810	--	--	--	--	--	--	--	--	0.76	0.37	381	0.38	0.38	0.38
	West Shore Pipeline Company-Granville Station	0.001	--	--	--	--	--	--	--	--	--	--	--	--	--	5	--	--	--	--	--	--
	Western Metal Specialty Division	0.017	--	--	--	--	--	--	--	--	--	--	--	4	16	670	--	--	--	--	--	--
	Wisconsin Electric Power Company (Valley)[b]	73.50	--	--	--	--	--	--	--	575	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal	77.344	92,630	--	40	60	25,810	6,810	--	575	--	--	9	4	16	22,030	0.76	0.37	437	0.38	0.38	0.38
Menomonee Municipal	Germantown Sewage Treatment Plant	1.277	47,770	383,300	1,560	--	43,660	--	--	2,471	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal	1.277	47,770	383,300	1,560	--	43,660	--	--	2,471	--	--	--	--	--	--	--	--	--	--	--	--
Milwaukee Industrial	A. O. Smith Corporation	2.633	30,840	--	200	--	--	--	--	--	--	3	--	--	45	10,320	--	--	--	--	--	--
	Advance Die Casting	0.011	--	--	--	--	--	--	--	--	--	--	--	--	8	--	--	--	--	--	--	--
	American Motors Corporation-Milwaukee Manufacturing Plant	0.100	1,040	--	--	--	--	--	--	--	--	--	--	--	--	440	--	--	--	--	--	--
	Aqua-Chem, Inc.	0.025	30	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Badger Meter, Inc.	0.125	--	--	--	--	--	--	--	--	--	--	--	--	--	410	--	--	--	--	--	--
	Culligan Water Conditioning of Milwaukee	0.032	1,000	--	--	--	--	--	26,350	--	--	--	--	--	--	--	--	--	--	--	--	--
	James B. Downing Company	0.329	21,000	--	--	2,210	--	--	80	--	--	--	--	--	--	--	--	--	--	--	--	--
	Johnson Brass & Machine Foundry	0.016	280	--	--	--	--	--	--	--	--	--	--	--	--	210	--	--	--	--	--	--
	Level Valley Dairy Company	0.272	358,130	--	--	--	324,900	--	--	140	--	--	--	--	--	--	--	--	--	--	--	--
	Evinrude Motors--Division of Outboard Marine Corporation	0.842	--	--	--	--	--	--	--	--	--	--	--	--	--	900	--	--	--	--	--	--
	Regal Ware, Inc.	0.322	1,410	--	--	--	--	--	--	--	3	--	--	57	--	--	--	--	--	--	--	--
	Subtotal	4.707	413,730	--	200	2,210	324,900	--	26,430	140	3	3	--	57	53	12,280	--	--	--	--	--	--
Milwaukee Municipal	Random Lake Sewage Treatment Plant	0.304	2,680	2,400	450	--	3,310	--	--	85	--	--	--	--	--	--	--	--	--	--	--	--
	Kewaskum Sewage Treatment Plant	0.441	11,180	5,548,000	900	1,300	56,712	--	--	1,315	--	--	--	--	--	--	--	--	--	--	--	--
	Campbellsport Sewage Treatment Plant	2.121	83,110	2,009,700	--	--	89,503	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Cascade Sewage Treatment Plant	0.052	3,050	137,000	--	--	2,950	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Cedarburg Sewage Treatment Plant	2.022	126,530	31,716,700	4,080	1,680	45,160	--	--	190	--	--	--	--	--	--	--	--	--	--	--	--
	Fredonia Sewage Treatment Plant	0.197	2,350	36,500	--	--	8,080	--	--	120	--	--	--	--	--	--	--	--	--	--	--	--
	Grafton Sewage Treatment Plant	1.187	27,960	1,425,100	2,560	1,880	15,510	--	--	2,130	--	--	--	--	--	--	--	--	--	--	--	--
	Jackson Sewage Treatment Plant	0.348	5,710	36,500	590	680	4,470	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Newburg Sewage Treatment Plant	0.061	4,490	3,428,700	--	--	4,840	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Saukville Sewage Treatment Plant	0.515	12,220	100,500	800	--	17,730	--	--	265	--	--	--	--	--	--	--	--	--	--	--	--
	Thiensville Sewage Treatment Plant	0.883	34,020	2,521,300	--	--	21,320	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	West Bend Sewage Treatment Plant	3.750	4,810	3,370,800	5,390	310	7,000	--	--	85	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal	11.881	318,110	50,333,200	14,770	5,850	276,580	--	--	4,190	--	--	--	--	--	--	--	--	--	--	--	--
Upstream Industrial		9.061	509,040	--	240	2,270	350,710	6,810	26,430	840	3	3	9	61	69	32,415	0.76	0.37	437	0.38	0.38	0.38
Municipal		13.158	365,880	50,716,500	16,330	5,850	320,240	--	--	4,190	--	--	--	--	--	--	--	--	--	--	--	--
Total		22.219	874,920	50,716,500	16,570	8,120	670,950	6,810	26,430	5,030	3	3	9	61	69	32,415	0.76	0.37	437	0.38	0.38	0.38
Inner Harbor[b] Industrial		73.501	20	--	--	--	--	--	--	575	--	--	--	--	--	2,110	--	--	--	--	--	--
Municipal		--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total		73.501	20	--	--	--	--	--	--	575	--	--	--	--	--	2,110	--	--	--	--	--	--
Total Industrial		82.562	509,060	--	240	2,270	350,710	6,810	26,430	1,415	3	3	9	61	69	34,525	0.76	0.37	437	0.38	0.38	0.38
Total Municipal		13.158	365,880	50,716,500	16,330	5,850	320,240	--	--	4,190	--	--	--	--	--	--	--	--	--	--	--	--
Total		95.720	874,940	50,716,500	16,570	8,120	670,950	6,810	26,430	5,605	3	3	9	61	69	34,525	0.76	0.37	437	0.38	0.38	0.38

[a] *Unless otherwise noted, all figures indicate pounds per year.*

[b] *Facilities which discharge directly to the Inner Harbor.*

Source: Wisconsin Department of Natural Resources, Wisconsin Pollutant Discharge Elimination System Permits and Discharge Monitoring Reports.

Table 128

ESTIMATED ANNUAL POLLUTANT LOADINGS DISCHARGED INTO THE OUTER HARBOR FROM THE JONES ISLAND WASTEWATER TREATMENT PLANT: 1984

Pollutant	Estimated Annual Loading (pounds unless noted)
Suspended Solids	7,060,100
Biochemical Oxygen Demand	4,569,000
Fecal Coliform	1.27×10^{15} counts
Total Phosphorus	169,500
Soluble Phosphorus	85,900
Ammonia Nitrogen	2,561,000
Nitrate Nitrogen	410,500
Nitrite Nitrogen	205,000
Total Kjeldahl Nitrogen	3,956,000
Total Residual Chlorine	470,100

Source: Milwaukee Metropolitan Sewerage District.

A comparison of the point source loadings of selected indicators discharged upstream of the inner harbor to the total river loadings is provided in Table 129. The data in this table suggest that point sources of pollution contribute a relatively small portion of the total river loadings transported to the inner harbor. A portion of point source pollutant loadings discharged within the upstream drainage areas may be expected to settle in the stream channel, or to be reduced by chemical and biological processes before reaching the inner harbor. For analysis purposes, however, it was assumed that the entire point source load would be transported downstream to the inner harbor. The comparison of the point source loadings to total river loadings, as set forth in Table 129, indicates that point sources may be expected to account for about 2 percent of the suspended solids load, less than 1 percent of the fecal coliform load, about 8 percent of the phosphorus load, about 3 percent of the ammonia nitrogen load, about 11 percent of the biochemical oxygen demand load, and less than 1 percent of the cadmium, chromium, copper, lead, and zinc loads. Thus, the majority of the river pollutant loadings upstream of the inner harbor are contributed by nonpoint sources, rather than by point sources.

Combined Sewer Pollutant Loadings

Pollutant loadings are discharged from combined sewer overflows to surface waters upstream of the inner harbor, directly into the inner harbor, and directly into the outer harbor, including the South Shore Harbor. The combined sewer service area totals about 15,300 acres, or 23.8 square miles in area, and 109 combined sewer outfalls are located along the streams and watercourses of the area.

The volume of combined sewer overflows discharged annually was calculated using 1981 through 1983 precipitation amounts and a modified version of the STORM model. The quality of combined sewer overflows, although highly variable, was characterized with data collected as part of the Milwaukee Metropolitan Sewerage District's combined sewer overflow pilot plant treatment study.[37] The data used for this analysis were collected during seven rainfall or snowmelt events over the period April 3, 1978 through March 19, 1979. The data used were collected at three combined sewer outfall stations—at Kern Park on the Milwaukee River, at Humboldt Avenue on the Milwaukee River, and at S. 27th Street and S. Kinnickinnic Avenue on the Kinnickinnic River. Data collected under the pilot plant treatment study at two additional sampling stations located within the Jones Island wastewater treatment plant were not used for this analysis because the wastewater at the Jones Island stations contained both combined sewer overflow and raw sanitary sewage from separate sewered areas. Fecal coliform measurements were not collected at the above three stations during the pilot plant treatment study. The fecal coliform levels in combined sewer overflows used for this analysis were therefore those estimated in SEWRPC Technical Report No. 21, Sources of Water Pollution in Southeastern Wisconsin: 1975, 1978.

Table 130 summarizes the estimated concentrations of selected water quality indicators in combined sewer overflow discharges and the annual pollutant loadings discharged from combined sewers upstream of the inner harbor, directly to the inner harbor, and directly to the outer harbor. About 33 percent of the total pollutant loadings

[37] *Milwaukee Metropolitan Sewerage District, Combined Sewer Overflow, Vol. I, Characterization, Storage and Pilot Plant Treatment, Milwaukee Water Pollution Abatement Program, May 1979.*

Table 129

COMPARISON OF THE EXISTING UPSTREAM POINT SOURCE LOADINGS TO THE TOTAL RIVER LOADINGS OF POLLUTANTS

Pollutant	Known Point Source Loadings Upstream of Inner Harbor (pounds unless noted)	Total River Loadings to Inner Harbor (pounds unless noted)	Point Source Percent of Total River Loading
Suspended Solids	907,500	45,860,000	1.98
Fecal Coliform	5.0×10^{14} counts	537.1×10^{14} counts	0.93
Phosphorus	17,100	227,700	7.51
Ammonia Nitrogen	8,100	300,000	2.70
Biochemical Oxygen Demand	683,500	6,267,000	10.91
Chemical Oxygen Demand	6,800	43,800,000	0.02
Cadmium	3	1,800	0.17
Chromium	3	8,000	0.04
Lead	61	84,800	0.07
Zinc	69	22,200	0.31

Source: SEWRPC.

Table 130

SUMMARY OF ESTIMATED QUALITY OF COMBINED SEWER OVERFLOW DISCHARGES AND ANNUAL POLLUTANT LOADINGS: 1981-1983

Pollutant	Mean Concentration (mg/l unless noted)	Annual Loadings: 1981-1983[a] (pounds, except fecal coliform in number of organisms)			
		Upstream of Inner Harbor	Directly to Inner Harbor	Directly to Outer Harbor[b]	Total
Total Solids	643	15,284,000	28,252,000	2,778,000	46,314,000
Total Suspended Solids	258	6,132,000	11,336,000	1,115,000	18,583,000
Volatile Suspended Solids	138	3,280,000	6,064,000	596,000	9,940,000
Biochemical Oxygen Demand	86	2,044,000	3,778,000	372,000	6,194,000
Chemical Oxygen Demand	265	6,299,000	11,644,000	1,145,000	19,088,000
Total Phosphorus	2.02	48,000	88,000	9,000	145,000
Soluble Phosphorus	0.24	6,000	10,000	1,000	17,000
Ammonia Nitrogen	1.73	41,000	76,000	8,000	125,000
Nitrate Nitrogen	1.21	29,000	53,000	5,000	87,000
Total Kjeldahl Nitrogen	10.9	259,000	479,000	47,000	785,000
Chloride	303	7,202,000	13,313,000	1,310,000	21,825,000
Cadmium	0.01	230	430	40	700
Chromium	0.08	1,900	3,500	400	5,800
Copper	0.08	1,900	3,500	400	5,800
Lead	1.07	25,500	47,000	4,600	77,100
Zinc	0.67	15,900	29,500	2,900	48,300
Fecal Coliform	7.0×10^5 no./100 ml	0.75×10^{17}	1.39×10^{17}	0.14×10^{17}	2.28×10^{17}

[a] *Based on an estimated average annual discharge of* 8,600 million gallons.

[b] *Includes South Shore harbor.*

Source: Milwaukee Metropolitan Sewerage District, U. S. Environmental Protection Agency, and SEWRPC.

Table 131

COMPARISON OF THE UPSTREAM COMBINED SEWER OVERFLOW LOADINGS TO THE UPSTREAM WET-WEATHER TOTAL RIVER LOADINGS: 1981-1983

Pollutant	Upstream Combined Sewer Overflow Loadings (pounds/year)	Total Wet-Weather River Loadings (pounds/year)	Combined Sewer Overflow Percent of Wet-Weather River Loadings
Total Solids	15,284,000	426,471,000	3.6
Total Suspended Solids	6,132,000	32,003,000	19.2
Volatile Suspended Solids	3,280,000	8,723,400	37.6
Biochemical Oxygen Demand	2,044,000	4,783,400	42.7
Chemical Oxygen Demand	6,299,000	31,940,000	19.7
Total Phosphorus	48,000	148,910	32.2
Soluble Phosphorus	6,000	68,210	8.8
Ammonia Nitrogen	41,000	195,230	21.0
Nitrate Nitrogen	29,000	883,900	3.3
Total Kjeldahl Nitrogen	259,000	1,062,100	24.4
Chloride	7,202,000	52,831,000	13.6
Cadmium	230	1,055	21.8
Chromium	1,900	4,625	41.1
Copper	1,900	3,920	48.5
Lead	25,500	53,075	48.0
Zinc	15,900	16,800	94.6

Source: SEWRPC.

from combined sewer overflows is discharged to surface waters upstream of the inner harbor; about 61 percent is discharged directly to the inner harbor; and the remaining 6 percent is discharged directly to the outer harbor.

A comparison of the upstream combined sewer overflow pollutant loadings to upstream wet weather river loadings is set forth in Tàble 131. Combined sewer overflows are estimated to account for a relatively large portion of the total wet-weather river loadings to the inner harbor. In particular, combined sewer overflows are estimated to contribute from 22 to nearly 95 percent of the wet-weather river metals loadings; from 3 to 32 percent of the various nutrient loadings; from 20 to 43 percent of the organic loadings expressed as biochemical oxygen demand, chemical oxygen demand, and volatile suspended solids; and from 4 to 10 percent of the total solids and suspended solids loadings. A comparison of combined sewer overflow loadings of fecal coliform to wet-weather river loadings of fecal coliform is not provided in Table 131 because the variability of fecal coliform levels both in combined sewer overflow discharges and in the rivers is too large to permit a meaningful comparative analysis.

Summary of Pollutant Loadings to the Inner Harbor

The relative contribution of pollutant loadings to the inner harbor is summarized in Table 132 and illustrated in Figure 159. Upstream river loadings are estimated to account for at least one-half of the total inner harbor loadings of all pollutants except biochemical oxygen demand, lead, and zinc. The two largest sources of pollutant loadings to the inner harbor are the combined sewer system and upstream nonpoint sources of pollution. Combined sewer overflows which discharge both upstream and directly to the inner harbor account for about 50 percent of the total inner harbor volatile suspended solids loading, 58 percent of the biochemical oxygen demand loading, 55 percent of the lead loading, and 88 percent of the zinc loading. Upstream nonpoint sources of pollution are estimated to account for over 90 percent of the total inner harbor loadings of total solids, nitrate nitrogen, and copper, and for over 50 percent of the loadings of total suspended solids, chemical oxygen demand, total and soluble phosphorus, ammonia nitrogen, total Kjeldahl nitrogen, chloride, cadmium, and chromium. Upstream point sources of pollution contribute less than 7 percent of the loadings of all pollutants analyzed; direct point source loadings to the inner harbor are insignificant.

This study indicates that the relative importance of combined sewer overflows to annual pollutant loadings is greater than was indicated in SEWRPC Technical Report No. 21, Sources of Water Pollution in Southeastern Wisconsin: 1975, 1978. This difference occurs because this study compares combined sewer overflow loadings to estimated loadings of pollutants actually being transported in the rivers. SEWRPC Technical Report No. 21, however, compared combined sewer overflow loadings to total loadings to all drainage channels. Only a portion of the channel loadings would be transported to downstream reaches. However, both this study and SEWRPC Technical Report No. 21 indicate that upstream nonpoint sources of pollution contribute a large portion—over one-half—of the loadings of most pollutants.

SUMMARY

The assessment of existing water quality, sediment quality, and biological conditions in the Milwaukee Harbor estuary constituted an important step in the water resource management planning effort for the estuary. These existing conditions must be compared to desired conditions and the problem areas identified as the first step in the process of developing a plan to achieve selected water quality objectives. Existing conditions and problems were characterized using data collected during a three-year study period of March 1981 through December 1983, supplemented with inventory data on toxic and hazardous substances collected in earlier studies.

Water Quality Conditions

Water quality samples were collected at 10 upstream river stations, nine inner harbor stations, 10 outer harbor stations, and five near-shore Lake Michigan stations. In all, a total of 10,310 baseline and runoff event samples were collected and analyzed over the three-year period. These data were used to assess existing water quality conditions, which were then compared to the conditions needed to achieve the recommended water use objectives and to determine and characterize the types of water quality problems which exist.

Analyses of the water quality data indicate that the recommended water use objectives and supporting water quality standards as set forth in Chapter II of Volume Two of this report were not fully met in any portion of the estuary during the survey period. The standards violated and the severity of those violations in each reach of the estuary are shown graphically on Map 98. In addition to considering the water quality standards for conventional water quality indicators, the study considered the standards for other substances which can cause acute and chronic toxicity in fish and other aquatic life. Map 98, therefore, also compares existing water quality conditions to the acute and chronic toxic levels of selected substances.

With regard to dissolved oxygen, the recommended 30-day mean standards were at times violated between June and October at all inner harbor stations, while the upstream stations and outer harbor stations met the 30-day mean standards throughout the survey period. The recommended one-day mean dissolved oxygen standards were violated from 40 to 80 percent of the time during the summer months in the inner harbor, but for less than 10 percent of the time at the upstream and outer harbor stations. The absolute minimum dissolved oxygen standards were violated up to 50 percent of the time during the summer months at the inner harbor stations, but not at all at the upstream or outer harbor stations. In the inner harbor, dissolved oxygen levels of less than 0.1 milligram per liter (mg/l) were recorded, while levels as low as 2.0 mg/l were recorded at the upstream stations and 3.6 mg/l at the outer harbor stations. The violations occurred primarily during low-flow/dry-weather conditions, with isolated instances of problems occurring during wet-weather periods.

With regard to fecal coliform levels, the recommended 30-day mean standard was violated more than 90 percent of the time over the three-year sampling period at both the upstream and inner harbor stations. The standard was violated from 25 to 60 percent of the time in the outer harbor. During periods when the standards were violated, levels in the inner harbor reached as high as 930,000 most probable number per 100 milliliters (MPN/100 ml), several magnitudes greater than the standard.

Table 132

SUMMARY OF EXISTING TOTAL POLLUTANT LOADINGS TO THE INNER HARBOR

Pollutant	Upstream Loadings							
	Point Source		Combined Sewer Overflow		Nonpoint Source		Total Upstream	
	Loading (pounds)	Percent of Total Loading	Loading (pounds)	Percent of Total Loading	Loading (pounds)	Percent of Total Loading	Loading (pounds)	Percent of Total Loading
Total Solids	--	0.0	15,284,000	2.1	693,616,000	94.1	708,900,000	96.2
Total Suspended Solids	907,500	1.6	6,132,000	10.7	38,820,500	67.9	45,860,000	80.2
Volatile Suspended Solids	--	0.0	3,280,000	17.7	9,244,000	49.7	12,524,000	67.4
Biochemical Oxygen Demand	683,500	6.8	2,044,000	20.4	3,539,500	35.2	6,267,000	62.4
Chemical Oxygen Demand	6,800	<0.1	6,299,000	11.4	37,494,200	67.6	43,800,000	79.0
Total Phosphorus	17,100	5.4	48,000	15.2	162,600	51.5	227,700	72.1
Soluble Phosphorus	--	0.0	6,000	4.9	106,900	87.0	112,900	91.9
Ammonia Nitrogen	8,100	2.2	41,000	10.9	250,900	66.7	300,000	79.8
Nitrate Nitrogen	--	0.0	29,000	2.0	1,381,000	94.4	1,410,000	96.4
Total Kjeldahl Nitrogen	--	0.0	259,000	12.0	1,421,000	65.8	1,680,000	77.8
Chloride	--	0.0	7,202,000	7.6	74,948,000	78.5	82,150,000	86.1
Cadmium	5	0.2	230	10.3	1,565	70.2	1,800	80.7
Chromium	5	0.1	1,900	16.5	6,095	53.0	8,000	69.6
Copper	--	0.0	1,900	2.7	65,600	92.4	67,500	95.1
Lead	60	0.1	25,500	19.3	59,240	44.9	84,800	64.3
Zinc	70	0.1	15,900	30.8	6,230	12.0	22,200	42.9

Pollutant	Direct Loadings to the Inner Harbor						Total Loadings	
	Point Source		Combined Sewer Overflow		Total Direct Loading to the Inner Harbor			
	Loading (pounds)	Percent of Total Loading	Loading (pounds)	Percent of Total Loading	Loading (pounds)	Percent of Total Loading	Loading (pounds)	Percent of Total Loading
Total Solids	--	0.0	28,252,000	3.8	28,252,000	3.8	737,152,000	100
Total Suspended Solids	20	0.1	11,336,000	19.8	11,336,020	19.8	57,196,020	100
Volatile Suspended Solids	--	0.0	6,064,000	32.6	6,064,000	32.6	18,588,000	100
Biochemical Oxygen Demand	--	0.0	3,778,000	37.6	3,778,000	37.6	10,045,000	100
Chemical Oxygen Demand	--	0.0	11,644,000	21.0	11,644,000	21.0	55,444,000	100
Total Phosphorus	--	0.0	88,000	27.9	88,000	27.9	315,700	100
Soluble Phosphorus	--	0.0	10,000	8.1	10,000	8.1	122,900	100
Ammonia Nitrogen	--	0.0	76,000	20.2	76,000	20.2	376,000	100
Nitrate Nitrogen	--	0.0	53,000	3.6	53,000	3.6	1,463,000	100
Total Kjeldahl Nitrogen	--	0.0	479,000	22.2	479,000	22.2	2,159,000	100
Chloride	--	0.0	13,313,000	13.9	13,313,000	13.9	95,463,000	100
Cadmium	--	0.0	430	19.3	430	19.3	2,230	100
Chromium	--	0.0	3,500	30.4	3,500	30.4	11,500	100
Copper	--	0.0	3,500	4.9	3,500	4.9	71,000	100
Lead	--	0.0	47,000	35.7	47,000	35.7	131,800	100
Zinc	--	0.0	29,500	57.1	29,500	57.1	51,700	100

Source: SEWRPC.

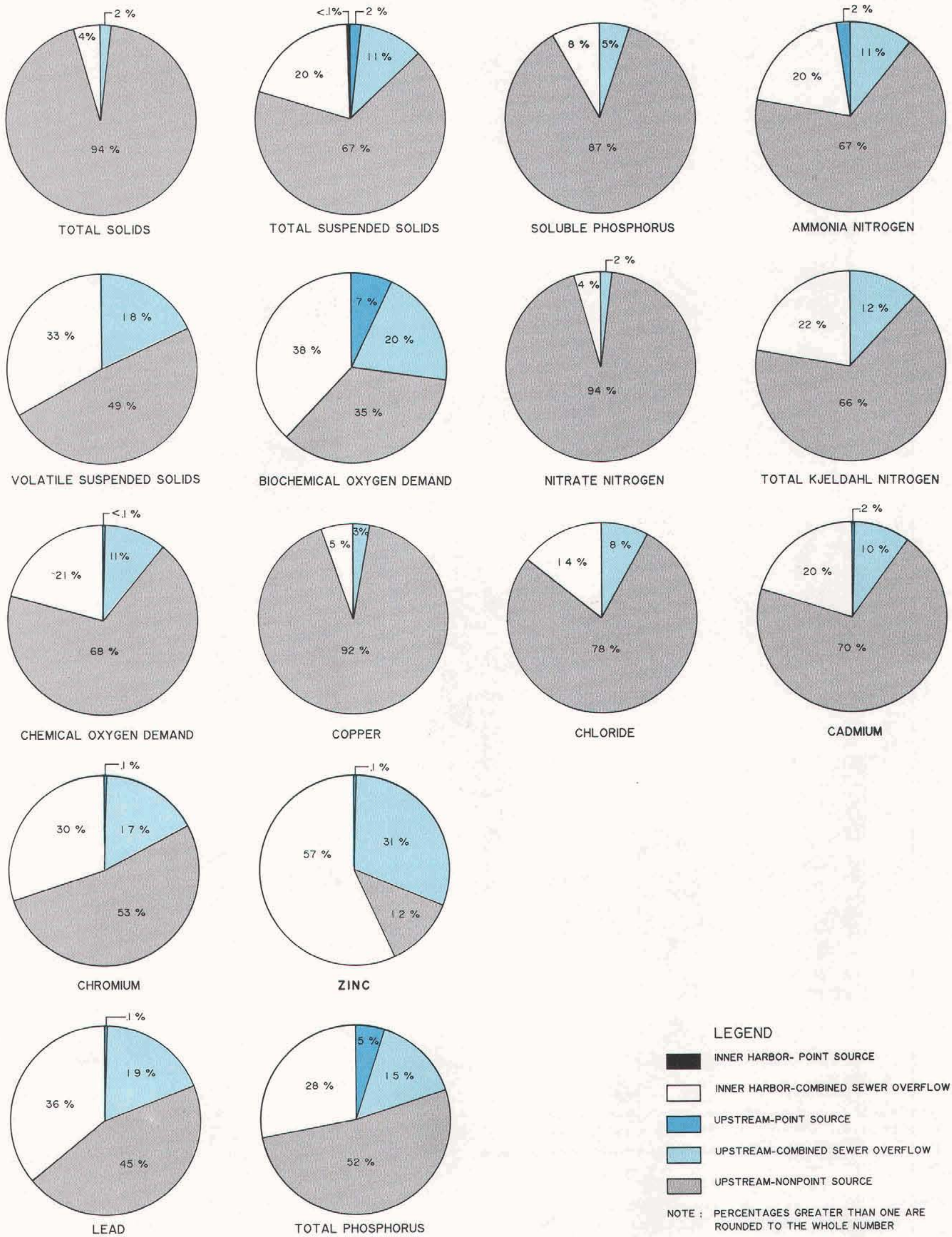
Levels as high as 240,000 MPN/100 ml were reached at both the upstream stations and the outer harbor stations.

With regard to phosphorus, the Commission-recommended standard was violated about 70 percent of the time in the Milwaukee River estuary and about 80 percent of the time in the upstream reaches of the Milwaukee River. The recommended water quality standards for the Kinnickinnic and Menomonee River portions of the estuary do not include a phosphorus standard. The recommended phosphorus standard was violated from 10 to 15 percent of the time in the outer harbor. The maximum phosphorus concentrations measured at the representative upstream Milwaukee River station, Milwaukee River estuary station, and outer harbor stations were 0.34 mg/l, 0.65 mg/l, and 0.35 mg/l, respectively.

With regard to un-ionized ammonia nitrogen, over the three-year sampling period the recommended standards were violated during two months at the Kinnickinnic River upstream station, and during one month at the south outer harbor station. Violations of the acute standard for un-ionized

Figure 159

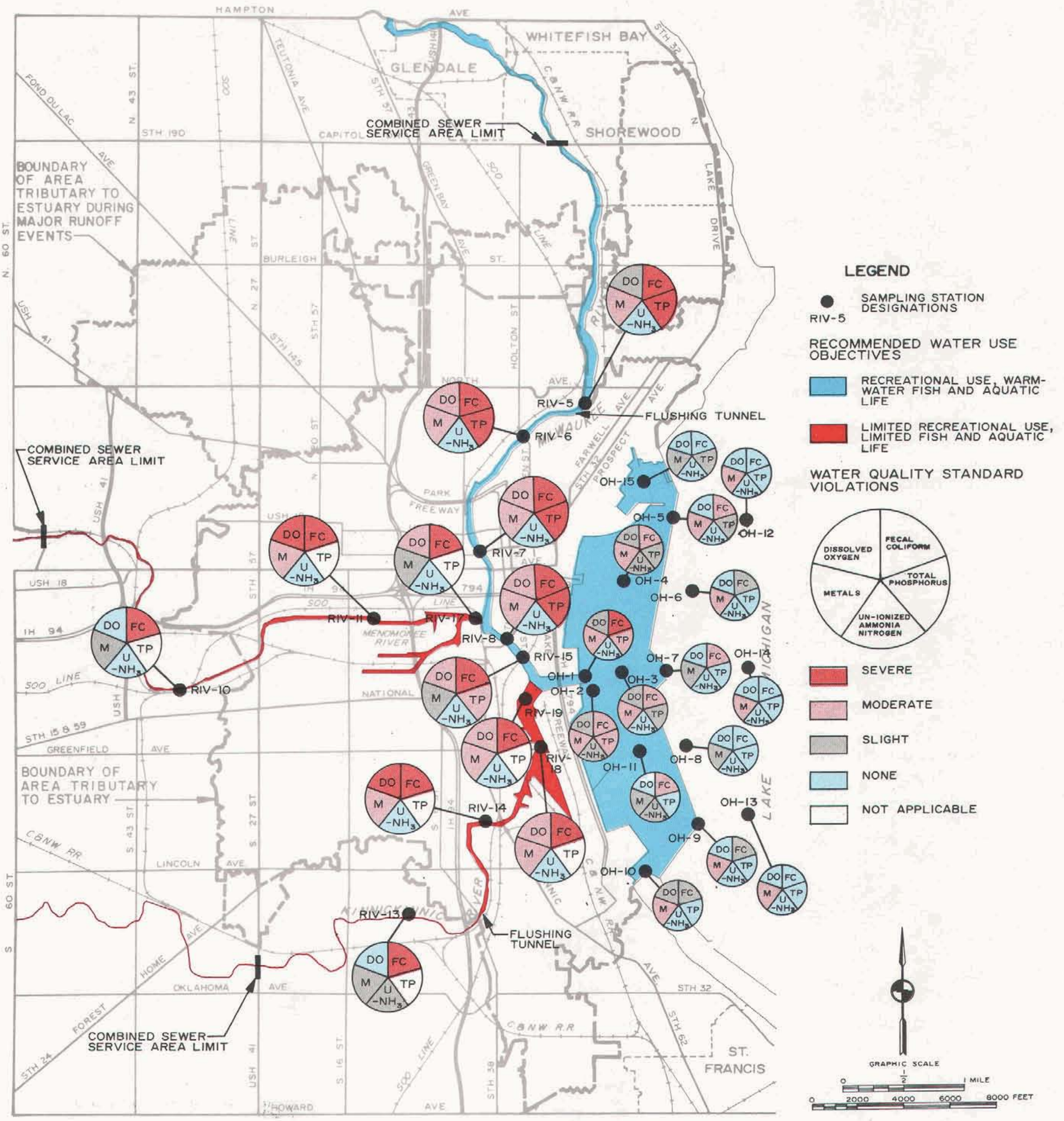
EXISTING SOURCES OF POLLUTION TO THE INNER HARBOR



Source: SEWRPC.

Map 98

EXISTING WATER QUALITY PROBLEMS IN THE MILWAUKEE HARBOR ESTUARY



Over the period from 1981 through 1984, over 10,300 water quality samples were collected at 34 sampling stations. The extent to which recommended water use objectives were being met was determined by comparing the measured data to water quality standards which support those objectives. The recommended water use objectives and supporting water quality standards are set forth in Chapter II of Volume Two of this report. As shown on this map, the recommended water use objectives were not fully met in any portion of the estuary during the survey period.

Source: SEWRPC.

ammonia nitrogen were also observed, although rarely, in the outer harbor. No violations of the acute standard were observed in the inner harbor or upstream reaches.

With regard to metals, the recommended standards, developed and promulgated by the U. S. Environmental Protection Agency since the completion of the data collection efforts under the Milwaukee Harbor estuary study, are expressed in terms of acid-soluble concentrations. The data collected as part of the Milwaukee Harbor estuary study were expressed as total metal concentrations. While the survey data cannot, therefore, be directly compared to the standards, it may be inferred from the data that chronic toxic conditions exist within the Milwaukee Harbor estuary due to the elevated concentrations of some metals, but that acute toxic conditions are generally not present.

During wet-weather conditions, concentrations of most water quality indicators—including fecal coliform, total suspended solids, total phosphorus, volatile suspended solids, biochemical oxygen demand, chromium, lead, and zinc—were higher than during dry-weather conditions. These higher concentrations are apparently due to the effects of nonpoint sources of pollution and combined sewer overflows. Other pollutant concentrations, however, did not increase during wet-weather conditions. Dry-weather levels of cadmium, copper, ammonia nitrogen, and un-ionized ammonia nitrogen were either similar to or greater than the wet-weather levels.

The data indicated that during wet-weather conditions the pollutant sources have only a moderate effect on dissolved oxygen levels. Contrary to the conventional wisdom, wet-weather conditions generally do not result in severe depressions of dissolved oxygen levels within the estuary. Sediment-associated oxygen demand is apparently insufficient to cause severe dissolved oxygen depletions during wet-weather conditions. Such depletions, when they occur, are more likely to be caused by reduced photosynthetic production of oxygen by algae, and, in the case of the Milwaukee River estuary, by the movement of oxygen-depleted waters from the Kinnickinnic and Menomonee River estuaries. Critical low dissolved oxygen levels are more often associated with summer low-flow and high temperature conditions.

An analysis of temporal variations in baseline data indicated that seasonal trends exist for dissolved oxygen, chlorophyll-a, total suspended solids, volatile suspended solids, and nutrients. The dissolved oxygen levels were generally lower during the summer, while the levels of the remaining indicators were generally higher in the summer. The upstream and estuarine portions of the Milwaukee River generally exhibited a more pronounced seasonal trend in water quality conditions than did the Menomonee and Kinnickinnic Rivers.

Three special water quality studies were conducted to provide estimates of the effects upon estuary water quality of: 1) operation of the Milwaukee and Kinnickinnic River flushing tunnels; 2) polluted surface runoff from industrialized areas draining directly into the Kinnickinnic and Menomonee River estuaries; and 3) polluted groundwater discharging to the Menomonee River estuary from the industrial valley.

The special study of the flushing tunnel effects found significant improvement in water clarity and dissolved oxygen in the Milwaukee and Kinnickinnic River estuaries during periods of flushing tunnel operations. During periods of such operations, dissolved oxygen levels during both daytime and nighttime periods exceeded 5 mg/l at nearly all the sampling stations in these two estuaries. Some flow from the flushing tunnels was also found in the Menomonee River estuary up to about N. 6th Street, but the beneficial effects upon dissolved oxygen appeared minimal.

Annual pollutant loadings of metals and phenols from industrial drainage areas directly tributary to the Menomonee and Kinnickinnic River portions of the estuary were estimated using data collected at eight sampling stations during two storm events. Maximum annual loading rates in pounds per acre were 0.09 for arsenic, 0.70 for chromium, 6.40 for lead, 0.02 for mercury, and 0.13 for phenols. Coal storage areas exhibited the highest unit-area loading for arsenic; salt storage areas, inexplicably, for chromium and lead; and scrap iron storage areas for mercury and phenols. The annual lead loading from the industrial direct drainage areas to the inner harbor was estimated to be 8 percent of the loading from the tributary Menomonee and Kinnickinnic Rivers. Toxic organic substances were analyzed in the surface runoff samples from one of the storm surveys. Detectable levels of polychlorinated biphenyl's (PCB's) and toxaphene were found at four stations, while dichloro-diphenyl-trichloro-ethane (DDT) and dichloro-diphenyl-dichoroethylene (DDE) were found at one station.

A special groundwater impact study was conducted which included measurements of groundwater levels and groundwater pollutant concentrations in six observation wells placed in the Menomonee Valley. The data collected were used in a groundwater flow simulation model to estimate groundwater pollutant loadings to the Menomonee River estuary. Water quality indicators analyzed included dissolved organo-chlorides, total phenols, and metals. A very small amount of groundwater discharge to the Menomonee River estuary—averaging 0.01 cubic foot per second—was found during the study. Therefore, computed groundwater pollutant loadings to the estuary were found to be negligible with the exception of sodium and chloride loadings, which respectively totaled 53,000 and 61,000 pounds annually. The groundwater loading of chloride, however, represented less than 0.2 percent of the total Menomonee River loading.

Sediment Quality Conditions

Because bottom sediment quality can have adverse effects upon the water column and upon aquatic biota in both the sediments and water column, an extensive sediment data program was conducted at 15 stations in the tributary rivers and inner harbor. In all, approximately 1,500 samples were collected and analyzed over the two-year period. The evaluation involved collection, analysis, and interpretation of data for sediment cores, interstitial water, sediment gas production, sediment oxygen demand, and sediment deposition. Previously collected sediment data were also utilized as needed.

Sediments appeared to be well mixed and exhibited much temporal and spatial variability. Inner harbor sediments, relative to upstream river sediments, were found to be more flocculent and had higher concentrations of organic substances and nitrogen. Synthetic organic compounds analyzed in previous studies generally were present in higher concentrations in the inner harbor than in the upstream reaches, with some exceptions, however. The outer harbor sediments were found to contain higher concentrations of phosphorus and metals when compared to the upstream and inner harbor river sediments.

The classification of the sediment quality based upon U. S. Environmental Protection Agency guidelines is shown graphically on Map 99. Bottom sediments upstream from the estuary on all three rivers, except the reach above the North Avenue dam as represented by the Locust Street sampling station on the Milwaukee River, generally are moderately polluted for most substances. The Locust Street sampling station is located within, and is representative of, the impoundment formed by the North Avenue dam. Sediments at Locust Street were found to be heavily polluted, as were sediments at all inner and outer harbor stations for nearly all indicators. PCB levels were highly variable throughout the inner harbor, but in general were lower than the heavily polluted category level.

Movement of substances from the bottom sediments to the water column was found to be important because in-place sediments exert a large oxygen demand on the overlying water column, resulting in low oxygen levels in the water column, particularly during periods of warm weather and low flow. The organic matter content of the overflows from the 107 combined sewer outfalls which discharge to the inner harbor and the upstream rivers was estimated for the sediment analyses using wet-weather influent samples taken at the Jones Island wastewater treatment plant, while the volume of the combined sewer overflows was estimated using the U. S. Army Corps of Engineers STORM model algorithms. Overall, combined sewer overflows were found to account for about 60, 72, and 93 percent of the loading of particulate organic carbon reaching the estuarine portions of, respectively, the Milwaukee, Menomonee, and Kinnickinnic Rivers. The bulk of the remaining particulate organic carbon was found to be comprised of algae and detritus from upstream sources. For the Milwaukee River, then, a relatively large percentage of the particulate organic carbon reaching the estuary consists of algae and detritus. However, little of this upstream material is deposited in the bottom sediments of the inner harbor because of its relatively slow settling rates.

Evaluation of sedimentation rates in the inner harbor, resuspension of bottom sediments, interstitial water quality, and dissolved oxygen indicated that immediate oxygen demand by scoured bottom sediments was minor compared to other sinks of dissolved oxygen. This finding is in contradiction to findings of previous studies of the estuary.

Long-term average annual net sedimentation rates in the inner harbor were computed by the Commission using detailed sounding data collected by the U. S. Army Corps of Engineers. The rates calculated for different segments of the estuary ranged from about 1.8 to 7.9 inches per year in the Milwaukee River, from 4.3 to 19 inches per year in the Menomonee River, and from 3.4 to 8.5 inches per year in the Kinnickinnic River portions of the estuary. Significantly higher and lower net sedimentation rates were found at individual stations—the highest being 43 inches per year in the Menomonee River estuary near S. 25th Street.

Laboratory studies of sediment decomposition and stabilization were made in an effort to determine the duration of effects of existing in-place sediments upon water quality. The study results indicated that 70 to 95 percent of the organic material in the bottom sediments of the inner harbor was inert, and decomposed at a negligible rate.

Biological Conditions

The resident biological communities that exist within the Milwaukee Harbor estuary waters are, in part, a reflection of the water quality, as well as the physical limitations, of the water bodies. The existing biota—fish, benthic invertebrates, zooplankton, and algae—were described in this chapter for the estuarine portions of the Milwaukee, Menomonee, and Kinnickinnic Rivers, and for the outer harbor, to help evaluate the overall ecological health and stability of the water body, as well as to provide the information necessary to determine desired and attainable water use objectives. A summary of the biological conditions within the Milwaukee Harbor estuary is shown in Figure 160.

Extensive fishery surveys were conducted within the estuarine portions of the Milwaukee, Menomonee, and Kinnickinnic Rivers, and within the outer harbor, by the Wisconsin Department of Natural Resources (DNR) in 1983 as part of the Milwaukee Harbor estuary study. Between 429 and 13,102 fish were caught within the inner harbor portions of each of the three rivers and within the outer harbor during the study for a total of 16,747 fish, and representing a total of 45 species of fish. Of the total species of fish, 13, or 29 percent, were rated as intolerant of pollution, 22, or 49 percent, were rated as tolerant of pollution, and 10, or 22 percent, were rated as very tolerant of pollution. Generally, carp and white sucker were the most abundant fish caught within the inner harbor, comprising approximately 30 to 55 percent of the total fish captured, while yellow perch were the most abundant fish caught within the outer harbor, comprising 44 percent of the total fish captured. Fish recapture studies indicated there is little movement of fish between the inner and outer harbors. The predominant fish species caught in both the inner and outer harbors are tolerant of polluted water conditions, including low levels of dissolved oxygen.

Concentrations of toxic organic substances and metals in the tissue of fish caught in the three rivers and the outer harbor were measured. From one to 28 tissue samples were analyzed for from four to 12 fish species within each upstream and inner harbor portion of the three rivers and within the outer harbor. Tissue samples were also analyzed for one turtle. In general, polychlorinated biphenyl (PCB) concentrations were highest in the tissue of fish taken from the Milwaukee River estuary, followed by the tissue of fish taken from the Kinnickinnic estuary, the Menomonee estuary, and the outer harbor. PCB concentrations were also generally higher within the inner harbor compared to concentrations within the upstream reaches of the rivers. Because the levels of PCB present in the fish tissue exceed the health standard established by the U. S. Food and Drug Administration, the DNR has issued a health advisory for persons consuming fish from the Milwaukee River downstream of Cedar Creek, the Menomonee and Kinnickinnic River estuaries, and the outer harbor.

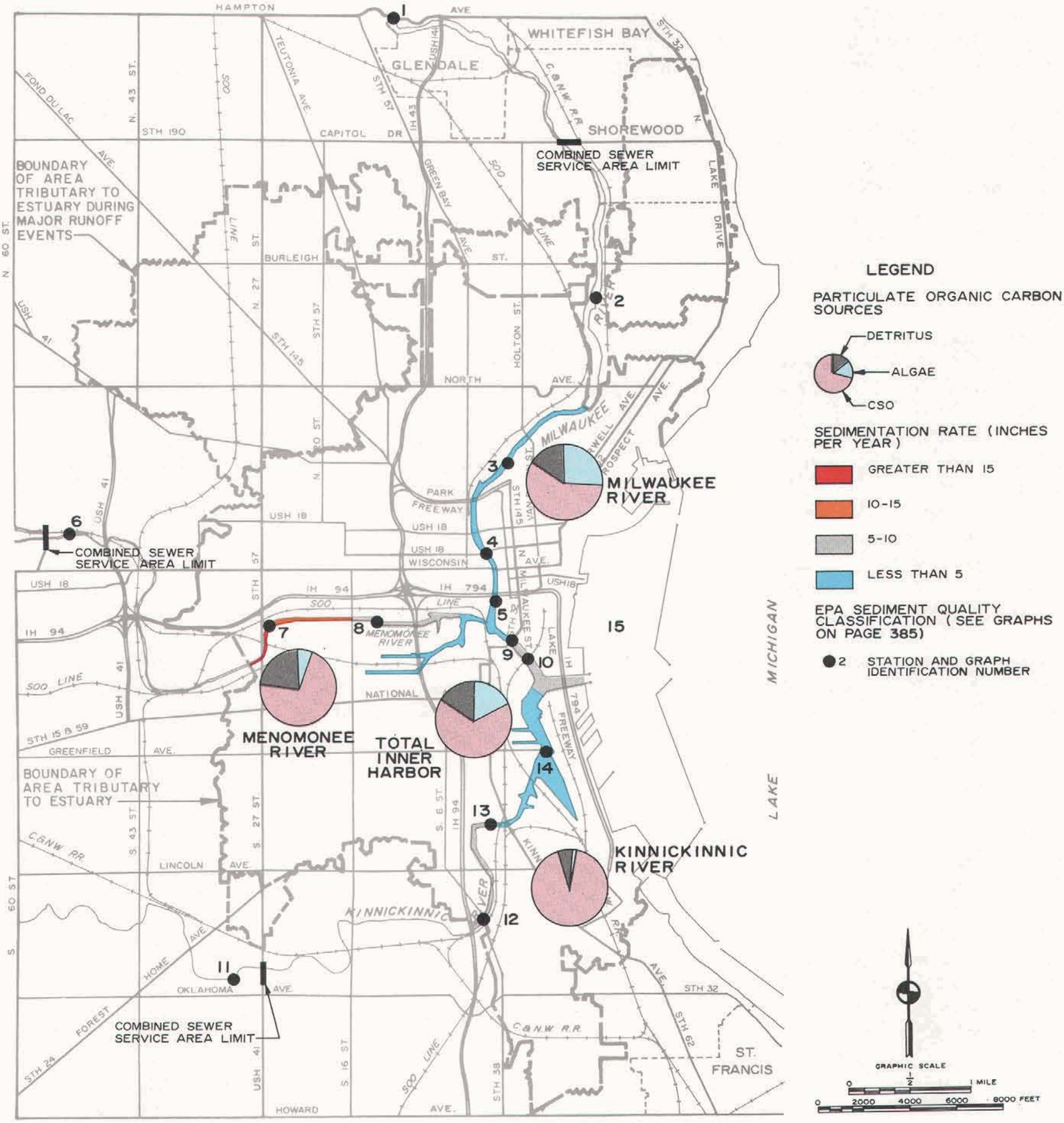
Data on benthic macroinvertebrates indicated that the most common organisms found within the inner harbor reaches of the three rivers are normally associated with organically enriched habitats. In addition, the DNR reported that only organisms very tolerant of pollution are present within the inner harbor because of the soft mucky substrates, anaerobic sediments, and in-place pollutants present.

The types of algae commonly found within the inner and outer harbor are indicative of nutrient-enriched conditions and are pollution tolerant. The mean summer concentrations of chlorophyll-a ranged from 5 to 71 percent higher than the annual means.

Based on the aquatic habitat evaluations provided by the DNR, the inner harbor provided fair habitat for aquatic organisms, while portions of the outer harbor provided good habitat for the propagation of warmwater fish and other aquatic life. Within the inner harbor, the DNR found that the bottom substrate conditions provided poor habitat for fish and other aquatic life. The adequate water depth, inflow of relatively clean water from Lake Michigan, and migration of fish from the upstream reaches and the outer harbor, however, allow warmwater fish to reside within the inner harbor. The DNR attributed the currently impaired survival of aquatic life within the inner harbor to pollutant loadings from combined sewer overflows,

Map 99

SEDIMENT CONDITIONS IN THE MILWAUKEE HARBOR ESTUARY: 1982-1983



In 1982 and 1983, an extensive sediment sampling program involving the collection and analysis of about 1,500 sediment samples from 15 upstream and inner harbor stations was conducted. The bottom sediments were found to be highly variable in quality, to be vertically well-mixed, and flocculent, and—especially in the inner harbor—to contain relatively high levels of organics, nutrients, and metals. The sediments in the upstream reaches were generally classified as moderately polluted, while the inner harbor sediments were generally classified as heavily polluted. Sediment data previously collected from the outer harbor indicated that the sediments were heavily polluted with respect to total phosphorus, ammonia nitrogen, and lead; and moderately polluted with respect to chemical oxygen demand. The sediments in the inner harbor were found to exert a large oxygen demand on the overlying water column. Historical sedimentation rates were highest in the upper portions of the Menomonee and Kinnickinnic River estuaries, and in the Milwaukee River downstream of its confluence with the Menomonee River.

Source: SEWRPC.

Map 99 (continued)

Figure 160

EXISTING BIOLOGICAL CONDITIONS IN THE MILWAUKEE HARBOR ESTUARY

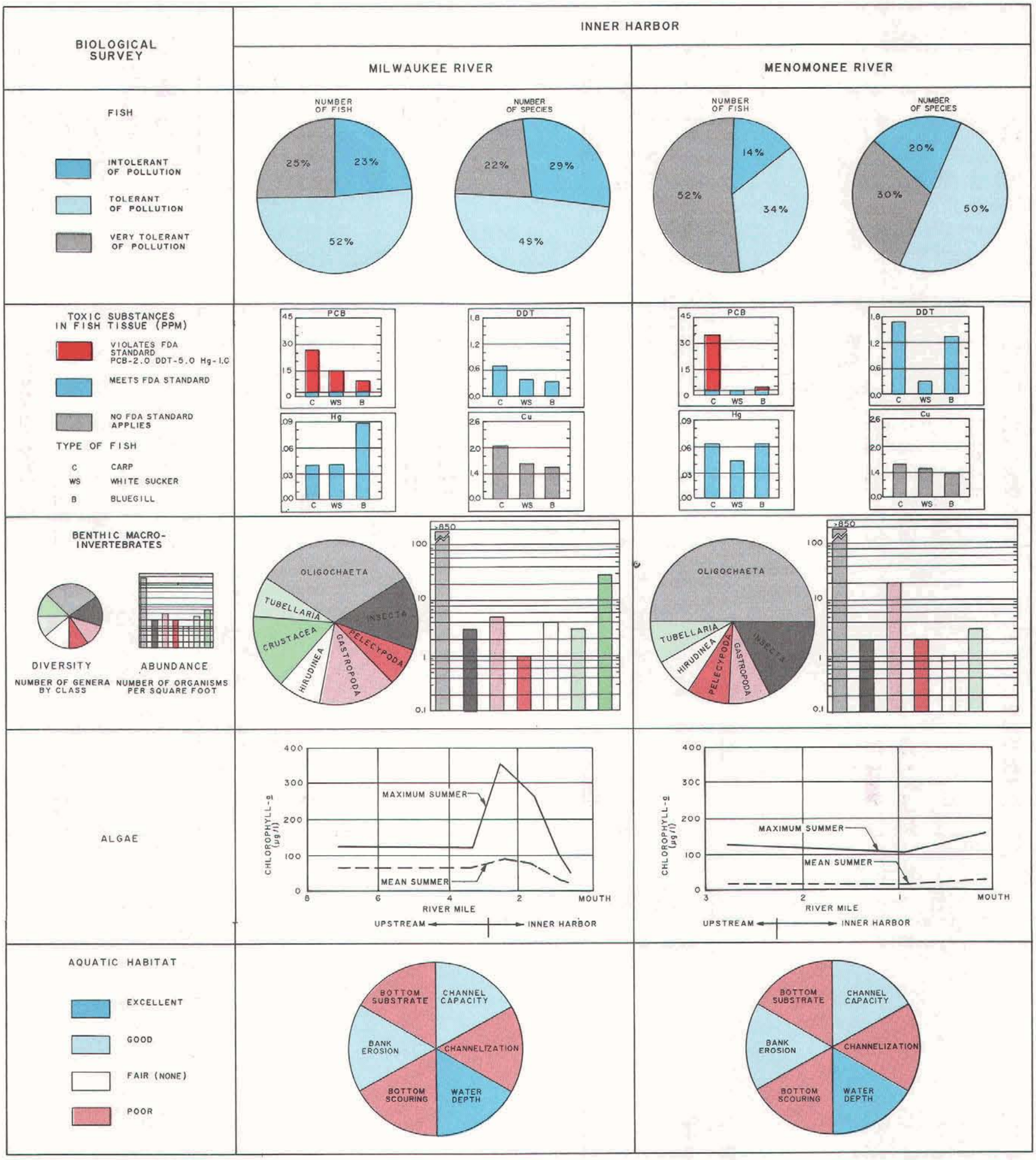
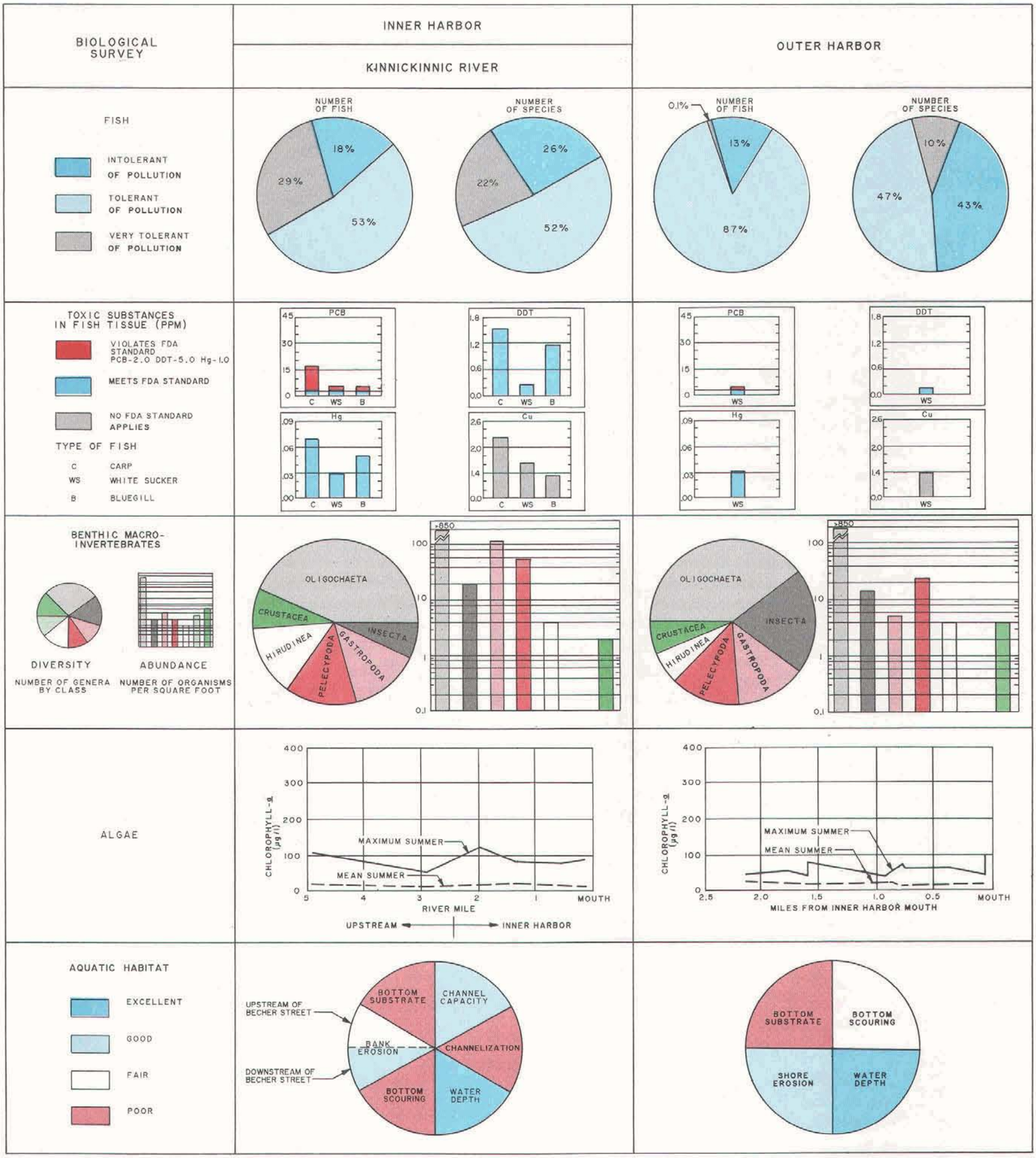


Figure 160 (continued)



Source: SEWRPC.

urban stormwater runoff, industrial spills and discharges, toxic substances in the water and in the bottom sediments, and severe scouring and deposition within the river channel.

Five special biological toxicity surveys were conducted as a part of the Milwaukee Harbor estuary study to provide additional information on acute and chronic toxic conditions within the upstream river reaches, inner harbor, outer harbor, and Lake Michigan. Water column samples were collected at 16 stations during each survey. The faunal toxicity surveys studied the survival and the reproduction of Ceriodaphnia affinis/dubia during wet-weather and dry-weather conditions. The toxicity test results indicate that chronic toxic conditions exist which would affect reproduction, and that these conditions are more likely to occur during wet-weather conditions than during dry-weather conditions. In general, the most acute toxic conditions, which affect the survival of the adult Ceriodaphnia over a short time period, also appear to occur more often during wet, as compared to dry, weather conditions.

Pollutant Loadings

Wet-weather and dry-weather pollutant loadings to the inner harbor from nonpoint sources, point sources, and combined sewer overflows were estimated based upon a combination of measured river flow and pollutant concentrations, estimates of combined sewer overflow volumes using modeling techniques and measured pollutant concentration data, and measured point source discharge data. Annual river loading estimates, based on baseline water quality data collected over the period 1981 through 1983, indicated that the 1982 and 1983 estimated loadings were generally higher than the 1981 loadings because of increased runoff volumes and river flows. Of the total loadings to the inner harbor from the rivers of all pollutants except chlorophyll-a and copper, from 57 to 85 percent were from the Milwaukee River, from 12 to 33 percent from the Menomonee River, and from 1 to 19 percent from the Kinnickinnic River. About 96 to 97 percent of the total loadings of chlorophyll-a and copper were from the Milwaukee River.

About 33 percent of the total pollutant loadings from combined sewer overflows was estimated to be discharged to surface waters upstream of the inner harbor, about 61 percent was estimated to be discharged directly to the inner harbor, and the remaining 6 percent was estimated to be discharged directly to the outer harbor. Combined sewer overflows located upstream of the inner harbor were estimated to account for a relatively large portion of the total wet-weather river loadings to the inner harbor.

Combined sewer overflows that discharge both upstream and directly to the inner harbor account for from 50 to 60 percent of the total inner harbor loadings of volatile suspended solids, biochemical oxygen demand, and lead; and for nearly 90 percent of the zinc loading. Upstream nonpoint sources of pollution are estimated to account for over 50 percent of the total inner harbor loadings of total solids, total suspended solids, chemical oxygen demand, total and soluble phosphorus, ammonia nitrogen, nitrate nitrogen, total Kjeldahl nitrogen, chloride, copper, cadmium, and chromium. Upstream point sources of pollution contribute less than 7 percent of the loadings of all pollutants analyzed, with direct point source loadings to the inner harbor being insignificant.

Chapter VII

WATER RESOURCES SIMULATION MODELS

INTRODUCTION

Mathematical simulation models were used extensively in plan design and evaluation in the Milwaukee Harbor estuary study. This chapter discusses the need for, and limitations of, simulation modeling, and describes the simulation models used in the study. Simulation modeling for the study was conducted by the U. S. Geological Survey (USGS), the Southeastern Wisconsin Regional Planning Commission (SEWRPC), and HydroQual, Inc. (HQI), consultant to the Commission. The USGS applied two simulation models: 1) a hydrologic model—also utilized within the Region by the Regional Planning Commission—which simulated runoff quality from shoreland areas directly tributary to the harbor estuaries, and 2) a hydraulic model which simulated in one dimension the flows from Lake Michigan entering and moving through the inner harbor estuary. SEWRPC applied a hydrologic/hydraulic model which simulated combined sewer overflow rates and volumes. HQI developed, calibrated, and applied a water quality simulation model for the inner and outer harbors, this model being comprised of submodels for sediment-water interactions and steady-state and attendant conditions in the water column, for time-variable conditions in the water column, for simulating random water quality conditions related to the occurrence of precipitation, and for simulating three dimensional flows in the estuary.

NEED FOR AND LIMITATIONS OF SIMULATION MODELING

In the Milwaukee Harbor estuary study, simulation models were used both to describe existing and historical conditions and to predict probable future conditions. Existing conditions can be measured, monitored, or sampled but, as a practical matter, for only limited durations and areal extents. Budgetary limitations generally restrict the amount of data that can be collected. Moreover, critical historical conditions cannot be measured, monitored, or sampled after the fact. Such conditions can, however, be simulated if necessary model input data representing the period or conditions of interest are available. Simulation modeling can also be used to provide information not only for sites where data have been collected, but for desired intermediate locations. This allows the identification of, and provision of information for, critical locations under historical, existing, and future conditions, and assists in achieving a more complete understanding of the system being evaluated and of the probable future conditions in this system under alternative scenarios.

To ensure reliability, mathematical simulation models are calibrated by comparing observed and simulated data, making appropriate changes in the model to improve the comparison until it is acceptable. Ideally, simulation models should be verified by use of independent sets of data not used in the calibration process. The utility of a simulation model is severely limited if insufficient data are available for model formation, calibration, and verification.

HYDROLOGICAL SIMULATION PROGRAM-FORTRAN (HSPF)

The Hydrological Simulation Program-Fortran (HSPF) was utilized by the U. S. Geological Survey to estimate pollutant loadings from intensively used material storage areas immediately adjacent and directly tributary to the estuary portions of the Kinnickinnic and Menomonee Rivers, the South Menomonee Canal and the Burnham Canal, and the estuary portion of the Milwaukee River from its confluence with the estuary of the Menomonee River to the outer harbor. Pollutant loadings to the Milwaukee River estuary upstream of its confluence with the Menomonee River estuary were not modeled since field inspections indicated that sites of the type concerned no longer existed along this reach of the river.

HSPF consists of three major submodels—the hydrologic submodel, hydraulic submodel 1, and the water quality submodel. These three submodels originally were contained within a program package known as "Hydrocomp Simulation

Programming."[1] These submodels, which were the property of the consulting firm, Hydrocomp, Inc., had been under development since the early 1960's when pioneering work in hydrologic-hydraulic modeling was done at Stanford University.[2] The hydrologic submodel, hydraulic submodel 1, and the water quality submodel are all continuous process models and were installed on the Regional Planning Commission computer system in 1974. These submodels were used, among other applications, in the conduct by the Commission of the Menomonee, Kinnickinnic, and Pike River watershed studies, and of the regional water quality management planning program.[3]

In early 1984, a new computer program was installed on the Regional Planning Commission computer system to replace the Hydrocomp program package. This computer program, called Hydrological Simulation Program-Fortran (HSPF), was obtained from the U. S. Environmental Protection Agency (EPA) and represents a refined version of the original Hydrocomp program package.[4] For the Milwaukee Harbor estuary study, the HSPF program was used by the USGS for the simulation of direct runoff from estuary shoreland areas not served by combined sewers. Of the three HSPF submodels, only the hydrologic submodel was used in the Milwaukee Harbor estuary study.

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[1] *Hydrocomp, Inc., Hydrocomp Simulation Programming Operations Manual, 4th Edition, January 1976; and Hydrocomp, Inc., Hydrocomp Water Quality Operations Manual, April 1977.*

[2] *N. H. Crawford and R. K. Linsley, Digital Simulation in Hydrology: Stanford Watershed Model IV, Technical Report No. 39, Department of Civil Engineering, Stanford University, July 1966.*

[3] *SEWRPC Planning Report No. 30, A Regional Water Quality Management Plan for Southeastern Wisconsin: 2000, February 1979; Planning Report No. 26, A Comprehensive Plan for the Kinnickinnic River Watershed, December 1978; and Planning Report No. 35, A Comprehensive Plan for the Pike River Watershed, June 1983.*

[4] *U. S. Environmental Protection Agency, Environmental Research Laboratory, Hydrological Simulation Program-Fortran, User's Manual for Release 8.0, Athens, Georgia, April 1984.*

For the Milwaukee Harbor estuary study, the USGS utilized the hydrologic submodel of HSPF to simulate mean runoff in 1981, 1982, and January through September 1983 from storage areas for coal, salt, and scrap iron, and from other industrial land uses in the shoreland areas directly tributary to the inner harbor. The location of the study area is shown on Map 78 in Chapter VI of this volume. Meteorological input data for HSPF were provided by the records of the National Weather Service station at General Mitchell Field, which is located about six miles south of the inner harbor. The HSPF program was not calibrated for runoff because no flow calibration data were collected since only rough estimates were necessary of pollutant loads associated with direct runoff.

Storage areas for coal, salt, and scrap iron within the shoreland areas draining directly to the estuary were identified and measured on 1 inch equals 100 feet scale topographic maps prepared for the study, and were found to total, respectively, within the study area, 1.8, 3.3, and 18.0 acres. The entire shoreland area considered totaled 367 acres. Land use within this area is depicted in Figure 161. Field inspection of the coal, salt, and scrap iron storage sites indicated that an area about three times the actual storage area was effectively saturated with the stored material. Therefore, the measured storage areas were multiplied by 4 for use in the model.

Simulated runoff was used with estimated mean concentrations of lead, phenols, chromium, mercury, and arsenic obtained from the sampling data described in Chapter VI to compute annual loads of these substances to the two rivers from shoreland areas. The results of the simulation modeling are presented in Chapter VI of this volume.

U. S. GEOLOGICAL SURVEY BRANCH NETWORK MODEL

The U. S. Geological Survey developed, calibrated, and applied a one-dimensional unsteady flow hydraulic simulation model which was utilized to provide estimates of Lake Michigan flood and ebb flows within the inner harbor. The following section briefly describes the formulation and calibration of this model, called the Branch Network Model. The results of the application of this model are described in Chapter V of this volume.

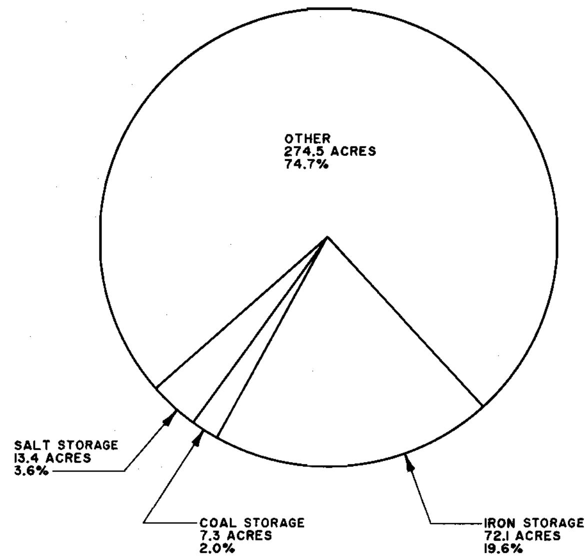
Description of the Branch Network Model

A complete description of the Branch Network Model developed by the U. S. Geological Survey was published by the agency in 1981.[5] The model was developed to simulate unsteady one-dimensional flows in reaches of river channels or in networks of interconnected channels that are subject to variable backwater effects caused, for example, by tides or seiches such as those that occur in Lake Michigan.

The Branch Network Model uses a four-point, implicit, finite-difference approximation of the unsteady flow equations. The equations are linearized over the computation time interval. Branch transformations are formulated that describe the relationships between unknowns at the end points of the channels. A matrix resulting from the transformation and boundary condition equations is solved by Gaussian elimination using maximum pivot strategy.

Figure 161

LAND USE WITHIN THE SHORELINE AREA DRAINING DIRECTLY TO THE INNER HARBOR AND NOT SERVED BY COMBINED SEWERS: 1980



Source: U. S. Geological Survey and SEWRPC.

The flow equations in the model are:

$$\frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{2\beta Q}{gA^2}\frac{\partial Q}{\partial x} - \frac{\beta Q^2}{gA^3}\frac{\partial A}{\partial x} + \frac{\partial Z}{\partial x} + \frac{k \quad Q \,|\, Q|}{A^2 R^{4/3}} - \frac{\xi B \quad U_a^2 \cos\alpha}{gA} = 0$$

and the equation of continuity:

$$B\frac{\partial z}{\partial t} + \frac{\partial Q}{\partial t} = 0,$$

where:
- Q is channel discharge,
- A is channel cross-sectional area,
- B is channel top width,
- Z is water surface elevation,
- R is channel hydraulic radius,
- U_a is wind velocity,
- x is longitudinal channel distance,
- g is the acceleration of gravity,
- t is elapsed time,
- k is function of flow resistance coefficient,
- α is wind-direction angle,
- β is Boussinesq momentum coefficient,
- ξ is wind-resistance coefficient, and
- ∂ is a symbol for partial derivative.

The river channel geometry for Branch Network Model simulation should be such that one-dimensional flow is predominant. The flow must be essentially homogeneous in density and possess subcritical velocities. The model can simulate the effects of tributary flow, diversions, variable winds, and downstream water level changes upon flow and water levels upstream.

Input to the model includes channel geometry, and time series data for tributary flow, diversions, wind velocity, and downstream water level fluctuations. Output from the model are net average discharge and water level at each cross-section in a time series format. An example of output for the Milwaukee River estuary is presented in Table 56 in Chapter V of this volume.

[5] *R. W. Schraffranek, R. A. Baltzer, and D. E. Goldberg, A Model for Simulation of Flow in Singular and Interconnected Channels: Techniques of Water Resources Investigations of the U. S. Geological Survey, Book 7, Chapter C3, 1981.*

Development of the Branch Network Model for Milwaukee Harbor Estuary

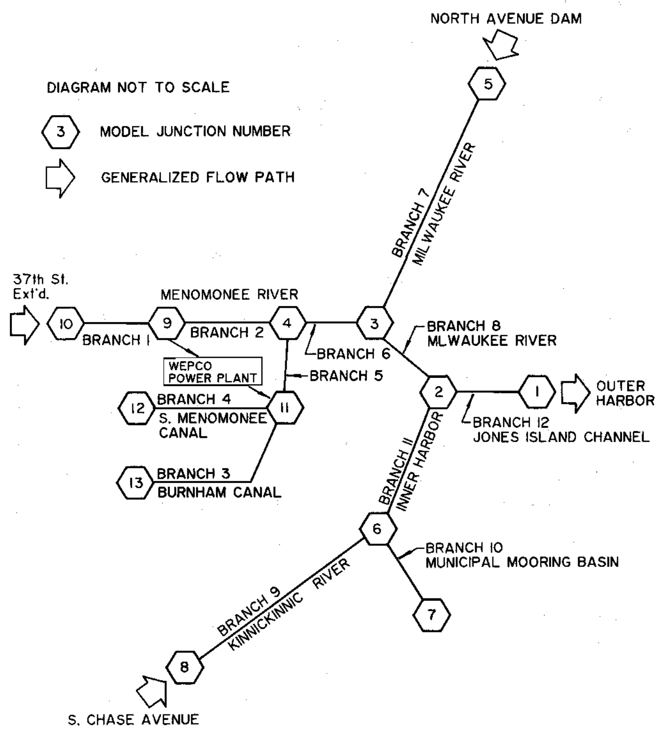
The U. S. Geological Survey developed the Branch Network Model for the Milwaukee Harbor estuary using a 12-branch segmentation for the inner harbor, as shown in Figure 162. Each branch was represented by at least one segment of two cross-sections reflecting local channel geometry. Upstream boundary conditions were defined by continuous streamflow records collected by the USGS for the Kinnickinnic River at S. 11th Street; for the Menomonee River at either S. 37th Street extended or N. 70th Street, depending on the backwater effect of Lake Michigan; and for the Milwaukee River at the North Avenue dam. For the Municipal Mooring Basin, the Burnham Canal, and the South Menomonee Canal, the upstream boundary conditions were represented by zero flows. The downstream boundary conditions were represented by continuous water level records collected by the USGS near the mouth of the Milwaukee River at Jones Island, or by records collected at the U. S. Coast Guard Station in the outer harbor when recorder malfunctions occurred at the inner harbor site. A comparison of concurrent water level records collected at both sites found very close agreement in stage and time, validating this substitution.

A Wisconsin Electric Power Company power plant withdraws condenser cooling water from the Menomonee River and discharges it to the South Menomonee Canal. This diversion was represented in the model by a negative inflow at Junction 9 of 250 cubic feet per second (cfs) and a positive inflow of 250 cfs at Junction 11, as shown in Figure 162. The inflow locations for the Kinnickinnic and Milwaukee River flushing tunnels are not shown in the figure because the tunnels were not in operation during the periods simulated.

Channel geometry input to the Branch Network Model was taken from detailed sounding data collected in the inner harbor by the U. S. Army Corps of Engineers, Kewaunee Field Office, as part of that agency's annual survey of areas requiring maintenance dredging for navigation purposes. Because routine dredging is not conducted in the Milwaukee River north of E. Buffalo Street, examination soundings are not made in that reach of the estuary. At the request of the Commission, however, the Corps conducted soundings of that reach which were utilized to develop channel geometry input for not only the Branch Network Model, but also the water quality model which is described later in this chapter.

Figure 162

BRANCH NETWORK MODEL SCHEMATIC OF THE INNER HARBOR



Source: U. S. Geological Survey.

Channel conveyance and storage characteristics were developed for each segment of the model using channel geometry, segment length, Manning's roughness coefficient, and the momentum coefficient for velocity distribution. More detail on model construction is presented in the USGS report prepared for the estuary study.[6]

Calibration of Branch Network Model for Milwaukee Harbor Estuary

Calibration of the Branch Network Model for the Milwaukee River estuary was achieved by appropriate adjustments to certain model parameters until satisfactory agreement was found between observed and simulated water levels and flows measured at the mouth of the Milwaukee River. Model parameters considered for adjustment included the water-surface wind-drag coefficient, the momentum coefficient for velocity distribution, the Manning's roughness coefficient, the finite-difference weighting factor, and the geometry weighting factor.

[6] *Leo B. House, Unsteady Flow Model of the Milwaukee Harbor Estuary at Milwaukee, Wisconsin, U. S. Geological Survey Water Resources Investigations Report, 1986.*

The calibration process found that the model was not sensitive to changes made in the wind-drag coefficient, nor to the effects of wind. Therefore, wind effects were not included in the final model. Changes in the value of the Manning's roughness coefficient also were found to have insignificant effects on simulated results. An average roughness coefficient of 0.024 was used throughout the inner harbor with satisfactory results. Momentum coefficients assigned ranged from 1.00 to 1.02 and were based on previous model applications by the USGS elsewhere. These values were found to yield satisfactory results in the Milwaukee Harbor.

The calibration process found that the model was sensitive to the weighting factors for the finite difference and for the geometry parameters, factors affecting the finite-difference computation. Possible values for the weighting factors ranged from 0.0 to 1.0.[7] Computational stability was found to occur when these values exceed 0.6 for the finite-difference factor, and 0.5 for the geometry parameters factor. The best calibration results were obtained using weighting factors of 0.7 and 0.6, respectively.

[7] *R. W. Schraffranek, R. A. Baltzer, and D. E. Goldberg, A Model for Simulation of Flow in Singular and Interconnected Channels: Techniques of Water Resources Investigations of the U. S. Geological Survey, Book 7, Chapter C3, 1981.*

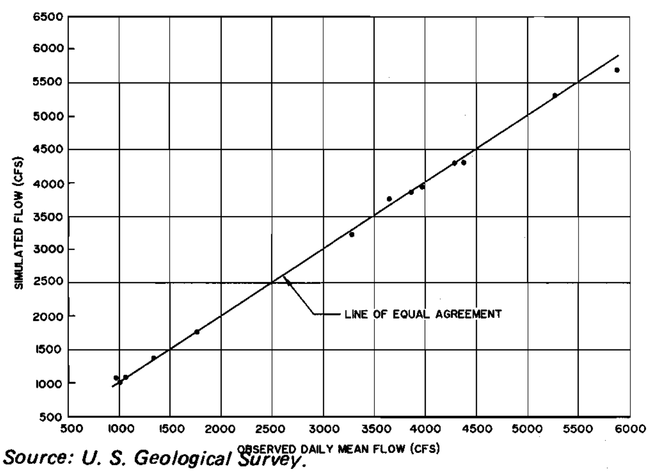
The calibration process found that a five-minute computation interval more accurately simulated rapidly changing unsteady flow than did a 15- or 60-minute interval. Mean daily flows were simulated equally well by all three time intervals, however.

Figure 163 presents the results of a typical model calibration run for the period March 28 to April 9, 1983, comparing simulated daily mean flow at the mouth of the Milwaukee River with the sum of the measured inflows for the three rivers tributary to the estuary. As shown, the simulated and measured values are almost identical.

Figure 164 presents results of a typical calibration run for September 8, 1983, in which observed and simulated stages are compared for the Milwaukee River at Water Street. As indicated, the simulated stages are generally within 0.1 foot of the observed stages. Sometimes there is a five-minute lag in the peak and trough values between the simulated and observed data. The overall fit,

Figure 163

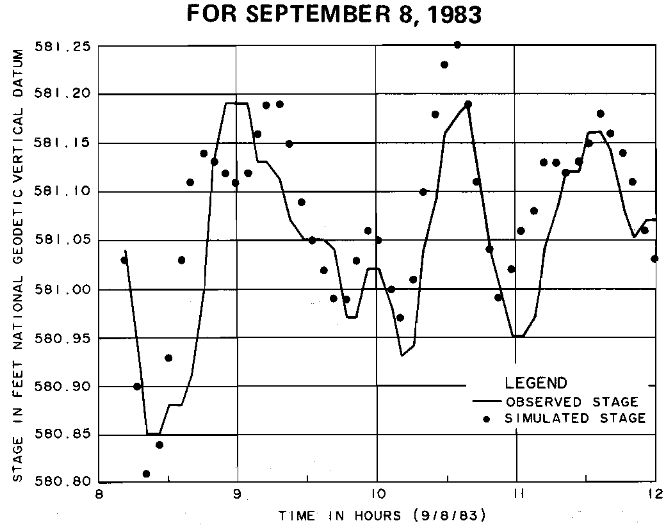
COMPARISON OF OBSERVED AND SIMULATED FLOW FOR THE MILWAUKEE RIVER AT THE MOUTH FROM THE BRANCH NETWORK MODEL FOR THE PERIOD MARCH 28 TO APRIL 9, 1983



Source: U. S. Geological Survey.

Figure 164

COMPARISON OF OBSERVED AND SIMULATED STAGES FOR THE MILWAUKEE RIVER AT WATER STREET FROM THE BRANCH NETWORK MODEL FOR SEPTEMBER 8, 1983



Source: U. S. Geological Survey.

however, appears satisfactory. Additional detail on model calibration can be found in the report prepared by the USGS.[8]

SIMULATION OF GROUNDWATER FLOW AND POLLUTANT LOADS TO THE MENOMONEE ESTUARY

Potential pollution of the Menomonee River estuary from groundwater discharging from the industrialized Menomonee Valley was investigated by the U. S. Geological Survey as part of the Milwaukee Harbor estuary study. Because the land surface of the valley was occupied by industrial and commercial buildings and accompanying uncovered storage and work yards, infiltrating precipitation polluted by undesirable substances on the land surface could potentially pollute the near-surface aquifer and thence the adjacent Menomonee River estuary. To evaluate the pollution potential, the U. S. Geological Survey constructed a network of six observation wells in the Menomonee Valley for collection of groundwater level and chemistry data to be used in the simulation of pollutant loads to the Menomonee River estuary. The data collected for this effort are described in Chapter VI of this volume along with the simulated results. This section, therefore, only describes the model and its development and application and provides a brief summary of the results.

Description of Groundwater Flow Model

A computer program was developed by the U. S. Geological Survey for the estuary study to estimate groundwater inflow to the Menomonee River estuary based upon Darcy's Law.

Groundwater flow to the river occurs in the model only when the gradient is positive as determined by a comparison of water table and river level records. Flow is calculated through a cross-sectional area of the aquifer perpendicular to the flow direction through a series of cross-sections. Each cross-section is associated with an observation well water-level record. The aquifer area-contributing flow per foot of riverbank is equal to the river depth.

Development of Groundwater Flow Model for the Menomonee River Estuary

The groundwater flow model for the Menomonee River estuary was constructed around three pairs of observation wells placed along and on opposite sides of the river, as shown on Map 31 in Chapter IV of this volume. The wells were all cased, screened, and sealed. The hydraulic conductivity for each well was measured using a modified "slug test" method.[9] The water table gradient was determined by comparing simultaneous water levels collected manually at weekly to biweekly intervals at the wells and automatically at the river by a continuous stage recorder at N. 23rd Street extended operated by the City of Milwaukee, Bureau of Engineers. The aquifer area-contributing flow per foot of riverbank was computed using an effective river depth of 22 feet. The length of the reach simulated was about 9,000 feet.

Application of Groundwater Flow Model

The groundwater flow model for the Menomonee River estuary was operated for water year 1983 to determine an annual mean groundwater discharge to the reach. The unit discharge for each well was multiplied by an associated reach length. The reach flows were summed to get total discharge to the river. A total flow of 275,000 cubic feet was computed, which was equivalent to an average continuous flow of only 0.01 cubic foot per second, or 5,600 gallons per day.

The principal equation applied was:

$$q = KIA$$

where: q = discharge per foot of river reach length (cubic feet per day),
K= hydraulic conductivity (feet per day),
I = groundwater flow gradient (foot per foot), and
A= area of aquifer per foot of river reach length (square feet).

[8] *Leo B. House, Unsteady Flow Model of the Milwaukee Harbor Estuary at Milwaukee, Wisconsin, U. S. Geological Survey Water Resources Investigations Report, 1986.*

[9] *H. Bouwer and R. C. Rice, "A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells," Journal of Water Resources Res., Vol. 12, No. 3, June 1976.*

Simulation of Groundwater Pollutant Transport Load

Groundwater pollutant loads for water year 1983 were estimated by applying the model discharges to July and September contaminant concentrations for well number 2 because flow for the reach represented by this well was 75 percent of the total flow. This procedure provided conservatively high load estimates because contaminant concentrations in well number 2 tended to be greater than in the other five observation wells. Computed loads are presented and discussed in Chapter VI of this volume. Study results indicated that groundwater contaminant loadings to the Menomonee River estuary were generally insignificant. Sodium and chloride loads from the groundwater were relatively large, however.

SYSTEM ANALYSIS MODEL FOR COMBINED SEWER OVERFLOW

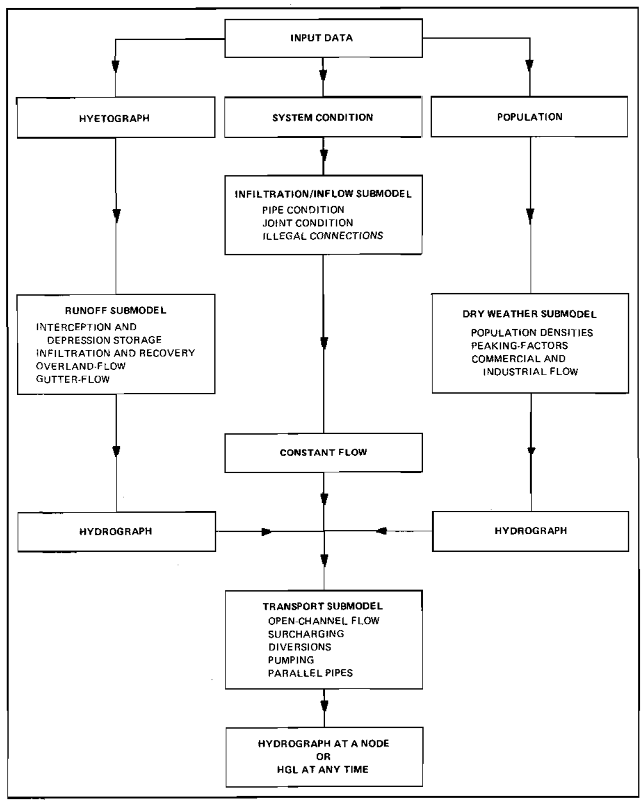
The measurement of flows from the combined sewer system via the 109 outfalls concerned into the Milwaukee Harbor estuary and the tributary rivers over the three-year monitoring period was impractical. To quantify combined sewer overflow (CSO) volume, and ultimately to estimate pollutant loads discharged from the combined sewer overflows, a mathematical model of the combined sewer service area (CSSA) drainage network previously developed for the Milwaukee Metropolitan Sewerage District for facilities planning was adapted for use in the Milwaukee Harbor estuary study. The model is called the Wastewater Collection System Analysis Model (SAM). The model was utilized in the estuary study to simulate the storm event of September 10, 1983, an event for which intensive water sampling was conducted as part of the storm event sampling program described in Chapters IV and VI of this volume. The results were used to verify the volume of combined sewer overflow set forth in Chapter VI of this volume.

Description of the System Analysis Model—SAM

The SAM model was originally developed by CH2M-Hill, Inc., and is fully described in documentation prepared for the City of Portland, Oregon.[10] The model is written in FORTRAN IV

Figure 165

FLOW CHART OF THE INTERRELATIONSHIP BETWEEN RUNOFF, DRY-WEATHER FLOW, INFILTRATION/INFLOW, AND TRANSPORT SUBMODELS



Source: SEWRPC.

and is composed of four submodels: 1) the runoff submodel, 2) the dry-weather flow submodel, 3) the infiltration/inflow submodel, and 4) the transport submodel. Figure 165 presents a flow chart for the program showing the relationship between the four submodels. A water quality submodel was not used in the harbor estuary study, and therefore is not described herein.

Runoff Submodel: Input to the SAM runoff submodel consists principally of a time series of rainfall. Rainfall losses due to infiltration, vegetal interception, depression storage, evaporation, and transpiration are calculated, with the remaining rainfall excess constituting runoff.

Horton's equation[11] is used to compute infiltration. Interception and depression storage affected by vegetation and topography are calculated

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[10] *Wesley G. O'Neal, Allen L. Davis, and Kenneth W. VanDusen, Wastewater System Analysis Model (SAM), User's Manual, Report for Department of Public Works, City of Portland, Oregon, by CH2M-Hill, Inc., Corvallis, Oregon, 1976.*

[11] *Ray K. Linsley, Jr., Max A. Kohler, and Joseph L. Paulhus, Hydrology for Engineers (New York: McGraw-Hill Book Company), 1958.*

based upon a normal distribution relationship between storage depth and the area with depression storage satisfied. Computed runoff at any given time is dependent upon the proportion of the basin having no remaining available storage. The recovery of storage occurs by simulated infiltration and evaporation.

Runoff is calculated using kinematic wave equations for overland flow. Small time intervals are used to approximate steady-state conditions. Variables in the equations include Manning's roughness coefficient for the runoff surface, basin length, average basin slope, and surface detention storage. If gutters exist, gutter flow routing is provided using gutter geometry, slope, and roughness.

Data requirements for the runoff submodel include a hyetograph, Horton's infiltration parameters, average interception and depression storage, percent pervious area, average slope, roughness coefficient, average length of each contributing subbasin, and evaporation rate.

Dry-Weather Flow Submodel: Dry-weather flow is that flow which occurs independently of precipitation, and is comprised of wastewater flows from domestic, commercial, and industrial sources. The presence of dry-weather flow during a storm reduces the storm runoff-carrying capacity of the sewer and thus is an important consideration in the flow analysis of an existing combined sewer system.

The data required for the dry-weather submodel, are population density for each subbasin, average daily per capita flow, and commercial and industrial flows. Average dry-weather flow is multiplied by a time-based daily peaking factor so that the flow rate at any time of day can be estimated. Large commercial and industrial sources can be input as point sources. Average domestic flow is computed using resident population and average flow per capita.

Infiltration/Inflow Submodel: Infiltration/inflow (I/I) is an important consideration in analysis of storm flow in a combined sewer system. Such flow can be relatively large, significantly affecting the stormwater-carrying capacity of the system. Because determination of I/I is difficult, the submodel utilizes a simplified approach for estimating infiltration/inflow. Five infiltration/inflow rates can be stored in the submodel and are based on the condition of a 12-inch pipe 100 feet in length. Infiltration/inflow is computed by multiplying a user-selected rate times the ratio of actual pipe circumference and length to that for a 12-inch 100-foot pipe in the same condition.

Input to the infiltration/inflow submodel consists of I/I rates provided by the user, or rates which are estimated using a table in the user's manual.

Transport Submodel: The transport submodel simulates the movement of water through the conveyance system. At the upstream end of a pipe segment, the hydrographs are summed for dry-weather flow, for surface runoff or gutter flow, and for infiltration/inflow. The hydrograph from an upstream pipe or open channel, if any, is also added. The resultant hydrograph is then routed (mathematically moved) through the downstream conduit by one of two methods—the modified kinematic wave method[12] or the Cincinnati method.[13] The former method is used if detailed analysis is desired, whereas the latter method is used for general application.

The transport submodel also considers the effects of surcharging, noncircular pipes, conduits with variable roughness, pumping stations, diversions, and parallel pipes. Input data include conduit size, shape, length, slope, roughness, and leakage condition; pumping station capacities and operating data; and diversion rating curves for depth and flow rate.

Development of SAM for the
Milwaukee Combined Sewer Service Area

The SAM model was developed for the Milwaukee Metropolitan Sewerage District (MMSD) to simulate flow at each of the 109 CSO outfalls discharging from the combined sewer service area to the Kinnickinnic, Menomonee, and Milwaukee Rivers. The area tributary to each outfall was divided into subareas of about 10 to 20 acres each, with each having times of concentration of about 5 to 10 minutes. Not every pipe in each subarea was included in the model, with the

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[12] *U. S. Environmental Protection Agency, Stormwater Management Model, Water Pollution Control Research Series 11023DOC07/71, 1971.*

[13] *Constantine N. Papadakis and Herbert C. Preul, "Testing of Methods for Determination of Urban Runoff," ASCE Journal of Hydraulics Division, Vol. 99, No. HY9, 1973, pp. 1319-1335.*

smallest being eliminated to minimize the cost of model construction and computer time. Areas served by these small pipes were represented in the land surface runoff submodel, however, with little associated error in the computed peak flows at the CSO outfalls. The pipes that were included were chosen to provide an even distribution of branches throughout the tributary area.

Land surface slopes and overland flow lengths were measured from system plans provided by the City of Milwaukee. Impervious areas were based on land use. Within each subarea, the pervious and impervious areas were modeled separately, with the respective runoff hydrographs being added at the sewer inlet node. Manning's roughness coefficients used for overland flow were 0.250 and 0.020 for pervious and impervious areas, respectively. The dry-weather flows at each outfall as determined in the facility planning study were distributed according to tributary area.

Calibration of SAM

Model calibration was performed using a one-minute simulation time step and the kinematic wave method. A five-minute simulation interval appeared to produce less accurate results, based on comparisons of simulated peak overland flows with flows computed using the rational method. The rational method flows were found to be in good agreement with the overland flows simulated with a one-minute interval, however. Transport submodel calibration was achieved by comparison of simulated peak flows at CSO outfalls with rational method flows. These comparisons also were generally found to be in good agreement.[14]

MILWAUKEE HARBOR ESTUARY WATER QUALITY SIMULATION MODELS

Water quality conditions in the Milwaukee Harbor estuary are influenced by two complex phenomena. One of these phenomena is the circulation within the estuary, which is influenced by flood and ebb flows from Lake Michigan, time-variable inflows from the rivers tributary to the estuary, the withdrawal and discharge of condenser cooling water from the Menomonee inner harbor by the Wisconsin Electric Power Company Valley power plant, and large intermittent inflows from the Kinnickinnic River and Milwaukee River flushing tunnels. This circulation affects the dilution and transport of pollutants in the estuary.

The second of the phenomena affecting water quality conditions in the estuary is the nature of occurrence of the pollutant discharges to the estuary. Combined sewer overflows discharge directly to the estuary and to the tributary rivers from a combined sewer service area of about 23.8 square miles in extent. These discharges occur with rainfall, and are by far the largest source of oxygen-demanding substances discharged to the estuarine sediments. Combined sewer overflows are also a major contributor of fecal coliform bacteria. Chapter VI presents specific data on water quality conditions, and on loadings and sources of pollutants within the estuary.

The combination of the two major phenomena described above—the complex estuary hydrodynamics and the randomness of occurrence of combined sewer overflow—necessitated the development and calibration of a suite of mathematical simulation models in order to assure meaningful analyses of existing and projected water quality conditions.

Consequently, models were developed and calibrated to simulate sediment processes, dry-weather steady-state conditions, and dry- and wet-weather time-variable conditions. A statistical model was also developed for predicting fecal coliform and toxic metal concentrations in the estuary.

Simulation of Sediment Processes

Two models were developed and applied by HydroQual, Inc., to simulate organic material fluxes from the bottom sediments to the overlying water column, and to quantify the effect of the bottom sediments on dissolved oxygen concentrations in the overlying water. The sediment diagenesis model is a model of particulate organic matter decomposition. Sediment diagenesis refers to all of the chemical, biochemical, and physical changes that sediments undergo from the time of deposition. Diagenetic processes include physical rearrangement of the sediments by compaction, bioturbation by organisms, infiltration of clay-sized particles, and deformation; biochemical and organic processes such as decomposition; and physiochemical processes such as cementation, solution, and recrystallization. Most of these processes result in a reduction in porosity and permeability.

[14] *Milwaukee Metropolitan Sewerage District, unpublished CSO/SAM document A-26/D-1/ Bennett/C10A11.F5820/27 January 1982/1g/ 1-G-2 A19.*

Many of the diagenetic processes required for metamorphism occur very slowly over geologic time, i.e., thousands of years. These very slow processes, such as changes in the structure and size of limestone crystals, are often effected by pressure, heat, and changes in water content. Other sediment modifications take place during and immediately following deposition. These short-term modifications are often influenced by biochemical phenomena, including vigorous bacterial activity. These sediment changes are affected by characteristics of the sediments and interstitial water, including hydrogen ion content (pH), oxidation potential (Eh), ionic adsorption phenomena, temperature, and depth of burial. Some of these relatively short-term processes consume substances, such as dissolved oxygen, from the overlying water, while others release substances, such as metals, ammonia, and methane. Total sediment diagenesis, therefore, refers collectively to the changes that sediments undergo from deposition until metamorphism is reached.

This study, however, is primarily concerned with the sediment diagenetic reactions that involve the decomposition of organic matter, and especially with those reactions that exert an oxygen demand on the overlying water. The amounts of both inert and reactive organic matter in the sediments are quantified and are used in the analyses. For the purposes of this study, the term sediment diagenesis refers only to those processes that involve the decomposition of organic matter present in the bottom sediments. The rates of organic decomposition determined in the diagenesis model served as input functions for the sediment flux model, a more detailed model of sediment diagenetic reactions used to compute the component fluxes required in the water quality models.

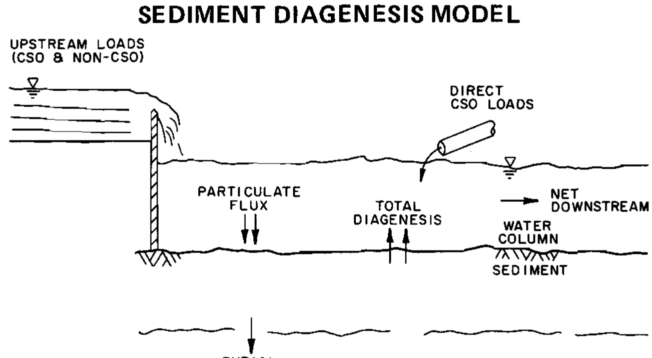
Sediment Diagenesis Model: A sediment diagenesis model was developed to compute the decomposition and stabilization of particulate organic matter, and to quantify the annual mean diagenetic rates in the Milwaukee Harbor estuary. A schematic diagram illustrating the principal components of the sediment diagenesis model is shown in Figure 166. Upstream and direct sources of organic matter—specifically, particulate organic carbon—discharged to the inner harbor either settle to the sediment-water interface or are transported to the outer harbor and Lake Michigan. The particulate material consists of an essentially inert fraction, which reacts at a negligibly slow rate, and a reactive fraction, which is either labile (rapidly reactive) or refractory (slowly reactive). The reactive material decomposes, with resultant transfer of diagenetic end-products to the overlying water column. The sediment diagenesis model computes the total flux of diagenetically produced end-products to the water column.

The diagenesis modeling analysis provided a quantitative measure of the importance of both combined sewer overflow and upstream pollution sources to the carbon flux to the bottom sediments, and to the total diagenetic rates of the sediments. In order to evaluate the effects of organic carbon loadings on the inner harbor, the harbor was segmented into 15 reaches as shown on Map 100. The water column was modeled as a two-layer flow pattern, with a countercurrent circulation pattern in the downstream reaches. Annual average upstream flows and upstream and combined sewer overflow particulate organic carbon loads, presented in Table 87 of Chapter VI of this volume, were assigned to represent external sources of carbon to the inner harbor.

The relative amounts of inert, labile, and refractory carbon in both combined sewer overflow and noncombined sewer overflow loadings were assigned as shown in Table 133 for the diagenesis model. Combined sewer overflow and noncombined sewer overflow sources were estimated to be 30 and 60 percent reactive, respectively, of which 80 percent of the combined sewer overflow reactive material load, and 100 percent of the noncombined sewer overflow reactive material load, were estimated to be labile. The reactive and labile portions of the combined sewer overflow and noncombined sewer overflow loadings are higher than those estimated in the diagenesis

Figure 166

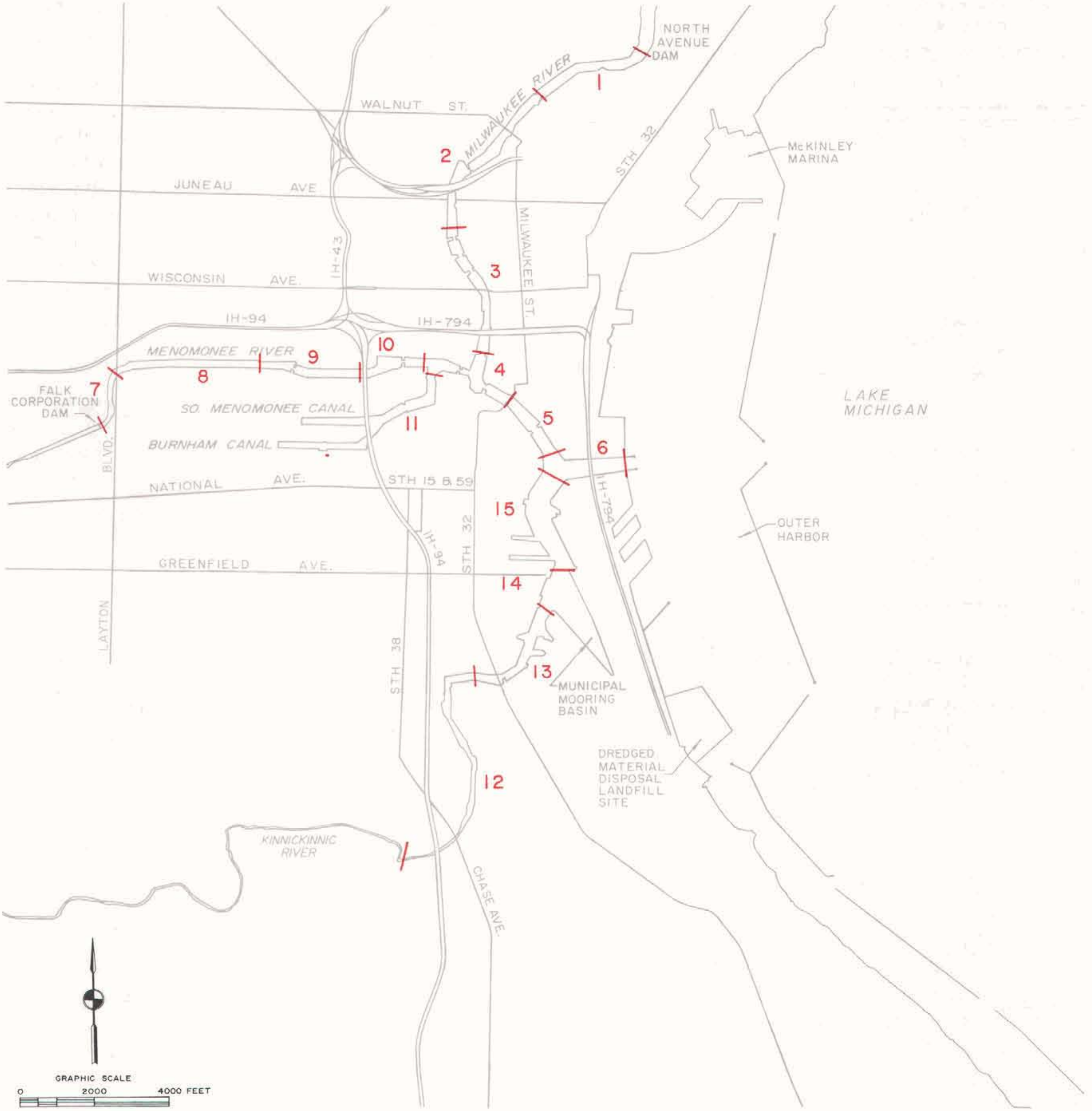
SCHEMATIC DIAGRAM OF THE SEDIMENT DIAGENESIS MODEL



Source: HydroQual, Inc.

Map 100

SEDIMENT DIAGENESIS MODEL SEGMENTATION



For sediment diagenesis modeling the inner harbor was divided into 15 segments. The sediment diagenesis model was used to simulate the effects of organic carbon loadings to the inner harbor from combined sewer overflows and from upstream pollution sources within each segment. The model included a two-layer flow system, and the segments shown were applied to both the surface and bottom water layers.

Source: HydroQual, Inc.

experiment described in Chapter VI because the in-place sediments examined in the diagenesis experiment were already in various stages of decomposition. Reactive material in the water column was assigned an aerobic oxidation rate of 0.065 per day, while labile and refractory materials in the sediment were assigned anaerobic rates of decomposition of 0.150 and 0.005 per day, at

Table 133

THE RELATIVE AMOUNTS OF DECOMPOSITION COMPONENTS ASSIGNED TO COMBINED SEWER OVERFLOW AND NONCOMBINED SEWER OVERFLOW LOADINGS OF ORGANIC CARBON IN THE DIAGENESIS MODEL

Carbon Classification	Relative Amount (percent)	
	Combined Sewer Overflow	Noncombined Sewer Overflow
Inert	70	40
Reactive	30	60
Labile	24	60
Refractory	6	0

Source: HydroQual, Inc.

20° C, respectively, based on the diagenesis experiment results. Sediment layer depths were set equal to two years of sedimentation, such that the annual average rate of decomposition was approximately equal to the annual flux of material to the sediment, and loss of reactive material by burial was negligible.

Model Calibration: The sediment diagenesis model was calibrated using diagenesis experimental data collected under the harbor estuary study and described in Chapter VI. Calibration results for the sediment diagenesis model are shown in Figure 167. Water column profiles of particulate organic carbon concentrations in the surface and bottom water layers show good agreement between calculated results and mean annual data. A significant concentration variability is indicated by the large standard deviations exhibited by the measured data. The Milwaukee and Menomonee River estuary concentrations are not significantly higher than the upstream boundary concentrations because of the high particle settling rates attendant to solids from combined sewer overflows. The high organic loadings contributed by the combined sewer overflows thus rapidly settle to the bottom, thereby only modestly increasing the organic content of the water column.

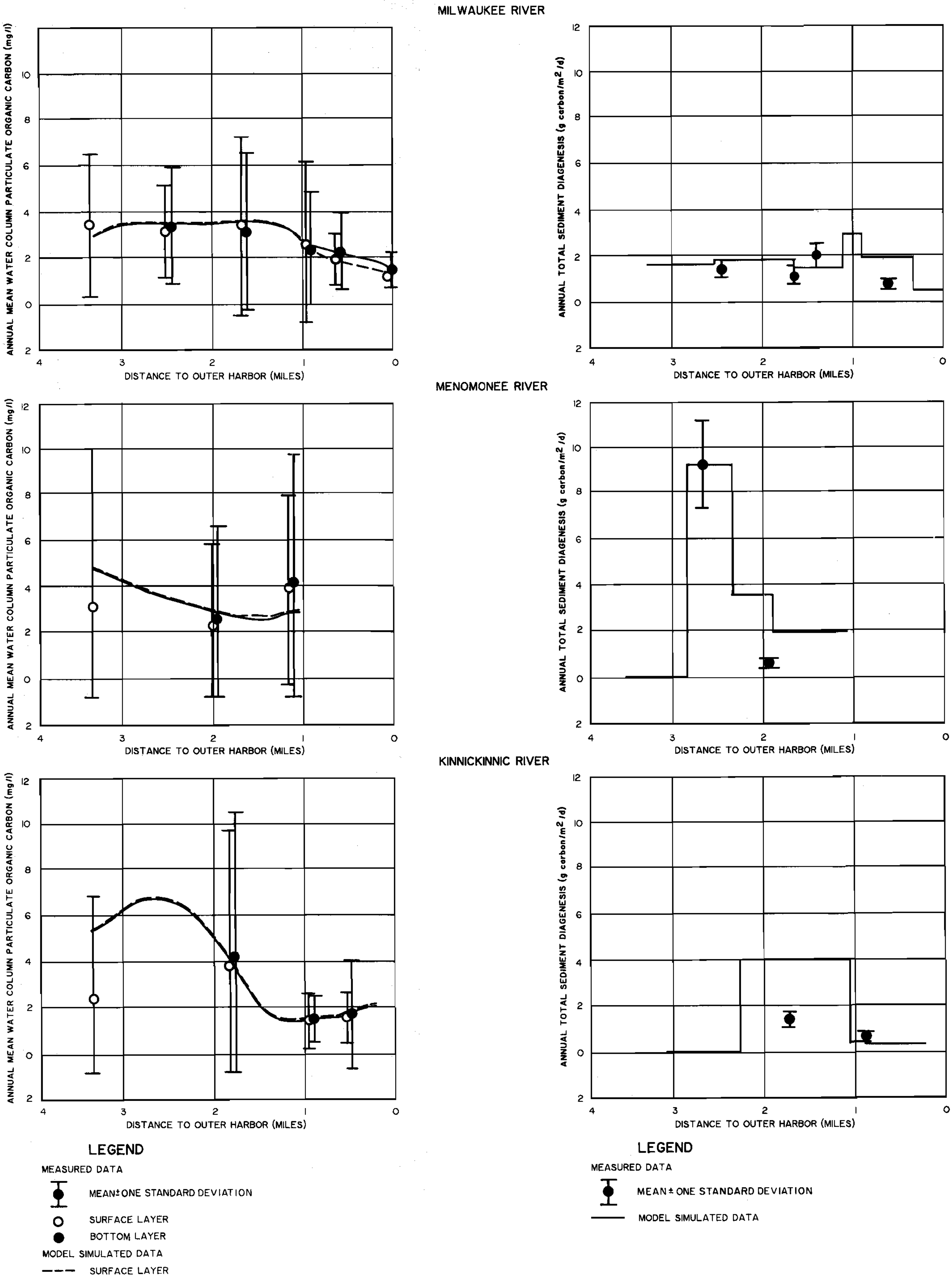
Sediment decomposition reactions were calibrated against mean annual total diagenetic rates, also shown in Figure 167. The total diagenetic rates are expressed in grams of carbon per square meter per day, and include the sum of the carbon fluxes across the sediment-water interface by methane gas ebullition and dissolved methane oxidation and diffusion. The computed diagenetic rates were in reasonably good agreement with the measured data. The overall spatial trends in the measured data were simulated reasonably well by the model, with high total diagenesis rates corresponding to inner harbor reaches with high net sedimentation. The ability of the diagenesis model to reproduce observed diagenesis rates is important, since the total diagenesis rates computed with this model form the basis of the sediment interactions and effects on water quality that are incorporated into the water quality model calibration efforts.

Mean Annual Organic Carbon Balance: The diagenesis model was used to help establish the total carbon balance in the inner harbor. The results of the modeling effort provided a quantitative means of assessing the significance of different carbon sources to the carbon flux to the sediment. Figure 168 summarizes the percentage contribution of combined sewer overflow and noncombined sewer overflow carbon sources to the bottom sediments of the inner harbor. Fifty-four percent of the carbon flux to the sediment, 91 percent of which was of combined sewer overflow origin, was inert material which decomposed at a negligible rate. The remaining 46 percent was reactive material: 7 percent was refractory combined sewer overflow material, 25 percent was labile combined sewer overflow material, and 14 percent was labile noncombined sewer overflow material. Thus, both combined sewer overflow and noncombined sewer overflow sources were significant inputs of reactive material in the sediments, with the CSO contribution thereof being about 70 percent. Algae represented approximately one-third of the noncombined sewer overflow contribution to the sediment carbon flux in the inner harbor, and 10 percent of the overall flux of reactive particulate organic carbon to the sediment.

Sediment Flux Model: The consumption of dissolved oxygen by sediment reactions is an important factor affecting dissolved oxygen levels in the inner harbor. The primary reaction that results in sediment oxygen demand is the bacterial decomposition of particulate sedimentary organic matter, referred to as the diagenesis reaction. The diagenesis reaction liberates carbon, nitrogen, and associated potential oxygen demand to the

Figure 167

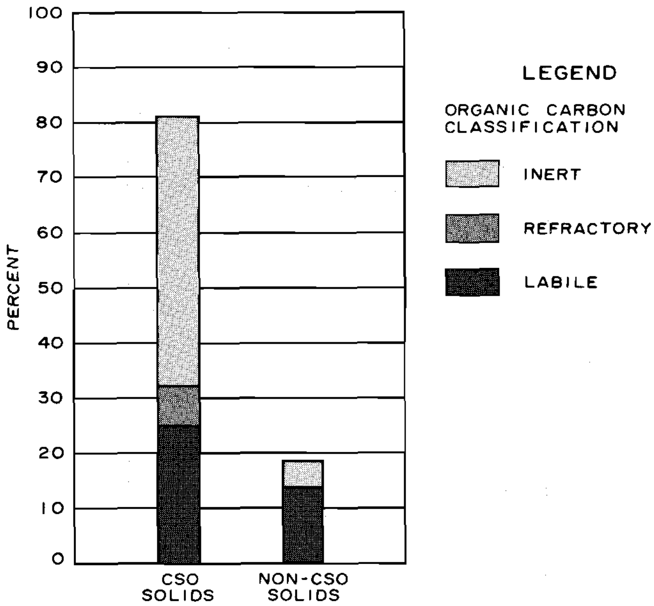
SEDIMENT DIAGENESIS MODEL CALIBRATION



Source: HydroQual, Inc.

Figure 168

RELATIVE CONTRIBUTION OF THE DECOMPOSITION COMPONENTS OF CARBON FROM COMBINED SEWER OVERFLOW AND FROM OTHER SOURCES TO INNER HARBOR SEDIMENTS



Source: HydroQual, Inc.

interstitial water of the sediment. These dissolved constituents diffuse to the sediment-water interface where they undergo oxidation, which is expressed as sediment oxygen demand. The sediment flux model is comprised of two submodels: a methane oxidation submodel and an ammonia oxidation submodel. The submodels link a sequence of reduction-oxidation reactions together with mass transport mechanisms to simulate sediment oxygen demand. The sediment oxygen demand estimates were used in the water quality model simulations.

Methane Oxidation Submodel: The composition of gas released from the bottom sediments as described in Chapter VI suggests that the primary component of sediment oxygen demand is the oxidation of methane and ammonia. The predominance of methane in gas released from the inner harbor sediments suggests that methane oxidation is an important source of sediment oxygen demand. The methane, along with ammonia, is produced by the anaerobic fermentation of organic matter, as shown by the following reaction:

$$(CH_2O)(NH_3)_\alpha \rightarrow (½CH_4 + ½CO_2) + \alpha NH_3$$

Thus, the end products of the reaction are methane (CH_4), carbon dioxide (CO_2), and ammonia (NH_3). The principal component of the oxygen demand exerted by the diagenesis reaction is the oxidation of dissolved methane. Gaseous methane is assumed to escape and not be oxidized at the sediment-water interface.

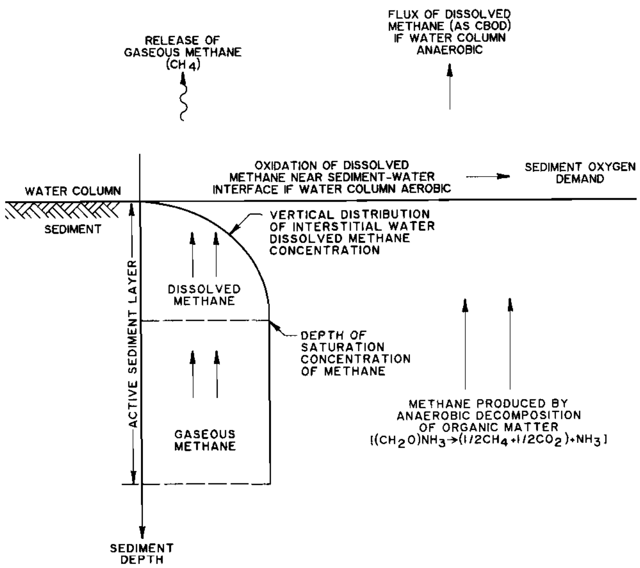
The methane oxidation submodel is illustrated in Figure 169. The diagenesis reaction produces methane within the active sediment layer. This dissolved methane is transported to the sediment-water interface, where, if the water column is aerobic, it is oxidized, consuming oxygen. When the overlying water column is anaerobic, no oxidation can occur and the dissolved methane diffuses into the water column. The concentration of dissolved methane in the sediments generally increases with sediment depth, as is illustrated by the vertical distribution of the dissolved methane concentrations in the interstitial water.

The production of methane may be so rapid that the resulting concentration of dissolved methane in the interstitial water reaches the saturation concentration of methane at the temperature and pressure of the sediment. At this point, any additional production of methane results in the formation of gaseous methane which escapes from the sediment without undergoing oxidation. Thus, as shown in Figure 169, the vertical distribution of dissolved methane increases until the depth of saturation, at which the maximum possible concentration of methane is reached. Above the depth of saturation, all of the methane produced is dissolved. Below the depth of saturation, the dissolved methane concentration is constant, no diffusion occurs, and the methane produced escapes as gas. The depth of methane saturation is a function of the diagenesis rate, the methane saturation concentration, and the diffusiveness of methane in the sediment interstitial water.

Ammonia Oxidation Submodel: Although the primary component of gas released from the inner harbor bottom sediments is methane, there is also

Figure 169

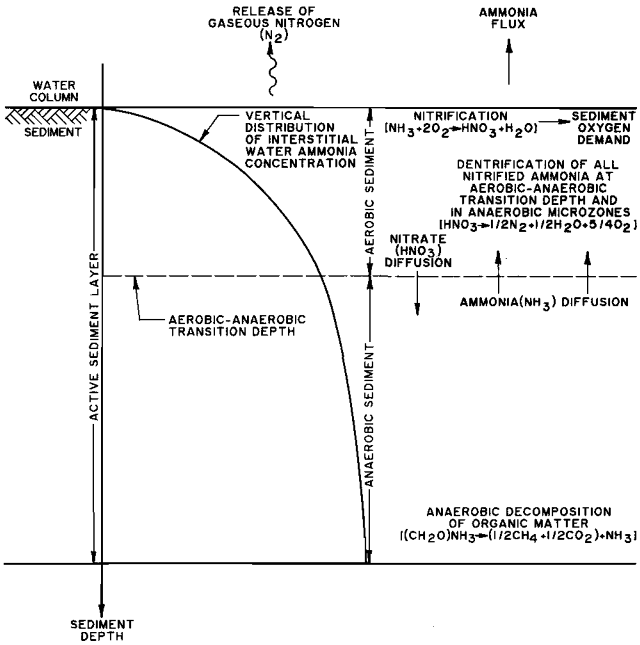
METHANE OXIDATION SUBMODEL



Source: HydroQual, Inc.

Figure 170

AMMONIA OXIDATION SUBMODEL



Source: HydroQual, Inc.

a significant release of nitrogen gas. This gas is produced by the oxidation of ammonia, probably via nitrification-denitrification. The ammonia oxidation reactions can be expressed as follows:

Nitrification

$$NH_3 + 2O_2 \rightarrow HNO_3 + H_2O$$

Denitrification

$$HNO_3 \rightarrow \frac{1}{2}N_2 + \frac{1}{2}H_2O + \frac{5}{4}O_2$$

The resulting combined nitrification-denitrification reaction is therefore:

$$NH_3 + \frac{3}{4}O_2 \rightarrow \frac{1}{2}N_2 + \frac{3}{2}H_2O$$

This equation indicates that one and one-half moles of oxygen would be consumed for each mole of nitrogen gas produced. In terms of mass, 1.714 grams of oxygen would be consumed for each gram of nitrogen gas produced.

Nitrification is defined as the biological conversion of organic or inorganic nitrogen to a more oxidized state. In the simplified nitrification reaction equation above, ammonia (NH_3) is converted to nitrate (HNO_3) and water (H_2O) in the presence of oxygen (O_2). Although oxygen is required, nitrification can occur at a dissolved oxygen level as low as 0.3 milligram per liter (mg/l).[15] Denitrification is defined as the biochemical reduction of nitrate or nitrite to gaseous nitrogen (N_2). The gas is released from the sediments to the overlying water column and ultimately to the atmosphere. Denitrification occurs under anaerobic conditions.

The ammonia oxidation submodel is illustrated in Figure 170. The figure shows the vertical distribution of ammonia in the interstitial water. The ammonia concentration is lower near the surface of the sediment owing to nitrification-denitrification reactions, and higher in the deeper sediments where anaerobic decomposition of organic matter occurs. The ammonia produced by anaerobic decomposition diffuses upward to the aerobic sediment layer. The submodel assumed that no oxidation of ammonia occurs in the anaerobic sediment layer, and that no ammonia is trans-

[15] *D. R. Keeney, "The Nitrogen Cycle in Sediment-Water Systems,"* Journal of Environmental Quality, *Vol. 2, No. 1, 1973, pp.15-19.*

ported to the deeper sediments beneath the active sediment layer. Within the aerobic surface sediment layer, the ammonia is nitrified, which exerts an oxygen demand. It was further assumed that all nitrified ammonia is denitrified, either at the transition depth between the aerobic and anaerobic sediment layers, or in anaerobic micro-zones—localized anaerobic regions located within the aerobic sediment layer. The denitrification produces gaseous nitrogen which is released to the water column, and ultimately to the atmosphere. The aerobic-anaerobic transition depth is a function of the sediment oxygen demand, with higher oxygen demands resulting in shallower aerobic layers.

Model Calibration: The sediment flux model was calibrated using both laboratory and field data. A laboratory test referred to as the sediment dilution experiment was conducted by HydroQual, Inc., and designed to examine the variation of sediment oxygen demand, gas production, and ammonia flux as the diagenesis rate varied. The field calibration data collected by the Milwaukee Metropolitan Sewerage District included sediment oxygen demand, collected using a chamber technique, and gas production and composition, collected using a gas trap, measured at nine stations within the inner harbor. Four stations were located on the Milwaukee River, three on the Menomonee River, and two on the Kinnickinnic River.

Two dilution experiments were conducted using a sediment sample actively undergoing diagenesis which was collected from the Menomonee River at the Falk Corporation dam. The sediment sample was diluted at various ratios with inert material—clean sand—and the sediment oxygen demand, total gas flux, and ammonia flux were measured at each dilution ratio. Although the diagenesis rate of the original sediment was unknown, the diagenetic rates were in proportion to the quantity of reactive sediment present.

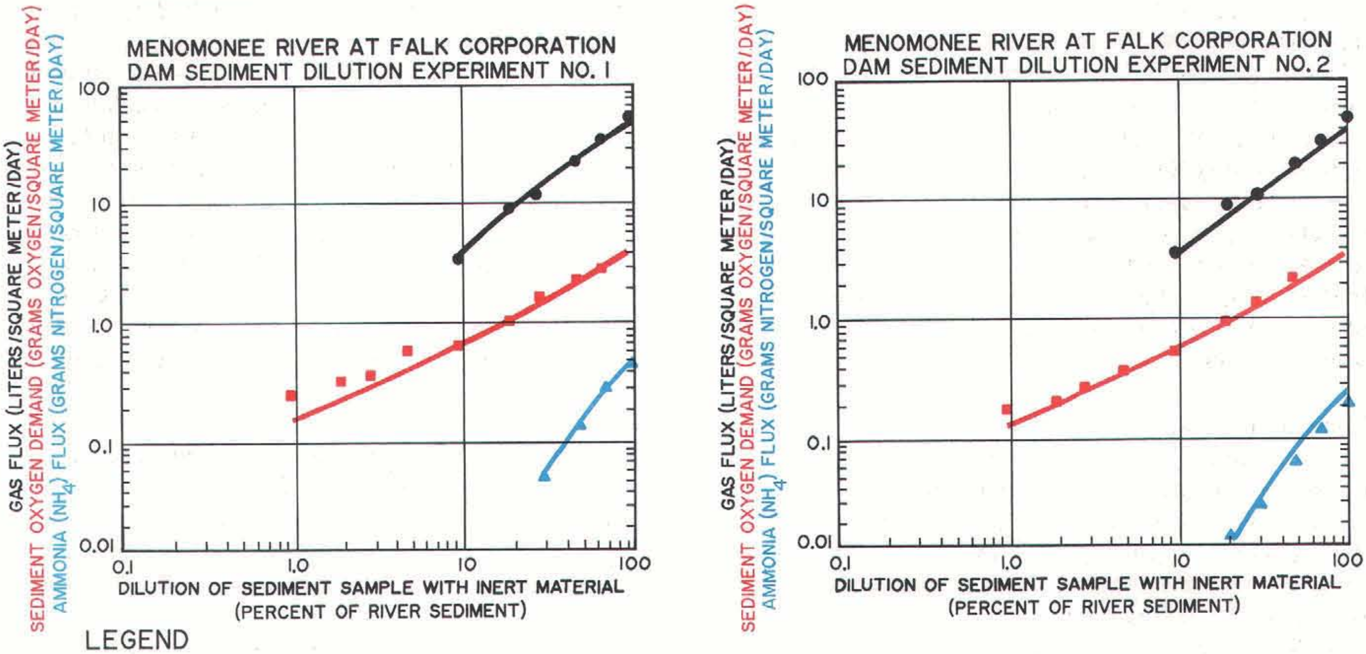
The measured and model-simulated sediment oxygen demand, gas flux, and ammonia flux rates are compared in Figure 171. The comparison indicates that the principal features that determine sediment oxygen demand, gas production, and ammonia flux were well represented by the sediment flux model. The model reproduced the observed gas flux, which is essentially proportional to the dilution fraction at the higher dilutions but decreases sharply below a dilution rate of about 10 percent. The model appears to underestimate the sediment oxygen demand slightly at the very lowest dilution rates. The simulated ammonia flux compared well with the observed flux and increased sharply at dilution rates above 20 percent. This sharp increase is due to the decreasing depth of the aerobic zone as the sediment oxygen demand rises, which reduces the depth over which ammonia oxidation can occur. Thus, as sediment oxygen demand rises, less ammonia is oxidized to nitrogen gas and more can escape as an ammonia flux. Sediment dilution experiment number 2 had a slightly lower diagenesis rate than did experiment number 1, due presumably to the decay of reacting material in the time interval between the two measurements. In addition, experiment number 2 had a slightly higher ammonia oxidation rate, apparently due to acclimation of the bacterial populations.

As described in Chapter VI, sediment oxygen demand and gas production and decomposition were measured at inner harbor stations during 1982 and 1983. The sediment flux model was calibrated with measured data collected from the Milwaukee River at Walnut Street, Wells Street, St. Paul Avenue, and the Chicago & North Western (C&NW) Railway bridge; from the Menomonee River at N. 25th Street, Muskego Avenue, and N. 2nd Street; and from the Kinnickinnic River at S. 1st Street and E. Greenfield Avenue extended. The sediment diagenesis rates used to calibrate the model were calculated from the measured methane gas fluxes.

A comparison of sediment flux model simulations to measured instream data is shown in Figure 172. The data from the individual sampling stations are pooled in the figure. The left panel in the figure shows the methane gas flux, expressed in oxygen equivalents, versus total sediment oxygen demand. The methane gas flux is an approximate measure of the diagenesis rate at the higher flux rates since oxidation of methane is a relatively small part of the total diagenesis. Although the simulated data compare well with the measured data, the model appears to underestimate sediment oxygen demand at lower levels of diagenesis, although, in general, the model accurately simulates the relationship between sediment diagenesis and sediment oxygen demand. It is important to note that both the measured and simulated data indicate that changes in the diagenesis rate, as represented by the methane gas flux, do not result in a proportional change in sediment

Figure 171

SEDIMENT FLUX MODEL CALIBRATION WITH SEDIMENT DILUTION EXPERIMENT DATA



LEGEND

MEASURED DATA

- GAS FLUX (x10)
- SEDIMENT OXYGEN DEMAND
- AMMONIA (NH_4) FLUX

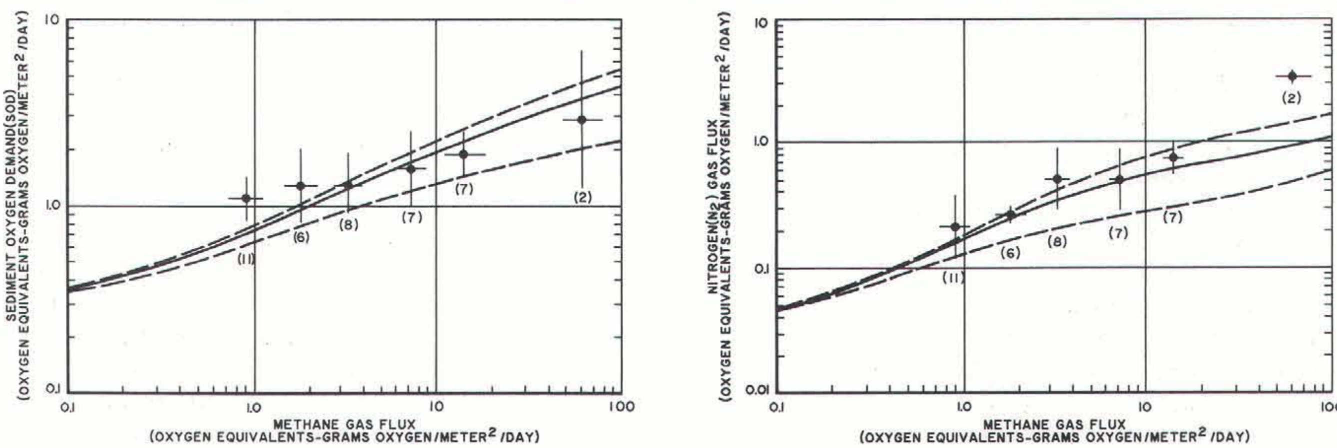
MODEL SIMULATED DATA

- GAS FLUX (x10)
- SEDIMENT OXYGEN DEMAND
- AMMONIA (NH_4) FLUX

Source: HydroQual, Inc.

Figure 172

SEDIMENT FLUX MODEL CALIBRATION WITH INNER HARBOR FIELD DATA



LEGEND

MEASURED DATA

- MEAN
- MEAN ± 1 LOGARITHMIC STANDARD DEVIATION
- (7) NUMBER OF SAMPLES

SIMULATED DATA

- SOD AT MEAN DISSOLVED OXYGEN LEVEL IN WATER COLUMN
- SOD AT MEAN DISSOLVED OXYGEN LEVEL IN WATER COLUMN ± 1 ARITHMETIC STANDARD DEVIATION

LEGEND

MEASURED DATA

- MEAN
- MEAN ± 1 LOGARITHMIC STANDARD DEVIATION
- (7) NUMBER OF SAMPLES

SIMULATED DATA

- N_2 FLUX AT MEAN DISSOLVED OXYGEN LEVEL IN WATER COLUMN
- N_2 FLUX AT MEAN DISSOLVED OXYGEN LEVEL IN WATER COLUMN ± 1 ARITHMETIC STANDARD DEVIATION

Source: HydroQual, Inc.

oxygen demand. For example, reducing the diagenesis rate (methane gas flux) from 10 grams of oxygen/square meter/day ($gO_2/m^2/d$) to $1gO_2/m^2$/day, a reduction of 90 percent, would result in only a 50 to 60 percent reduction in sediment oxygen demand. As shown in Figure 171, changes in the diagenesis rate have greater effects on gas production and ammonia flux, and less effect on sediment oxygen demand. Nevertheless, large reductions in the diagenesis rate will result in significant reductions in sediment oxygen demand.

The right panel in Figure 172 shows the nitrogen gas flux versus the methane gas flux, both expressed in units of oxygen equivalents. The simulated data compare well with the measured data except at the highest flux rates, indicating that the model simulates the composition of gases produced by sediment diagenesis reasonably well. The left and right panels also indicate that the nitrogenous sediment oxygen demand and carbonaceous sediment oxygen demand are well represented by the model. HydroQuol, Inc., conducted analyses of the differences between measured and simulated sediment oxygen demand and nitrogen gas flux levels to determine whether there were any systematic trends in the differences which could be related to water depth, sediment depth, methane gas flux, sediment temperature, or water column dissolved oxygen. The analyses indicated that the deviations in the factors were random, and no systematic trends were evident. A regression analysis was performed to quantify the effect of sediment temperature on the sediment diagenesis rate. The results of the analysis provided a temperature correction coefficient which was found to be consistent with values calculated in other studies.

Steady-State Water Quality Simulation

Steady-state simulation modeling incorporates the integrated effects of several inherently time-variable phenomena. These phenomena, such as sediment-water interactions and diurnally varying oxygen production, were evaluated using procedures based on the principles of conservation of mass and fluid flow. The steady-state modeling effort was comprised of four components: 1) a conservative tracer analysis which was used to calibrate a two-layer transport model which simulated estuarine circulation patterns; 2) the previously described sediment diagenesis model which simulated the decomposition and stabilization of organic matter within the bottom sediments; 3) the previously described sediment flux model which simulated diagenetic sediment-water interactions; and 4) a water quality model which, coupled with the transport model and sediment diagenesis and flux models, simulated water quality within specified water body segments under steady flow conditions. The steady-state models were calibrated using the extensive data base compiled under the Milwaukee Harbor estuary study. The two-layer transport and steady-state water quality models were calibrated using data collected during four periods, ranging in duration from one day to 24 days.

Conservative Tracer Analysis: Lacustrine estuaries, such as the inner harbor, are frequently characterized by a two-layer hydrodynamic transport structure which is controlled by a density-driven underflow in the upstream direction and a countercurrent downstream flow in the surface layer. The density-driven currents are induced by the intrusion of colder, denser lake water at the downstream end of the inner harbor beneath the warmer, less dense flow from upstream. The hydrodynamic transport structure in the inner harbor is further complicated by Wisconsin Electric Power Company plant cooling-water intakes and thermal discharges, changes in flow from upstream, and changes in water surface elevation resulting from lake seiche. The intrusion of water from the lake has a significant effect on water quality, since the lake water dilutes the relatively polluted inner harbor water with cleaner water. Hence, the quantitative evaluation of this mixing phenomenon is a prerequisite to any meaningful water quality modeling of the inner harbor.

Conservative indicators, such as conductivity and chloride, serve as tracers for water and provide an effective means of quantifying the effects of lake water intrusion, provided the concentrations of these tracers at the upstream boundaries of the inner harbor are significantly different from ambient lake concentrations. As upstream water flows toward and begins to mix with the lake, the concentrations of the conservative tracers are reduced by dilution, and the degree of dilution is a direct indication of the amount of lake water which has advanced to any given location. The conservative tracer analysis provided a relatively simple, yet effective, means of characterizing advective and dispersive transport in the inner harbor. Analyses were performed to characterize advective and dispersive transport in the inner harbor and to confirm that reasonable flows have been assigned to upstream and point source inputs. The analysis of conservative tracers provided a means of assessing the effects of dilution alone, without the complicating factors of biological kinetics or sediment interactions which accompany the analysis of other nonconservative indicators such as dissolved oxygen. As such, the transport patterns determined were used in subsequent analyses of these more complex water quality indicators.

The inner and outer harbors were segmented to reflect changes in channel geometry, location of tributary inputs, and significant longitudinal and vertical concentration gradients. The segmentation utilized in the steady-state model is illustrated on Map 101. Inner harbor segments are generally about 820 feet (250 meters) long, with exceptions at the upstream end of each river and canal. Segment lengths were established to ensure that computed model profiles adequately resolve the significant longitudinal concentration gradients frequently observed in the estuary. The outer harbor segmentation is comprised of a relatively fine grid in the immediate vicinity of the entrance channel and the Jones Island wastewater treatment plant, and a somewhat coarser grid in more distant areas where spatial gradients are less pronounced.

The numerical representation of the bottom of the inner and outer harbors is based on sounding data provided by the U. S. Army Corps of Engineers and on data given on National Oceanic and Atmospheric Administration nautical charts. The Milwaukee River estuary has a cross-sectional area of about 3,000 square feet and an average depth of 12 to 15 feet upstream of the confluence with the Menomonee River estuary, and increases to about 18,000 square feet and 25 to 30 feet deep between the confluence with the Menomonee River estuary and the outer harbor entrance channel. The rapid increase occurs in the reach of the Milwaukee River estuary located downstream of the confluence with the Menomonee River estuary where dredging to maintain navigation is performed. The Menomonee River estuary has a uniform channel cross-sectional area of 4,000 square feet and mean depth of about 25 feet, although it is much shallower upstream of N. 25th Street, where maintenance dredging is terminated. The Kinnickinnic River estuary is characterized by an expanding area between S. 1st Street and the turning basin, and has a relatively large cross-section—20,000 to 24,000 square feet—and a depth of 30 to 35 feet downstream of this reach. The outer harbor is quite deep relative to most of the inner harbor, having an average depth of about 30 feet.

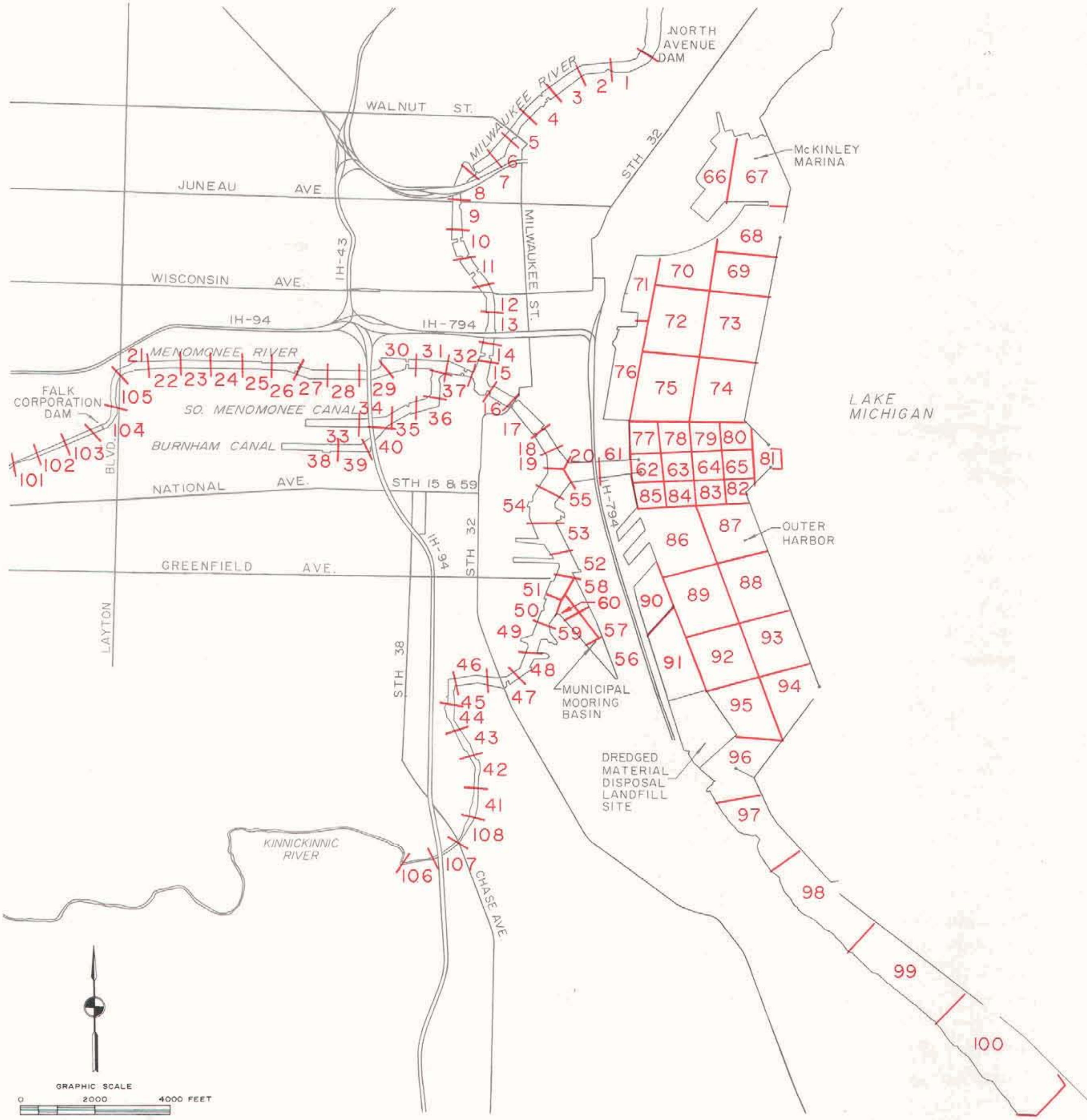
The baseline and storm runoff event water quality monitoring data demonstrated that many water quality indicators exhibit significant vertical variances within the water column. The lower temperature, conductivity, and chloride levels in the bottom layer relative to the surface layer indicate intrusion of water from Lake Michigan, and provide a measure of the diluting influence of the lake. A two-layer modeling structure was developed to simulate these vertical gradients.

Longitudinal and vertical mixing coefficients were assigned in the steady-state modeling analysis. The vertical mixing coefficient controls the degree of mixing between surface and bottom layers and, hence, vertical stratification. Vertical mixing coefficients used were 0.0025 square feet per second (ft^2/sec) in the Milwaukee River and Kinnickinnic River upstream of the turning basin; 0.0050 ft^2/sec in the Menomonee River; 0.0005 ft^2/sec between the inner harbor entrance channel and the Kinnickinnic River turning basin; and 0.0001 ft^2/sec in the outer harbor. These coefficients were assigned on the basis of the conductivity and chloride calibration results presented below.

Longitudinal mixing within the estuary is primarily accounted for by the two-layer countercurrent flow fields. Hence, longitudinal mixing was set at zero within most of the inner harbor. An exception was the relatively wide reach of the Kinnickinnic River between the turning basin and the inner harbor entrance channel. The data indicate that a two-layer countercurrent flow field alone does not provide an adequate representation of the complex transport characteristics in this reach. The analysis of tracer data suggests that surface-layer water from the Milwaukee River is transported into this portion of the Kinnickinnic River, since surface-layer concentrations are spatially uniform and indicative of a longitudinally well-mixed reach. Since the normal two-layer flow pattern incorporates surface-layer flows in the downstream direction in the Kinnickinnic River, it is not possible to specify an advective flow field which also transports surface layer water in the upstream direction from the Milwaukee River as well. Hence, a longitudinal

Map 101

SEGMENTATION OF THE MILWAUKEE HARBOR ESTUARY FOR STEADY-STATE MODELING



For steady-state modeling purposes, the Milwaukee Harbor estuary was divided into 108 segments in both the surface and bottom layers. Within each of these segments, the vertical and longitudinal variations in water quality conditions were calculated. The steady-state model included a two-layer flow system. The segment locations shown on this plan view were applied to both the surface water layer and the bottom water layer.

Source: HydroQual, Inc.

mixing coefficient of 50 ft^2/sec was assigned to simulate the observed data. Application of the hydrodynamic model, described later in this chapter, also indicated a relatively complex transport regime in this reach of the Kinnickinnic River.

Model Calibration: The two-layer transport model was calibrated for four survey periods with a range of flow and water temperature conditions. The survey periods were selected based upon a careful review of rainfall, river flow, and baseline water quality sampling data indicating relatively constant conditions within the estuary. Survey periods 1 to 4 are generally in order of increasing flow and decreasing temperature. Survey periods 1 and 2 were relatively low-flow and high temperature periods. Survey period 3 had an intermediate-flow condition and a significantly cooler water temperature. And survey period 4 had the highest average flows and the coldest water temperature. Table 134 presents a summary of the Jones Island wastewater treatment plant effluent and boundary flows and conservative tracer levels utilized in the steady-state analysis of survey periods 1 through 4. Table 135 summarizes the surface and bottom layer flows used for the survey periods. Figure 173 illustrates the flow pattern and mixing coefficients established for the two-layer transport model calibration.

Survey period 1 covered a 15-day period from July 25 through August 8. During that period, the Milwaukee River and Kinnickinnic River flushing tunnels were operated intermittently. The Kinnickinnic River flushing tunnel had been operated intermittently prior to and during that period—nine hours per day on July 22, 23, 24, 27, 28, and 29. In addition, the Milwaukee River flushing tunnel had been operated for eight hours on July 25 and 26 and for 16 hours on July 27, 28, and 29. Water quality samples were taken on July 25, August 1, and August 8. Thus, the flushing tunnels were not in operation for from 0 to 10 days prior to sampling. The dilution impact of this flushing tunnel operation varies in the different segments of the estuary system. In order to properly consider the impact of the flushing tunnel on water quality in the various segments of the estuary system, it was necessary to apply the model in three different ways. The first model run assumed no flow from the tunnels. The water quality data developed in this simulation were considered comparable to water quality data collected in reaches with short detention times, where the dilution impacts may be expected to last for only short periods of time after the operation of the tunnel ends, such as the upper reaches of the Milwaukee River estuary where the river flow was about 140 cfs during survey period 1.

The second model run assumed a flow from the tunnels equal to the average tunnel discharge over the 15-day survey period. The water quality data developed in this simulation were considered to be representative of water quality conditions for the Menomonee River and the upper reaches of the Kinnickinnic River, where the impacts of the flushing tunnel may be expected to be longer lasting owing to the lower river flows and longer detention times. Conductivity sample data collected as part of the study indicated that in the lower reaches of the Milwaukee and Kinnickinnic Rivers, the impact of the flushing tunnels lasts longer, with the tunnel water being retained longer than in the upper reaches which are impacted to a lesser degree and for a shorter time period after tunnel operations are terminated. To explore the potential impacts of the operation of the tunnel on the lower reaches of the estuary river systems, a third model application was made assuming operation of the tunnels on a continuous basis during the survey period. Under this model application, the simulation results more closely fit the measured data for the downstream reaches. This survey period was difficult to simulate precisely owing to the intermittent operation of the flushing tunnels; however, review of the three sets of water quality simulation data indicates that the model was accurately representing the performance of the system.

Using the assigned boundary conditions, the steady-state model was used to compute the resulting tracer profile. Adjustments were made to the specified transport and mixing coefficients until computed results were in agreement with observed data. Figures 174, 175, and 176 show the results of the analysis of conservative tracers for survey period 1. Spatial profiles of measured conductivity and chloride data are compared to steady-state model computations for each of the three rivers. The computed and measured data are in satisfactory agreement throughout the inner and outer harbor areas for both tracers. The tracer profiles were similar in all three rivers, with a gradual decline in upstream tracer levels to the levels found in near-shore Lake Michigan within a distance of about three miles. The vertically mixed water column in the upstream part of the estuary in all three rivers became increasingly

Table 134

BOUNDARY CONDITIONS USED IN CONSERVATIVE TRACER MODEL CALIBRATION

Station	Flow (cfs)	Temperature (°F)	Conductivity (µmhos/cm)	Chloride (mg/l)
Survey Period 1: July 25 Through August 8, 1983				
Upstream				
Milwaukee River at North Avenue Dam (RIV5)	140	80.6	623	54
Menomonee River at S. 37th Street (RIV10)	18	75.2	824	102
Kinnickinnic River at S. 9th Place (RIV13)	11	84.2	684	69
Outer Harbor				
North Breakwater Gap (OH5)				
Surface	619	70.7	326	15
Bottom	-531	61.7	293	13
Main Entrance (OH7)				
Surface	987	71.6	353	15
Bottom	-818	59.0	299	13
South Breakwater Gap (OH9)				
Surface	541	70.7	346	20
Bottom	-428	56.3	289	12
Jones Island Wastewater Treatment Plant	200	75.6	1,100	89
Survey Period 2: July 26, 1982				
Upstream				
Milwaukee River at North Avenue Dam (RIV5)	288	79.7	533	34
Menomonee River at S. 37th Street (RIV10)	48	77.0	708	94
Kinnickinnic River at S. 9th Place (RIV13)	32	69.8	817	89
Outer Harbor				
North Breakwater Gap (OH5)				
Surface	652	66.2	380	16
Bottom	-531	57.2	313	8.4
Main Entrance (OH7)				
Surface	1,090	66.2	406	19
Bottom	-818	57.2	315	7.6
South Breakwater Gap (OH9)				
Surface	583	66.2	410	21
Bottom	-428	57.2	314	9
Jones Island Wastewater Treatment Plant	179	70.7	987	99
Survey Period 3: September 26 Through October 10, 1983				
Upstream				
Milwaukee River at North Avenue Dam (RIV5)	360	59.0	657	42
Menomonee River at S. 37th Street (RIV10)	30	60.8	836	89
Kinnickinnic River at S. 9th Place (RIV13)	8	66.2	693	78
Outer Harbor				
North Breakwater Gap (OH5)				
Surface	312	55.4	376	23
Bottom	-189	51.8	326	12
Main Entrance (OH7)				
Surface	635	55.4	427	27
Bottom	-290	51.8	319	15
South Breakwater Gap (OH9)				
Surface	309	59.0	356	18
Bottom	-152	51.8	312	123
Jones Island Wastewater Treatment Plant	226	68.0	900	165

Table 134 (continued)

Station	Flow (cfs)	Temperature (^{o}F)	Conductivity (µmhos/cm)	Chloride (mg/l)
Survey Period 4: April 22 Through May 21, 1983				
Upstream				
Milwaukee River at North Avenue Dam (RIV5)	604	49.8	610	39
Menomonee River at S. 37th Street (RIV10)	104	51.6	944	116
Kinnickinnic River at S. 9th Place (RIV13)	25	58.3	965	126
Outer Harbor				
North Breakwater Gap (OH5)				
Surface	311	45.1	332	14
Bottom	-133	45.0	323	15
Main Entrance (OH7)				
Surface	732	47.1	428	25
Bottom	-205	46.6	406	26
South Breakwater Gap (OH9)				
Surface	334	49.8	427	21
Bottom	-107	46.6	419	26
Jones Island Wastewater Treatment Plant	200	61.3	907	89

NOTE: At the outer harbor stations, positive flows are from the outer harbor to Lake Michigan. Negative flows are from Lake Michigan to the outer harbor.

Source: HydroQual, Inc.

Table 135

SUMMARY OF DAILY MEAN FLOWS AT SELECTED REFERENCE POINTS IN TWO-LAYER TRANSPORT MODEL ANALYSIS OF THE SURVEY PERIODS

Reach Locations[a]	Surface (Q_s) and Bottom (Q_b) Layer Flows (cfs)[b]							
	Survey Period 1		Survey Period 2		Survey Period 3		Survey Period 4	
	Q_s	Q_b	Q_s	Q_b	Q_s	Q_b	Q_s	Q_b
A	230	-90	144	144	180	180	302	302
B	284	-265	316	267	296	-265	370	-266
C	708	-550	770	-433	556	-165	788	-80
D	50	-39	108	-76	23	-15	100	-75
E	873	-704	1,072	-704	648	-250	909	-176
F	619	-531	652	-531	312	-189	311	-133
G	987	-818	1,090	-818	635	-290	732	-205
H	541	-428	583	-428	309	-152	334	-107

[a]Confluence of Milwaukee and Menomonee Rivers to:
A. Upstream Milwaukee River.
B. Upstream Menomonee River.

Confluence of Milwaukee and Kinnickinnic Rivers to:
C. Milwaukee River confluence with Menomonee River.
D. Upstream Kinnickinnic River.

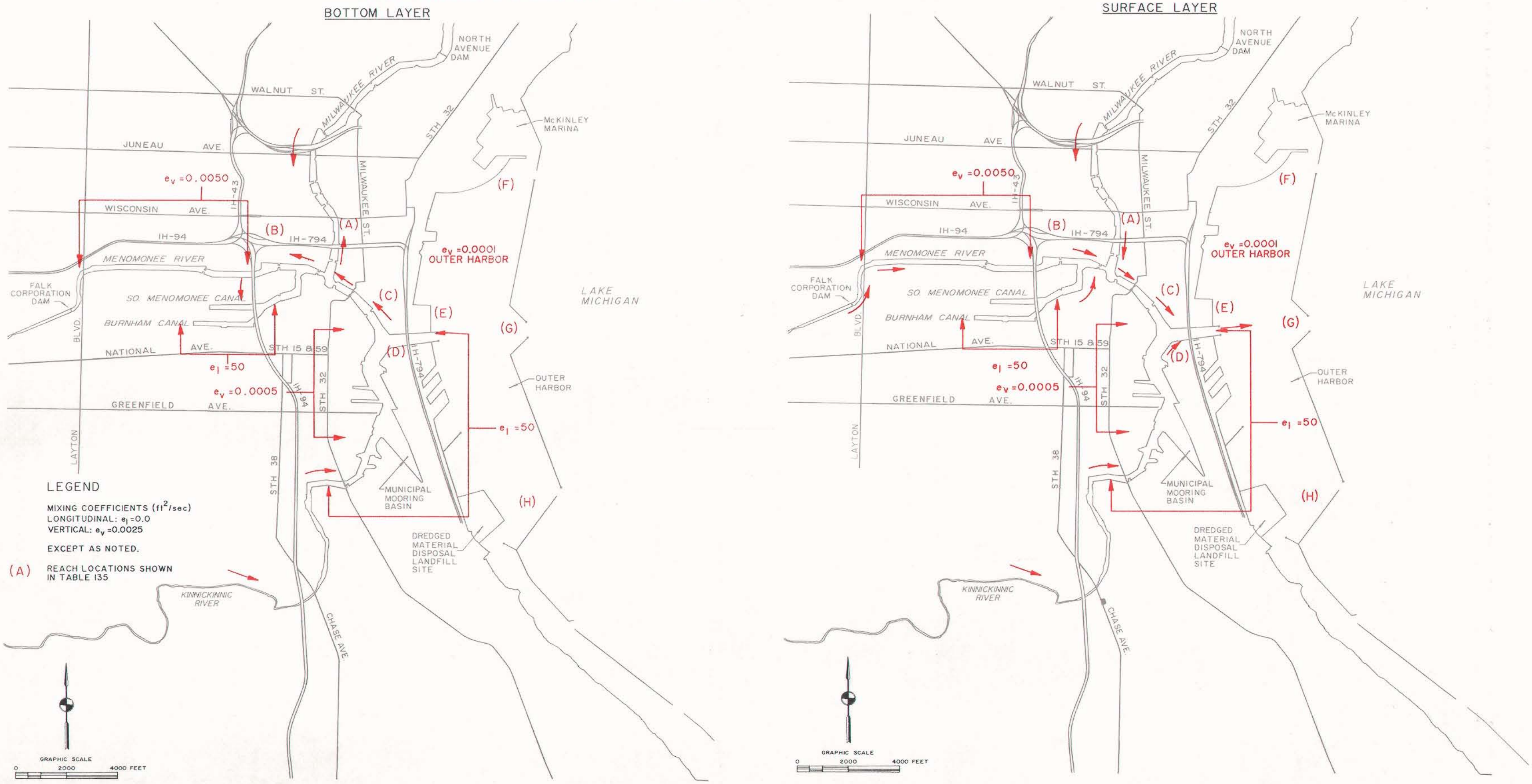
Outer Harbor
E. Inner Harbor Entrance Channel.
F. North Entrance to Lake Michigan.
G. Middle Entrance to Lake Michigan.
H. South Entrance to Lake Michigan.

[b]Positive flows are in a downstream direction toward Lake Michigan. Negative flows are in an upstream direction.

Source: HydroQual, Inc.

Figure 173

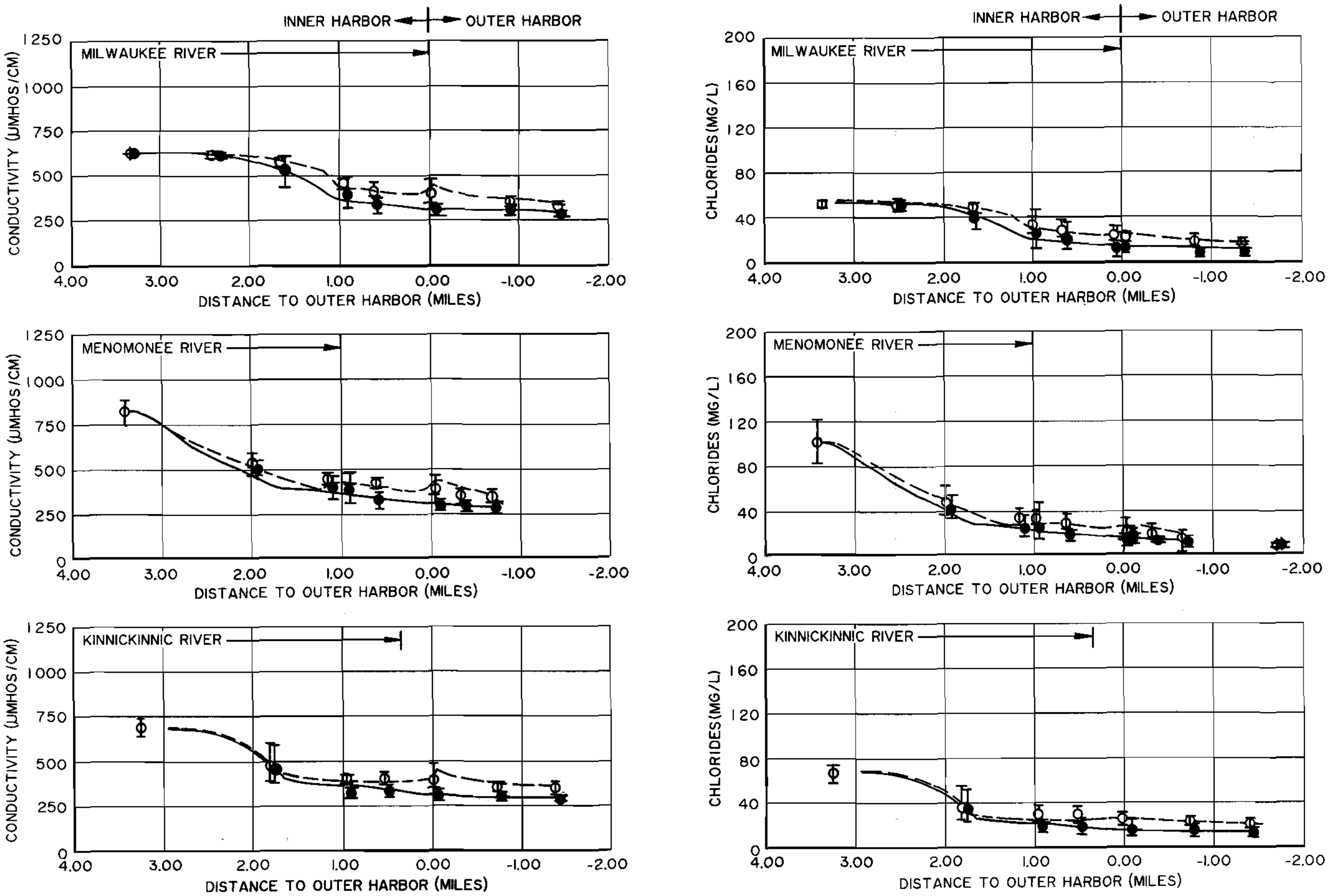
SCHEMATIC DIAGRAM OF TWO-LAYER TRANSPORT IN THE INNER HARBOR



Source: HydroQual, Inc.

Figure 174

CONSERVATIVE TRACER CALIBRATION WITH NO FLUSHING TUNNEL INPUT: SURVEY PERIOD 1



LEGEND

MEASURED DATA

- MEAN AND RANGE OF DATA
- o SURFACE LAYER
- ● BOTTOM LAYER

MODEL SIMULATED DATA

- --- SURFACE LAYER
- —— BOTTOM LAYER

NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

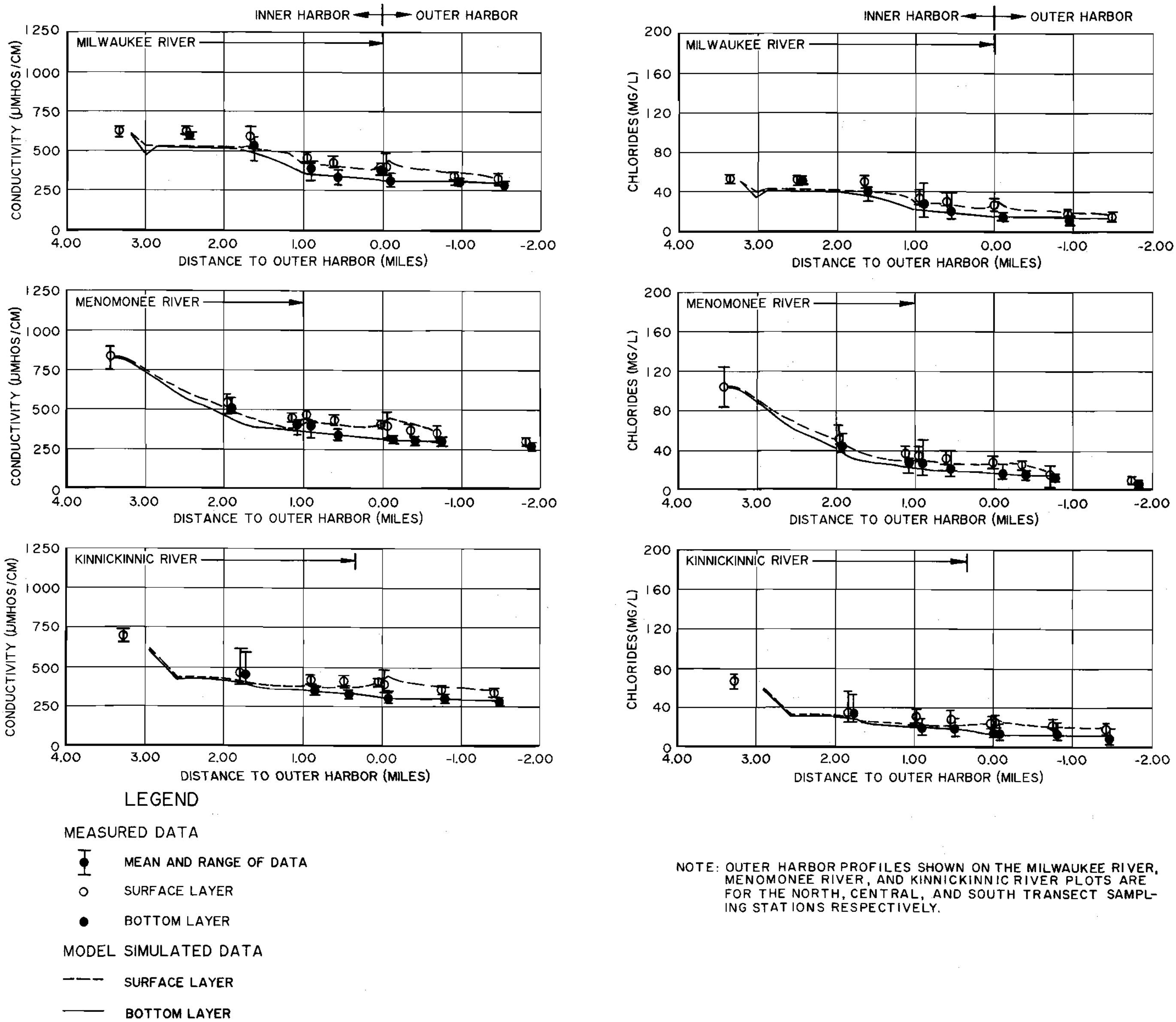
Source: HydroQual, Inc.

stratified in the downstream direction, with marked vertical gradients present at the downstream inner harbor and outer harbor stations.

It can be noted that there generally are very few differences in the simulated values of the conservative tracers under each of the three model applications, with only the upper reaches of the Milwaukee and Kinnickinnic Rivers being significantly impacted by the flushing tunnel inflow. This is due in part to the intrusion of lake water, particularly in the lower layers of the downstream reaches. The simulated data fit the measured data reasonably well for all three simulations except for the simulation of the upper reaches of the Milwaukee and Kinnickinnic Rivers under the continuous tunnel operation scenario. In this case, the dilution impacts resulted in the simulated values being significantly lower than the observed values.

Figure 175

CONSERVATIVE TRACER CALIBRATION WITH INPUT EQUAL TO THE AVERAGE FLUSHING TUNNEL FLOW: SURVEY PERIOD 1



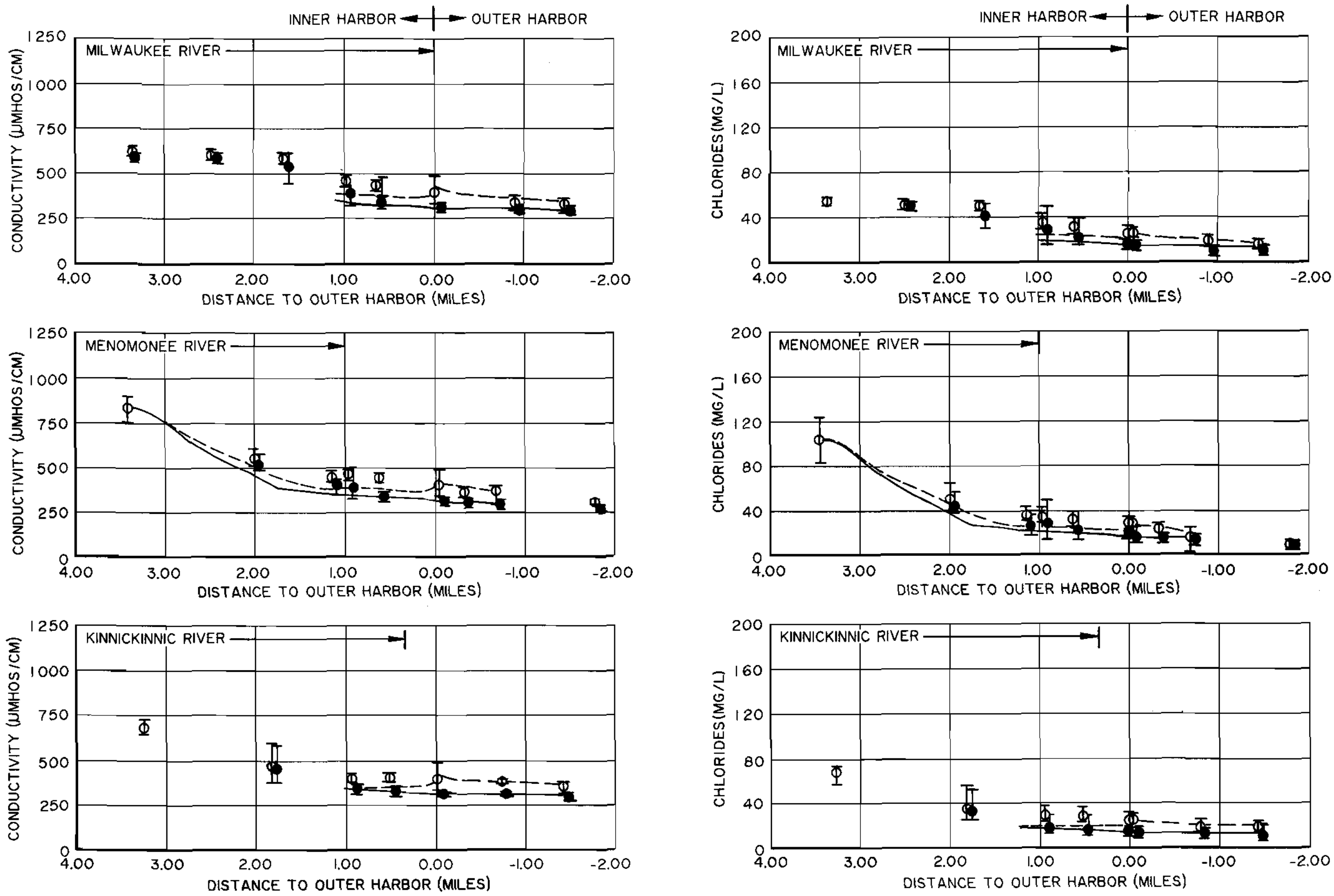
Source: HydroQual, Inc.

Model results are compared with measured data from survey periods 2, 3, and 4 in Figures 177 through 179. The simulated data are again in good agreement with the measured data. These figures indicate that the tracer profiles were quite similar during these three survey periods.

The flushing tunnels were not operated during or immediately prior to these survey periods and there appeared to be less evidence of lake water intrusion in the Milwaukee River upstream of the confluence with the Menomonee River. Conservative tracer levels measured in the Milwaukee River at the North Avenue dam continued downstream into the Milwaukee River estuary at least as far as Wells Street, at milepoint 1.41, without showing any indication of significant dilution with lake water. At Wells Street on the Milwaukee River estuary, however, the effect of dilution with lake water is evident, as surface conductivity

Figure 176

CONSERVATIVE TRACER CALIBRATION ASSUMING INPUT EQUAL TO THE CONTINUOUS OPERATION OF THE FLUSHING TUNNELS: SURVEY PERIOD 1



LEGEND

MEASURED DATA

MEAN AND RANGE OF DATA

SURFACE LAYER

BOTTOM LAYER

MODEL SIMULATED DATA

SURFACE LAYER

BOTTOM LAYER

NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

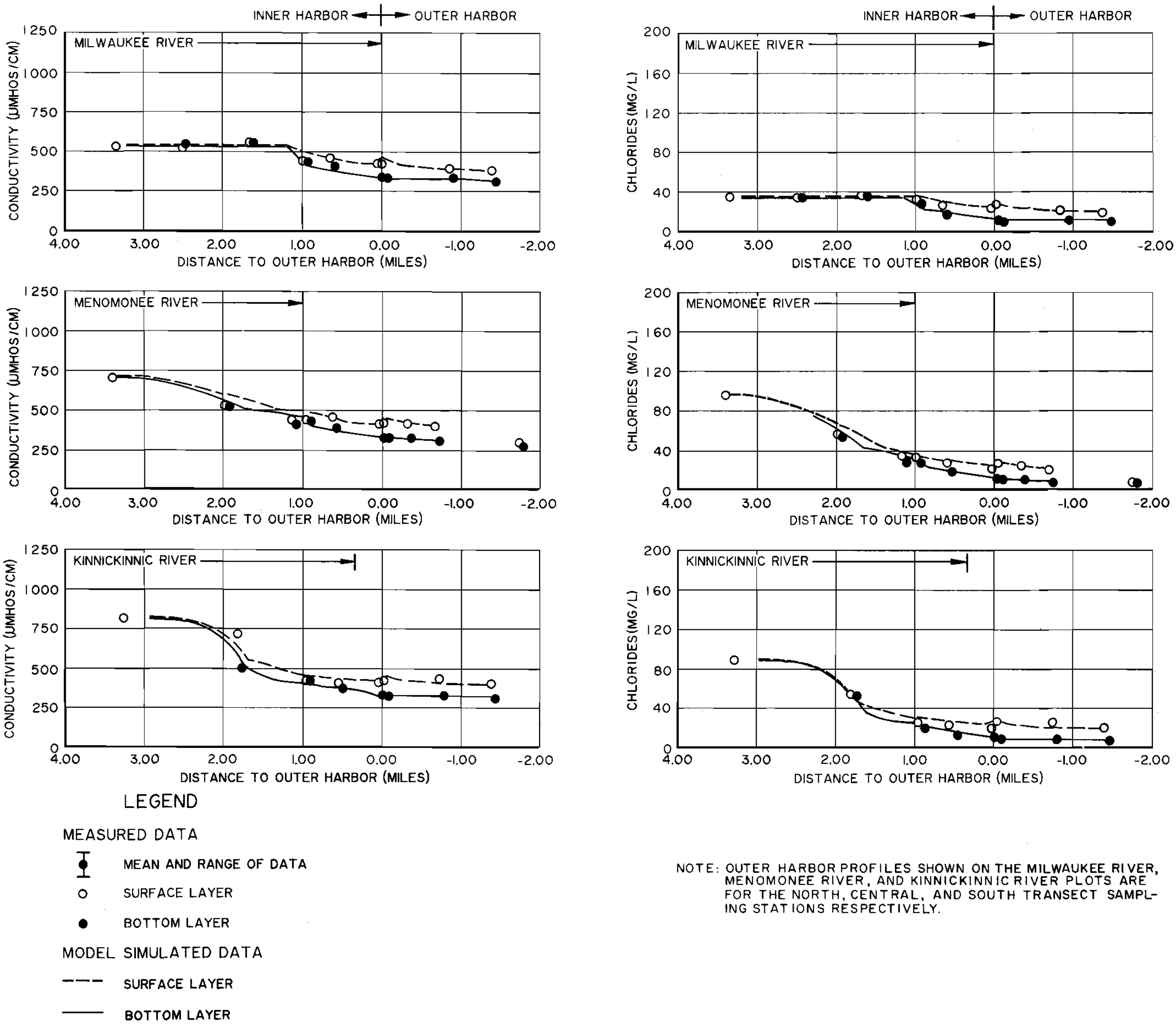
Source: HydroQual, Inc.

and chloride levels are slightly reduced, while average bottom layer conductivity and chloride levels are significantly reduced by dilution with lake water. The generally lower tracer levels in the bottom layer reflect the net upstream flow in the bottom layer from the lake. This water mixes with the net downstream flow in the surface layer, resulting in progressively less lake water intrusion as distance from the lake increases. Conversely, surface-layer tracer concentrations tend to be higher because the upstream river water, which has relatively high tracer levels, tends to remain in the surface layer as a result of its warmer temperature and lower density in comparison to the intruding lake water.

In general, the two-layer pattern of stratification is apparent for a greater distance upstream in the Menomonee River estuary than in the Milwaukee or Kinnickinnic River estuaries. This persistent

Figure 177

CONSERVATIVE TRACER CALIBRATION: SURVEY PERIOD 2



NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

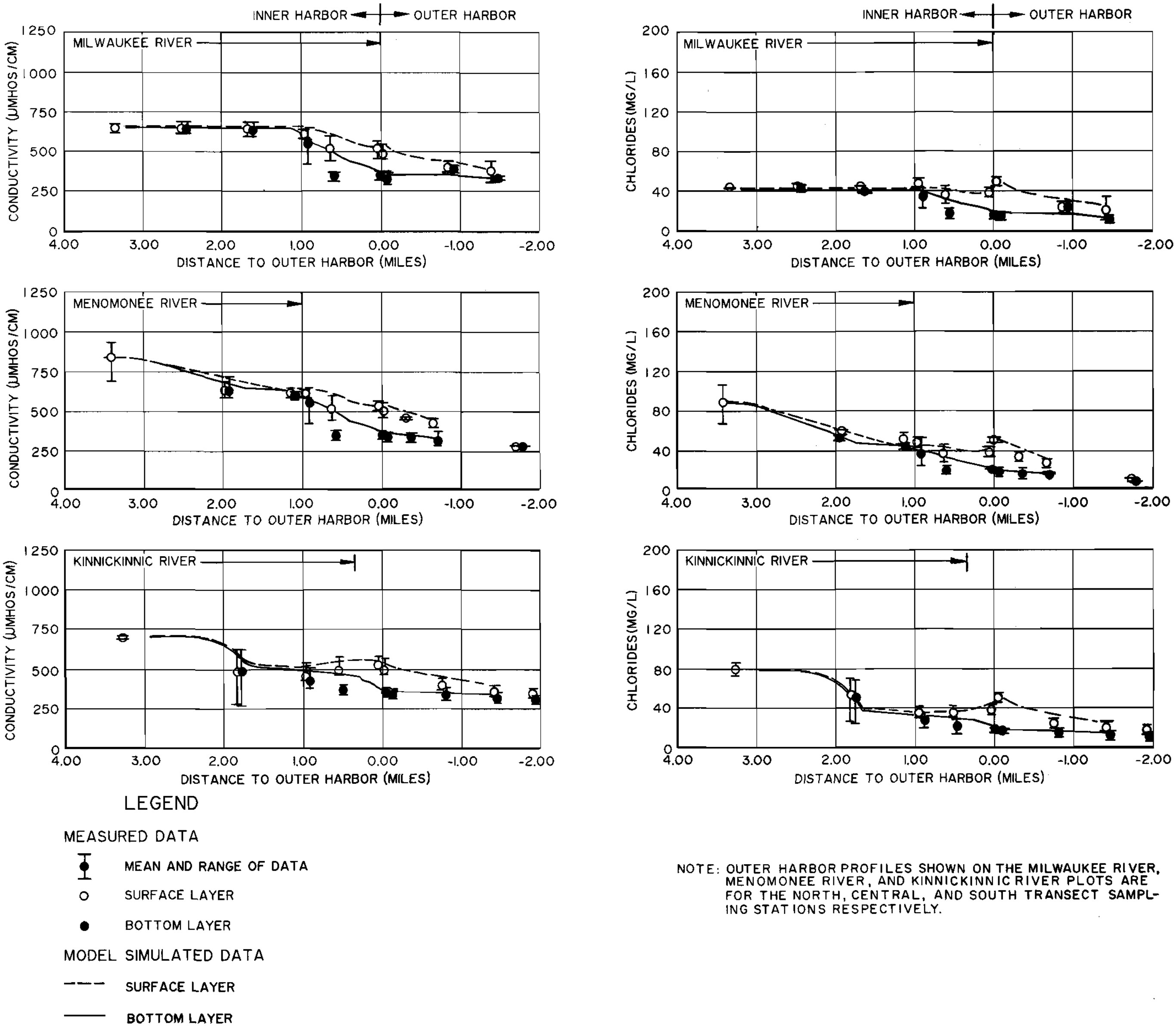
Source: HydroQual, Inc.

pattern is attributed to the effects of the Wisconsin Electric Power Company power plant condenser cooling water intake from the Menomonee River estuary and thermal discharge to the South Menomonee Canal, and to relatively low upstream flows, which contribute to the more pronounced intrusion of lake water.

Steady-State Water Quality Model: A water quality model was developed and applied by HydroQual, Inc., to evaluate dissolved oxygen levels in the inner harbor under steady-state boundary and flow conditions. The steady-state model of dissolved oxygen incorporates the two-layer transport presented above in the conservative tracer analysis and the sediment-water interactions described earlier in this chapter. The remaining sources and sinks of dissolved oxygen in the oxygen balance of the inner harbor were quantified and integrated with the above components into a unified modeling framework. The model was calibrated for chlorophyll-a,

Figure 178

CONSERVATIVE TRACER CALIBRATION: SURVEY PERIOD 3



Source: HydroQual, Inc.

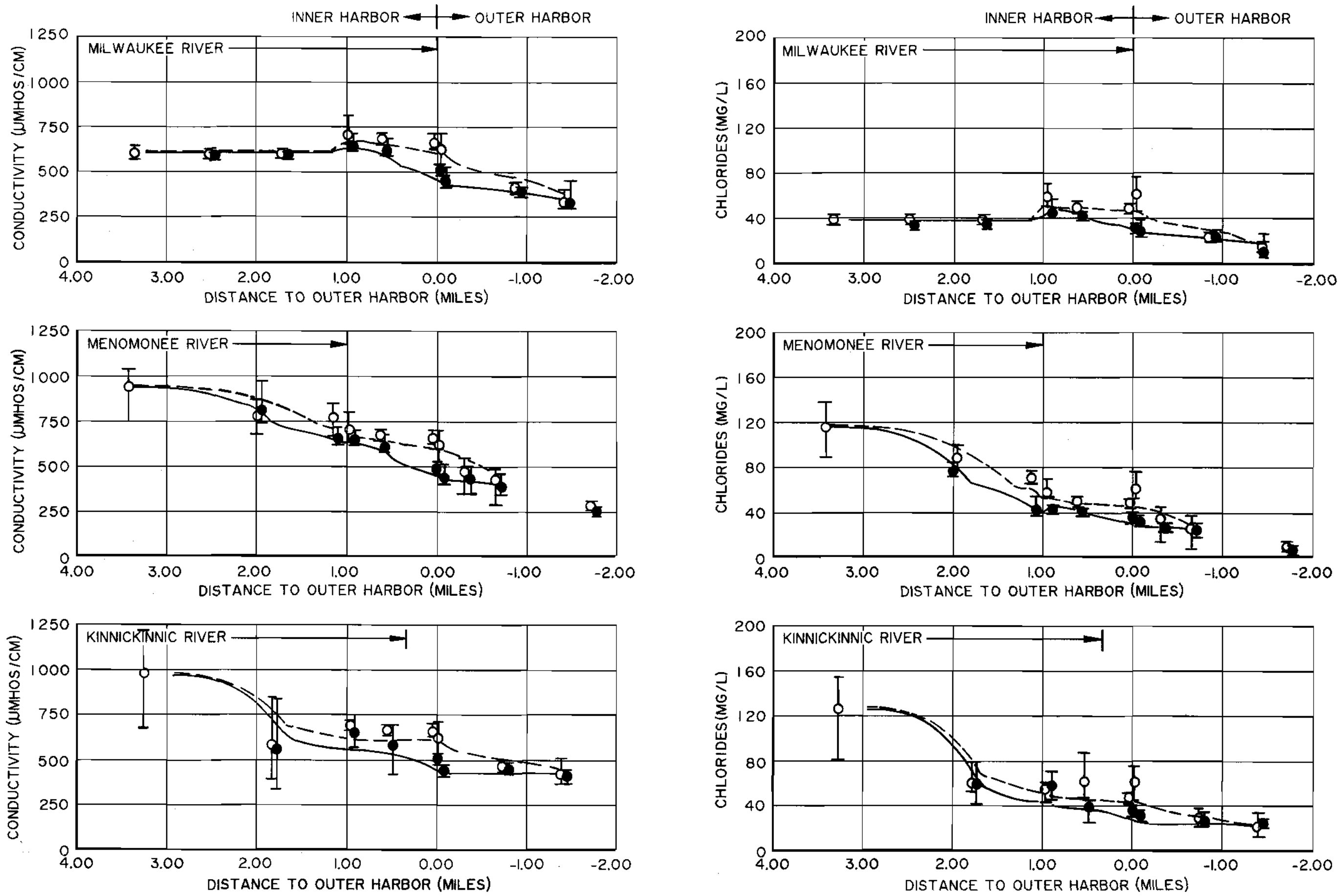
ammonia and nitrate nitrogen, carbonaceous biochemical oxygen demand (CBOD), and dissolved oxygen.

Evaluation of Sources and Sinks of Oxygen: Analysis of the dissolved oxygen levels in the inner harbor required a detailed evaluation of the important sources and sinks of oxygen affecting the dissolved oxygen balance of the receiving water. The primary sources and sinks of dissolved oxygen are illustrated in Figure 180. Special studies were performed to evaluate the significance of the oxidation of organic matter, algal photosynthesis and respiration, and sediment-water interactions. The important model parameters associated with these sources and sinks of oxygen and assigned in the steady-state water quality model calibration are summarized in Table 136.

Oxidation of Organic Carbon: The stabilization of organic material by bacteria consumes dis-

Figure 179

CONSERVATIVE TRACER CALIBRATION: SURVEY PERIOD 4



LEGEND

MEASURED DATA

- MEAN AND RANGE OF DATA
- SURFACE LAYER
- BOTTOM LAYER

MODEL SIMULATED DATA

- SURFACE LAYER
- BOTTOM LAYER

NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc.

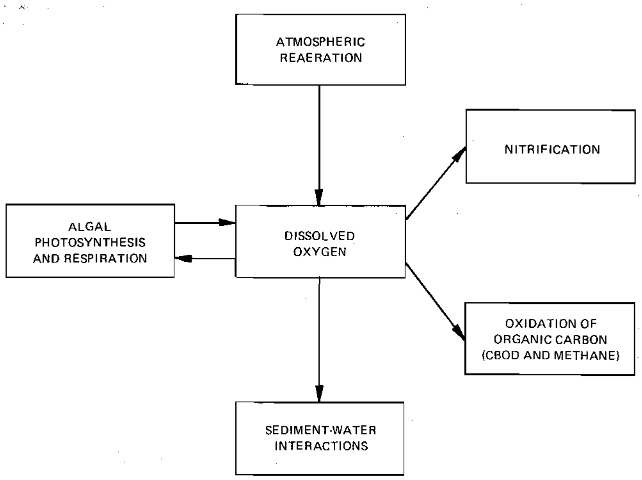
solved oxygen from the water column. The five-day biochemical oxygen demand (BOD_5) test is used as a measure of the concentration of oxidizable material in the water. Since BOD_5 represents only a portion of the oxygen demand, it was used to calculate the ultimate biochemical oxygen demand by means of BOD_5 time series measurements. Biochemical oxygen demand time series measurements were made once per month at the inner harbor sampling stations over an approximately one-year period. The samples were analyzed to differentiate between carbonaceous and nitrogenous biochemical oxygen demand. Based on a statistical analysis of the BOD time series results, all BOD_5 data were multiplied by a factor of 4 to estimate ultimate carbonaceous biochemical oxygen demand for calibration of the steady-state model. A carbonaceous biochemical oxygen demand removal and deoxygenation rate coefficient of 0.065 per day was calculated from the measured BOD data and applied in the model.

An additional source of carbonaceous oxygen demand included in this model was the methane system. Dissolved methane enters the water column via diffusion from the sediment and gas-to-liquid transfer from methane bubbles rising through the water column. The presence of methane in the water column was confirmed by measurements of dissolved methane completed by the Milwaukee Metropolitan Sewerage District during 1986. The results of the analyses during cold-weather periods are shown in Table 137. The data, all obtained at water temperatures of less than 40°F, showed near saturation levels of methane in nearly all samples. In contrast, subsequent warm-weather samples taken in August and September of 1986 contained concentrations of less than 1.0 mg/l of dissolved methane. Differences in these two sets of data are presumably the result of methane oxidation at warmer temperatures. Special consideration was given to the methane component of the oxygen demand since initial calibration results showed a discrepancy between calculated and observed dissolved oxygen levels in the upper reaches of the Menomonee and Kinnickinnic Rivers. The laboratory test results indicated that oxygen demand from dissolved methane was not measured in any significant amounts in the BOD test owing to air stripping of the methane from the sample during the sample preparation, and because the bacteria utilizing the methane are micro-aerophiles which favor low dissolved oxygen conditions of less than 2.0 mg/l. Therefore, methane was incorporated into the model as a distinct system, similar to CBOD, but capable of being oxidized at a different rate—0.8 per day—and of being removed from the water column via exchange across the air-water interface. The methane oxidation rate coefficient of 0.8 per day used in the model is comparable to water column first-order-rate coefficients, which have been measured in studies under conditions of dissolved oxygen levels of less than 2.0 mg/l.[16]

<u>Algal Photosynthesis and Respiration</u>: Algae act as both a source and sink of dissolved oxygen in the receiving water. Oxygen is produced in the euphotic zone during daylight hours as a

Figure 180

SOURCES AND SINKS OF DISSOLVED OXYGEN IN NATURAL SURFACE WATERS



Source: HydroQual, Inc.

by-product of photosynthesis, and consumed throughout the depth of the water column during both night and day by algal respiration. The net effect of these processes determines whether the algae are a net source or sink of oxygen. Since photosynthesis takes place only in the presence of light, the incident solar radiation and the rate of light extinction in the water column control net productivity.

Figure 181 illustrates schematically the manner in which sunlight is related to algal photosynthesis. During daylight hours, the incident solar radiation penetrates the water column and decreases exponentially with depth. Since the algal productivity rate varies nonlinearly with sunlight intensity, as shown in the right panel of Figure 181, these temporal and spatial variations in light intensity result in a complex pattern of algal productivity. Over moderately low light intensities, productivity increases with available sunlight, but at approximately 300 to 400 langleys/day, the sunlight intensity is optimal, and maximum rates of photosynthesis take place. At still higher light intensities, productivity is enhanced only slightly, or in some instances, may even be inhibited. The latter situation results in a reduction in oxygen production rates for limited periods of time near the surface of the water.

Algal respiration, which consumes oxygen, proceeds concurrently with the production of oxygen by algae. In contrast to the temporal and spatial variation of oxygen production in the water column, however, algal respiration is assumed to occur at a constant fixed percentage of the max-

[16] *John W. Rudd, R. D. Hamilton, and N. E. R. Campbell, "Measurements of Microbial Oxidation of Methane in Lake Water," <u>Limnology and Oceanographic Journal</u>, Volume 19(3), May 1974.*

Table 136

SUMMARY OF PARAMETER VALUES USED IN STEADY-STATE WATER QUALITY MODELING ANALYSIS

Description	Symbol	Value	Units
Carbonaceous Biochemical Oxygen Demand Removal Rate Coefficient	K_r	0.065[a,b]	1/day
Carbonaceous Biochemical Oxygen Demand Deoxygenation Rate Coefficient	K_d	0.065[a,b]	1/day
Methane Oxidation Rate Coefficient	K_c	0.8[b]	1/day
Nitrification Rate Coefficient	K_n	0.0[b]	1/day
Ratio of Ultimate Carbonaceous Biochemical Oxygen Demand to Five-day Carbonaceous Biochemical Oxygen Demand	f	4.0	- -
Ratio of Algal Carbon to Chlorophyll-a	- -	40.0	- -
Saturated Photosynthesis Rate	P_s	0.214[b]	Milligrams of oxygen per liter per day / Micrograms of chlorophyll-a per liter
Talling Light Intensity Parameter	I_k	100.0	Langleys/day
Algal Respiration Rate	R	$0.15 \times P_s$[b]	Milligrams of oxygen per liter per day / Micrograms of chlorophyll-a per liter
Oxygen Surface Transfer Coefficient	K_L	2.0[b]	Feet/day
Methane Surface Transfer Coefficient	$K_L(CH_4)$	2.0[b]	Feet/day
Temperature Correction Factors[c]	θ	- -	- -
K_r, K_d, K_c		1.047	- -
J_T (diagenesis)		1.123	- -
P_s and R		1.065	- -
K_L		1.024	- -

NOTE: Sediment oxygen demand and sediment fluxes of methane and ammonia varied spatially with temperature and were calculated with the sediment flux model.

[a] *Lower rate coefficients were used for those reaches with very low oxygen levels.*

[b] *Coefficient values at a temperature of 20°C.*

[c] $K(T) = K(20^\circ C) \times \theta^{T-20}$.

Source: HydroQual, Inc.

Table 137

SUMMARY OF ANALYSIS OF CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND AND DISSOLVED METHANE

Date	Site Identification	$CBOD_5$ (mg/l)		Dissolved Methane (mg/l)
		Aerated	Nonaerated	
February 21, 1986	RIV06	2.2	3.1	22
	RIV07	2.0	8.7	35
	RIV20	0.9	8.9	30
	RIV11	1.6	10.0	29
	RIV17	1.0	7.6	32
	Beecher Street	1.1	8.2	57
	RIV14	1.2	8.6	74
February 27, 1986	RIV06	3.7	2.8	26
	RIV07	6.5	6.0	29
	RIV20	5.7	5.1	39
	RIV11	6.2	6.8	33
	RIV17	6.6	5.7	23
	Beecher Street	7.6	8.1	126
	RIV14	7.5	7.8	27
February 28, 1986	RIV06	1.4	1.0	36
	RIV07	4.6	5.0	32
	RIV20	3.8	3.8	26
	RIV11	4.6	4.0	19
	RIV17	7.2	6.6	21
	Beecher Street	7.8	7.4	15
	RIV14	7.8	7.4	20
March 6, 1986	RIV06	1.4	2.2	26
	RIV07	4.2	3.4	28
	RIV20	7.0	4.5	29
	RIV11	8.2	7.6	28
	RIV17	6.4	3.6	27
	Beecher Street	8.3	8.1	86
	RIV14	8.2	8.4	42

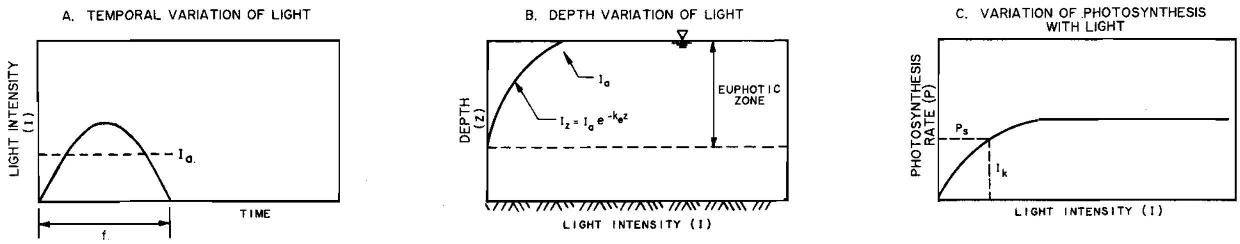
Source: Milwaukee Metropolitan Sewerage District and HydroQual, Inc.

imum rate of photosynthesis throughout the entire day. The maximum rate of photosynthesis during a day is considered to be indicative of the total amount of algae present, with the respiration of those algae being constant during the day.

Analysis of Light and Dark Bottle Data: The results of light and dark bottle studies were used to relate algal productivity to sunlight intensity in the inner harbor. These studies were performed by placing replicate water samples in a series of light and dark bottles suspended at different depths in the water column. The change in dissolved oxygen concentration in the light bottles over the period of incubation is a measure of net oxygen production by algae (gross oxygen production minus community respiration), while the decrease in dissolved oxygen in the dark bottles is a measure of community respiration alone. The net difference of changes in the light bottle and the dark bottle is a measure of gross oxygen production. Since the bottles were

Figure 181

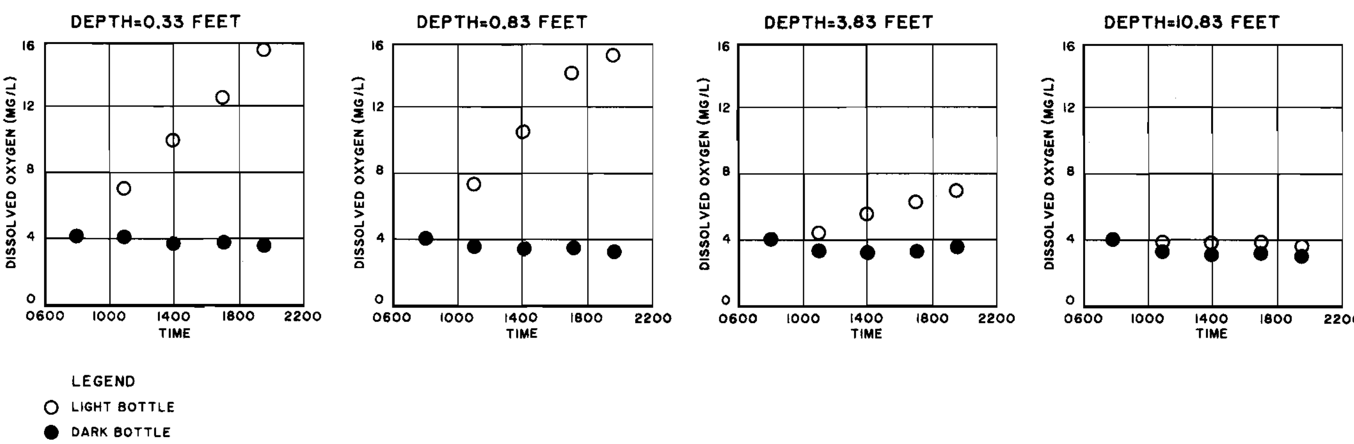
RELATIONSHIP BETWEEN PHOTOSYNTHESIS AND LIGHT



Source: HydroQual, Inc.

Figure 182

LIGHT AND DARK BOTTLE STUDY RESULTS FOR THE MILWAUKEE RIVER ESTUARY AT THE C&NW RAILWAY BRIDGE: AUGUST 12, 1982



Source: Milwaukee Metropolitan Sewerage District and HydroQual, Inc.

suspended at different depths in the water column, differences in oxygen production rates reflected changes in sunlight intensity with depth. Similarly, measurements made over different time periods during the day reflected the temporal variation of sunlight. Results from different stations in the inner harbor and different times of the year were normalized to the concentration of algae by dividing productivity rates by the chlorophyll-a concentration. Normalized productivity rates were plotted versus in-situ light intensity to establish the relationship between gross oxygen production per unit of chlorophyll-a and sunlight intensity.

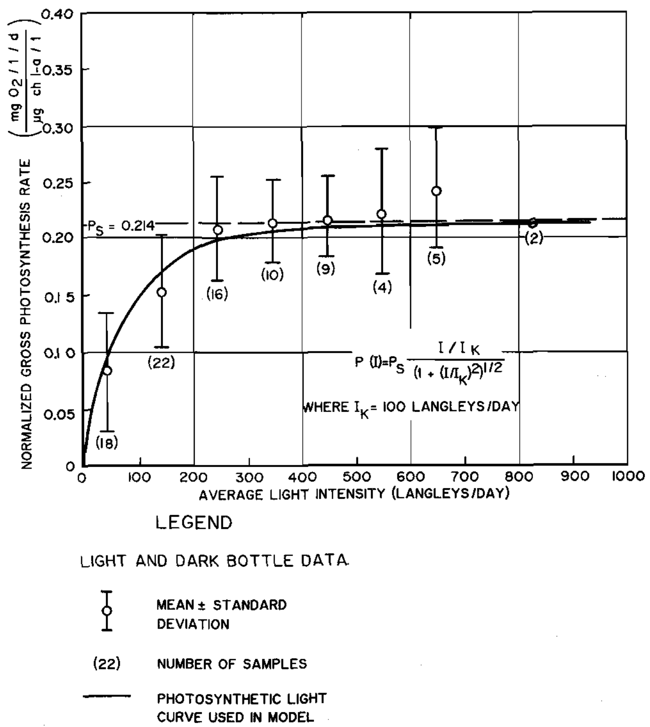
Figure 182 presents representative light and dark bottle data for a chlorophyll-a level of 30 micrograms per liter (μg/l) for the Milwaukee River estuary at the C&NW Railway bridge. Data from four depths are shown. At 0.33 and 0.83 feet, relatively high rates of oxygen production were observed throughout most of the daylight hours. At a depth of about 3.8 feet, however, the rate was markedly reduced as a result of the high degree of light attenuation in the water column. The difference between light and dark bottle results was negligible at 10.83 feet, since minimal sunlight penetrates to this depth in the water column, and photosynthesis is effectively eliminated. Since the dark bottles prevented sunlight from irradiating the samples, regardless of depth in the water column, they represent a series of replicate measurements of community respiration. The dissolved oxygen concentrations in the dark bottles were, therefore, averaged to estimate community respiration. Since the productivity rates used in the steady-state modeling analysis were average daily values, the photosynthetic light curve was developed on the basis of cumulative production rates integrated over the entire period of exposure, rather than the shorter two- to three-hour incubation period. Production rates were normalized by the initial chlorophyll-a concentration and adjusted to account for the change in algal biomass in the light bottle during the period of incubation.

Data from 15 productivity studies conducted at three Milwaukee River stations, one Menomonee River station, and two Kinnickinnic River stations, representing a chlorophyll-a range of 3.6 to 230 $\mu g/l$, were analyzed by HydroQual, Inc., and used to develop the relationship between light intensity and photosynthetic rate. The measured data, as well as the resultant photosynthetic light curve used in the steady-state model, are shown in Figure 183. In the model, the photosynthetic rate represented by the light curve was reduced by the fraction of sunlight occurring during a day in order to estimate the average daily rate of photosynthesis. The measured data shown in the figure exclude those measurements that were identified as representing potentially nutrient-limiting conditions, which would suppress photosynthesis. Nutrient-limiting conditions were occasionally detected during periods of high chlorophyll-a levels.

Chlorophyll-a and Net Productivity: Chlorophyll-a was used as a direct measure of algal biomass for purposes of modeling algal productivity in the inner harbor. The light and dark bottle studies showed the relationship between chlorophyll-a, solar radiation, and gross oxygen production by algae. Respiration by algae, bacteria, and other microorganisms is an important sink in the oxygen balance of the receiving water. The net photosynthesis rate is the difference between the average daily depth-averaged gross photosynthetic rate and the respiration rate. The respiration rate was calculated as a fixed percentage of the light-saturated photosynthetic rate. A consistent value for respiration rate was computed by determining the chlorophyll-a distribution for a range of respiration rates, thereby assuring the assignment of a reasonable net productivity rate. Table 138 summarizes the solar radiation data and daily average photosynthesis and respiration rates used in the steady-state modeling analysis. The survey periods were the same as those used in the conservative tracer analysis. In the application of the steady-state water quality model, an algal respiration rate of 15 percent of the light-saturated photosynthetic rate and an algal settling rate of

Figure 183

PHOTOSYNTHESIS VERSUS LIGHT INTENSITY FROM LIGHT AND DARK BOTTLE DATA



Source: Milwaukee Metropolitan Sewerage District and HydroQual, Inc.

about 0.33 foot per day were assumed. The product of the light extinction coefficient and surface layer depth was assigned a value of 7.5 throughout the estuary in all simulations. This is equivalent to a light extinction coefficient of about 1.25/foot in the upstream portion of the Milwaukee River estuary and 0.50/foot in the outer harbor, and corresponds to a 1 percent light level at between 4 to 7 feet below the water surface. Thus, photosynthesis is significant only in the surface layer, while respiration occurs throughout the water column.

Sediment-Water Interactions: The sediment diagenesis and sediment flux models were used to compute the dissolved organic carbon flux, inorganic nitrogen flux, and sediment oxygen demand for the steady-state water quality model. The sediment diagenesis model was used to compute the total diagenesis flux from the sediment, and the sediment flux model was used to compute the diagenesis components, including carbon and nitrogen fluxes, gas production, and sediment oxygen demand. The flux of

Table 138

PHOTOSYNTHESIS AND RESPIRATION RATES USED IN STEADY-STATE MODEL CALIBRATION

Survey Period	Dates	Average Daily Radiation[a] (langleys)	Fraction of Sunlight Hours	I_a[b] (langleys/day)	Normalized Average Daily	
					Photosynthesis[c]	Respiration[c]
1	July 25 to August 8, 1983	505	0.604	836	0.2267	0.150
2	July 26, 1982	451	0.610	739	0.2191	0.150
3	September 26 to October 10, 1983	308	0.450	684	0.1570	0.150
4	April 22 to May 21, 1983	437	0.577	757	0.2091	0.150

[a]*Computed clear sky values reduced for observed minutes of sunshine at Mitchell Field.*

[b]*Average rate of solar radiation during daylight hours.*

[c]$\dfrac{\textit{Milligrams of oxygen per liter per day}}{\textit{Micrograms of chlorophyll-}\underline{a}\textit{ per liter}}$

Source: HydroQual, Inc.

organic carbon, as methane, occurs via diffusion of dissolved methane across the sediment-water interface or, if the saturation concentration of methane is exceeded, by the release of methane gas. The dissolved methane oxidizes to exert a sediment oxygen demand under aerobic conditions in the water column, or diffuses into the overlying water as a component of carbonaceous biochemical oxygen demand under anaerobic conditions. The gaseous methane flux is transported through the water column to the atmosphere. Some gaseous methane may diffuse into the water column and become a component of carbonaceous biochemical oxygen demand.

The decomposition of sedimentary material also results in the release of ammonia to the sediment interstitial water. The ammonia may undergo nitrification in the surface aerobic sediment layer, thereby exerting a sediment oxygen demand, or diffuse directly into the overlying water. It is assumed in the modeling analysis that all of the ammonia that is nitrified to nitrate in the sediment is denitrified to nitrogen gas.

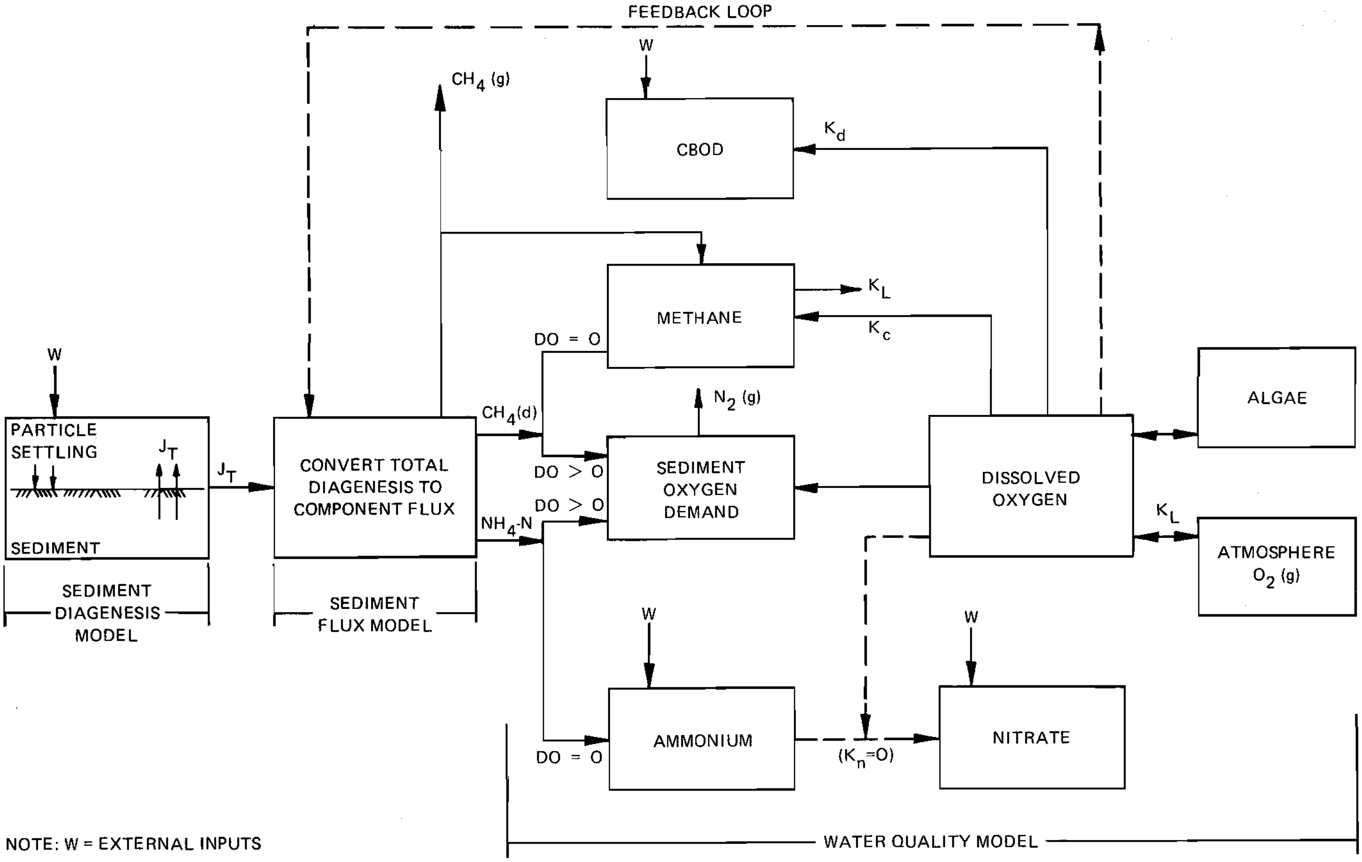
The oxidation of dissolved methane and ammonia at the sediment-water interface and within the water column affects the water column dissolved oxygen concentration, which in turn controls the magnitudes of the component fluxes in the sediment flux model. Thus, the sediment and water column computations are performed interactively in the steady-state modeling analysis. Initial water column dissolved oxygen concentrations were established and the component fluxes computed with the sediment flux model. These fluxes provided input data for the steady-state water quality model which computed the water column dissolved oxygen concentrations, which were returned to the sediment flux model to allow recomputation of the sediment fluxes. This iterative process was repeated until computed dissolved oxygen concentrations stabilized.

Model Calibration: Figure 184 presents a schematic diagram of the steady-state water quality model framework used in the model calibration. For the calibration of the water quality model, survey-specific sediment flux rates were determined by temperature-correcting average annual diagenetic rates of 68°F (20°C) to rates at the water temperature about three feet above the sediment. The steady-state water quality model was calibrated for the same four survey periods used for the conservative tracer analysis. The boundary flows and concentrations of the pertinent water quality indicators used in the steady-state model are set forth in Table 139 for each of the survey periods.

In general, boundary conditions were based upon measured data with one major exception—the upstream boundary conditions for dissolved oxygen on the Menomonee and Kinnickinnic

Figure 184

STEADY-STATE WATER QUALITY MODEL



Source: HydroQual, Inc.

Rivers which were found during survey periods 1 and 3 to be in the super-saturation range. The boundary dissolved oxygen levels in these surveys were reduced to the saturation level, as can be seen in Figures 191 and 199. This was done in order to represent average daily conditions since the measured values were considered to be higher than the daily average values owing to the time of sampling, which was expected to cause a reflection of higher dissolved oxygen levels as a result of the influence of periphyton and, to a lesser extent, phytoplankton in upstream areas.

Survey Period 1—July 25 through August 8, 1983: Survey period 1 had the lowest upstream flows and highest temperatures of any of the calibration survey periods. There was also a relatively high chlorophyll-a concentration in the Milwaukee River during this period, resulting in a significant algal contribution to the oxygen balance. As previously noted, the flushing tunnels on the Milwaukee and Kinnickinnic Rivers were operated intermittently prior to and during this survey period. Because of the varying impact of these flushing tunnels on different reaches of the estuary, it was necessary to operate the model assuming three different sets of conditions in order to assure that the model was properly simulating conditions. These conditions varied with regard to the flushing tunnel input. The first simulation assumed no flow from the flushing tunnel and the resulting data were considered comparable to water quality data collected in reaches with short detention times, where the dilution impacts may be expected to last for only short periods of time after the operation of the tunnel is ended, such as in upper reaches of the Milwaukee River estuary. The second model run assumed a flow from the tunnel operations equal to the average tunnel discharge over the 15-day

Table 139

BOUNDARY CONDITIONS USED IN STEADY-STATE MODEL CALIBRATION

Station	Flow (cfs)	Temperature (°F)	Ammonia Nitrogen (mg/l)	Nitrate Nitrogen (mg/l)	Chlorophyll-a (μg/l)	5-Day Carbonaceous Biochemical Oxygen Demand (mg/l)	Dissolved Oxygen (mg/l)
Survey Period 1: July 25 Through August 8, 1983							
Upstream							
Milwaukee River at North Avenue Dam (RIV5)	140	80.6	0.06	0.02	109.0	3.7	6.7
Menomonee River at S. 37th Street (RIV10)	18	75.2	0.14	0.16	19.2	3.7	12.2
Kinnickinnic River at S. 9th Place (RIV13)	11	84.2	0.05	0.04	12.3	2.7	13.4
Outer Harbor							
North Breakwater Gap (OH5)							
Surface	619	70.7	0.17	0.18	12.7	- -	9.0
Bottom	-531	61.7	0.10	0.19	7.6	- -	9.8
Main Entrance (OH7)							
Surface	987	71.6	0.47	0.24	14.3	- -	8.7
Bottom	-818	59.0	0.17	0.17	9.5	1.3	8.5
South Breakwater Gap (OH9)							
Surface	541	70.7	0.33	0.18	29.2	- -	9.3
Bottom	-428	56.3	0.17	0.17	7.9	- -	8.0
Jones Island Wastewater Treatment Plant	200	75.6	6.78	1.86	- -	9.0	5.2
Survey Period 2: July 26, 1982							
Upstream							
Milwaukee River at North Avenue Dam (RIV5)	288	79.7	0.12	0.02	108.0	3.2	6.5
Menomonee River at S. 37th Street (RIV10)	48	77.0	0.27	0.19	13.3	1.5[a]	5.5
Kinnickinnic River at S. 9th Place (RIV13)	32	79.7	0.09	0.04	4.3	1.0[b]	14.8
Outer Harbor							
North Breakwater Gap (OH5)							
Surface	652	67.1	0.33	0.25	11.1	- -	9.1
Bottom	-531	58.1	0.16	0.33	3.6	- -	11.4
Main Entrance (OH7)							
Surface	1,090	67.1	0.31	0.23	5.5	- -	8.5
Bottom	-818	58.1	0.13	0.26	8.6	0.8	11.9
South Breakwater Gap (OH9)							
Surface	583	67.1	0.44	0.25	13.8	- -	9.7
Bottom	-428	58.1	0.16	0.23	5.5	- -	9.8
Jones Island Wastewater Treatment Plant	179	70.7	8.50	0.30	- -	10.0	5.2
Survey Period 3: September 26 Through October 10, 1983							
Upstream							
Milwaukee River at North Avenue Dam (RIV5)	360	59.0	0.11	0.61	38.0	1.4	10.5
Menomonee River at S. 37th Street (RIV10)	30	60.8	0.08	0.49	7.6	2.2	12.6
Kinnickinnic River at S. 9th Place (RIV13)	8	66.2	0.13	0.22	2.9	0.7	16.2
Outer Harbor							
North Breakwater Gap (OH5)							
Surface	312	55.4	0.18	0.36	14.0	- -	10.7
Bottom	-189	51.8	0.17	0.28	5.2	- -	10.6
Main Entrance (OH7)							
Surface	635	55.4	0.30	0.47	8.5	- -	9.2
Bottom	-290	51.8	0.15	0.33	7.3	0.7	10.3
South Breakwater Gap (OH9)							
Surface	309	53.6	0.24	0.41	5.2	- -	9.2
Bottom	-152	51.8	0.14	0.32	4.7	- -	9.5
Jones Island Wastewater Treatment Plant	226	68.0	3.10	3.23	- -	9.6	5.0
Survey Period 4: April 22 Through May 21, 1983							
Upstream							
Milwaukee River at North Avenue Dam (RIV5)	604	49.8	0.10	0.82	25.3	2.5	11.1
Menomonee River at S. 37th Street (RIV10)	104	51.6	0.08	0.65	21.1	3.9	14.5
Kinnickinnic River at S. 9th Place (RIV13)	25	58.3	0.07	0.52	16.8	2.8	12.3
Outer Harbor							
North Breakwater Gap (OH5)							
Surface	311	45.1	0.16	0.31	7.1	- -	11.7
Bottom	-133	45.0	0.13	0.37	6.7	- -	11.8
Main Entrance (OH7)							
Surface	732	47.1	0.40	0.37	5.4	- -	9.3
Bottom	-205	46.6	0.38	0.44	5.4	1.1	11.3
South Breakwater Gap (OH9)							
Surface	334	47.1	0.36	0.43	4.9	- -	10.2
Bottom	-107	46.6	0.34	0.46	5.4	- -	11.0
Jones Island Wastewater Treatment Plant	200	61.3	6.30	0.22	- -	14.2	4.7

NOTE: At the outer harbor stations, positive flows are from the outer harbor to Lake Michigan. Negative flows are from Lake Michigan to the outer harbor.

[a]*Data from Menomonee River at N. 68th Street (RIV09).*

[b]*Data from Kinnickinnic River at S. 29th Street (RIV12).*

Source: HydroQual, Inc.

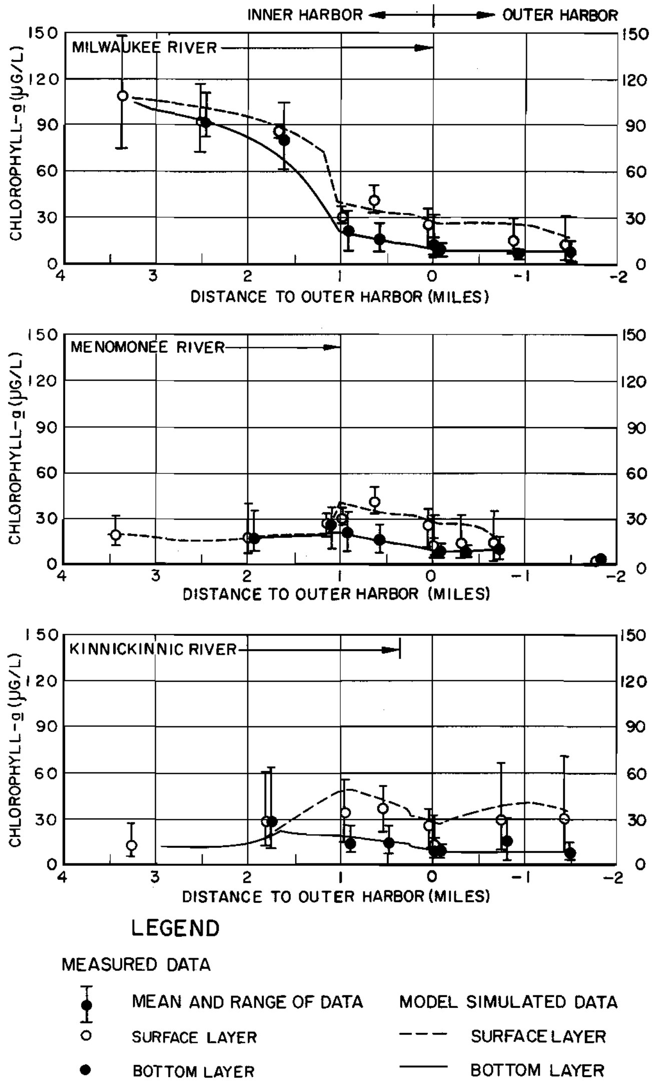
period. This water quality simulation is considered to be representative of water quality conditions for the Menomonee River and the upper reaches of the Kinnickinnic River, where the impacts of the flushing tunnel are expected to last longer owing to the lower river flows and longer detention times. The third model application was made assuming operation of the tunnels on a continuous basis during the survey period. This simulation was considered to be applicable in the lower reaches of the Milwaukee, Menomonee, and Kinnickinnic Rivers, where it has been shown, based upon conductivity data collected as part of the study, that the impact of the flushing tunnels lasts longer, with the tunnel water being retained in the system for relatively long periods.

The chlorophyll-a calibration of the steady-state water quality model during survey period 1 is shown in Figures 185, 186, and 187. In general, the simulated data compare well with the measured data, considering that the simulation assuming no tunnel operation is most appropriate for the upper reaches of the Milwaukee River. The bottom chlorophyll-a levels in the upper Kinnickinnic and Milwaukee River estuaries may be undersimulated somewhat. The pronounced decrease in chlorophyll-a in the downstream reach of the inner harbor is attributed to dilution with water from Lake Michigan, rather than to settling of the algae.

Figures 188, 189, and 190 present model calibration results for ammonia nitrogen and nitrate nitrogen. The nitrification rate coefficient was set to zero for these simulations, and, hence, both ammonia nitrogen and nitrate nitrogen values are conservative. The simulated Milwaukee River ammonia nitrogen profile is in generally good agreement with the measured data under all of the three flushing tunnel scenarios except the full tunnel operation scenario for the upper portion of the Milwaukee River and Kinnickinnic River estuary reaches. The gradual increase in ammonia nitrogen in the Milwaukee River upstream of River Mile 1.0 reflects the release of ammonia nitrogen from the sediments, while the sharp increase in the vicinity of River Mile 0.0 is due to the Jones Island wastewater treatment plant discharge. Assuming no flushing tunnel operation, the simulated ammonia nitrogen profile in the Menomonee River is significantly higher than the measured data in the upstream estuarine area, but decreases sharply and shows much better agreement downstream of Muskego Avenue, at River Mile 1.94. A similar fit of the data is apparent in

Figure 185

CHLOROPHYLL-a CALIBRATION OF THE STEADY-STATE MODEL WITH NO FLUSHING TUNNEL INPUT: SURVEY PERIOD 1



NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

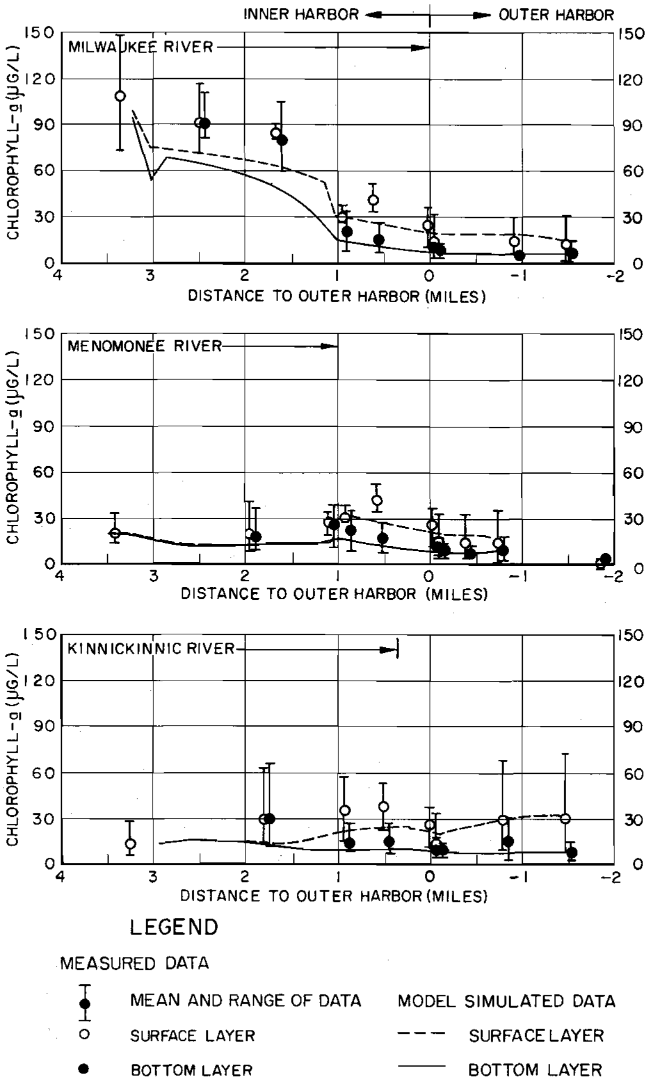
Source: HydroQual, Inc.

the Kinnickinnic River. The simulation was improved under the scenarios which assumed the flushing tunnel to be in operation.

The simulated and measured increase in ammonia nitrogen concentrations in the upstream reaches of the Menomonee and Kinnickinnic River estuaries is a result of the diagenetic release of

Figure 186

CHLOROPHYLL-a CALIBRATION OF THE STEADY-STATE MODEL WITH INPUT EQUAL TO THE AVERAGE FLUSHING TUNNEL FLOW: SURVEY PERIOD 1

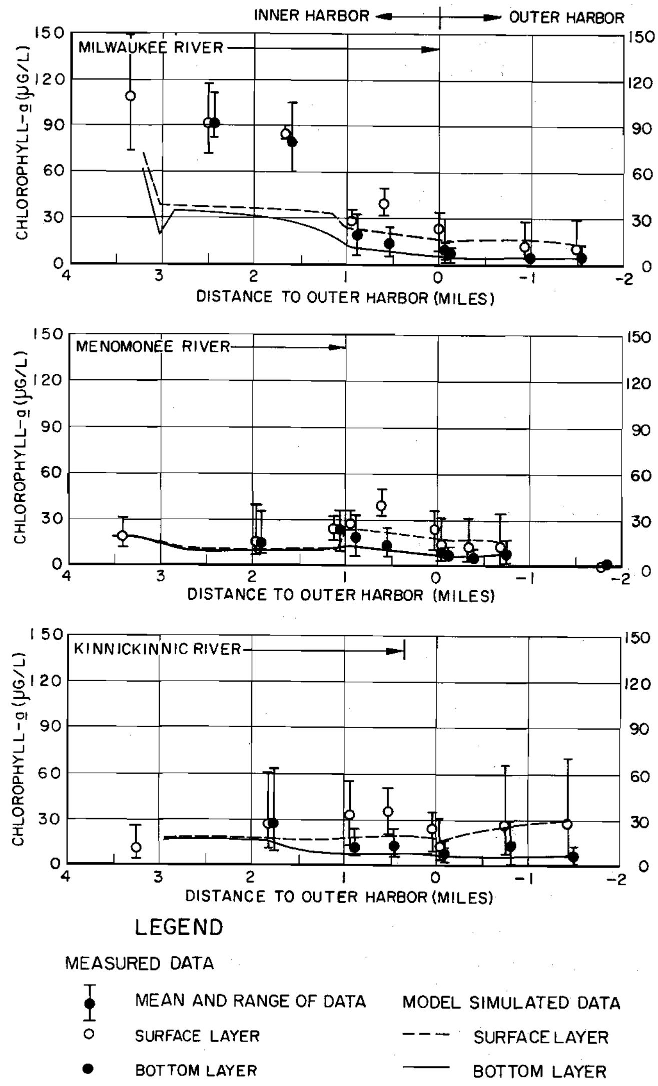


NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc.

Figure 187

CHLOROPHYLL-a CALIBRATION OF THE STEADY-STATE MODEL WITH INPUT EQUAL TO THE CONTINUOUS OPERATION OF THE FLUSHING TUNNEL: SURVEY PERIOD 1



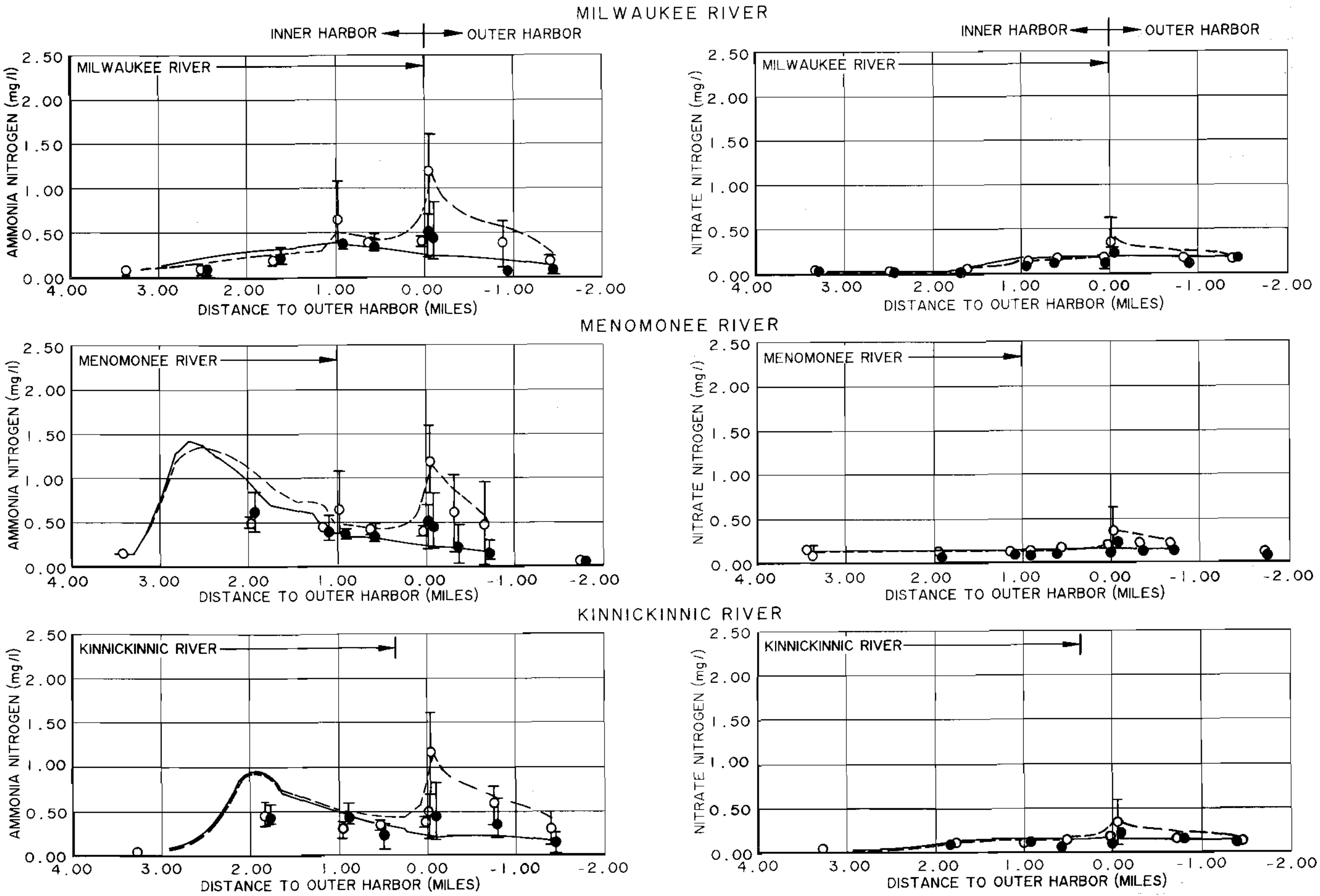
NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc.

ammonia from the sedimentary decomposition of organic material. The oversimulation of the ammonia nitrogen concentration at the frist inner harbor station in the Menomonee River estuary may reflect an overestimate of the total diagenesis rate in this area in the diagenesis model. The model is normally based on the average annual load of organic material to the sediment, and seasonally adjusts diagenesis rates based on sediment temperature. If the organic load from combined sewer overflows prior to and during this survey period was low relative to the average annual load, the model would tend to overestimate the rate of total diagenesis. A

Figure 188

AMMONIA NITROGEN AND NITRATE NITROGEN CALIBRATION OF THE STEADY-STATE MODEL WITH NO FLUSHING TUNNEL INPUT: SURVEY PERIOD 1



LEGEND

MEASURED DATA

- MEAN AND RANGE OF DATA
- ○ SURFACE LAYER
- ● BOTTOM LAYER

MODEL SIMULATED DATA

- --- SURFACE LAYER
- —— BOTTOM LAYER

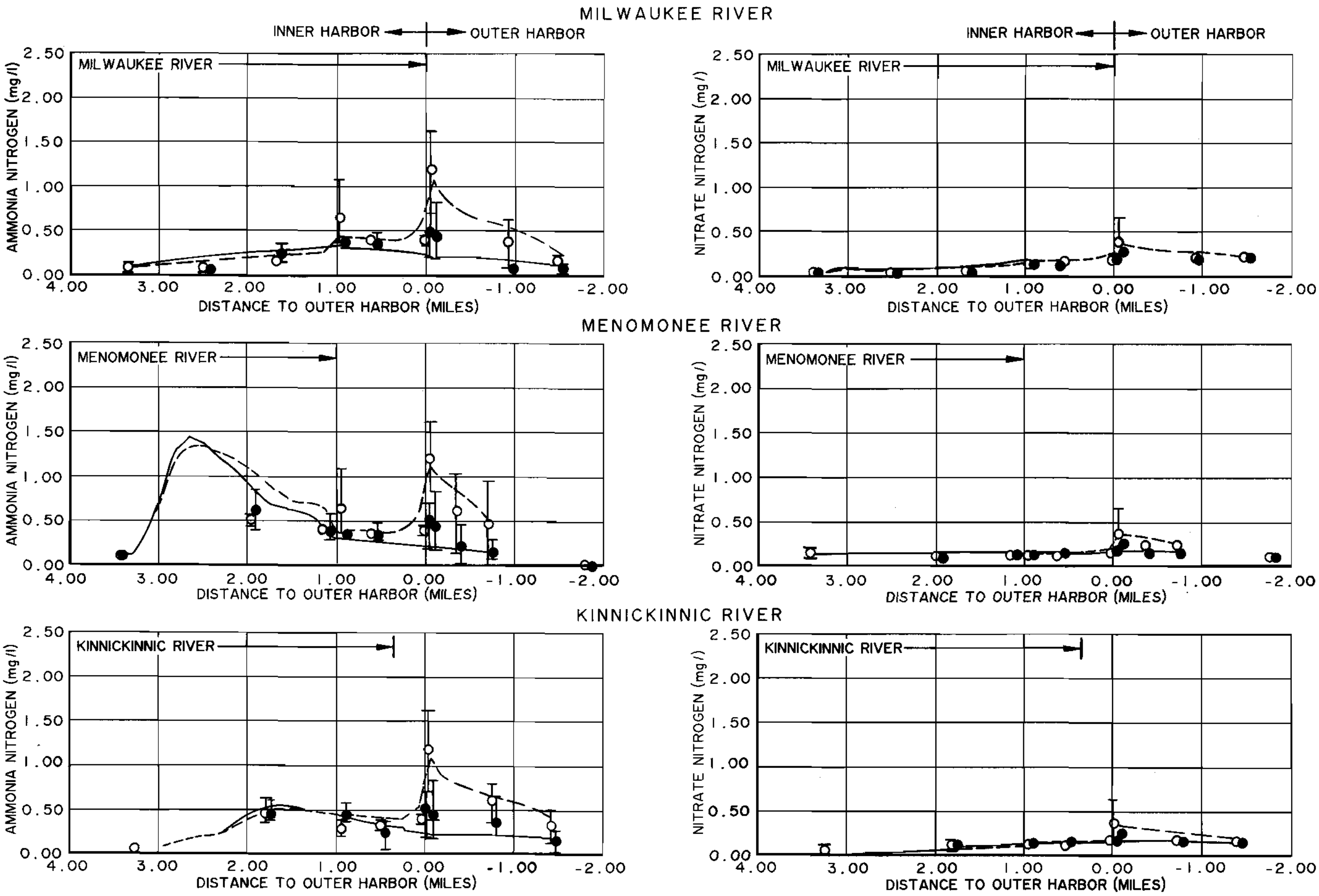
NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc.

review of rainfall records for the two-month period prior to sampling showed that rainfall was less than 50 percent of the monthly average, and, hence, diagenesis rates were proportionately reduced. This resulted in a reasonably accurate simulation of ammonia for this survey period. Model results in the upstream inner harbor areas tended to overestimate observed data in both low-flow, high temperature survey periods, but, as shown for the latter survey periods, were in better agreement during the higher flow, colder temperature conditions. In view of the interrelationship of simulated ammonia release rates during all surveys via the diagenesis model and the overall

Figure 189

AMMONIA NITROGEN AND NITRATE NITROGEN CALIBRATION OF THE STEADY-STATE MODEL WITH INPUT EQUAL TO THE AVERAGE FLUSHING TUNNEL: SURVEY PERIOD 1



LEGEND

MEASURED DATA

- MEAN AND RANGE OF DATA
- o SURFACE LAYER
- ● BOTTOM LAYER

MODEL SIMULATED DATA

- --- SURFACE LAYER
- —— BOTTOM LAYER

NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc.

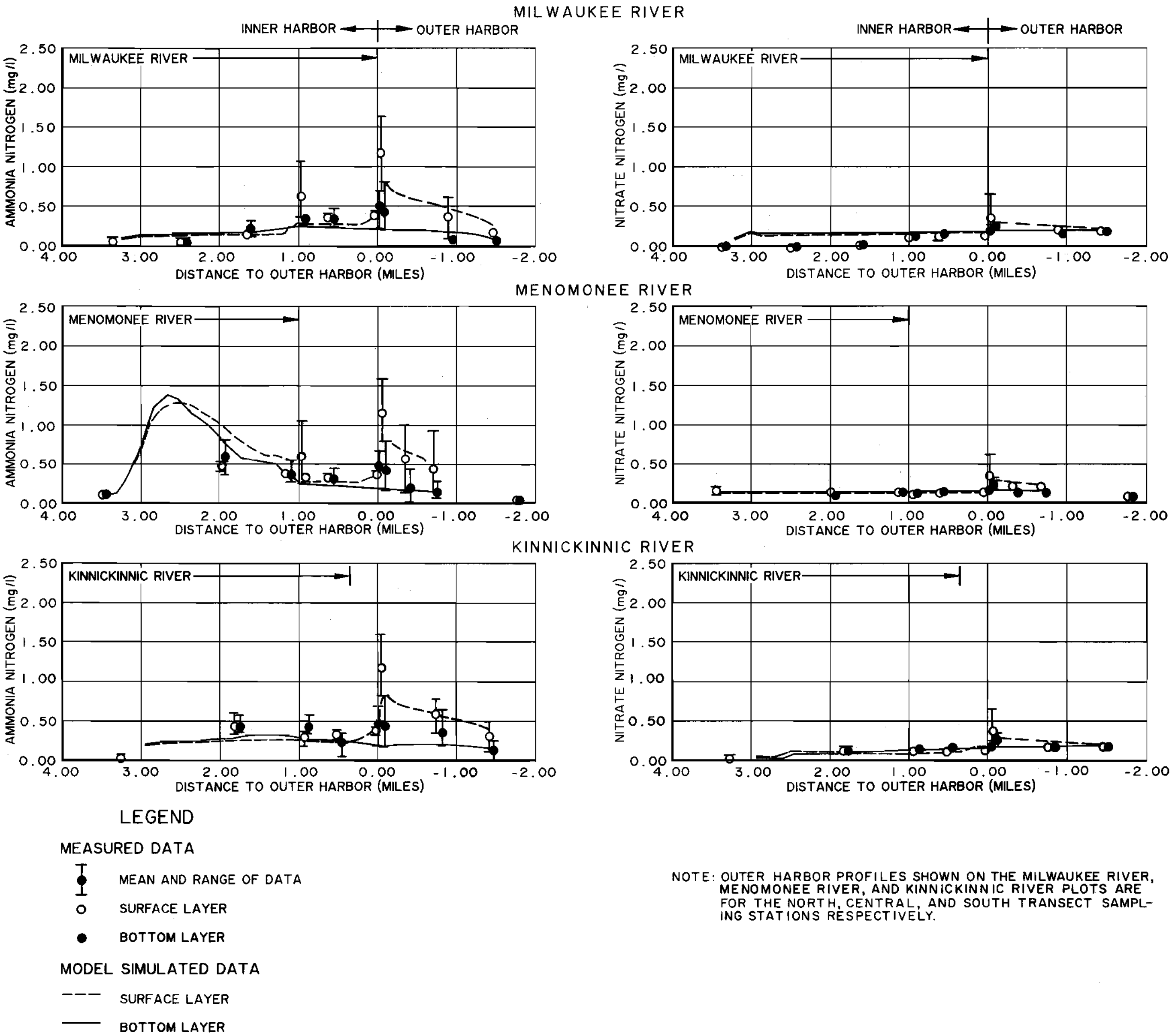
agreement between simulated and measured data, further refinements in the ammonia calibration were not considered warranted.

Nitrate nitrogen calibration results, also shown in Figure 188, indicated generally low simulated nitrate concentrations of about 0.2 mg/l, which are in good agreement with the measured data throughout the inner and outer harbors. The calibration did not indicate any increase of nitrate resulting from the conversion of ammonia via nitrification. Hence, the results support the assumption that nitrification was not significant in the water column in the Milwaukee Harbor estuary.

Figures 191, 192, and 193 present calibration results for survey period 1 for carbonaceous biochemical oxygen demand and dissolved oxygen. The carbonaceous biochemical oxygen

Figure 190

AMMONIA NITROGEN AND NITRATE NITROGEN CALIBRATION OF THE STEADY-STATE MODEL WITH INPUT EQUAL TO THE CONTINUOUS OPERATION OF THE FLUSHING TUNNEL: SURVEY PERIOD 1

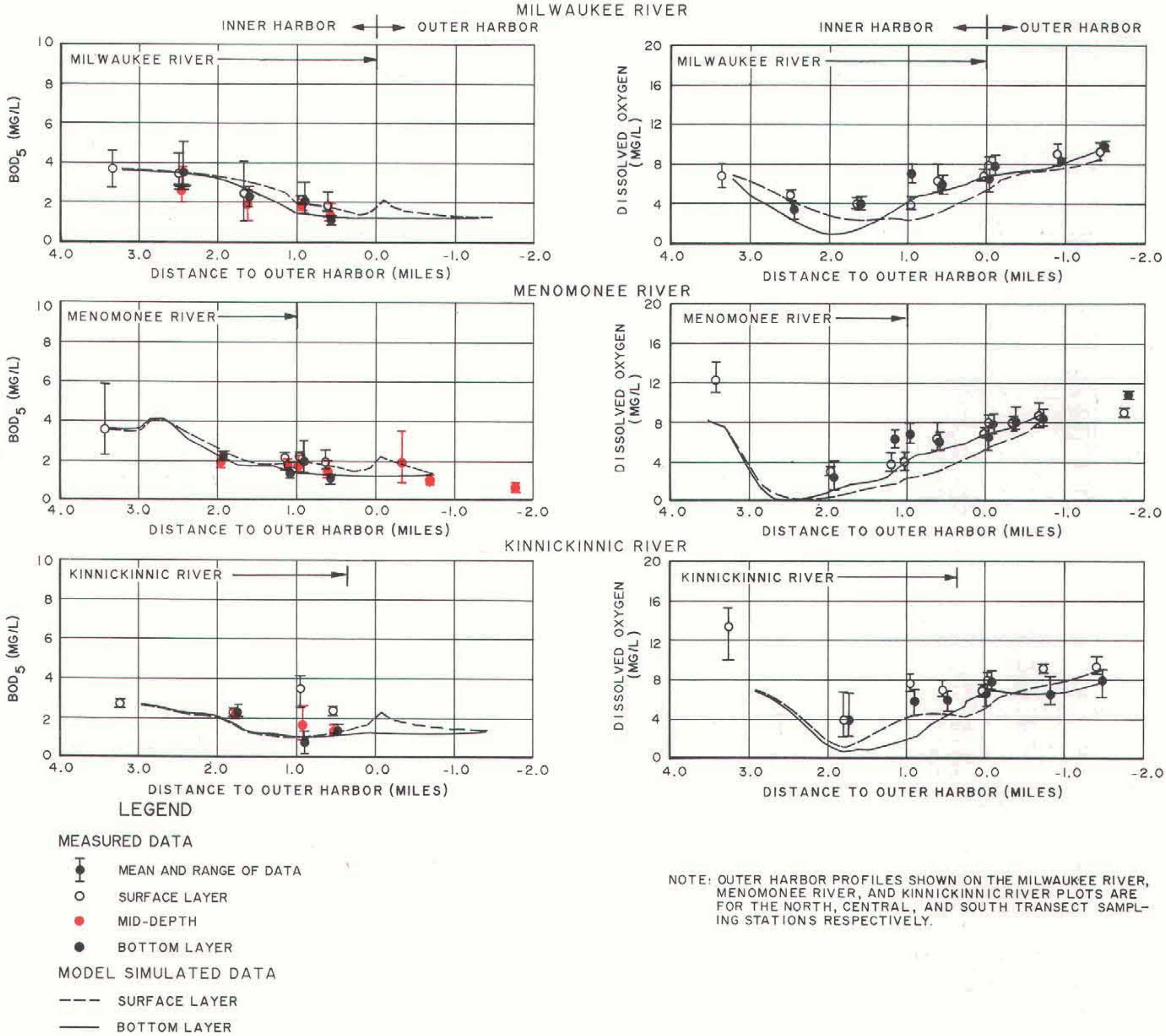


Source: HydroQual, Inc.

demand simulation results include the transfer of dissolved methane from both the sediment interstitial water and the gas phase to the water column as a carbon source. Both computed and observed profiles under all three scenarios regarding the flushing tunnels show a gradual decrease in the downstream direction in the Milwaukee River due to the combined effects of carbonaceous biochemical oxygen demand oxidation and dilution, which more than offset the transfer of dissolved methane to the water column from sediment interstitial water and from the gas phase in the water column. Simulated increases in biochemical oxygen demand in the water column are most apparent in the upper Menomonee River estuary, although the available measured data do not allow a rigorous calibration of the model results in this reach. Data collection in the outer harbor was limited to mid-depth sampling along the central transect; the collected data appear to

Figure 191

CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND AND DISSOLVED OXYGEN CALIBRATION OF THE STEADY-STATE MODEL WITH NO FLUSHING TUNNEL INPUT: SURVEY PERIOD 1



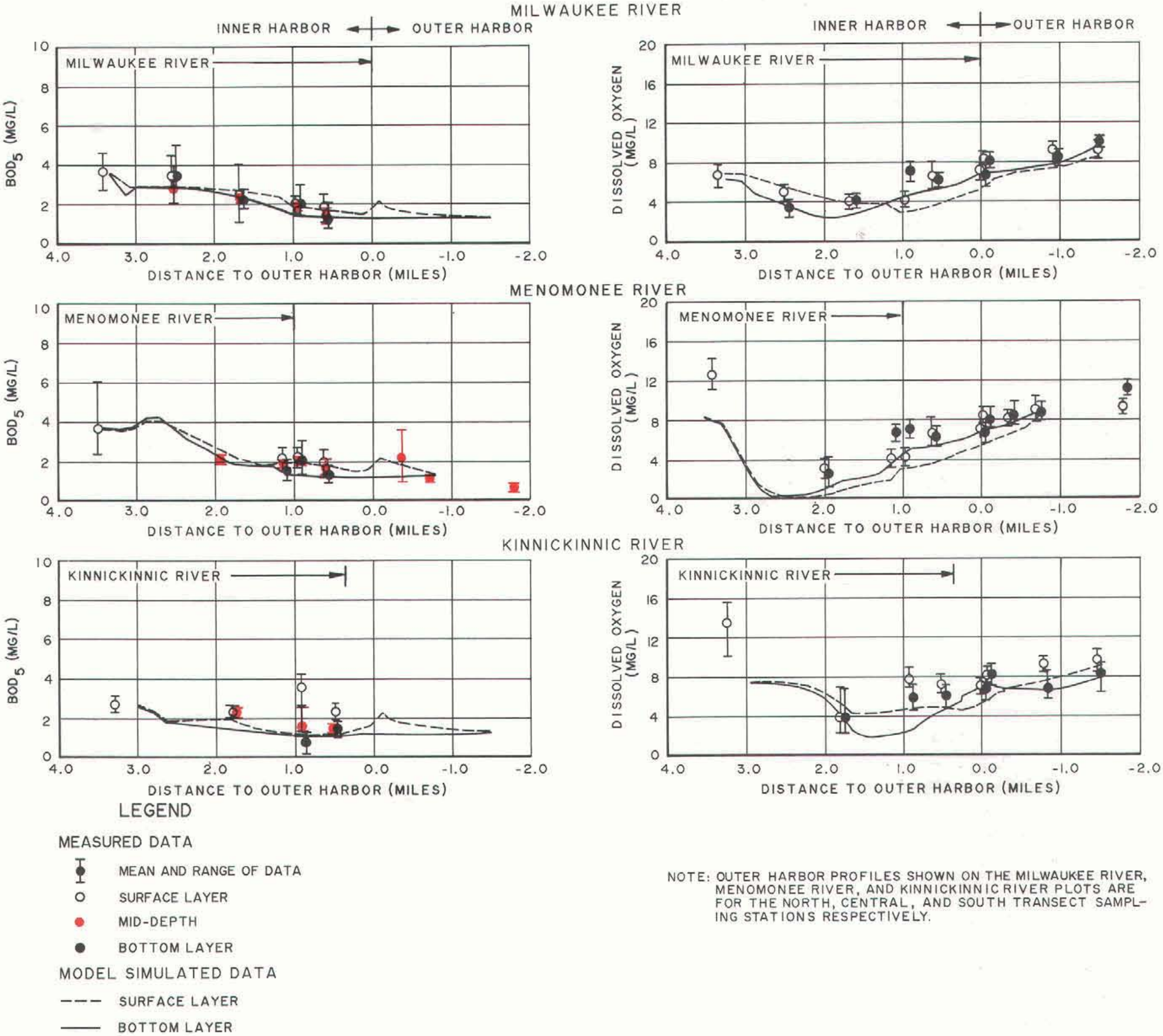
Source: HydroQual, Inc.

be consistent with simulated profiles. The increase in carbonaceous biochemical oxygen demand in the Milwaukee River near River Mile 0.0 is due to the Jones Island wastewater treatment plant effluent.

Dissolved oxygen simulation results, also shown in Figure 191, generally reproduce the measured profiles. The dissolved oxygen concentration entering the Milwaukee River estuary at the North Avenue dam was approximately 7 mg/l, but decreased to less than 3 mg/l at Walnut Street at River Mile 2.25. Simulated and measured dissolved oxygen concentrations in the surface layer were higher than in the bottom layer in this reach, as would normally be expected, owing to photosynthesis and reaeration acting as sources of oxygen in the surface layer and sediment

Figure 192

CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND AND DISSOLVED OXYGEN CALIBRATION OF THE STEADY-STATE MODEL WITH INPUT EQUAL TO THE AVERAGE FLUSHING TUNNEL FLOW: SURVEY PERIOD 1



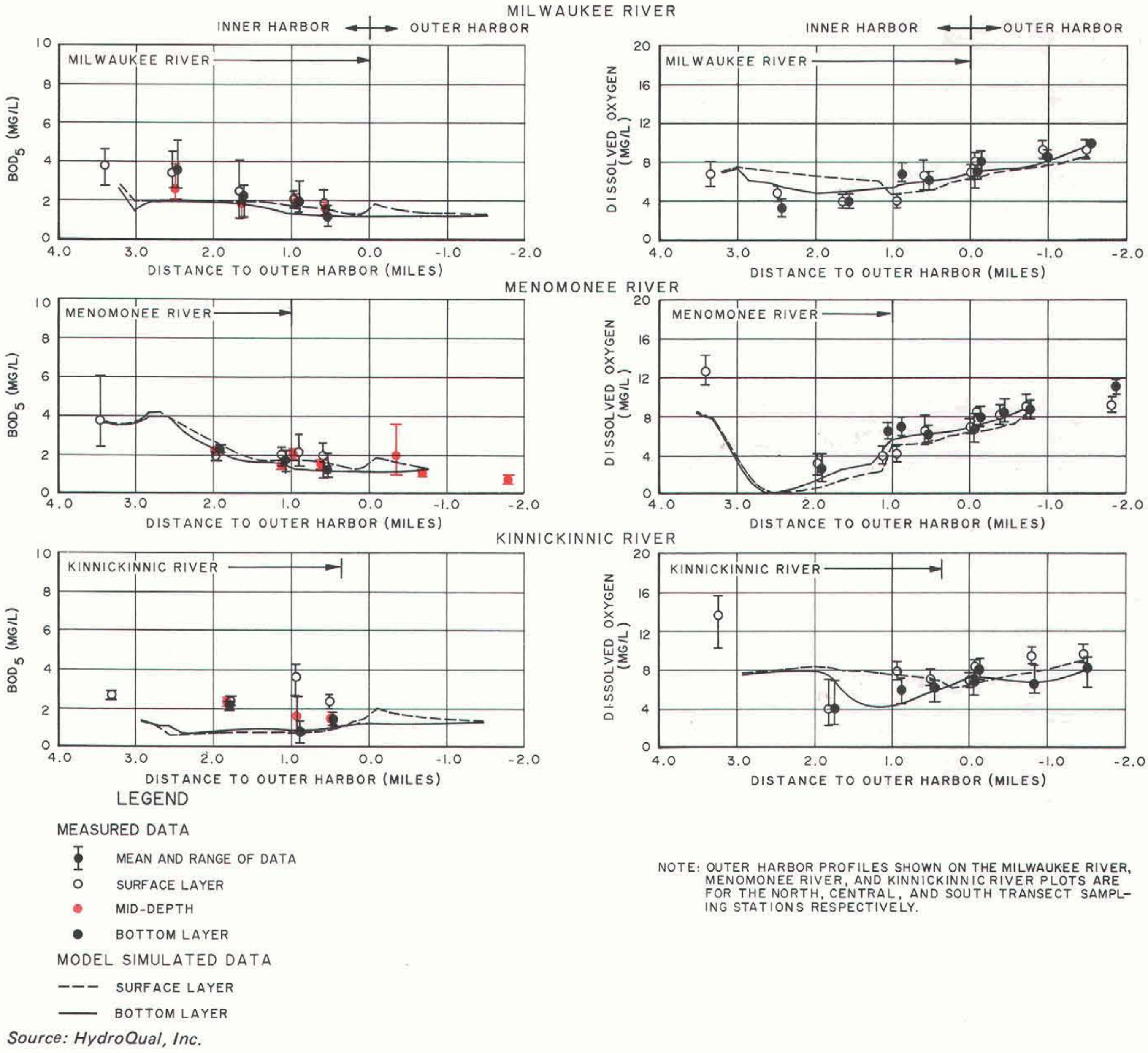
Source: HydroQual, Inc.

oxygen demand as a sink of oxygen in the bottom layer. A distinct inversion occurred near Wells Street, at River Mile 1.41, as a result of the relatively oxygen-enriched water from Lake Michigan intruding into the inner harbor in the bottom layer. This inversion is a typical characteristic of lacustrine estuaries such as the inner harbor. The dissolved oxygen concentration progressively improved in the direction of the outer harbor as a result of the increasing degree of mixing with high-dissolved-oxygen water from the lake, as well as of reaeration.

The dissolved oxygen within the Menomonee River estuary exhibited a rapid decrease, changing from about 12 mg/l to 2 mg/l within less than 1.5 miles. The decrease is attributed both to sediment impacts and, to a lesser degree, oxidation of

Figure 193

CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND AND DISSOLVED OXYGEN CALIBRATION OF THE STEADY-STATE MODEL WITH INPUT EQUAL TO THE CONTINUOUS OPERATION OF THE FLUSHING TUNNEL: SURVEY PERIOD 1



Source: HydroQual, Inc.

carbonaceous biochemical oxygen demand from upstream sources. Downstream of about River Mile 2.0, the dissolved oxygen improved in the direction of the outer harbor.

The Kinnickinnic River dissolved oxygen profile is similar to the Menomonee River profile. The dissolved oxygen decreased from 13 mg/l to about 4 mg/l, and the simulated and measured data are in generally good agreement. In the extreme lower reaches of the Kinnickinnic River, the simulated dissolved oxygen levels were generally higher in the bottom layer than in the surface layer as a result of the density-driven undercurrent of oxygen-enriched lake water. The simulated data for the upper reaches of the Kinnickinnic River estuary tend to be substantially lower than the measured data assuming no flushing tunnel operation, and higher than the measured data assuming full flushing tunnel operation. The simulation assuming the average flushing tunnel operation replicates the measured data well. Since that condition is most appropriate for the upper reaches of the estuary, it was concluded that the model was properly simulating existing conditions.

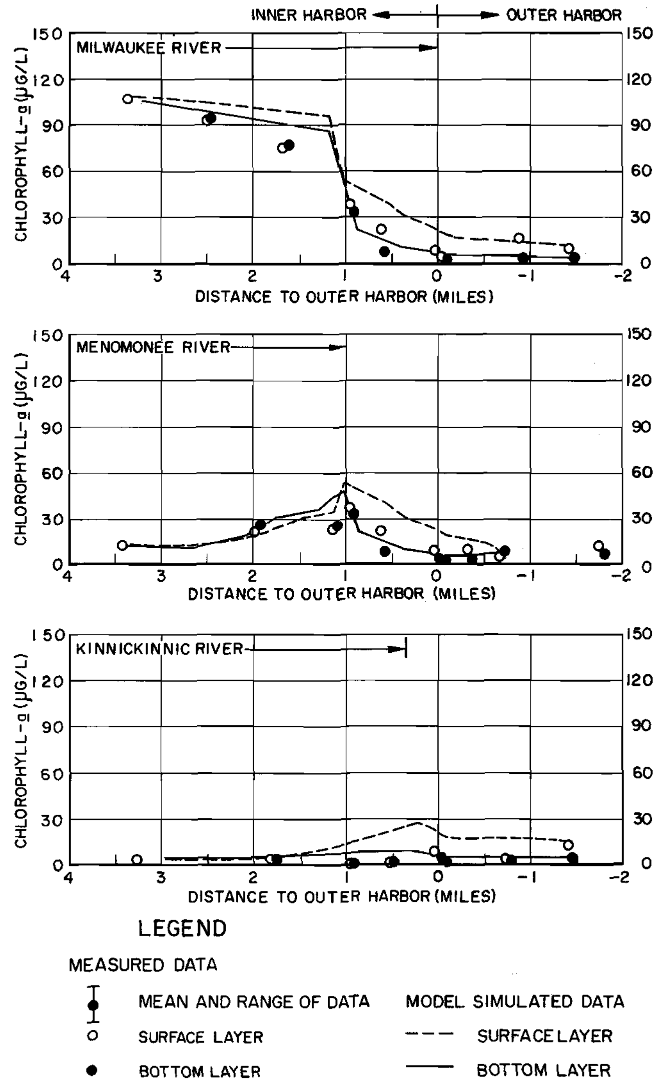
Survey Period 2—July 26, 1982: Survey period 2 represents only a one-day sampling period. On the sampling day and for the preceding 10 days, river flows averaged 288 cubic feet per second (cfs) in the Milwaukee River, 48 cfs in the Menomonee River, and 32 cfs in the Kinnickinnic River. The river flows were therefore about 100 percent higher in the Milwaukee River, about 180 percent higher in the Menomonee River, and about 190 percent higher in the Kinnickinnic River than during survey period 1. Average water temperatures were slightly lower than temperatures during survey period 1. This data set also reflects Milwaukee River chlorophyll-a levels in excess of 100 μg/l, and thus, algae are again a significant factor in the oxygen balance.

The chlorophyll-a calibration for survey period 2 is shown in Figure 194. The model appears to slightly oversimulate surface chlorophyll-a levels in the Milwaukee River estuary and lower reaches of the Kinnickinnic River estuary, and in the Menomonee River estuary. The chlorophyll-a levels simulated in the bottom water layer generally compare well with measured data.

Ammonia nitrogen and nitrate nitrogen calibration results for survey period 2 are shown in Figure 195. The simulated and measured ammonia nitrogen profiles are similar to those described for survey period 1. The model essentially reproduced the spatial variation of ammonia nitrogen throughout most of the inner and outer harbor areas, although the prominent increase in ammonia nitrogen indicated in the Menomonee River estuary was somewhat of an overestimation. The agreement between simulated and measured data in the Kinnickinnic River estuary is relatively good in this survey. These computations highlight the significance of the decomposition of sedimentary material as a source of ammonia nitrogen in the estuary. The nitrification rate is zero and, as shown in Figure 195, a satisfactory fit of the relatively low measured nitrate nitrogen data was obtained. Assignment of a nonzero nitrification rate to convert ammonia to nitrate in order to improve the ammonia nitrogen calibration in the Menomonee River estuary would result in a significant increase in nitrate levels which could not be supported by the measured data. The anaerobic conditions in the Menomonee River estuary during this survey also precluded the possibility that significant nitrification was occurring.

Figure 194

CHLOROPHYLL-a CALIBRATION OF THE STEADY-STATE MODEL: SURVEY PERIOD 2

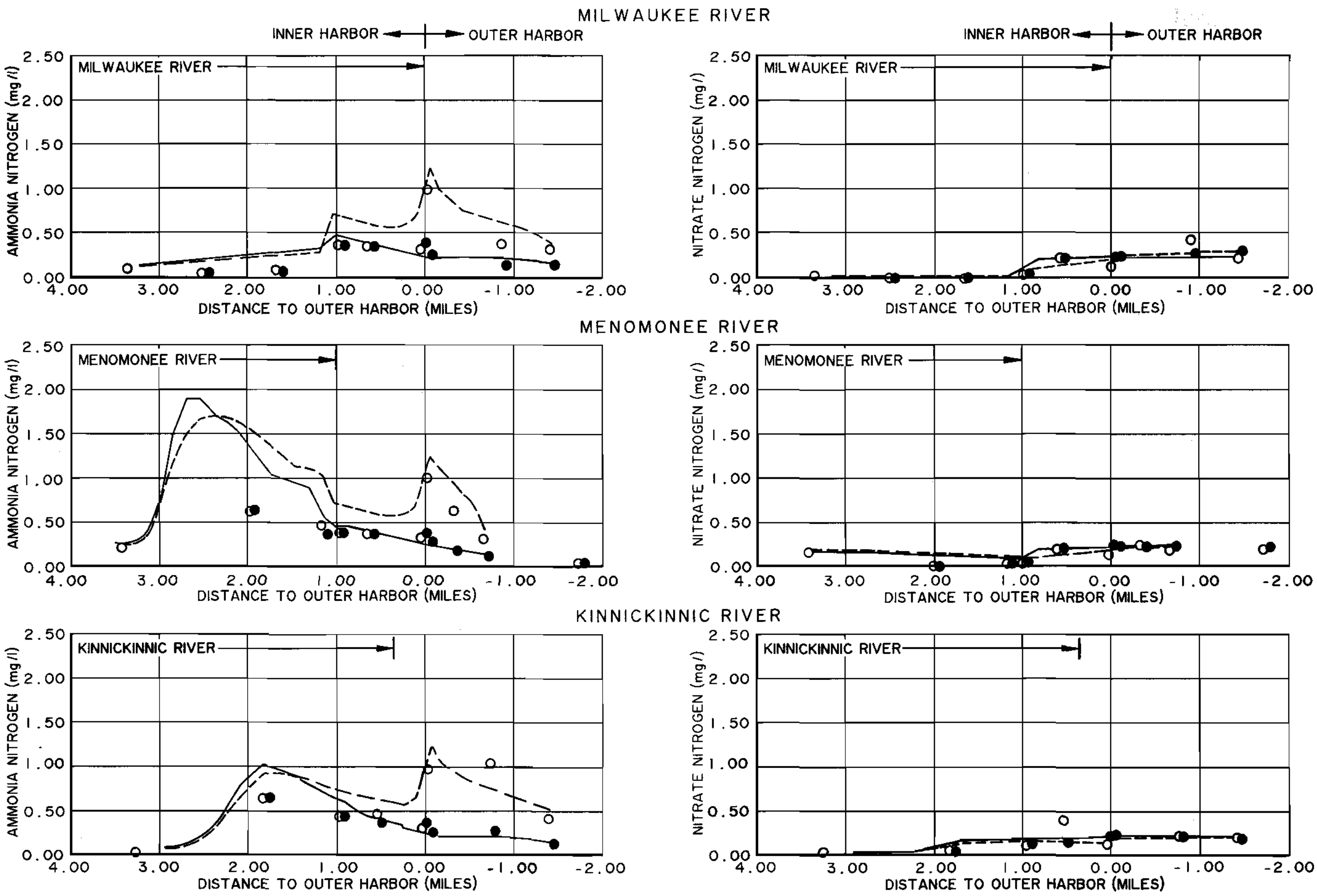


NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc.

Figure 195

AMMONIA NITROGEN AND NITRATE NITROGEN CALIBRATION OF THE STEADY-STATE MODEL: SURVEY PERIOD 2



LEGEND

MEASURED DATA

- MEAN AND RANGE OF DATA
- O SURFACE LAYER
- ● BOTTOM LAYER

MODEL SIMULATED DATA

- --- SURFACE LAYER
- —— BOTTOM LAYER

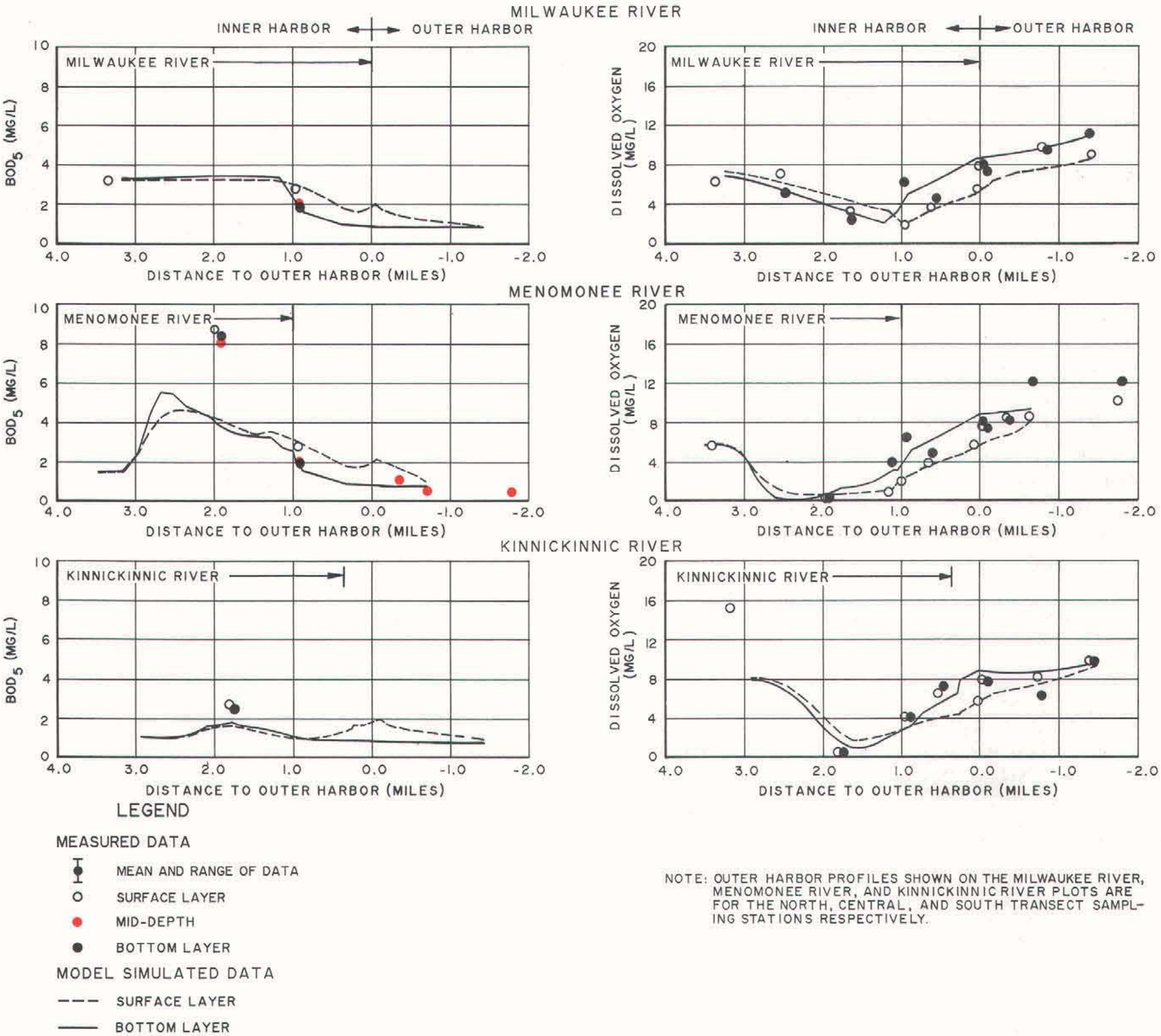
NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc.

Carbonaceous biochemical oxygen demand and dissolved oxygen calibration results are presented in Figure 196. Relatively few biochemical oxygen demand measurements were made during the survey period. The simulated and available measured data, however, show generally good agreement. The vertical gradient of carbonaceous biochemical oxygen demand concentrations evident downstream of Water Street at River Mile 0.94 in the Milwaukee River was properly simulated by the model, and is due to the two-layer transport regime in this reach of the inner harbor. Both the Menomonee River and Kinnickinnic River estuaries exhibited increases in carbonaceous biochemical oxygen demand within the inner harbor. These increases resulted from the flux of unoxidized dissolved methane from the sediment and the transfer of dissolved

Figure 196

CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND AND DISSOLVED OXYGEN CALIBRATION OF THE STEADY-STATE MODEL: SURVEY PERIOD 2



Source: HydroQual, Inc.

methane from the gas phase to the dissolved phase in the water column. This suggests that the diffusive flux of unoxidized material from the sediment increased significantly under nearly anaerobic conditions, as was predicted by the diagenesis model.

Dissolved oxygen calibration results for survey period 2, as also shown in Figure 196, are in generally good agreement with the measured data. The boundary dissolved oxygen concentration in the upstream end of the Milwaukee River estuary at the North Avenue dam of 6.5 mg/l decreased to a minimum level of less than 4 mg/l, and then increased to a concentration of greater than 9 mg/l in the outer harbor. The Menomonee River dissolved oxygen level decreased sharply within the Menomonee River estuary to less than 1 mg/l.

At the Menomonee River sample station near the confluence of the Milwaukee River, as well as within the downstream reaches of the Milwaukee River, both simulated and measured data indicated significant vertical gradients, with the lowest dissolved oxygen levels occurring in the surface layer. These vertical gradients may be attributed to the low dissolved oxygen water from the Menomonee River estuary flowing toward the lake in the surface layer and the relatively high dissolved oxygen water from the lake flowing in the upstream direction in the bottom layer.

The dissolved oxygen profile of the Kinnickinnic River estuary exhibited a rapid decrease in dissolved oxygen levels between the upstream boundary and S. 1st Street, at River Mile 1.94. The model did not simulate the occurrence of nearly anaerobic conditions at S. 1st Street well. The supersaturated dissolved oxygen conditions upstream of the Kinnickinnic River estuary suggest that there is substantial diurnal variability at the boundary, and the measured data at S. 1st Street may reflect a lower boundary dissolved oxygen concentration than was assigned in this simulation.

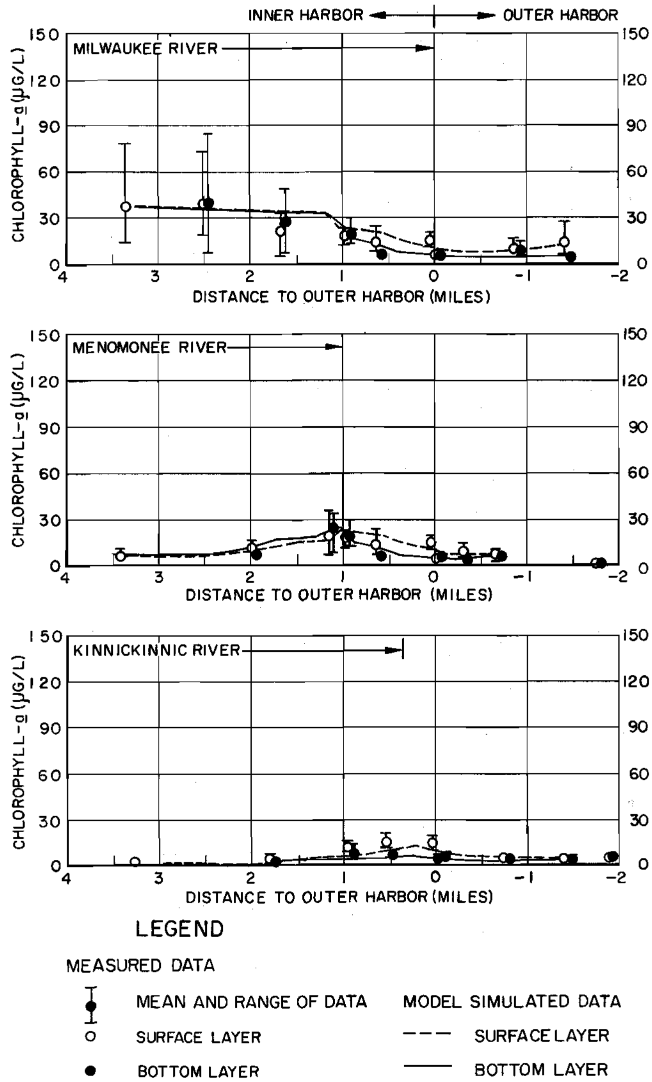
Survey Period 3—September 26 through October 10, 1983: The Milwaukee River flow of 360 cfs during survey period 3 was about 25 percent higher than the flows during survey period 2. The Menomonee River flow of 30 cfs was slightly lower than during survey period 2 but higher than survey period 1. The Kinnickinnic River flow of only 8 cfs was the lowest flow recorded during the four survey periods. Water temperatures in all three rivers were lower than during survey periods 1 and 2. Chlorophyll-a levels were also significantly lower, averaging less than 40 μg/l in the Milwaukee River at the North Avenue dam, and less than 10 μg/l at the upstream boundaries in the Menomonee and Kinnickinnic River estuaries.

The chlorophyll-a calibration for survey period 3 is shown in Figure 197. The calibration shows a good correspondence between simulated and measured data, indicating that the steady-state model satisfactorily represents the relatively low chlorophyll-a levels.

Ammonia nitrogen and nitrate nitrogen simulation results for survey period 3 are shown in Figure 198. Simulated ammonia profiles compared well with measured data in each of the three rivers, as well as within the outer harbor.

Figure 197

CHLOROPHYLL-a CALIBRATION OF THE STEADY-STATE MODEL: SURVEY PERIOD 3



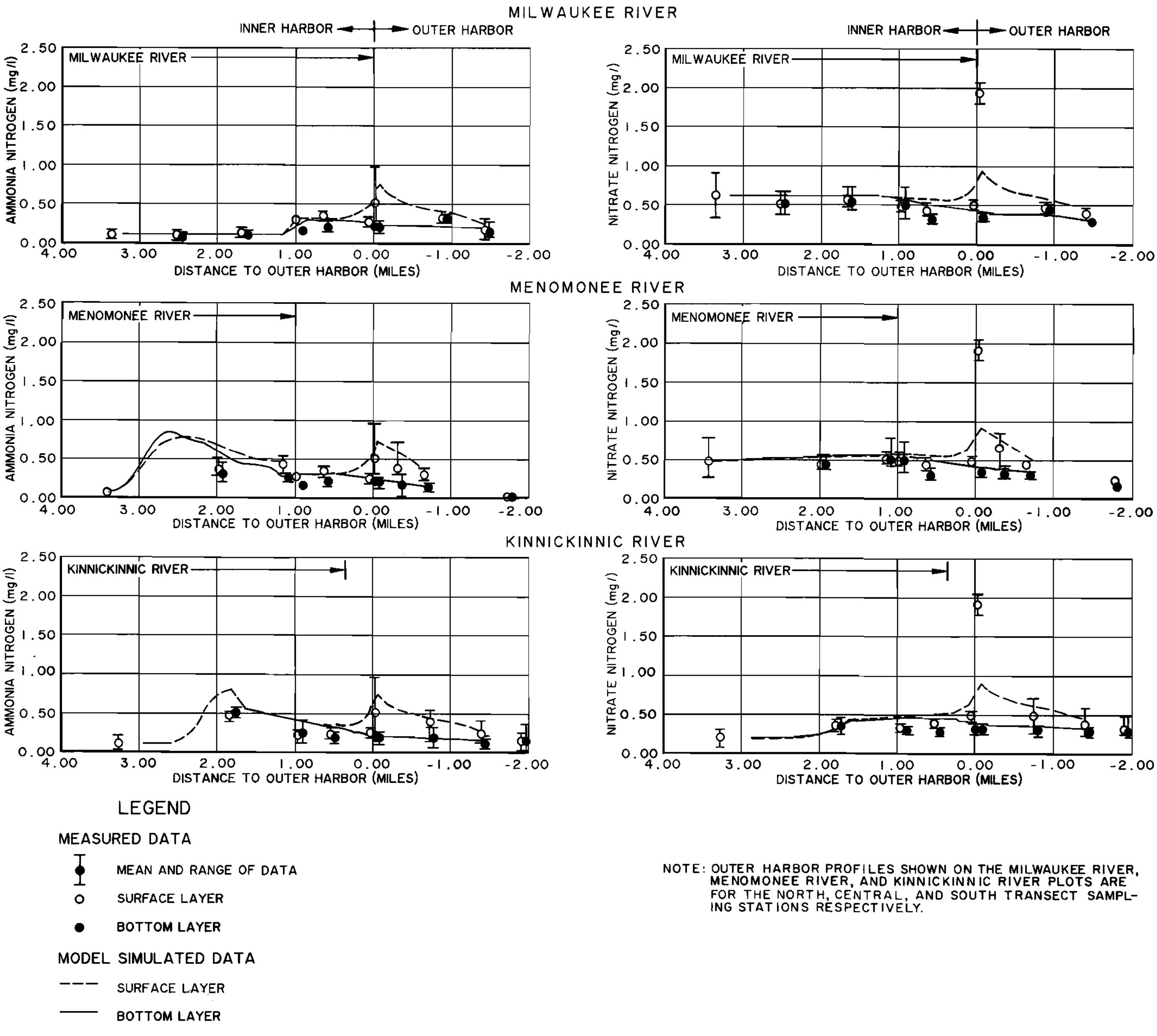
NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc.

Milwaukee River estuary ammonia nitrogen levels remained relatively constant at less than 0.3 mg/l owing to the high river flow rate which minimized the impact of sediment sources of ammonia. The relatively colder water temperatures also decreased sediment decomposition rates and the associated release of ammonia nitrogen. Although the increases in ammonia nitrogen concentration within the Menomonee and Kinnickinnic River

Figure 198

AMMONIA NITROGEN AND NITRATE NITROGEN CALIBRATION OF THE STEADY-STATE MODEL: SURVEY PERIOD 3

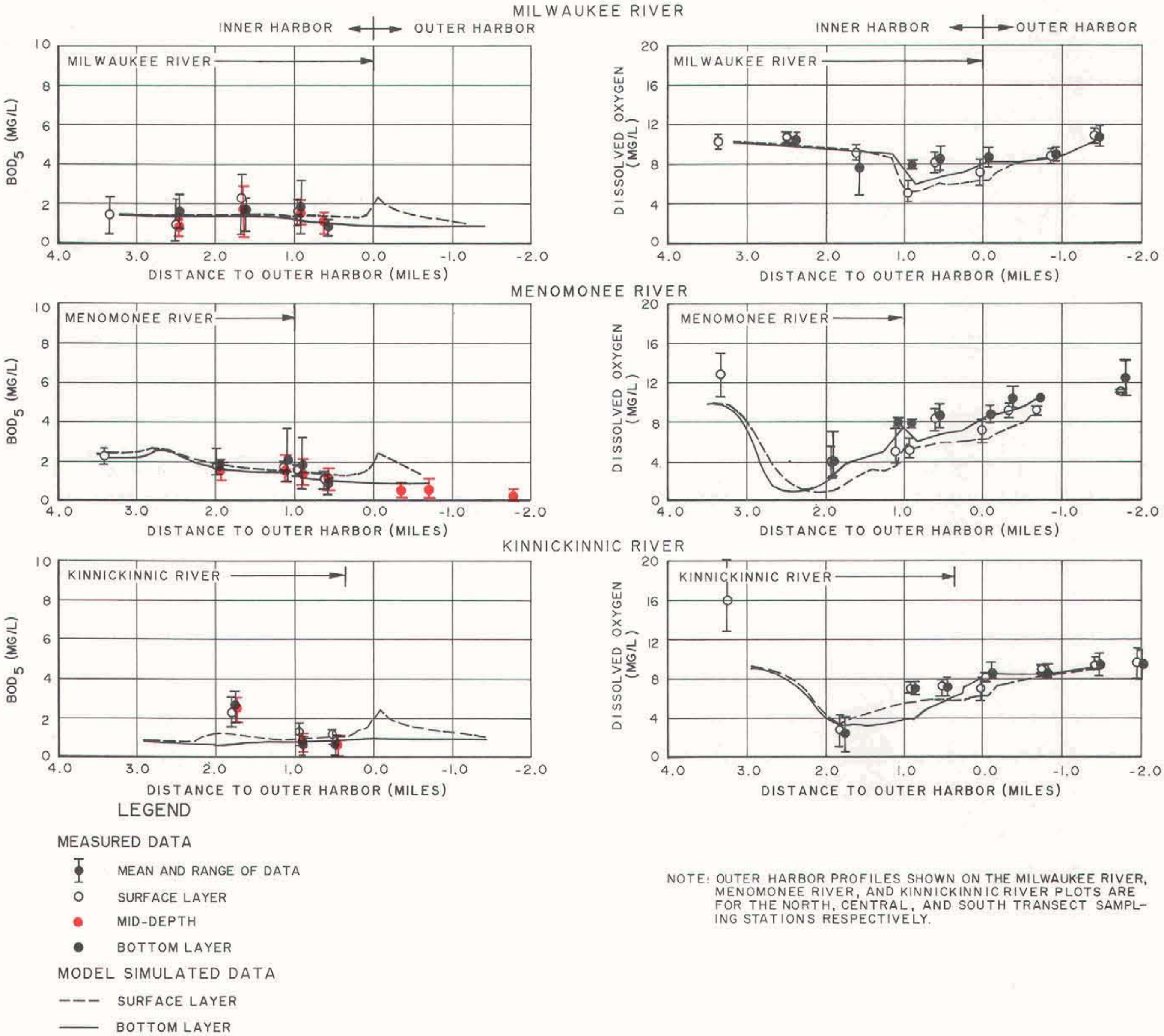


Source: HydroQual, Inc.

estuaries were not as great as in the higher temperature survey periods 1 and 2, they were nevertheless significant. Nitrate nitrogen levels were generally higher throughout the estuary and tributary streams during this survey period than during survey periods 1 and 2. This may be due to low algal levels at this time of year, which would result in less nutrient uptake. The simulated and measured data exhibited good agreement at most estuary stations, with a slight oversimulation of measured concentrations in the most downstream reaches of the Milwaukee River. Figure 198 indicates a single sample at station 0.00 which is substantially higher than the simulated value. This is due to the proximity of the sampling station to the outfall of the Jones Island sewage treatment plant, which likely resulted in sampling prior to complete mixing. The simulation results represent

Figure 199

CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND AND DISSOLVED OXYGEN CALIBRATION OF THE STEADY-STATE MODEL: SURVEY PERIOD 3



Source: HydroQual, Inc.

a nitrification rate of zero. These results further support the assumption that nitrification is not a significant sink of oxygen in the estuary.

Carbonaceous biochemical oxygen demand and dissolved oxygen calibration results for survey period 3 are summarized in Figure 199. Although the data exhibited significant variability over this time period, the simulated and measured profiles are in generally good agreement. The measured and simulated carbonaceous biochemical oxygen demand concentrations were relatively constant in the Milwaukee River estuary and increased slightly in the Menomonee and Kinnickinnic River estuaries. Simulated dissolved oxygen concentrations were in good agreement with measured data at nearly all Milwaukee River stations. The measured dissolved oxygen levels were not at critically low levels. Dissolved oxygen levels in the Menomonee and Kinnickinnic Rivers exhibited a marked decrease downstream of the boundary stations, and the simulated and measured profiles agreed at most stations within the rivers.

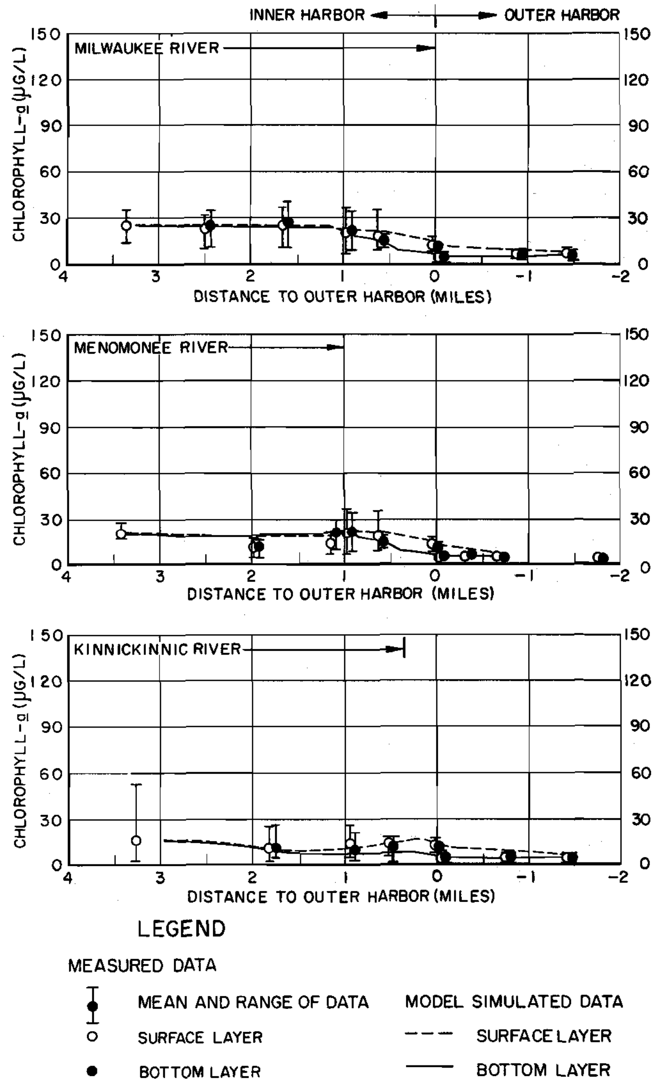
Survey Period 4—April 22 through May 21, 1983: Survey period 4 had the highest river flow and lowest water temperature of any steady-state calibration period, and therefore was the least critical period with respect to dissolved oxygen in the estuary. During survey period 4, the upstream boundary flows were 68 percent higher for the Milwaukee River and over three times higher for the Menomonee and Kinnickinnic Rivers than during survey period 3. The chlorophyll-a concentration in the Milwaukee River at the North Avenue dam of 27 μg/l was the lowest Milwaukee River boundary concentration recorded during the four survey periods, although the upstream boundary chlorophyll-a concentrations of nearly 20 μg/l and 10 μg/l in the Menomonee and Kinnickinnic Rivers, respectively, represent relatively high algal concentrations for those rivers.

The chlorophyll-a calibration of the steady-state water quality model during survey period 4 is shown in Figure 200. The simulated profiles and the measured data were in satisfactory agreement in all three rivers and in the outer harbor.

Figure 201 shows the calibration results for ammonia nitrogen and nitrate nitrogen for survey period 4. The simulated and measured ammonia nitrogen data compare well in the inner harbor, with little increase in ammonia nitrogen concentration evident in the Milwaukee River, and a relatively small increase in the Menomonee and Kinnickinnic Rivers. The model did not oversimulate the ammonia nitrogen concentrations in the upstream areas of the Menomonee and Kinnickinnic River estuaries, as it tended to do in the warm-weather survey periods. Simulated ammonia nitrogen concentrations were somewhat high in the surface layer in the outer harbor, but generally within the range of data. Figure 201 indicates a single sample at station 0.00 which is substantially higher than the simulated value. As already noted, this is due to the proximity of the sampling station to the outfall of the Jones Island sewage treatment plant, which likely resulted in sampling prior to complete mixing. The calibration suggested that a higher degree of vertical mixing than had been assigned in the outer harbor may have been justified during this period. Nitrate nitrogen calibration results also showed a reasonably good comparison between

Figure 200

CHLOROPHYLL-a CALIBRATION OF THE STEADY-STATE MODEL: SURVEY PERIOD 4



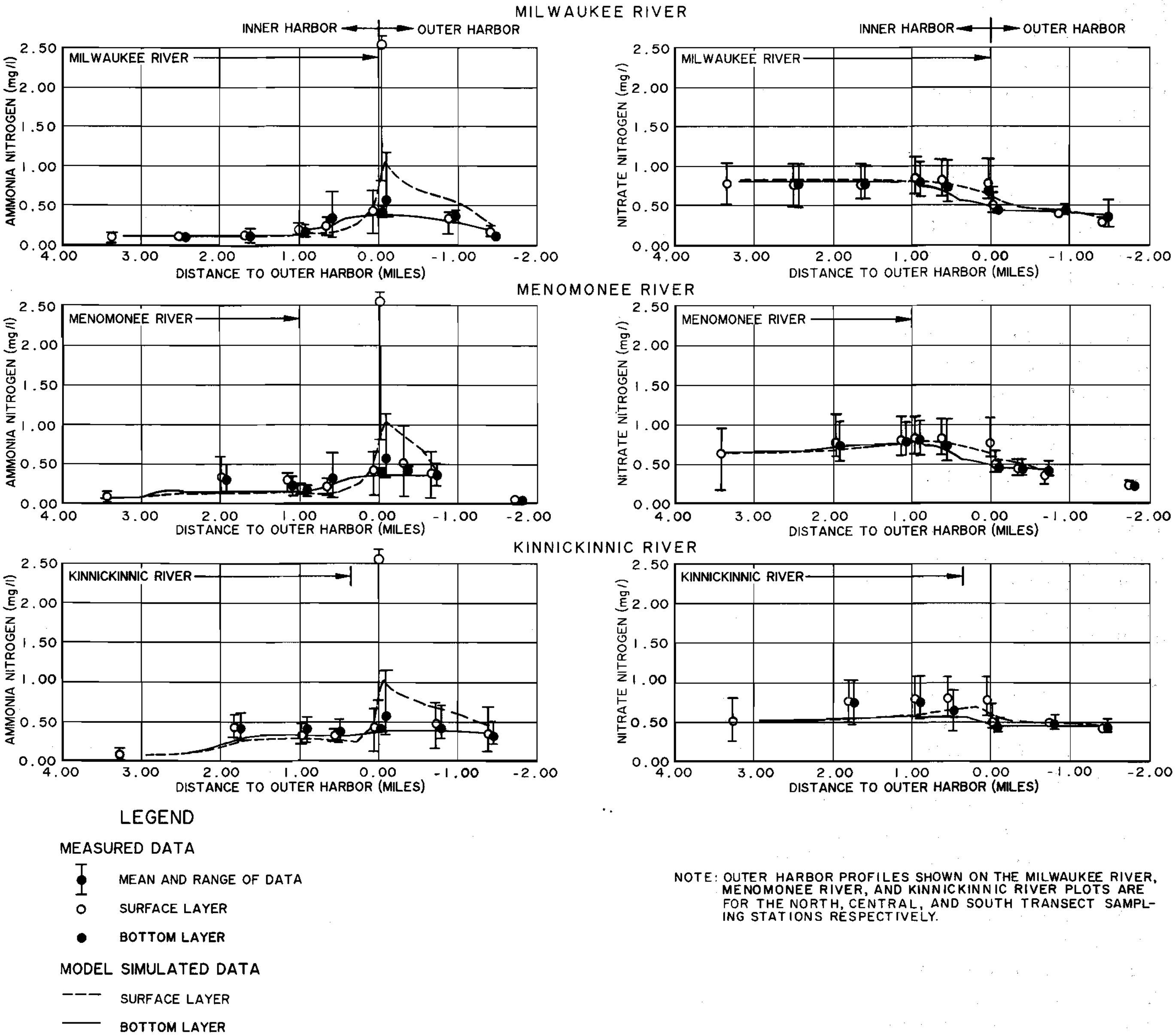
NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc.

simulated and measured data. The measured nitrate nitrogen levels are relatively high, generally ranging from 0.5 and 1.0 mg/l, and the simulated profile compares well with these data, with the exception of a slight undersimulation in the Kinnickinnic River estuary.

Figure 201

AMMONIA NITROGEN AND NITRATE NITROGEN CALIBRATION
OF THE STEADY-STATE MODEL: SURVEY PERIOD 4

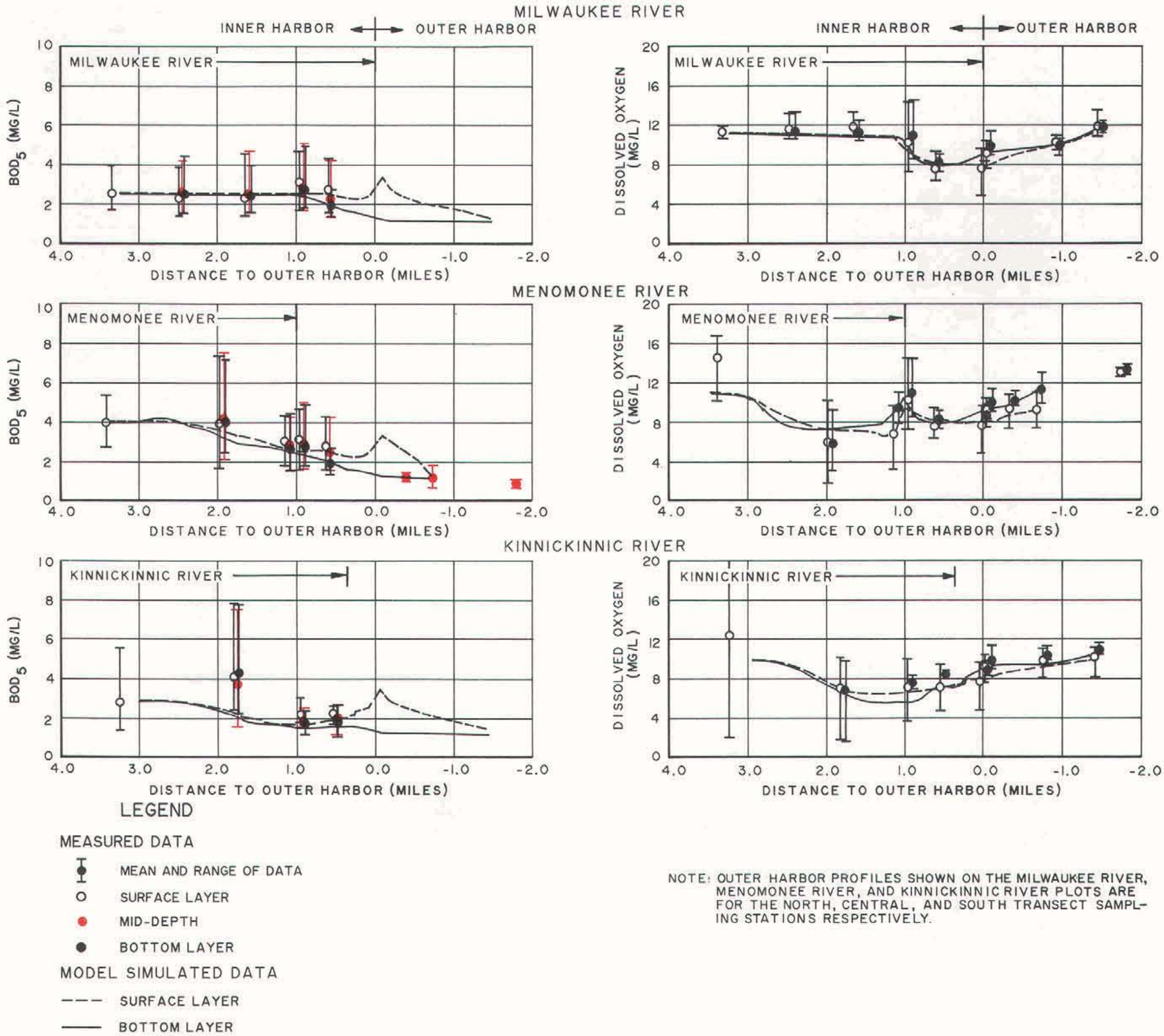


Source: HydroQual, Inc.

Carbonaceous biochemical oxygen demand and dissolved oxygen calibration results of survey period 4 are shown in Figure 202. The range in carbonaceous biochemical oxygen demand concentration was relatively high, but the simulated profiles compared well with the mean surface and bottom data at most estuary stations. Both the simulated and measured data showed little evidence of a significant vertical gradient in the upstream inner harbor reaches, but in the downstream portion of the inner harbor and in the outer harbor a vertical gradient was simulated, with the highest levels being found in the surface water layer. Mean measured dissolved oxygen concentrations were above 5 mg/l at all stations during this survey period, although some variability was apparent, and minimum dissolved oxygen concentrations of less than 5 mg/l did

Figure 202

CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND AND DISSOLVED OXYGEN CALIBRATION OF THE STEADY-STATE MODEL: SURVEY PERIOD 4



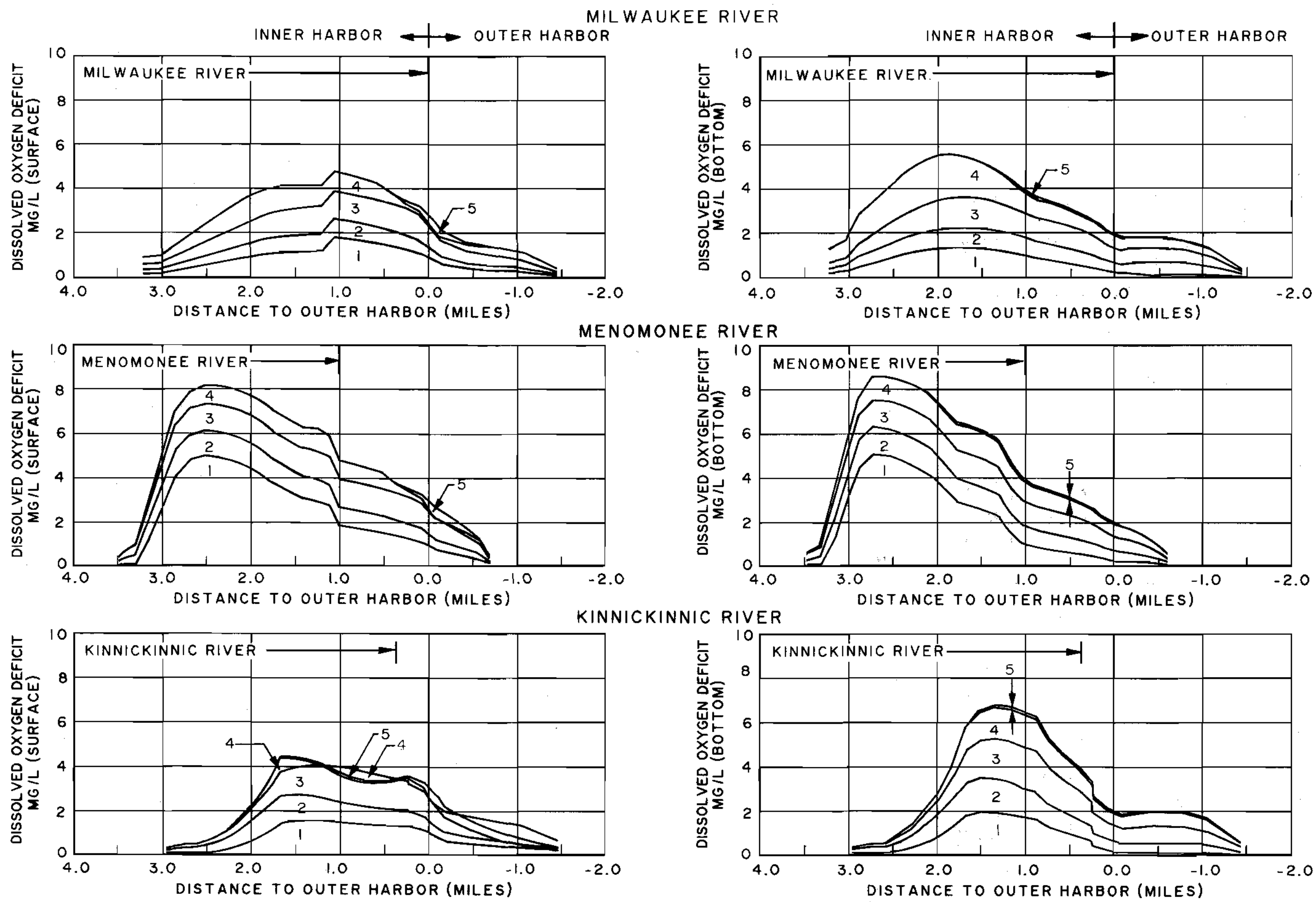
Source: HydroQual, Inc.

occur. The data indicated that vertically well-mixed conditions prevailed throughout the estuary area, and the simulated dissolved oxygen levels were consistent with the measured data.

Components of Dissolved Oxygen Deficit: In assessing the significance of the individual sources and sinks of oxygen, it is useful to consider the components of the dissolved oxygen deficit. These components include sediment oxygen demand; the demand exerted by the oxidation of organic carbon (CBOD) from upstream sources; the demand exerted by the Jones Island sewage treatment plant discharge; and net photosynthesis by algae, as described in this chapter. Spatial profiles of computed components of the dissolved oxygen deficit in the surface and bottom layers are presented in Figures 203, 204, 205, and 206.

Figure 203

COMPONENTS OF DISSOLVED OXYGEN DEFICIT: SURVEY PERIOD 1



LEGEND

1 SEDIMENT FLUX

2 SEDIMENT OXYGEN DEMAND

3 CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND

4 NET PHOTOSYNTHESIS

5 JONES ISLAND SEWAGE TREATMENT PLANT

Source: HydroQual, Inc.

NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

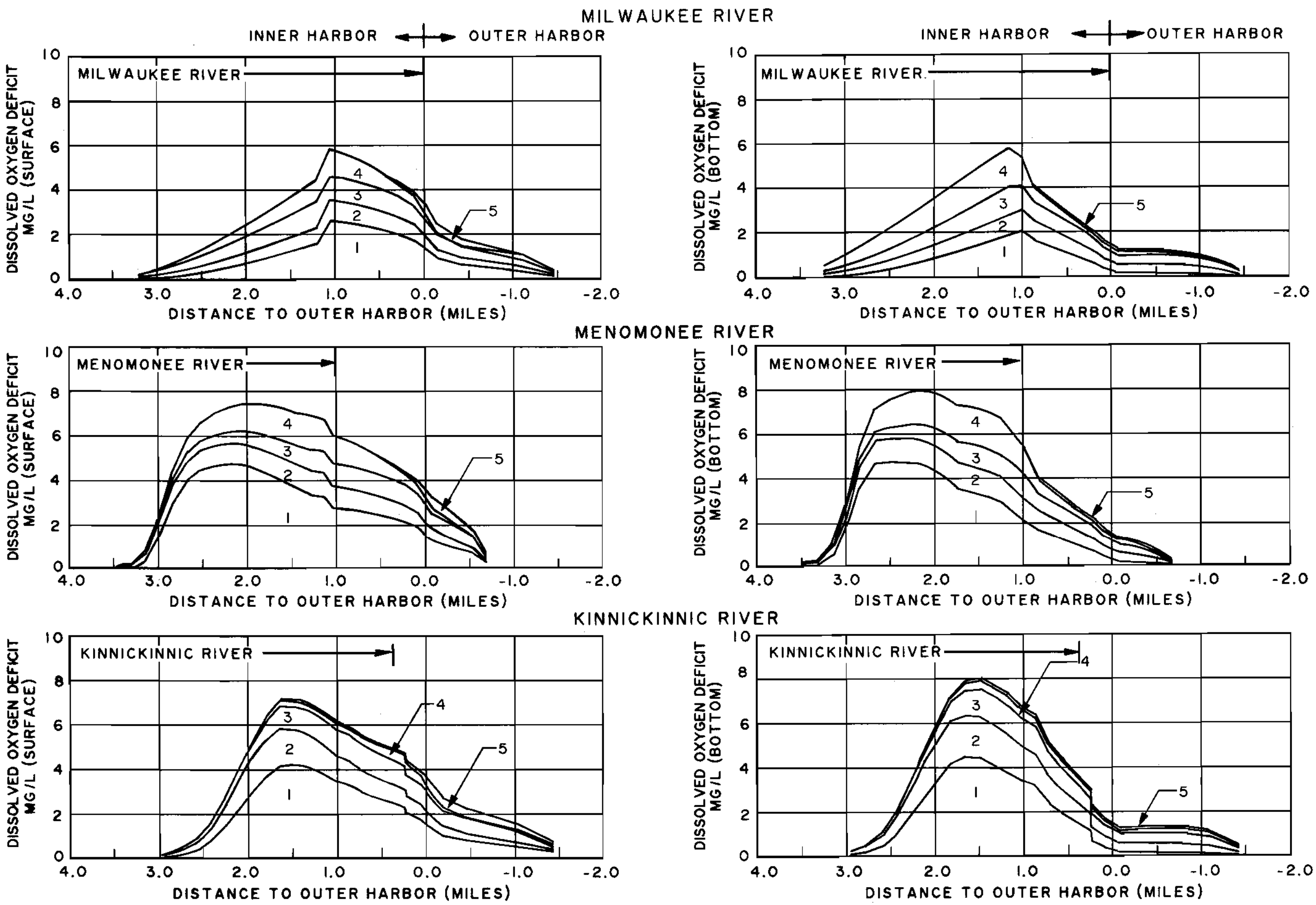
D. O. DEFICIT DATA SHOWN ARE FOR CONDITIONS ASSUMING FLUSHING TUNNEL INPUTS EQUAL TO AVERAGE FLUSHING TUNNEL INPUT OVER THE SURVEY PERIOD. DEFICITS ARE SIMILAR FOR SIMULATIONS ASSUMING NO FLUSHING TUNNEL OPERATION INPUT OVER THE SURVEY PERIOD.

The components of the dissolved oxygen deficit for survey period 1 are shown in Figure 203. The dissolved oxygen deficit associated with sediment processes accounts for about one-third of the total deficit in the Milwaukee and Kinnickinnic Rivers and over one-half of the deficit in the Menomonee River. This deficit may be attributed primarily to the oxidation in the water column of the dissolved organic carbon flux from the sediment. The deficit due to the Jones Island sewage treatment plant discharge is relatively insignificant in both the inner and outer harbors.

The dissolved oxygen deficit due to CBOD from upstream of the estuary is significant, accounting for 1.0 to 1.5 mg/l of the deficit in the Milwaukee and Kinnickinnic Rivers and for as much as 2.0 mg/l of the deficit in the Menomonee River. The deficit resulting from net photosynthesis by algae is clearly a sink of dissolved oxygen in the Milwaukee and Menomonee Rivers. The net photosynthetic demand is considerable in the Milwaukee River owing to the high chlorophyll-a levels and light-limiting conditions. Figure 203 also shows that the algae are sometimes a net source of

Figure 204

COMPONENTS OF DISSOLVED OXYGEN DEFICIT: SURVEY PERIOD 2



LEGEND

1 SEDIMENT FLUX

2 SEDIMENT OXYGEN DEMAND

3 CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND

4 NET PHOTOSYNTHESIS

5 JONES ISLAND SEWAGE TREATMENT PLANT

Source: HydroQual, Inc.

NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

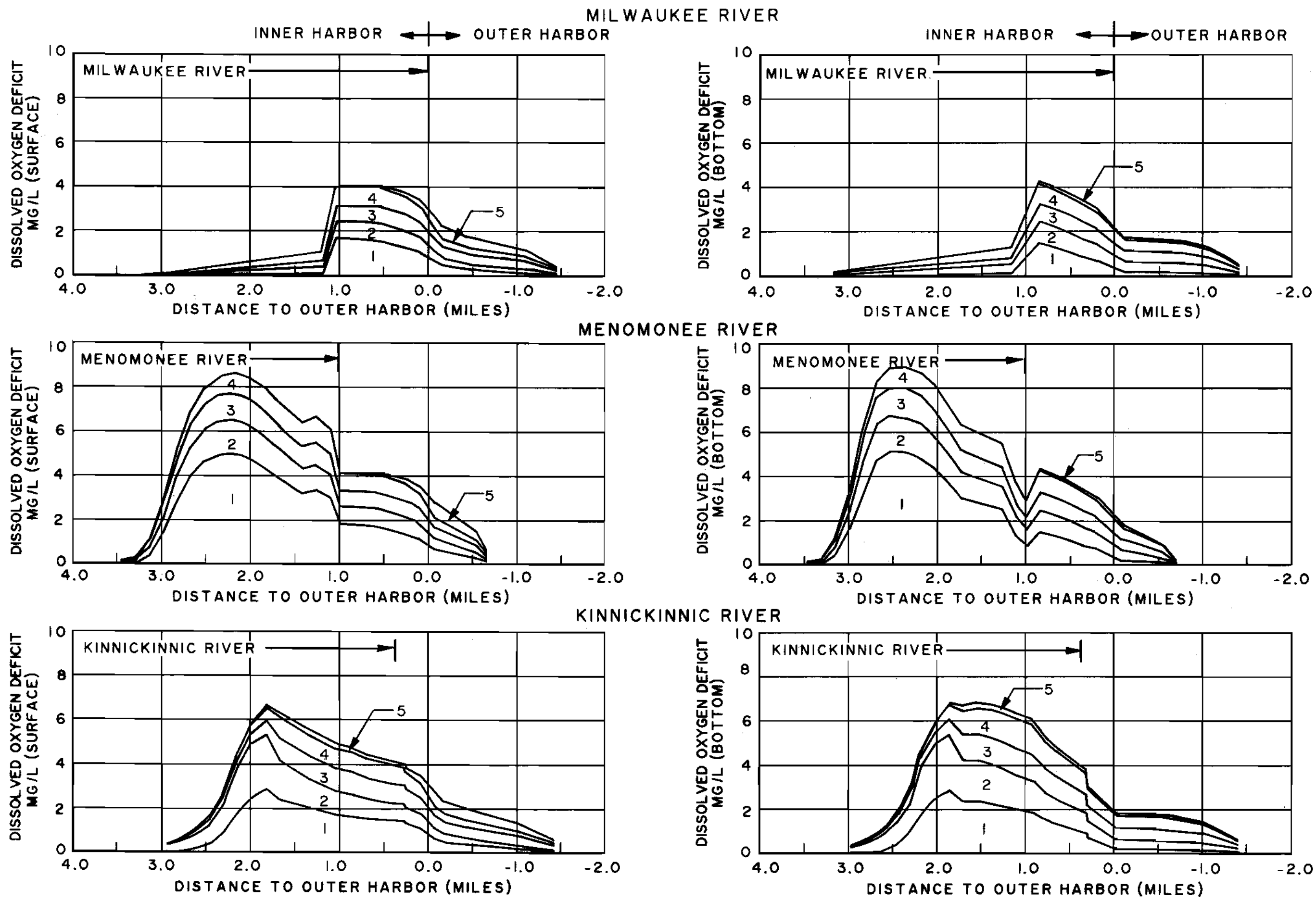
oxygen in the Kinnickinnic River and in the outer harbor, as indicated by the crossover of the lines delineating the deficit due to boundary CBOD and net photosynthesis. These areas are characterized by lower light extinction coefficients and hence favor the net production of oxygen.

The spatial profile of the components of deficit in the bottom layer is similar to that in the surface layer for survey period 1, except the algal component is consistently a net sink of oxygen throughout the study area. This is due to the absence of photosynthesis in the bottom layer. The deficit due to net photosynthesis in the bottom layer is as high as 3 mg/l in the Milwaukee River, and as high as 1 to 2 mg/l in the Menomonee and Kinnickinnic Rivers. The components are similar in magnitude to the surface layer deficits.

The components of deficit for survey period 2 are presented in Figure 204. The magnitude of the deficit in the Milwaukee River is significantly lower in comparison to survey period 1, especially upstream of the Menomonee River, even though

Figure 205

COMPONENTS OF DISSOLVED OXYGEN DEFICIT: SURVEY PERIOD 3



LEGEND

1 SEDIMENT FLUX

2 SEDIMENT OXYGEN DEMAND

3 CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND

4 NET PHOTOSYNTHESIS

5 JONES ISLAND SEWAGE TREATMENT PLANT

NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

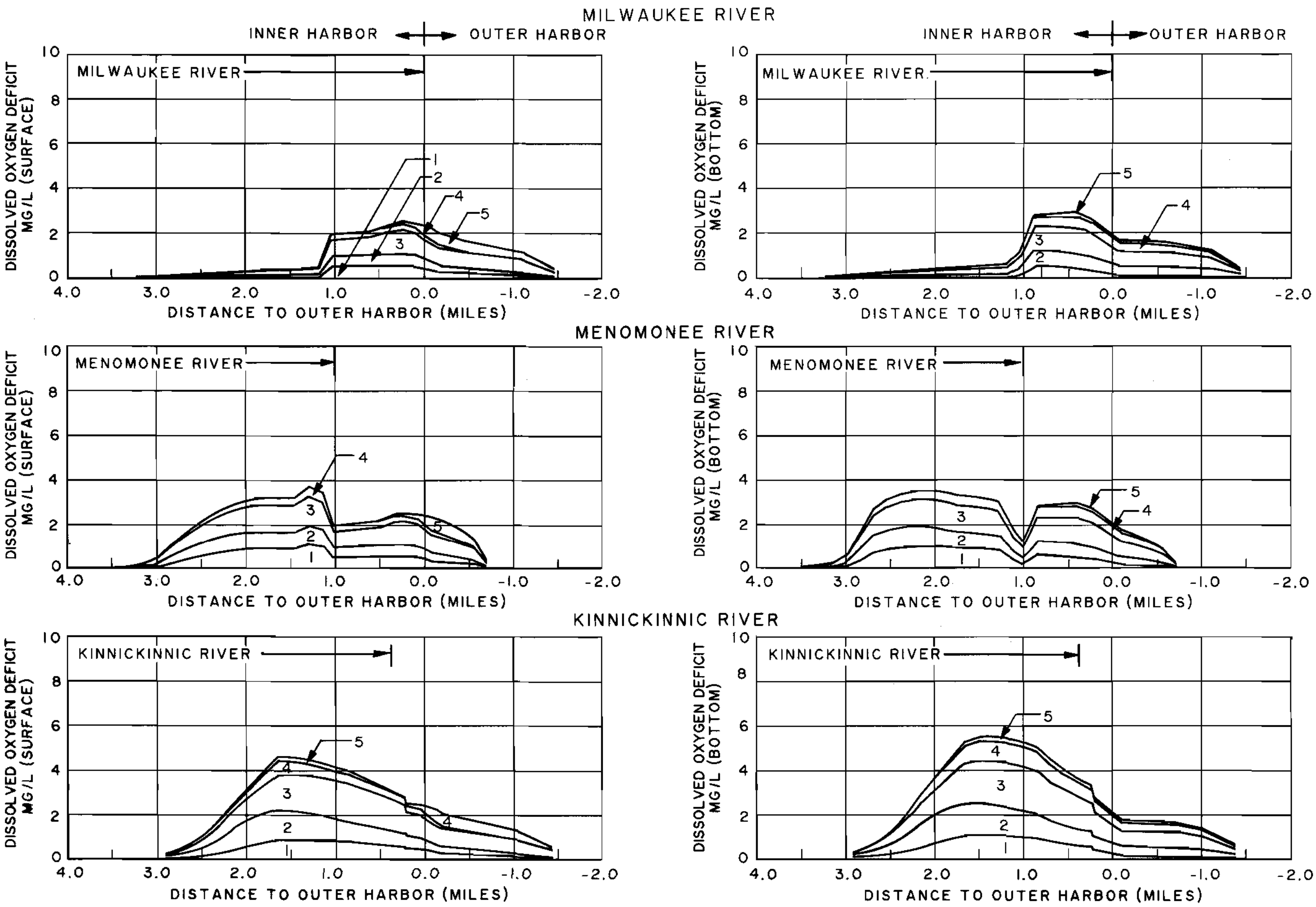
Source: HydroQual, Inc.

comparable sources and sinks of dissolved oxygen were assumed. This difference may be explained by the increased upstream flow at the North Avenue dam which shortens the travel time and increases the distance to achieve spatial steady state with respect to the dissolved oxygen deficit. In other regions of the estuary, the deficit is very similar to that in survey period 1 except for a slight decrease in magnitude.

Spatial profiles of computed components of deficit for survey period 3 are presented in Figure 205. The shape of the graphs of the components of deficit profiles resembles the shape of the graphs for survey period 2. The magnitude of the component deficits is lower in the Milwaukee River relative to survey period 2 as a result of the increased flow rate, and is generally lower in both the Milwaukee and Menomonee Rivers owing to the lower temperature during this survey period. The deficits due to the boundary CBOD and algae are approximately 50 percent of those of the preceding survey period, reflecting a greater than 50 percent

Figure 206

COMPONENTS OF DISSOLVED OXYGEN DEFICIT: SURVEY PERIOD 4



LEGEND

1 SEDIMENT FLUX

2 SEDIMENT OXYGEN DEMAND

3 CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND

4 NET PHOTOSYNTHESIS

5 JONES ISLAND SEWAGE TREATMENT PLANT

NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc.

decrease in CBOD at the North Avenue dam and a 65 percent reduction in chlorophyll-a. The decrease in total deficit in the Menomonee River is due to a reduction associated with the oxidation of sediment carbon and net photosynthesis. The components of the Kinnickinnic River dissolved oxygen deficit are similar in magnitude to those of the September-October survey period.

A spatial profile of the computed components of the dissolved oxygen deficit for the surface and bottom layers for survey period 4 is presented in Figure 206. The magnitude of component deficits is further reduced in the Milwaukee River, the Menomonee River, and the outer harbor, with no change in the Kinnickinnic River, while the shape of the deficit profile remains the same.

Time-Variable Water Quality Simulation

Steady-state simulation models provide time-averaged values which are adequate for most water quality management planning needs. Steady-state models, however, do not fully account for actual conditions when large transient changes in flow or in inflow water quality occur, such as during combined sewer overflow events. Since steady-state simulation integrates time-variable phenomena, extreme conditions may be masked by the simulation. When extreme values may be expected to be significantly different from time-averaged values, additional simulation modeling provided by a more complete analytical framework becomes desirable.

Detailed time-variable simulations of two phenomena were conducted under the Milwaukee Harbor estuary study. The effects of combined sewer overflows were simulated to determine if acute dissolved oxygen conditions occur during such overflows, as reported in past studies of the inner harbor. Diurnal dissolved oxygen variation was simulated in an effort to understand the erratic dissolved oxygen record provided by the continuous monitoring station located on the Milwaukee River at St. Paul Avenue.

The following sections of this chapter describe the development of the time-variable water quality simulation model, and its subsequent use to simulate two combined sewer overflow events, and the diurnal dissolved oxygen trends at St. Paul Avenue.

Time-Variable Model: The time-variable water quality simulation model of the Milwaukee inner harbor may have been the first successful union of a state-of-the-art hydrodynamic simulation model with a water quality simulation model. The effort required to produce this union was deemed necessary in order to adequately simulate the response of the inner harbor to relatively large and rapid changes in inflow and in inflow water quality. Such rapid changes can be caused by combined sewer overflow events, significant seiches on Lake Michigan, and diurnal algal production.

The mathematical equations used to simulate currents under such changing conditions were long and firmly established in engineering practice, the phenomena concerned being governed by laws of the conservation of mass, heat, and momentum. The momentum equations include the effects of river flows; flushing tunnel flows; condenser cooling water withdrawals and discharges by the Wisconsin Electric Power Company Valley power plant on the Menomonee River estuary; and inflow from Lake Michigan. Water depths in, and the channel geometry of, the inner harbor had to be adequately delineated for satisfactory application of the momentum equations in the simulation model.

The hydrodynamic submodel of the time-variable water quality model included the effects of the circulation induced by the interaction of both barotropic and baroclinic pressure gradients. The barotropic pressure gradient is due to the mean slope of the water surface, and is independent of depth. The baroclinic pressure gradient is caused by longitudinal differences in water temperature, and increases with depth. The interaction of these pressures, together with the turbulence caused by Lake Michigan seiches, caused the vertical variations in velocity and temperature observed in the inner harbor. The condenser cooling water intakes and discharges of the Valley power plant had a large effect upon these vertical variations.

Equations and Boundary Conditions: The equations for inner harbor dynamics were simplified by eliminating the lateral direction component. This was done on the assumption that lateral mixing was virtually complete in the relatively narrow channel system, and that only longitudinal and vertical differences were important. The relevant equations are those for continuity, momentum, pressure, temperature conservation and boundary conditions, unreactive solute tracer conservation and boundary conditions, vertical mixing, turbulent transport, free surface and bottom boundary conditions, and lake level boundary conditions. A conservative tracer, specific conductance, measured in the extensive field sampling program conducted under the study, was used to check calibration of the hydrodynamic submodel.

The continuity equation is:

$$\frac{\partial (BU)}{\partial \mathcal{L}} + B\,\frac{\partial W}{\partial z} = 0$$

where: B is river width,
U is the horizontal velocity,
W is the vertical velocity,
$\mathcal{L}$ is the system of rectangular coordinates in the longitudinal direction,
z is the vertical direction increasing upward.

The momentum equations are: for the horizontal component,

$$\frac{\partial U}{\partial t} + \frac{1}{B}\frac{\partial}{\partial \pounds}(U^2 b) + \frac{\partial}{\partial z}(WU) - \frac{1}{p_o}\frac{\partial P}{\partial \pounds} + \frac{\partial}{\partial z}\left(K_M \frac{\partial u}{\partial z}\right) = 0$$

and for the vertical hydrostatic component,

$$pg = \frac{\partial P}{\partial z}$$

where: p_o is the reference density,
p is the in-situ density,
g is the acceleration of gravity,
P is the pressure, and
K_M is the vertical eddy diffusiveness.

The pressure at any depth z is:

$$p(\pounds,z,t) = gp_o\ E + g\int_z^0 p(\pounds,z,t,)dz'$$

where: E is the water level, and the contribution of atmospheric pressure to total pressure is neglected.

The conversion equation for temperature is:

$$\frac{\partial \theta}{\partial t} + \frac{1}{B}\frac{\partial}{\partial \pounds}(BU\theta) + \frac{\partial}{\partial z}(W\theta) = \frac{\partial}{\partial z}\left(K_H \frac{\partial \theta}{\partial z}\right)$$

where: K_H is the vertical turbulence mixing coefficient and θ is the temperature.

The equation for a conservative solute tracer is:

$$\frac{\partial S}{\partial t} + \frac{1}{B}\frac{\partial}{\partial \pounds}(BUS) + \frac{\partial}{\partial z}(WS) = \frac{\partial}{\partial z}\left(K_H \frac{\partial S}{\partial z}\right)$$

where: S is the tracer concentration.

When the direction of flow was from the outer to the inner harbor, temperature and tracer boundary conditions were taken from the data collected at the mouth of the Milwaukee River under the study. When flow was toward the outer harbor, temperature and tracer concentrations were calculated using:

$$\frac{\partial(\theta,S)}{\partial t} + U\frac{\partial(\theta,S)}{\partial \pounds} = 0\ .$$

River and flushing tunnel inflow temperature and conductivity data and power plant effluent temperature data were specified along with the respective flow rates.

The river and flushing tunnel flow temperature and conductivity data were incorporated using:

$$C_n = \frac{Q_r C_r + Q_f C_f}{Q_r + Q_f}$$

where: Q_r and Q_f are the river and flushing tunnel flow rates, respectively, expressed in cfs; and C_r and C_f are the respective temperatures or conductivities expressed in mg/l.

The vertical mixing coefficients, K_M and K_H, were calculated according to Mellor and Yamada:[17]

$$K_M = S_M lq \text{ and } K_H = S_H lq$$

where: l is the turbulence length scale expressed in meters; and
$q^2/2$ is the turbulence kinetic energy expressed in $meters^2/sec^2$.

The boundary conditions at the free water surface, $z = E(\xi, t)$, are:

$$p_o K_M \frac{\partial U}{\partial z} = \tau_o ,$$

$$p_o K_H \left(\frac{\partial \theta}{\partial z}, \frac{\partial S}{\partial z}\right) = (0, 0) ,$$

$$q^2 = \alpha \left| \tau_o \right| ,$$

$$q^2 l = 0 \text{ , and}$$

$$W = \frac{\partial E}{\partial t} + U' \frac{\partial E}{\partial \mathcal{L}}$$

where: $\alpha = 6.50$ is a constant from the turbulence closure formulation,
τ_o is the wind stress in the longitudinal ($\mathcal{L}$) direction, and
U' is the surface velocity.

The boundary conditions at the bottom are:

$$p_o K_h \left(\frac{\partial \theta}{\partial z}, \frac{\partial S}{\partial z}\right) = (0,0) ,$$

$$q^2 = \alpha \left| \tau_B \right| \text{ , and}$$

$$q^2 l = 0$$

where: τ_B is the bottom frictional stress at $z = H(\mathcal{L})$.

The boundary condition for the vertical velocity, W, is:

$$W = -U'' \frac{\partial H}{\partial \mathcal{L}}$$

where: U'' is the velocity at the bottom just above the laminar boundary layer.

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[17] *G. L. Mellor and T. Yamada, "Development of a Turbulence Closure Model for Geophysical Fluid Problems," Review of Geophysics and Space Physics, Vol. 20, 1982, pp. 851-875.*

Thus, a no-slip condition at the very bottom is satisfied using:

$$U \approx \frac{\tau_B}{p_o} \frac{1}{ku_*} \ln \left(\frac{H + z}{z_o}\right) \text{ as } z \rightarrow -H$$

where: u_* is the bottom friction velocity, $u_* \approx (\tau_B / p_o)^{1/2}$,
$k = 0.40$ is von Karman's constant, and
z_o is the local bottom roughness = 1 cm.

At the mouth of the Milwaukee River, lake water-level records collected by the U. S. Geological Survey were subjected to harmonic analysis as described in Chapter V of this volume.

The lake level boundary condition, based partially on the results of the harmonic analysis, was incorporated into the hydrodynamic submodel as:

$$E(t) = E_o(t) + E_1 \sin(\Omega_1, t) + E_2 \sin(\Omega_2 t)$$

where: $\Omega_1 = 2\pi/T_1, \Omega_2 = 2\pi/T_2$, where $T_1 = 1$ hour and $T_2 = 2$ hours,
E_o is a daily mean lake level,
E_1 and E_2 are the amplitudes of the Ω_1, and Ω_2 harmonic, respectively, and
t is elapsed time.

Solution Technique: The hydrodynamic submodel equations and boundary conditions are used together in finite difference form and stepped forward in time. The finite difference scheme is explicit in the advective transport terms and implicit in the vertical diffusive flux terms. The scheme is formally second order accurate in space and first order accurate in time. The temporal error cannot be large, however, because of the short computation time step used, which ranged from two seconds to two minutes depending on wave speed, reach length, and current velocity.

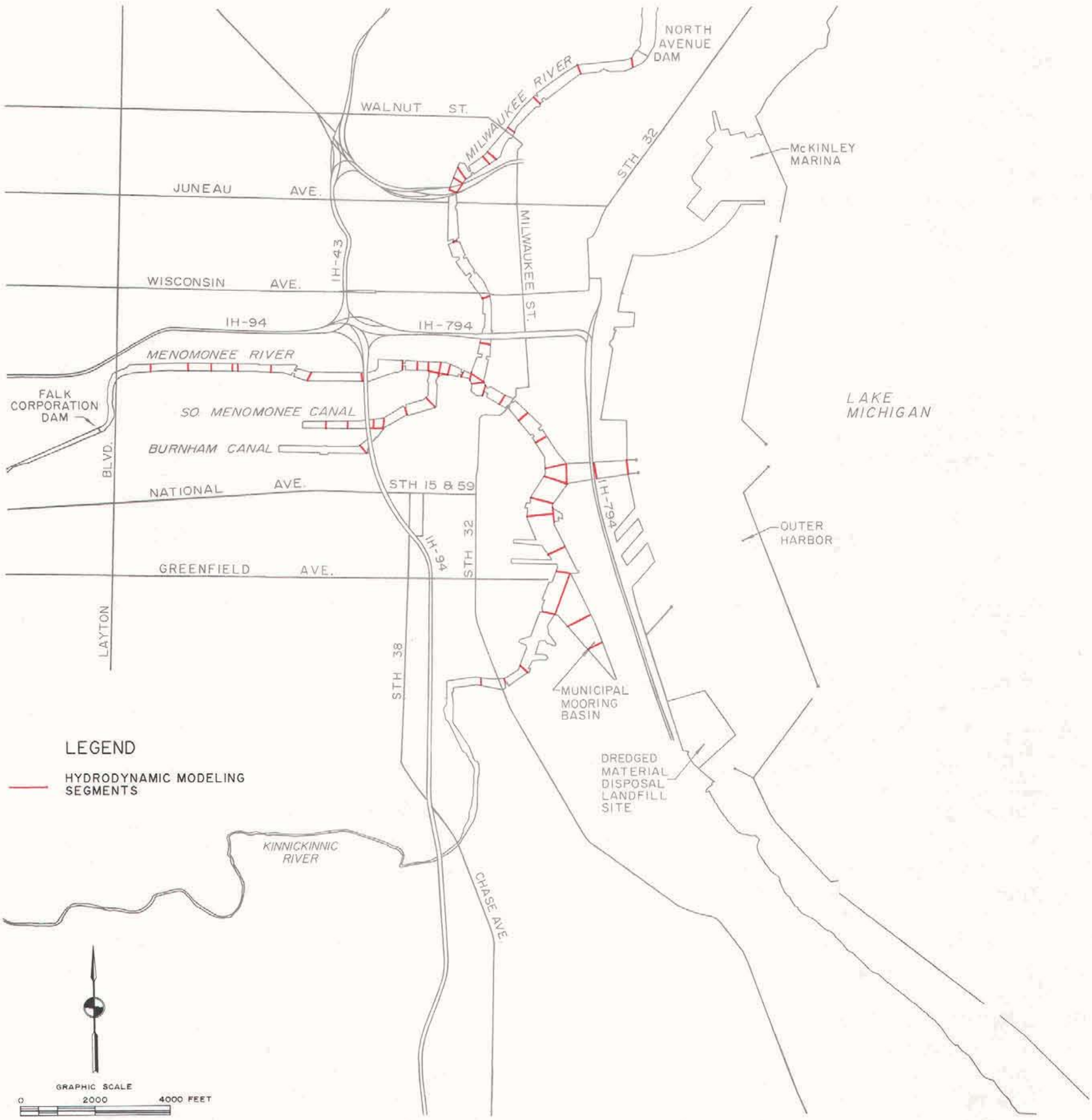
A salient feature of the submodel is a barotropic-baroclinic mode-splitting technique in which the continuity and momentum equations are vertically integrated to form a barotropic set of equations which are then integrated over time using the short time step described above. The full set of equations is then integrated over time using a longer time step determined by the baroclinic interval wave speed. The baroclinic mode computes bottom friction and vertical integrals of density and horizontal velocity which are provided to the barotropic mode. The barotropic mode in turn computes surface elevation for use in the baroclinic mode. Irregular bottom topography and time-dependent water surface elevation are integrated into the computation scheme.

Model Construction for the Inner Harbor: The hydrodynamic submodel equations described previously were in a form which allowed variable horizontal resolution. Therefore, the submodel grid network could be adapted to variations in channel geometry, rapid flow changes, or locations of special interest. The network constructed for the inner harbor of Milwaukee is shown in Figure 207. The average grid spacing is about 820 feet (250 meters), but the resolution is as small as 245 feet (75 meters) in some locations. Vertically, the model was constructed in 10 equal layers. Channel geometry data were taken from the same data base upon which the steady-state water quality model was constructed—namely, that collected by the U. S. Army Corps of Engineers.

The large number of bridge abutments in the inner harbor had a significant effect on flow. A recirculating gyre behind an abutment typically had a length of from 5 to 10 times the abutment length, causing well-mixed zones along both banks, particularly for the Milwaukee River. To represent the effects of the abutments without actually incorporating the geometry of each abutment into the submodel, the energy dissipation in a reach without abutments was computed. A similar computation was made dividing the reach width by two, typically, to represent the

Figure 207

COMPUTATIONAL NETWORK FOR THE INNER HARBOR HYDRODYNAMIC SUBMODEL



Source: HydroQual, Inc.

effective width due to the abutments. The computation for a reach with abutments yielded a dissipation twice that for a reach without abutments. This effect was represented in the submodel by use of a bottom drag coefficient twice that originally input, thus producing the appropriate response without explicitly resolving the abutments. Utilizing the relationship so developed along with the equation for a no-slip boundary, the effective bottom roughness was computed to be 0.4 inch (1 centimeter), which is in accord with the findings of Oey, Mellor, and Hires[18] in the New York Harbor, where the major driving forces and bathymetric features were also determined.

The hydrodynamic submodel was coupled with the steady-state water quality simulation submodel described earlier in this chapter to provide a more detailed simulation of mixing and transport. It was necessary to make certain simplifications to the steady-state water submodel during the model coupling process to facilitate the development of the coupling framework as indicated by the following changes:

1. Sediment oxygen demand was assigned rather than computed with the sediment flux model.

2. Only the Milwaukee River was modeled for reactive, oxidizable material.

3. Algal photosynthesis was simulated on a daily average basis.

Items 1 and 2 were found to be reasonable simplifications for assessment purposes. It was found, however, that photosynthesis was a major factor, and more detailed diurnal simulation was also conducted.

Model Calibration: Time variable water quality model calibration was conducted for three "events," one being the steady-state period of July 26, 1982; the second, the wet-weather sampling period of September 10 through 14, 1983; and the third, the runoff event of August 10 through 12, 1983. In addition, a fourth simulation was conducted of the three-month period from July 1 through September 30, 1983, concentrating on diurnal production by algae in the inner harbor.

Dry-Weather Simulation for July 26, 1982: The time-variable water quality simulation model was initially tested by comparing simulated conservative indicators with measured conservative indicators—namely, specific conductance and temperature—for July 26, 1982, which was a dry-weather period. Figures 208 and 209 show vertical profiles of conductivity and temperature at nine locations in the inner harbor comparing the simulated data with the measured data. The comparison between the simulated and measured values appears quite satisfactory, with the average errors for conductivity and temperature being 3.7 and 4.9 percent, respectively. Descriptions of the simulation period and the model input are presented in Chapter VI of this volume.

Wet-Weather Simulation for September 10 through 14, 1983: The intensive storm runoff sampling event of September 10 through 14, 1983, is described in Chapter VI of this volume. Time-variable simulation for this event initially required a steady-state simulation for the period prior to the storm so that each of the 600 model grid points could be assigned not only initial water quality values, but also initial current velocity values. Combined sewer overflow loadings were estimated using the procedure described in Chapter VI.

Conductivity and temperature were first simulated for the runoff event. The results of these simulations are summarized in Figures 210 and 211, which compare the measured and simulated values at 11 stations in the inner harbor and at the upstream estuary boundary sampling stations. As indicated, the simulated results are in reasonably good agreement with the measured data at most of the inner harbor stations. The decrease in conductivity and temperature at S. 1st Street on the Kinnickinnic River (RIV-14) occurred when the flushing tunnel was activated. The simulated results for both variables show that lake water intrusion was slightly underestimated.

For carbonaceous biochemical oxygen demand, an overall oxidation rate of 0.3 per day was used to represent the presumably more labile characteristics of the raw sewage entering the system from the combined sewer overflows. Figure 212

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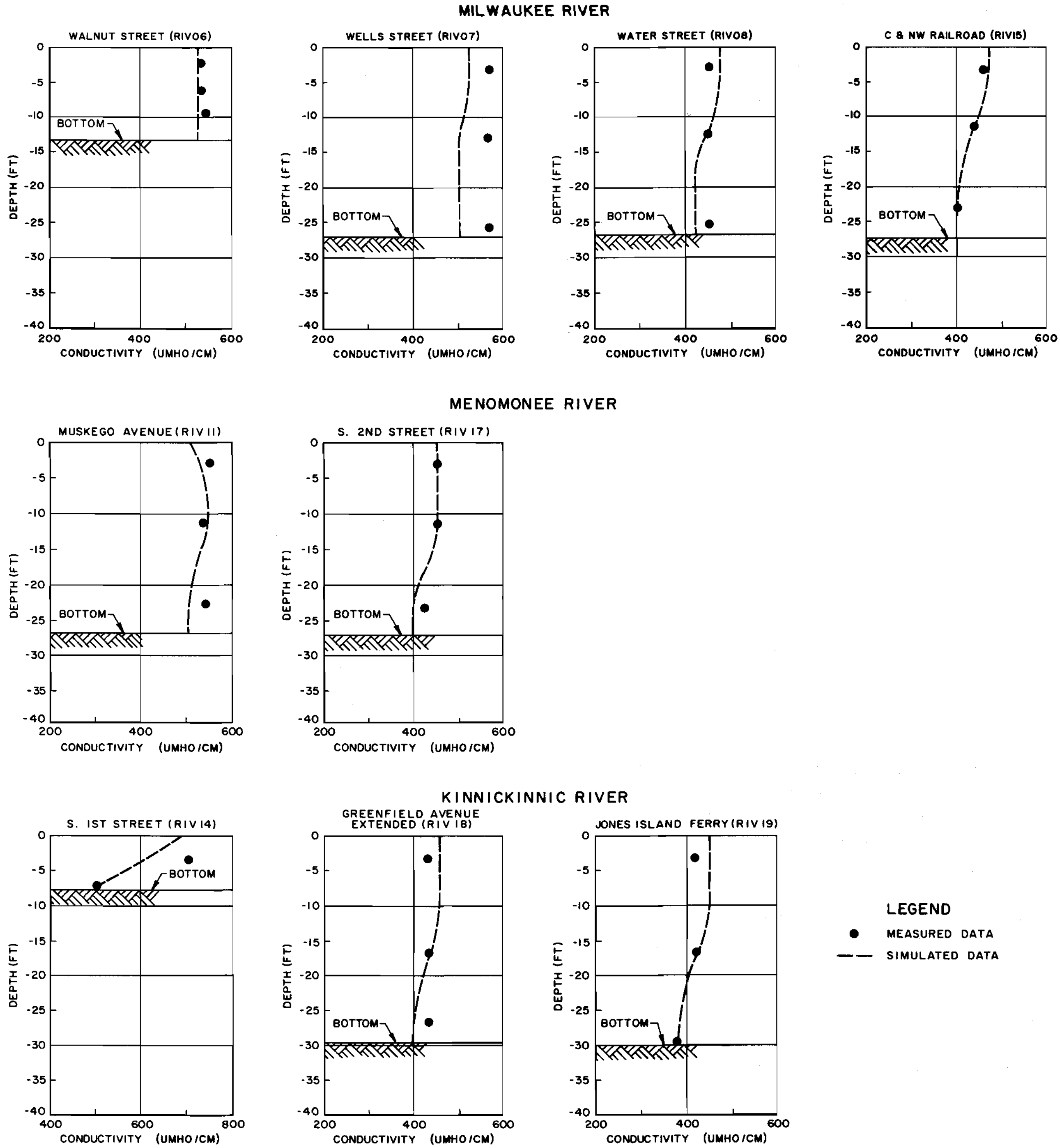
[18] *L. Y. Oey, G. L. Mellor, and R. P. Hires, "A Three-Dimensional Simulation of the Hudson-Raritan Estuary,"* Part I, II, and III: Journal of Physical Oceanography, *1986.*

Figure 208

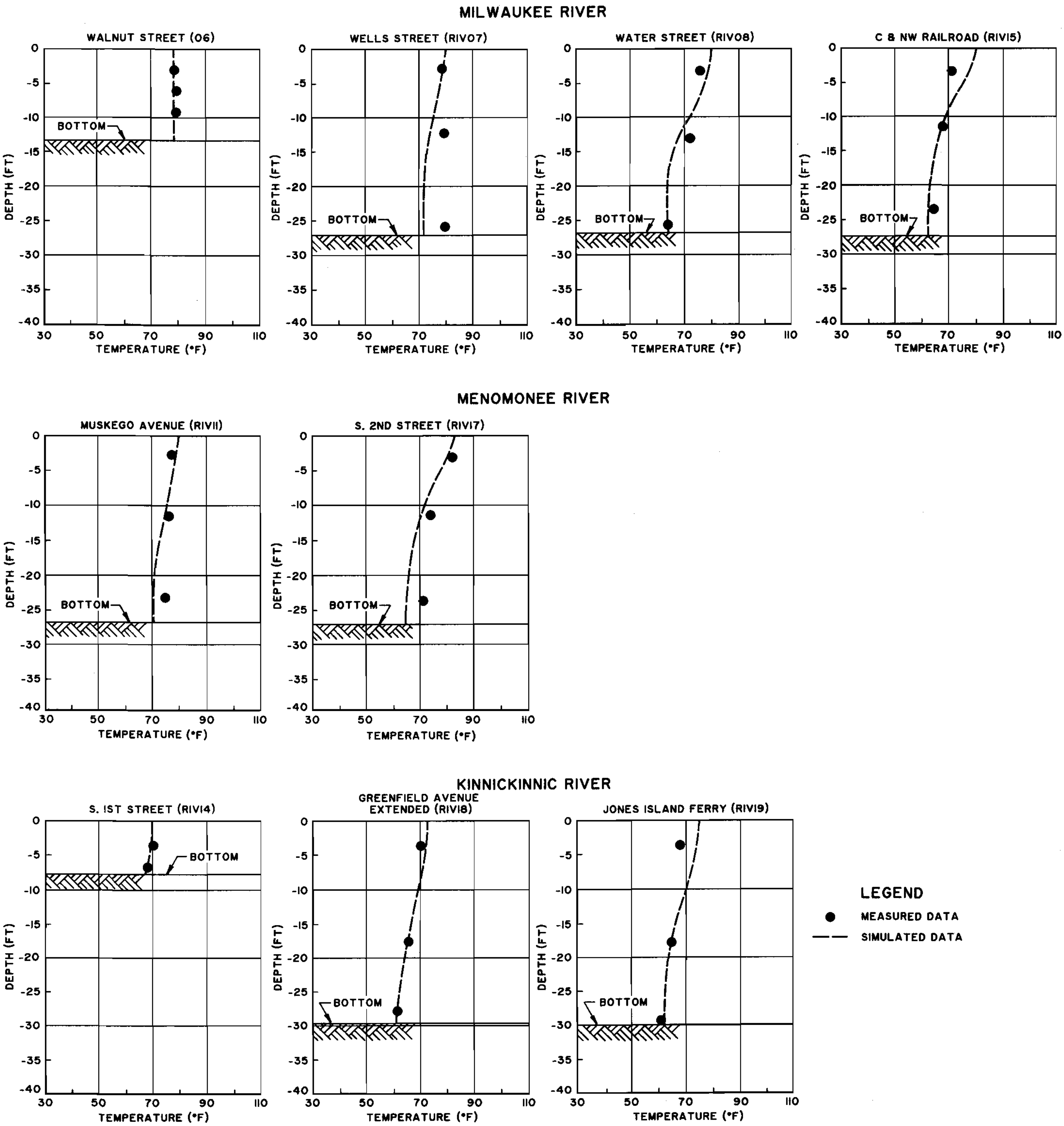
COMPARISON OF SIMULATED AND MEASURED SPECIFIC CONDUCTANCE IN THE INNER HARBOR FOR JULY 26, 1982



Source: HydroQual, Inc.

Figure 209

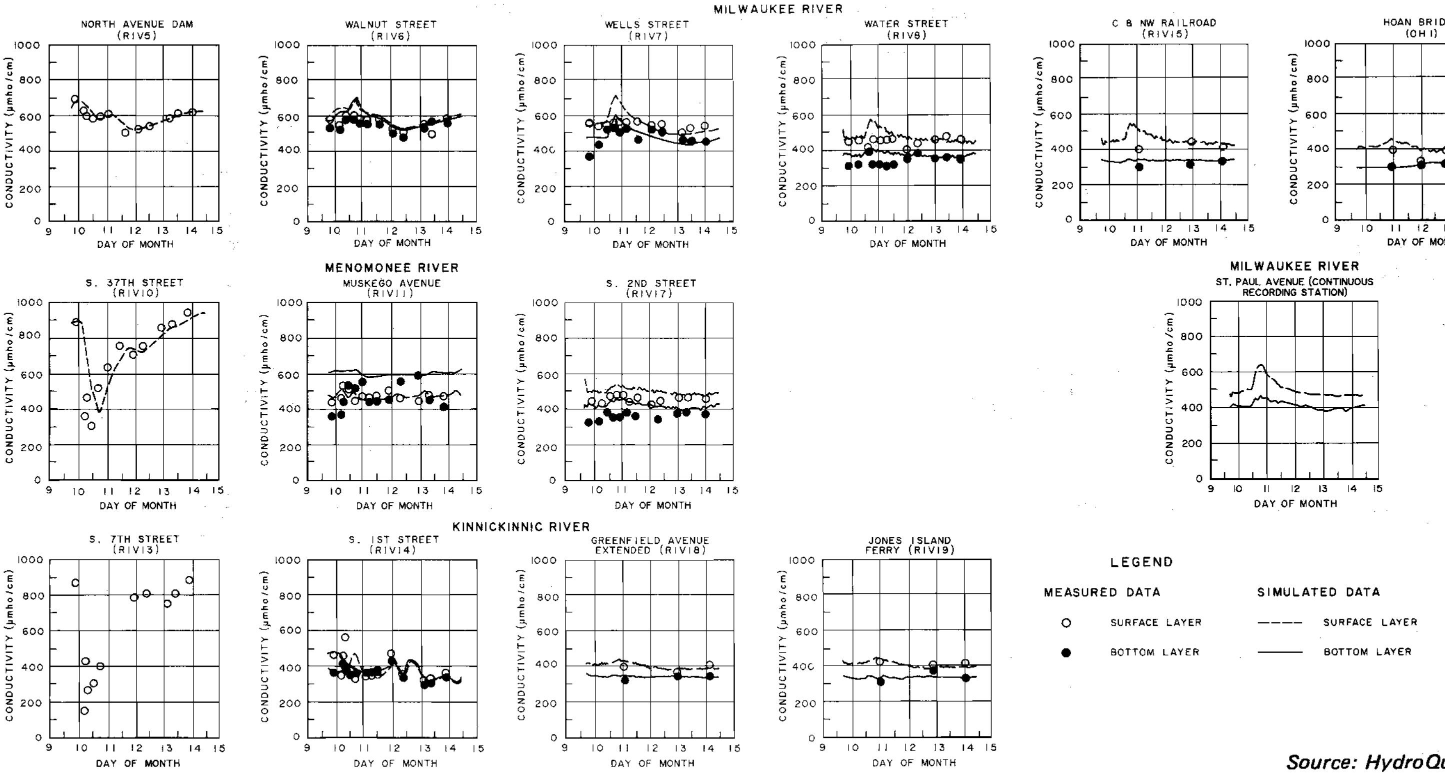
COMPARISON OF SIMULATED AND MEASURED WATER TEMPERATURE
IN THE INNER HARBOR FOR JULY 26, 1982



Source: HydroQual, Inc.

Figure 210

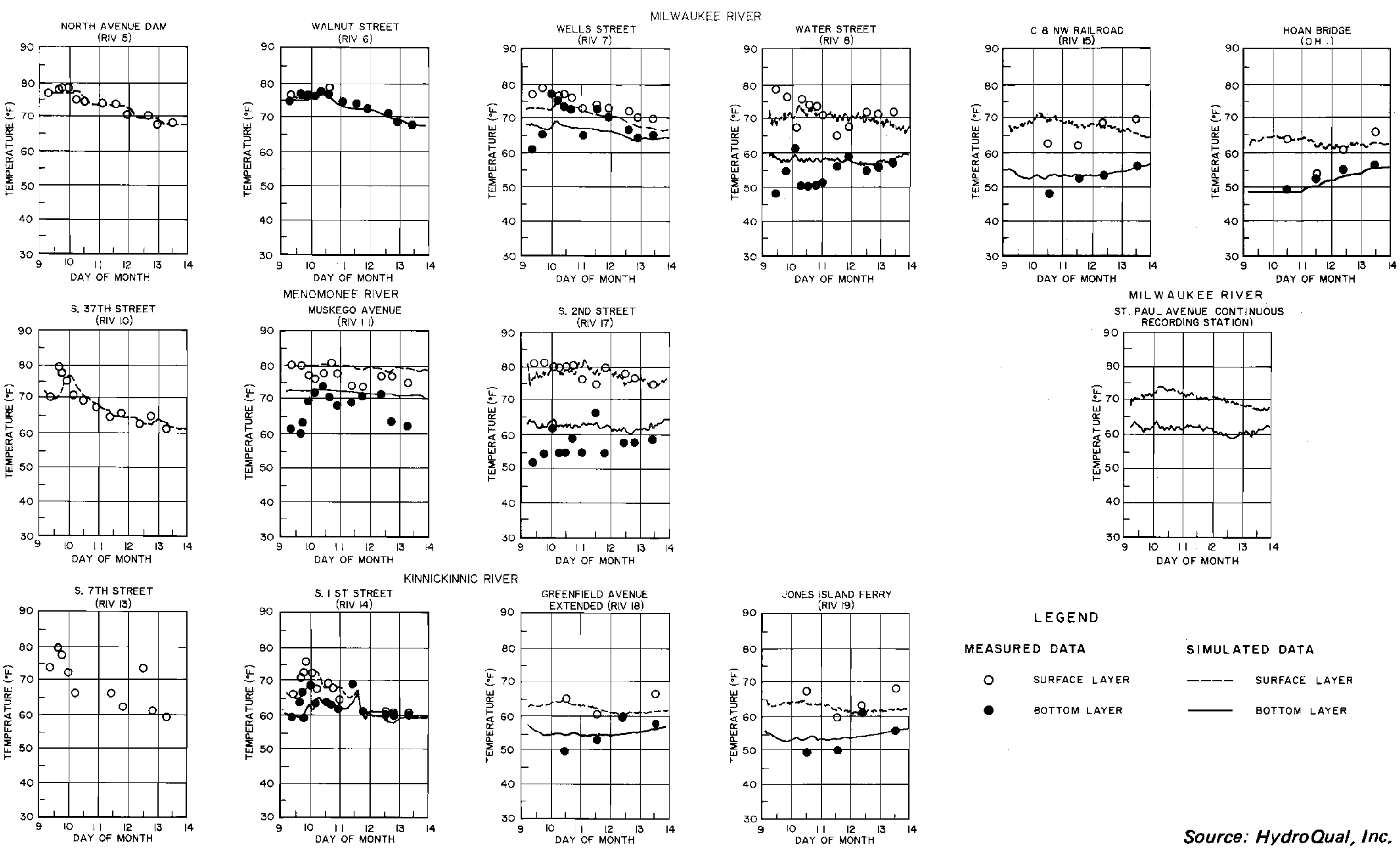
COMPARISON OF SIMULATED AND OBSERVED SPECIFIC CONDUCTANCE IN THE INNER HARBOR FOR SEPTEMBER 10-14, 1983



Source: HydroQual, Inc.

Figure 211

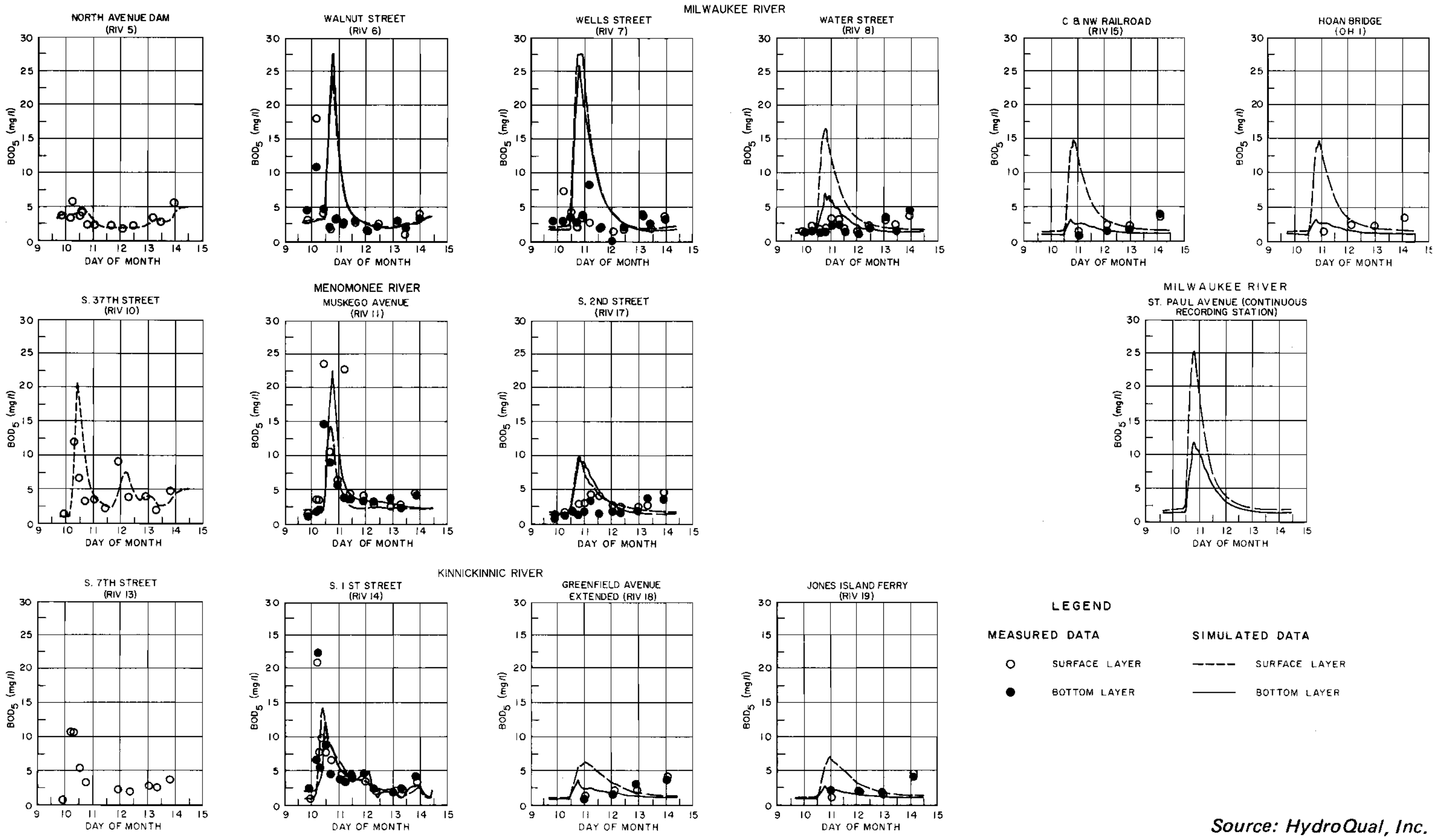
COMPARISON OF SIMULATED AND OBSERVED WATER TEMPERATURE IN THE INNER HARBOR FOR SEPTEMBER 10-14, 1983



Source: HydroQual, Inc.

Figure 212

COMPARISON OF SIMULATED AND OBSERVED CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND IN THE INNER HARBOR FOR SEPTEMBER 10-14, 1983



Source: HydroQual, Inc.

compares the simulated and measured results. As indicated, fairly good agreement was found between the simulated data and the measured data, except for the rainfall period on September 10, when simulated values exceeded the measured values significantly for three of the Milwaukee River stations. This was likely due to the variability of the combined sewer overflow carbonaceous biochemical oxygen demand. Toward the latter part of the simulation period an increase in measured carbonaceous biochemical oxygen demand occurred, which was not simulated. This may be partially explained by the relatively high oxidation rate used which was held constant throughout the simulation period.

For dissolved oxygen, difficulties occurred initializing the model with assumed steady-state conditions, resulting in the differences between initial observed and simulated values shown in Figure 213. These differences were translated downstream, with simulated dissolved oxygen values being too low at several sites, especially in the bottom layer. Some of the difference may be attributable to the underestimation of lake water intrusion apparent in the conductivity simulation.

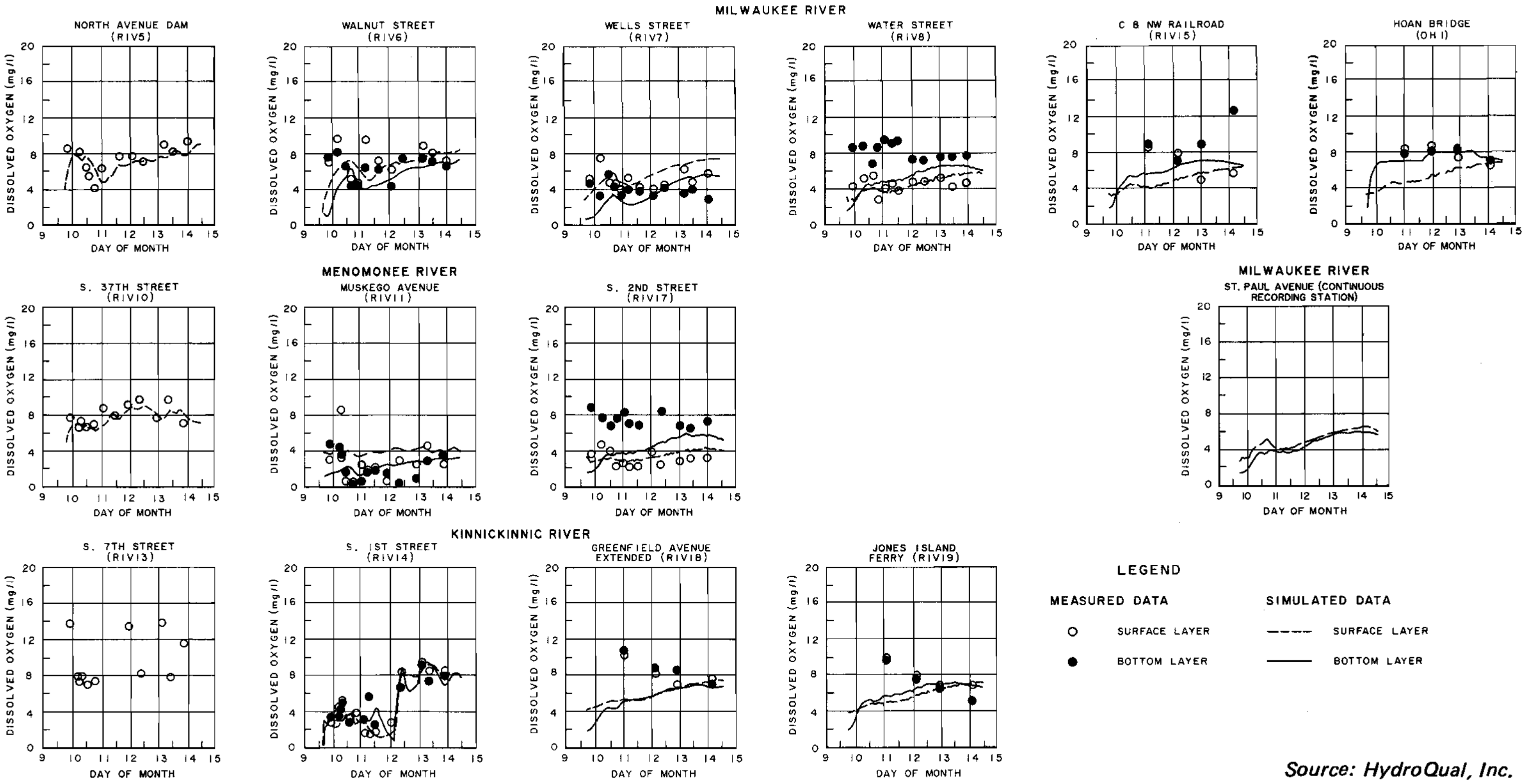
The large increase in dissolved oxygen observed in the Kinnickinnic River on September 12 occurred when the flushing tunnel was activated, and is indicative of the effectiveness of the flushing system.

Wet-Weather Simulation for August 10 through 12, 1983: A significant decrease in dissolved oxygen occurred in the inner harbor following a thunderstorm on August 10, 1983. This decrease occurred despite the fact that combined sewer overflows did not occur in significant amounts. Because of this absence of combined sewer overflows, sampling for the event was terminated early, resulting in a sparse amount of data. The event was simulated, nevertheless, to learn more about the large dissolved oxygen reduction which occurred primarily near St. Paul Avenue in the Milwaukee River.

Initially, the model was used to determine if the low dissolved oxygen observed at the continuous monitor at St. Paul Avenue was produced by the flow of low dissolved oxygen water up the Milwaukee River from the Menomonee River, which exhibited very low dissolved oxygen levels

Figure 213

COMPARISON OF SIMULATED AND OBSERVED DISSOLVED OXYGEN IN THE INNER HARBOR FOR SEPTEMBER 10-14, 1983



Source: HydroQual, Inc.

prior to the storm. First, simulations of conductivity and water temperature were made to check the accuracy of model transport. Comparisons of the simulated and measured results are shown in Figures 214 and 215. Although the success of the transport simulation is not readily ascertainable owing to the lack of data, the simulated and observed results appear reasonably consistent.

Following model transport simulation, carbonaceous biochemical oxygen demand and dissolved oxygen were simulated and compared to the measured data, as shown in Figures 216 and 217. Again, minimal measured data were available for comparison, but it was apparent that the flow reversal found in the simulation was not of sufficient duration at St. Paul Avenue to account for the dissolved oxygen levels observed in the Milwaukee River at that location during this time period.

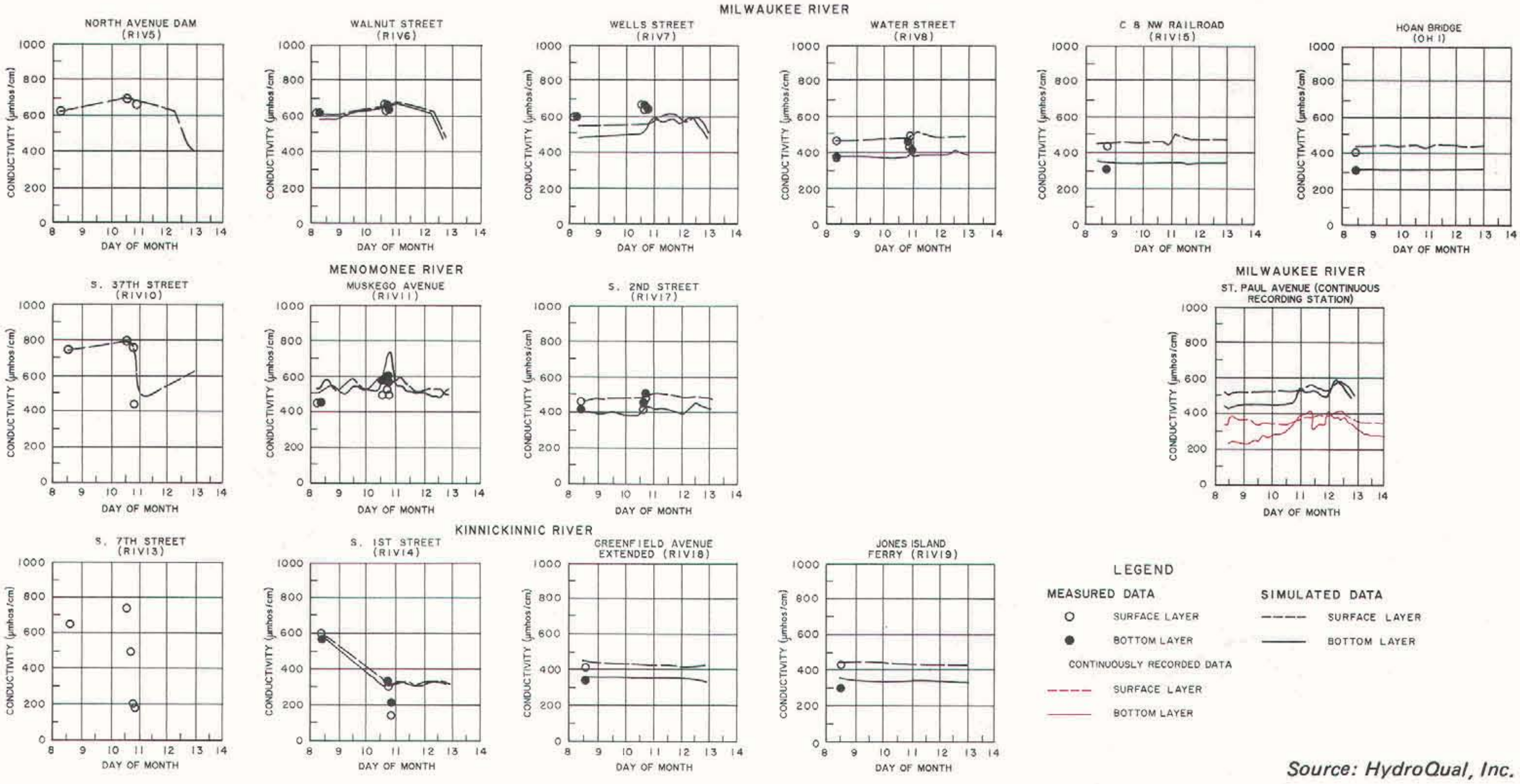
A review of the dissolved oxygen data collected prior to and during the simulation period indicated that a possible cause of the rapid and large decline in dissolved oxygen observed at St. Paul Avenue was the apparent decline in algal photosynthesis which likely occurred beginning on August 10, as cloud cover moved in prior to the storm. Figure 218 presents meteorological data collected by the National Weather Service at Mitchell Field for the period August 6 through 15, 1983, which indicates a large decrease in solar radiation on August 10 and continuing into August 11. Therefore, the simulation was repeated without photosynthesis to check this hypothesis. The results supported the hypothesis as indicated by Figure 219, which compares the simulated and measured values.

Diurnal Dissolved Oxygen Simulation for July 1 through September 30, 1983: To further understand the effects of algal productivity upon dissolved oxygen in the estuary, time-variable simulations were conducted for the three-month period July 1 through September 30, 1983. The modeling analysis was conducted to determine whether the large rapid dissolved oxygen reductions observed in the inner harbor corresponded with reductions in algal photosynthesis attributable to reductions in solar radiation caused by the presence of daytime cloud cover.

To test the hypothesis, a simplified version of the time-variable model was constructed for the reach of the Milwaukee River from the North Avenue

Figure 214

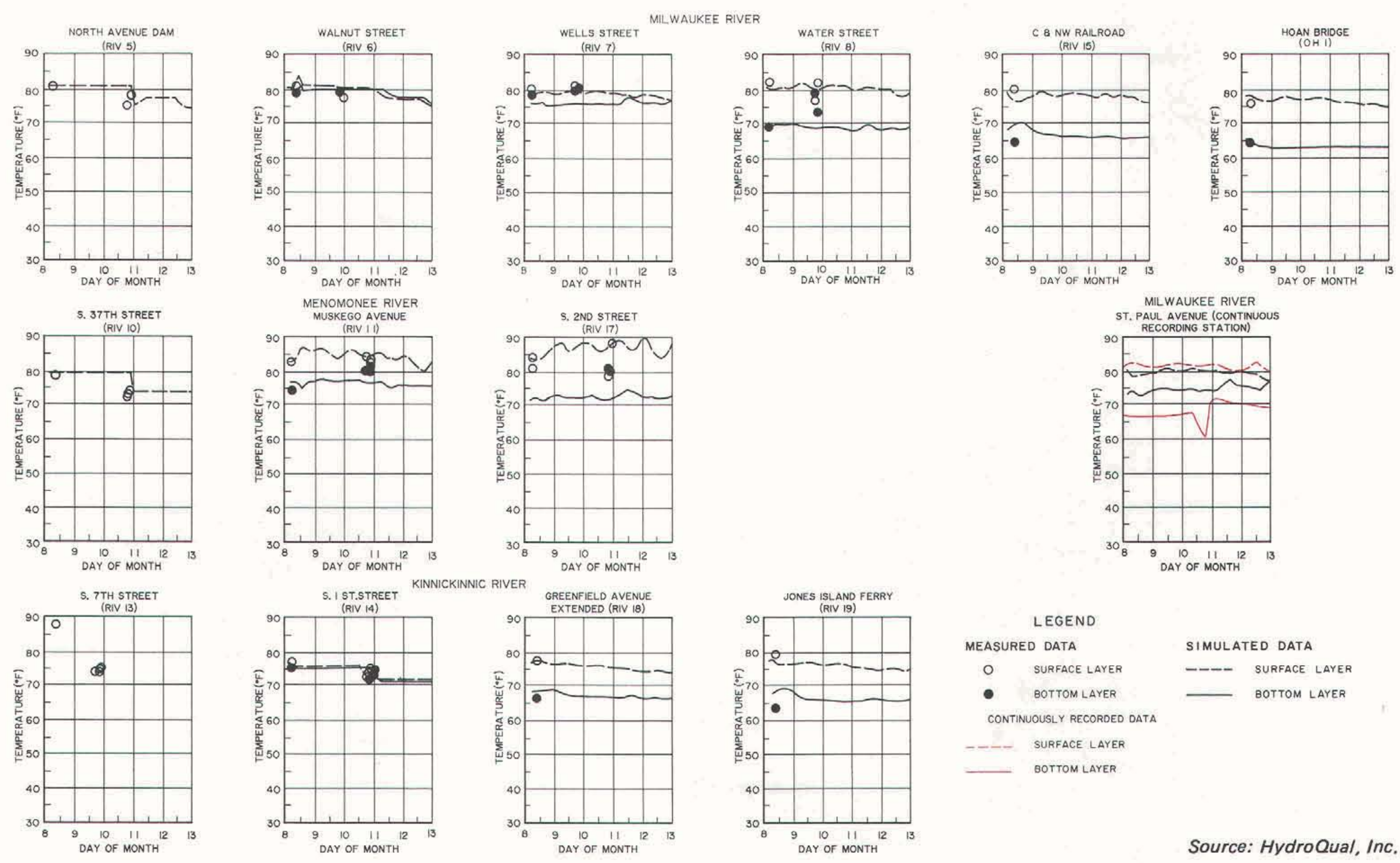
COMPARISON OF SIMULATED AND OBSERVED SPECIFIC CONDUCTANCE IN THE INNER HARBOR FOR AUGUST 8-12, 1983



Source: HydroQual, Inc.

Figure 215

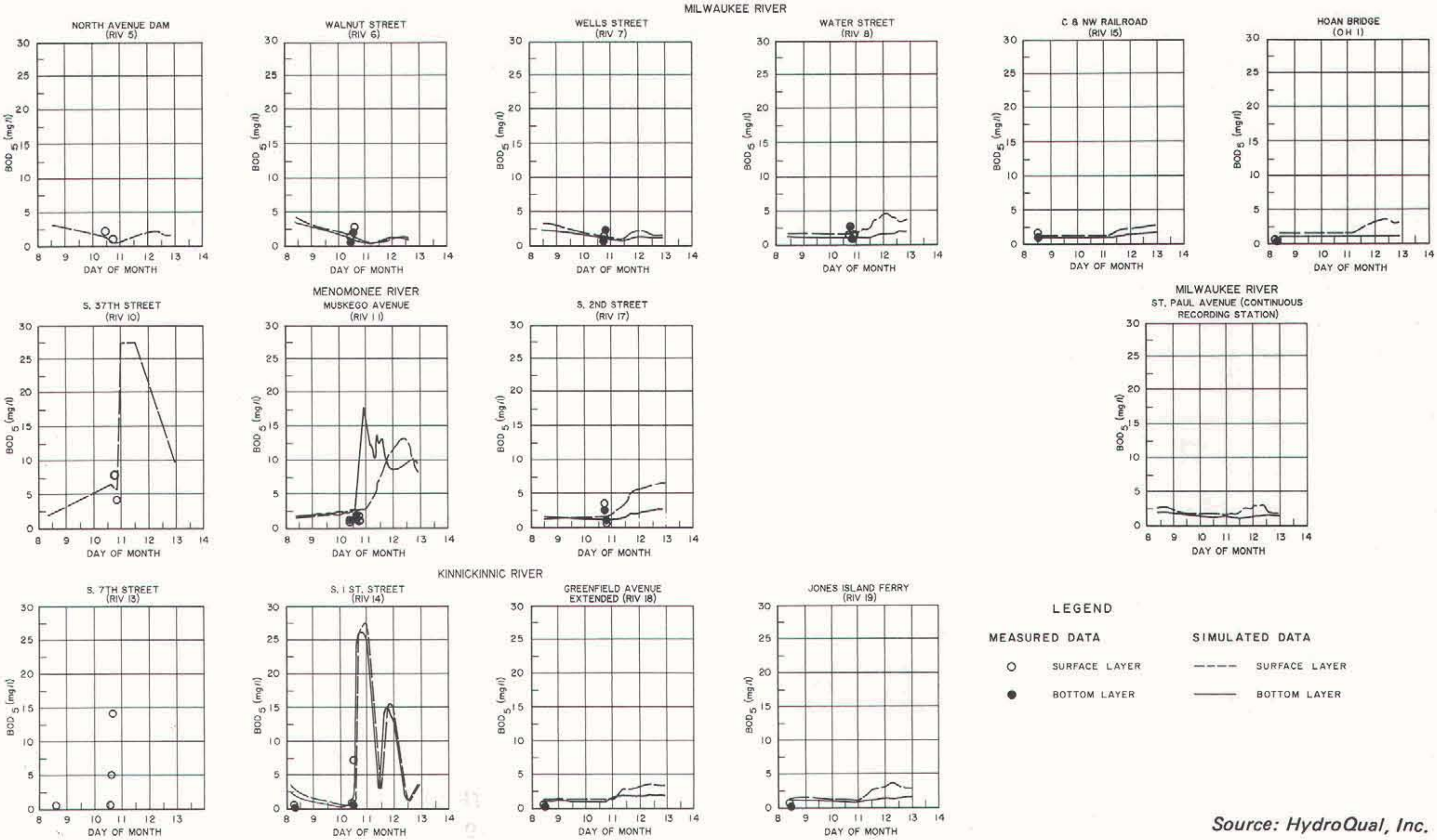
COMPARISON OF SIMULATED AND OBSERVED WATER TEMPERATURE IN THE INNER HARBOR FOR AUGUST 8-12, 1983



Source: HydroQual, Inc.

Figure 216

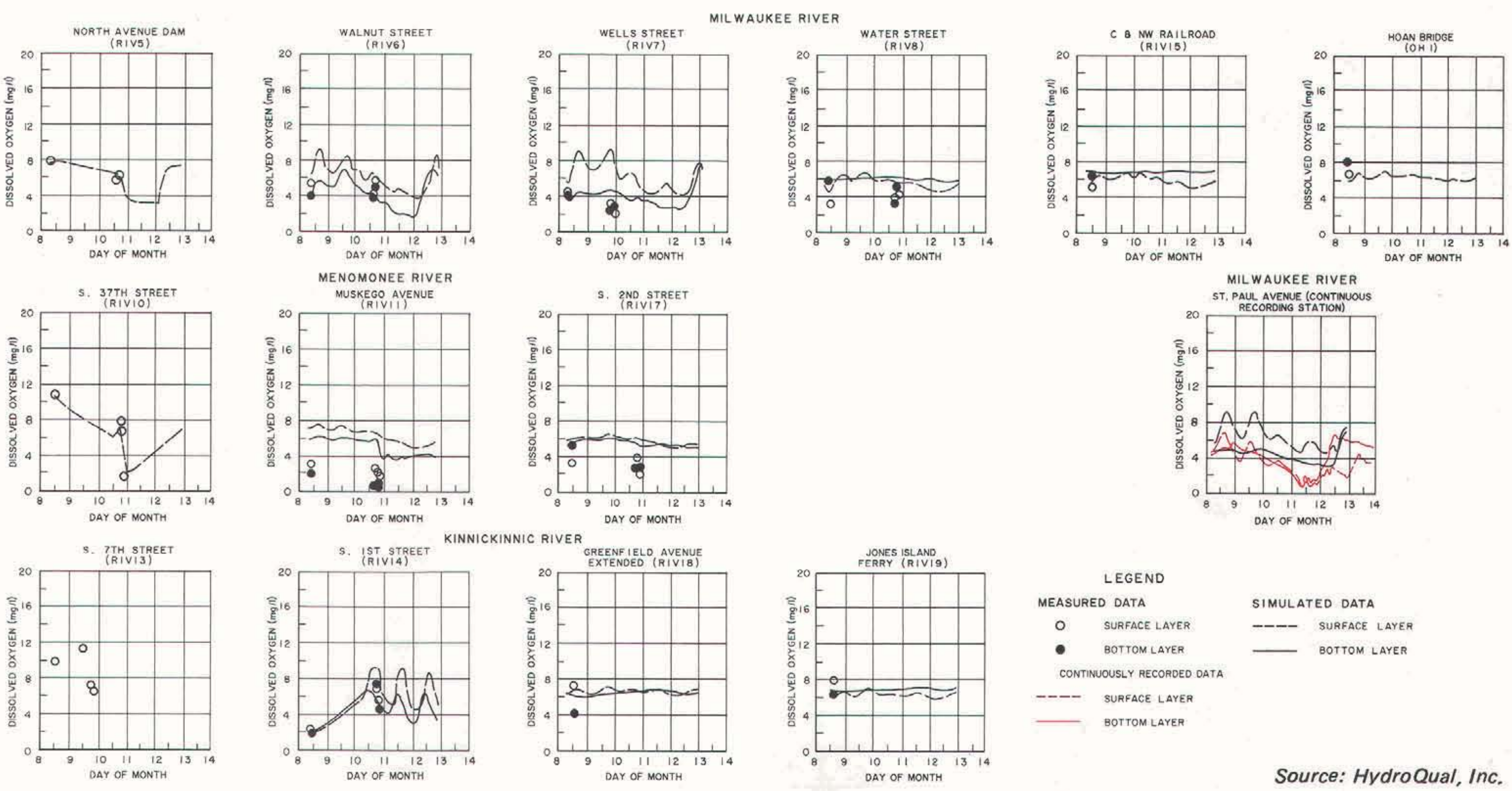
COMPARISON OF SIMULATED AND OBSERVED CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND IN THE INNER HARBOR FOR AUGUST 8-12, 1983



Source: HydroQual, Inc.

Figure 217

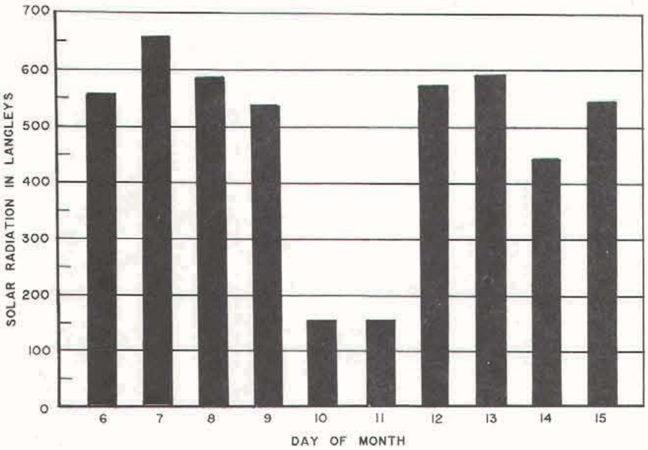
COMPARISON OF SIMULATED AND OBSERVED DISSOLVED OXYGEN IN THE INNER HARBOR FOR AUGUST 8-12, 1983



Source: HydroQual, Inc.

Figure 218

SOLAR RADIATION OF MITCHELL FIELD
FOR AUGUST 6-15, 1983



Source: National Weather Service and HydroQual, Inc.

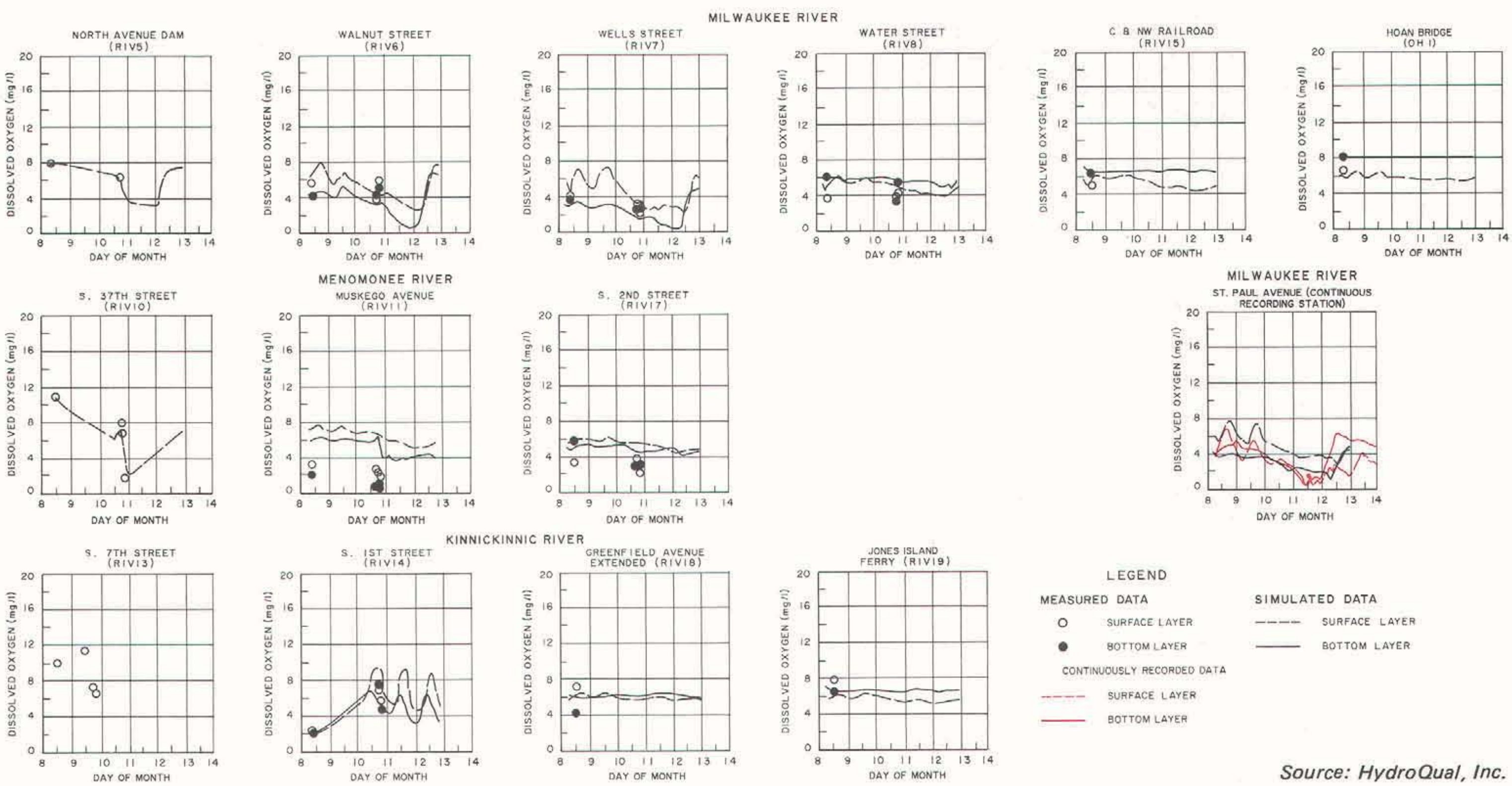
dam to the confluence with the Menomonee River, having one layer rather than 10 layers. Input to the model were average daily flow at North Avenue, weekly chlorophyll-a and dissolved oxygen data, and daily solar radiation estimated from General Mitchell Field data. Total daily solar radiation was converted to an incident solar radiation which varied as a half sine wave over the daylight hours. The combined effects of carbonaceous biochemical oxygen demand and sediment oxygen demand were represented by a constant oxygen demand equivalent to 2 grams per square meter per day. No interactive sediment-water column effects were simulated.

Initial simulations were unsatisfactory, although promising. Review of wet- and dry-weather light extinction data and suspended solids data indicated that an increase of 50 to 100 percent in the light extinction coefficients was called for during wet weather, as indicated in Figure 220, which presents probability plots of extinction coefficients and suspended solids comparing wet- and dry-weather periods. The adjustments were made accordingly, and the input and resultant ouput from the model are shown, along with rainfall, in Figure 221.

As indicated in Figure 221, the diurnal dissolved oxygen variation due to algae was most apparent in the surface layer at the St. Paul Avenue monitor, but was also evident at greater depths because of vertical mixing. On five occasions, significant overall decreases in dissolved oxygen occurred which generally correlated with rainfall periods and days of low solar radiation. The simulated

Figure 219

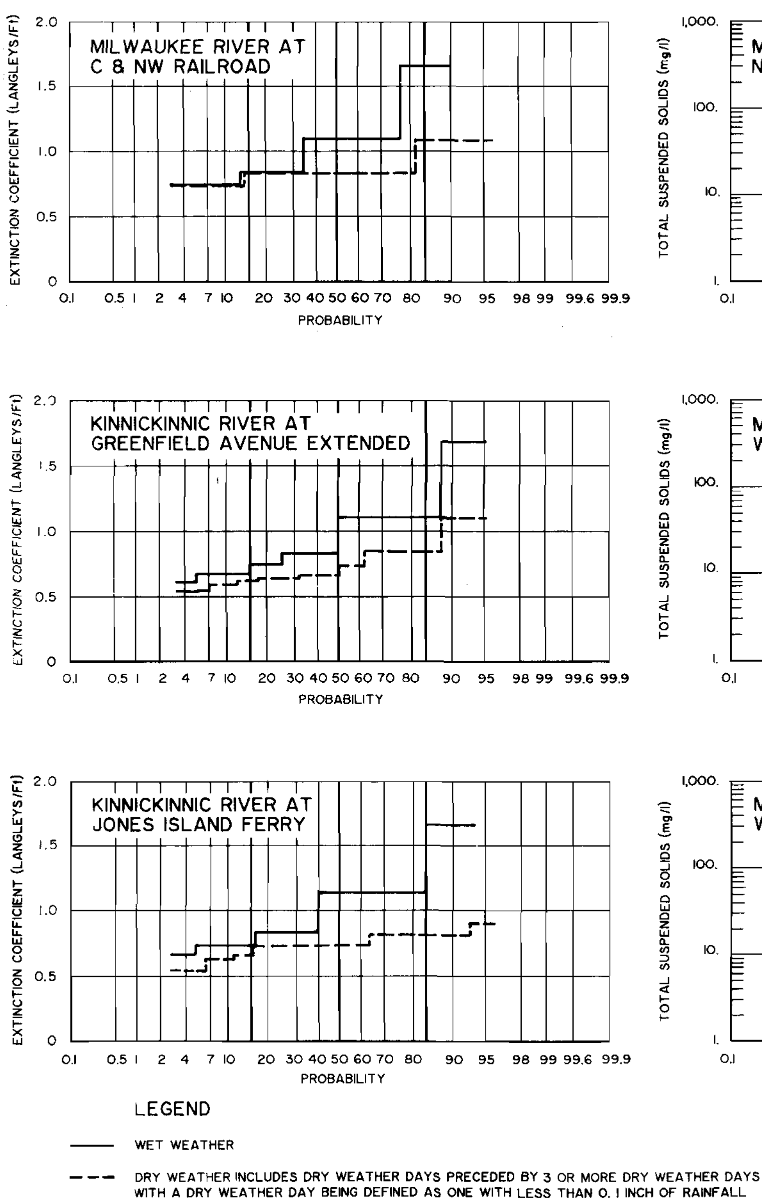
COMPARISON OF SIMULATED AND OBSERVED DISSOLVED OXYGEN
FOR AUGUST 8-12, 1983 WITHOUT ALGAL PHOTOSYNTHESIS



Source: HydroQual, Inc.

Figure 220

PROBABILITY PLOTS COMPARING WET- AND DRY-WEATHER DATA FOR LIGHT EXTINCTION COEFFICIENTS AND SUSPENDED SOLIDS



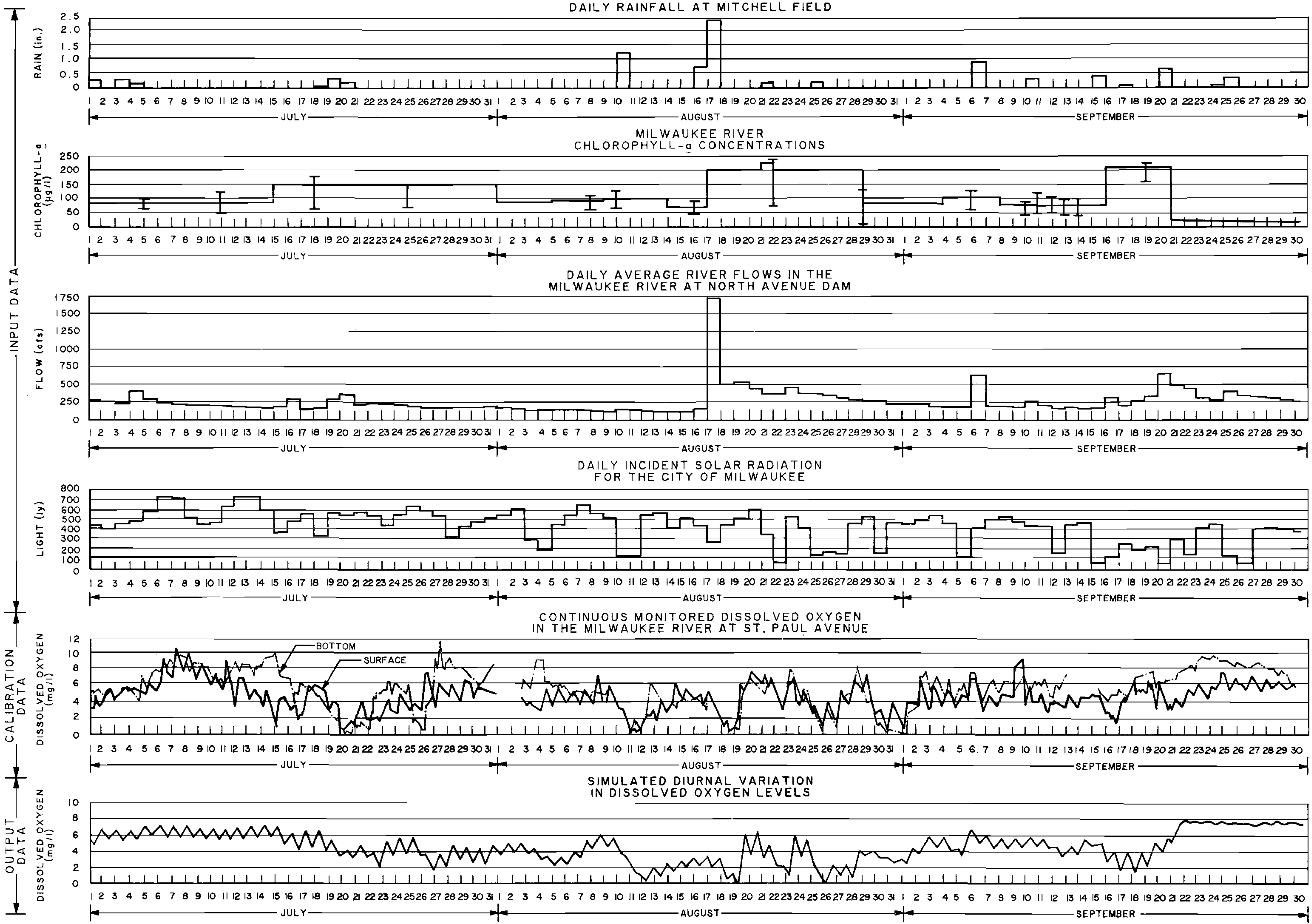
Source: HydroQual, Inc.

dissolved oxygen levels explained most of the occasional depletions quite well except for that of July 20. For that date, it was found that good agreement occurred if algal productivity was set equal to zero, suggesting that one of the input parameters such as solar radiation may have been misrepresented.

The results of the three-month simulation indicated that dissolved oxygen depletion was sensitive to the level of solar radiation, the number of sequential days of low sunlight intensity, the chlorophyll-a concentration, and river flow. Computed daily mean dissolved oxygen decreased most significantly after sequential days of low

Figure 221

INPUT, CALIBRATION, AND OUTPUT DATA FOR TIME-VARIABLE SIMULATION FOR JULY 1-SEPTEMBER 30, 1983



Source: HydroQual, Inc.

sunlight. When flow was high and chlorophyll-a low, dissolved oxygen did not change significantly even with reduced sunlight several days in a row.

Further simulations were then conducted to determine if any change in algal productivity occurred during periods of low dissolved oxygen. Light/dark respirometer field data for August 12, 1983, at Walnut Street and the Milwaukee River, and similar data at North Avenue for September 1, 1983, were examined and found to depart significantly from the basic photosynthetic-light curve. The basic curve, fit through the entire productivity data set, had a light-productivity coefficient of 100 langleys/day as reported in Chapter VI of this volume. A curve fit through the light and dark bottle data representing days with depleted dissolved oxygen levels had a coefficient of 220 langleys/day. A repeat simulation using this coefficient on days when the observed dissolved oxygen decreased significantly yielded results very similar to those of the previous three-month simulation.

It was not possible to determine the cause of reduced algal productivity in the inner harbor and the resultant dissolved oxygen depletions with the available data. Increased light extinction caused by increased turbidity during wet weather and/or changes in algal productivity characteristics were the most likely causes. Other possible factors were algae inhibition by sudden temperature changes resulting from hydraulic surges, or high concentrations of metals from combined sewer overflow, as supported by results of the Ceriodaphnia toxicity tests where wet-weather conditions appeared to be related to increased mortality. The data base analysis, however, favored the hypothesis that light extinction coefficients were higher during wet-weather periods, and the final modeling results were based on this premise.

Statistical Water Quality Simulation

Some water quality indicators, namely fecal coliform and lead, were found to exhibit stochastic characteristics. A comparison of probability distributions of the weekly baseline data for these indicators and of the data representing only dry-weather conditions indicated a significant difference, presumably caused by combined sewer overflows. Although the time-variable water quality model technically was capable of simulating these indicators, a statistical approach was deemed more suitable. The statistical model was first calibrated using a conservative tracer for transport, and then calibrated for fecal coliform and lead.

Description of Statistical Modeling Approach: The statistical model developed and used for the inner and outer harbors and adjacent area of Lake Michigan relates the statistics of runoff and certain characteristics of the receiving water body to the statistics of the indicator concentrations within the receiving water. The mean, variance, and correlation time of the pollutant sources were input, and the resultant mean and variance of indicator concentrations within the receiving water body were computed. The correlation time was the minimum time interval over which serial measurements are essentially uncorrelated.

The computed indicator concentration means and variances were then used with normal probability theory to determine log-normal distributions of concentrations. The statistical model computed the 14th, 50th (median), and 86th percentiles of the log-normal distribution for a given water quality indicator. These results were then compared with statistics of measured data to check model calibration. In addition, the distributions for existing and projected conditions were used for water quality standards compliance analysis.

The statistical model utilized the same segmentation of the estuary as that used for the steady-state water quality model and was based on summer average flows for the three tributary rivers, and on combined sewer overflow loads calculated using rainfall statistics and the combined sewer overflow/rainfall relationship described earlier in this chapter. Summer was defined as the period between June 21 and September 21. Both dry-weather and all-weather conditions were simulated. Dry-weather data included all samples collected that were preceded by three or more days of dry weather, including the sampling day. Dry weather was defined as a day in which less than 0.1 inch of rainfall occurred.

Average summer conditions for 1981 through 1983 were utilized for calibration and analysis of compliance with standards because fecal coliform standard violations were most relevant during the summer, and because the impact of combined sewer overflow discharges on receiving water concentrations was greatest during summer low-flow periods. Fecal coliform die-off was also lower during the warm summer months, resulting in higher sustained concentrations than during other periods. Data for the three summers were pooled to create a statistically adequate data base.

Model Calibration: The statistical model was first calibrated for transport using the conservative tracer conductivity, then subsequently calibrated for fecal coliform and lead. The following sections describe the calibration procedure and results.

Transport: The conservative tracer conductivity was used in the statistical modeling analysis to calibrate the model for summer average transport and to verify the applicability of the statistical technique employed. As in the steady-state water quality modeling, accurate simulation of water transport is important because water quality concentrations are affected by not only chemical reaction kinetics, sedimentation, and die-off, but also by transport processes, such as advection and diffusion. Indeed, transport can be the dominant factor in many situations.

Conductivity data collected as part of the weekly baseline sampling program in the tributary rivers and the inner and outer harbors were statistically analyzed to determine the sample means and variances. Variance was expressed in terms of the coefficient of variation, which is the ratio of the standard deviation to the mean. These statistics were computed for both dry-weather and all-weather data as shown in Table 140, which also contains model input data for fecal coliform and lead. Summer average flows for the three tributary rivers for 1981 through 1983 input to the dry-weather and all-weather statistical models are listed in Table 141.

Because the sample data were collected at weekly intervals, correlation time was not directly determinable and, therefore, was used as a calibration parameter. An initial correlation time of one day was assigned and used in the first simulation attempt for summer dry-weather conditions. The simulated and measured mean levels of conductivity were in generally good agreement but the percentile ranges were not, because, presumably, variability was reduced by mixing in the estuary. Trial and error analysis through further simulations found that a 10-day correlation time produced satisfactory comparisons of simulated and measured statistics, probably because as autocorrelation increased, the smoothing effect of dispersive mixing on boundary variability was less effective.

Graphical comparisons of measured and simulated conductivity levels are presented in Figure 222. The undersimulation of variability near milepoint 2.0 on the Kinnickinnic River suggested that an

The coefficient of variation $\nu(c)$ for log-normally distributed concentration data is:

$$\nu(c) = [\exp(\sigma^2) - 1]^n$$

where: σ is the standard deviation of the data and n is 0.5. The coefficient of variation for CSO volumes $\nu(V)$ is:

$$\nu(V) = \frac{\sigma(V)}{\mu(V)}$$

where: $\mu(V)$ and $\sigma(V)$ are the mean and standard deviation of the combined sewer overflow volumes, respectively.

The coefficient of variation of mass loading $\nu(m)$ is a function of concentration and combined sewer overflow volume variability and is computed by:

$$\nu(m) = \nu(c) \ x\nu(V) \ [\frac{1}{\nu^2(c)} + \frac{1}{\nu^2(V)}]n$$

where: n = 0.5.

Table 140

SUMMARY OF INPUT STATISTICS FOR STATISTICAL MODEL

Source	Conductivity (µmhos/cm)				Lead (micrograms/liter)				Fecal Coliform (most probable number/100ml)			
	Dry Weather		Composite		Dry Weather		Composite		Dry Weather		Composite	
	Mean	Coefficient of Variation	Mean	Coefficient of Variation	Mean	Coefficient of Variation	Mean	Coefficient of Variation	Mean	Coefficient of Variation	Mean	Coefficient of Variation
Milwaukee Boundary	594	0.112	545	0.124	30	0.54	33	0.50	1,461	3.51	7,150	7.08
Menomonee Boundary	711	0.172	732	0.250	37	0.54	37	0.52	8,512	1.89	13,000	1.93
Kinnickinnic Boundary.	714	0.104	709	0.157	32	0.59	32	0.76	2,545	2.09	18,000	8.13
Outer Harbor												
North Breakwater Gap (OH5)												
Surface	353	0.123	353	0.123	34	0.69	49	0.82	--	--	--	--
Bottom.	291	0.072	291	0.072	34	0.50	48	0.68	--	--	--	--
Main Entrance (OH7)												
Surface	364	0.147	364	0.147	34	0.32	56	0.66	--	--	--	--
Bottom.	296	0.077	296	0.077	38	0.26	58	0.56	--	--	--	--
South Breakwater Gap (OH9)												
Surface	362	0.112	362	0.112	38	0.45	54	0.60	--	--	--	--
Bottom.	301	0.085	301	0.085	42	0.53	54	0.60	--	--	--	--
Jones Island Effluent	1,118	0.196	1,118	0.196	105	1.00	105	1.00	--	--	--	--
Combined Sewer Overflow. . . .	--	--	--	2.66	--	--	--	2.82	--	--	--	3.01
Dry-Weather Overflow												
Milwaukee	--	--	--	--	--	--	--	--	--	7.10	--	7.10
Menomonee	--	--	--	--	--	--	--	--	--	9.40	--	9.40
Kinnickinnic.	--	--	--	--	--	--	--	--	--	10.50	--	10.50

NOTE: Correlation time is one day for coliform and 10 days for conductivity and lead. CSO loads are assumed to be independent, with a mean time between storms of 4.8 days.

Source: HydroQual, Inc.

unknown source of conductivity may have existed in the inner harbor. Generally, however, the model showed that boundary variability accounted for most of the variability found in the inner harbor and, therefore, the dry-weather transport simulated by the statistical model was reasonable.

A similar simulation was conducted for all-weather summer conditions and required that boundary means and variances be determined for the pertinent indicators for all the weekly data collected in the summers of 1981, 1982, and 1983. Statistics for combined sewer overflow loadings also had to be included, and are listed in Table 142.

Measured and simulated conductivity are compared in Figure 223 for all-weather summer conditions. As indicated, fair agreement was obtained for mean concentrations, but variability was oversimulated at many locations. Also, the simulated mean near milepoint 2.0 on the Kinnickinnic River was oversimulated, but measured and simulated variances were similar. Model discrepancies may reflect the unsuitability of using three dry days to define dry-weather data for a conservative indicator.

Table 141

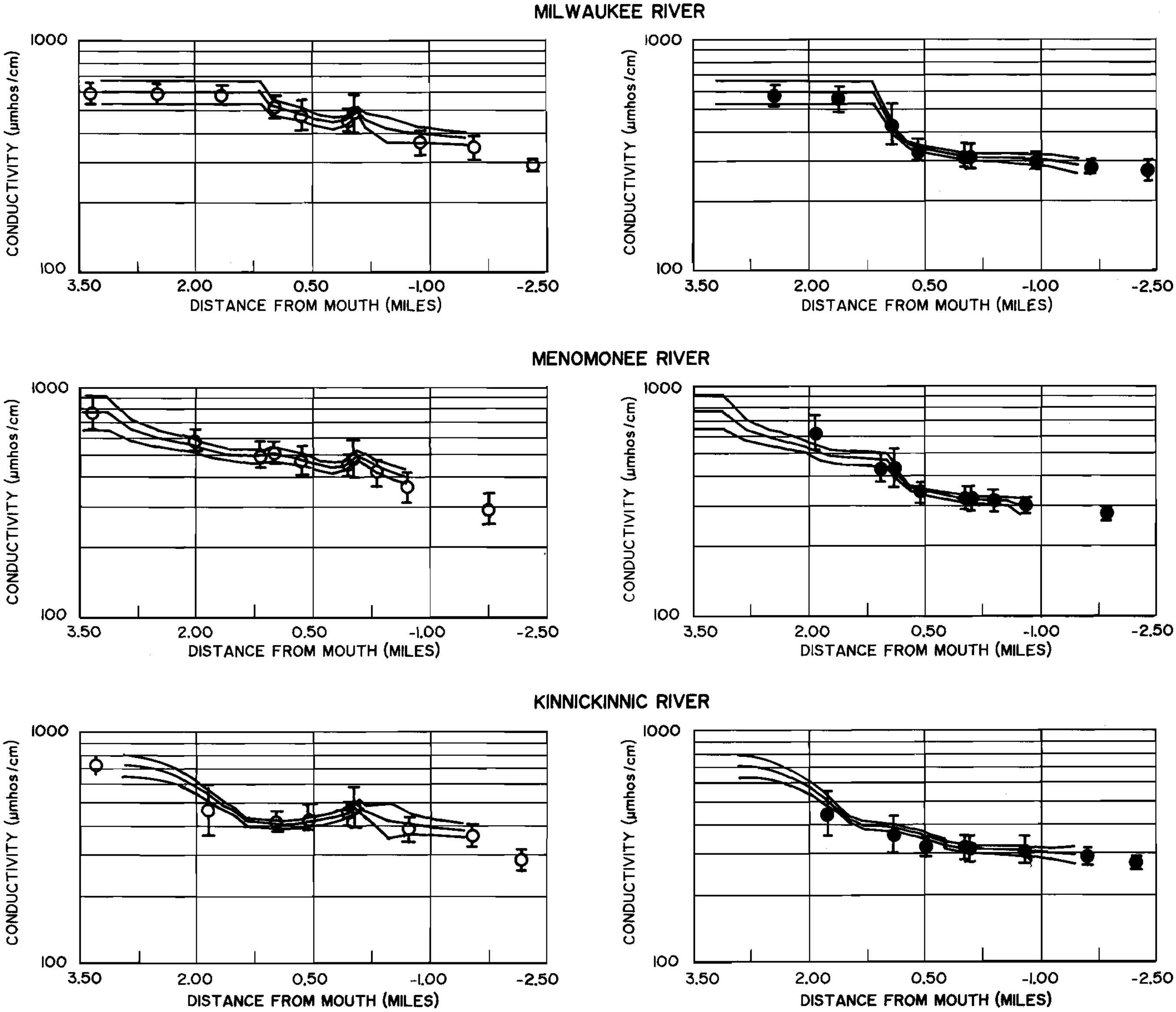
TRIBUTARY RIVER FLOWS INPUT TO THE STATISTICAL MODEL

River	Dry-Weather Flow (cfs)	All-Weather Flow (csf)
Milwaukee	246	330
Menomonee	16	60
Kinnickinnic	6.6	24

Source: HydroQual, Inc., and U. S. Geological Survey.

Figure 222

COMPARISON OF SIMULATED AND MEASURED SUMMER DRY-WEATHER CONDUCTIVITY FOR 10-DAY CORRELATION TIME



LEGEND

MEASURED DATA

- GEOMETRIC MEAN ± ONE LOG STANDARD DEVIATION
- ○ MEAN VALUE IN SURFACE LAYER
- ● MEAN VALUE IN BOTTOM LAYER

MODEL SIMULATED DATA

- SIMULATED GEOMETRIC MEAN ± ONE LOG STANDARD DEVIATION

NOTE : OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc.

Table 142

COMBINED SEWER OVERFLOW CHARACTERISTICS USED IN THE STATISTICAL MODEL

Indicator	Data Base[a]	Number of Samples	Log-Normal Statistics[b]		Normal Statistics[c]		
			μ	σ	$\mu(c)$	$\nu(c)$	$\nu(m)$
Conductivity	1	210	6.86	0.392	1,019	0.407	2.66
Fecal Coliform	2	102	14.2	1.06	2.6×10^6	1.44	3.01
Lead	3	≈ 50	6.21	0.800	699	1.00	2.82

[a]*Data base: 1) Jones Island wastewater treatment plant wet-weather influent grab samples; 2) Jones Island influent wet-weather grab samples; 3) Milwaukee Metropolitan Sewerage District combined sewer overflow facility plan, May 1979.*

[b] *Symbols: μ and σ are the mean and standard deviation of the log-transformed data, respectively.*

[c]*$\mu(c)$ is mean of concentration data; $\nu(c)$ is the coefficient of variation of the concentration data, $\nu(c) = [\exp(\sigma^2) - 1]^n$, where $n = 0.5$; $\nu(m)$ is the coefficient of variation of mass loading,*

$$\nu(m) = \nu(c) \cdot \nu(V) \cdot \left(\frac{1}{\nu^2(c)} + \frac{1}{\nu^2(V)}\right)^{1/2}, \text{ where } \nu(V) = 2.64.$$

Source: HydroQual, Inc.

Fecal Coliform: Dry- and all-weather simulations for summer periods were conducted for fecal coliform. Transport characteristics and concentration characteristics using statistical input data from Tables 140, 141, and 142 were input to the model.

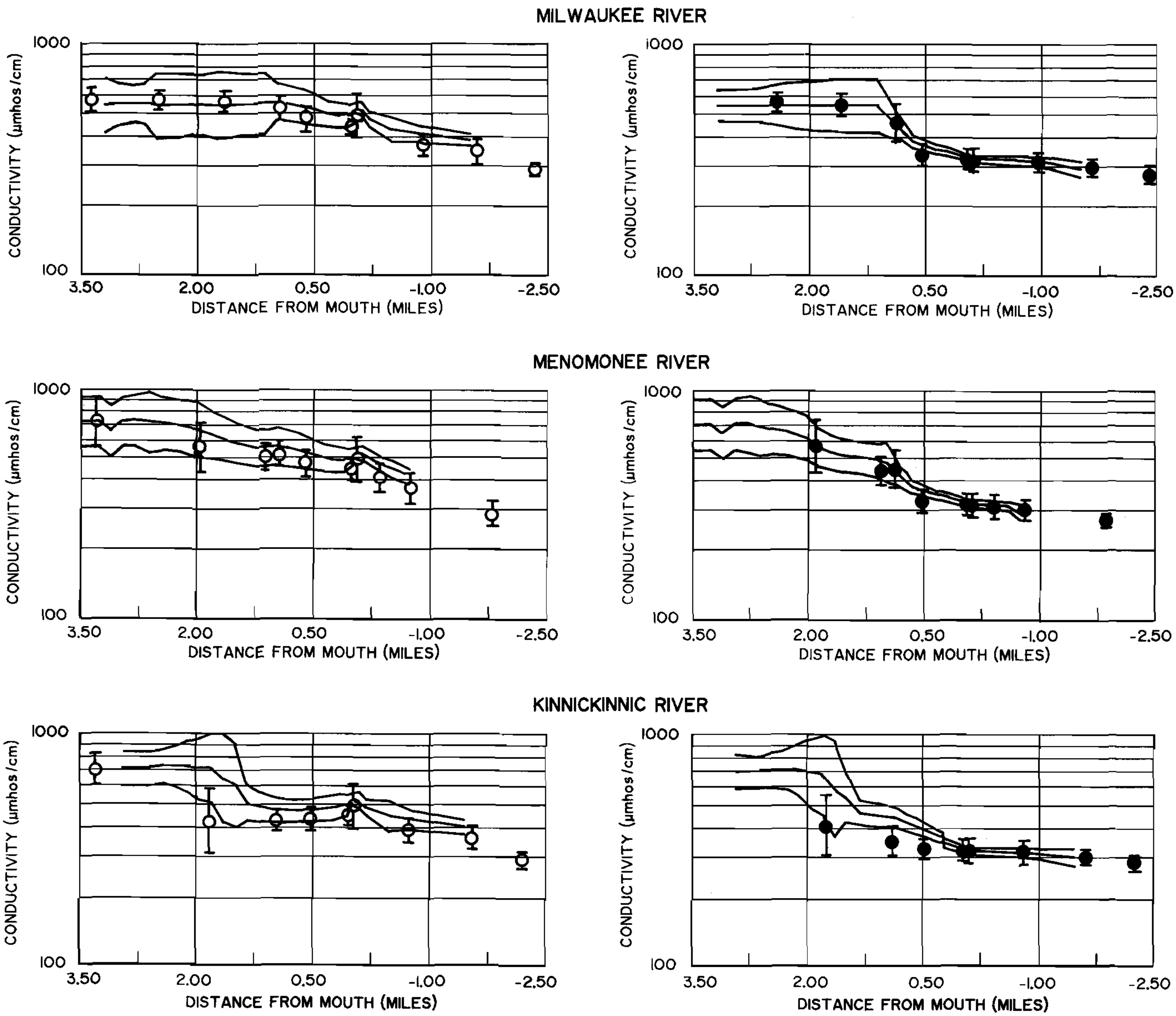
Fecal coliform were assumed to behave according to first-order reaction rate kinetics. A die-off rate of 1.0 per day was used for boundary river sources and 2.0 per day for combined sewer overflow and dry-weather overflow from separate sanitary sewers. The lower rate for the tributary rivers reflects the more resistent bacteria remaining from upstream sources. In the estuary, the coliform die-off rate in the bottom layer was set to zero because ultraviolet light, which kills coliform, does not penetrate to those depths. The outer harbor and Jones Island wastewater treatment plant effluent loadings of fecal coliform during dry weather were relatively small. Consequently, the modeling results for dry weather primarily reflect the effects of upstream sources.

The dry-weather simulation used a correlation time of one day because day-to-day coliform levels were essentially independent. Only the surface layer is illustrated because only surface layer coliform data were collected. Measured and simulated results are compared in Figure 224. The figure includes the results of two simulations: one without dry-weather overflow, and one with it. The simulation without dry-weather overflow underestimated mean coliform levels, although variability was similar. The high measured mean levels suggested that a significant source of coliform, such as dry-weather overflow, was not accounted for in the model. Dry-weather overflow statistical characteristics were estimated from Jones Island wastewater treatment plant influent data and input to the model. The dry-weather overflow volume was determined by trial-and-error fitting to the receiving water data.

The all-weather simulation of summer fecal coliform was also performed with and without dry-weather overflow. Measured and simulated results are compared in Figure 225. In contrast

Figure 223

COMPARISON OF SIMULATED AND MEASURED ALL-WEATHER SUMMER CONDUCTIVITY FOR 10-DAY CORRELATION TIME



LEGEND

MEASURED DATA

GEOMETRIC MEAN ± ONE LOG STANDARD DEVIATION

○ MEAN VALUE IN SURFACE LAYER

● MEAN VALUE IN BOTTOM LAYER

MODEL SIMULATED DATA

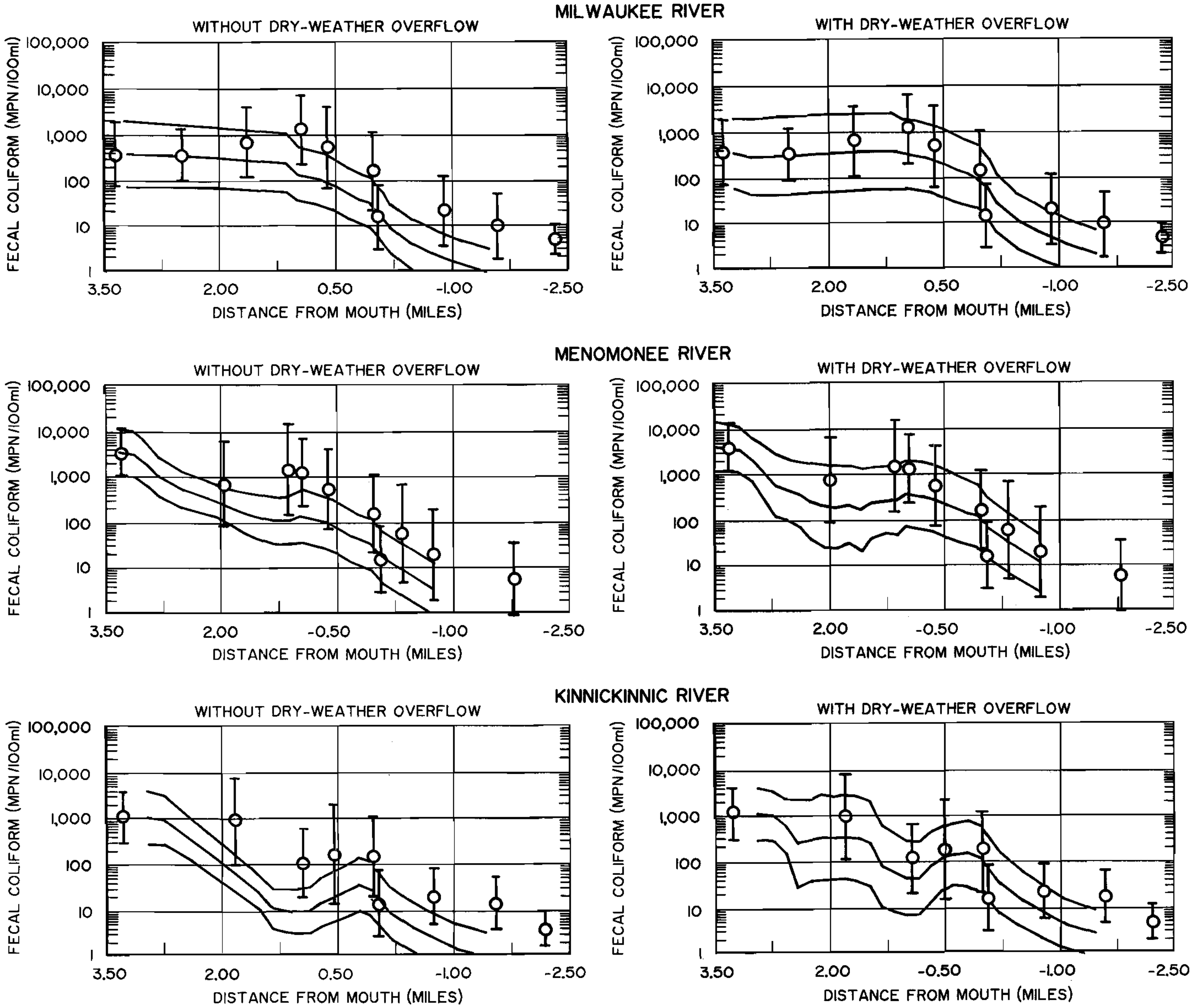
SIMULATED GEOMETRIC MEAN ± ONE LOG STANDARD DEVIATION

NOTE : OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc. and SEWRPC.

Figure 224

COMPARISON OF SIMULATED AND MEASURED DRY-WEATHER SUMMER FECAL COLIFORM LEVELS FOR ONE-DAY CORRELATION TIME



LEGEND

MEASURED DATA

GEOMETRIC MEAN ± ONE LOG STANDARD DEVIATION

O MEAN VALUE IN SURFACE LAYER

MODEL SIMULATED DATA

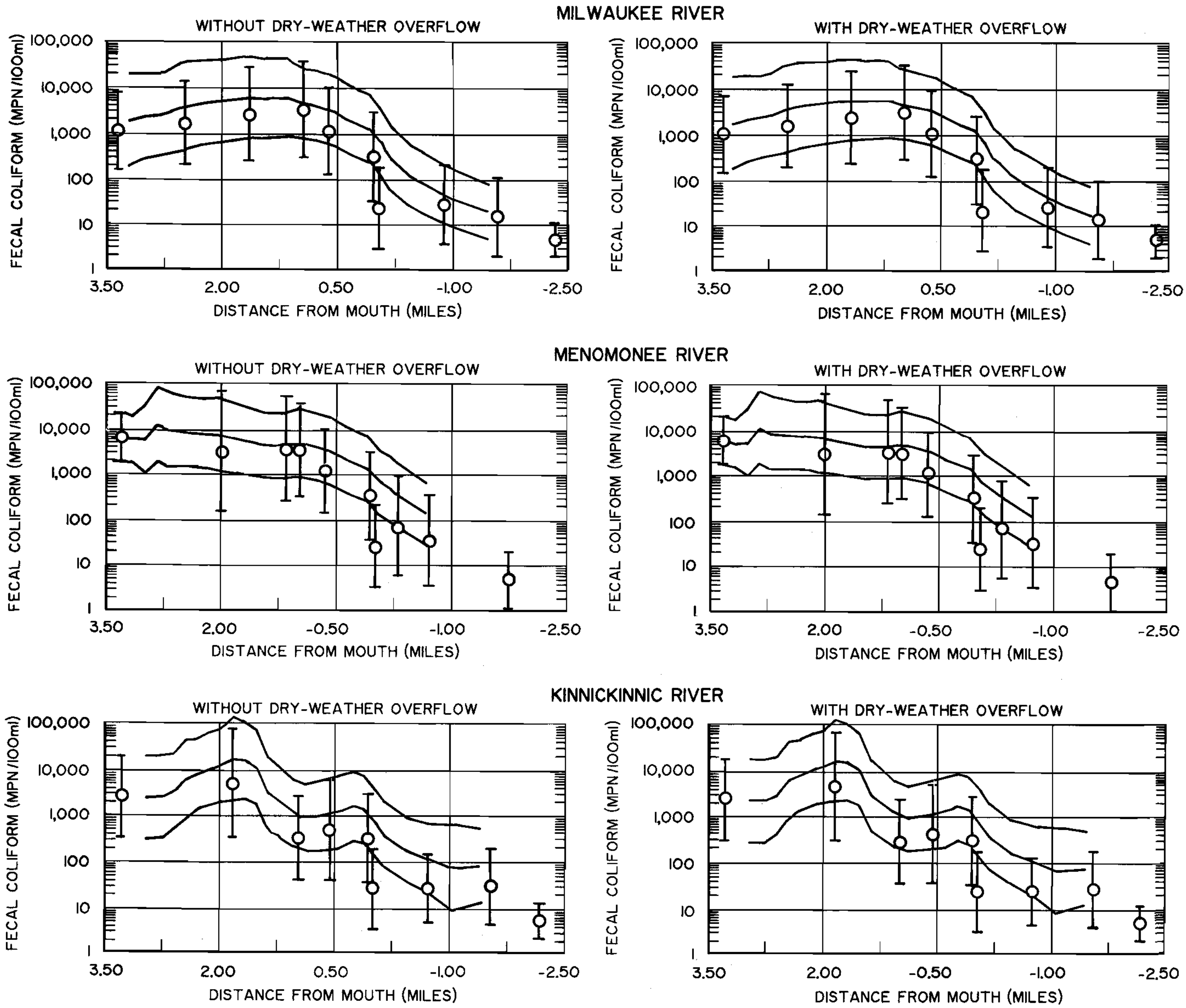
SIMULATED GEOMETRIC MEAN ± ONE LOG STANDARD DEVIATION

NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc. and SEWRPC.

Figure 225

COMPARISON OF SIMULATED AND MEASURED ALL-WEATHER SUMMER FECAL COLIFORM LEVELS FOR ONE-DAY CORRELATION TIME



LEGEND

MEASURED DATA

GEOMETRIC MEAN ± ONE LOG STANDARD DEVIATION

O MEAN VALUE IN SURFACE LAYER

MODEL SIMULATED DATA

SIMULATED GEOMETRIC MEAN ± ONE LOG STANDARD DEVIATION

NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc. and SEWRPC.

to the dry-weather simulations, the all-weather simulation without dry-weather overflow fit the observed data satisfactorily, in part because the fecal coliform levels in the estuary were dominated by combined sewer overflow. The simulation with dry-weather overflow was only marginally different.

Lead: Dry- and all-weather simulations for summer periods were also conducted for lead. Transport characteristics and statistical characteristics from Tables 140, 141, and 142 were input to the model. All-weather means were similar to dry-weather means, but exhibited significantly higher variability. Because only five summer samples were analyzed for lead at each station, the accuracy of the statistical characteristics for lead was limited.

Measured and simulated lead concentrations for dry weather are compared in Figure 226. As indicated, mean lead concentrations in the surface and bottom layers of the Milwaukee River and the north transect of the outer harbor are satisfactorily reproduced by the model. There was a slight oversimulation in the vicinity of the confluence with the Menomonee River. Simulated lead variability for the Milwaukee River was generally satisfactory.

Surface and bottom layer mean lead concentrations and variability were satisfactorily reproduced by the model for dry weather in both the Menomonee inner harbor and the middle transect of the outer harbor with the exception of the reach in the vicinity of the confluence with the Milwaukee River. In the Kinnickinnic inner harbor, surface layer mean lead concentrations and variability were satisfactorily simulated by the model at the sampling stations except at S. 1st Street (RIV-14), where the simulated mean was significantly higher than the measured mean. Simulated bottom layer means were generally satisfactory.

The all-weather summer simulation for lead generally satisfactorily simulated concentrations in the surface layer in both the inner and outer harbors, with the exception of surface and bottom layers of the Kinnickinnic inner harbor, the south transect, and the confluence of the Milwaukee and Menomonee Rivers, where the lead concentrations were slightly oversimulated, as shown in Figure 227.

SUMMARY

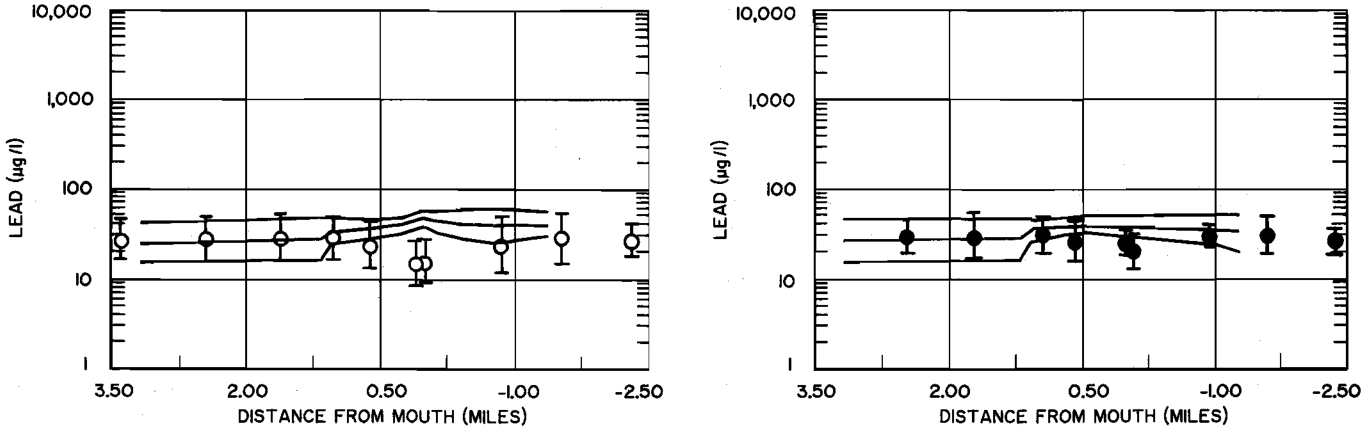
Mathematical simulation modeling was used extensively in the Milwaukee Harbor estuary study. Simulation modeling for the study was conducted by the U. S. Geological Survey, the Southeastern Wisconsin Regional Planning Commission, and HydroQual, Inc., consultant to the Commission. The U. S. Geological Survey operated two simulation models: 1) a hydrologic model (HSPF Model), also utilized within the Region by the Regional Planning Commission, which simulated runoff from inner harbor estuary shoreland areas not served by combined sewers; and 2) a hydraulic model (Branch Network Model) which simulated in one dimension the flow rates within the inner harbor estuary. The Regional Planning Commission operated a hydrologic/hydraulic model (Systems Analysis Model) which simulated combined sewer overflow rates and volumes. HydoQual, Inc., operated the water quality simulation model for the inner and outer harbor estuaries, this model being comprised of: a submodel for bottom sediment processes and sediment-water column interaction; a submodel for steady-state conditions in the water column; a submodel for time-variable conditions in the water column which required hydrodynamic simulation; and a statistical submodel for simulating random water quality conditions related to the occurrence of precipitation. The relationship of the simulation models used in the estuary study is shown graphically in Figure 228.

This simulation modeling was used to describe existing and historical conditions and to predict probable future conditions. Existing conditions could have been measured, monitored, or sampled, but, as a practical matter, for only a limited duration and areal extent. Also, critical conditions of the past could not be measured after the fact. These conditions, however, could be simulated using a mathematical model. Simulation modeling was utilized to provide information not only at sites where data had been collected, but also at desired intermediate locations. This allowed for identification of information at critical locations for existing and probable future conditions, including such conditions under alternative pollution abatement plans.

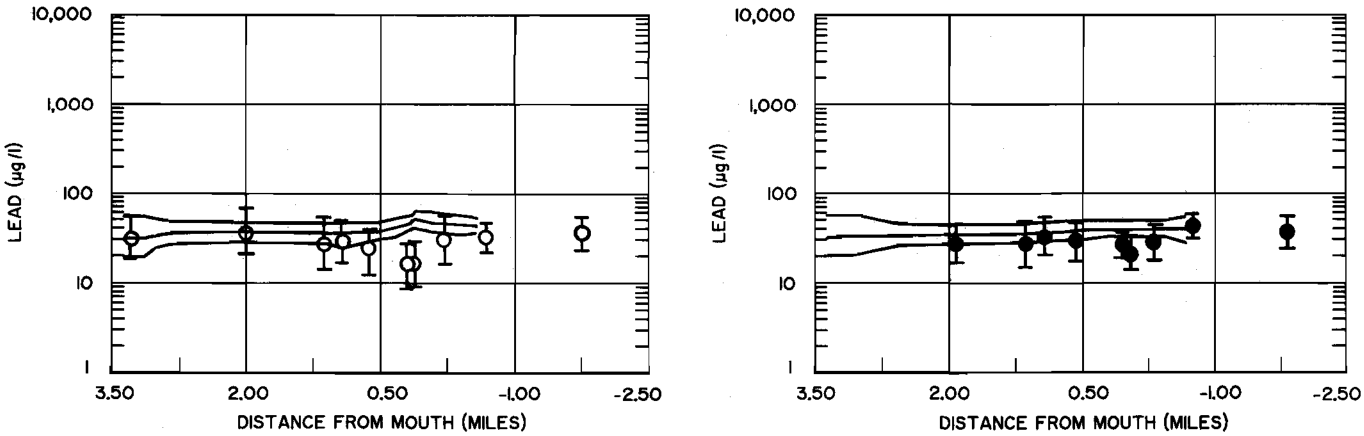
Figure 226

COMPARISON OF SIMULATED AND MEASURED DRY-WEATHER SUMMER LEAD CONCENTRATIONS

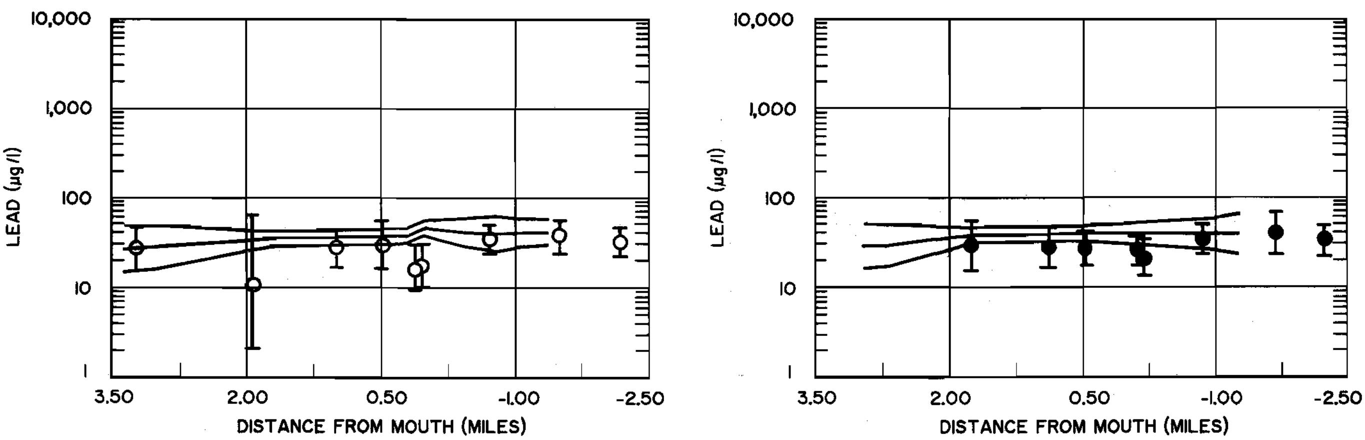
MILWAUKEE RIVER



MENOMONEE RIVER



KINNICKINNIC RIVER



LEGEND

MEASURED DATA

GEOMETRIC MEAN ± ONE LOG STANDARD DEVIATION

O MEAN VALUE IN SURFACE LAYER

● MEAN VALUE IN BOTTOM LAYER

MODEL SIMULATED DATA

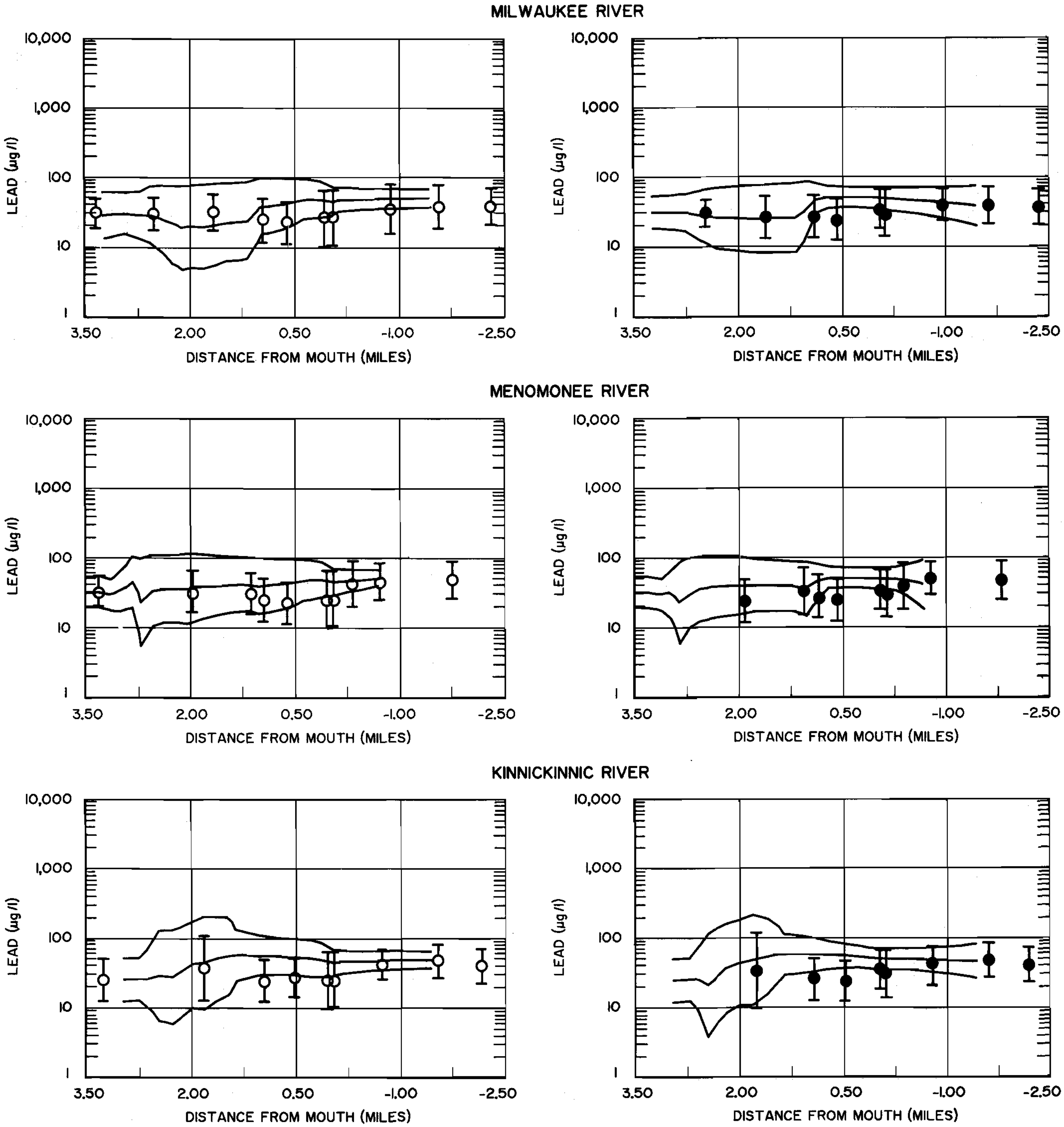
SIMULATED GEOMETRIC MEAN ± ONE LOG STANDARD DEVIATION

NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc.

Figure 227

COMPARISON OF SIMULATED AND MEASURED ALL-WEATHER SUMMER LEAD CONCENTRATIONS



LEGEND

MEASURED DATA

GEOMETRIC MEAN ± ONE LOG STANDARD DEVIATION

O MEAN VALUE IN SURFACE LAYER

● MEAN VALUE IN BOTTOM LAYER

MODEL SIMULATED DATA

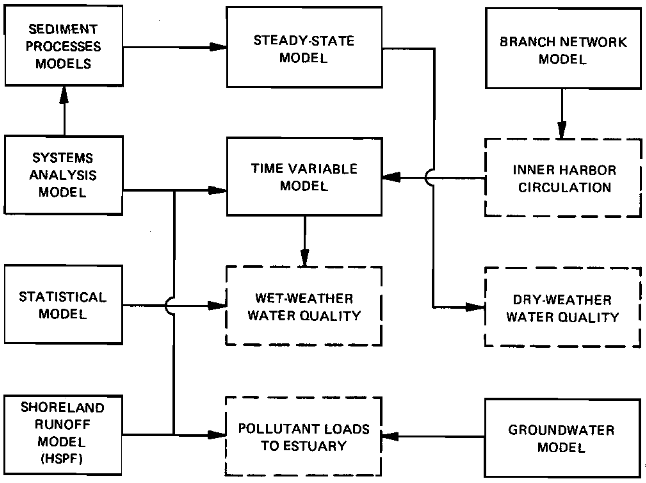
SIMULATED GEOMETRIC MEAN ± ONE LOG STANDARD DEVIATION

NOTE: OUTER HARBOR PROFILES SHOWN ON THE MILWAUKEE RIVER, MENOMONEE RIVER, AND KINNICKINNIC RIVER PLOTS ARE FOR THE NORTH, CENTRAL, AND SOUTH TRANSECT SAMPLING STATIONS RESPECTIVELY.

Source: HydroQual, Inc. and SEWRPC.

Figure 228

RELATIONSHIPS OF SIMULATION MODELS USED IN THE ESTUARY STUDY



Source: SEWRPC.

The utility of a simulation model is severely limited if insufficient calibration data are available. The accuracy of the calibrated model, however, only need be sufficient to meet the accuracy required in the model outputs. Of the models and submodels operated for the estuary study, some outputs were more critical than others and, consequently, some models or submodels were more thoroughly calibrated than others. In all cases, however, modeling accuracy was deemed adequate for the intended purposes.

The Hydrological Simulation Program-Fortran, commonly referred to as HSPF, was utilized by the U. S. Geological Survey to simulate runoff for use in estimating pollutant loadings from 367 acres of tributary area not served by combined sewers and draining directly to the inner harbor.

The U. S. Geological Survey utilized the hydrologic submodel of HSPF to simuate mean runoff for 1981, 1982, and January through September 1983 from storage areas for coal, salt, and scrap iron, and from other industrial land use shoreland areas. The storage areas for coal, salt, and scrap iron totaled, respectively, 1.8, 3.3, and 18.0 acres in area. Simulated runoff was used with estimated mean concentrations of lead, phenols, chromium, mercury, and arsenic obtained from sample data described in Chapter VI to compute annual loads of these substances to the inner harbor from shoreland areas. The results of the modeling are described in Chapter VI of this volume.

The U. S. Geological Survey also operated a hydraulic model of the inner harbor estuary, called the Branch Network Model, which is a one-dimensional unsteady flow simulation model utilized to provide estimates of Lake Michigan flood and ebb flow within the inner harbor. The model was developed to simulate unsteady one-dimensional flows in reaches of the interconnected channels of the inner harbor that were subject to variable backwater effects caused by seiches and storm surges that occurred on Lake Michigan. The Branch Network Model used a four-point, implicit, finite-difference approximation of the unsteady flow equations as the computational approach.

Input to the Branch Network Model included channel geometry, and time series data for tributary flow, diversions, wind velocity, and Lake Michigan water level fluctuations. Output from the Branch Network Model were net average discharge and water level in a time series format at selected locations in the inner harbor. Calibration of the Branch Network Model for the inner harbor of Milwaukee was achieved by appropriate adjustments to certain model parameters until satisfactory agreement occurred between observed and simulated water levels and flows measured by the U. S. Geological Survey. Model parameters subjected to adjustment included the water-surface wind-dry coefficient, the momentum coefficient for velocity distribution, the Manning's roughness coefficient, the finite-difference weighting factor, and the geometry weighting factor.

The calibration process found that the model was not sensitive to changes made in the wind-drag coefficient, nor to the effects of the wind, nor to changes in the value of the roughness coefficient. An average coefficient of 0.024 was used throughout the inner harbor with satisfactory results. Momentum coefficients assigned ranged from 1.00 to 1.02, and were based on previous model applications by the U. S. Geological Survey elsewhere. These values also were found to yield satisfactory results in the Milwaukee Harbor.

In contrast, the calibration process found that the model was sensitive to the weighting factors for the finite difference and for geometry parameters. The best calibration results were obtained using weighting factors of 0.7 and 0.6, respectively. The calibration process found that a five-minute computation interval more accurately simulated rapidly changing flow than did a 15-minute or 60-minute interval. Mean daily flows were simulated equally well by all three time intervals, however.

Stages simulated by the Branch Network Model were generally within 0.1 foot of the observed stages. There were occasional five-minute lags in the peak and trough values between the simulated and observed data. The overall fits, however, appeared satisfactory. The results of the modeling are described in Chapter V of this volume.

Potential pollution of the Menomonee River estuary from groundwater discharge in the industrialized Menomonee River Valley was investigated by the U. S. Geological Survey as part of the Milwaukee Harbor estuary study. Because the land surface of the valley was occupied by industrial and commercial buildings and accompanying uncovered storage and work yards, pollution of infiltrating precipitation by undesirable substances on the land surface could potentially pollute the near-surface aquifer and, through discharge of the polluted groundwater, the adjacent Menomonee River estuary. To evaluate the pollution potential, the U. S. Geological Survey constructed a network of six observation wells in the Menomonee Valley for collection of groundwater level and chemistry data to be used in simulation of pollutant loads to the Menomonee River estuary.

The groundwater flow model for the Menomonee River estuary was constructed around three pairs of observation wells placed along and on opposite sides of the river. The flow model was operated for water year 1983 to determine an annual mean groundwater discharge to the reach. The unit discharge for each well was multiplied by an associated reach length. The reach flows were summed to obtain total discharge to the river. A total flow was computed of 275,000 cubic feet, which was equivalent to an average continuous flow of only 0.01 cubic foot per second, or 5,600 gallons per day. Groundwater pollutant loads for water year 1983 were estimated by applying the model discharges to measured contaminant concentrations. Computed loads are presented and discussed in Chapter VI of this volume. Study results indicated that, with the exceptions of sodium and chloride, the contaminant loadings contributed to the Menomonee River estuary from groundwater were generally insignificant compared to upstream river loadings.

It would have been impractical to measure the flow from the 109 outfalls in the combined sewer system of Milwaukee into the Milwaukee Harbor estuary and the tributary rivers for the three-year field monitoring period. To quantify combined sewer overflow volume, and ultimately to estimate pollutant loads discharged from combined sewer overflow, a mathematical model of the combined sewer service area drainage network previously developed for the Milwaukee Metropolitan Sewerage District was utilized in the Milwaukee Harbor estuary study. The model was called the Wastewater Collection System Analysis Model (SAM). The model was utilized in the estuary study to simulate a storm event on September 10, 1983. The simulated results were used to check a simpler method for estimating combined sewer overflow volume which was used for other storms during the monitoring period.

SAM was composed of four submodels: 1) the runoff submodel; 2) the dry-weather flow submodel; 3) the infiltration/inflow submodel; and 4) the transport submodel. Input to the SAM runoff submodel was principally a time series of rainfall. Rainfall losses due to infiltration, vegetal interception, depression storage, evaporation, and transpiration were calculated, with the rainfall excess being allowed to run off.

The runoff rate was calculated by SAM using kinematic-wave equations for overland flow. Variables in the equations included Manning's roughness coefficient for the runoff surface, basin length, average basin slope, and surface detention storage. The area tributary to each outfall was divided into subareas of about 10 to 20 acres each, with each having times of concentration of about 5 to 10 minutes. Within each subarea the pervious and impervious areas were modeled separately, with the respective runoff hydrographs being added together at the sewer inlet node. Manning's roughness coefficients used for overland flow were 0.250 and 0.020 for pervious and impervious areas, respectively.

Data required by SAM for the dry-weather submodel were population density for each subbasin, average daily per capita flow, and commercial and industrial flow. Average dry-weather flow in SAM was multiplied by a time-based daily peaking factor so that the flow rate at any time of day could be estimated.

The infiltration/inflow submodel of SAM either was based on measured flow rates, or computed the flow rates by multiplying a user-selected rate times the ratio of actual pipe circumference and length to that for a 12-inch, 100-foot pipe in the same condition.

The transport submodel of SAM simulated the movement of water through the combined sewer system. Hydrographs were routed through the conduits by the modified kinematic wave method. The transport submodel also analyzed surcharging, noncircular pipes, conduits with variable roughness, pump stations, diversions, and parallel pipes. Input data included conduit size, shape, length, slope, roughness, and leakage condition; pump station dimensions and operating criteria; and diversion rating curves for depth and flow rate.

Runoff calibration was performed by comparing simulated peak overland flows with flows computed using the rational method, and with satisfactory agreement. Transport submodel calibration was achieved by comparing simulated peak flows at combined sewer overflow outfalls with rational method flows, again with satisfactory agreement. Modeling results for the period September 10-14, 1983, are described in Chapter VI of this volume.

Water quality conditions in the Milwaukee Harbor estuary are influenced by the hydrodynamic circulation within the estuary, which affects the dilution and transport of pollutants, and by the nature of occurrence of the pollutant discharges to the estuary, especially from combined sewer overflows. The combination of these two phenomena necessitated the development and calibration of mathematical simulation models to assure meaningful analyses of existing and projected water quality conditions. Mathematical simulation models were subsequently developed and calibrated to study sediment processes, dry-weather steady-state conditions, and dry- and wet-weather time-variable conditions. A statistical model for predicting fecal coliform and toxic metal concentrations in the estuary was also developed.

Two models were developed and applied by HydroQual, Inc., to simulate organic material fluxes from the bottom sediments to the overlying water column, and to quantify the effect of the bottom sediments on dissolved oxygen concentrations in the overlying water—namely, the sediment diagenesis model and the sediment flux model. The sediment diagenesis model simulated particulate organic carbon decomposition and was used to quantify total diagenetic rates in the inner harbor. These rates served as input functions for the sediment flux model, a more detailed model of sediment diagenetic reactions used to compute the component fluxes required in the water quality models. The sediment diagenesis and sediment flux model inputs, functional parameters, and outputs are listed in Table 143, along with the basis for selection of each component parameter.

The sediment diagenesis model was calibrated using the experimental diagenesis data described in Chapter VI of this volume. Water column profiles of particulate organic carbon concentrations in the surface and bottom water layers showed good agreement between calculated results and mean annual data. The large standard deviations exhibited by the measured data indicated a significant concentration variability.

The diagenesis modeling analysis also provided a quantitative measure of the importance of both combined sewer overflow and upstream pollution sources to the carbon flux to the bottom sediments. In order to evaluate the effects of organic carbon loadings on the inner harbor, the water column was simulated by a two-layer model with a countercurrent circulation pattern in the downstream reaches of the inner harbor.

Particulate organic carbon in combined sewer overflow and noncombined sewer overflow was estimated to be 30 and 60 percent reactive, respectively, of which 80 percent of the combined sewer overflow reactive material load, and 100 percent of the noncombined sewer overflow reactive material load, were estimated to be labile, or rapidly reacting. The remaining 70 percent of the organic carbon loading from combined sewer overflows, and 40 percent of the organic carbon

Table 143

COMPONENTS OF THE WATER QUALITY MODEL

Submodel Component	Basis
I. Sediment Diagenesis Model (average annual)	
A. Input	
1. Upstream Load	Probability analysis of baseline data
2. Combined Sewer Overflow Load	Wet-weather raw sewage grab samples
3. System Geometry	U. S. Army Corps of Engineers sounding data
B. Model Parameters	
1. Diagenesis Rates	Diagenesis experiment
2. Labile Fractions	Diagenesis experiment
3. Particle Settling Rates	Sediment traps, column tests, literature
4. Net Sedimentation Rate	SEWRPC analysis of U. S. Army Corps of Engineers sounding data
C. Output	
1. Water Column Particulate Organic Carbon	Calibration results
2. Total Diagenesis Rate (at Mean Temperature)	Calibration results
II. Sediment Flux Model (each survey period)	
A. Input	
1. Total Diagenesis ($J[O_2+]$)	Sediment diagenesis model (IC2, above)
at Survey Specific Temperature (O, T)	Regression analysis
2. Water Temperature (T_w) and Depth (H)	Baseline monitoring data
to Compute Diffusiveness (D_s) and Saturation (C_s)	Calculated
3. Water Column Dissolved Oxygen (L_a Computed)	Observed or computed
B. Model Parameters Nitrification Rate Coefficient (K_n), Methane Oxidation Rate Coefficient (K_c), and Depth of the Water Column (H)	Fit to field data
C. Output	
1. Sediment Oxygen Demand	Calibration results
2. Gas Flux (methane and nitrogen)	Calibration results
3. Diffusive Flux (dissolved methane and ammonia)	Calibration results
III. Water Quality Model (each survey period)	
A. Input	
1. Upstream Flow	U. S. Geological Survey gaging station data
2. Boundary Water Quality	Baseline monitoring data
3. Sediment Fluxes	Computed (IIC, above)
4. Jones Island Sewage Treatment Plant Load	Milwaukee Metropolitan Sewerage District
5. Solar Radiation	Computed (Mitchell Field minutes of sunshine)
6. Water Temperature	Observed baseline data
7. System Geometry	U. S. Army Corps of Engineers sounding data
B. Model Parameters	
1. Advective and Dispersive Transport	Tracer calibration
2. Carbonaceous Biochemical Oxygen Demand Removal and Deoxygenation Rate f	Biochemical Oxygen Demand time series analysis
3. Nitrification Rate Coefficient	Ammonia and nitrate calibration
4. Reaeration Rate Coefficient	Minimum surface transfer coefficient
5. Photosynthesis-Light Relationship (P_s, I_n)	Light and dark bottle studies
6. Algal Respiration Rate	Chlorophyll-a calibration
C. Output	
1. Conductivity and Chlorides	Calibration results
2. Ammonia and Nitrate Nitrogen	Calibration results
3. Chlorophyll-a Calibration	Calibration results
4. Carbonaceous Biochemical Oxygen Demand and Dissolved Oxygen	Calibration results

Source: HydroQual, Inc.

loadings from sources other than combined sewer overflows, were estimated to be inert.

The diagenesis model was used to help establish the total carbon balance in the inner harbor, thereby providing quantitative assessment of the significance of different carbon sources, including combined sewer overflows, to the carbon flux to the sediment. Fifty-four percent of the carbon flux to the sediment, 91 percent of which was of combined sewer overflow origin, was estimated to be inert material which decomposed at a negligible rate. The remaining 46 percent was estimated to be reactive material: 7 percent was refractory—or slowly reacting—combined sewer overflow material, 25 percent was labile—or rapidly reacting—combined sewer overflow material, and 14 percent was labile noncombined sewer overflow material. Thus, both combined sewer overflow and noncombined sewer overflow sources constitute significant inputs of reactive material to the sediments, with the combined sewer overflow contribution thereof being about 70 percent. Algae represented approximately one-third of the noncombined sewer overflow contribution to the sediment carbon flux in the inner harbor, and 10 percent of the overall flux of reactive particulate organic carbon to the sediment.

The sediment flux model was comprised of two submodels: a methane oxidation submodel and an ammonia oxidation submodel. The submodels linked a sequence of reduction-oxidation reactions together with mass transport mechanisms to simulate sediment oxygen demand. That sediment oxygen demand was caused by the oxidation of dissolved substances—primarily methane and ammonia—which were produced by the diagenesis reactions and which diffused to the sediment-water interface. A predominance of methane in gas released from the inner harbor sediments suggested that methane oxidation is the major source of sediment oxygen demand. The methane, along with ammonia, is produced by the anaerobic fermentation of organic matter. The principal component of the oxygen demand exerted by the diagenesis reaction was the oxidation of dissolved methane. Gaseous methane was assumed to escape and to not be oxidized at the sediment-water interface.

Although the primary component of gas released from the inner harbor bottom sediments was methane, there was also a significant release of nitrogen gas produced by the oxidation of ammonia and subsequent denitrification of the nitrate so produced. Nitrification is defined as the biological conversion of organic or inorganic nitrogen—such as ammonia—to a more oxidized state—such as nitrate. Denitrification is defined as the biochemical reduction of nitrate or nitrite to gaseous nitrogen. Denitrification occurs under anaerobic conditions.

The sediment flux model was calibrated using both laboratory and field data. A sediment dilution laborary experiment was conducted to examine the variation of sediment oxygen demand, gas production, and ammonia flux as the diagenesis rate varied. A comparison of the model-simulated data to the sediment dilution experiment data indicated that the principal features that determine sediment oxygen demand, gas production, and ammonia flux were well represented by the sediment flux model. The model reproduced the observed gas and ammonia fluxes, but underestimated the sediment oxygen demand slightly at the very lowest dilution rates.

The sediment flux model was also calibrated with sediment oxygen demand and gas production and decomposition data collected at nine inner harbor stations during 1982 and 1983. Although the simulated data compared well with the measured data, the model appeared to underestimate sediment oxygen demand at lower levels of diagenesis. Both the measured and simulated data indicated that changes in the diagenesis rate, as represented by the methane gas flux, resulted in a smaller proportional change in sediment oxygen demand. Thus, changes in the diagenesis rate had greater effects on gas production and ammonia flux, and less effect on sediment oxygen demand. The sediment flux model calibration also indicated that the model simulated the composition of gases produced by sediment diagenesis reasonably well.

A steady-state water quality model, coupled with a two-layer transport model and the sediment diagenesis and flux models, was used to simulate water quality conditions within the inner and outer harbors under steady flow and pollutant loading conditions. The inputs, functional parameters, and outputs of this model are listed in Table 143, along with the basis for selection of each component parameter.

Estuaries such as the inner harbor are frequently characterized by a two-layer flow regime which is controlled by a density-driven underflow in the upstream direction and a countercurrent downstream flow in the surface layer. The conservative indicators, conductivity and chloride, were used as tracers to provide an effective means of quantifying the effects of lake water intrusion, thereby providing a relatively simple, yet effective, means of characterizing advective and dispersive transport in the inner harbor.

The two-layer transport model was calibrated for four survey periods with a range of flow and water temperature conditions. The period ranged from one day to 24 days in duration. The survey periods were selected based upon a careful review of rainfall, river flow and baseline water quality sampling data which indicated relatively constant conditions within the estuary. Using the assigned boundary conditions, the steady-state model was used to compute the resulting tracer profile. The computed and measured data were in satisfactory agreement throughout the inner and outer harbor areas for both tracers. The tracer profiles were similar in all three rivers, with a gradual decline in upstream tracer levels to near-shore Lake Michigan tracer levels within a distance of about three miles. The vertically mixed water column in the upstream part of the estuary in all three rivers became increasingly stratified in the downstream direction, with marked vertical gradients present at the downstream inner harbor and outer harbor stations. However, during three of the four survey periods, there did not appear to be much lake water intrusion in the Milwaukee River upstream of the confluence with the Menomonee River.

In general, the two-layer pattern of stratification was apparent for a greater distance upstream in the Menomonee River estuary than in the Milwaukee or Kinnickinnic River estuaries. This persistent pattern was attributed to the effects of the Wisconsin Electric Power Company power plant condenser cooling water intake from the Menomonee River estuary and thermal discharge to the South Menomonee Canal, to relatively low upstream flows which contribute to the more pronounced intrusion of lake water, and to the greater depths in the Kinnickinnic and Menomonee River estuaries which are dredged to maintain commercial navigation.

Analysis of the dissolved oxygen levels in the inner harbor required a detailed evaluation of the important sources and sinks of oxygen affecting the dissolved oxygen balance. Special studies were performed to evaluate the significance of the oxidation of organic matter, algal photosynthesis and respiration, and sediment-water interactions.

For the steady-state water quality model, the sediment diagenesis model was used to compute the total diagenesis flux from the sediment, and the sediment flux model was used to compute the diagenesis components, including carbon and nitrogen fluxes, gas production, and sediment oxygen demand. The oxidation of dissolved methane and ammonia at the sediment water interface and within the water column affected the water column dissolved oxygen concentration, which in turn controlled the magnitudes of the component fluxes in the sediment flux model. Thus, the sediment and water column computations were performed interactively in the steady-state modeling analysis. The steady-state water quality model was calibrated for the same four survey periods used for the calibration of the two-layer transport model.

The model was calibrated for chlorophyll-a, ammonia nitrogen, nitrate nitrogen, biochemical oxygen demand, and dissolved oxygen. During each of the individual survey periods, simulated levels of some indicators were not in good agreement with measured levels. When considered for all four survey periods together, however, the modeling results compared well with the measured data, indicating that the modeling assumptions and input parameters were reasonable and satisfactory.

In assessing the significance of the individual sources and sinks of oxygen, it is useful to consider the components of the dissolved oxygen deficit. The dissolved oxygen deficits computed in the steady-state simulation of four different survey periods indicated that from one-third to over one-half of the deficit results from sediment processes, with the highest proportion being caused by the oxidation in the water column of the dissolved organic carbon flux from the sediment and, to a lesser degree, the direct oxygen demand of the sediment. The dissolved oxygen deficit due to the Jones Island sewage treatment plant discharge was relatively insignificant in both the inner and outer harbors. The dissolved oxygen deficit due to CBOD contributed from sources upstream of the estuary is significant, accounting for between 1.0 and 2.0 mg/l, or about 25 percent of the total deficit which varies from 4 to 9 mg/l. Finally, the deficit resulting from net photosynthesis by algae is clearly a sink of dissolved oxygen in the Milwaukee and Menomonee Rivers, but is normally not a significant sink of oxygen in the Kinnickinnic River or in the outer harbor.

The time-variable water quality simulation model of the inner harbor of Milwaukee was the first successful union of a state-of-the-art hydrodynamic model with a water quality model for the Milwaukee estuary system. This effort was deemed necessary in order to simulate the response of the inner harbor to relatively large and fast changes in inflow and inflow water quality during the periods to be simulated. Such periods included combined sewer overflow events, significant seiches on Lake Michigan, and diurnal algal production. The model inputs, functional parameters, and outputs of this model are listed in Table 143, along with the basis for selection of each component parameter.

The hydrodynamic submodel of the time-variable water quality model included circulation induced by the interaction of both barotropic and baroclinic pressure gradients. The interaction of these pressures, along with the turbulence caused by the seiche from Lake Michigan, caused the vertical variations in velocity and temperature observed in the inner harbor. The condenser cooling water withdrawals and discharges by the Valley power plant had a large effect on these vertical variations.

The equations for inner harbor hydrodynamics were simplified by eliminating the lateral direction component. This was based on the assumption that lateral mixing was virtually complete in the relatively narrow channel system, and on the assumption that only longitudinal and vertical differences were important. Therefore, the model was two-dimensional in scope. The relevant equations were those for continuity, momentum, pressure, vertical mixing, and turbulent transport; and for temperature conservation and boundary conditions, unreactive solute tracer conservation and boundary conditions, free surface and bottom boundary conditions, and lake level boundary conditions.

The lake level boundary condition at the mouth of the Milwaukee River, based partially on the results of harmonic analysis of water level records, was incorporated into the hydrodynamic submodel in the form of an algorithm which described two prominent seiches found in the data. The hydrodynamic submodel equations and boundary conditions were used together in finite-difference form and stepped forward in time. The finite-difference scheme is explicit in the advective transport terms and implicit in the vertical diffusive flux terms. The computation time step ranged from two seconds to two minutes, depending on wave speed, reach length, and current velocity.

The model equations were in a form which allowed variable horizontal resolution. The average grid spacing was about 820 feet (250 meters), but the resolution was as small as 245 feet (75 meters) in some locations. Vertically, the model was constructed in 10 equal layers to represent the effects of the large number of bridge abutments in the inner harbor without actually incorporating the geometry of each into the model. A bottom drag coefficient twice that originally input was found to produce the appropriate response without explicitly resolving the abutments. The effective bottom roughness was computed to be 0.4 inch (1 centimeter), which was in accord with findings for other, similar systems, including the New York Harbor, where the major driving forces and bathymetric features were also resolved.

Coupling of the hydrodynamic submodel with the water quality simulation model allowed a more detailed simulation of mixing and transport in the inner harbor. It was necessary to make certain simplications to the water quality submodel during the coupling process to facilitate the development of the coupling framework.

Time-variable water quality model calibration was conducted for three "events," one being a dry-weather period ending July 26, 1982; the second being the storm runoff sampling period of September 10 through 14, 1983; and the third being the runoff event of August 10 through 12, 1983. In addition, a fourth simulation was conducted of a three-month period from July 1 through September 30, 1983, concentrating on diurnal production by algae in the inner harbor.

The time-variable water quality model was initially calibrated for solute transport simulation accuracy by comparing simulated indicators with observed conservative indicators—namely, specific conductance and temperature—for a dry-weather period ending on July 26, 1982. Good agreement was found between simulated and observed data.

For the wet-weather simulations, conductivity and temperature were first simulated to check transport calibration, followed by calibration runs for carbonaceous biochemical oxygen demand and dissolved oxygen. Reasonably good agreement with the data was found at most of the inner harbor sites.

For the wet-weather simulation of August 10-12, 1983, however, a significant decrease in dissolved oxygen, not well reproduced by the model, occurred in the inner harbor following a thunderstorm. This decrease occurred despite the fact that combined sewer overflow did not occur in significant amounts. A review of the dissolved oxygen data collected prior to and during the simulation period indicated that a possible cause of the rapid and large decline in dissolved oxygen observed at St. Paul Avenue during the runoff event was the apparent decline in algal photosynthesis, which likely occurred beginning on August 10 as cloud cover moved in prior to the storm. The event was resimulated to learn more about the large dissolved oxygen reduction and without photosynthesis to check the hypothesis, which confirmed that decline in algal productivity due to reduced solar radiation caused by cloud cover resulted in rapid dissolved oxygen decline.

To further understand the effects of algal productivity upon dissolved oxygen in the estuary, time-variable simulations were conducted for the three-month period of July 1 to September 30, 1983, with a simplified version of the time-variable model constructed for the reach of the Milwaukee River from the North Avenue dam to the confluence with the Menomonee River. The results of the three-month simulation indicated that dissolved oxygen depletion was sensitive to the level of solar radiation, the number of sequential days of low sunlight intensity, chlorophyll-a concentration, and river flow. Computed daily mean dissolved oxygen decreased most significantly after sequential days of low sunlight. When flow was high and chlorophyll-a low, dissolved oxygen did not change significantly even with reduced sunlight several days in a row.

With the available data, it was not possible to identify the specific cause(s) of reduced algal productivity in the inner harbor and the resultant rapid dissolved oxygen depletions. Increased light extinction caused by increased turbidity during wet weather and/or changes in algal productivity characteristics were the most likely causes. Other possible factors were algae inhibition by sudden temperature changes resulting from hydraulic surges, or high concentrations of heavy metals from combined sewer overflow.

Some water quality indicators—namely, fecal coliform and lead—were found to exhibit stochastic characteristics. A comparison of probability distributions of the weekly baseline data for these variables and of the data representing only dry weather indicated a significant difference, presumably caused in large part by combined sewer overflow. Although the time-variable water quality model technically was capable of simulating these variables, a statistical approach was deemed more suitable.

The statistical model of the inner and outer harbors of Milwaukee and adjacent Milwaukee Bay related the statistics of runoff and the parameters of the receiving water body to the statistics of the receiving water concentrations. The mean, variance, and correlation time of the pollutant sources were input, and the mean and variance of receiving water concentrations were computed.

The simulated receiving water concentration means and variances were then used with normal probability theory to determine log-normal distributions of concentrations of selected water quality indicators. These results were then compared with like distributions for observed data to check model calibration.

The statistical model utilized the same segmentation as that used for the steady-state water quality model and was based on summer average flows for the three tributary rivers, and on combined sewer overflow loads calculated using rainfall statistics and the combined sewer overflow/rainfall relationship. Both dry-weather and all-weather conditions were simulated.

For summer average transport calibration, conductivity data were subjected to statistical analysis to determine the sample means and variances. These statistics were computed for both dry-weather and all-weather data. Because the sample data were collected at weekly intervals, correlation time was not directly determinable and, therefore, was used as a calibration parameter.

Generally, for dry-weather conductivity the model showed that boundary variability accounted for most of the variability found in the estuary and, therefore, the dry-weather transport simulated by the statistical model appeared reasonable. For all-weather conditions, statistics for combined sewer overflow load also had to be included. A comparison of observed and simulated conductivity results for all-weather summer conditions indicated that fair agreement was obtained for mean concentrations, but variability was oversimulated at many locations.

Dry- and all-weather simulations for summer periods were conducted for fecal coliform bacteria. Transport characteristics and statistical characteristics for fecal coliform were input to the model.

Fecal coliform was assumed to behave according to first-order reaction rate kinetics. A die-off rate of 1.0 per day was used for boundary sources and 2.0 per day for combined sewer overflow and dry-weather overflow from separate sanitary sewers. In the estuary, the coliform die-off rate in the bottom layer was set to zero because ultraviolet light, which kills coliform, does not penetrate to those depths. The outer harbor and Jones Island effluent boundary levels for dry weather were relatively small. Consequently, the modeling results for dry weather primarily reflect the effects of upstream sources of fecal coliform.

The simulation analysis for dry weather suggested that a significant source of coliform, perhaps dry-weather overflow, was a major contributor to the high levels of coliform observed. In contrast to the dry-weather simulations, the all-weather simulation without dry-weather overflow fits the observed data satisfactorily, probably because the fecal coliform levels in the estuary were dominated by combined sewer overflow.

Dry- and all-weather simulations for summer periods were also conducted for lead. Transport characteristics and statistical characteristics were input to the model. Wet-weather means were 25 to 75 percent higher than dry weather means, and had significantly higher variability also. Because only five summer samples were analyzed for lead at each site, the accuracy of the statistical characteristics for lead was very limited.

A comparison of observed and simulated results for dry weather indicated that mean lead concentrations in the surface layer generally were satisfactorily reproduced by the model. A less accurate fit was computed by the model for bottom layer means. Simulated lead variability was generally satisfactory.

The all-weather summer simulation for lead generally oversimulated concentrations in the surface layer in both the inner and outer harbors. Simulated bottom layer mean concentrations were generally satisfactory, however.

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Chapter VIII

SUMMARY AND CONCLUSIONS

INTRODUCTION

The major waterways forming the Milwaukee Harbor estuary have, over time, become increasingly polluted, to the point where the pollution has significantly impaired the potential recreational use and aesthetic quality of the estuary, and desirable forms of aquatic life in the estuary. Land use development and redevelopment in areas bordering the estuary have also been adversely affected. The severely polluted condition of these waterways also threatens water quality conditions and fishery resources within Lake Michigan itself, and thereby the use of the lake as a public water supply and a recreational resource. Additional problems that exist within the estuary, problems which must be addressed in any comprehensive study of the estuarine environment, include: flooding, maintenance for commercial navigation and the ultimate disposition of dredge spoils, and storm damage prevention and shoreline protection.

In recognition of the serious water pollution problems existing within the Milwaukee Harbor estuary, the Common Council of the City of Milwaukee, in July 1973, formally requested the Southeastern Wisconsin Regional Planning Commission, upon completion of comprehensive studies of the tributary Milwaukee, Menomonee, and Kinnickinnic River watersheds, to undertake a comprehensive study of the estuary. Prior to the completion of the last prerequisite watershed study, that of the Kinnickinnic River watershed, the Commission, assisted by a Technical and Citizens Advisory Committee on Coastal Management in Southeastern Wisconsin, prepared a prospectus for a planning program that would define and address the problems of the Milwaukee Harbor estuary, as well as of the five other estuaries within the Region. This prospectus was published in September 1978, and transmitted to the governmental agencies concerned for their consideration and action.

In March 1980, the Wisconsin Department of Natural Resources (DNR) submitted a pre-application for a federal grant in partial support of a proposed project identified as: "Demonstration of the Resident Pollutant Impact on Milwaukee Harbor Estuary Water Quality." In response, the U. S. Environmental Protection Agency (EPA), in June 1980, requested the Southeastern Wisconsin Regional Planning Commission to prepare a study design for a comprehensive water resources planning program for the Milwaukee Harbor estuary. The study design was completed in September 1981 under the guidance of an Ad Hoc Technical Task Force, and proposed a cooperative planning effort by the Milwaukee Metropolitan Sewerage District, the Regional Planning Commission, the Wisconsin Department of Natural Resources, the U. S. Geological Survey, and the U. S. Environmental Protection Agency.

Work on the Milwaukee Harbor estuary planning program as outlined in the study design began in February 1982, utilizing funds made available through an agreement between the U. S. Environmental Protection Agency and the Milwaukee Metropolitan Sewerage District (MMSD). The U. S. Geological Survey, under an agreement with the Regional Planning Commission, also provided funding and staff services for specific work elements detailed in the study design.

The findings and recommendations of this intensive planning program are presented in a two-volume report. This, the first of the two volumes, sets forth the basic principles and concepts underlying the program, and the findings of the extensive inventories and analyses conducted under the program. It describes the man-made and natural resource base of the area tributary to the Milwaukee Harbor estuary; describes the hydrologic and hydraulic characteristics of the estuary; identifies and defines the existing water resource problems within the estuary and its tributaries; identifies the sources of surface water pollution in the area tributary to the estuary; and describes the mathematical simulation models and other analytical techniques used in the planning effort.

The information presented in this volume is intended to identify and definitively describe the existing water resource problems in the Milwaukee Harbor estuary, and to provide the basis for forecasts of probable future water resource problems in the estuary. This information, together with the recommended water use objectives and supporting water quality standards set forth in Volume Two of this report, was used to evaluate alternative water quality management plans, alternative dredging and dredge spoils disposal plans, and alternative storm damage protection and flood control plans. The two-volume report is intended to allow for careful, critical consideration of potential water resource management strategies for the Milwaukee Harbor estuary by public officials, agency personnel, and citizen leaders, and to provide the basis for plan adoption and implementation by the federal, state, and local units and agencies of government concerned.

STUDY PURPOSE AND ORGANIZATION

The primary purpose of the Milwaukee Harbor estuary study was to develop a sound and workable plan for the abatement of water pollution within the Milwaukee Harbor estuary so as to meet established water use objectives and supporting water quality standards in a cost-effective manner, and so as to further the protection and wise use of the natural resource base. More specifically, the study was intended to develop a plan to abate water pollution from combined sewer overflows—including a determination of the level of protection to be provided—other point sources, and nonpoint sources; to provide instream measures as may be needed to help achieve water use objectives; to abate damage caused by flooding; to provide for the continued navigation of deep draft commercial vessels through a maintenance dredging program which ensures the environmentally safe disposal of polluted spoils; to ameliorate damage in the harbor area caused by storm and wave action, and to prevent deterioration of the shoreline within the estuary; and to maximize the utilization of the estuary as a prime urban recreational area.

The technical work required was carried out by the Regional Planning Commission staff with the assistance of the staffs of cooperating governmental agencies, including the Milwaukee Metropolitan Sewerage District, the Wisconsin Department of Natural Resources, and the U. S. Geological Survey, and of private consultants engaged by the Commission, including HydroQual, Inc., Aero-Metric Engineering, Inc., and National Survey & Engineering, Inc. These organizations were selected for participation in the Milwaukee Harbor estuary study because of their skills and experience in specialized phases of water resources planning, engineering, and management. The disciplines provided through such assistance included topographic mapping and related land and control surveys; stream- and groundwater flow measurement; surface water, suspended sediment, bottom sediment, and groundwater quality sampling and analyses; fisheries studies; sediment process studies; algal studies; and hydrologic-hydraulic water quality simulation modeling. In addition, special laboratory biotoxicity tests were conducted by the U. S. Environmental Protection Agency Research Laboratory-Duluth and Ecological Analysts Engineering, Science and Technology, Inc.

INVENTORY FINDINGS

Study Area

The study area was defined as the drainage area tributary to the Milwaukee Harbor estuary. This area totals about 858 square miles, and encompasses portions of four counties in the Southeastern Wisconsin Region—Milwaukee, Ozaukee, Washington, and Waukesha—together with portions of adjacent Dodge, Fond du Lac, and Sheboygan Counties. The primary focus of the study, however, was on the inner harbor—or estuarine—portion of each of the three tributary rivers, and on the outer harbor. Although the tributary rivers are an important influence on the water quality conditions in the inner and outer harbors, the inner harbor itself—that is, the river estuaries—comprises a distinct planning unit because of its complex hydraulic interactions with the outer harbor and Lake Michigan. That portion of the total study area draining directly to the Milwaukee Harbor estuary totals about 22.2 square miles, of which about 20.7 square miles, or about 93 percent, drain directly to the inner harbor, and about 1.5 square miles, or about 7 percent, drain directly to the outer harbor.

The total study area includes all or portions of seven counties, 12 cities, 24 villages, and 30 towns. In addition to these 73 local units of government, there are numerous special districts, certain state and federal units and agencies of government, and an international agency which also have water resource and water resource-related management responsibilities. These include, among others, the Milwaukee Metropolitan Sewerage District, the Wisconsin Department of Natural Resources, the U. S. Environmental Protection Agency, the U. S. Army Corps of Engineers, and the International Joint Commission-United States and Canada.

Population

The resident population and the socioeconomic activities of that population are important determinants of pollutant loadings to surface waters, of existing and desired water uses, and of the associated need for pollution abatement and water quality management actions. This is particularly true in the case of the Milwaukee Harbor estuary, which is impacted by the activities and demands of a large and highly urbanized resident population widely distributed over the watersheds of the three tributary rivers.

The resident population of the Milwaukee Harbor estuary direct drainage area, which as of 1980 stood at 255,200 persons, or about 27 percent of the total resident population of the study area, decreased by approximately 162,600 persons, or 39 percent, between 1950 and 1980. Over the same time period, however, the resident population of the total study area, which as of 1980 stood at 970,200 persons, increased by about 154,000 persons, or about 19 percent. The resident population of the study area peaked in 1970 at about 1.04 million persons.

The Milwaukee Harbor estuary direct drainage area encompasses the most intensively urbanized portion of the Region, including the central business district of the City of Milwaukee and the heavily industrialized Menomonee River Valley. The resident population density of the direct drainage area—11,600 persons per square mile in 1980—was very high in comparison to the overall study area population density of 1,130 persons per square mile, and the overall Southeastern Wisconsin Region population density of 650 persons per square mile. Augmenting the resident population of the direct drainage area is the daily influx of commuters into the central business district of the City of Milwaukee. This daily influx was determined by Commission travel surveys to approximate 131,000 persons in 1972, and represents a more than 50 percent increase in the approximately 255,000-person resident population of the direct drainage area. This daily influx has been estimated to have increased to approximately 145,000 persons as of 1984. In addition, large seasonal influences of population seeking recreation occur.

Land Use

One of the central concepts underlying the Milwaukee Harbor estuary planning program is that land use, surface water quality conditions, and the need for water quality management facilities are closely interrelated. The type, intensity, and spatial distribution of land use are important determinants of surface water quality conditions, which in turn influence land use development and redevelopment patterns. An inventory of existing land use and of historic trends in such land use is, therefore, an important part of any water quality management planning effort.

The movement of European settlers into what is now the greater Milwaukee area was well underway by 1830 in the Milwaukee Harbor estuary direct drainage area. This early development was centered on the harbor facilities, and expanded in concentric rings around that area. By 1980, approximately 20.4 square miles, or 93 percent, of the Milwaukee Harbor estuary direct drainage area was in urban land uses, with only about 1.6 square miles, or 7 percent of the area, in open lands and surface waters. The dominant land uses in the direct drainage area are transportation and utility uses, which occupy about 8.10 square miles, or about 37 percent of the area; and residential uses, which occupy about 7.7 square miles, or about 35 percent of the area. Commercial, industrial, and governmental and institutional land uses each occupy between 1.1 and 1.3 square miles, or from 5 to 6 percent of the direct drainage area. Recreational uses, which occupy about 0.8 square mile, or 4 percent of the direct drainage area, account for the remaining urban land. In contrast, about 74 percent, or 639 square miles, of the total study area was still in rural uses in 1980, predominantly agricultural, with only 26 percent, or 219 square miles, in urban uses.

Climate

Climate, especially the extreme variations in the principal elements of climate—temperature, precipitation, and snow cover—directly affects water quality conditions and management needs. Climate determines to a large extent the recreational interests and pursuits that can be followed by residents of an area; affects the design of structures of various kinds and the cost of operating and maintaining both private and public facilities and services; and affects the kinds of agricultural crops which can be produced, as well as the yields.

The study area has a continental-type climate characterized primarily by a continuous progression of markedly different seasons and by frequent, distinct changes in weather conditions which, particularly in the winter and spring, usually occur once every two or three days. Air temperatures within the Milwaukee Harbor estuary and its tributary river watersheds are subject to great seasonal change and yearly as well as diurnal variations, and influence many of the chemical processes which take place in surface waters. Temperatures within the study area range from a daily average of about 18° Fahrenheit in January to about 70° Fahrenheit in July. Temperature extremes, as measured at the City of Milwaukee over a 112-year period, range from a low of 26° below zero Fahrenheit to a high of 105° Fahrenheit.

Based on precipitation and snowfall data for representative observation stations in the study area, the average annual total precipitation of the area is 30.1 inches expressed as water equivalent, with monthly averages ranging from a low of 1.04 inches in February to a high of 3.69 inches in July. The average annual amount of snow and sleet in the study area approximates 47.8 inches. About 90 percent of the annual snowfall occurs in the months of December, January, February, and March.

Physiography and Geology

The land forms and physical features of the study area that affect water resources include the topography, subsurface geology, surface drainage pattern, and soils. The topography and physiographic features of the study area have largely been determined by the underlying bedrock and overlying glacial deposits. The topography of the study area is asymmetrical, with the eastern border of the study area generally lower in elevation than the western border. Surface elevations in the area range from approximately 580 feet above National Geodetic Vertical Datum (Mean Sea Level Datum) at the mouth of the Milwaukee River estuary, to approximately 1,310 feet above NGVD at Parnell Lookout Tower in the Town of Mitchell, Sheboygan County. The bedrock formations that lie beneath the study area slope gently downward toward the east and predominantly consist of, in ascending order, crystalline rocks of the Precambrian Era, Cambrian through Devonian Period sedimentary rocks of the Paleozoic Era, and unconsolidated surficial deposits of glacial origin.

A wide range of soil types have developed within the Milwaukee Harbor estuary study area as a result of the interaction over time of parent glacial deposits covering the study area, the resulting topography, the climate, and the plants and animals of the area. Under a detailed soil survey conducted for the Commission by the U. S. Soil Conservation Service, the location and extent of the soil types within the Region were mapped; the physical, hydrologic, chemical, and biological properties of the various soil types identified; and the limitations of the various soil types for various rural and urban uses established. Within the heavily urbanized Milwaukee Harbor estuary direct drainage area, data on the nature of the underlying soils, as needed for the hydrologic analyses, were determined from the soil characteristics of contiguous areas for which detailed soils data are available from sewer and water utility construction records, and from well digging logs.

Surface Water Resources

Surface water resources, consisting of streams and lakes and associated floodlands, form the singularly most important element of the natural resource base of the study area. The contribution of these resource features to the economic development, recreational activity, and aesthetic quality of the environment is very great. There are about 419 lineal miles of perennial stream within the study area. The Milwaukee Harbor estuary itself includes the 3.1-mile reach of the Milwaukee River below the North Avenue dam, the 2.2-mile reach of the Menomonee River below the Falk Corporation dam, and the 2.4-mile reach of the Kinnickinnic River below the Chase Avenue bridge. The Milwaukee Harbor estuary, including the outer harbor as contained within the breakwater structure, has a total surface water area of about 1,630 acres, or about 2.55 square miles. Of this total, about 2.03 square miles, or about 80 percent, is represented by the outer harbor.

There are no major lakes—lakes having a surface area of 50 acres or more—within the Milwaukee Harbor estuary direct drainage area. The Milwaukee River watershed, however, contains 21 major lakes having a combined surface water area of 3,438 acres, or 0.63 percent of the total study area, and a total shoreline length of 59 miles. In addition, there are 50 minor lakes—lakes having a surface area of between 5 and 50 acres—within the Milwaukee River watershed, 14 minor lakes within the Menomonee River watershed, and 3 minor lakes within the Kinnickinnic River watershed. These minor lakes have a combined surface water area of 790 acres, or about 0.14 percent of the total study area, and a total shoreline length of 47 miles.

Groundwater Resources

Groundwater resources in the area sustain lake levels, provide the base flow of the streams tributary to the Milwaukee Harbor estuary, and are the source of water supply for approximately 46 percent of the people who reside in the study area. The aquifers that underlie the study area attain a combined thickness in excess of 2,200 feet in the Milwaukee Harbor estuary direct drainage area, and may be divided into three distinct formations. These are, in descending order: 1) the sand and gravel deposits of the overlying glacial drift; 2) the shallow dolomite formations in the underlying bedrock; and 3) the deep sandstone, dolomite, and siltstone formations underlying the shallow dolomite formations but hydraulically separated from those formations by a layer of essentially impervious shale. The amount of water stored in the aquifers beneath the study area is estimated to exceed 88 million acre-feet.

Fish and Wildlife Resources

The fish and wildlife resources of the Milwaukee Harbor estuary direct drainage area are particularly important because of their recreational, educational, and aesthetic values, and because of the naturalness and diversity they provide to the otherwise intensively developed urban environment. Unfavorable habitat conditions imposed by water pollution and channel modifications have, however, limited the resident fish populations of the Milwaukee Harbor estuary to the more pollution-tolerant species. Some pollution-intolerant species, including anadromous fish—species that instinctively migrate for the purpose of spawning, such as coho salmon—are also found throughout the estuary at times. Because of intensive urbanization, there has been a progressive decline in the diversity and quantity of wildlife, and a diminished quality and extent of wildlife habitat areas, within the Milwaukee Harbor estuary direct drainage area. The remnant wildlife habitat areas in the Milwaukee Harbor estuary direct drainage area are concentrated in and around park and other open space areas. The most significant forms of wildlife in terms of number and diversity are birds; about 270 species of birds either reside in, winter in, or migrate through the Milwaukee Harbor estuary direct drainage area.

Environmental Corridors

Regional Planning Commission studies have indicated that valuable natural resource and related features in southeastern Wisconsin are generally concentrated in narrow elongated areas of the landscape termed environmental corridors by the Commission. The primary environmental corridors are a composite of the best remaining elements of the natural resource base. Such corridors occupy about 170 square miles, or about 20 percent of the total study area. The preservation of these corridors in essentially natural, open uses is essential to maintaining a high level of environmental quality in the Milwaukee Harbor estuary direct drainage area and its tributary river watersheds.

WATER RESOURCE MONITORING PROGRAM

Extensive water resource monitoring programs were conducted as a part of the Milwaukee Harbor estuary water resources planning effort. The sediment and water quality sampling programs, in particular, were massive, with a large number of sampling stations and a high sampling frequency. This sampling program was necessary to provide the data required to develop a thorough understanding of the complex estuarine system concerned, and to facilitate reliable analyses of water quality conditions and of the potential effects of alternative means of water quality management. The field work required to develop these primary data for the planning effort was conducted in 1982 through 1984 and included the collection of data on meteorology; groundwater levels and quality; streamflow, surface water levels, and water quality; physical and chemical characteristics of bottom and suspended sediments; and the fishery resources and algal productivity of the estuary.

Meteorological Data

Meteorological data were collected within the study area at 13 stations operated by the National Weather Service; 15 stations operated by the City of Milwaukee, Bureau of Engineers; four stations operated by the Milwaukee Metropolitan Sewerage District; and two stations operated by the U. S. Geological Survey. The records consisted primarily of precipitation data; however, pertinent data on wind speed and direction, air temperature, and relative humidity were also collected at selected stations on a continuous basis over the monitoring period. The data collected were used to characterize meteorological conditions during the three-year surface water monitoring program, and as input to hydrologic, hydraulic, and water quality simulation models; the data were also used in algal productivity studies.

Groundwater Monitoring

Long-term groundwater level data were collected at 16 stations by the U. S. Geological Survey in the study area and vicinity, to determine short-term changes and long-term trends in groundwater levels and to relate the changes in groundwater levels to reservoir storage volumes. Groundwater level and quality data were collected from October 1982 through July 1984 at six observation wells installed by the USGS in the Menomonee Valley specifically for the estuary study. During the monitoring period, water levels were measured weekly or biweekly, and groundwater samples were collected four times and analyzed for dissolved organochloride contaminants and total phenols, metals, phosphorus, and other dissolved inorganic contaminants. The data collected were used to estimate the potential impact of groundwater on surface water flow and quality and the pollutant loadings to the estuary contributed by groundwater.

Surface Water Monitoring

Continuous streamflow data were collected by the U. S. Geological Survey throughout the monitoring period at eight locations on the rivers tributary to the Milwaukee Harbor estuary. In addition, the Regional Planning Commission collected streamflow data, on an intermittent basis, at four stations to provide stage-discharge relationships at these locations. The resulting data were used to assist in characterizing the hydrologic and hydraulic conditions of the rivers tributary to the estuary; to assist in characterizing discharges from the combined sewer outfalls; to assist in calibration and verification of the hydrologic and hydraulic simulation models of the estuary; and to compute pollutant transport loads using water quality data collected during the monitoring program.

From January 1982 through November 1984, continuous water level monitoring was conducted by the U. S. Geological Survey at six stations in the inner harbor; by the Milwaukee Metropolitan Sewerage District at four stations; by the City of Milwaukee, Bureau of Engineers, at four stations; and by the National Ocean Survey at one station. The water level data collected during this monitoring program were used to assist in the hydrodynamic characterization of the inner harbor. The data served as the basis for the calibration and verification of a one-dimensional flow simulation model and a two-dimensional hydrodynamic model. The outputs of these models were used, in turn, as inputs to the water quality simulation models of the estuary. The outer harbor water level data were used to analyze the effects of long- and short-term lake level oscillations upon water levels, circulation, and pollutant dispersion.

Continuous monitoring of current speed and direction at multiple depths in the estuary was conducted by the Milwaukee Metropolitan Sewerage District at three locations. In addition, the U. S. Geological Survey made periodic current measurements near the mouth of the Milwaukee River, and the Sewerage District made periodic current measurements at two stations in the inner harbor and five stations in the outer harbor. The data collected were used in determining the effects of Lake Michigan on estuary circulation and the effects of the Wisconsin Electric Power Company Valley power plant cooling water intakes and discharges on circulation in the estuary, and in quantifying the volumes of the discharges at the downstream limits of the inner harbor to assist in calibration-verification of the one-dimensional flow simulation model of the inner harbor. The data were also used to provide the necessary calibration and verification data for the two-dimensional hydrodynamic model of the inner harbor.

The surface water quality data collection program in the upstream rivers, the inner harbor, the outer harbor, and the near-shore of Lake Michigan included weekly baseline sampling at 34 stations by the Milwaukee Metropolitan Sewerage District, and intensive sampling of five selected runoff events at these 34 stations by the U. S. Geological Survey, the Sewerage District, and the Regional Planning Commission. These data were collected in 1982, 1983, and 1984 as part of the estuary study. In addition, baseline water quality data collected by the Sewerage District in 1981 were used in the study. Continuous water quality monitoring at three stations in the inner harbor and two stations on the upstream Milwaukee River was also conducted by the Sewerage District from January 1982 through December 1983. Two stormwater runoff quality surveys were conducted by the U. S. Geological Survey at eight stations located in industrial areas immediately adjacent, and directly tributary, to the inner harbor. Water quality indicators measured during each of these monitoring programs were, for the most part, conventional pollutants affecting water quality conditions, including dissolved oxygen, phosphorus, nitrogen, organic carbon, biochemical oxygen demand, chemical oxygen demand, and suspended solids. In addition, metals, organic substances, and bacteria were measured.

The overall purpose of the surface water quality monitoring program was to identify sources of pollution by sampling at strategically located stations within rural areas, and at sites in separate sewered, combined sewered, and unsewered areas within urban areas; evaluate the effects of pollutants on receiving water quality; and provide data for calibration and verification of water quality simulation models to be used for determining water quality conditions during selected critical historical periods, and under alternative future land use conditions and water pollution abatement measures.

Sediment Quality Monitoring

The sediment data collection program conducted by the Milwaukee Metropolitan Sewerage District under the study included the collection and analysis of sediment core and interstitial water quality samples at 15 stations, and the analysis of sediment gas production at eight stations, sediment oxygen demand at eight stations, and sediment deposition at nine stations. The sediment sampling program was conducted over the period April 1982 through December 1983 on a rotating basis such that each station was sampled from six to eight times per year. In addition, during the period June 1982 through December 1983, the U. S. Geological Survey monitored suspended sediment at seven gaging stations on a daily basis, with more intensive automatic sampling during selected runoff events. At nine other stations the U. S. Geological Survey also sampled suspended sediment on a weekly to monthly basis, with more intensive sampling during selected runoff events. The U. S. Geological Survey also made a limited number of measurements of bedload sediment transport to supplement the suspended sediment data. The data collected during these monitoring programs were used to assist in the analysis of bottom sediment processes, to determine the source and magnitude of constituents important in those processes, to provide calibration-verification data for sediment algorithms used in the estuary water quality model, and to provide data for dredging and dredge spoils disposal studies.

Biological Monitoring

Aquatic biological data were collected during the field monitoring program through plankton sampling at four stations in the outer harbor by the Milwaukee Metropolitan Sewerage District during baseline water quality surveys; habitat surveys conducted by the Wisconsin Department of Natural Resources in 1984 for both the inner harbor and the outer harbor; algal productivity surveys at five stations by the Sewerage District; fish surveys at 42 stations by the Wisconsin Department of Natural Resources; and faunal toxicity surveys at 16 stations during wet-weather and dry-weather conditions by the Sewerage District, with the U. S. Environmental Protection Agency Environmental Research Laboratory-Duluth and Ecological Analysts Engineering, Science and Technology, Inc., conducting the laboratory tests. The fish surveys were conducted during the period March 1983 through October 1984. Algal productivity surveys were conducted in the summers of 1982 and 1983. A series of five toxicity surveys was conducted over the period August 20, 1984, through November 8, 1984. The data collected described baseline biological conditions; identified rare, endangered, or threatened species and their habitat; documented levels of toxic substances in fish tissues; and quantified algal productivity for input to the estuary water quality simulation model, and for use in predicting algal biomass in the estuary following pollution abatement. These data thus provided useful information for establishing final recommended water use objectives for the Milwaukee Harbor estuary.

HYDROLOGIC-HYDRAULIC CHARACTERISTICS

Comprehensive planning for sound management of the water resources of the Milwaukee Harbor estuary requires a knowledge and understanding of hydrologic-hydraulic processes, the functions performed by these processes in the cause and resolution of developmental and environmental problems, and the physical factors that influence the hydrologic-hydraulic regime of the estuary. Flow rates and circulation patterns within the Milwaukee Harbor estuary, particularly within the inner harbor, are influenced by runoff from the tributary rivers and the combined sewer service area, by flood and ebb flows caused by Lake Michigan water level oscillations, by flushing tunnel flows from Lake Michigan discharging near the upstream end of the Kinnickinnic and Milwaukee River estuaries, and by the effects of condenser water withdrawals and discharges by the Wisconsin Electric Power Company Valley power plant in the Menomonee inner harbor. These factors collectively create the circulation pattern in the estuary, and this pattern has a major impact upon water quality conditions in the estuary. Changes in Lake Michigan water levels not only affect estuary circulation, but also affect the design and construction of structures in the coastal zone, as well as the development of nonstructural remedies to coastal zone problems.

Lake Michigan Water Level Fluctuations

Review of water level records collected for Lake Michigan at Milwaukee indicated that the recorded maximum annual mean level of 582.2 feet National Geodetic Vertical Datum (NGVD), or 580.9 feet International Great Lakes Datum (IGLD), occurred in 1886, with the second highest annual mean level of record being 582.0 feet NGVD, or 580.7 feet IGLD, in 1985. The 20th century instantaneous maximum lake level of 583.73 feet NGVD, or 582.43 feet IGLD, occurred on November 9, 1985. Conversely, the minimum annual mean level occurred in 1964—577.1 feet NGVD, or 575.8 feet IGLD. The instantaneous minimum recorded elevation was 574.0 feet NGVD, or 572.7 feet IGLD, on May 29, 1976. The range between the maximum and minimum annual mean levels was, therefore, 5.1 feet, with the difference between maximum and minimum instantaneous levels recorded being 9.7 feet.

Frequency analyses of water level records found the mean annual lake level under existing diversions, outlets, and regulation schedules to be 579.5

feet NGVD, or 578.2 feet IGLD, with the 1 percent exceedance level being 3.4 feet higher at an elevation of 582.9 feet NGVD, or 581.6 feet IGLD. The elevation of the instantaneous maximum water level at the 1 percent exceedance probability is 584.5 feet NGVD, or 583.2 feet IGLD. Conversely, the 99 percent exceedance levels for the minimum annual mean and instantaneous minimum are 576.1 feet NGVD, or 574.8 feet IGLD, and 574.5 feet NGVD, or 573.2 feet IGLD, respectively.

Analyses of short-term rises in lake levels attributable to storm surges and seiches found the 100-year recurrence interval annual maximum rise to be 1.9 feet in Milwaukee. Rise magnitude-frequency characteristics were computed for use in the conduct of coastal zone construction and for short- and long-term planning and design. The tidal range at Milwaukee is about 0.09 foot. Therefore, astronomical tides have very minor impact on both water levels and circulation in the estuary.

Hydrologic-Hydraulic
Characteristics of the Harbor Estuary

Frequency analyses were also conducted of hydrologic data for the rivers tributary to Milwaukee Harbor. Long-term mean annual flows of the Kinnickinnic, Menomonee, and Milwaukee Rivers were determined to be 23, 90, and 408 cubic feet per second (cfs), respectively. In comparison, the mean annual overflow from the combined sewers tributary to the harbor estuary was estimated to be 32 cfs. The 7-day, 10-year low flows of the tributary rivers were determined to be, respectively, 6.0, 4.7, and 25.1 cfs. In comparison, the flushing tunnel flows intermittently discharged Lake Michigan waters to the upstream termini of the Kinnickinnic and Milwaukee River estuaries at rates of about 350 and 400 cfs, respectively. The condenser cooling water withdrawal and discharge rates for the Wisconsin Electric Power Company Valley power plant on the Menomonee River estuary, consisting primarily of Lake Michigan water, averaged about 250 cfs. In comparison, Lake Michigan flood and ebb flows in the inner harbor were estimated to range from 2,000 to 13,000 cfs on a daily basis. The larger flows to and from the lake were attributed to seiche action. The 100-year recurrence interval peak discharges for the tributary Kinnickinnic, Menomonee, and Milwaukee Rivers were, respectively, 5,000, 13,500, and 16,000 cfs. The effects of groundwater inflows and outflows upon estuary flow rates and estuary circulation were found to be miniscule.

A time series analysis of water level records in the inner harbor found two significant long waves from Lake Michigan, which frequently traveled through the inner harbor with periods of 0.9 hour and 2.2 hours. The 0.9-hour wave may have been a multinodal seiche. The 2.2-hour wave was probably the transverse seiche of Lake Michigan which was generated by meteorological disturbances. The 0.9-hour wave height was found to be on the order of 0.1 to 0.4 foot; whereas the 2.2-hour seiche was found to be of variable height, but on the order of about 0.1 to 1.0 foot in the estuary. The principal significance of these waves is that they generate large inflows of water from Lake Michigan into the inner harbor, thereby affecting the mixing and dilution of pollutants from the rivers, combined sewer overflows, and direct surface runoff.

Water circulation within the inner harbor was simulated using a 10-layered, two-dimensional hydrodynamic model which found that Lake Michigan inflow, and condenser cooling water withdrawals and discharges from the Valley power plant on the Menomonee River estuary, dominated circulation in the inner harbor when the flushing tunnels were not in operation. During calm weather, the simulation model indicated that currents moved upstream on the surface and near the bottom, with a return flow near mid-depth in the Menomonee and Kinnickinnic estuaries, and in the Milwaukee River estuary upstream to its confluence with the Menomonee River estuary. Velocities generally ranged from 0.0 to 0.5 foot per second, with a median of about 0.1 to 0.2 foot per second. The model studies indicated that the Milwaukee River estuary upstream of the confluence with the Menomonee River estuary exhibits a two-layered flow system up to about Cherry Street, with surface currents moving downstream and bottom currents upstream. Lake water penetrates nearly the entire length of the Kinnickinnic and Menomonee estuaries because of the relatively small river flows and the relatively deep navigation channels, which range from 20 to 25 feet in depth. Penetration of lake waters into the Milwaukee River estuary north of the confluence with the Menomonee River estuary is restricted by the relatively large flow of that river and because of the relatively shallow depth of about 11 to 15 feet through most of the reach. While lake waters apparently do not move all the way up the river estuary, the levels and flow patterns in that estuary upstream of Cherry Street are nevertheless impacted significantly.

EXISTING POLLUTION LOADINGS AND SOURCES AND WATER QUALITY, SEDIMENT QUALITY, AND BIOLOGICAL CONDITIONS

Pollution Loadings and Sources

Pollutant loadings to the Milwaukee Harbor estuary are contributed by both point and nonpoint sources, with generally about one-half of the pollutant loadings studied coming from nonpoint sources. The largest and most important point source loadings are those discharged from combined sewers, both upstream of, and directly adjacent to, the inner and outer harbors and upstream tributary rivers. Most of the combined sewer overflow loadings are discharged directly to the inner harbor. Pollutants contributed from nonpoint sources are primarily transported to the inner harbor via the three tributary rivers. Thus, most nonpoint source pollutants are discharged to surface waters upstream of the Milwaukee Harbor estuary, rather than directly to the estuary. In addition to combined sewer overflows and nonpoint sources, the Jones Island wastewater treatment plant is a major source of pollution to the outer harbor. Tables 144 and 145 set forth a summary of pollution sources and loadings to the tributary rivers upstream of the estuary, and to the inner harbor.

Tributary Rivers: Annual and wet-weather and dry-weather loadings of pollutants transported by the three rivers tributary to the inner harbor were estimated using the 1981 through 1983 baseline water quality data. On an average annual basis, the estimated loadings of selected pollutants to the tributary rivers were: 45.9 million pounds of total suspended solids, 12.5 million pounds of volatile suspended solids, 6.3 million pounds of biochemical oxygen demand, 230,000 pounds of total phosphorus, 300,000 pounds of ammonia nitrogen, and 85,000 pounds of lead. The Milwaukee River contributed from 57 to 97 percent of the total annual river loadings of the various pollutants considered; the Menomonee River contributed from 3 to 33 percent of the total loadings; and the Kinnickinnic River contributed from less than 1 to 19 percent of the total loadings. Overall, approximately two-thirds of the pollutant loadings carried by the three rivers were contributed during wet-weather conditions, with the remaining one-third of the loadings being carried during dry-weather conditions.

Three primary sources of pollutants to the three tributary rivers were quantified: combined sewer overflows, other point sources, and nonpoint sources, as shown in Table 144. Nonpoint sources accounted for most of the pollutant loadings, contributing about 38.8 million pounds, or 85 percent, of the total suspended solids loading to the river; 9.2 million pounds, or 74 percent, of the volatile suspended solids loading; 3.5 million pounds, or 56 percent, of the biochemical oxygen demand loading; 163,000 pounds, or 71 percent, of the total phosphorus loading; 251,000 pounds, or 84 percent, of the ammonia nitrogen loading; and 59,000 pounds, or 70 percent, of the lead loading. About 33 percent of the total combined sewer overflow pollutant loadings were discharged to the tributary rivers upstream of the estuary. The combined sewer overflows that discharged upstream of the estuary accounted for about 6.1 million pounds, or 13 percent, of the total suspended solids river loading; 3.3 million pounds, or 26 percent, of the volatile suspended solids loading; 2.0 million pounds, or 33 percent, of the biochemical oxygen demand loading; 48,000 pounds, or 21 percent, of the total phosphorus loading; 41,000 pounds, or 14 percent, of the ammonia nitrogen loading; and 25,500 pounds, or 30 percent, of the lead loading. Other point sources of pollution to the tributary rivers were relatively insignificant. These other point sources accounted for about 908,000 pounds, or 2 percent, of the total suspended solids river loading; 684,000 pounds, or 11 percent, of the biochemical oxygen demand loading; 17,000 pounds, or 8 percent, of the total phosphorus loading; 8,000 pounds, or 3 percent, of the ammonia nitrogen loading; and 60 pounds, or 0.1 percent, of the lead loading. Loadings of volatile suspended solids from other point sources were not estimated.

Inner Harbor: Pollutant loadings to the inner harbor were estimated using the tributary river loadings set forth above, along with estimated loadings from combined sewer outfalls that discharge directly to the inner harbor. Only an insignificant amount of pollutants was discharged directly to the inner harbor from point sources other than combined sewer overflows. The nonpoint source loadings and point source loadings to the tributary rivers were discharged to the inner harbor. In addition, combined sewer overflows discharged directly to the inner harbor. On an average annual basis, the total estimated loadings of selected pollutants to the inner harbor from all sources were: 57.9 million pounds of total suspended solids, 18.8 million pounds of volatile

Table 144

SUMMARY OF ANNUAL LOADINGS AND SOURCES OF POLLUTANTS TO THE TRIBUTARY RIVERS UPSTREAM OF THE ESTUARY: 1981-1983

Pollutants	Combined Sewer Overflows		Other Point Sources		Nonpoint Sources		Total	
	Loading (pounds)	Percent of Total	Loading (pounds)	Percent of Total	Loading (pounds)	Percent of Total	Loading (pounds)	Percent of Total
Total Suspended Solids.	6,132,000	13.4	907,500	2.0	38,820,500	84.6	45,860,000	100.0
Volatile Suspended Solids . . .	3,280,000	26.2	- -	0.0	9,244,000	73.8	12,524,000	100.0
Biochemical Oxygen Demand .	2,044,000	32.6	683,500	10.9	3,539,500	56.5	6,267,000	100.0
Total Phosphorus	48,000	21.1	17,100	7.5	162,600	71.4	227,700	100.0
Ammonia Nitrogen	41,000	13.7	8,100	2.7	250,900	83.6	300,000	100.0
Lead	25,500	30.1	60	0.1	59,240	69.8	84,800	100.0

Source: SEWRPC.

Table 145

SUMMARY OF ANNUAL LOADINGS AND SOURCES OF POLLUTANTS TO THE INNER HARBOR: 1981-1983

Pollutants	Combined Sewer Overflows						Other Point Sources: Upstream and Directly Tributary To Inner Harbor		Upstream Nonpoint Sources		Direct Draining Nonpoint Sources		Total	
	Upstream		Direct Inner Harbor		Total									
	Loading (pounds)	Percent of Total	Loading (pounds)	Percent of Total	Loading (pounds)	Percent of Total	Loading (pounds)	Percent	Loading (pounds)	Percent	Loading (pounds)	Percent	Loading (pounds)	Percent of Total
Total Suspended Solids.	6,132,000	10.6	11,336,000	19.6	17,468,000	30.2	907,500	1.6	38,820,500	67.0	722,000	1.2	57,918,000	100.0
Volatile Suspended Solids . . .	3,280,000	17.5	6,064,000	32.3	9,344,000	49.8	- -	0.0	9,244,000	49.2	187,400	1.0	18,775,400	100.0
Biochemical Oxygen Demand .	2,044,000	20.2	3,778,000	37.4	5,822,000	57.6	683,500	6.8	3,539,500	35.0	58,600	0.6	10,103,600	100.0
Total Phosphorus	48,000	15.2	88,000	27.8	136,000	43.0	17,100	5.4	162,600	51.3	1,000	0.3	316,700	100.0
Ammonia Nitrogen	41,000	10.9	76,000	20.2	117,000	31.1	8,100	2.1	250,900	66.7	300	0.1	376,300	100.0
Lead	25,500	19.0	47,000	35.1	72,500	54.1	60	0.1	59,240	44.2	2,200	1.6	134,000	100.0

Source: SEWRPC.

suspended solids, 10.1 million pounds of biochemical oxygen demand, 317,000 pounds of total phosphorus, 376,000 pounds of ammonia nitrogen, and 134,000 pounds of lead.

Three primary sources of pollutants to the inner harbor were quantified: combined sewer overflows, other point sources, and nonpoint sources. As shown in Table 145, the combined sewer overflow loadings were further categorized as loadings discharged upstream of the inner harbor, and as loadings discharged directly to the inner harbor. Compared to nonpoint source contributions to the tributary rivers, nonpoint sources accounted for a smaller, yet significant, portion of the loadings to the inner harbor. Although the actual nonpoint source loadings to the inner harbor are nearly the same as those to the tributary rivers, the percentage contributions were lower, with nonpoint sources accounting for about 68 percent of the inner harbor suspended solids loading, 50 percent of the volatile suspended solids loading, 36 percent of the biochemical oxygen demand loading, 52 percent of the total phosphorus loading, 67 percent of the ammonia nitrogen loading, and 46 percent of the lead loading. Similarly, the inner harbor loadings from point sources other than combined sewer overflows were the same as the tributary river point source loadings, although the percentage contributions again were lower, with point sources accounting for 2 percent of the inner harbor suspended solids loading, 7 percent of the biochemical oxygen demand loading, 5 percent of the total phosphorus loading, 2 percent of the ammonia nitrogen loading, and 0.1 percent of the lead loading. About 94 percent of the overall

Table 146

SUMMARY OF ANNUAL LOADINGS AND SOURCES OF POLLUTANTS TO THE OUTER HARBOR[a]: 1981-1983

Pollutants	Inner Harbor		Jones Island Wastewater Treatment Plant		Combined Sewer Overflows Discharged Directly to Outer Harbor		Total	
	Loading (pounds)	Percent of Total	Loading (pounds)	Percent of Total	Loading (pounds)	Percent of Total	Loading (pounds)	Percent of Total
Total Suspended Solids.	22,593,500	73.4	7,060,100	22.9	1,115,000	3.7	30,768,600	100.0
Biochemical Oxygen Demand . .	6,018,900	54.9	4,569,000	41.7	372,000	3.4	10,959,900	100.0
Total Phosphorus	220,400	55.2	169,500	42.5	9,000	2.3	398,900	100.0
Ammonia Nitrogen	121,800	4.5	2,561,000	95.2	8,000	0.3	2,690,800	100.0
Lead	68,800	67.5	28,600	28.0	4,600	4.5	102,000	100.0

[a]*Does not include pollutant loadings to the outer harbor from Lake Michigan.*

Source: SEWRPC.

combined sewer overflow loadings of all pollutants were discharged either upstream of, or directly to, the inner harbor; 33 percent of the loadings were discharged upstream of the inner harbor, and 61 percent of the loadings were discharged directly to the inner harbor. All of the combined sewer overflows, including those discharged upstream of, and directly to, the inner harbor contributed about 17.5 million pounds, or 30 percent, of the overall suspended solids loading to the inner harbor; 9.3 million pounds, or 50 percent, of the volatile suspended solids loading; 5.8 million pounds, or 58 percent, of the biochemical oxygen demand loading; 136,000 pounds, or 43 percent, of the total phosphorus loading; 117,000 pounds, or 31 percent, of the ammonia nitrogen loading; and 72,500 pounds, or 54 percent, of the lead loading.

Solids contributed by combined sewers were found to be substantially more settleable than solids contributed by other pollution sources. This higher settling rate increases the importance of combined sewer overflow as a source of sediment particulate organic carbon loadings which, in turn, affect the diagenetic reaction and its effect on the dissolved oxygen concentration in the overlying water. Combined sewer overflows are also the major source of the very high levels of fecal coliform in the estuary. Rainfall events resulting in overflows from combined sewers generally increase the fecal coliform levels in the estuary by several orders of magnitude.

Outer Harbor: Pollutant loadings to the outer harbor were estimated by analyzing the flow rates and circulation patterns between the outer harbor and the inner harbor, and by determining the pollutant loadings discharged directly to the outer harbor by combined sewers and the Jones Island wastewater treatment plant. A summary of the annual pollutant loadings to the outer harbor is set forth in Table 146.

Inflow from the inner harbor contributed about 22.6 million pounds of total suspended solids; about 6.0 million pounds of biochemical oxygen demand; about 220,000 pounds of total phosphorus; about 122,000 pounds of ammonia nitrogen; and about 69,000 pounds of lead to the outer harbor annually. About 6 percent of the overall combined sewer overflow pollutant loadings were discharged directly to the outer harbor. These combined sewer overflows accounted for about 1.1 million pounds of total suspended solids, about 372,000 pounds of biochemical oxygen demand, about 9,000 pounds of total phosphorus, about 8,000 pounds of ammonia nitrogen, and about 4,600 pounds of lead. The Jones Island wastewater treatment plant was a major source of pollutants to the outer harbor. The plant contributed about 7.1 million pounds of total suspended solids, about 4.6 million pounds of biochemical oxygen demand, about 170,000 pounds of total phosphorus, about 2.6 million pounds of ammonia nitrogen, and about 29,000 pounds of lead annually.

A comparison of the total inner harbor loadings to the loadings discharged from the inner harbor to the outer harbor provides an indication of the portion of the total pollutant loadings which is trapped in the inner harbor. The trapping efficiency of the inner harbor is estimated to be 60 percent for total suspended solids, 40 percent for biochemical oxygen demand, 30 percent for total phosphorus, 68 percent for ammonia nitrogen, and 48 percent for lead.

Existing Water Quality Conditions

A comparison of the existing water quality conditions in the Milwaukee Harbor estuary to the recommended water use objectives and supporting water quality standards set forth in Chapter II of Volume Two of this report indicates that those standards were not met in any portion of the estuary. Considerable spatial and temporal variations in water quality conditions were found, however, especially within the inner harbor.

The water quality indicator of principal interest in the study was dissolved oxygen. Generally, the dissolved oxygen levels at all sampling stations were found to be highest in the winter, with essentially all of the extremely low dissolved oxygen levels occurring in the summer under dry-weather conditions. Low concentrations of dissolved oxygen limit the survival, growth, and reproduction of fish and other desirable forms of aquatic life. During the summer months, all dissolved oxygen standards were essentially met at all sampling stations within the upstream reaches and outer harbor. The standards, however, were often violated at the inner harbor sampling stations.

At the representative sampling station located on the Milwaukee River estuary at Wells Street, the recommended minimum 30-day mean dissolved oxygen standard of 5.5 milligrams per liter (mg/l) was violated 56 percent of the time during the summer months, and 18 percent of the time during the entire monitoring period. The recommended 7-day mean dissolved oxygen standard of 6 mg/l and the 1-day mean standard of 5 mg/l, which apply from March 15 to July 31, were violated about 30 percent of the time and 19 percent of the time, respectively. The recommended 1-day mean standard of 4 mg/l, which applies from August 1 to March 14, was violated about 8 percent of the time. The absolute minimum dissolved oxygen standard of 2.5 mg/l recommended for the Milwaukee River estuary was violated about 5 percent of the time during the summer months, but only about 2 percent of the time during the entire monitoring period.

At the representative sampling station located on the Menomonee River estuary at Muskego Avenue, the recommended minimum 30-day mean dissolved oxygen standard of 4.5 mg/l was violated at all times during the summer months, and 50 percent of the time during the entire survey period. The recommended 7-day mean dissolved oxygen standard of 5.0 mg/l and the 1-day mean standard of 4.0 mg/l, which apply from March 15 to July 31, were violated about 66 percent of the time and 58 percent of the time, respectively. The recommended 1-day mean dissolved oxygen standard of 3.0 mg/l, which applies from August 1 to March 14, was violated about 34 percent of the time. The absolute minimum dissolved oxygen standard of 1.5 mg/l was violated about 55 percent of the time during the summer months, and about 25 percent of the time during the entire survey period.

At the representative sampling station located on the Kinnickinnic River estuary at S. 1st Street, the recommended minimum 30-day mean dissolved oxygen standard of 4.5 mg/l was violated 66 percent of the time during the summer months, and 43 percent of the time during the entire survey period. The recommended 7-day mean dissolved oxygen standard of 5.0 mg/l and the 1-day mean standard of 4.0 mg/l, which apply from March 15 to July 31, were violated about 43 percent of the time and 36 percent of the time, respectively. The recommended 1-day mean standard of 3.0 mg/l, which applies from August 1 to March 14, was violated about 40 percent of the time. The absolute minimum dissolved oxygen standard of 1.5 mg/l recommended for the Kinnickinnic River estuary was violated about 35 percent of the time during the summer months, and about 23 percent of the time during the entire survey period.

During periods of low flow and attendant low dissolved oxygen levels, the flows of the Milwaukee and Kinnickinnic Rivers are augmented by water pumped from Lake Michigan into the rivers through two flushing tunnels. Field studies conducted found significant improvement in water clarity and dissolved oxygen levels in the Milwaukee and Kinnickinnic River estuaries when the tunnels were in operation. For example, in the Milwaukee River estuary at St. Paul Avenue, continuous dissolved oxygen measurements made from August 26 through September 7, 1982, indicated that the pre-operation dissolved oxygen levels were about 4 mg/l, with levels increasing to about 7 to 10 mg/l when the tunnels were operating.

Fecal coliform levels in the tributary streams, inner harbor, and outer harbor showed significant variation, with the highest levels found in the inner harbor. High levels of fecal coliform present a potential health hazard to recreational users of surface waters. An analysis of the fecal coliform levels indicated that the recommended 30-day mean fecal coliform standard of a maximum of 200 counts per 100 milliliters (ml) was violated from 65 to 100 percent of the time at the sampling stations located upstream of the inner harbor; from 90 to 100 percent of the time at the Milwaukee River estuary stations; from 94 to 100 percent of the time at the Menomonee River estuary stations; from 80 to 97 percent of the time at the Kinnickinnic River estuary stations; and from less than 10 to 78 percent of the time at the outer harbor stations. Fecal coliform levels as high as 930,000 counts per 100 ml were found in the inner harbor, while levels as high as 240,000 counts per 100 ml were reported in the outer harbor. Fecal coliform levels were generally greatest during wet-weather conditions, reflecting the impact of combined sewer overflows. Fecal coliform levels generally increased downstream, with the maximum mean concentrations occurring at Water Street on the Milwaukee River, Muskego Avenue on the Menomonee River, and S. 1st Street on the Kinnickinnic River. The fecal coliform levels then decreased markedly in the direction of the outer harbor.

Phosphorus and nitrogen are important determinants of river and estuary water quality because of their effect on algal productivity, and the consequential effects on dissolved oxygen. With regard to phosphorus, the recommended standard of 0.1 mg/l was found to have been violated about 63 to 76 percent of the time at the upstream sampling stations on the Milwaukee River; about 44 to 75 percent of the time at the Milwaukee River estuary stations; and from less than 10 to 28 percent of the time at the outer harbor stations. Although the recommended phosphorus standard was not intended to apply to the Kinnickinnic and Menomonee Rivers, phosphorus levels exceeded 0.1 mg/l about 13 to 83 percent of the time at the upstream Menomonee River and Kinnickinnic River sampling stations; about 53 to 54 percent of the time at the Menomonee River estuary sampling stations; and about 17 to 62 percent of the time at the Kinnickinnic River estuary stations. Concentrations of total phosphorus were generally higher during wet-weather conditions than during dry-weather conditions.

The recommended chronic standard for un-ionized ammonia nitrogen was 0.025 mg/l throughout the Milwaukee Harbor estuary and tributary rivers. At the upstream sampling stations, this standard was violated at two stations on the Milwaukee River and two stations on the Menomonee River, those violations occurring less than 7 percent of the time at each station. The chronic standard was violated at only one inner harbor sampling station, located on the Kinnickinnic River, where the standard was violated less than 3 percent of the time. The chronic standard also was violated at three stations within the outer harbor, those violations occurring less than 15 percent of the time at each station. The acute standard for un-ionized ammonia nitrogen varied by sampling station, being dependent upon the temperature and pH of the water. Violations of the recommended acute standards for un-ionized ammonia nitrogen, which varied from 0.081 to 0.116 mg/l, were also observed in the outer harbor, although rarely—less than 3 percent of the time at any station. No violations of the acute standard were observed at the inner harbor or upstream river stations.

The water quality samples were also analyzed for the presence of certain metals, including cadmium, copper, lead, and zinc. The recommended standards for metals, developed and promulgated since the completion of the data collection efforts under the Milwaukee Harbor estuary study, are expressed in terms of acid-soluble concentrations. The data collected as part of the Milwaukee Harbor estuary study were expressed as total concentrations. While the survey data cannot, therefore, be directly compared to the standards, it may be inferred from the data that chronic toxic conditions exist within the Milwaukee Harbor estuary owing to the elevated concentrations of some metals, but that acute toxic conditions are not present. Concentrations of lead and zinc were found to increase under wet-weather conditions, while concentrations of cadmium and copper were found to be highest under dry-weather conditions. This suggests that point sources of cadmium and copper—other than combined sewer overflows—which have their greatest water quality impacts during dry-weather conditions, may be of more significance than nonpoint sources and combined sewer overflows. These dry-weather sources are unknown, but may be separate sewer overflows or industrial wastewater discharges.

Existing Sediment Quality Conditions

Because bottom sediment quality can have adverse effects upon water quality and upon aquatic biota, an intensive sampling program of in-place sediments in the tributary rivers and inner harbor was undertaken to complement the water quality monitoring program. The data collected indicated that the sediments for most indicators were well mixed vertically, although exhibiting substantial spatial variability. In general, the inner harbor sediments had a lower percentage of total solids and were therefore more flocculent than were the upstream sediments. The inner harbor sediments also had a higher organic content than did the upstream sediments, as well as higher concentrations of total phosphorus, ammonia nitrogen, total Kjeldahl nitrogen, lead, zinc, cadmium, and copper. Sediment quality was classified based upon U. S. Environmental Protection Agency guidelines. The sediments at the upstream stations, except at the Milwaukee River station at Locust Street, which is located within the North Avenue dam impoundment, generally were moderately polluted for most indicators. Sediments at Locust Street, however, as well as at the inner harbor stations, were heavily polluted for nearly all indicators.

The process of decomposition and stabilization of sediment organic material, referred to as diagenesis, and the associated material fluxes significantly affect the water quality of the inner and outer harbors. The sources of particulate organic carbon were determined in order to quantify the effects of combined sewer overflows and upstream pollution sources on the inner harbor sediments. Combined sewer overflows were found to account for about 60 to 93 percent of the loading of particulate organic carbon reaching the inner harbor. The remaining particulate organic carbon loading was contributed from upstream algae and detritus, most of which was transported to the inner harbor by the Milwaukee River. The sediment diagenesis and flux studies, as well as a detailed analysis of continuous water quality monitoring data collected from the Milwaukee River at St. Paul Avenue, indicated that sediment scouring during combined sewer overflow events was not the major cause of severe dissolved oxygen depletions in the inner harbor. Rather, most dissolved oxygen depletions occurred during dry-weather, low-flow, high temperature periods. When wet-weather dissolved oxygen depletions did occur, they were more likely to be caused by reduced algal photosynthesis than by sediment scouring.

The long-term average annual net sedimentation rate within the inner harbor was found to be about 4.5 inches, with rates averaging 1.8 to 7.9 inches in the Milwaukee River estuary; 4.3 to 19 inches in the Menomonee River estuary; and 3.4 to 8.5 inches in the Kinnickinnic River estuary. The lowest average annual sedimentation rates were found in that reach of the Milwaukee River estuary upstream of the confluence with the Menomonee River estuary, and the highest average annual sedimentation rates were found within the dredged reaches of the Menomonee and Kinnickinnic River estuaries.

Laboratory studies of sediment decomposition and stabilization were made in an attempt to determine the probable duration of the effects of existing in-place sediments upon water quality. The composition of gas released by the bottom sediment in the inner harbor was found to be primarily methane, which suggests that oxidation of dissolved methane is a major source of oxygen demand. The presence of nitrogen gas, however, also indicates that ammonia oxidation via nitrification-denitrification also contributes to the sediment oxygen demand.

Existing Biological Conditions

The resident biological communities that exist within the Milwaukee Harbor estuary waters are a reflection of the water quality, as well as of the physical limitations of the water bodies. Therefore, a description of the existing biota—fish, benthic invertebrates, zooplankton, and algae—and of the physical habitat of the surface water systems provides important information about the overall ecological health and stability of the water bodies, information that is useful in determining desirable and attainable future water use objectives.

Extensive fishery surveys were conducted within the Milwaukee, Menomonee, and Kinnickinnic River estuaries by the Wisconsin Department of Natural Resources in 1983. Of the total of 40 species caught from the inner harbor during the surveys, 10 species, or 25 percent, were rated as intolerant of pollution; 20 species, or 50 percent, were rated as tolerant of pollution; and 10 species, or 25 percent, were rated as very tolerant of pollution.

Extensive fishery surveys were also conducted in the outer harbor by the Wisconsin Department of Natural Resources as part of the Milwaukee Harbor estuary study. Of the total of 30 species caught from the outer harbor during the surveys, 13 species, or 43 percent, were rated as intolerant of pollution; 14, or 47 percent, were rated as tolerant of pollution; and three species, or 10 percent, were rated as very tolerant of pollution.

An analysis of toxic organic substances and metals in the tissue of fish indicated that polychlorinated biphenyl (PCB) levels exceeded the human health standard established by the U. S. Food and Drug Administration in fish taken from the upstream and inner harbor portions of the three rivers and from the outer harbor. The highest PCB concentrations were found in the tissue of fish taken from the Milwaukee River estuary, with progressively lower concentrations found in the tissue of fish taken from the Kinnickinnic River estuary, the Menomonee River estuary, and the outer harbor. In addition, the benthic macroinvertebrates and algae identified within the inner harbor were generally classified as tolerant of pollution owing to the soft mucky substrates, anaerobic sediments, and in-place pollutants present.

A special faunal toxicity survey was conducted to provide additional information on acute and chronic toxic conditions within the estuary. The survival and reproduction of the zooplankton Ceriodaphnia affinis/dubia were studied using water samples from the estuary collected under both wet-weather and dry-weather conditions. The toxicity test results suggested the occurrence of chronic toxicity, which reduced the production of young Ceriodaphnia. These toxic conditions were more likely to occur during wet-weather conditions than during dry-weather conditions. Acute toxic conditions, which affect the survival of the adult Ceriodaphnia over a short time period, also appeared to occur more often during wet-weather conditions than during dry-weather conditions, especially in the Menomonee River.

Based on aquatic habitat evaluations conducted by the Wisconsin Department of Natural Resources, the inner harbor portions of all three rivers can provide fair habitat for fish and other desirable forms of aquatic organisms, while the outer harbor can provide good habitat. Although the inner harbor bottom substrate conditions were found to be unsuitable for fish and aquatic life, the water depth, inflow of relatively clean water from Lake Michigan, and migration of fish both from the upstream reaches and from the outer harbor allowed warmwater fish to exist within the inner harbor. Compared to the inner harbor, the outer harbor exhibited more favorable bottom substrate conditions and less polluted water, due in part to greater dilution from Lake Michigan.

WATER RESOURCE SIMULATION MODELS

Mathematical simulation modeling for the Milwaukee Harbor estuary study was conducted by the U. S. Geological Survey, the Southeastern Wisconsin Regional Planning Commission, and Hydro-Qual, Inc., consultant to the Commission. The simulation modeling was used to describe existing and historical conditions and to predict probable future conditions. The models provided information not only at sites where data had been collected, but also at desired intermediate locations.

Three models were utilized by the U. S. Geological Survey to simulate certain pollutant loading and hydrologic and hydraulic characteristics of the study area. The Hydrological Simulation Program-Fortran Model, referred to as the HSPF Model, was used to simulate stormwater runoff from 367 acres of tributary area not served by combined sewers and located within 200 feet of the shoreline of the inner harbor. The simulated stormwater runoff amounts were used to estimate pollutant loadings from this direct drainage area. The Branch Network Model, a one-dimensional unsteady flow simulation model, was utilized to provide estimates of Lake Michigan flood and ebb flow within the inner harbor. The model was developed to simulate unsteady one-dimensional flows in reaches of the interconnected channels of the inner harbor that were subject to variable backwater effects caused by seiches and storm surges that occurred on Lake Michigan.

The U. S. Geological Survey also developed and utilized a groundwater flow model for the Menomonee River estuary to assist in evaluating the pollutant loadings to the estuary via groundwater intrusion. The model was constructed using data collected at three pairs of groundwater observation wells placed along and on opposite sides of the river. The model was designed to compute annual mean groundwater discharge to the river. Groundwater pollutant loadings were estimated by applying the model discharges to measured contaminant concentrations. Study results indicate that, with the exception of sodium and chloride, the contaminant loadings to the estuary from groundwater were generally insignificant.

Since it was impractical to measure the flows from each of the 109 combined sewer outfalls discharging to the Milwaukee Harbor estuary and the tributary rivers during the three-year field monitoring period, a mathematical model of the combined sewer service area drainage network previously developed for the Milwaukee Metropolitan Sewerage District was utilized to quantify the combined sewer overflow discharge volumes. The model, called the Wastewater Collection System Analysis Model, was utilized to simulate the storm event of September 10, 1983. The simulated results were used to check a simpler method for estimating combined sewer overflow volume which was used for other storms during the monitoring period.

Water quality conditions in the Milwaukee Harbor estuary are influenced by the hydrodynamic circulation within the estuary, which affects the dilution and transport of pollutants; and by the nature and occurrence of the pollutant discharges to the estuary, especially from combined sewer overflows. The complexity of these two phenomena and their interaction necessitated the development and calibration of mathematical simulation models for the characterization of existing and projected water quality conditions. Mathematical simulation models were subsequently developed and calibrated to study sediment processes, dry-weather steady-state conditions, and dry- and wet-weather time-variable conditions. Statistical models for predicting fecal coliform and toxic metals concentrations in the estuary were also developed.

Two models were developed and applied by HydroQual, Inc., to evaluate sediment processes. The sediment diagenesis model simulated particulate organic matter decomposition and was used to quantify total diagenetic rates in the inner harbor. The diagenesis model thus simulated organic material fluxes from the bottom sediments to the overlying water column. The diagenesis modeling analysis also provided a quantitative measure of the importance of both combined sewer overflow and upstream pollution sources to the carbon flux to the bottom sediments. The diagenetic rates served as input functions for the sediment flux model, a more detailed model of sediment diagenetic reactions used to compute the component fluxes required in the water quality models. The sediment flux model quantified the effect of the bottom sediments on dissolved oxygen concentrations in the overlying water.

The diagenesis model provided a quantitative assessment of the significance of different carbon sources, including combined sewer overflows, to the carbon flux to the sediment. Fifty-four percent of the carbon flux to the sediment, 91 percent of which was of combined sewer overflow origin, was estimated to be inert material which decomposes at a negligible rate. The remaining 46 percent was estimated to be reactive material which decomposes at a more rapid rate. Combined sewer overflow was estimated to contribute about 70 percent of the reactive carbon material to the bottom sediments.

The sediment flux model was comprised of two submodels: a methane oxidation submodel and an ammonia oxidation submodel. The submodels simulated sediment oxygen demand, which is caused by the oxidation of dissolved substances—primarily methane and ammonia—produced by the diagenesis reactions. The methane and ammonia are produced by the anaerobic fermentation of organic matter.

The inner harbor is characterized by a two-layer flow regime which consists of a density-driven underflow in the upstream direction and a countercurrent downstream flow in the surface layer. Two conservative indicators, conductivity and chloride, were used as tracers to provide an effective means of quantifying the effects of lake water intrusion, thereby providing a relatively simple, yet effective, means of characterizing advective and dispersive transport in the inner harbor.

The analysis of the dissolved oxygen levels in the inner harbor required a detailed evaluation of the important sources and sinks of oxygen affecting the dissolved oxygen balance. Special studies were performed to evaluate the significance of the oxidation of organic matter, algal photosynthesis and respiration, and sediment-water interactions.

A steady-state water quality model, together with a two-layer transport model and the sediment diagenesis and flux models, was used by HydroQual, Inc., to simulate water quality conditions within the inner and outer harbors under steady flow and pollutant loading conditions. For the steady-state model, the sediment diagenesis model was used to compute the total diagenesis flux from the sediment. The sediment flux model was used to compute the diagenesis components, including carbon and nitrogen fluxes, gas production, and sediment oxygen demand. The oxidation of dissolved methane and ammonia at the sediment water interface and within the water column affected the water column dissolved oxygen concentration, which in turn controlled the magnitudes of the component fluxes in the sediment flux model. Thus, the sediment and water column computations were performed interactively in the steady-state modeling analysis. The steady-state model simulated chlorophyll-a, ammonia nitrogen, nitrate nitrogen, biochemical oxygen demand, and dissolved oxygen levels.

A time-variable water quality simulation model of the inner harbor was developed and applied by

HydroQual, Inc., in order to simulate the response of the inner harbor to relatively large and fast changes in inflow and inflow-water quality during combined sewer overflow events, significant seiches on Lake Michigan, and diurnal variations in algal production. The hydrodynamic submodel of the time-variable water quality model considered circulation induced by the interaction of both barotropic and baroclinic pressure gradients. The interaction of these pressures along with the turbulence caused by the seiche from Lake Michigan is the primary cause of the vertical variations in velocity and temperature observed in the inner harbor. The equations for inner harbor hydrodynamics were simplified by eliminating the lateral direction component. The hydrodynamic submodel was therefore two-dimensional.

Coupling of the hydrodynamic submodel with the water quality simulation model allowed a more detailed simulation of the mixing and transport phenomenon in the inner harbor. Time-variable water quality model simulation was conducted for three "events," one being a dry-weather period ending July 26, 1982; the second being the storm runoff sampling period of September 10 through 14, 1983; and the third being the runoff event of August 10 through 12, 1983. In addition, a fourth simulation was conducted of a three-month period from July 1 through September 30, 1983, concentrating on diurnal production and use of oxygen by algae in the inner harbor.

For the wet-weather simulation for August 10 through 12, 1983, a significant decrease in dissolved oxygen, not well reproduced by the model, occurred in portions of the inner harbor following the storm event. This decrease occurred despite the fact that there were no significant combined sewer overflows during this event. A review of the dissolved oxygen data collected prior to and during the simulation period, along with the additional simulation modeling, indicated that the probable cause of the rapid and large decline in dissolved oxygen observed in the Milwaukee River at St. Paul Avenue during the runoff event was the apparent decline in algal photosynthesis resulting from increased cloud cover.

The time-variable simulations conducted for the three-month period of July 1 to September 30, 1983, of the Milwaukee River estuary from the North Avenue dam to the confluence with the Menomonee River estuary provided a further understanding of the effects of algal productivity on dissolved oxygen levels in the estuary. The results of the three-month simulation indicated that dissolved oxygen depletion was sensitive to the level of solar radiation, the number of sequential days of low sunlight intensity, chlorophyll-a concentrations, and river flow.

Statistical models of the inner and outer harbors were developed and applied by HydroQual, Inc., relating the statistics of runoff and the characteristics of the receiving water body to the statistics of concentrations of fecal coliform bacteria and lead. The mean, variance, and correlation times of the pollutant sources were input, and the mean and variance of receiving water concentrations were computed. The simulated indicator concentration means and variances were then used with normal probability theory to determine log-normal distributions of concentrations. These results were then compared with like distributions for observed data to check model calibration. These statistical models was used to simulate concentrations of fecal coliform and lead.

Fecal coliform was assumed to behave according to first-order reaction rate kinetics. The simulation analysis for dry weather suggested that a significant source of coliform, probably dry-weather separate sanitary sewer overflow, was resulting in high dry-weather fecal coliform levels. However, the all-weather simulation indicated that, overall, the highest fecal coliform levels in the estuary were caused by combined sewer overflows.

Similarly, dry- and all-weather simulations for summer periods were conducted for lead. All-weather mean lead concentrations were found to be similar to dry-weather concentrations, but exhibit significantly higher variability.

ANALYSIS OF INVENTORY RESULTS

A 1985 report on Great Lakes water quality prepared by the Great Lakes Water Quality Board[1] identified 10 river inlets and harbors on Lake Michigan as having particularly serious water pollution problems. Of these, four water bodies—the Fox River inlet to Green Bay, Wisconsin; the Waukegan Harbor, Illinois; the Grand Calumet

[1] *Great Lakes Water Quality Board, 1985 Report on Great Lakes Water Quality, Report to the Canadian-United States International Joint Commission, June 1985.*

River and Indiana Harbor Canal, Indiana; and the Milwaukee Harbor estuary—were further identified as exhibiting severe impairment of desired water uses and as the most polluted waterways on, or tributary to, Lake Michigan. The inventory data presented in this volume confirm that a serious pollution problem exists in the Milwaukee Harbor estuary, such pollution affecting not only the water, but also the bottom sediments and biological communities residing within the estuary. While the inventories confirm the existence of a pollution problem in the estuary, the data also indicate that the estuary has the potential to become a valuable asset to the greater Milwaukee area if effective pollution abatement efforts are identified and implemented.

Lake Michigan itself is an invaluable asset of the greater Milwaukee area. It serves as a readily available and abundant source of clean water for domestic, commercial, and industrial use, and provides an important route for waterborne commerce. The lake is an important resource for sport and commercial fishing, for recreational boating, and for swimming and other body-contact recreational activities. The lake provides, in proximity to an intensively urbanized area, diverse and healthy aquatic communities and natural aesthetic amenities, helping to enhance the quality of life for residents of, and visitors to, the greater Milwaukee area. The importance of Lake Michigan to the residents of Milwaukee can, therefore, be expressed in terms of the beneficial and desired uses it offers.

With respect to the attainment of desired water uses, the Milwaukee Harbor estuary stands in sharp contrast to Lake Michigan. In addition, the estuary may pose a threat to the continued long-term maintenance of desired water uses for the near-shore areas of Lake Michigan. The degraded water quality conditions within the estuary can be viewed in terms of the foreclosed beneficial uses. Water-body contact recreational activities are prevented by the severe bacterial contamination of the water. The estuary, especially the inner harbor, does not offer the aesthetic amenities required to promote pleasure boating and related activities, or to promote commercial and residential development and redevelopment along the shorelines of the estuary. Although warmwater and even some coldwater fish can be found in the inner harbor, the water quality conditions and the soft, organic, fine-grained, heavily polluted sediments found throughout most of the inner harbor provide a poor habitat for desirable organisms. There are localized areas within the inner harbor, however, that provide suitable feeding, cover, and spawning habitats for warmwater fish and aquatic life. For example, in the Milwaukee River from the North Avenue dam to Humboldt Avenue, there are numerous scoured areas with a substrate of rocks, sand, and hard clay. Certain warmwater species, including walleye, smallmouth and largemouth bass, northern pike, bullhead, catfish, suckers, carp, and sunfish, currently spawn in this reach. Similarly, there are localized shallow areas in the upper reaches of the Menomonee and Kinnickinnic River estuaries, as well as in the upper reaches of the Burnham and South Menomonee Canals, that support rooted aquatic vegetation and are used for spawning by northern pike, yellow perch, carp, and sunfish. Many of the fish that spawn in the inner harbor migrate in from Lake Michigan during spring and summer.

Within the outer harbor, 36 different species of fish were collected in 1982 and 1983. The existing bottom sediments, although classified as heavily polluted, are adequate for the successful propagation of diverse populations of warmwater fish and aquatic life. However, the bottom sediments and the water quality of the outer harbor are not conducive to the maintenance of self-sustaining coldwater salmonid populations.

The polluted conditions in the estuary also adversely affect near-shore portions of Lake Michigan. In 1985, the Great Lakes Water Quality Board reported that Milwaukee was the only major harbor on Lake Michigan that required beach closings on the lake because of excessive bacterial levels.[2] The Milwaukee Harbor estuary also contributes to the eutrophication of Lake Michigan, especially in adjacent near-shore areas. The approximately 300,000 pounds of phosphorus discharged annually from the Milwaukee Harbor estuary—including the tributary watershed loadings—to Lake Michigan represents about 2 percent of the total phosphorus load to the lake from all sources.

At the present time, the inner harbor portion of the Milwaukee Harbor estuary is not suitable for most recreational uses, or for the support of healthy populations of warmwater fish. The inner harbor experiences excessive levels of bacterial contamination during both wet-weather and

[2] *Ibid.*

dry-weather periods; dissolved oxygen concentrations that are too low to sustain desired fish and aquatic life, especially during warm, dry-weather periods; excessive nutrient levels which in the upstream reaches support heavy growths of algae, especially in the Milwaukee River; and concentrations of metals and organic substances that exceed levels considered to be toxic to aquatic organisms. Water quality conditions in the Milwaukee and Kinnickinnic River estuaries, especially with respect to dissolved oxygen and temperature levels, are, however, substantially improved when the flushing tunnels are in operation.

To help investigate the existing water resource problems in the Milwaukee Harbor estuary and evaluate alternative means of resolving these problems, state-of-the-art technologies and analytic procedures were employed in the study. The study went beyond recommending water use objectives and supporting water quality standards and then determining which pollutant sources needed to be abated or eliminated in order to achieve these standards. The study attempted to define the numerous interacting processes that significantly and adversely affect the ecosystem comprising the estuary. Several mathematical models, in addition to large amounts of primary field data, as described in Chapters VI and VII of this volume, were developed and employed to facilitate the careful observation of the interrelationships between variables under controlled conditions.

The study thus helped to uncover and better define "new" subtle, pervasive, and threatening forms of water pollution in the estuary. The Milwaukee Harbor estuary study involved the collation and summary of all available data on toxic substances; the collection of additional data on toxic substances in water, sediment, and the tissue of fish; and the conduct of laboratory toxicity bioassays using zooplankton in water samples taken from the estuary.

Because of advances in analytic technology with regard to toxic substances, such substances can be detected and measured at much lower levels of concentration than was formerly possible. As a result, the apparent dimension of the toxic contamination problem has increased. This has, in turn, lead to attempts by the U. S. Environmental Protection Agency to develop standards for toxic substances not only with respect to water, but also with respect to bottom sediments and the tissue of fish.

This study of the Milwaukee Harbor estuary has attempted to address all of the important water quality issues that were raised by the 1980 Milwaukee Metropolitan Sewerage District facility plan,[3] and by the 1981 U. S. Environmental Protection Agency and Wisconsin Department of Natural Resources environmental impact statement concerning that plan.[4] Those major issues include the following:

1. What are the desired and achievable water use objectives and supporting water quality standards for the Milwaukee Harbor estuary?

2. What level of protection in combined sewer overflow abatement is required to meet those water use objectives?

3. Is there a need for abating in-place pollution and what are the recommended methods of abating such pollution?

4. What reductions in pollutant loadings from nonpoint and point sources that discharge upstream of the Milwaukee Harbor estuary will be required to meet the water use objectives within the estuary?

5. Are toxic conditions affecting the beneficial use of the Milwaukee Harbor estuary?

It should be noted that complete responses to these issues require consideration of the alternative plans set forth in Volume Two of this report. This volume of the report, however, addresses each of these issues to some degree. The inventory findings reported in this volume help to better define these issues and direct the subsequent plan preparation efforts.

Water Use Objectives and Water Quality Standards

Recommended water use objectives and supporting water quality standards for the Milwaukee Harbor estuary are set forth in Chapter II of Volume Two of this report. Those recommended objectives and standards are based upon careful consideration of

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[3] *Milwaukee Metropolitan Sewerage District, MMSD-Wastewater System Plan, 1980.*

[4] *U. S. Environmental Protection Agency and Wisconsin Department of Natural Resources, Environmental Impact Statement for the Milwaukee Water Pollution Abatement Program, 1981.*

the physical characteristics of the various estuary reaches and existing and proposed riparian land uses, as well as of existing and potential water uses and related water quality conditions. This volume describes the existing water uses and water resource conditions and provides a basis for informed judgments concerning which water quality problems can and should be controlled or mitigated and, therefore, what water uses can and should be achieved.

With respect to achievable water use objectives, there are five major findings of this study which contribute significantly to an improved understanding of the causes and effects of the existing and potential conditions in the Milwaukee Harbor estuary. These are as follows:

1. The aquatic habitat conditions in most of the inner harbor, which are of poor quality and which for the most part prevent the successful reproduction of desired fish species, are caused only in part by combined sewer overflows. While abatement of such overflows may be expected to result in substantial improvement in the habitat conditions within the estuary, physical modifications such as vertical dock walls and channel-side linings may limit the establishment of suitable aquatic habitat in certain reaches of the estuary. Also of importance in this respect are the types and intensities of existing and proposed land use development immediately adjacent to portions of the inner harbor. Clearly, this intensive land use affects not only the potential of the waterways, but also the desired uses of the waterways, particularly the Menomonee and Kinnickinnic River estuaries.

2. Considering its poor water quality conditions, poor sediment quality conditions, and poor habitat conditions, the inner harbor has a surprisingly diverse fishery. Desired fish species exist, however, largely because of the inflow of large amounts of relatively clean Lake Michigan water, and because of the migration of fish from the lake and from upstream reaches. Because of a lack of habitat and the presence of in-place pollutants, the successful reproduction of desired fish species does not occur within most of the inner harbor.

3. The benthic invertebrate communities found in the inner harbor, which are pollution-tolerant and representative of grossly polluted bottom conditions, are limited by the presence of low dissolved oxygen levels in the interstitial and overlying water, by the highly organic content of the sediments, by the toxic substances contained within the sediments and interstitial water, by scouring caused by combined sewer overflows, and by high sedimentation rates. Thus, the abatement of combined sewer overflows, with the concomitant reduction in pollutant loadings, sediment contributions, and scouring impacts, may be expected to enhance the establishment of desired benthic communities in the inner harbor. The development of desired benthic communities is a fundamental step in establishing healthy populations of fish, since the benthic organisms are an important food source for many fish.

4. Full and partial body-contact recreational uses of the estuary, currently limited by high fecal coliform bacteria levels, by excessive algal plant growth stimulated by high nutrient levels, and by high turbidity levels, are significantly affected by both combined sewer overflows and upstream pollution sources. While the abatement of combined sewer overflows will greatly improve the recreational use potential, upstream nonpoint source water pollution controls and perhaps instream measures will also be required in order to fully meet recreational use standards.

5. Critical water quality conditions in the inner harbor were found by water quality simulation modeling analyses to be significantly affected by hydrologic and hydraulic conditions. During low flows of tributary rivers, circulation in the inner harbor, and thus pollutant dilution and transport, is dominated by periodic flood and ebb flows from Lake Michigan, by the large condenser cooling water withdrawals from the Menomonee River estuary by the Wisconsin Electric Power Company Valley power plant, and by the flushing tunnels which intermittently discharge lake water at the upstream ends of the Milwaukee River estuary and the Kinnickinnic River estuary. Water quality conditions within the inner harbor are substantially improved when the inflow of lake water is increased.

Combined Sewer Overflow Abatement

While the specific level of protection needed for combined sewer overflow abatement is addressed in the second volume of this report, some informed judgments can be made on the relative impacts of constructing and operating the combined sewer overflow storage facilities as designed and sized in the adopted regional water quality management plan and the Milwaukee Metropolitan Sewerage District facility plan to contain discharge from the separate sewered and combined sewered drainage areas.[5] Abatement of the separate and combined sewer overflows at the existing estimated level of protection is expected to result in substantially reduced fecal coliform levels; improved dissolved oxygen levels through lower biochemical oxygen demand and sediment oxygen demand levels; the decomposition and stabilization of the organic bottom sediments; enhanced aquatic habitat; and lower levels of toxic and hazardous substances in the water and in the bottom sediments. While significant improvement in the water quality and related resources will result, the separate and combined sewer overflow abatement efforts alone will not fully achieve the proposed recreational use and warmwater fishery and aquatic life objectives and supporting standards. Control of upstream sources of pollution which cause excessive upstream levels of fecal coliform and algae will also be required to fully meet these objectives.

In-Place Pollution and
Associated Dissolved Oxygen Problems

Large amounts of sediment and organic material, as well as metals and toxic organic substances, have been deposited within the inner and outer harbors. Some of the sediment and pollutants have been periodically removed by dredging to maintain deep water, commercial navigation. Thus, pollutants deposited over the past decades, as well as existing sources of pollution, contribute to the poor water quality conditions of the estuary.

Review of the extensive data base developed under the study on dissolved oxygen levels indicates that the immediate oxygen demand caused by sediment scour at combined sewer outfalls is insufficient to account for the rapid dissolved oxygen depletions occasionally observed during wet-weather periods. It was therefore concluded that dissolved oxygen depletion in the estuary is not caused by sediment scour during overflow events. This conclusion is contrary to the conclusions reached in previous studies. When wet-weather dissolved oxygen depletions occur in the Milwaukee River, they are attributable to the inhibition of oxygen production by algal photosynthesis and respiration. Occasionally, wet-weather dissolved oxygen depletions in the Menomonee and Kinnickinnic River estuaries are attributable to the inflow of oxygen-poor river waters into the estuaries. Depressed dissolved oxygen levels were found to occur primarily under warm, dry-weather, low-flow conditions, often accompanied by cloudy skies. Sediments in an undisturbed rather than a resuspended state were found to be a major sink of dissolved oxygen. About 70 percent of the reactive organic sediments are contributed by combined sewer overflows. Once the combined sewer overflows are abated, the bottom sediments may be expected to decompose and stabilize relatively quickly—within a two-year period. The sediment oxygen demand would be low enough under these conditions that the bottom sediments would probably not need to be removed in order to provide adequate dissolved oxygen levels in the water. Since most of the organic matter and algae from upstream of the estuary pass through the estuary without settling, and since upstream pollution abatement measures may be expected to reduce these organic loadings, these upstream sources are expected to be a minor component of the total organic flux to the sediments.

Toxic Conditions

Toxic substances were found in the water and bottom sediments of the estuary, as well as in the tissue of fish, suggesting that biological uptake of toxic substances through the food chain, of which benthic biota are a major link, may be related to the presence of sediments contaminated by toxic substances. The uptake of toxic substances by fish that reside within the Milwaukee Harbor estuary was shown by the detection of three metals and 17 toxic organic substances in the tissue of fish captured in the estuary. With respect to human health, the greatest known hazard is related to the consumption of fish containing excessive levels of polychlorinated biphenyls (PCB's). The fish probably acquire most of the toxic substances through ingestion of benthic invertebrates and zooplankton, and probably to a lesser degree by absorption through the gills and skin. Worms and other invertebrates sorb toxic substances from the interstitial water in the bottom sediments. Hence, some metals—such as cadmium and mercury—and

[5]*As of February 1986, the Milwaukee Metropolitan Sewerage District had estimated that the storage facilities designed to contain excess discharge from the separate sewered areas would also provide for combined sewer overflow abatement at a 0.7-year level of protection.*

toxic organic substances deposited into the bottom sediments may be released to and biomagnified in the food chain. Zooplankton may obtain toxic substances directly from the water, or may ingest contaminated bacteria and other micro-organisms. With regard to the toxic substances in fish tissue, it is important to note that the levels of these substances in fish in the estuary are in the range of levels of these substances in fish in Lake Michigan. Since some of the fish migrate between the lake and the estuary, and since the estuary receives large inflows of lake water, the removal of the sediments from the estuary may not entirely prevent the accumulation of toxic substances in fish. The reduction in toxic substances in fish tissue achieved will likely vary substantially depending upon the specific substance and the specific species considered.

Using state-of-the-art methodologies, the relationship between toxic substances in the bottom sediments and in the biota can be only qualitatively inferred. Therefore, analyses of the severity of toxic contamination to support the development and analysis of remedial actions, such as dredging, to decrease toxic substance concentrations in aquatic biota could not be carried out owing to a lack of assessment criteria and suitable laboratory analysis techniques. Once adequate criteria become available and accepted laboratory procedures are developed by the U. S. Environmental Protection Agency, the toxic substances problem in the estuary can be properly defined.

Pollutant Loadings from Upstream Sources

Two major water quality problems within the Milwaukee Harbor estuary are directly related to pollutant loadings from sources located upstream of the estuary. The first problem involves excessive levels of fecal coliform bacteria. A relatively high level of reduction in fecal coliform loadings—ranging from about 80 to more than 95 percent—would be required to achieve the recommended recreational use objectives and supporting water quality standards in the tributary Milwaukee, Menomonee, and Kinnickinnic Rivers. The primary nonpoint sources of fecal coliform are livestock operations, malfunctioning septic tank systems, and urban stormwater runoff. The primary point sources are combined and separate sewer overflows. While some of these sources are controllable to a high degree, others, such as urban runoff, may not be practically controlled. Thus, it may be concluded that bacterial levels in the tributary rivers may not be reduced enough to support full body-contact recreational uses, and the establishment of partial body contact use objectives for the Milwaukee Harbor estuary should therefore be considered.

The second problem involves excessive growths of algae, which impair the attractiveness of the estuary and subject the biota to large diurnal fluctuations in dissolved oxygen levels. Although algal growth within the estuary itself is often light-limited, it is likely that algal growth upstream of the estuary is at times limited by the concentration of the nutrients nitrogen and phosphorus. Within the Milwaukee River, upstream of the combined sewer service area, nonpoint sources and wastewater treatment plants both contribute substantial amounts of nitrogen and phosphorus. The study results indicate that, to meet the recommended phosphorus standard in the Milwaukee River portion of the estuary, a high level of reduction in phosphorus loadings from both nonpoint sources and the treatment plants would be required. The phosphorus reductions with respect to the latter will have to be higher than presently required. In the Menomonee and Kinnickinnic Rivers, nonpoint sources account for most of the upstream phosphorus loadings, although the Germantown wastewater treatment plant also discharges a significant amount of phosphorus into the Menomonee River.[6]

A potential third problem is the contribution of toxic substances to the waterways upstream of the estuary and the resultant deposition of those substances within the estuary sediments. Because combined sewer overflows are suspected to be a major source of the toxic sediments in the inner harbor, abatement of such overflows is expected to result in a major reduction in the amount of such sediments reaching the inner harbor. Subsequent burial by long-term deposition of sediments from upstream sources may be expected to further reduce the concentrations of toxic substances in the sediments and aquatic biota.

[6]*In the adopted regional water quality management plan, the Germantown sewage treatment plant is proposed to be abandoned and its tributary service area connected to the Milwaukee metropolitan sewerage system. Efforts to abandon this plant were initiated in 1985. The necessary trunk sewers required for connection of the Germantown sanitary sewerage system to the Milwaukee metropolitan sewerage system were under construction in 1986.*

Table 147

SUMMARY OF EXISTING WATER RESOURCE PROBLEMS IN THE MILWAUKEE HARBOR ESTUARY: 1981-1983

	Severity						Source				
	Inner Harbor										
Water Resource Problems	Milwaukee River	Menomonee River	Kinnickinnic River	Outer Harbor	Primary Causes	Secondary Causes	Combined Sewer Overflow	Upstream Nonpoint	Upstream Point[a]	Dry-Weather Sanitary Sewer Overflows	Jones Island Wastewater Treatment Plant (outer harbor only)
1. Low dissolved oxygen levels during dry-weather, warm periods	Severe	Severe	Severe	Slight	Sediment oxygen demand	Algal respiration	Major	Minor	- -	- -	- -
2. Low dissolved oxygen levels during wet-weather periods	Moderate	Moderate	Moderate	Slight	Algal respiration/ inhibition of algal photosynthesis (Milwaukee River)	Biochemical oxygen demand	Major (Menomonee and Kinnickinnic Rivers) Minor (Milwaukee River)	Major (Milwaukee River) Minor (Menomonee and Kinnickinnic Rivers)	- -	- -	- -
3. High fecal coliform levels	Severe	Severe	Severe	Moderate	Wet-weather bacteria loadings	Dry-weather bacteria loadings	Major (wet weather)	Major (wet weather)	- -	Major (dry weather)	- -
4. High phosphorus levels	Severe	Moderate	Moderate	Moderate	Wet- and dry-weather phosphorus loadings	- -	Major	Major	Minor	- -	Major
5. Un-ionized ammonia nitrogen toxicity	None	None	None	Moderate	Wet- and dry-weather ammonia loadings	- -	Minor	Minor	- -	- -	Major
6. Toxic substances in the tissue of fish	Severe	Severe	Severe	Severe	Ingestion of contaminated food organisms	Diffusion of toxic substances in water through gills and skin	Major	Minor	Minor	- -	Minor
7. Toxic substances in bottom sediments	Severe	Severe	Severe	Moderate	Particulate toxic substance loadings	- -	Major	Major	Minor	- -	Minor
8. Toxic substances in water column	Moderate	Moderate	Moderate	Moderate	Dissolved and particulate toxic substance loadings	Release of toxic substances from the bottom sediments	Major	Major	Minor	- -	Minor
9. Poor quality benthic habitat and communities	Severe	Severe	Severe	Moderate	Highly organic toxic sediments; scouring; high sedimentation rate	Low dissolved oxygen in overlying water; dredging; lining of channel sides	Major	Minor	- -	- -	Minor
10. Limited fish communities	Moderate	Moderate	Moderate	Slight	Inadequate water quality and aquatic habitat. Possible toxic conditions	- -	Major	Minor	Minor	- -	Major
11. Excessive algal growths	Severe	Slight	Slight	Slight	High phosphorus and nitrogen levels; suitable hydraulic conditions	- -	Minor (Milwaukee River)	Major (Milwaukee River)	Minor	- -	Major
12. Poor aesthetic quality	Moderate	Moderate	Moderate	Slight	High algal growths in Milwaukee River; high turbidity; floating debris; dead fish	- -	Major	Major	- -	- -	Minor

[a] *Includes municipal wastewater treatment plants and industrial wastewater discharges.*

Source: SEWRPC.

CONCLUSION

The above discussion demonstrates that the Milwaukee Harbor estuary has a variety of water resource problems which adversely affect not only the aquatic life which reside in the waterway, but also the use of the estuary by humans for recreational purposes. Furthermore, these problems are complex and interrelated, requiring a large data collection effort and detailed analytic techniques and mathematical simulation models to properly define and understand. The data and analytic techniques employed for the Milwaukee Harbor estuary study were designed to characterize the water resource problems, to define the conditions which cause these problems, and to quantify the sources of pollution that contribute to these conditions. Table 147 summarizes the water resource problems and the causes and sources of these problems.

It was clearly demonstrated that combined sewer overflows are the most important cause of the dissolved oxygen and fecal coliform problems within the inner harbor. The next most important cause of these problems is the nonpoint source pollution loadings generated in the tributary watersheds. While the combined sewer overflow abatement program is expected to substantially improve conditions in the estuary, it is important to note that the recommended water quality standards were frequently violated at the upstream boundaries of both the estuary and the combined sewer service area. Thus, abatement of both combined sewer overflows and upstream pollution sources will be required to meet the recommended water use objectives and supporting water quality standards.

More specifically, the following conclusions can be reached from the results of the inventories conducted under the Milwaukee Harbor estuary study:

1. Based upon the analyses of existing water quality conditions and sources of pollution, warmwater fish and aquatic life use objectives should, with effective pollution abatement, be achievable throughout the Milwaukee Harbor estuary. However, the achievement of the warmwater fish and aquatic life objective in the Burnham Canal, South Menomonee Canal, and Menomonee River portions of the estuary may not be practical because of irreversible physical channel modifications and the character of adjacent land uses. Indeed, it may be desirable to consider filling in the Burnham and South Menomonee Canals as a means of disposal of dredged material for maintenance of navigation.

2. The proposed deep tunnel combined sewer overflow storage capacity would, in conjunction with other measures, result in about one combined sewer overflow event on the average of every eight months. This capacity should provide adequate abatement of the effects of existing overflows and, along with other point and nonpoint source control and instream measures, may be expected to result in water quality conditions meeting warmwater fish and aquatic life and partial body-contact recreational water use objectives for dissolved oxygen, fecal coliform, and other conventional pollutants.

3. With regard to conventional pollutants, there is no need to remove the existing bottom sediments within the Milwaukee Harbor estuary. With regard to toxic substances, additional information on the sources, fate, uptake, and transport of these substances is required.

4. If combined sewer overflows are abated and no instream measures are implemented, an estimated reduction in upstream loadings of about 95 percent for fecal coliform, and up to 70 percent for chlorophyll-a and biochemical oxygen demand, will be required to meet the full recreational use, warmwater fish and aquatic life water use objectives in the Milwaukee and Kinnickinnic River estuaries. In the Menomonee River estuary, full warmwater fish and aquatic life water use objectives cannot be achieved at all times even with the maximum practicable reductions in upstream loadings unless instream measures are installed. The operation of the flushing tunnels on the Milwaukee and Kinnickinnic River estuaries substantially improves the dissolved oxygen levels and significantly reduces the concentrations of other pollutants. During operation of the tunnels, the dissolved oxygen concentrations are expected to be suitable to support warmwater fish and aquatic life even with only minimal upstream control measures.

5. Toxic substances limit recreational uses of the estuary only to the extent that the consumption of fish from the estuary and from upstream rivers tributary to the estuary should be restricted, as recommended in the state fish consumption advisory. Such restrictions are also recommended for fish from Lake Michigan.

The inventory data presented in this volume are used in Volume Two of this report as a basis for the development and evaluation of alternative water pollution abatement plans for the Milwaukee Harbor estuary and for the selection of a recommended plan.

APPENDICES

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Appendix A

TECHNICAL ADVISORY COMMITTEE
MILWAUKEE HARBOR ESTUARY COMPREHENSIVE
WATER RESOURCES MANAGEMENT PLAN

Herbert A. Goetsch, Chairman .... Former Commissioner of Public Works, City of Milwaukee
Helen M. Jacobs, Vice-Chairman .... Member, Milwaukee River Restoration Council
Kurt W. Bauer, Secretary .... Executive Director, Southeastern Wisconsin Regional Planning Commission
Earl K. Anderson .... Harbor Engineer, Port of Milwaukee
Jeannette Bell .... State Representative, 2nd District; Representative, League of Women Voters
Kent B. Fuller .... Chief of Environmental Planning, Great Lakes National Program Office, U. S. Environmental Protection Agency
John D. Haliday .... Rear Commodore, Milwaukee Yacht Club
Jay G. Hochmuth .... Assistant Administrator, Division of Environmental Standards, Wisconsin Department of Natural Resources
Peter E. Hughes .... Hydrologist, U. S. Geological Survey
Andrew E. Jackson .... Chairman of the Board, Edward E. Gillen Company
John J. Justen .... Member, Greater Milwaukee Committee
Ronald W. Kazmierczak .... Assistant District Director, Wisconsin Department of Natural Resources-Southeast District
Orville L. Kurth .... District Conservationist, U. S. Soil Conservation Service
Dr. Norman P. Lasca .... Professor, Department of Geological Sciences, University of Wisconsin-Milwaukee
Edwin J. Laszewski, Jr. .... City Engineer, City of Milwaukee
Patrick Marchese .... Executive Director, Milwaukee Metropolitan Sewerage District
Jan Marsh .... Member, Wisconsin Audubon Society
Robert J. Miller .... President, Miller Compressing Company
William D. Rogan .... Commissioner, Southeastern Wisconsin Regional Planning Commission
Harold F. Ryan .... Washington County Board Supervisor; Commissioner, Southeastern Wisconsin Regional Planning Commission
Rudolpho N. Salcedo .... Environmental Scientist, Department of City Development, City of Milwaukee
Harout O. Sanasarian .... Supervisor, Milwaukee County Board
David F. Schulz .... Director, Department of Parks, Recreation and Culture, Milwaukee County
Gerald Schwerm .... Director of Transportation, Department of Public Works, Milwaukee County
George Watts .... President, George Watts & Son, Inc.
Walter T. Woelfle .... Attorney, Wisconsin Electric Power Company
Dr. Alphonse E. Zanoni .... Professor, Department of Civil Engineering, Marquette University

WATER QUALITY MODELING SUBCOMMITTEE

Dale J. Patterson Chairman	Environmental Engineer, Wisconsin Department of Natural Resources
Carl W. Birks	Director, Department of Engineering, Energy and Environment, Milwaukee County
David A. Gruber	Group Manager, Water Resources Research, Milwaukee Metropolitan Sewerage District
Peter E. Hughes	Hydrologist, U. S. Geological Survey
Dr. Vladimir Novotny	Professor, College of Engineering, Marquette University
William L. Richardson	Environmental Scientist, Large Lakes Research Station, U. S. Environmental Protection Agency

Appendix B

SOURCES OF ORGANIC TOXIC SUBSTANCE AND METAL CONCENTRATION MEASUREMENTS IN THE BOTTOM SEDIMENTS: 1975-1985

The sampling stations identified in the following data sources are shown on Map 93. The organic toxic substance data are summarized in Table 83.

Symbol on Map 93	Data Source
Analysis of Both Organic Toxic Substances and Metals:	
A	Limno-Tech, Inc., Field Methodology and Results for Milwaukee Harbor, Kinnickinnic River and Menomonee River, prepared for the U. S. Army Engineer District, Detroit, June 1984.
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Symbol on Map 93	Data Source
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