TECHNICAL REPORT NO. 40

RAINFALL FREQUENCY IN THE SOUTHEASTERN WISCONSIN REGION

SOUTHEASTERN WISCONSIN REGIONAL PLANNING COMMISSION

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RAINFALL FREQUENCY IN THE SOUTHEASTERN WISCONSIN REGION

Prepared for the

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SOUTHEASTERN WISCONSIN REGIONAL PLANNING COMMISSION

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STATEMENT OF THE EXECUTIVE DIRECTOR

The Southeastern Wisconsin Regional Planning Commission has periodically updated rainfall depth-duration-frequency data for the Region. This report presents the results of the most recent Commission study to update those data and, for the first time, it also provides a recommended time distribution for the development of design storms. The need for this study was accentuated by several heavy rain storms that occurred within the Region over the past 14 years.

The primary purpose of this report is to 1) provide data and procedures to be used for the determination of rainfall depths of various frequencies and durations; and 2) to enable the synthesis of design storms suitable for use in stormwater and floodland management studies and in the design of water management facilities within the Southeastern Wisconsin Region.

The National Weather Service (NWS), Office of Hydrology, was consulted during the preparation of this study. The methodologies used to analyze rainfall data are consistent with the procedures that the NWS is using in its ongoing studies to update rainfall frequency data in the Midwest.

It is the hope of the Commission staff that the data and procedures presented in this report will be helpful to planners, engineers, and scientists in both the public and private sectors in providing sound stormwater and floodland management throughout the Region.

Respectfully submitted,

Philip C. Evenson

Philip C. Evenson
Executive Director

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OBJECTIVE AND PURPOSE

INTRODUCTION

This report presents the findings of analyses undertaken to determine rainfall depths for use in the design of stormwater management facilities throughout the seven county Southeastern Wisconsin planning region. The development of the design rainfall depths required consideration of:

- historical rainfall records from locations in and around the Southeastern Wisconsin Region;
- recent extreme rainfall events in the area;
- statistical evaluation of the frequency and duration of extreme rainfall events;
- the variation of extreme rainfall events across the Southeastern Wisconsin Region; and
- the time variation of extreme rainfall within the overall duration of the storm.

The end products of this investigation are recommended design storm depths for a range of event frequencies and duration and guidance for the use of these depths with respect to regional and temporal variations. This report defines design storms in terms of depth, duration, and distribution for all locations throughout the seven-county Southeastern Wisconsin planning region.

BACKGROUND

The Southeastern Wisconsin Regional Planning Commission (SEWRPC) has used and maintained design rainfall information since the 1960s. The recommended depths have been reviewed periodically, most recently in 1990. Significant advancements in statistical procedures used to characterize rainfall prompted SEWRPC to consult with outside experts in this 2000 review and evaluation of rainfall design depths. This consultation has resulted in a major change in the methods used to derive design rainfall. Previous analyses used techniques similar to procedures in use at those times by the National Weather Service (NWS) and generally confirmed NWS results. This study uses a new statistical procedure, which is consistent with current NWS methods, and the resulting depths are generally higher than previous estimates. Previous analyses relied heavily on a single gauge record, while this study considers several nearby gauges. This study also contains an assessment of the variation in extreme rainfall across the seven-county planning region. In the past, SEWRPC has deferred to other agencies for guidance on time distribution of the rainfall. This report examines distribution data specific to the Southeastern Wisconsin planning region.

ORGANIZATION OF REPORT

This report is divided into five sections including this introduction. Chapter II discusses the need for, and appropriate uses of, the design rainfall data developed in this report. That section also describes previous rainfall studies that produced recommended rainfall depths and the recent extreme rainfall events that partly motivated this study. Chapter III presents a review of available suitable rainfall data in the region. It also describes the tests conducted to evaluate the statistical reliability of the data. The frequency analysis of extreme rainfalls is presented in Chapter IV, including the analysis methods, results, and recommended rainfall depths. The regional variation of extreme rainfall is a component of these results. Chapter V deals with the time distribution of extreme rainfall. It presents distributions in current use and results obtained based on evaluation of storms in Southeastern Wisconsin.

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Chapter II

BACKGROUND

DEFINITION AND PURPOSE OF DESIGN RAINFALL DEPTHS

Design rainfall depths are widely used in stormwater management planning, regulation, and design. They provide consistent standards for the evaluation of alternatives. The term quantile refers to a flood flow or rainfall amount corresponding to a particular probability, or recurrence interval, such as the 10-year or 100-year recurrence interval. It is not always possible or practical to derive the flow quantile needed to design each element of a project or alternative because calculation of a flood quantile requires a nearby streamflow gauge or continuous simulation of flows. This process may need to be repeated many times to obtain all flows needed to complete a design. The preferred approach is to utilize design rainfall events with a hydrologic model to obtain design flows.

Rainfall frequency is influenced by both the depth and duration of the rainfall storm event. Historically, design rainfall has been presented as intensity-duration-frequency (IDF) curves. Such curves are a plot of rainfall intensity versus the duration of the rainfall. A particular rainfall quantile will produce a concave curve that decreases with increasing duration. A set of rainfall quantiles forms a family of nearly parallel curves. IDF curves were highly applicable in the days when design flows were calculated by hand. The usual procedure was to select the intensity corresponding to the drainage basin time of concentration and use the intensity to calculate the peak flow via the rational formula. Computerized hydrologic models use overall depth and time distribution of the rainfall total as input. The appropriate storm duration is determined by a "critical duration analysis" where successive storm durations are analyzed to find the duration that produces the maximum flow. This approach, which is equivalent to matching the storm duration to the time of concentration, is applicable to complex watershed networks.

DESIGN RAINFALL ESTIMATES IN CURRENT USE

There are three commonly used sources of design rainfall depths available that provide data for Southeastern Wisconsin. These are the following:

1. "Rainfall Frequency Atlas of the United States-Technical Paper 40," David Hershfield, May 1961.

2. "Rainfall Frequency Atlas of the Midwest," by Floyd A. Huff and James R. Angel, Illinois State Water Survey Bulletin 71, 1992.

3. Rainfall intensity-duration-frequency data as published by SEWRPC in CAPR No. 152, Stormwater Drainage and Flood Control System Plan for the Milwaukee Metropolitan Sewerage District, December 1990.

These sources are respectively known as TP-40, Bulletin 71, and the SEWRPC 1990 extreme rainfall depths. A brief description of the methods used to obtain each is provided in the following.

TP-40

TP-40 provides design rainfall depths for the two-, five-, 10-, 25-, 50- and 100-year recurrence interval events for durations of one-half hour, one, two, three, six, 12, and 24 hours. These depths are provided in 48 separate isopluvial contour maps of the United States. The maps were developed by analysis of the highest quality rainfall records available in the late 1950s. Rainfall quantiles were obtained by fitting the records to the Extreme Value Type 1 (EV1), or Gumbel, distribution. Many of the Gumbel fits were completed in the development of NWS HYDRO 25 documents in 1955. Apparently, considerable smoothing was employed in drawing the TP-40 contour maps. The isopluves on each map are smooth and sweeping indicating a consistent trend of decreasing rainfall depth with increasing distance from humidity sources such as the Gulf of Mexico. The TP-40 estimate for the 100-year, 24-hour rainfall in the Southeastern Wisconsin Region is approximately 5.5 inches.

In recent years, TP-40 has become less used nationally due to its age, although it remains the only source of rainfall depths currently accepted by the Wisconsin Department of Natural Resources. However, the document contains important procedures and findings. These include the widespread use of the Gumbel distribution to fit rainfall, the relationships between "calendar" hour rainfall and peak hour rainfall, and the published selection of durations and recurrence intervals provided in the report which have since become a standard.

Bulletin 71

Illinois State Water Survey (ISWS) Bulletin 71 presents the results of an analysis of 275 gauge records in nine Midwestern states including Wisconsin. The computed rainfall depths are presented in two formats: as tables providing rainfall quantiles for each of 76 climatic regions (nine of which are in Wisconsin) and as isopluvial maps. There is an extraordinary difference between the Bulletin 71 maps and the TP-40 maps. The TP-40 maps intend to illustrate the logical variation of rainfall, while the Bulletin 71 maps meticulously document the variations in the result obtained from the analyses of 275 rainfall records. The difference can mislead users who are familiar with TP-40. The highs and lows of the Bulletin 71 maps usually indicate the locations of anomalous gauge records rather than real regional trends.

The Bulletin 71 results are based on a computational procedure that is unknown outside Huff's own publications. The method relies on fitting a curve to a plot of the logarithm of the estimated recurrence interval versus the logarithm of extreme rainfall. Daily records are primarily used in the method. Short duration storms were derived according to ratios obtained from a few hourly records and studies previously conducted by Huff in Illinois. Only three of the gauge records used in the Bulletin 71 analysis are located in the Southeastern Wisconsin area.

SEWRPC 1990

Early comprehensive estimates of rainfall frequency were conducted around 1955 for the HYDRO-25 study by the U.S. Weather Bureau using Milwaukee rainfall recorded from 1903 through 1951. The HYDRO-25 results were incorporated into the isopluvial maps published as TP-40. In 1969, SEWRPC conducted an independent analysis of rainfall frequency (SEWRPC, 1973). Like TP-40, the estimates were based on fits to the Extreme Value Type 1 (EV1), or Gumbel, distribution. The Milwaukee rainfall gauge, now located at General Mitchell Field, was the only long record available. The SEWRPC analysis extended the period of record used for NWS HYDRO-25 and TP-40 by 15 years, considering rainfalls from 1903 through 1966. The additional 15 years of data had little impact on the estimated 100-year, 24-hour rainfall yielding an estimate of 5.71 inches.

Shortly after the storm of August 6, 1986, SEWRPC reevaluated the rainfall series that had now grown to 84 years (from 1903 through 1986). Once again, the estimates were derived by fitting to the Gumbel distribution. This analysis resulted in an estimated 100-year, 24-hour rainfall of about 5.5 inches (SEWRPC, 1990). This design depth along with the other data shown in Tables 1 and 2 has generally served as the design standard in Southeastern Wisconsin for the past 10 years.

RECENT EXTREME STORMS

Four extreme summer rain storms have occurred in the Southeastern Wisconsin Region in the past 14 years. The rainfall pattern for the August 6, 1986, storm is shown on Map 1, the pattern for the June 20 and 21, 1997, storm is shown on Map 2, and the pattern for the August 6, 1998, storm is shown on Map 3. The fourth extreme storm, occurred in the City of Port Washington from June 16 through June 18, 1996, and was more localized than the other three storms. The largest observed rainfalls at recording rain gauges operated by the National Weather Service, the City of Milwaukee, or the Milwaukee Metropolitan Sewerage District (MMSD) during the 1986, 1997, and 1998 storms, supplemented with data collected by local public works departments, news media, and businesses, are shown in Figure 1. The severe rainfall events were accompanied by widespread surface ponding and flooding, by extended periods of widespread electric power failure,

Table 1

DESIGN STORM DEPTHS IN CURRENT USE IN SOUTHEASTERN WISCONSIN
(Total Rainfall Depths in Inches)

TP-40 (Hershfield, 1961)						
Recurrence Interval	Storm Duration (hours)					
	1	2	3	6	12	24
2 Years	1.41	1.63	1.72	2.00	2.34	2.63
5 Years	1.71	2.02	2.15	2.50	2.94	3.36
10 Years	1.93	2.29	2.50	2.90	3.38	3.83
25 Years	2.23	2.58	2.80	3.34	3.88	4.42
50 Years	2.41	2.88	3.12	3.69	4.27	5.00
100 Years	2.69	3.18	3.51	4.06	4.86	5.44

SEWRPC (1990)[a]						
Recurrence Interval	Storm Duration (hours)					
	1	2	3	6	12	24
2 Years	1.30	1.52	1.67	1.97	2.29	2.69
5 Years	1.62	1.90	2.07	2.44	2.86	3.34
10 Years	1.85	2.16	2.37	2.78	3.24	3.80
25 Years	2.16	2.53	2.78	3.25	3.81	4.46
50 Years	2.42	2.83	3.11	3.64	4.27	5.01
100 Years	2.66	3.11	3.41	3.99	4.68	5.47

Bulletin 71 (Huff, 1992)						
Recurrence Interval	Storm Duration (hours)					
	1	2	3	6	12	24
2 Years	1.27	1.57	1.73	2.03	2.35	2.70
5 Years	1.57	1.93	2.13	2.50	2.90	3.33
10 Years	1.81	2.24	2.47	2.89	3.36	3.86
25 Years	2.19	2.70	2.98	3.49	4.05	4.66
50 Years	2.53	3.12	3.44	4.03	4.68	5.38
100 Years	2.93	3.62	3.99	4.68	5.43	6.24

[a]To enable consistent comparison with the TP-40 and Bulletin 71 depths, factors presented in TP-40 were applied to the SEWRPC (1990) annual series depths with recurrence intervals of two, five, and 10 years, converting those depths to the partial duration series amount set forth in this table.

Source: U.S. Department of Commerce, Weather Bureau; Illinois State Water Survey; and SEWRPC.

and by the attendant surcharging of sanitary sewers and the backup of sanitary sewage into the basements of buildings. The resulting property damage and hazards to public health resulted in a public demand for corrective measures that would avoid the recurrence of such emergency conditions. This demand refocused the attention of public officials within the Region on the condition and performance of the sanitary sewerage and stormwater and floodland management systems of the Region. The storms are described below.

August 6, 1986

This thunderstorm was centered in a one- to four-mile-wide band extending northwesterly from the City of Oak Creek through General Mitchell International Airport (General Mitchell Field) to the northern portion of the City of Wauwatosa near Lawrence J. Timmerman Field. As shown on Map 1, within that band, rainfall amounts exceeded six inches. The storm total rainfall of 6.84 inches in 24 hours is the single day record

Table 2

COMPARISON OF SEWRPC (1990) AND BULLETIN 71 DESIGN STORM DEPTHS TO TP-40 DEPTHS

Recurrence Interval	Difference in SEWRPC Depths Relative to TP-40 Depths (percent)					
	Storm Duration (hours)					
	1	2	3	6	12	24
2 Years	-8	-7	-3	-2	-2	-2
5 Years	-6	-6	-4	-2	-3	0
10 Years	-4	-6	-5	-4	-4	-1
25 Years	-3	-2	-1	-3	-2	1
50 Years	0	-2	0	-1	0	0
100 Years	-1	-2	-3	-2	-4	1

Recurrence Interval	Difference in Bulletin 71 Depths Relative to TP-40 Depths (percent)					
	Storm Duration (hours)					
	1	2	3	6	12	24
2 Years	-10	-4	1	1	0	3
5 Years	-8	-4	-1	0	-1	-1
10 Years	-6	-2	-1	0	-1	1
25 Years	-2	5	6	4	4	5
50 Years	5	8	10	9	10	8
100 Years	9	14	14	15	12	15

Source: Camp, Dresser & McKee.

at the General Mitchell Field recording station. A total of 5.24 inches of rain fell in a two-hour period during the peak of the storm.

Flooding occurred not only in known floodplains, but also in areas where sheet flow over yards, streets, and alleys carried stormwater around and into structures and surcharged storm and sanitary sewerage systems, causing backup of stormwater and sanitary sewage into buildings. The most significant impacts of the storm were experienced in the Kinnickinnic River watershed in the reach between 6th and 16th Streets and along Wilson Park Creek. Other areas which were significantly impacted include: 1) areas north of the Menomonee River in the City of Wauwatosa; 2) the near northwestern portion of the City of Milwaukee, including the area along the Menomonee River and Woods Creek adjacent to County Stadium; 3) areas along Lilly Creek in the Village of Menomonee Falls; 4) General Mitchell Field, which is located on the border of the Kinnickinnic River and Oak Creek watersheds; and 5) the eastern portion of the City of West Allis. Severe basement flooding due to sewer backup was experienced in numerous other areas in the Menomonee and Kinnickinnic River watersheds which are remote from streams.

The August 1986 event is the largest observation in the NWS Milwaukee site systematic gauging record at all durations of 60 minutes or longer, with the 120-minute intensity most extreme relative to its estimated distribution. This 120-minute event has an estimated occurrence interval of over 700 years. The potential frequency of this and other recent extreme rainfall events is discussed in Chapter IV.

June 16 though June 18, 1996

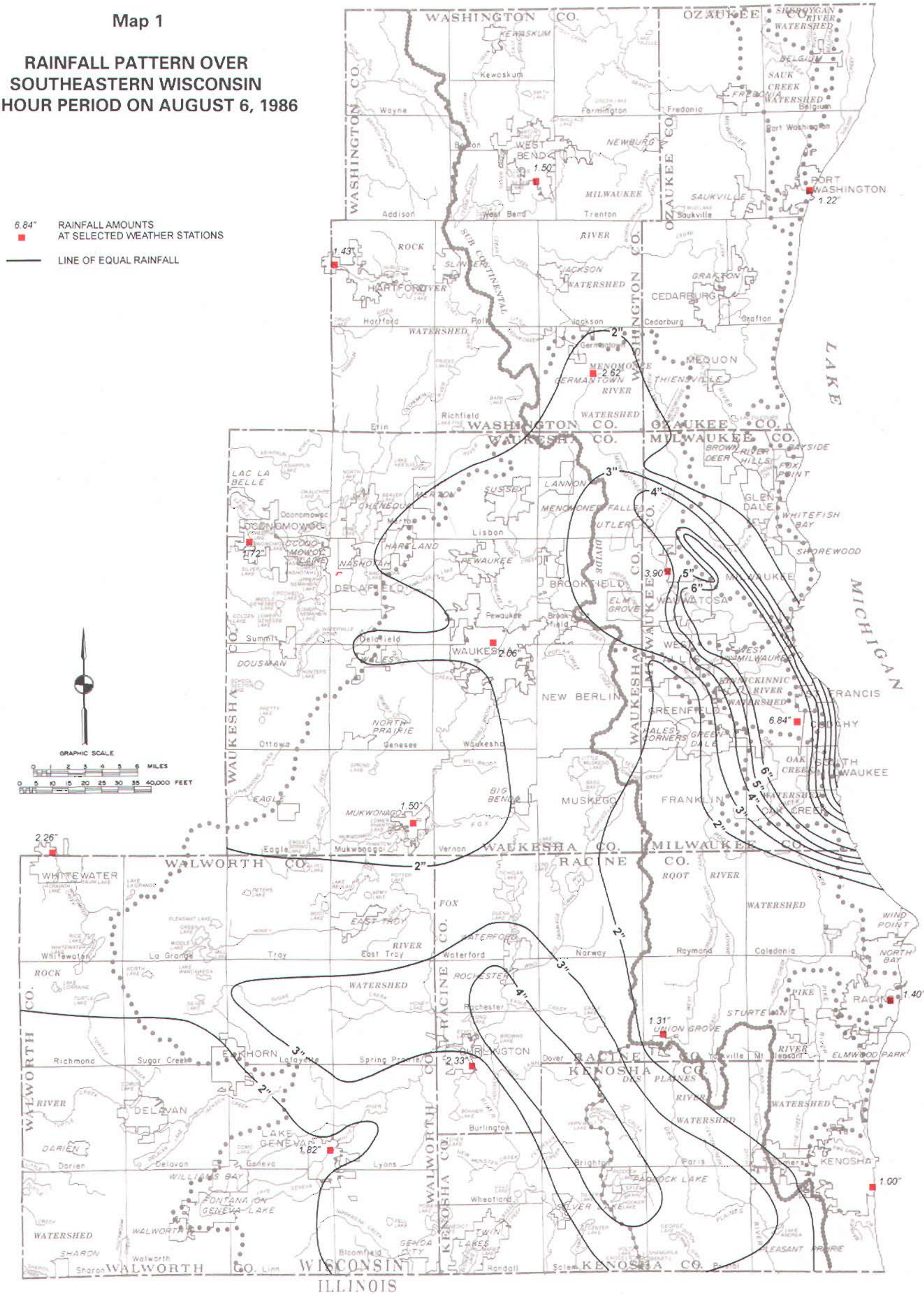
Considerable damage occurred in the City of Port Washington in Ozaukee County as a result of heavy rains totaling 13.52 inches over three days, with a peak 24-hour total of 9.87 inches. There is no known record of this rainfall captured by an automatic recording gauge, which would have provided an hourly distribution for this storm.

June 20-21, 1997

Heavy thunderstorms on June 20 and 21, 1997, created severe stormwater drainage and flooding

Map 1

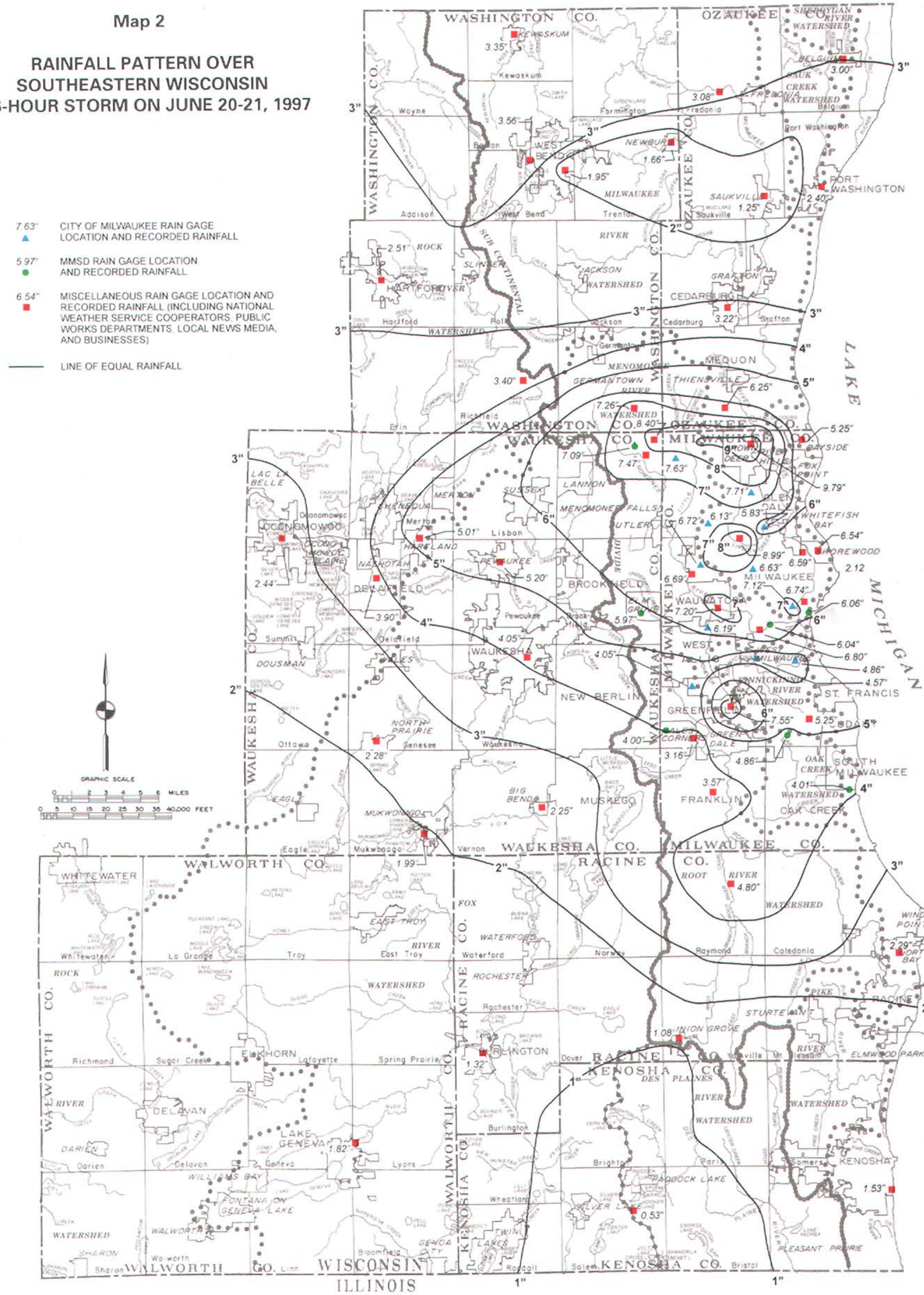
RAINFALL PATTERN OVER SOUTHEASTERN WISCONSIN 24-HOUR PERIOD ON AUGUST 6, 1986



Source: SEWRPC.

Map 2

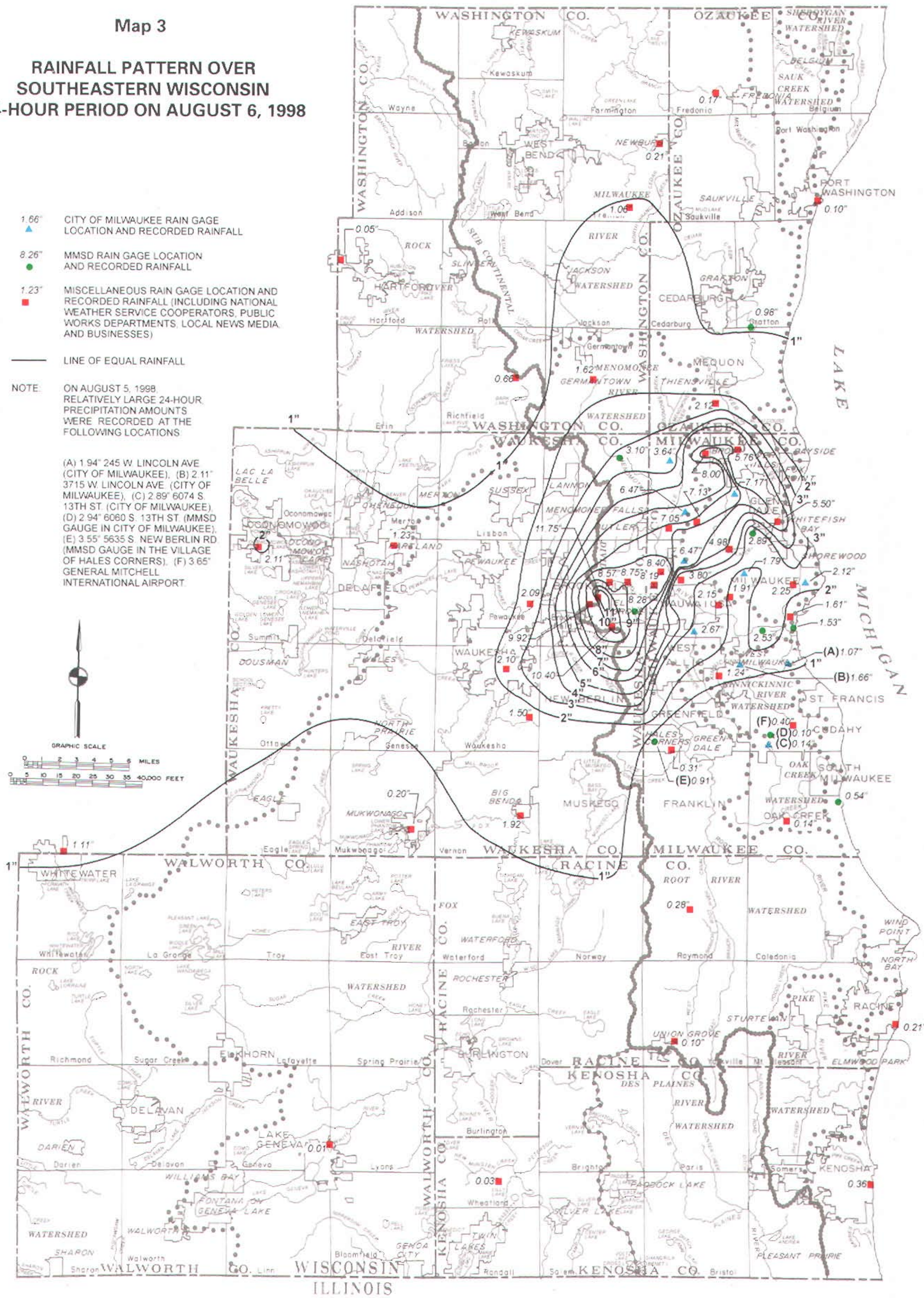
RAINFALL PATTERN OVER SOUTHEASTERN WISCONSIN 26-HOUR STORM ON JUNE 20-21, 1997



Source: SEWRPC.

Map 3

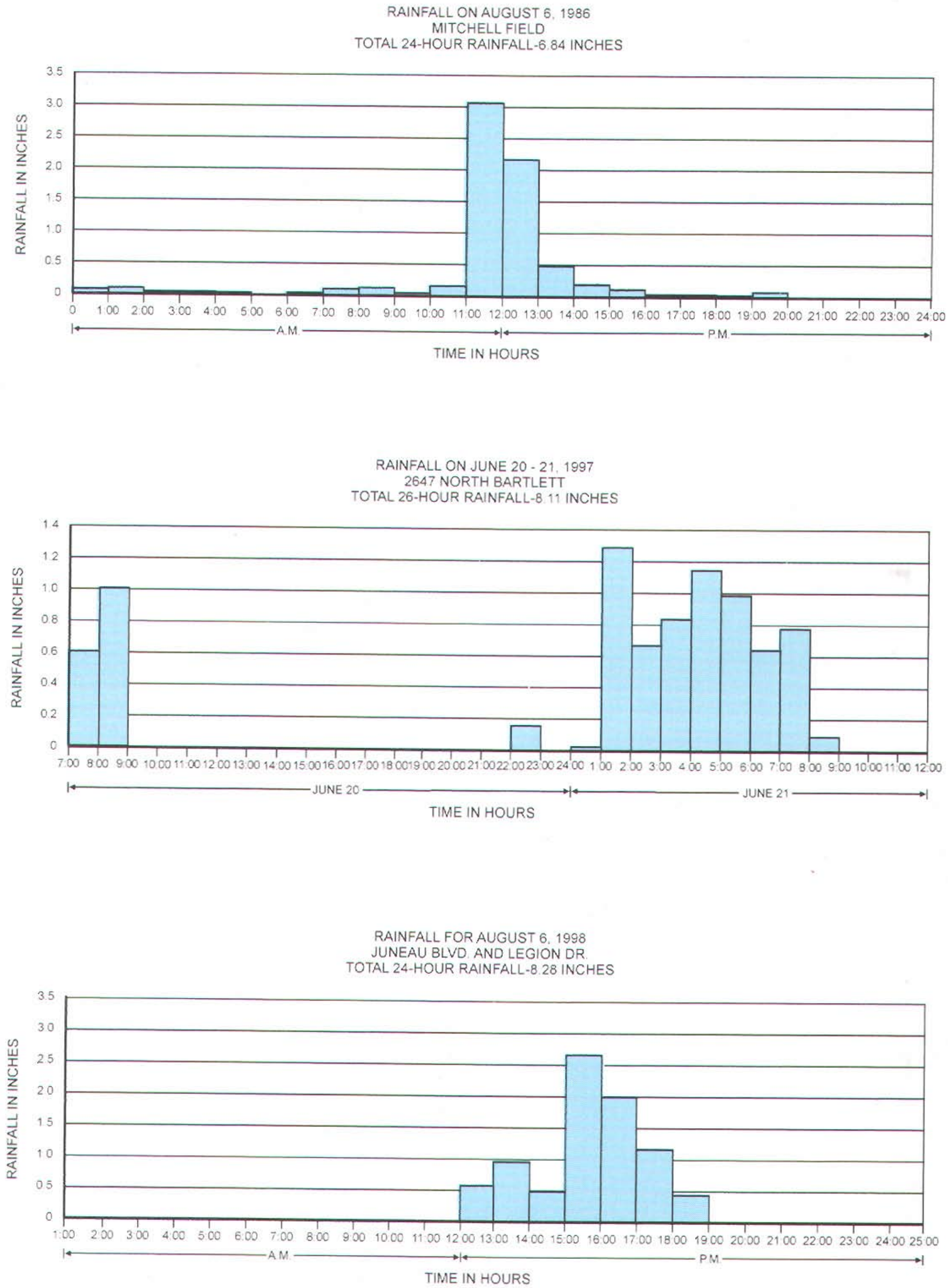
RAINFALL PATTERN OVER SOUTHEASTERN WISCONSIN 24-HOUR PERIOD ON AUGUST 6, 1998



Source: SEWRPC.

Figure 1

MAJOR HISTORICAL RAINFALL EVENTS SINCE 1986



Source: National Weather Service, City of Milwaukee, Milwaukee Metropolitan Sewerage District, and Camp, Dresser & McKee.

problems in Milwaukee, Ozaukee, Washington, and Waukesha Counties. A period of moderate rainfall during the morning of June 20 was followed by intense thunderstorms which generally occurred over about a 10-hour period, beginning shortly before midnight on June 20. As shown on Map 2, the most intense rainfall was centered in northern Milwaukee County and covered a 13-mile-wide, 18-mile-long band which also included the extreme southern portion of Ozaukee County, southeastern Washington County, and northeastern Waukesha County. Within that band, six or more inches of rain fell in a 26-hour period on June 20 and 21. The greatest reported 26-hour rainfall was 9.79 inches in the Village of Brown Deer.

Flooding occurred throughout those communities located within the band of most intense rainfall described above. Locations that experienced severe, direct overland flooding included areas along 1) Lincoln Creek in the City of Milwaukee, 2) the Menomonee River in the Cities of Milwaukee and Wauwatosa, 3) Underwood Creek in the City of Brookfield and the Village of Elm Grove, 4) Lilly Creek in the Village of Menomonee Falls, 5) Southbranch Creek in the Village of Brown Deer, and 6) Indian Creek in the Villages of Bayside and Fox Point. In addition, there were numerous occurrences of stormwater drainage and sanitary sewer backup problems in communities located throughout the areas of heavy rainfall.

August 6, 1998

Heavy thunderstorms on August 6, 1998, were produced by the combination of a stalled warm front, weak winds in the upper atmosphere, and an abundant atmospheric moisture supply to the south of the front. Those thunderstorms created severe stormwater drainage and flooding problems in northern Milwaukee County and eastern Waukesha County. The storm of August 6, 1998, was preceded by two months of below normal precipitation. Moderate rainfalls occurred on August 4 and 5, with daily totals that were generally about one inch or less. The exception to this occurred in southern Milwaukee County in a relatively narrow west to east band where from two to almost four inches of rain fell on August 5, 1998. However, that area generally experienced relatively light rains on August 6. As shown on Map 3, the most intense rainfall on August 6 covered a five-mile-wide, 16-mile-long band which included northern Milwaukee County and northeastern Waukesha County. Within that band, five or more inches of rain fell. The rainfall totals listed on Map 3 were reported as 24-hour totals, however, examination of recording gauge records indicate that the rain generally occurred over a 19- to 20-hour period, with the heaviest rainfalls falling within about a seven- to ten-hour period. The greatest reported 24-hour rainfall was 11.75 inches in the City of Brookfield. A 24-hour total of 8.00 inches was reported in the Village of Brown Deer.

Flooding occurred throughout those communities located within the band of most intense rainfall described above. Locations that experienced severe, direct overland flooding for the second consecutive year included areas along 1) Lincoln Creek in the City of Milwaukee, 2) the Menomonee River in the City of Wauwatosa, 3) Underwood Creek in the City of Brookfield and the Village of Elm Grove, and 4) Southbranch Creek in the Village of Brown Deer. As in 1986 and 1997, there were numerous occurrences of stormwater drainage and sanitary sewer backup problems in communities located throughout the areas of heavy rainfall.

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Chapter III

RAINFALL DATA IN THE SOUTHEASTERN WISCONSIN REGION

DATA SOURCES AND COVERAGE

The National Weather Service (NWS) maintains a national network of precipitation gauges currently consisting of approximately 300 primary, or first order, stations and over 8,000 cooperative stations. The former are staffed by NWS professionals and the latter primarily by volunteer observers (NRC, 1998). Two NWS data sets were used as the primary basis for frequency analysis at Milwaukee. The first consists of the time series of annual maximum n-minute precipitation, compiled by the National Weather Service, Office of Hydrology and generously provided to the authors of this study by Mr. Michael Yekta, a computer specialist with the NWS.

A supplemental data set was also assembled to provide a basis for regional homogeneity tests and frequency analysis. This consists of short-duration and hourly data from three additional NWS primary gauges and hourly data from 11 cooperative gauges located throughout Southeastern Wisconsin and Northeastern Illinois. Stations were selected on the basis of: 1) location, 2) time series coverage, and 3) completeness of data. Specifically, stations were considered for inclusion if they were located within or near Southeastern Wisconsin, had usable periods of record in excess of 30 years, and were more than 85 percent complete at hourly coverage. Long historical records of short duration and 24-hour precipitation, similar to those described above, were also available for the NWS first order gauges in Madison and Green Bay, in addition to hourly data. Most cooperative hourly records commence in 1948. Data on the 15 NWS gauges used as primary and secondary data sources in this study, as well as on other cooperative stations in or near the Region, are summarized in Table 3 and their locations are indicated on Map 4.

The NWS Milwaukee gauge has not occupied a single location throughout its period of operation. Primary NWS short duration and 24-hour records used in this study were collected at the Federal Building located in the Milwaukee central business district from beginning of the record to 1954, and at General Mitchell Field from 1955 to the present. Data have been collected continuously at General Mitchell field since July 1928, and systematic hourly data are available from 1940 to the present. The time series data, therefore, represent composite records, although they have been treated as homogenous records for statistical purposes, as consistent both with NWS criteria and statistical tests described in the following section. A station history for General Mitchell Field is included as Appendix A.

DATA QUALITY CONTROL, TESTING AND EVALUATION

Statistical frequency analysis typically rests on the assumptions of serially independent, identically distributed data. It is therefore advisable to evaluate these assumptions *a priori* in order to establish a credible basis for quantile estimation. In the context of this study, three potential sources of nonhomogeneity can be anticipated. The first is introduced by the movement of the primary NWS gauge from downtown Milwaukee to General Mitchell Field in 1955. The second is the impact of installing windshields on NWS precipitation gauges, beginning in the late 1940s, thereby increasing the catch efficiency of the gauges. In addition, it is possible that extreme rainfall has been impacted by nonstationarity in climate due to natural or human induced causes. Karl et al. (1996) observed that average annual rainfall has increased in selected locations during the Twentieth Century. However, that paper does not provide the meteorologic mechanism for these increases

Table 3

NATIONAL WEATHER SERVICE PRECIPITATION GAUGES

Station Name	State	Start Date	End Date	Number of Years	Percent Data Available	Gauge Location Latitude	Gauge Location Longitude
Gauges Included in the Study							
Berlin	WI	8/48	2/84	36	91	43:59	88:57
Chilton	WI	8/48	8/97	49	96	44:02	88:09
Eagle	WI	8/48	3/94	47	93	42:52	88:31
El Dorado 1 SSW	WI	8/48	2/84	37	88	43:48	88:38
Green Bay WSO	WI	8/48	9/97	49	100	44:30	88:07
Hartford 2W	WI	8/48	8/97	49	93	43:20	88:25
Janesville	WI	8/48	6/87	40	94	42:40	89:01
Madison WSO	WI	8/48	9/97	49	100	43:08	89:20
Milwaukee WSO	WI	1891	12/98	108	100	42.57[a]	87:54[a]
Portage	WI	8/48	12/96	49	95	43:32	89:26
Belvidere 1N	IL	7/48	12/96	49	92	42:16	88:50
Chicago O'Hare WSO	IL	6/62	12/96	35	100	42:00	87:53
McHenry WG Stratton	IL	7/48	12/96	48	91	42:17	88:14
Oregon 2E	IL	11/49	12/96	48	93	42:00	89:17
Rockford WSO	IL	1/51	12/96	40	99	42:12	89:06
Additional Gauges Excluded From the Study Due to Inadequate Record Length or Data Recovery							
Afton	WI	7/87	12/96	10	84	42:37	89:04
Burnett 3S	WI	8/48	11/70	23	96	43:28	88:42
Clinton	WI	7/91	12/96	6	90	42:33	88:50
Horicon	WI	11/70	12/96	27	88	43:26	88:38
Milwaukee WB City	WI	8/48	3/54	5	100	43:02	87:54
Sullivan	WI	9/94	12/96	3	76	42:58	88:33
Chicago Loyola	IL	7/48	5/68	21	71	42:00	87:40
Evanston Pump Station	IL	7/48	5/68	21	73	42:01	87:41
Oregon Waterworks	IL	7/48	10/49	2	99	42:01	89:20
Rockford CAA APO	IL	7/48	12/50	3	100	42:01	89:03
Skokie N S Treatment Works	IL	7/48	12/74	27	91	42:01	87:43

[a] *Milwaukee data refers to the General Mitchell Field location.*

Source: National Weather Service and Rodgers and Potter.

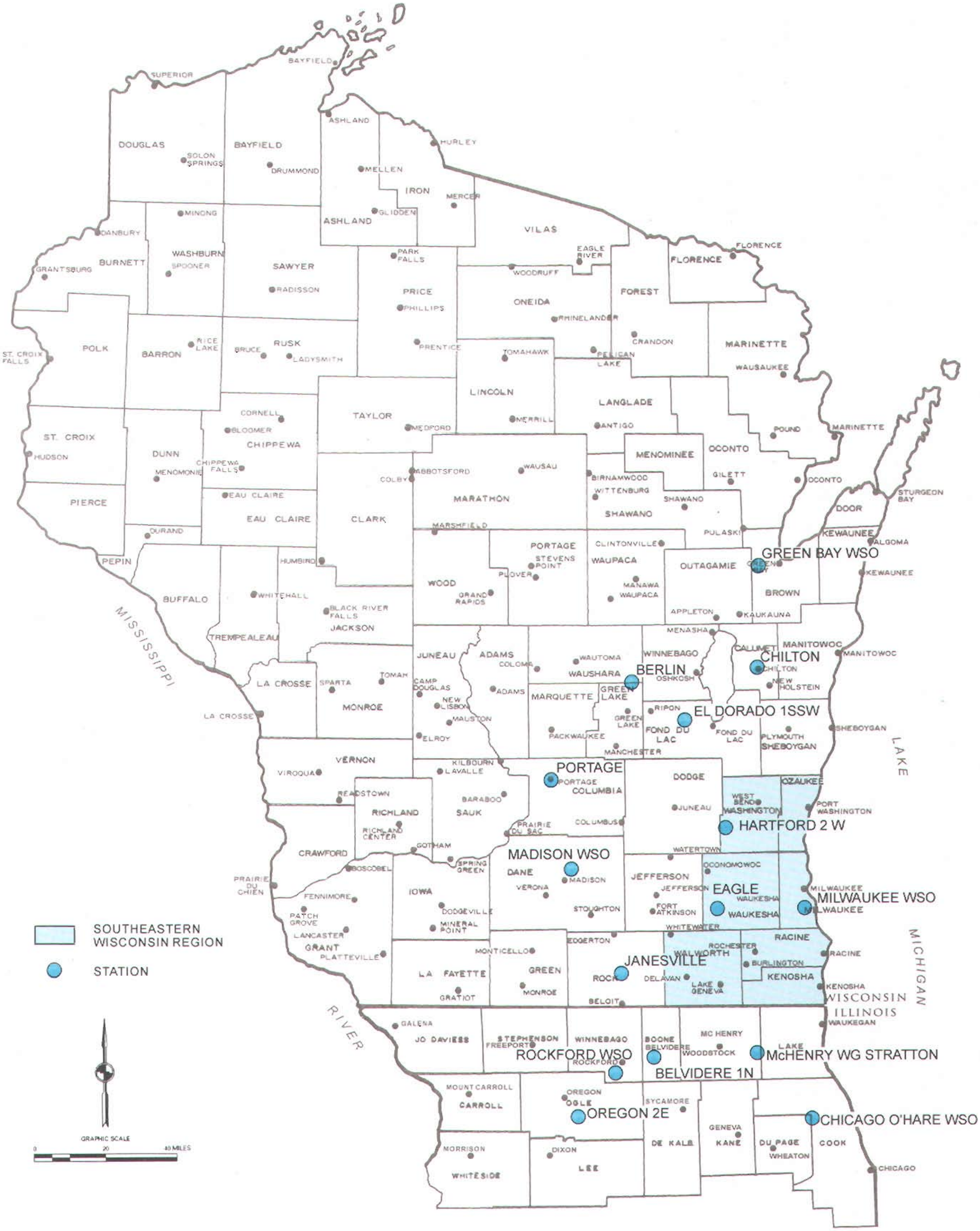
and does not explicitly address the frequency of extreme rainfall. This issue is discussed further in Chapter IV.

In this chapter, the potential sources of nonhomogeneity in the Milwaukee gauge record are investigated using appropriate statistical techniques. Two methods were structured to identify sudden changes which would be indicative of a nonhomogeneity caused by modification or relocation of the gauge and three methods were designed to test for the presence of a systematic trend which could be the result of changing climatic conditions, whether human induced or natural.

A variety of statistical tools were used to evaluate the hypothesis of time series homogeneity. Tests were performed for short duration (five-, 10-, 15-, 30-, 60-, and 120-minute) and 24-hour precipitation only. Figure 2 (five-minute), Figure 3 (10-minute), Figure 4 (15-minute), Figure 5 (30-minute), Figure 6 (60-minute), Figure 7 (120-minute), and Figure 8 (24-hour) display the historical behavior of the annual maxima. The procedures used to investigate homogeneity include 1) two-period tests for differences in mean and variance, 2) examination of L-moment ratio diagrams, 3) univariate tests for time trend, 4) bivariate tests for shift in mean, and 5) an analysis based on the partial duration

Map 4

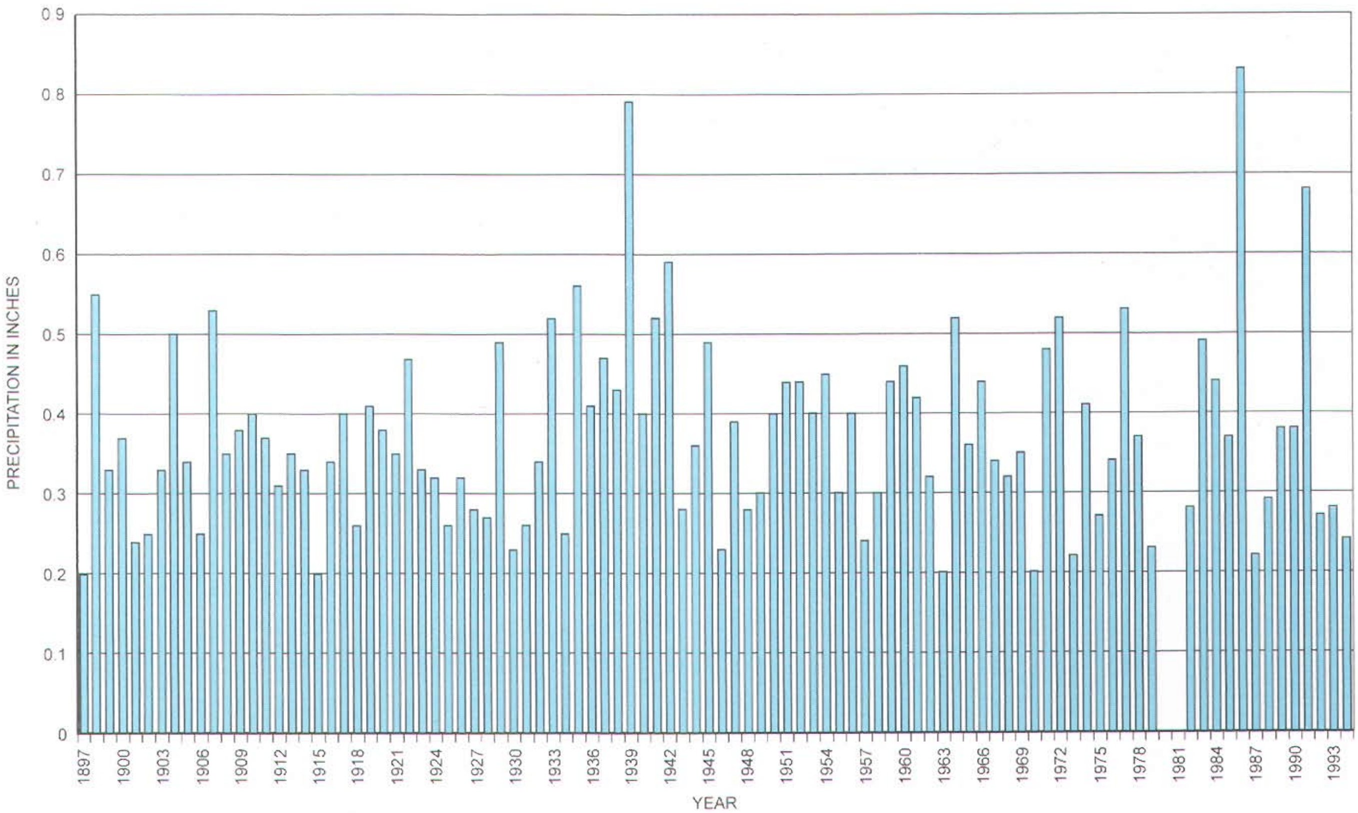
PRECIPITATION GAUGE LOCATIONS



Source: National Weather Service and SEWRPC.

Figure 2

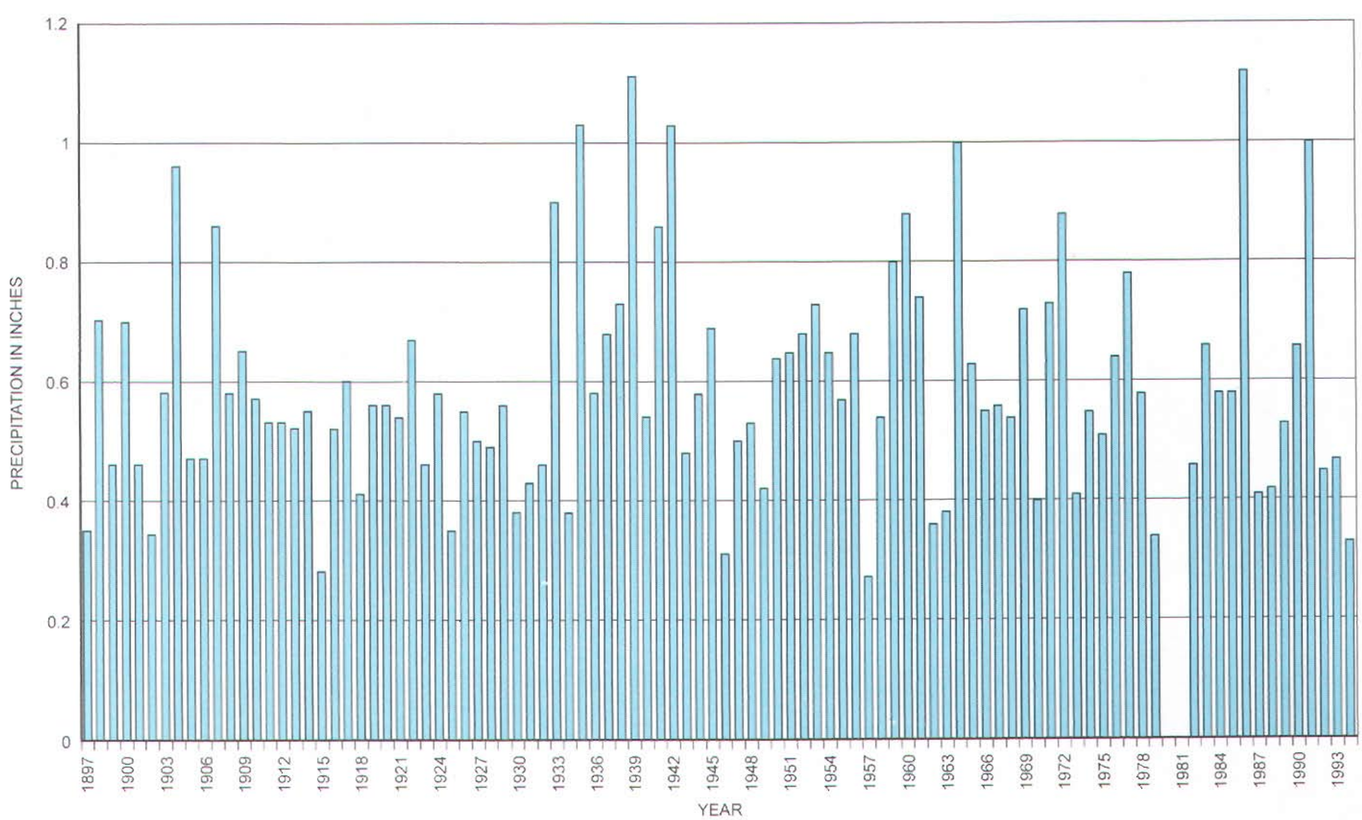
ANNUAL MAXIMUM FIVE-MINUTE PRECIPITATION: 1897-1994



Source: National Weather Service and Rodgers and Potter.

Figure 3

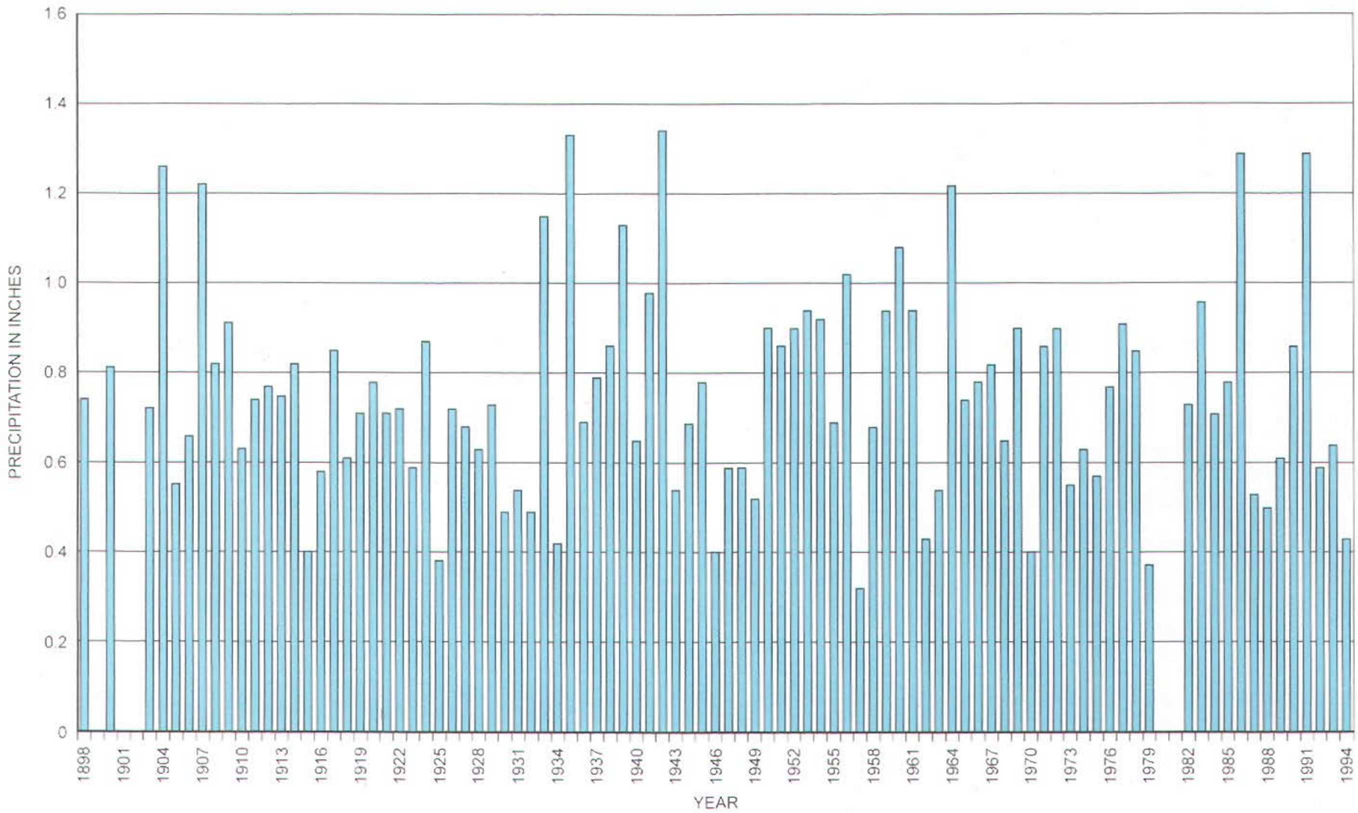
ANNUAL MAXIMUM 10-MINUTE PRECIPITATION: 1897-1994



Source: National Weather Service and Rodgers and Potter.

Figure 4

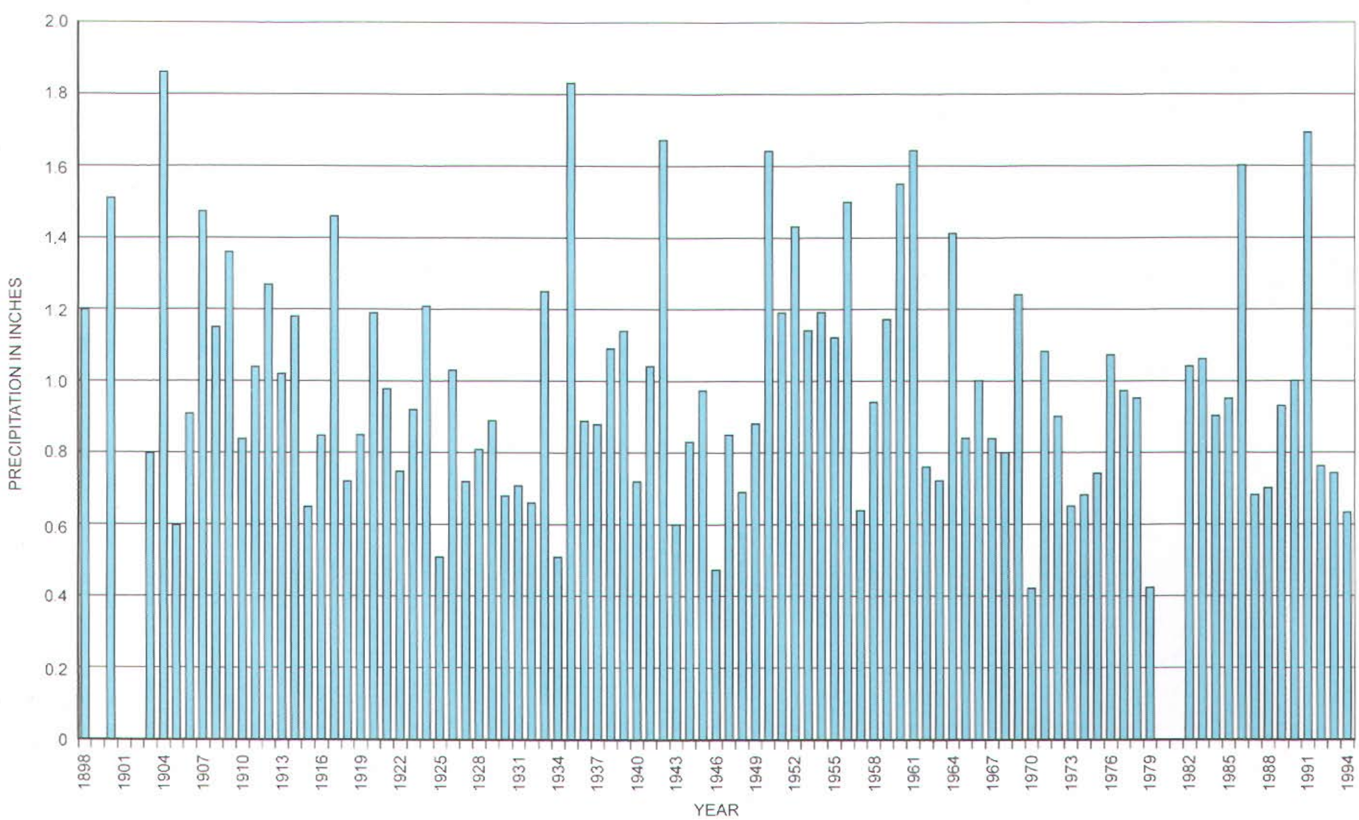
ANNUAL MAXIMUM 15-MINUTE PRECIPITATION: 1898-1994



Source: National Weather Service and Rodgers and Potter.

Figure 5

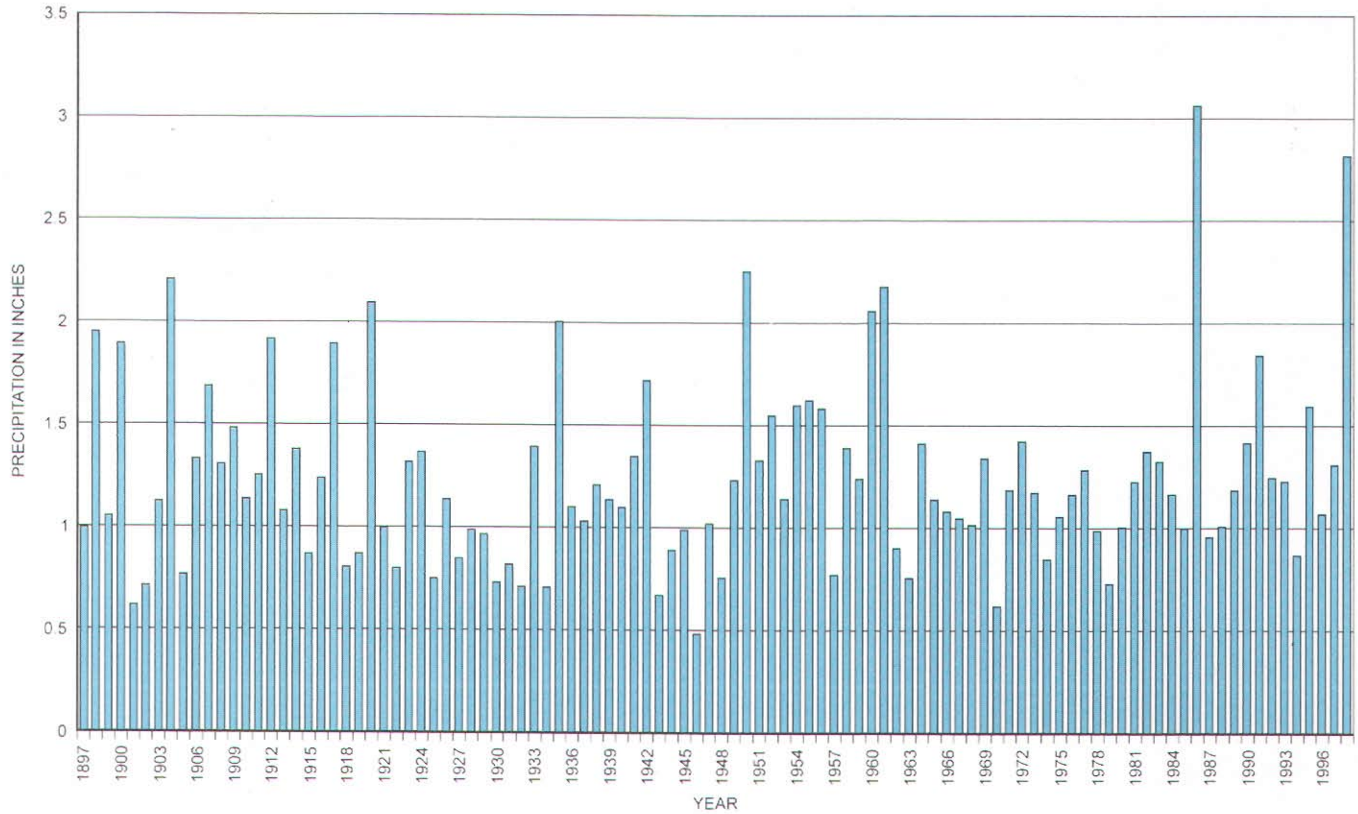
ANNUAL MAXIMUM 30-MINUTE PRECIPITATION: 1898-1994



Source: National Weather Service and Rodgers and Potter.

Figure 6

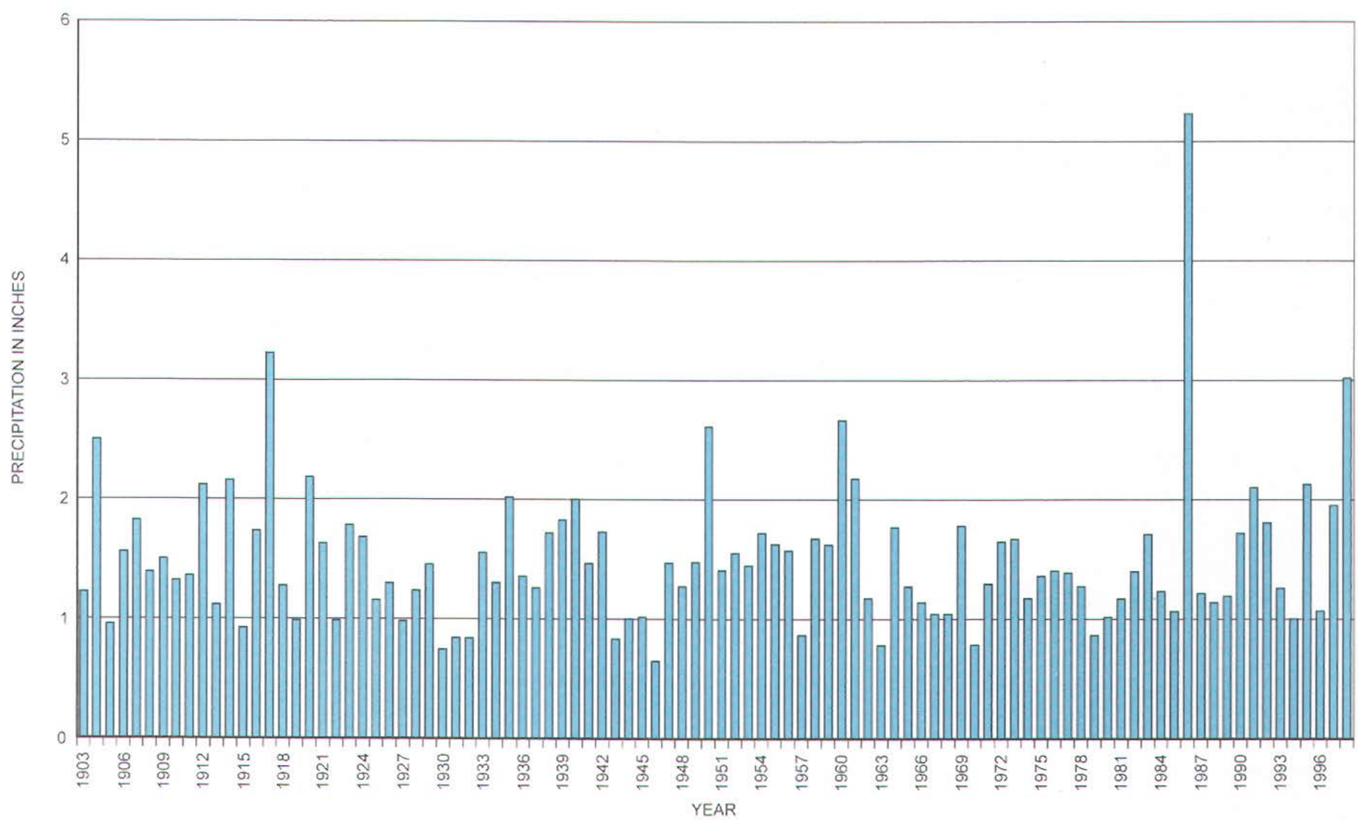
ANNUAL MAXIMUM 60-MINUTE PRECIPITATION: 1897-1998



Source: National Weather Service and Rodgers and Potter.

Figure 7

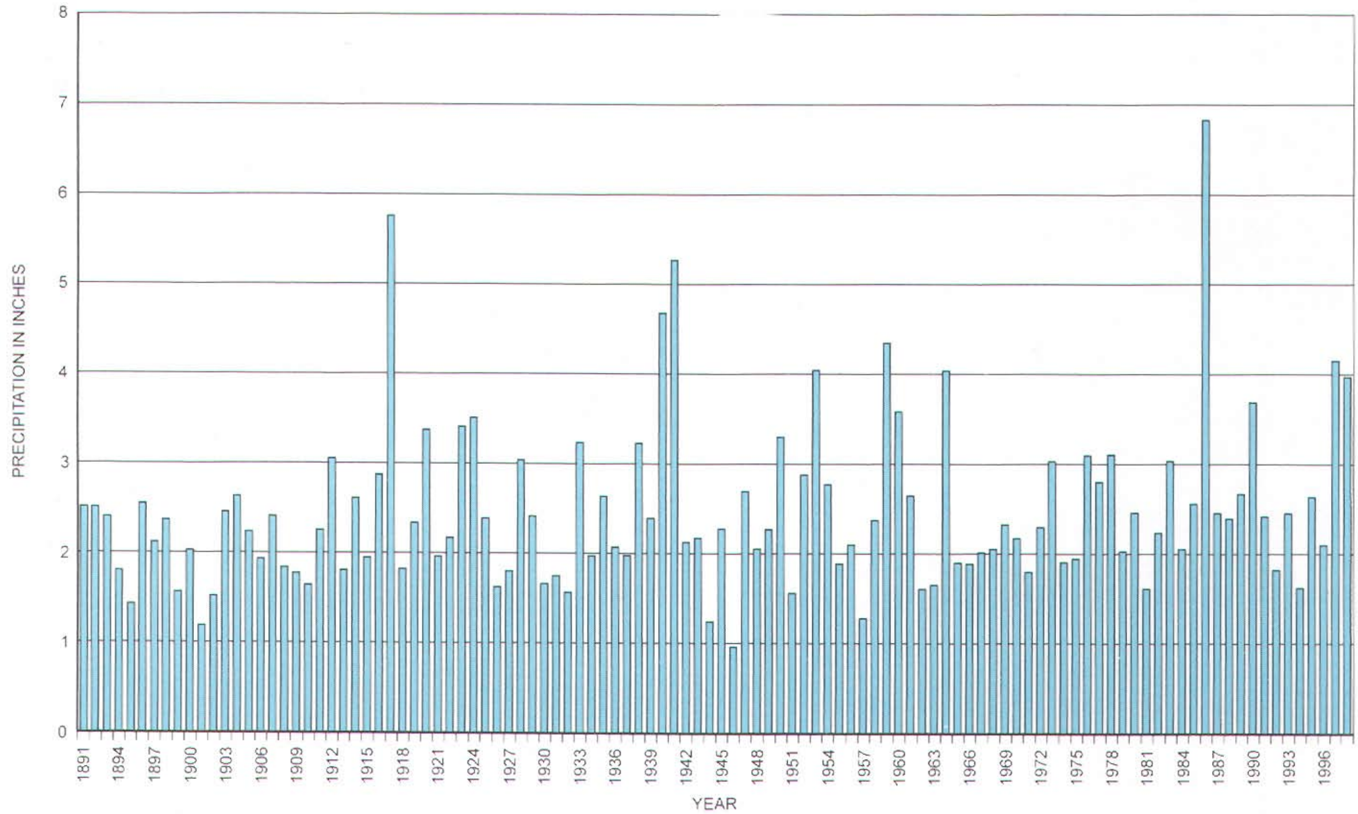
ANNUAL MAXIMUM 120-MINUTE PRECIPITATION: 1903-1998



Source: National Weather Service and Rodgers and Potter.

Figure 8

ANNUAL MAXIMUM 24-HOUR PRECIPITATION: 1891-1998



Source: National Weather Service and Rodgers and Potter.

(events above a threshold) series. Each is described in greater detail below.

In all subsequent analyses, data are used as they appear in published form. That is, precipitation observations have not been estimated, rounded or otherwise adjusted, or excluded from analysis, with two specific exceptions. The first relates to five-, 10-, and 60-minute annual maxima for 1896, the first year of record for those durations. These values have been excluded from all subsequent analysis for three reasons. The first and most important is that they are almost certainly erroneous values, since they are approximately one-half the magnitude of the next-smallest values and occur in the first year of record. The second is that if these observations were included in frequency analysis, they would exert an undue influence on estimated quantile values. Finally, if included, they would be unduly influential in determining the outcome of tests of trend and shift in mean.

The second exception relates to 60- and 120-minute data for years 1980, 1981, and 1982; and 1995-1998. Short-duration data are not currently available for those years (Julian, 1999), although clock-hour data are available. For those years, one-hour values were included as 60-minute observations, following an upward adjustment of 1.136, reflecting the mean one-hour bias, and two-hour values were adjusted by 1.043. The derivation of these correction factors is discussed in Chapter IV.

Two-Period Parametric Tests for Differences in Mean and Variance

Two clearly documented sources of nonhomogeneity in precipitation time series records are: 1) the relocation of primary NWS gauging stations to airports, where they are exposed to greater wind and consequently tend to undermeasure precipitation and 2) the introduction of shielded rain gauges, which increase catch accuracy and yield (Rasmussen et al., 1993; Yang et al., 1999).

Table 4

TWO-PERIOD Z-TESTS FOR DIFFERENCES IN SAMPLE MEAN

Period	Duration in Minutes						
	5	10	15	30	60	120	1440
Pre-1948							
Number of Observations	51	51	47	47	51	45	57
Mean (inches)	0.37	0.58	0.75	0.99	1.18	1.45	2.38
Standard Deviation (inches)	0.17	0.19	0.23	0.33	0.42	0.51	0.89
1948-Present							
Number of Observations	45	45	45	45	51	51	51
Mean (inches)	0.37	0.60	0.76	1.00	1.30	1.55	2.59
Standard Deviation (inches)	0.12	0.19	0.23	0.33	0.48	0.71	0.96
1948-Present (excluding 1986)							
Number of Observations	44	44	44	44	50	50	50
Mean (inches)	0.36	0.59	0.75	0.98	1.26	1.47	2.51
Standard Deviation (inches)	0.10	0.17	0.22	0.32	0.42	0.48	0.76
z-value[a] All Cases	-0.08	-0.53	-0.18	-0.11	-1.37	-0.76	-1.20
z-value[a] Excluding 1986	0.37	-0.23	0.07	0.09	-1.06	-0.21	-0.81

[a]The z test compares the earlier period to the later period, so a negative sign indicates a smaller earlier period mean. Z values exceeding 1.96 indicate that H(0): common distribution is rejected at 95 percent confidence (5 percent probability of Type-1 error).

Source: Rodgers and Potter.

According to protocols used by NWS to update TP-40, two or more discrete precipitation gauge records can be combined to form a single, continuous record if they are separated by no more than 0.07 decimal degrees of latitude or longitude (roughly 4.8 statute miles in this case) and 1,000 vertical feet in station elevation (Julian et al., 1999). The Federal Building and General Mitchell Field gauge locations are about six statute miles apart, thus, they are beyond the distance criterion. However, it can be argued that proximity to Lake Michigan is a far more influential factor than distance alone in this region, and the movement of the gauge should not, in principle, have introduced a bias. Therefore, the test for change in mean and variance focuses on homogeneity around the introduction of windshields. Windshields were first introduced in 1948, and became nearly universal by the 1960s. As it has not been possible to determine the precise point in time at which the NWS Milwaukee gauge was shielded, it has been assumed that 1948 is the first year in which data reflect the effect of gauge wind shielding, so that two-period tests are based on a partition of the record between 1947 and 1948.

The null hypothesis that two samples are drawn from the same population can be tested at a desired level of confidence using two-sample z-tests (large samples) or t-tests (small samples). No assumption of common variance is required for the z test, only independence of samples (Devore, 1991). The z-test was performed using the two subsamples corresponding to pre-windshield (beginning of record—1947) and windshield conditions. Statistics for the latter period were calculated with and without the extreme 1986 observation. Results are summarized in Table 4. No strong evidence of nonhomogeneity was observed, particularly when the influential 1986 observation was excluded. Post-1947 values do tend to exceed earlier values on average, consistent with the known bias associated with windshields.

Two-Period Comparison by L-Moment Ratio Diagrams

A complementary test for time series homogeneity was performed using L-moment ratio diagrams. The use of L-moment ratio diagrams in identifying plausible parent distributions for sample data is described in Chapter IV. The record for each duration was again partitioned around 1948, and L-moments and moment ratios calculated for each period were displayed in a common graph (Figure 9). Figure 9 indicates that the greatest discordance between periods occurs at one- and two-hour durations.

Univariate Tests for Time Series Trend

Two univariate trend tests were conducted to evaluate the hypothesis of time series nonstationarity of Milwaukee precipitation records. The first is a parametric test for linear trend based on the simple regression model:

$$P_t = \alpha + \beta \cdot t + \epsilon$$

where P_t is annual maximum n-hour precipitation in year t, α and β are intercept and linear coefficient, respectively, and ϵ is a residual error term, assumed normally distributed with 0 mean and independent of t. A significant trend is indicated if the estimated coefficient (β) is sufficiently large relative to its standard error.

The second test is the nonparametric Mann-Kendall test for time trend. This test is based on the relative magnitudes or ranks of the time series elements, whereas the regression test is based on their absolute magnitudes. The tests are thus complementary. The Mann-Kendall test statistic S is computed as:

$$S = \sum_{k-1}^{n-1} \sum_{j=k+1}^{n} \text{sign}(P_j - P_k)$$

where sign (P_j-P_k) is +1 for positive differences, -1 for negative differences, and 0 for ties (Hipel & McLeod, 1994).

Both tests were applied to the long duration Milwaukee precipitation time series and the results are summarized in Table 5. Results are in good general agreement, with the exception of the 120-minute (two-hour) series. Differing signs result from the extreme magnitude of the 1986 120-minute event (Figure 7)—when treated as an absolute value, a positive (although not statistically significant) trend results, but when treated as a rank, the trend is negative and weak. Neither test for linear trend is significant at the 95 percent confidence level; therefore, it cannot be concluded that there is a gradual, climate-induced increase in extreme rainfall during the period of record. The large, but not significant, t-value for the 24-hour storm might be an indicator of a possible trend. However, there are also several explanations for the high value that are independent of the existence of a trend. It has been unduly influenced by the three recent extreme storms (1986, 1997, and 1998) contrasted against the extreme drought years in the 1930s. These could be natural fluctuations which have not been shown here to be part of a statistically significant trend. In addition, the behavior is not evident in the other storm durations, as would be expected with a climate-induced trend.

Bivariate Tests (BT) for Time Series Homogeneity

The bivariate test for detecting a shift in a time series mean has been used successfully to identify inhomogeneity in precipitation gauging records caused by movement or relocation of the gauge (Potter, 1981). It is based on the joint time series behavior of the gauge record being evaluated (Milwaukee) and an ensemble of nearby gauges assumed to be correlated with the test series. Under suitable conditions, the test provides estimates of the magnitude and timing of any shift in the test series mean, should it exist. The test was applied to one-, two-, and 24-hour Milwaukee precipitation time series, using Madison and Green Bay as the regional series.[1] Results are presented in Figure 10 and do not indicate significant shifts in mean at Milwaukee around mid-century. The only significant value of the test statistic, for one-hour precipitation, occurs in the last year of the record where it carries no useful information.

A second bivariate test was conducted using Milwaukee River peak annual flood flows as the regional series and Milwaukee precipitation as the test series. This test may be more appropriate because the Milwaukee River flows integrate extreme rainfall over a wide area and are, in fact, more correlated with Milwaukee rainfall than the Madison or Green Bay precipitation. The bivariate test was applied to the 24-hour Milwaukee rainfall and results are presented in Figure 11. The results do not indicate any significant shifts in mean relative to the 95 percent confidence interval.

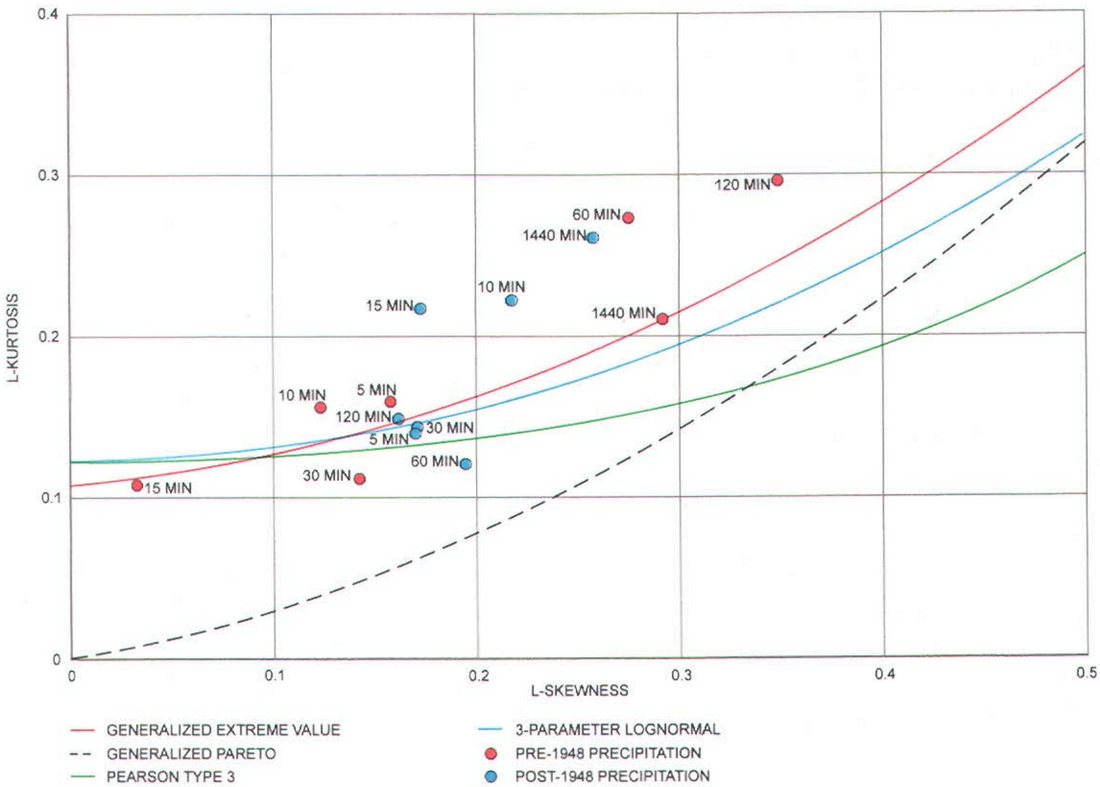
Tests for Trend in the Frequency of Occurrence of Extreme Rainfall

An additional concern beyond record homogeneity is the stationarity of time series data. If a data time series is found to exhibit a trend or nonstationarity (e.g., shift in mean or shift in variance) then the fundamental assumptions underlying statistical frequency analysis, specifically, serial independence and identical distribution of data, are compromised. This is true even

[1]*Note that the test will succeed in identifying a shift in time series mean at Milwaukee due to gauge relocation only if the Madison and Green Bay gauges were not themselves relocated around the same time. There is no record of such contemporary relocations.*

Figure 9

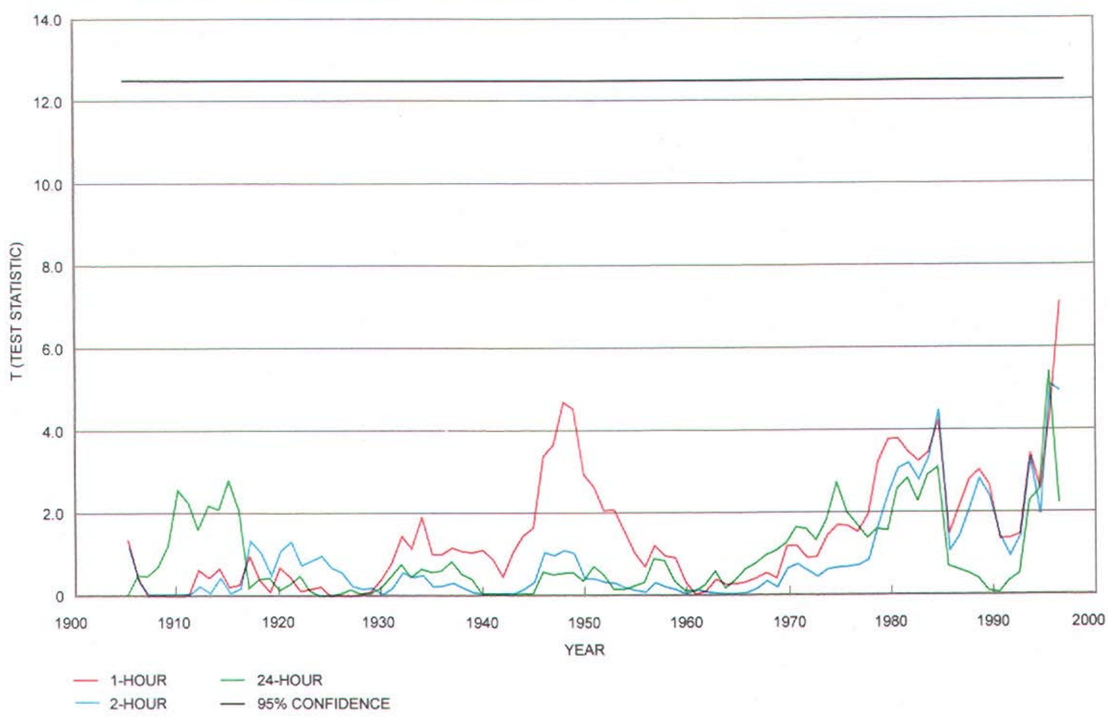
L-MOMENT RATIOS, PRE- AND POST-1948



Source: Rodgers and Potter.

Figure 10

RESULTS OF THE BIVARIATE TEST AGAINST MADISON AND GREEN BAY RAINFALL



Source: Rodgers and Potter.

Table 5

RESULTS OF TESTS OF LINEAR TREND

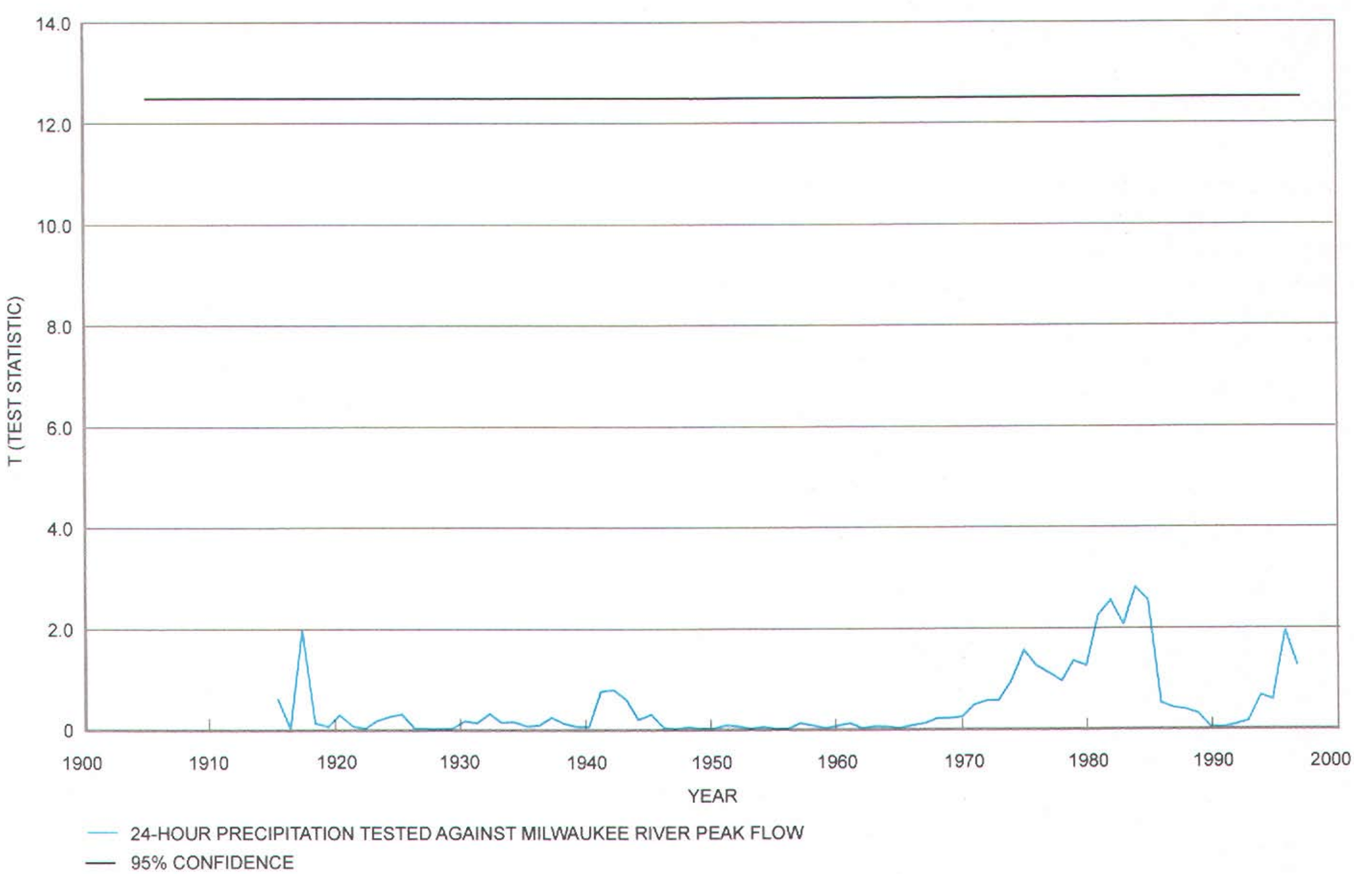
Duration	Number of Observations	Time Coefficient	Standard Error	t Statistic	Significant at 5 Percent[a]	Mann-Kendall	Significant at 5 Percent[a]
5 Minutes	96	0.000	0.000	0.852	No	0.533	No
10 Minutes	96	0.001	0.001	0.827	No	0.741	No
15 Minutes	92	-0.000	0.001	-0.139	No	-0.182	No
30 Minutes	92	-0.002	0.001	-1.202	No	-1.306	No
60 Minutes	102	0.001	0.002	0.665	No	0.619	No
120 Minutes	96	0.001	0.002	0.503	No	-0.146	No
24 Hours	108	0.005	0.003	1.850	No	1.856	No

[a]*A trend is judged significant at 5 percent if the t statistic exceeds 1.96.*

Source: Rodgers and Potter.

Figure 11

RESULTS OF THE BIVARIATE TEST AGAINST MILWAUKEE RIVER PEAK ANNUAL FLOOD FLOWS



Source: Rodgers and Potter.

if data have been collected at a single location and in a completely consistent manner. The previous tests for time series homogeneity and trend are based on the annual maximum precipitation series, and are intended primarily to evaluate questions of record homogeneity. Although the results of these tests support the position that the largest annual events at each duration (annual n-hour maxima) have not increased significantly in magnitude over the last several decades, it is nevertheless possible that the frequency with which "large" events occur has changed. The hypothesis that the frequency of large events is increasing due to climate change has been explored by Karl, et al (1996, 1998), Kunkel et al (1999), and others. In order to evaluate this hypothesis using Milwaukee data, a parametric test for time series stationarity in the return period of events equaling or exceeding specified thresholds (the *partial peak* series) was performed. The test is based on the observation that the number of events in each year exceeding a chosen threshold will tend toward a Poisson distribution as this threshold is raised (Keim, et al., 1998.) If this is shown to be the case, then the inter-storm arrival times (periods between successive events) will be exponentially distributed. For such data, a regression model with dependent variable Y = log(interarrival time) and independent variable X = (elapsed time) will have approximately normally distributed residuals, and the significance of the test statistic (linear time trend) can be evaluated at a chosen level of confidence.

Partial peak precipitation events for three durations, three, six and 12 hours, were extracted from General Mitchell Field hourly records covering the period 1940-1998. The corresponding thresholds used were 1.0 inch (three hours), 1.2 inches (six hours) and 1.3 inches (12 hours). The threshold values were chosen to yield between two and three events per year, on average. Events occurring during the period December 1 to March 31 were excluded to reduce the influence of mixed distributions. Each event is separated from its closest neighbor by a period equal to or greater than the duration itself, to ensure that the partial peaks are discrete events. Summary statistics appear in Table 6. The time series of partial peak rainfall events appear in Figure 12 (three-hour duration), Figure 13 (six-hour duration), and Figure 14 (12-hour duration.) No trend is apparent in the magnitudes of these events.

The hypothesis of Poisson-distributed partial peak events can be tested based on the equality of mean and variance of Poisson variables. This ratio will be distributed ($\chi^2_{N-1,\,a}$ / (N-1)) with N indicating the number of years in the sample and "a" equal to 1-confidence level (Cunnane, 1979). For N = 59 and a = 0.05 (95 percent confidence interval), the lower bound of the test statistic is 0.68. Observed values (Table 6) indicate that the Poisson hypothesis will not be rejected for these series. Storm interarrival times in units of decimal days (days + hours/24) were computed using a calendar year shortened to 244 days by the exclusion of December through March. Summary statistics for the regression models appear in Table 6. If the frequency of events exceeding the chosen threshold(s) were increasing over time, inter-event arrival times would decrease correspondingly, and a statistically significant negative coefficient (b) on elapsed time could be interpreted as evidence for such a change. The estimated (b) coefficients are not significantly different than 0, however, providing additional evidence to support the view that the behavior of extreme precipitation in the Milwaukee area is statistically stationary. That is, the frequency with which large rainfall events occur has not increased.

Summary, Evaluation of Data Homogeneity and Tests for Trend

No strong evidence appears that cautions against using the composite records (Downtown Milwaukee, General Mitchell Field) as a single gauging record for the purposes of statistical frequency estimation. The frequency analyses presented in the next chapter of this report made use of both the long (composite) records, and those for the period 1940-1998. The justification for the parallel analyses is internal consistency, since annual maximum precipitation data for durations of three, six, 12, 48, 72, 120, and 240 hours are available for the latter period only. Tests conducted to evaluate the stationarity and homogeneity of the precipitation data have determined that there is no statistically significant evidence of a climate change induced trend in the precipitation records used in the subsequent analyses.[2] Furthermore, analysis of partial duration (peaks above threshold) data for three-, six-, and 12-hour events provides no statistically significant evidence to contradict the hypothesis that the frequency of heavy rainfall events has not changed over the period 1940-1998.

[2] *It is not the intent of this study to investigate whether such climate change-induced trends are occurring in Southeastern Wisconsin.*

Table 6

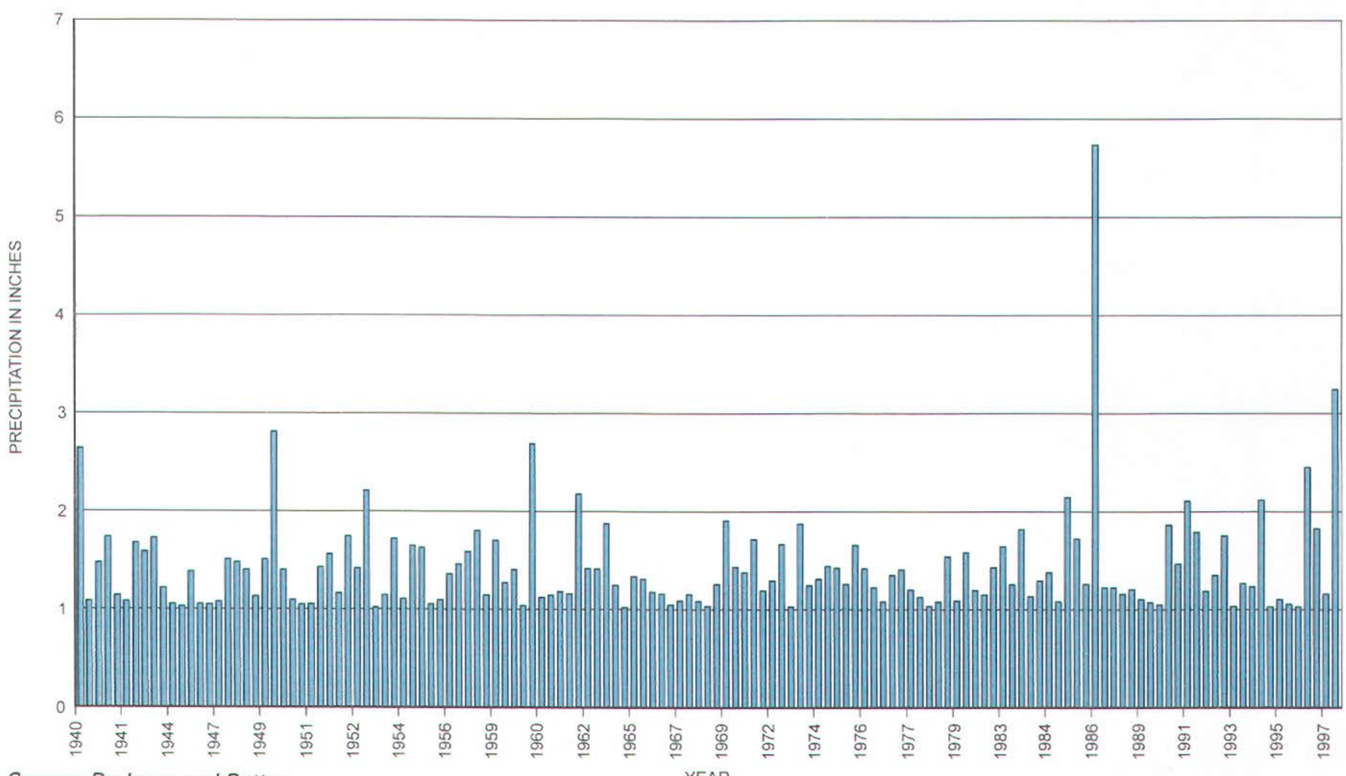
RESULTS OF THE PARAMETRIC TEST FOR CHANGE IN THE FREQUENCY OF LARGE PRECIPITATION EVENTS

Poisson Statistics	Event Duration			
	3-Hour	6-Hour	12-Hour	24-Hour
Number of Years	59	59	59	59
Mean Number of Events per Year	2.32	2.41	2.83	2.46
Standard Deviation Events per Year	1.38	1.45	1.46	1.39
Variance Events per Year	1.91	2.11	2.14	1.94
Ratio Variance per Mean	0.82	0.88	0.76	0.79
Regression Statistics, log (interval) = f (time from 1940)				
R^2	0.0009	0.0011	0.0011	0.0010
SE Regression	1.56	1.46	1.41	1.28
Number of Observations	136	141	166	144
Intercept (a)	3.814	3.808	3.653	4.061
Coefficient (b) *1000	0.011	0.012	0.011	-0.010
t Statistic	0.347	0.386	0.419	-0.382
Regression, log (interval) = f (year)				
R^2	0.0011	0.0013	0.0012	0.0009
SE Regression	1.56	1.46	1.41	1.28
Number of Observations	136	141	166	144
Intercept	-2.129	-2.364	-2.234	8.553
Coefficient	0.003	0.003	0.003	-0.002
t Statistic	0.382	0.422	0.453	-0.354

Source: Rodgers and Potter.

Figure 12

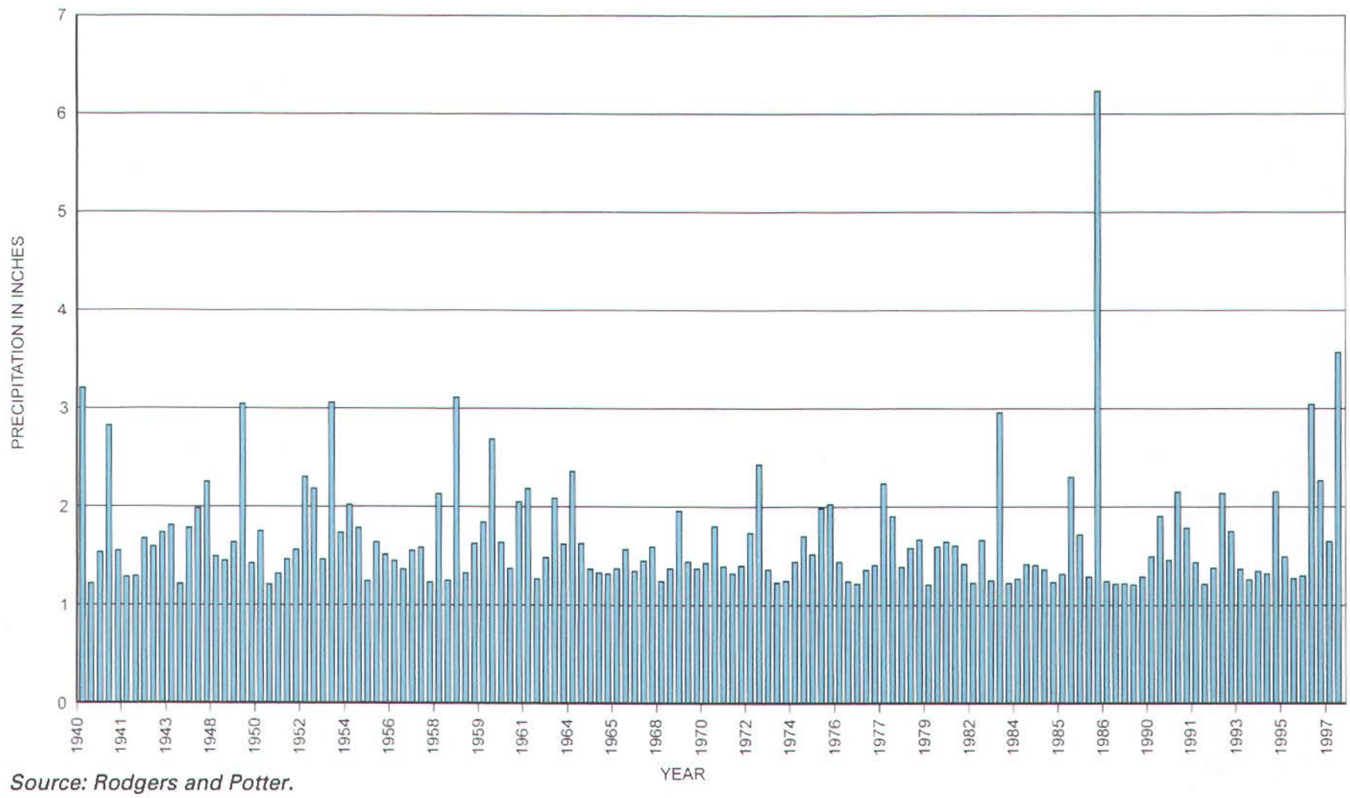
THREE-HOUR EVENTS ABOVE THRESHOLD (1940-1998)



Source: Rodgers and Potter.

Figure 13

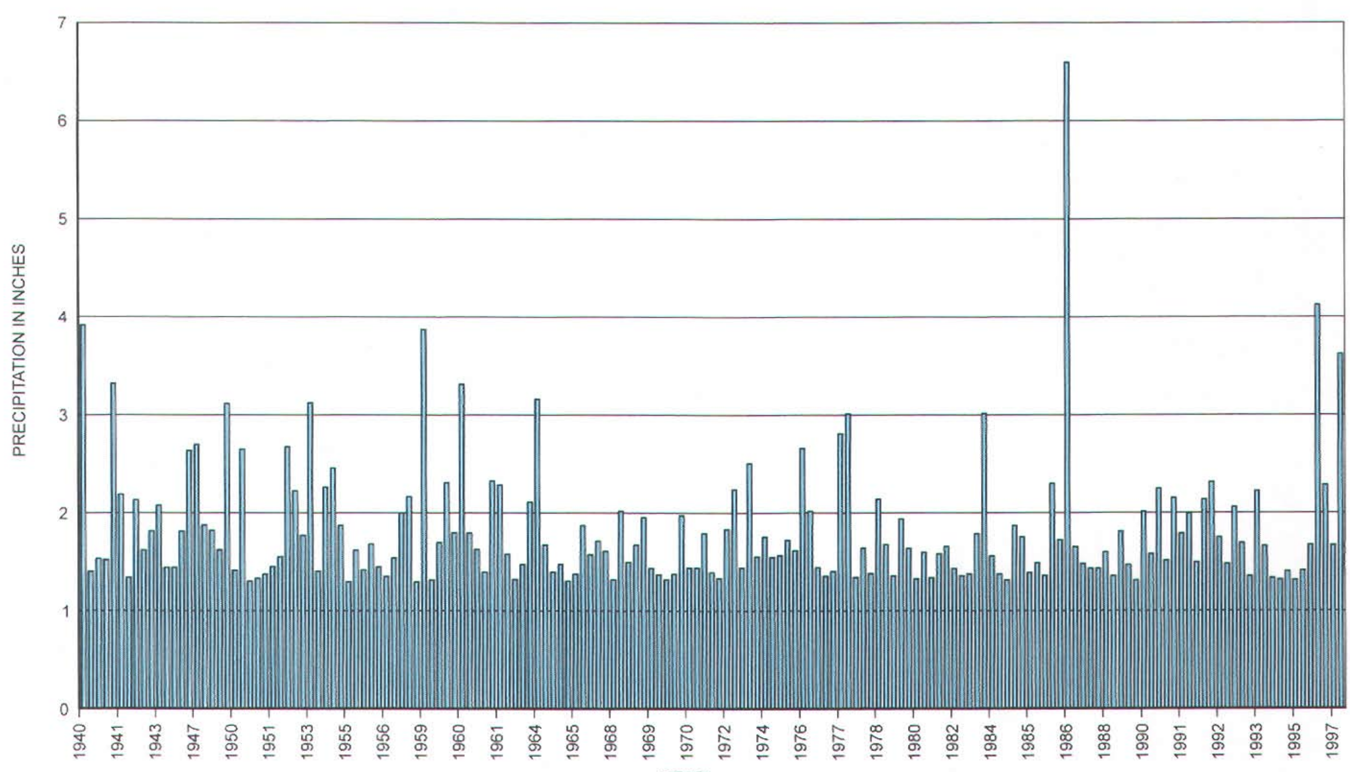
SIX-HOUR EVENTS ABOVE THRESHOLD (1940-1998)



Source: Rodgers and Potter.

Figure 14

12-HOUR EVENTS ABOVE THRESHOLD (1940-1998)



Source: Rodgers and Potter.

Chapter IV

FREQUENCY ANALYSIS OF EXTREME RAINFALL IN THE SOUTHEASTERN WISCONSIN REGION

The precipitation frequency analysis for Southeastern Wisconsin is based on the annual maximum precipitation amount for durations ranging from five minutes to 240 hours. The approach taken in this investigation is a combination of at-site and regional frequency analysis. At-site precipitation data for Milwaukee is reasonably complete, of long duration and high quality, and forms the primary statistical basis for locally applicable precipitation quantile estimates. This at-site analysis is supplemented by a regional analysis based on data from the Milwaukee gauge and 14 surrounding gauges. If certain statistical conditions are met, the regional approach can significantly increase the number of effective station-years available for analysis through "substitution of space for time" (NRC 1988; Stedinger et al. 1993). In this study, regional analysis is used to evaluate and to explore questions of spatial homogeneity, including the geographic scope of applicability of locally derived precipitation quantile estimates.

The use of annual maximum, rather than partial duration statistics, was mandated both by data availability and by methodological constraints. An additional consideration was a desire to achieve methodological consistency with investigators at the National Weather Service, Office of Hydrology, who are currently revising TP-40 for the Ohio River Valley (Julian et al., 1999). The primary methods of analysis used in this study, both at site and regional, are identical or similar to those being employed by NWS.

STATISTICAL ANALYSIS PROCEDURE

Stedinger, et al. (1993) identify three distinct perspectives that can be applied to the selection of an appropriate statistical distribution for frequency analysis:

1) What is the true distribution from which the precipitation observations are drawn?

2) What distribution should be used to obtain reasonably accurate and robust estimates of design quantiles and hydrologic risk?

3) Is a proposed distribution consistent with the available data for the site?

As these authors caution, Question 1 may not have a meaningful answer or, in any case, may be impossible to answer on the basis of finite samples. The approach used in this study therefore attempts to answer Questions 2 and 3 in upcoming sections of this chapter.

The World Meteorlogical Organization (WMO), in 1989, documented a wide range of statistical distributions historically used to model precipitation extremes worldwide, of which the most commonly used include Extreme Value Type 1 (Gumbel); lognormal; Generalized Extreme Value (GEV); Pearson and log-Pearson Type 3; and gamma distributions. More recently, the Generalized Logistic and Generalized Pareto have also been used to model precipitation maxima (Julian, et al. 1999). Traditionally, distribution parameters were estimated using the method of moments, or by the less biased method of maximum likelihood. The use of L-moments and probability weighted moments in fitting flood and precipitation distributions has become increasingly common, primarily because they are less sensitive to the influence of extreme values, particularly in small samples, and they are computationally more efficient than maximum likelihood methods for most distributions. The use of L-moments is discussed in Hosking and Wallis (1993), Stedinger, et al. (1993), and elsewhere. Consistent with Julian et al., L-moments are used here to identify the most likely candidate distribution and to estimate the parameters of the GEV and EV-1 distributions. They are also used to estimate the parameters of the regional probability model and to assess the hypothesis of regional homogeneity.

Comparison of Distributions by L-Moment Ratio Diagrams

Probability-weighted moments, L-moments, and L-moment ratios corresponding to the mean, coefficient of variation (CV), skewness, and kurtosis were calculated from the untransformed (real) and log-transformed data for each duration: five, 10, 15, 30, 60 and 120 minutes; and three, four, six, 12, 24, 48 and 72 hours. Sample moments were calculated using the full range of available data and for the period 1940 to most recent. The second set of estimates were made to explore and to eliminate, if necessary, any bias resulting from time series nonstationarity. Each set of L-skewness, L-kurtosis pairs were plotted in L-moment ratio diagrams (Hosking and Wallis, 1994) which appear as Figures 15 and 16, respectively. The location of sample data within these diagrams suggests that GEV, Log Pearson Type 3, or 3-parameter lognormal distributions are all likely candidates for reasonable models of precipitation frequency.

Comparison of Distributions by Probability Plot Correlation Coefficient (PPCC) Tests

Estimated parameters of GEV and EV-1 (Gumbel) distributions were obtained as functions of the sample L-moments (Hosking, et al., 1985). In addition, Pearson Type 3 parameters and normal parameters were estimated using the natural logs of the data by method of moments. A variety of statistical tests have been developed recently to evaluate the likelihood that sample data are consistent with a distribution type. Unlike conventional tests such as the χ^2 and Komolgonov-Smirnov, these distribution tests are applied at a specified probability of Type-1 error. The test statistic is based on the linear correlation between the observed (sample) data and values predicted by the estimated distribution moments and plotting position. Such tests, called probability plot correlation coefficient (PPCC) tests, have been developed for the normal and lognormal (Filliben 1975), EV-1 or Gumbel (Vogel 1986), Pearson Type 3 (Vogel and McMartin 1991), and GEV (Chowdhury et al. 1991) distributions.

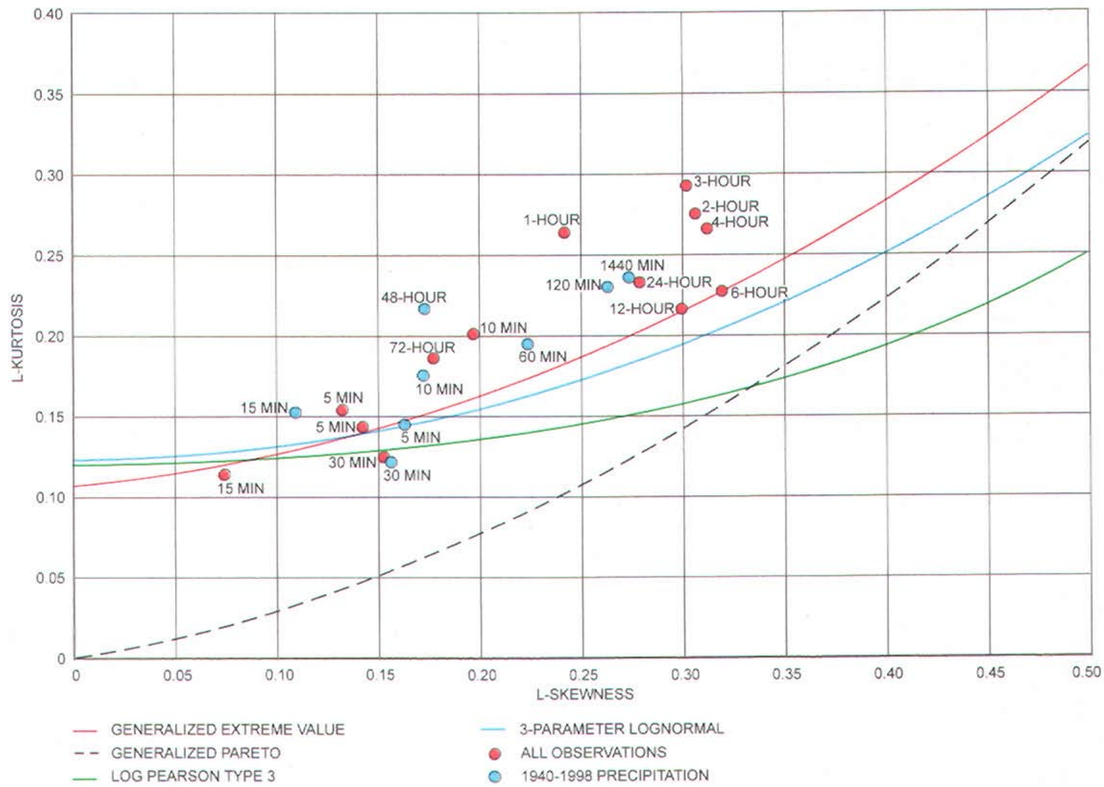
These tests were applied to the data and fitted distributions, and the results are summarized in Table 7. The Hosking, et al., 1985, test for GEV shape parameter significantly different than 0 was used as a test for EV-1 fit. Although PPCC tests represent an improvement over more traditional tests for distribution fit, they may nevertheless fail to return mutually exclusive outcomes. In other words, the distributional null hypothesis may not be rejected for any of a variety of potential distributions having similar characteristics. Thus, while in this analysis, the lognormal and EV-1 distributions are rejected at several durations on the basis of PPCC tests, both the GEV and LP-3 distribution appear to fit the range of durations reasonably well. This is consistent with evidence from the L-moment ratio diagrams.

Comparison of Distributions by Upper Tail Fit

In selecting an appropriate distribution for precipitation frequency analysis, the behavior of the upper tail of the distribution is critical, since quantiles of interest for design purposes are typically located well above the mean. As an additional means of assessing distribution fit, the conformity of the largest sample values to their respective predicted values was examined. Two statistics were examined: 1) the prediction error for the largest sample value, evaluated relative to the observed value and 2) the root mean square (RMS) prediction error for the five largest observations. The largest value for all durations exceeding 30 minutes was the 1986 event. Results are summarized in Figure 17 (percent error, largest observation) and Figure 18 (mean square error, five largest observations). The figures show that both GEV and Log Pearson Type 3 do far better than the lognormal in capturing upper tail behavior, with the GEV performing slightly better overall: for largest values, mean (absolute value) GEV error was 11.3 percent, LP-3 error 12.0 percent, and lognormal error 20.7 percent; for largest five, RMS error for GEV was 7.9 percent, LP-3 8.2 percent, and lognormal 11.2 percent.

Figure 15

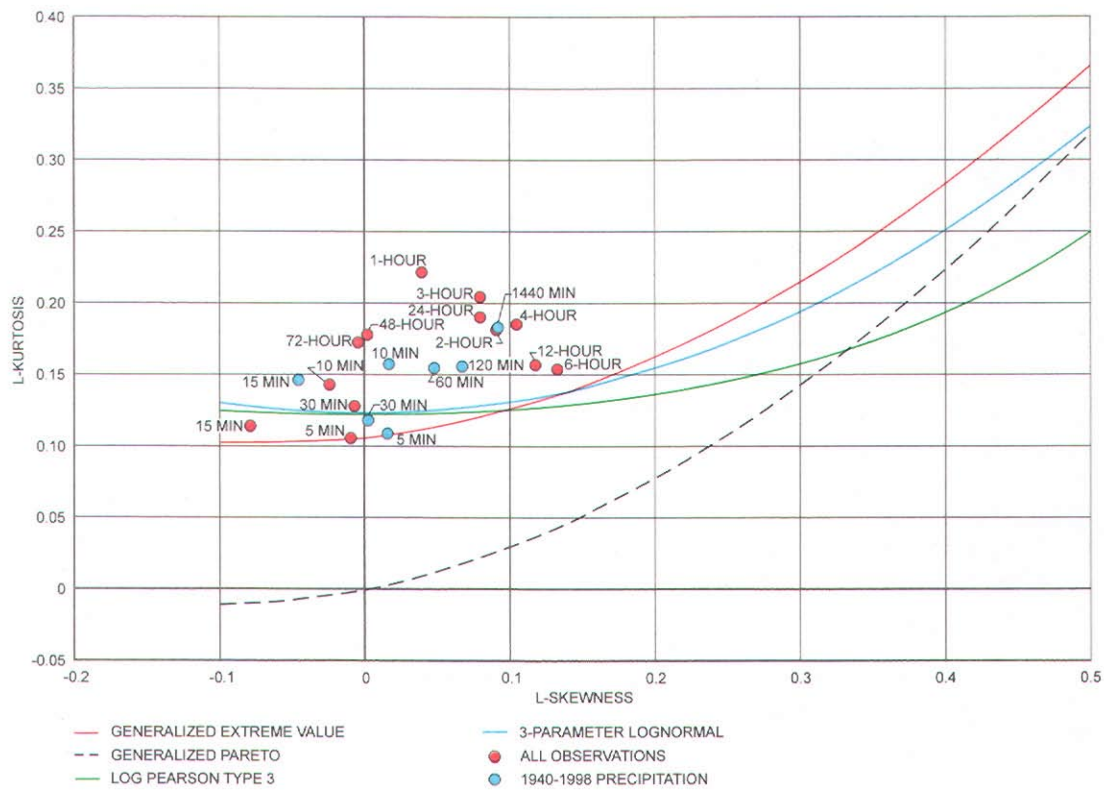
L-MOMENT RATIOS, REAL-SPACE MILWAUKEE DATA



Source: Rodgers and Potter.

Figure 16

L-MOMENT RATIOS, LOG-SPACE, MILWAUKEE DATA



Source: Rodgers and Potter.

Table 7

RESULTS OF THE PROBABILITY PLOT CORRELATION COEFFICIENT (PPCC) TESTS FOR DISTRIBUTION FIT[a]

All Observations, Period of Record				
Duration	GEV	LP-3	Lognormal	EV-1[b] (Gumbel)
5-Minute	1	1	1	1
10-Minute	1	1	1	1
15-Minute	1	1	1	1
30-Minute	1	1	1	1
60-Minute	1	1	1	1
120-Minute	1	1	0	1
1440-Minute	1	1	0	0
All Observations, 1940-Most Recent				
Duration	GEV	LP-3	Lognormal	EV-1[b] (Gumbel)
5-Minute	1	1	1	1
10-Minute	1	1	1	1
15-Minute	1	1	1	1
30-Minute	1	1	1	1
60-Minute	1	1	1	1
120-Minute	1	1	0	0
3-Hour	1	1	0	0
4-Hour	1	1	0	0
6-Hour	1	1	0	0
12-Hour	1	1	1	0
24-Hour	1	1	1	1
48-Hour	1	1	1	1
72-Hour	1	1	1	1

[a]*A "0" indicates a rejection of "H(0): data are distributed thus" at p=0.05 of Type-1 error.*

[b]*Hosking, Wallis, & Wood, 1985.*

Source: Potter and Rodgers.

Final Selection of Probability Distribution and Method

For the purposes of this study, the GEV distribution estimated by method of probability-weighted moments was selected as the reference distribution for the estimation of precipitation quantiles. There are three reasons for this. The first is that the foregoing analysis identifies the GEV, along with the LP-3, as capable of generating reasonable and consistent quantile values (Question 2) as consistent with available data (Question 3). The second is methodological consistency—the GEV fit by L-moments was determined by NWS (Julian, et al., 1999) to be the best-fit distribution overall for the annual maximum precipitation series they examined (Illinois, Indiana, Ohio). A third argument in favor of the GEV was the need for consistency between local (at-site) and regional frequency models. The regional index precipitation model used in this study and described below is also based on the GEV estimated by method of L-moments. Note, however, that the LP-3 distribution performed almost identically to the GEV in all tests based on at-site Milwaukee data, and LP-3 quantiles are nearly identical to GEV quantiles at all durations and recurrence intervals.

ANALYSIS RESULTS

Additional Quantile Estimation Issues

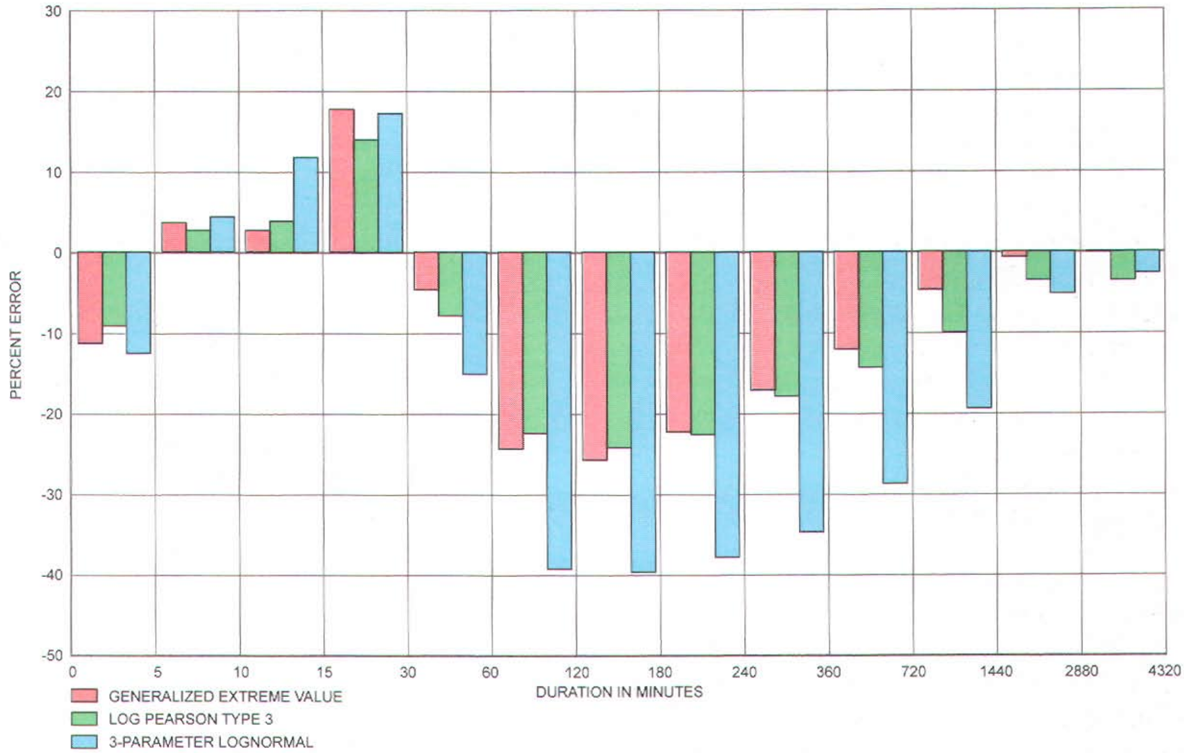
Prior to presenting recommended values of precipitation quantiles for the Milwaukee region, three additional statistical issues must be examined. The first is associated with the unequal periods of available record. Five-, 10-, 15-, 30-, 60-, 120-minute, and 24-hour data are available from around 1900 to the present. Three-, four-, six-, 12-, 48-, 72-, 120-, and 240-hour data are available from 1940 onward. A strong argument is typically made for using all available data irrespective of location in time, because longer data series will reduce variance in quantile estimates, all other factors being equal. However, if data are not independently and identically distributed, biases may arise due to secular variation, trends, or periodicities in the data. Although the Milwaukee data were examined for time series homogeneity (Chapter III), an additional examination of variation in quantile values due to record length was performed. This differs from the analysis described in Chapter III in the following way. The analysis summarized in Chapter III was based on a partitioning of the data series into two discrete (and presumed independent) subsamples. In the following analysis, the later period (1940 onward) is a subset of the entire period of record.

The second issue relates to the downward bias resulting when precipitation of a given duration is measured with reference to clock time or calendar day. Because the beginning of the true n-minute period of maximum intensity is a random variable with respect to clock (or calendar) time, maximum precipitation intensity as measured over these fixed intervals is the lower limit to the true maximum value (von Montfort, 1997). An appropriate model for correcting short-duration hourly data is required, primarily for the regional frequency model.

The final issue concerns the disproportionate influence on estimated moments of a single large observation, the August 1986 event that produced three inches of precipitation in 60 minutes and 5.24 inches in 120

Figure 17

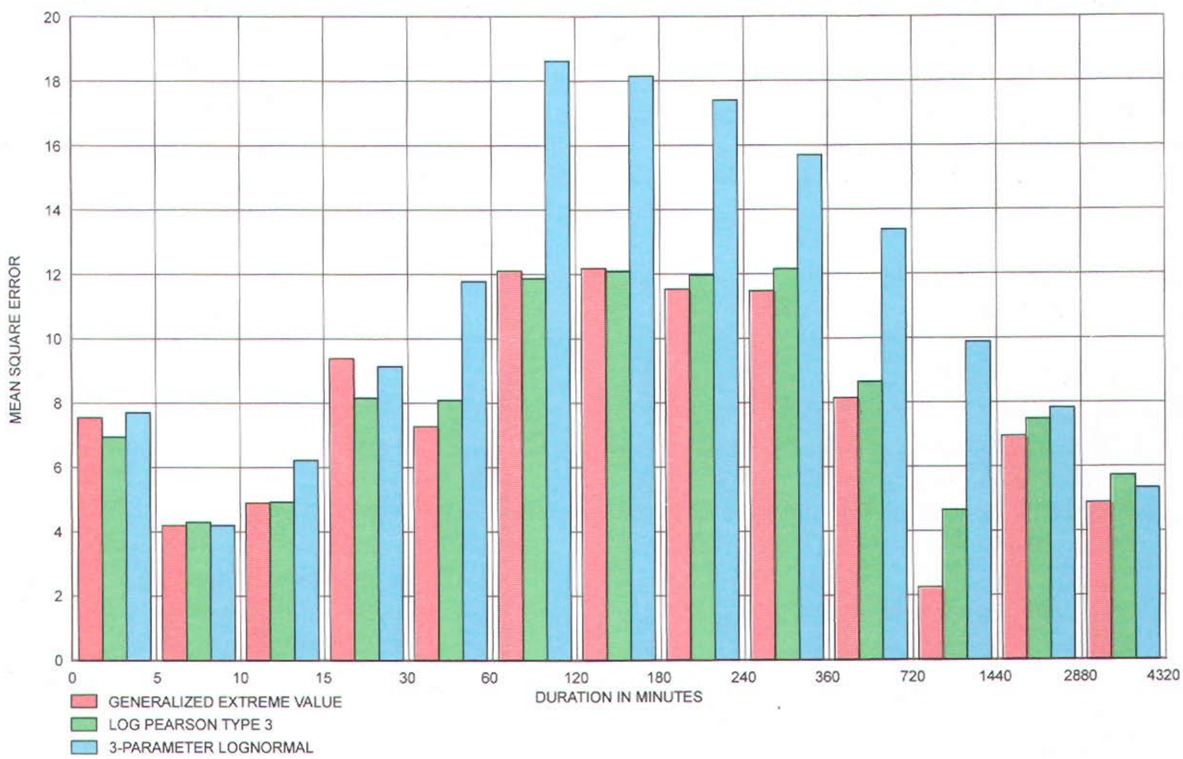
PERCENT ERROR, LARGEST OBSERVATION



Source: Rodgers and Potter.

Figure 18

MEAN SQUARE ERROR, FIVE LARGEST OBSERVATIONS



Source: Rodgers and Potter.

minutes at General Mitchell Field. Although there is no justification for excluding this observation from frequency analysis, it is important to recognize the sensitivity of estimated quantile magnitudes to this case. This sensitivity is examined in detail below.

Influence of Period of Record Length

Figures 15 (real-space data) and 16 (log-transformed) contain L-moment ratio plots for data at all durations, and for durations of five, 10, 15, 30, 60, 120 and 1440 minutes (24 hours), both for the entire period of record and for the period 1940-1998. If the pre-1940 portion of the record were drawn from the same parent distribution as the post-1940 data, the L-moment ratios would differ by amounts related to sampling variation only. By contrast, if the data are inhomogeneous, more substantial differences might be expected (recall Chapter III).

In Figure 15, L-moment ratio pairs associated with short-duration precipitation appear arbitrarily close, suggesting differences due to sampling variation alone. The largest differences appear at 60-minute and 120-minute durations, suggestive of inhomogeneity. An alternative view based on estimated quantile magnitudes is presented in Table 8 and Figure 19. In Figure 19, intensity-duration curves have been plotted for all available durations (five minutes through 72 hours) for two-, 25-, and 100-year recurrence intervals based on data from a constant period (1940-1998.) Quantiles estimated from the full period of record for available durations are superimposed as symbols. It is observed that, while estimates of precipitation quantiles with durations up to 60 minutes agree quite well, quantile estimates at longer durations (120 minutes and 24 hours) diverge increasingly for the reasons described in Chapter III.

Adjustment of Short-Duration (60-, 120-, and 180-minute) Quantiles

Biases associated with data discretization according to clock time or calendar day are well known (von Montfort 1997), and the standard approach to adjusting clock-time estimates of precipitation to actual (time-correct) values involves multiplying quantiles estimated from clock-hour (calendar day) data by "Hershfield factors" (H). H is typically the mean ratio of true to clock-time maximum precipitation, which is determined either theoretically or from available data on both measures. Hershfield (1961) determined the value of H to be approximately 1.14 for daily data. Due to regionally dependent storm rainfall intensity-duration characteristics, and other statistical arguments, the value of H is not anticipated to be independent of duration. It is also possible that the value of H is quantile dependent for a given duration.

The data assembled for this study contain both time-correct and clock-hour data for a range of years at three NWS first-order stations: Milwaukee, Madison and Green Bay. These paired data provided the basis for an empirical investigation conducted to determine the approximate value of H for one-, two-, and three-hour events, and to investigate potential variations in H related to location and recurrence interval. The primary justification for this investigation was the need to develop a sound protocol for reconciling one-, two-, and three-hour maximum values from the 12 cooperative reporting stations to the time-correct values available at Milwaukee, Madison, and Green Bay (short-duration data is not reported for cooperative stations). In addition, 180-minute (three-hour) data is available at Milwaukee for relatively few years, and three-hour values used in the at-site analysis should be adjusted to ensure that IDF curves are internally consistent.

Results are reported in Table 9 for the three gauges individually, and pooled. The empirical value of H for 60 minutes/one hour ("Bias," or mean value of the ratio of correct to clock hour), 1.136, was found to be very close to Hershfield's daily correction factor (1.14). H decreases to 1.043 for 120 minute/two-hour events, and 1.017, or 1.7 percent, for 180 minute/three-hour events, as anticipated. It appears that H is dependent on recurrence interval, at least for two- and three-hour durations. This suggests that smaller observations of the annual maximum are more biased on average than larger values.

Examination of the Impact of the 1986 Extreme Event on Quantile Estimates

The extreme precipitation event of August 6, 1986, is the largest event in the Milwaukee record for all durations between one hour (60 minutes) and 240 hours (10 days), and possibly longer. This event represents an extreme outlier, particularly at durations between one and six hours. The term "outlier" as used here, is not intended to suggest that the magnitude of the event is the result of measurement or other error. There is no reason to doubt the accuracy of the measured precipitation accumulation. However, it is important to understand the extent to which this single observation influences the magnitude of estimated quantiles, particularly when evaluating the at-site model relative to the

Table 8

VARIATION IN ESTIMATED QUANTILE VALUES DUE TO PERIOD OF RECORD FOR SELECTED DURATIONS

		Estimated Rainfall Quantiles		
Recurrence Interval (years)	Storm Duration (minutes)	Full Period of Record (inches)	1940-1998 (Inches)	Percent Difference
2	5	0.35	0.36	+2.9
25	5	0.62	0.63	+1.6
100	5	0.74	0.75	+1.4
2	10	0.56	0.58	+3.6
25	10	0.98	0.99	+1.0
100	10	1.17	1.18	+0.9
2	15	0.73	0.74	+1.4
25	15	1.21	1.22	+0.8
100	15	1.41	1.39	-1.4
2	30	0.94	0.93	-1.1
25	30	1.68	1.67	-0.6
100	30	2.02	2.02	0.0
2	60	1.15	1.16	-0.9
25	60	2.20	2.25	+2.3
100	60	2.82	2.92	+3.5
2	120	1.37	1.34	-2.2
25	120	2.73	2.84	+1.0
100	120	3.64	3.97	+9.1
2	1440	2.26	2.35	+4.0
25	1440	4.41	4.82	+9.3
100	1440	5.88	6.54	+11.2

Source: Rodgers and Potter.

regional model. If no events of comparable magnitude exist within the (roughly) 600 station-years of record comprising the regional network, the recurrence interval for this event may be longer than predicted by the at-site model. However, at least one similar three-hour rainfall occurred at Belvedere in 1977. This event strengthens that argument for including the August 1986 Milwaukee event in the frequency analysis.

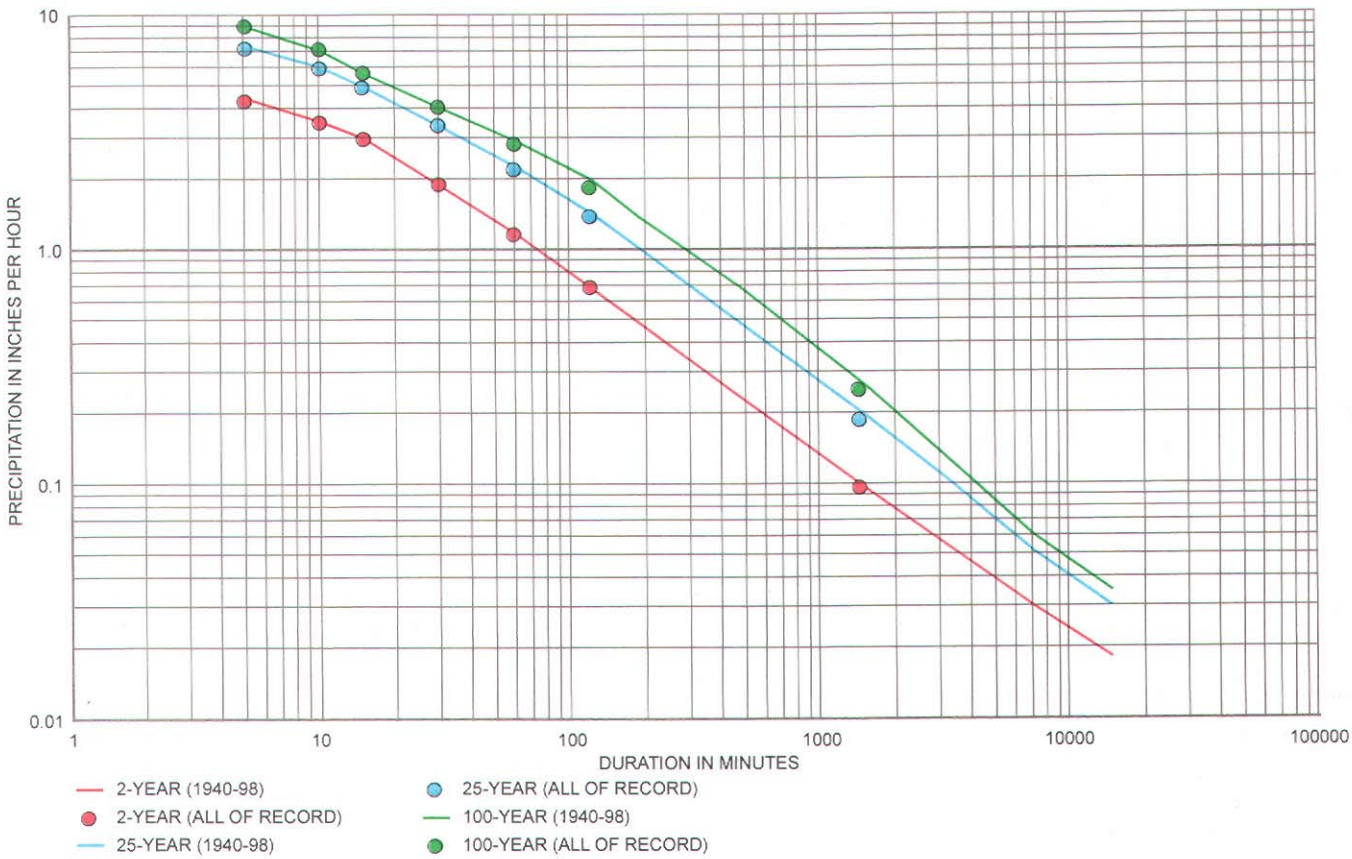
The frequency analysis based on clock-hour data for the period 1940-1998 and employing the GEV fit by method of L-moments was repeated, but excluding the 1986 value. Quantiles for durations from one to 72 hours, and for recurrence intervals of 10, 50, and 100 years were estimated and compared with those based on data inclusive of 1986. Results are summarized in Table 10. It is observed that the 1986 event is extremely influential, and exclusion results in decreases in estimated quantile values of up to 25 percent for long recurrence intervals, particularly at durations between two and four hours, where the magnitude of the 1986 event relative to series mean is greatest. This is not an argument for the exclusion of the 1986 data, however, and the most defensible at-site quantile estimates are those containing all valid observations. Furthermore, inclusion of the 1986 rainfall is backed up by the occurrence of similar extreme rainfalls at Brown Deer in 1997 and Elm Grove in 1998.

REGIONAL FREQUENCY ANALYSIS USING WEIGHTED L-MOMENT STATISTICS

The time series of precipitation recorded at a given location, and the distribution of annual maxima abstracted from this time series, are assumed to be finite samples drawn from a parent distribution with stable but unknown distribution parameters. It is well established that distribution parameters estimated on the basis of small samples, in particular the coefficient of skewness, are relatively high-variance, biased estimates relative to the true population values (Wallis, et al., 1974; Matalas, et al., 1975). In settings where data measured at several discrete locations can reasonably be viewed as samples drawn from a common "parent" distribution, methods of statistical regionalization can

Figure 19

MILWAUKEE INTENSITY-DURATION-FREQUENCY CURVES, 1940-1998 AND FULL PERIOD OF RECORD



Source: Rodgers and Potter.

be used to increase the effective record length, thereby reducing small sample bias and increasing the accuracy with which parameter values are estimated (Hosking and Wallis,1997, NRC 1988). Extreme precipitation-generating mechanisms in the upper Midwest, primarily convective and air-mass storms, are relatively homogenous in their spatial occurrence, and precipitation analysis is uncomplicated by such factors as orographic effects and tropical depressions. The hypothesis of precipitation homogeneity within the Southeastern Wisconsin Region was taken as a working assumption and a regional frequency analysis was performed. The objective was to provide a quasi-independent means of evaluating the at-site quantile estimates and, in particular, the relative frequency of extreme events observed at General Mitchell Field.

A general procedure for regional frequency analysis is described in Hosking and Wallis (1997). It consists of 1) screening of the data, 2) identification of homogenous region(s), 3) selecting the frequency distribution, and 4) estimating the parameters of this distribution via the regional L-moment algorithm. This algorithm involves estimating at-site L-moments and moment ratios for each location potentially belonging to the region, examining these values for regional coherence, and calculating the corresponding regional values as sample length-weighted averages of the local values. The resulting index precipitation model describes quantiles in unitless terms as multiples of the regional mean. To obtain quantile values for individual locations, the index values are multiplied by the at-site mean.

Screening of Data

The four NWS and eleven cooperative stations included in the regional analysis, selected on the basis of location, record length, and coverage, are described in Table 3 and Map 4. As indicated in Table 3, data for the four NWS stations is 100 percent complete, and

Table 9

CLOCK-HOUR BIAS FOR 60-, 120-, AND 180-MINUTE STORM DURATIONS

Station	Number of Observations	Bias Percent	Bias at Recurrence Interval (percent)				
			2-Year	10-Year	25-Year	50-Year	100-Year
60 Minutes/1 Hour							
Milwaukee............	36	13.8	8.5	15.4	18.7	26.7	32.2
Madison	46	11.0	10.7	9.6	9.2	8.5	8.1
Green Bay	46	16.2	14.9	9.8	8.7	6.5	5.2
Pooled	128	13.6	11.4	10.5	10.7	11.4	12.0
120 Minutes/2 Hour							
Milwaukee............	35	3.7	3.9	4.9	5.0	5.0	4.9
Madison	45	4.2	4.6	4.0	3.7	3.1	2.6
Green Bay	44	4.8	5.6	5.0	4.5	3.0	2.0
Pooled	124	4.3	4.8	4.5	4.1	3.3	2.7
180 Minutes/3 Hours							
Pooled	50	1.7	2.7	1.5	0.9	-0.04	-1.3

Source: Rodgers and Potter.

Table 10

SENSITIVITY OF ESTIMATED QUANTILE MAGNITUDES TO THE 1986 EVENT

Duration	10-Year Rainfall			50-Year Rainfall			100-Year Rainfall		
	Depth (inches)[a]	Depth (inches)[b]	Percent[c]	Depth (inches)[a]	Depth (inches)[b]	Percent[c]	Depth (inches)[a]	Depth (inches)[b]	Percent[c]
1-Hour	1.85	1.76	-4.5	2.57	2.32	-9.9	2.92	2.56	-12.4
2-Hour	2.24	2.07	-7.7	3.37	2.72	-19.2	3.97	3.00	-24.3
3-Hour	2.44	2.25	-7.9	3.63	2.92	-19.7	4.26	3.20	-24.9
4-Hour	2.61	2.42	-7.3	3.92	3.20	-18.2	4.62	3.55	-23.1
6-Hour	2.89	2.70	-6.5	4.37	3.66	-16.2	5.18	4.11	-20.7
12-Hour	3.34	3.15	-5.8	4.96	4.28	-13.8	5.82	4.80	-17.5
24-Hour	3.86	3.68	-4.9	5.63	5.01	-11.0	6.54	5.63	-13.8
48-Hour	4.49	4.31	-4.0	6.09	5.60	-8.0	6.81	6.14	-9.8
72-Hour	4.70	4.53	-3.6	6.21	5.76	-7.2	6.85	6.26	-8.7

[a]*All cases included, 1940-1998, 59 observations.*

[b]*1986 excluded, 58 observations.*

[c]*Percentage difference in quantile magnitude determined by excluding the August 1986 storm and quantile magnitude which includes the 1986 storm.*

Source: Rodgers and Potter.

for the 11 included cooperative stations between 88 percent and 99 percent complete. In screening incomplete data, the desire to maximize the number of usable annual records at each duration is offset by the need to avoid potential bias introduced by the inclusion of observations that are not true annual maximum values. Hourly records from cooperative stations contain quality control flags indicating periods of missing (M), accumulated (A), and deleted (D) data. Each type of flagged data presents a unique challenge to the identification of annual maximum values.

The validity of the annual maximum n-hour precipitation for a given year is compromised if a large proportion of the annual data are missing, particularly if these missing data are distributed within the period during which large storms typically occur (April-September). Identified maxima are also questionable if relatively short runs of data are selectively missing on or around dates corresponding to annual maximum events at other stations in the region. Missing winter season data, by contrast, do not necessarily warrant the exclusion of the station-year. Accumulated data are valid observations, albeit recorded as totals over the respective periods of accumulation, which are known via data flags. Observed periods of accumulation range from two hours to several months. If an accumulated value is identified as the annual maximum for a particular duration, it is useable provided the accumulation period is less than or equal to that duration. In general, it is not usable otherwise. However, the accumulation period is the period over which no incremental observations were taken, and not necessarily the duration of precipitation, whereas the true period of accumulation, an unknown, may be substantially shorter.

A computer program was written to search the hourly records and capture the largest consecutive n-hour totals, n=1,2,3,...,72, for each available year, irrespective of the percent annual coverage. If an identified period contained a flag, the search was repeated until the largest n-hour period without flags was located. Missing and deleted data were also identified and compiled by station-year. An initial attempt was made to specify a series of fixed, sequential rules by which station years were included or excluded on the basis of missing or accumulated flags. It soon became apparent that the rigid application of rules resulted in the elimination of so many station-years at each location that many records became unusably small. A second, manual screening, involving case by case evaluation of every flagged observation, allowed the reinstatement of many station-years. A final screening was performed to compare results across all durations, in an attempt to improve consistency.

In performing the regional analysis, data for Milwaukee, Madison, and Green Bay were restricted to the period 1940 through 1998, although longer periods of record are available at these locations for one-, two-, and 24-hour durations. This was done primarily to ensure that all gauge records were samples drawn from the same approximate time period, and to prevent any single station or subset of stations from dominating the weighted moments calculation by virtue of greatly unequal record lengths. For similar reasons, the regional analysis was restricted to durations of one hour and above, and data to clock-hour observations, since short-duration, time-correct data are not available at the cooperative stations. Precipitation data for the 15 regional stations is summarized in Tables 11 and 12. Data for the three Wisconsin NWS stations (Milwaukee, Madison, Green Bay) appearing in Table 11 are clock-hour values for the period 1940 through 1998, to provide consistency with cooperative data. It is observed that mean annual maximum precipitation at Milwaukee for 1940 through 1998 is very close to the regional mean at every duration.

Identification of Homogenous Regions

The procedure described in Hosking and Wallis (1997), and currently in use by NWS in their update of TP 40 for the Ohio River Valley, makes no initial assumptions about regional gauge membership. A variety of analyses based on L-moments, including cluster analysis, are used to sort gauges into regions on the basis of similarity of key parameters. Prospective members are then evaluated for homogeneity. By contrast, in this analysis, regional NWS and cooperative stations were selected on the basis of geographic proximity to Milwaukee and assumed, as a working hypothesis, to fall within a common region. When L-moment ratios calculated for individual stations are plotted jointly in L-skewness, L-kurtosis space (Figures 20 through 27), the pattern is relatively coherent, suggesting regional homogeneity.

It is nevertheless necessary to verify that no prospective regional member is atypical, or discordant, with respect to key parameters describing the distribution of annual maximum precipitation. The discordance measure recommended by Hosking and Wallis (1997) was used to screen the 15 NWS and cooperative gauge records for outliers. It is based on the L-moment parameters corresponding to distribution coefficient of variation, skewness, and kurtosis and takes the form:

$$D_i = \frac{n}{3}(u_i - \bar{u})^{\mathrm{T}} A^{-1} (u - \bar{u})$$

In this expression, D is the test statistic, i indexes site (i=1....15), u is the 3x1 vector of at-site parameters (coefficient of variation, skewness, kurtosis), and A is the matrix of sums and cross-products. D is a multivariate statistic comparable to the z-score in one dimension, and provides an indication of the likelihood that the vector of sample at-site characteristics would be drawn from a population described by regional mean characteristics. A site is identified as discordant if D exceeds approximately 3.0. It is typically examined for errors, and, if data are found to be accurate, the site is excluded from the regional model. The discordance test was applied to the Milwaukee regional data at all

Table 11

NUMBER OF USABLE STATION YEARS, AND MEAN AND STANDARD DEVIATION OF PRECIPITATION,15 REGIONAL STATIONS

Station	Precipitation Duration							
	1-Hour	2-Hour	3-Hour	6-Hour	12-Hour	24-Hour	48-Hour	72-Hour
Number of Usable Observations (Station-Years)								
Milwaukee	59	59	59	59	59	59	59	59
Madison	50	50	50	50	50	50	50	50
Green Bay	50	50	50	50	50	50	50	50
O'Hare	34	34	34	34	34	34	34	34
Belvidere	44	44	44	46	46	47	47	46
Berlin	32	32	32	30	30	30	30	30
Chilton	41	42	44	44	45	44	45	46
Eagle	35	35	37	39	40	39	40	40
El Dorado	26	26	26	27	27	29	30	30
Hartford	41	41	42	46	47	47	47	47
Janesville	30	31	32	30	29	31	33	33
McHenry	36	36	36	39	41	42	42	42
Oregon	41	41	41	43	44	44	40	42
Portage	42	42	42	42	42	41	41	41
Rockford	38	38	38	38	38	38	38	38
Sample Mean Precipitation (inches)								
Milwaukee	1.13	1.46	1.64	1.95	2.26	2.60	3.00	3.21
Madison	1.28	1.60	1.81	2.13	2.43	2.69	3.02	3.26
Green Bay	0.99	1.25	1.40	1.67	1.95	2.21	2.51	2.74
O'Hare	1.26	1.69	1.86	2.31	2.66	2.98	3.19	3.44
Belvidere	1.29	1.72	2.01	2.31	2.59	2.88	3.33	3.60
Berlin	0.99	1.30	1.51	1.75	1.97	2.18	2.48	2.66
Chilton	1.01	1.35	1.55	1.88	2.15	2.52	2.84	3.01
Eagle	1.20	1.51	1.64	1.89	2.15	2.42	2.74	2.93
El Dorado	1.06	1.46	1.67	1.85	2.08	2.23	2.50	2.72
Hartford	1.09	1.42	1.65	1.92	2.25	2.59	2.92	3.18
Janesville	1.23	1.53	1.69	2.01	2.27	2.42	2.85	3.02
McHenry	1.27	1.60	1.78	2.07	2.34	2.64	2.93	3.17
Oregon	1.26	1.75	1.91	2.18	2.55	2.98	3.50	3.68
Portage	1.11	1.47	1.66	1.95	2.25	2.53	2.82	3.09
Rockford	1.44	1.80	2.00	2.47	2.77	3.09	3.46	3.70
Sample Standard Deviation (inches)								
Milwaukee	0.447	0.675	0.741	0.838	0.925	1.038	1.151	1.137
Madison	0.360	0.474	0.554	0.620	0.647	0.766	0.925	0.921
Green Bay	0.440	0.444	0.476	0.525	0.650	0.772	0.806	0.854
O'Hare	0.352	0.569	0.640	0.967	1.226	1.356	1.441	1.471
Belvidere	0.519	0.755	0.937	1.078	1.154	1.149	1.335	1.437
Berlin	0.399	0.471	0.533	0.606	0.571	0.629	0.873	0.840
Chilton	0.324	0.474	0.574	0.685	0.855	1.047	1.224	1.170
Eagle	0.463	0.563	0.590	0.621	0.615	0.607	0.724	0.812
El Dorado	0.306	0.484	0.581	0.602	0.608	0.622	0.840	0.871
Hartford	0.322	0.449	0.572	0.723	0.804	0.950	1.060	1.081
Janesville	0.416	0.482	0.546	0.652	0.743	0.660	0.930	0.895
McHenry	0.422	0.552	0.664	0.749	0.748	0.931	1.056	1.089
Oregon	0.419	0.618	0.655	0.732	0.897	1.227	1.293	1.349
Portage	0.335	0.629	0.858	0.993	1.090	1.310	1.482	1.520
Rockford	0.505	0.625	0.693	0.854	0.933	1.114	1.239	1.326

Source: Rodgers and Potter.

Table 12

SUMMARY STATISTICS, 15 REGIONAL STATIONS

Statistic	Precipitation Duration 1-Hour	2-Hour	3-Hour	6-Hour	12-Hour	24-Hour	48-Hour	72-Hour
Sample Mean (inches)								
Minimum	0.99	1.25	1.40	1.67	1.95	2.18	2.48	2.66
Maximum	1.44	1.80	2.01	2.47	2.77	3.09	3.50	3.70
Mean	1.17	1.53	1.72	2.02	2.31	2.60	2.94	3.16
Standard Deviation	0.13	0.17	0.17	0.22	0.25	0.29	0.33	0.33
Coefficient of Variation	0.11	0.11	0.10	0.11	0.11	0.11	0.11	0.11
Sample Standard Deviation (inches)								
Minimum	0.31	0.44	0.48	0.52	0.57	0.61	0.72	0.81
Maximum	0.52	0.75	0.94	1.08	1.23	1.36	1.48	1.52
Mean	0.40	0.55	0.64	0.75	0.83	0.95	1.09	1.12
Standard Deviation	0.07	0.09	0.13	0.16	0.21	0.26	0.24	0.25
Coefficient of Variation	0.17	0.17	0.20	0.22	0.25	0.27	0.22	0.22
Sample Skewness								
Minimum	0.28	0.30	0.31	0.29	0.27	0.25	0.26	0.28
Maximum	0.44	0.46	0.52	0.51	0.49	0.52	0.53	0.49
Mean	0.34	0.36	0.37	0.37	0.36	0.36	0.37	0.35
Standard Deviation	0.05	0.05	0.06	0.06	0.07	0.08	0.06	0.06
Coefficient of Variation	0.15	0.13	0.16	0.17	0.19	0.21	0.17	0.16
25-year GEV Quantiles (inches)								
Minimum	1.60	2.18	2.40	2.68	3.15	3.51	4.15	4.47
Maximum	2.44	3.26	3.88	4.34	5.06	5.69	6.35	6.64
Mean	1.99	2.66	3.04	3.45	4.05	4.59	5.26	5.52
Standard Deviation	0.24	0.32	0.37	0.52	0.63	0.78	0.76	0.82
Coefficient of Variation	0.12	0.12	0.12	0.14	0.15	0.17	0.14	0.15
100-year GEV Quantiles (inches)								
Minimum	1.78	2.66	2.98	3.49	3.70	4.09	4.91	5.23
Maximum	3.10	4.25	5.33	6.11	7.24	8.10	9.16	9.16
Mean	2.46	3.34	3.85	4.64	5.23	5.99	6.92	7.11
Standard Deviation	0.38	0.53	0.67	0.88	1.13	1.42	1.30	1.40
Coefficient of Variation	0.16	0.16	0.17	0.19	0.22	0.24	0.19	0.20

Source: Rodgers and Potter.

durations, and the results are summarized in Table 13. No site was identified as discordant, and all 15 stations were consequently included in the estimation of the regional GEV model.

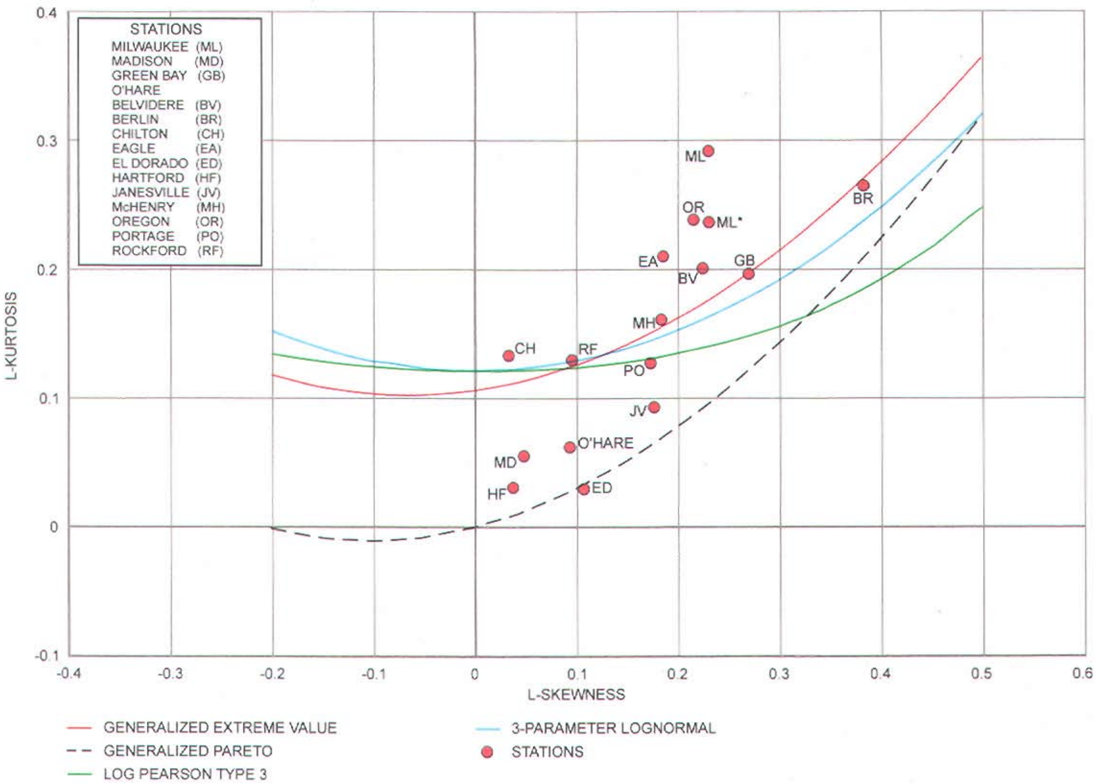
The Regional Probability-Weighted Moment (PWM) Algorithm and Results

The regional PWM model is conceptually simple: regional values of the L-moment ratios used to derive the parameters of the regional GEV distribution are the weighted averages of the at-site statistics, with samplesize serving as the linear weight. For each parameter(L-coefficient of variation, skewness, kurtosis), the regional value is:

$$\theta_r = \frac{\sum_{i=1}^{15} n_i \theta_i}{\sum_{i=1}^{15} n_i}$$

Figure 20

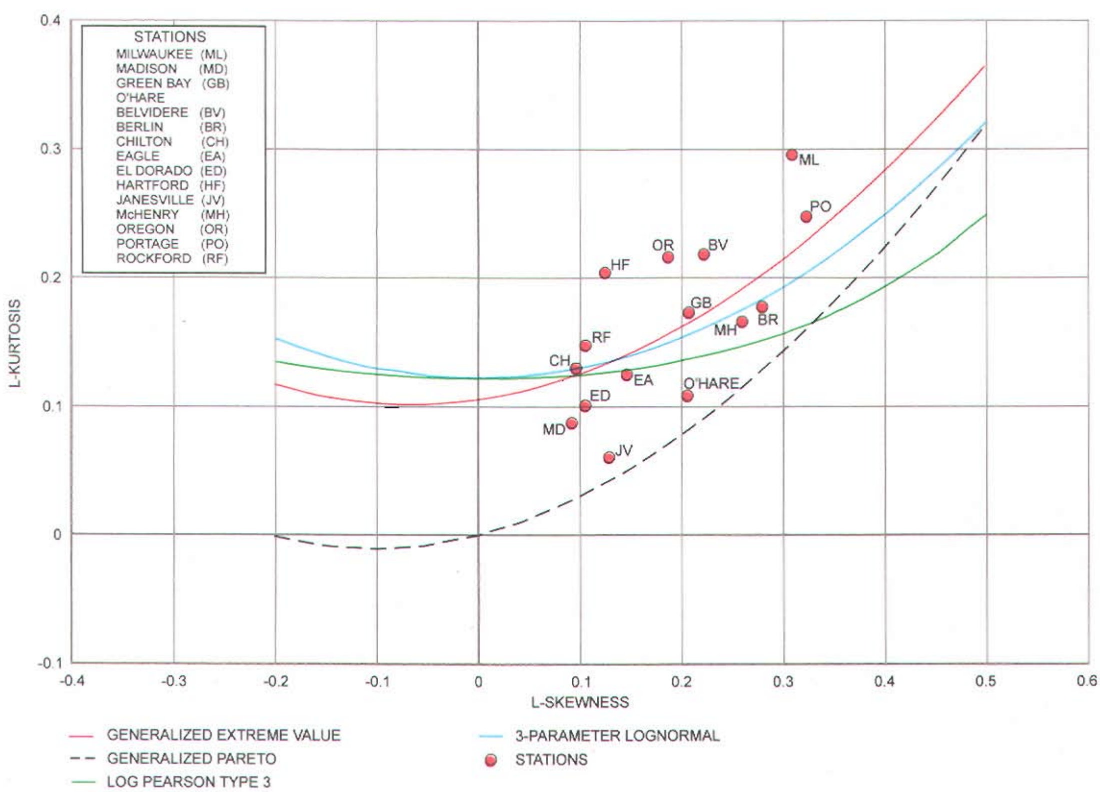
L-MOMENT RATIOS, REGIONAL STATIONS, ONE-HOUR



Source: Rodgers and Potter.

Figure 21

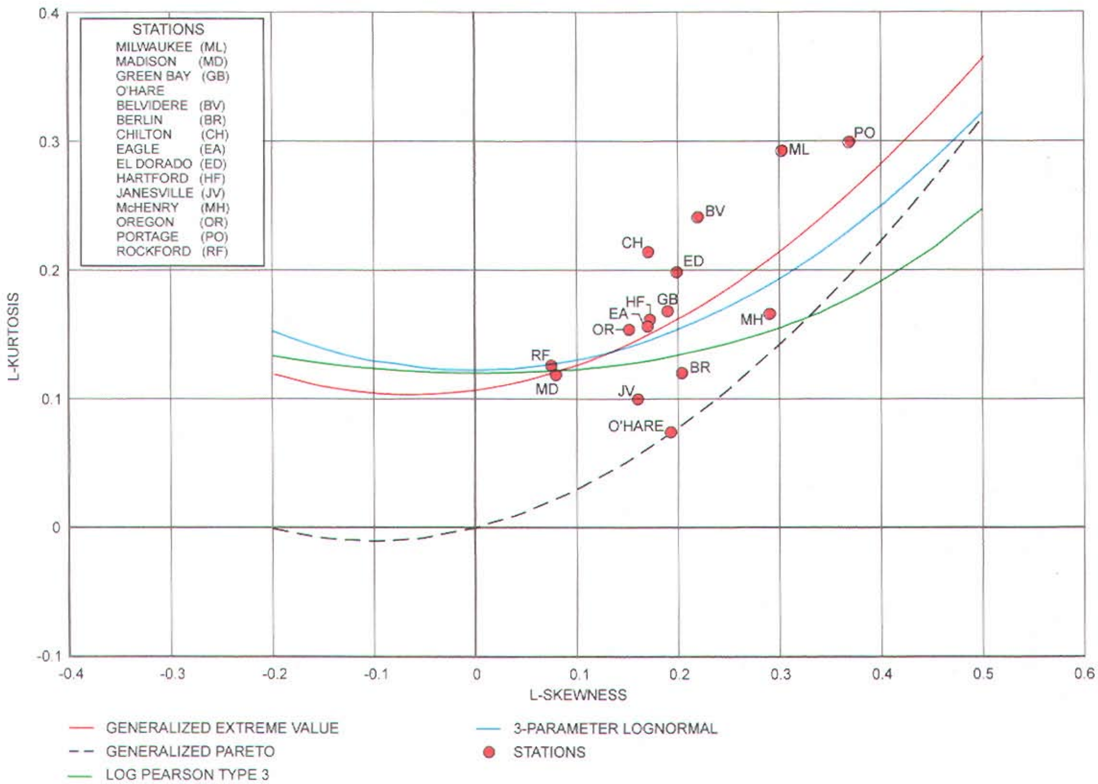
L-MOMENT RATIOS, REGIONAL STATIONS, TWO-HOUR



Source: Rodgers and Potter.

Figure 22

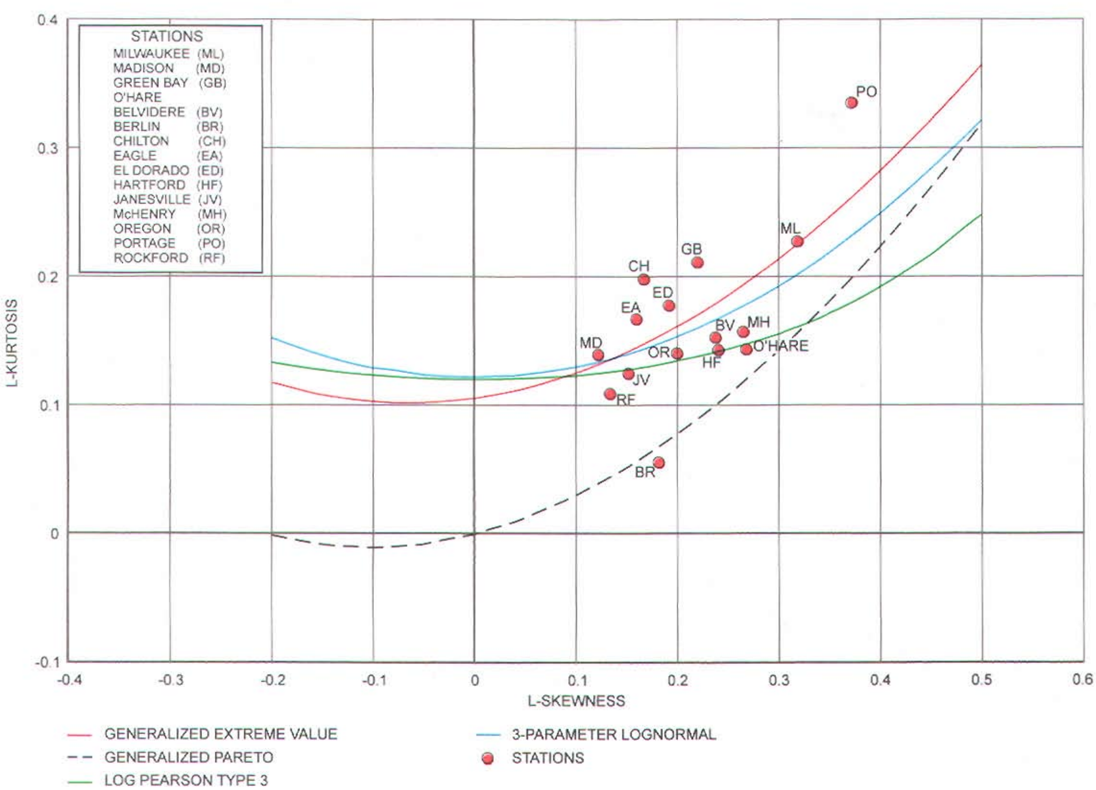
L-MOMENT RATIOS, REGIONAL STATIONS, THREE-HOUR



Source: Rodgers and Potter.

Figure 23

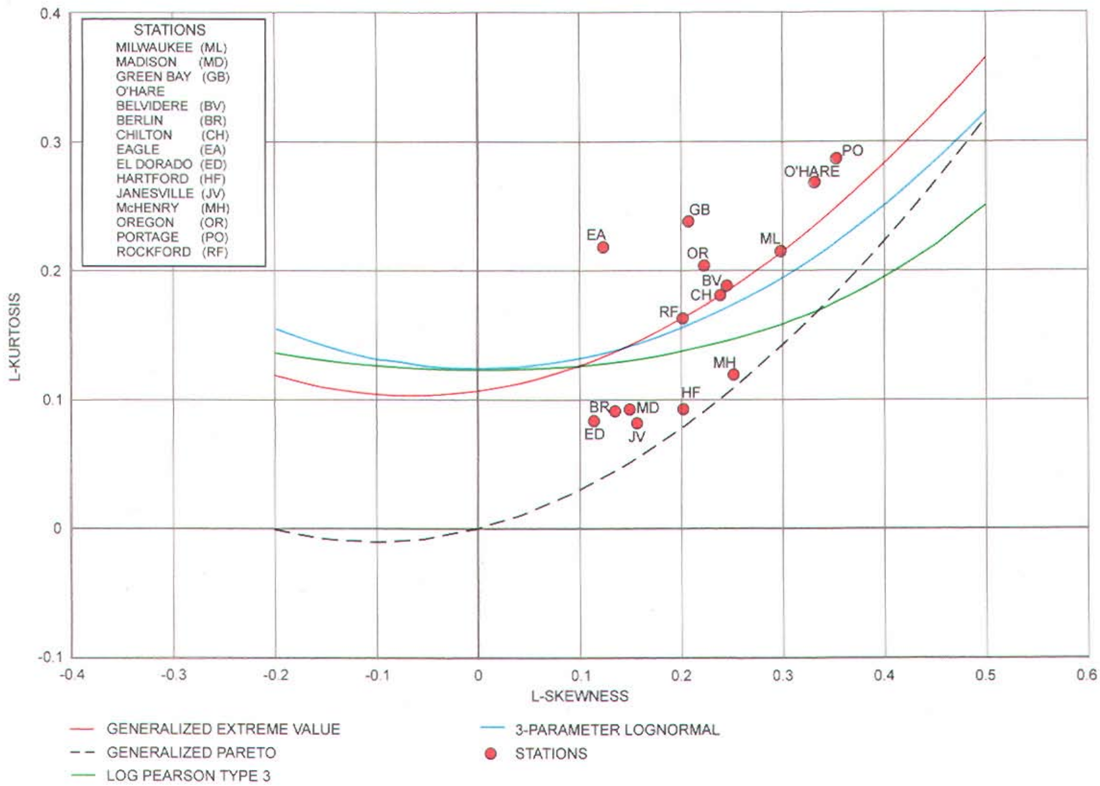
L-MOMENT RATIOS, REGIONAL STATIONS, SIX- HOUR



Source: Rodgers and Potter.

Figure 24

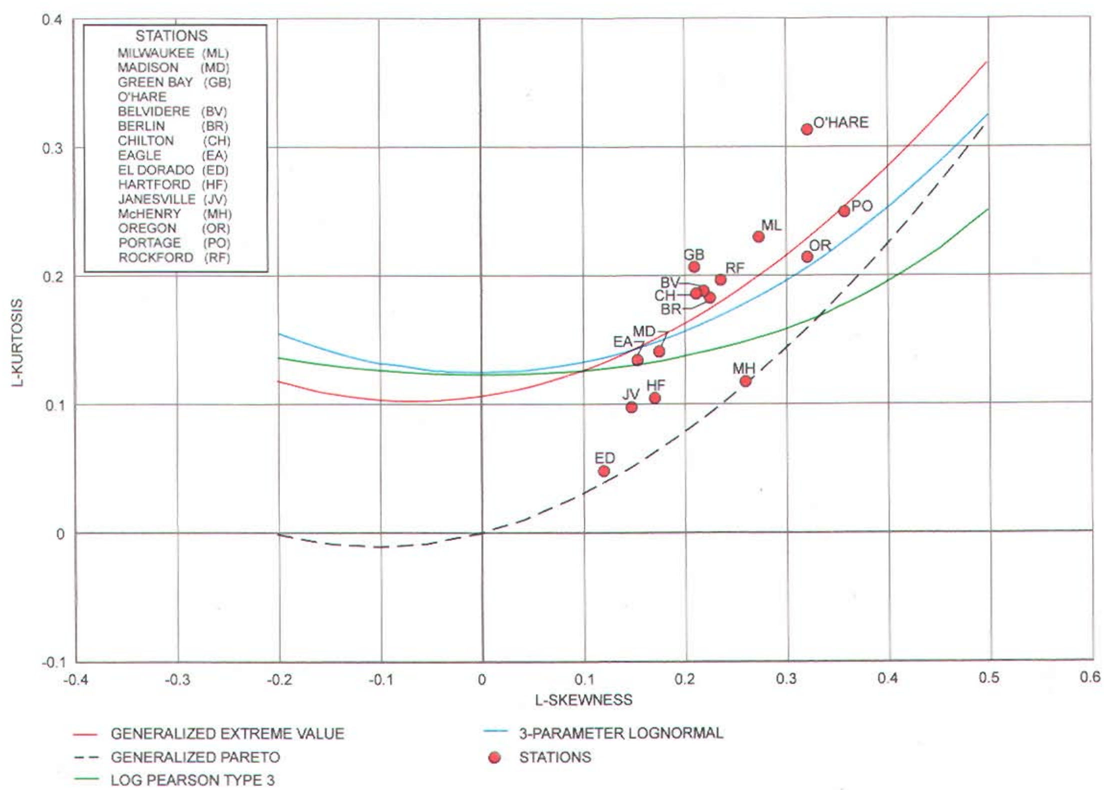
L-MOMENT RATIOS, REGIONAL STATIONS, 12-HOUR



Source: Rodgers and Potter.

Figure 25

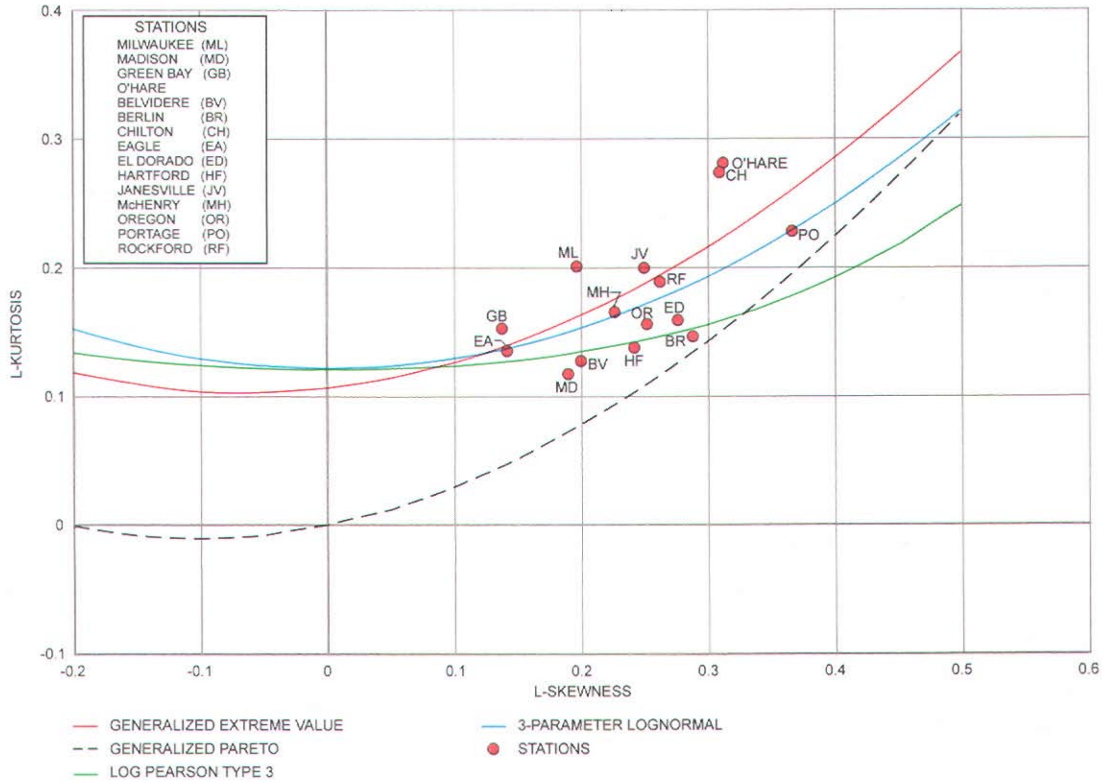
L-MOMENT RATIOS, REGIONAL STATIONS, 24-HOUR



Source: Rodgers and Potter.

Figure 26

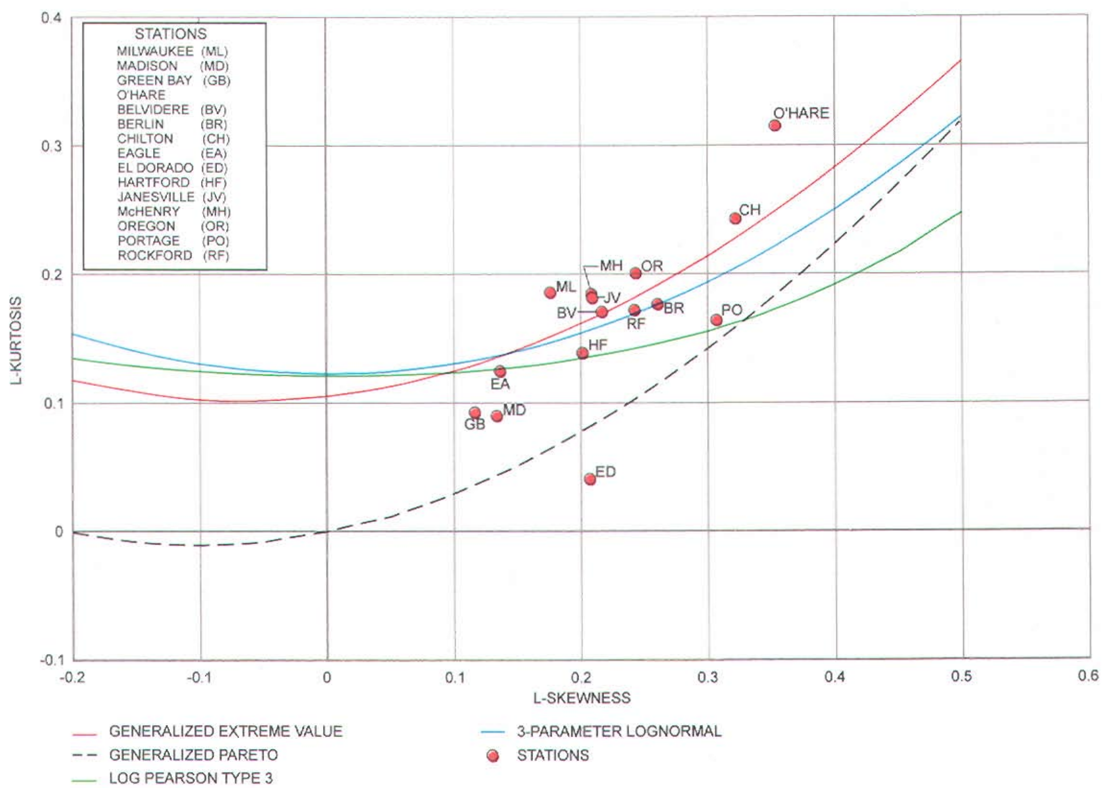
L-MOMENT RATIOS, REGIONAL STATIONS, 48-HOUR



Source: Rodgers and Potter.

Figure 27

L-MOMENT RATIOS, REGIONAL STATIONS, 72-HOUR



Source: Rodgers and Potter.

Table 13

VALUES OF D (REGIONAL DISCORDANCE MEASURE)[a]

Station	1-Hour	2-Hour	3-Hour	6-Hour	12-Hour	24-Hour	48-Hour	72-Hour
Milwaukee	1.536	1.512	2.011	0.997	0.555	0.251	1.229	1.125
Madison	0.667	0.875	0.933	0.949	1.054	0.415	0.589	0.723
Green Bay	2.225	0.058	0.329	1.242	0.968	0.568	1.305	0.938
O'Hare	0.676	0.829	1.735	0.748	1.167	1.825	1.600	2.049
Belvidere	0.688	1.490	1.832	2.088	2.095	0.688	1.705	0.754
Berlin	2.393	0.964	0.541	1.475	0.513	1.048	1.169	0.809
Chilton	1.460	0.873	0.581	1.324	0.430	1.155	1.317	0.902
Eagle	0.361	1.076	0.113	0.451	2.431	0.922	1.391	0.769
El Dorado	1.021	0.454	0.627	0.350	0.734	1.237	0.724	2.787
Hartford	0.737	2.025	0.070	0.295	0.849	1.305	0.406	0.066
Janesville	0.737	1.101	0.512	0.294	0.764	0.564	1.024	0.928
McHenry	0.037	0.834	1.422	0.823	1.875	2.041	0.053	0.207
Oregon	1.153	0.989	0.225	0.210	0.167	1.092	0.190	0.183
Portage	0.527	1.304	2.638	2.908	1.383	1.816	2.218	2.704
Rockford	0.783	0.617	1.431	0.845	0.016	0.074	0.078	0.056

[a]D greater than or equal to 3.0 indicates discordance.

Source: Rodgers and Potter.

In this expression, θ is one of the three statistical parameters and i indexes gauge. Next, the regional mean is set equal to 1 (unity), and GEV quantiles are derived from the regional L-moment ratios using the method of Hosking, et al. (1985). The resulting quantiles are dimensionless: each index quantile is expressed as the ratio of t-year precipitation (P_2, P_{10}, P_{25}, P_{50}, P_{100}) to the mean. To obtain an at-site quantile estimate based on the regional model, the index quantile is multiplied by the at-site mean. Index quantile values and the corresponding regional quantile estimates for General Mitchell Field appear in Tables 14 (index quantiles, dimensionless) and 15 (quantile estimates, inches). Quantiles estimated using at-site data are included for comparison.[1]

It is observed that quantile estimates based on the regional model tend to be lower than the corresponding at-site estimates for recurrence intervals of 10 years and longer. Exceptions are long recurrence intervals (50 and 100 years) for 48- and 72-hour quantiles. Overall agreement is good. This, along with the results of the discordance test, suggest that extreme precipitation probabilities in or near Milwaukee do not differ in any fundamental way from those characterizing the Southeastern Wisconsin Region. Maximum divergences occur for 100-year, two- and three-hour quantiles, reflecting to a large extent the relatively greater influence of the 1986 event on Milwaukee at-site estimates.[2] Regional estimates are in fact bracketed by Milwaukee at-site quantile estimates obtained when the 1986 event is included and excluded.

RECOMMENDED RAINFALL DEPTHS FOR DESIGN IN THE SOUTHEASTERN WISCONSIN REGION

A wide range of precipitation quantile estimates for Milwaukee and Southeastern Wisconsin have been generated, both within this study and in previous studies. A comparison of quantile values from various sources appears in Table 16, and the corresponding rainfall-frequency curves are plotted in Figures 28 to 31. The estimated GEV coefficients are provided in

[1]*Although the regional model is based on clock-hour data, the Milwaukee quantile estimates are based on time-correct mean values, thus they are adjusted for clock-hour bias.*

[2]*This event was exceeded at one regional location, Belvidere, at both 1- and 3-hour durations.*

Table 14

REGIONAL GEV INDEX QUANTILES (DIMENSIONLESS)

Duration	Mean	2-Year	10-Year	25-Year	50-Year	100-Year
1-Hour	1.0	0.944	1.453	1.707	1.895	2.080
2-Hour	1.0	0.934	1.468	1.750	1.965	2.183
3-Hour	1.0	0.931	1.479	1.772	1.998	2.228
6-Hour	1.0	0.924	1.475	1.784	2.028	2.284
12-Hour	1.0	0.926	1.458	1.758	1.995	2.244
24-Hour	1.0	0.923	1.461	1.770	2.017	2.280
48-Hour	1.0	0.920	1.468	1.787	2.045	2.320
72-Hour	1.0	0.929	1.450	1.741	1.970	2.210

Source: Rodgers and Potter.

Table 15

REGIONAL GEV QUANTILE ESTIMATES, MILWAUKEE

Duration	Mean	2-Year	10-Year	25-Year	50-Year	100-Year
Regional Quantile Estimates, 1940-1998 Means in Inches						
1-Hour..	1.26	1.19	1.84	2.16	2.39	2.63
2-Hour..	1.50	1.40	2.21	2.63	2.95	3.28
3-Hour..	1.64	1.53	2.43	2.91	3.28	3.66
6-Hour..	1.95	1.80	2.88	3.48	3.96	4.46
12-Hour..	2.26	2.09	3.30	3.97	4.51	5.07
24-Hour..	2.60	2.40	3.80	4.60	5.24	5.93
48-Hour..	3.00	2.76	4.40	5.36	6.13	6.96
72-Hour..	3.21	2.98	4.65	5.58	6.32	7.09
At-Site Estimates, 1940-1998 Means in Inches						
1-Hour..	1.26	1.16	1.85	2.25	2.57	2.92
2-Hour..	1.50	1.34	2.24	2.84	3.37	3.97
3-Hour..	1.64	1.47	2.44	3.07	3.63	4.26
6-Hour..	1.95	1.74	2.89	3.67	4.37	5.18
12-Hour..	2.26	2.03	3.34	4.21	4.96	5.82
24-Hour..	2.60	2.35	3.86	4.82	5.63	6.54
48-Hour..	3.00	2.78	4.49	5.40	6.09	6.81
72-Hour..	3.21	3.01	4.70	5.56	6.21	6.85
Regional Quantile Estimates, Period of Record Means in Inches						
1-Hour..	1.24	1.17	1.80	2.12	2.35	2.58
2Hour...	1.50	1.40	2.20	2.62	2.94	3.27
24-Hour..	2.48	2.28	3.62	4.38	4.99	5.64
At-Site Estimates, Period of Record Means in Inches						
1-Hour..	1.24	1.15	1.82	2.20	2.50	2.82
2-Hour..	1.50	1.36	2.21	2.73	3.16	3.64
24-Hour..	2.48	2.26	3.58	4.41	5.11	5.88

Source: Rodgers and Potter.

Table 16

COMPARISON OF PRECIPITATION QUANTILE ESTIMATES (INCHES) FOR MILWAUKEE

Duration	Depth (inches)						
	GEV[a]	GEV[b]	GEV[c]	LP-3[a]	TP-40 (1961)	SEWRPC (1990)[d]	Bulletin 71 (1992)
Recurrence Interval: 2 Years (p=0.5)							
1-Hour	1.16	1.15	1.19	1.17	1.41	1.30	1.27
2-Hour	1.34	1.36	1.40	1.32	1.63	1.52	1.57
3-Hour	1.47	- -	1.53	1.46	1.72	1.67	1.73
6-Hour	1.74	- -	1.80	1.73	2.00	1.97	2.03
12-Hour	2.03	- -	2.09	2.03	2.34	2.30	2.35
24-Hour	2.35	2.26	2.40	2.38	2.63	2.69	2.70
Recurrence Interval: 10 Years (p=0.1)							
1-Hour	1.85	1.82	1.84	1.87	1.93	1.85	1.81
2-Hour	2.24	2.21	2.21	2.27	2.29	2.16	2.24
3-Hour	2.44	- -	2.43	2.47	2.50	2.37	2.47
6-Hour	2.89	- -	2.88	2.92	2.90	2.78	2.89
12-Hour	3.34	- -	3.30	3.38	3.38	3.24	3.36
24-Hour	3.86	3.51	3.80	3.91	3.83	3.80	3.86
Recurrence Interval: 25 Years (p=0.04)							
1-Hour	2.25	2.20	2.16	2.24	2.23	2.16	2.19
2-Hour	2.84	2.73	2.63	2.91	2.58	2.53	2.70
3-Hour	3.07	- -	2.91	3.14	2.80	2.78	2.98
6-Hour	3.67	- -	3.48	3.71	3.34	3.25	3.49
12-Hour	4.21	- -	3.97	4.22	3.88	3.81	4.05
24-Hour	4.82	4.41	4.60	4.78	4.42	4.46	4.66
Recurrence Interval: 50 Years (p=0.02)							
1-Hour	2.57	2.50	2.39	2.54	2.41	2.42	2.53
2-Hour	3.37	3.16	2.95	3.47	2.88	2.83	3.12
3-Hour	3.63	- -	3.28	3.73	3.12	3.11	3.44
6-Hour	4.37	- -	3.96	4.40	3.69	3.64	4.03
12-Hour	4.96	- -	4.51	4.93	4.27	4.27	4.68
24-Hour	5.63	5.11	5.24	5.48	5.00	5.01	5.38
Recurrence Interval: 100 Years (p=0.01)							
1-Hour	2.92	2.82	2.63	2.84	2.69	2.66	2.93
2-Hour	3.97	3.64	3.28	4.11	3.18	3.11	3.62
3-Hour	4.26	- -	3.66	4.39	3.51	3.41	3.99
6-Hour	5.18	- -	4.46	5.18	4.06	3.99	4.68
12-Hour	5.82	- -	5.07	5.71	4.86	4.68	5.43
24-Hour	6.54	5.88	5.93	6.21	5.44	5.47	6.24

[a]*At-Site, Period 1940-1998.*

[b]*At-Site, Period of Record.*

[c]*Regional, Period 1940-1998.*

[d]*Converted to partial duration series depths using factors presented in U.S. Weather Bureau TP-40 (two- and 10-year recurrence intervals only).*

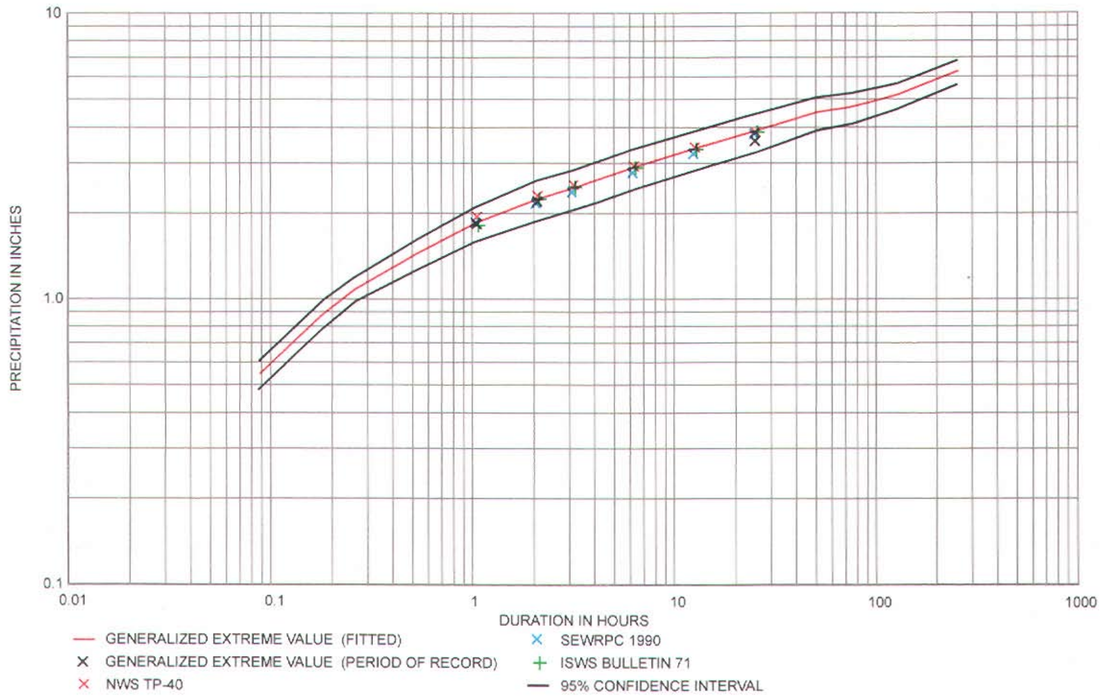
Source: Rodgers and Potter.

Appendix B. The seven sources of estimates are quite consistent in many cases. For example, the 10-year, one-hour rainfall estimate ranges between 1.81 inches (Bulletin 71) and 1.93 inches (TP-40) with all the GEV estimates from the current study nested within this range. None of the quantile sources consistently provide the highest or lowest value. Bulletin 71 yields the largest 100-year, 1-hour rainfall, but the lowest 10-year value.

Table 17 summarizes estimated quantiles for Milwaukee at durations from five minutes to 240 hours estimated from at-site data, and corresponding 95 percent confidence intervals. These confidence bounds appear in Figures 28 to 31. It is seen that the 95 percent confidence bounds on Milwaukee at-site estimates easily bracket all other estimates of Milwaukee precipitation quantiles.

Figure 28

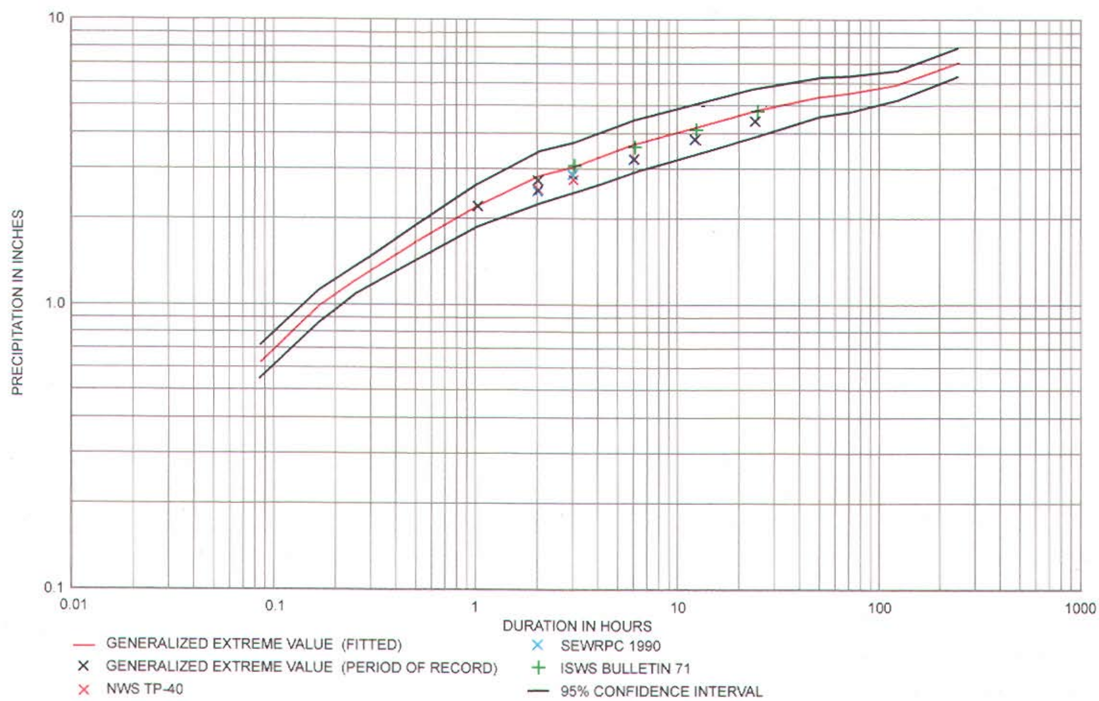
RAINFALL FREQUENCY CURVES AND 95 PERCENT CONFIDENCE INTERVAL, 10-YEAR



Source: Rodgers and Potter.

Figure 29

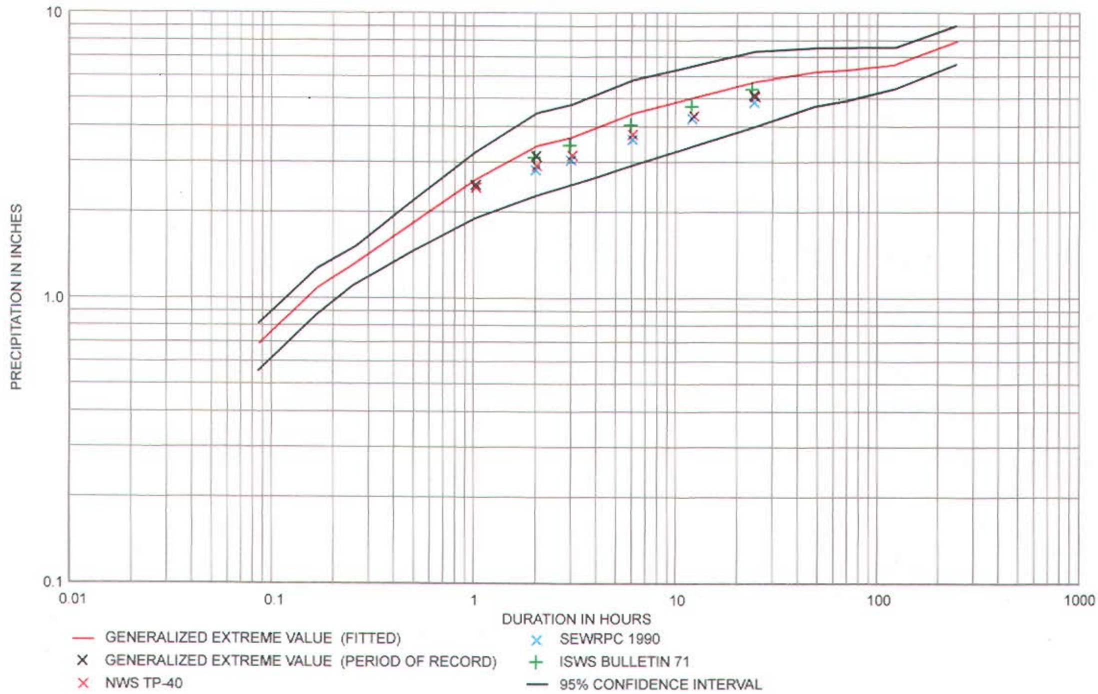
RAINFALL FREQUENCY CURVES AND 95 PERCENT CONFIDENCE INTERVAL, 25-YEAR



Source: Rodgers and Potter.

Figure 30

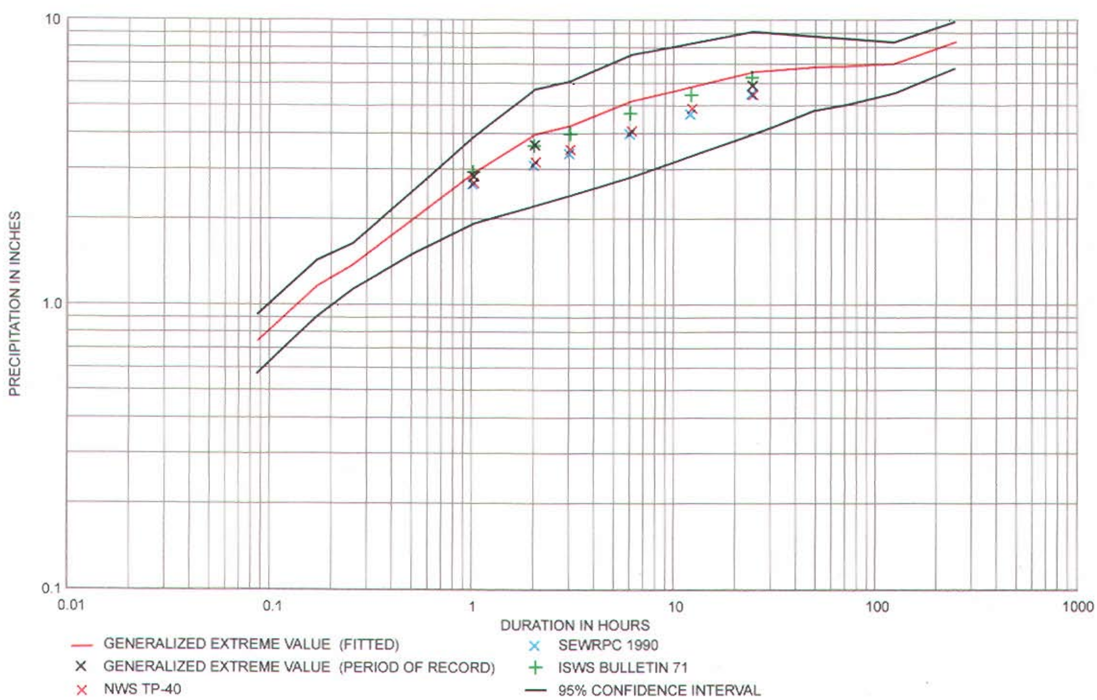
RAINFALL FREQUENCY CURVES AND 95 PERCENT CONFIDENCE INTERVAL, 50-YEAR



Source: Rodgers and Potter.

Figure 31

RAINFALL FREQUENCY CURVES AND 95 PERCENT CONFIDENCE INTERVAL, 100-YEAR



Source: Rodgers and Potter.

Table 17

LOCAL GEV QUANTILE ESTIMATES AND 95 PERCENT CONFIDENCE INTERVALS

Duration	10-Year Rainfall (inches)			25-Year Rainfall (inches)			50-Year Rainfall (inches)			100-Year Rainfall (inches)		
	Predicted	Lower Bound	Upper Bound	Predicted	Lower Bound	Upper Bound	Predicted	Lower Bound	Upper Bound	Predicted	Lower Bound	Upper Bound
Period 1940-1998												
5-Minute..........	0.54	0.48	0.60	0.63	0.54	0.71	0.69	0.56	0.82	0.74	0.57	0.92
10-Minute	0.86	0.77	0.96	0.99	0.86	1.12	1.09	0.89	1.28	1.18	0.91	1.44
15-Minute	1.08	0.97	1.19	1.22	1.08	1.35	1.31	1.11	1.50	1.39	1.13	1.64
30-Minute	1.43	1.26	1.60	1.67	1.43	1.91	1.85	1.47	2.22	2.02	1.51	2.52
1-Hour	1.85	1.59	2.10	2.25	1.86	2.63	2.57	1.91	3.24	2.92	1.94	3.90
2-Hour	2.24	1.88	2.60	2.84	2.26	3.43	3.37	2.28	4.45	3.97	2.23	5.71
3-Hour	2.44	2.05	2.82	3.07	2.45	3.69	3.63	2.49	4.77	4.26	2.44	6.09
4-Hour	2.61	2.19	3.03	3.30	2.63	3.98	3.92	2.65	5.18	4.62	2.57	6.67
6-Hour	2.89	2.42	3.36	3.67	2.91	4.44	4.37	2.93	5.82	5.18	2.82	7.55
12-Hour	3.34	2.82	3.87	4.21	3.37	5.05	4.96	3.41	6.51	5.82	3.35	8.28
24-Hour	3.86	3.27	4.46	4.82	3.89	5.75	5.63	3.97	7.30	6.54	3.96	9.11
48-Hour	4.49	3.89	5.08	5.40	4.53	6.26	6.09	4.68	7.50	6.81	4.82	8.80
72-Hour	4.70	4.13	5.28	5.56	4.75	6.38	6.21	4.91	7.51	6.85	5.05	8.66
120-Hour	5.17	4.63	5.70	5.93	5.22	6.65	6.46	5.39	7.53	6.96	5.54	8.37
240-Hour	6.29	5.68	6.90	7.16	6.35	7.96	7.74	6.55	8.94	8.29	6.71	9.87
All Available Observations												
5-Minute..........	0.53	0.48	0.58	0.62	0.55	0.68	0.68	0.58	0.78	0.74	0.60	0.88
10-Minute	0.84	0.76	0.91	0.98	0.87	1.08	1.08	0.92	1.25	1.19	0.96	1.41
15-Minute	1.06	0.98	1.15	1.21	1.10	1.32	1.31	1.15	1.48	1.41	1.19	1.62
30-Minute	1.44	1.31	1.57	1.68	1.50	1.86	1.85	1.57	2.13	2.02	1.64	2.40
60-Minute	1.82	1.63	2.01	2.20	1.92	2.48	2.50	2.04	2.97	2.82	2.14	3.49
120-Minute	2.21	1.96	2.47	2.73	2.34	3.12	3.16	2.47	3.85	3.64	2.59	4.68
24-Hour	3.58	3.20	3.96	4.41	3.82	5.00	5.11	4.05	6.17	5.88	4.26	7.51

NOTE: Predicted—estimated quantile
Lower Bound—95 percent confidence lower limit
Upper Bound—95 percent confidence upper limit

Source: Rodgers and Potter.

Even among the three GEV estimates prepared for the current study, there is no universal pattern. For the most part, the period of record estimate is smallest and the 1940 to 1998 estimate is largest with the regional estimate in between, but there are several exceptions. The quantiles based on the 1940 to 1998 record tend to be larger because the influence of the August 1986 event is stronger in the 59-year record than it is in the much longer full period of record.

The recommended rainfall quantiles for the Southeastern Wisconsin Region are the full period of record GEV estimates. These estimates are the best available quantiles because they are derived from the longest available gauge records and there is no compelling reason not to use them. No statistically significant evidence of nonstationarity in the full record has been found in the context of this study and the regional analysis indicates a tendency toward rainfall depths lower than the recent record at General Mitchell Field.

Implementation of this recommendation requires the development of quantile estimates for durations of three, six, 12, 48, 72, and 120 hours as described below.

Tables 16 and 17 summarize the estimated GEV quantile values for recurrence intervals of two, 10, 25, 50 and 100 years. Quantiles have been estimated using data from the period 1940-1998 for durations of five, 10, 15, 30, 60, and 120 minutes; and three, four, six, 12, 24, 48, 72, 120, and 240 hours. No corresponding estimates have been made using the long (period-of-record) data set for three to 12 hours and 48 to 240 hours, however, since annual maximum observations for these durations are not available prior to 1940. The following section contains a description of techniques used to estimate quantiles for these missing durations on the basis of the 1940-1998 quantile estimates.

When viewed in intensity-duration space, the GEV quantiles estimated from 1940-1998 data reveal a regularity in the shape and location of these curves. This regularity provides a basis for estimating missing quantile values for period-of-record data (three-12 hours; 48-240 hours). If it is assumed that the relative magnitude of quantiles across durations is consistent between the two data sets, then the missing quantile values can be interpolated using the following procedure.

Let d index event duration (d = three hours, six hours, 12 hours, etc.), and P_{RI} indicate precipitation intensity (inches/hour) for a given recurrence interval or exceedance probability, estimated on the basis of the 1940-1998 data. To estimate period-of-record quantiles for durations between two hours (120 minutes) and 24 hours, for which period-of-record quantiles are available, a parameter k, indexed to duration and recurrence interval, is calculated from the appropriate 1940-1998 quantiles as:

$$k_{d,RI} = \frac{\left(P_{d,RI} - P_{2,RI}\right)}{\left(P_{24,RI} - P_{2,RI}\right)}$$

The period-of-record quantile is obtained from k and the two-hour (120 minute) and 24-hour quantiles as:

$$P'_{d,RI} = P'_{2,RI} + k_{d,RI}\left(P'_{24,RI} - P'_{2,RI}\right)$$

where P' signifies the quantile value appropriate to the period-of-record data. Quantile values for durations exceeding 24 hours are obtained in an analogous fashion by assuming that the ratio P_d/P_{24} is independent of record length:

$$P'_{d,RI} = \left(\frac{P_{d,RI}}{P_{24,RI}}\right) \cdot P'_{24,RI}$$

The recommended design rainfall depths are set forth in Table 18. A set of point rainfall intensity-duration-frequency curves consistent with the recommended design rainfall depths are shown in Figure 32. These curves can be used to estimate quantile values over a continuous range of durations between five minutes and 24 hours. Comparisons of the TP-40, recommended SEWRPC 2000, and Bulletin 71 rainfall depths are provided in Tables 19 and 20.

RECOMMENDED RAINFALL REDUCTION FACTORS

Huff and Angel (1992) recommend rainfall reduction factors that are to be applied to estimate areal mean rainfall using point rainfall depths. They state that those factors were determined using data "from dense raingage networks in Illinois to provide...relationships ...applicable to the Midwest." It is recommended that those factors, as set forth in Table 21, be applied to the SEWRPC 2000 rainfall depths, as appropriate, to determine areal mean depths for areas greater than 10 square miles.

RECENT EXTREME STORMS IN THE CONTEXT OF THE FREQUENCY ANALYSIS

June 1997 and August 1998 Storms

The extreme storms of June 20-21, 1997 and August 6, 1998, described in Chapter II, resulted in heavy precipitation at locations throughout the Milwaukee area, although the greatest accumulations occurred at locations other than General Mitchell Field. Statistics summarizing these events, abstracted from the local network of 19 gauges maintained by the City of Milwaukee and the Milwaukee Metropolitan Sewerage District (MMSD), appear in Table 22. For each event and for durations of one hour through 24 hours, the network maximum precipitation are presented along with the gauge at which the maximum was recorded and the implied recurrence interval relative to the GEV frequency distributions fitted to the Milwaukee systematic data beginning in the 1890s and extending through 1998 (see Chapter III). At the location of maximum accumulation, the implied recurrence interval for the 1997 event exceeded 300 years for a 24-hour duration and the 1998 event exceeded 500 years for a 24-hour duration. To provide perspective, the 1986 General Mitchell Field two-hour event has an estimated recurrence interval of over 700 years on the basis of all available data, and the 1998 maximum two-hour event (recorded in the City of Milwaukee at 8414 W. Florist Avenue) has an estimated recurrence interval of over 300 years on the basis of all available data. For all durations three hours and above, the accumulated precipitation at MMSD gauge 1219 (Village of Elm Grove) exceeds the all time record 1986 accumulations at General Mitchell Field at corresponding durations. Table 23 presents a comparison of the peak seven-, 10-, 24-, and 26-hour rainfall totals that fell at the 19 City of

Table 18

RECOMMENDED DESIGN RAINFALL DEPTHS FOR THE SOUTHEASTERN WISCONSIN REGION

	Recurrence Interval and Depths (inches)					
Storm Duration	2 Years[a]	5 Years[a]	10 Years[a]	25 Years	50 Years	100 Years
5 Minutes	0.40	0.48	0.54	0.62	0.68	0.74
10 Minutes	0.64	0.76	0.85	0.98	1.08	1.19
15 Minutes	0.83	0.98	1.07	1.21	1.31	1.41
30 Minutes	1.07	1.29	1.45	1.68	1.85	2.02
60 Minutes	1.31	1.60	1.84	2.20	2.50	2.82
2 Hours	1.54	1.93	2.23	2.73	3.16	3.64
3 Hours	1.68	2.07	2.40	2.93	3.39	3.89
6 Hours	1.95	2.40	2.79	3.44	4.03	4.70
12 Hours	2.24	2.74	3.17	3.89	4.53	5.25
24 Hours	2.57	3.14	3.62	4.41	5.11	5.88
48 Hours	3.04	3.71	4.20	4.94	5.53	6.13
72 Hours	3.29	3.94	4.40	5.09	5.63	6.17
5 Days	3.77	4.42	4.84	5.43	5.86	6.26
10 Days	4.68	5.42	5.89	6.55	7.03	7.46

[a]Factors presented in U.S. Weather Bureau TP-40 were applied to the SEWRPC 2000 annual series depths with recurrence intervals of two, five, and 10 years, converting those depths to the partial duration series amounts set forth in this table. The annual series depths were adjusted as follows:

Two-year: multiplied by 1.136; five-year: multiplied by 1.042; and 10-year multiplied by 1.010.

Source: Rodgers and Potter and SEWRPC.

Milwaukee and MMSD gauges and at General Mitchell Field on June 20 and 21, 1997 and on August 6, 1998. The seven-hour and ten-hour durations were chosen because those time periods correspond to the periods of most intense rain on August 6, 1998 and June 20 and 21, 1997, respectively. The 26-hour duration was chosen because it includes the total period of heavy rain measured on June 20 and 21, 1997. The 24-hour duration is provided for comparison to the derived quantiles. The data in the table indicate that for nearly all of the 20 rain gauges, the June 1997 and August 1998 rainfalls were significantly different in magnitude. That observation illustrates that, counter to popular perceptions, extreme rainfalls did not occur in both years at many individual locations. Exceptions are at gauges 1205, 1207, 1210, and 1219, where extraordinary rainfall was recorded in both years.

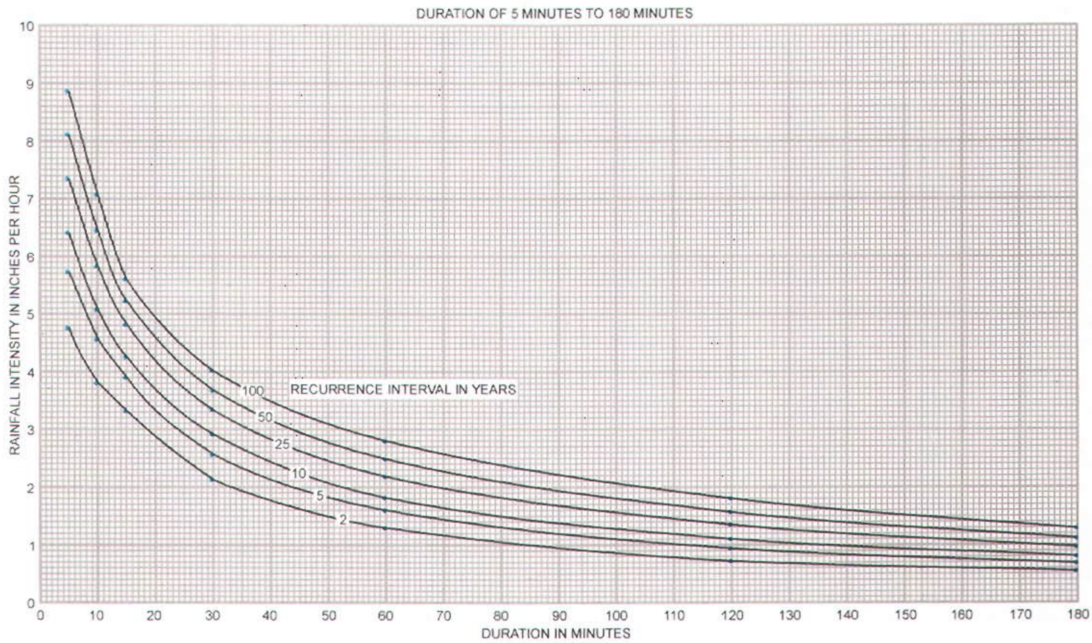
The chance of a certain magnitude storm occurring at a given location in any one year is most clearly expressed as a probability, rather than a recurrence interval. For example, a 100-year recurrence interval storm has a 1 percent chance of occurring in any year and a 500-year recurrence interval storm has a 0.2 percent chance of occurring in any year. It is entirely possible, although unlikely, that storms with small probabilities (corresponding to long recurrence intervals) can occur at the same location in consecutive years. Such occurrences do not necessarily provide an indication that extreme events are becoming more common at that location.

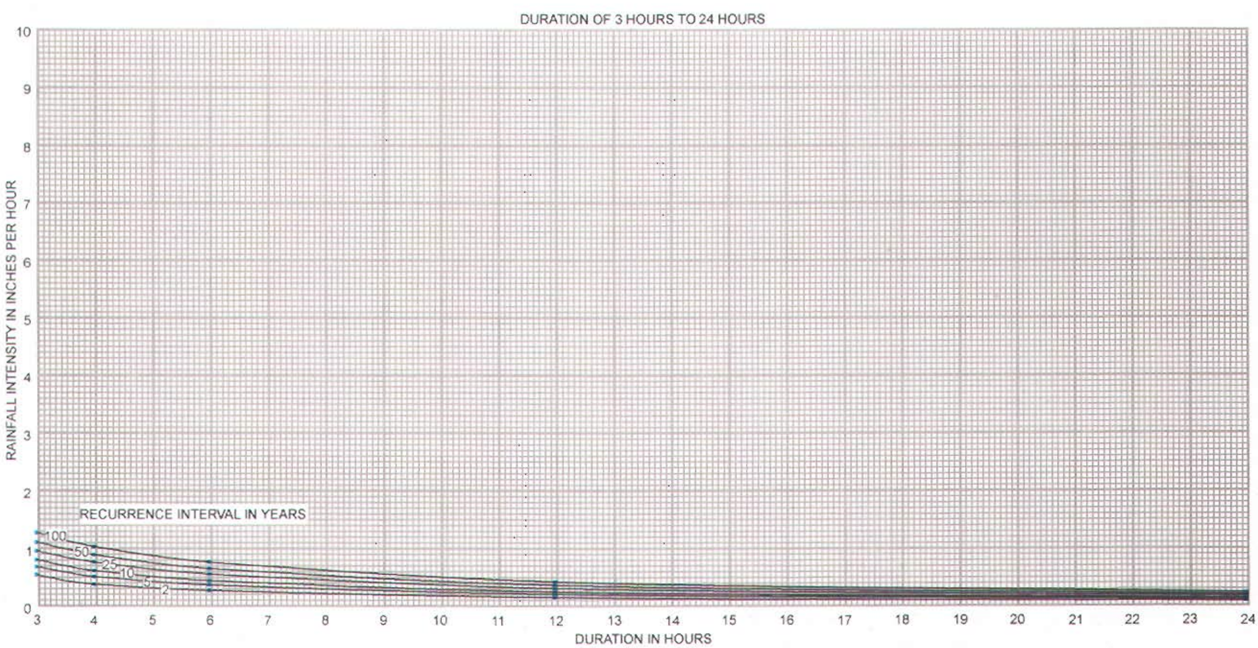
August 6, 1986 Storm

The August 6, 1986, event can be assigned a recurrence interval on the basis of each respective at-site GEV model. The model based on period-of-record data implies a rather long recurrence interval for the 1986 event at 120-minute duration—over 700 years. Results are summarized in Table 24. It is interesting in this context that the 1986 Milwaukee event is not the largest one-hour event in the region—Belvidere recorded 3.20 inches in 1977 versus 3.06 inches at Milwaukee in 1986 (Milwaukee is largest at two hours, 5.24 inches versus 4.9 inches at Belvidere, and Belvidere is larger at three hours, 6.10 inches versus 5.73 inches. Thus, we have evidence that events of this magnitude have happened elsewhere in an approximately homogenous region consisting of roughly 600 gauge-years.

Figure 32

POINT RAINFALL INTENSITY-DURATION-FREQUENCY CURVES FOR MILWAUKEE, WISCONSIN





[a]*The curves are based on Milwaukee rainfall data for the 108-year period of 1891 to 1998.*

Source: Rodgers and Potter and SEWRPC.

Table 19

TP-40, SEWRPC 2000, AND BULLETIN 71 DESIGN STORM DEPTHS
(Total Rainfall Depths in Inches)

TP-40 (Hershfield, 1961)						
Recurrence Interval	Storm Duration (hours)					
	1	2	3	6	12	24
2 Years	1.41	1.63	1.72	2.00	2.34	2.63
5 Years	1.71	2.02	2.15	2.50	2.94	3.36
10 Years	1.93	2.29	2.50	2.90	3.38	3.83
25 Years	2.23	2.58	2.80	3.34	3.88	4.42
50 Years	2.41	2.88	3.12	3.69	4.27	5.00
100 Years	2.69	3.18	3.51	4.06	4.86	5.44

SEWRPC (2000)						
Recurrence Interval	Storm Duration (hours)					
	1	2	3	6	12	24
2 Years	1.31	1.54	1.68	1.95	2.24	2.57
5 Years	1.60	1.93	2.07	2.40	2.74	3.14
10 Years	1.84	2.23	2.40	2.79	3.17	3.62
25 Years	2.20	2.73	2.93	3.44	3.89	4.41
50 Years	2.50	3.16	3.39	4.03	4.53	5.11
100 Years	2.82	3.64	3.89	4.70	5.25	5.88

Bulletin 71 (Huff, 1992)						
Recurrence Interval	Storm Duration (hours)					
	1	2	3	6	12	24
2 Years	1.27	1.57	1.73	2.03	2.35	2.70
5 Years	1.57	1.93	2.13	2.50	2.90	3.33
10 Years	1.81	2.24	2.47	2.89	3.36	3.86
25 Years	2.19	2.70	2.98	3.49	4.05	4.66
50 Years	2.53	3.12	3.44	4.03	4.68	5.38
100 Years	2.93	3.62	3.99	4.68	5.43	6.24

Source: U.S. Department of Commerce, Weather Bureau; Illinois State Water Survey; and SEWRPC.

ADDITIONAL COMMENTS ON STATIONARITY IN LIGHT OF RECENT EXTREME STORMS

The occurrence of heavy precipitation events in successive years (June 1997 and August 1998) at certain locations, primarily in Milwaukee and Waukesha Counties, must be evaluated within the context of the rainfall frequency estimates presented in this study, and those events need to be evaluated regarding their relationship to climatic stationarity. In placing these events in context, it is useful to consider the following:

1) Recent studies examining U.S. historical climatic data have identified long-term changes in both annual temperature and precipitation, and in the share of precipitation experienced as extreme rainfall at continental scales, consistent with results of general circulation model (GCM) simulations of the climatic impact of increasing atmospheric carbon dioxide and other "greenhouse" gases. Karl, et al. (1996, 1998) observed statistically significant increases in both the number of wet days and the proportion of precipitation from extreme events, defined as daily

Table 20

COMPARISON OF SEWRPC 2000, TP-40, AND BULLETIN 71 DESIGN STORM DEPTHS

Recurrence Interval	Difference in SEWRPC 2000 Depths Relative to TP-40 Depths (percent)					
	Storm Duration (hours)					
	1	2	3	6	12	24
2 Years	-7	-5	-2	-2	-4	-2
5 Years	-6	-5	-4	-4	-7	-7
10 Years	-5	-3	-4	-4	-6	-6
25 Years	-1	6	5	3	0	0
50 Years	4	10	9	9	6	2
100 Years	5	14	11	16	8	8

Recurrence Interval	Difference in SEWRPC 2000 Relative to Bulletin 71 Depths (percent)					
	Storm Duration (hours)					
	1	2	3	6	12	24
2 Years	3	-2	-3	-4	-5	-5
5 Years	2	0	-3	-4	-6	-6
10 Years	2	0	-3	-4	-6	-6
25 Years	0	1	-2	-1	-4	-5
50 Years	-1	1	-1	0	-3	-5
100 Years	-4	1	-3	0	-3	-6

Source: SEWRPC.

Table 21

RELATION BETWEEN AREAL MEAN AND POINT RAINFALL DEPTHS

Storm Period (hours)	Area (square miles)					
	10	25	50	100	200	400
	Ratio of Areal to Point Rainfall for Given Area					
0.5	0.88	0.80	0.74	0.68	0.62	0.56
1.0	0.92	0.87	0.83	0.78	0.74	0.70
2.0	0.95	0.91	0.88	0.84	0.81	0.78
3.0	0.96	0.93	0.90	0.87	0.84	0.81
6.0	0.97	0.94	0.92	0.89	0.87	0.84
12.0	0.98	0.96	0.94	0.92	0.90	0.88
24.0	0.99	0.97	0.95	0.94	0.93	0.91
48.0	0.99	0.98	0.97	0.96	0.95	0.94

Source: Huff and Angel (1992).

precipitation in excess of two inches, during the period 1910-1994. The 1996 study also estimated that annual mean temperatures had increased by around 2°C, and annual precipitation had increased by 5 to 10 percent in Southeastern Wisconsin during the Twentieth Century. The possibility that climatic nonstationarity is responsible for larger and more frequent precipitation events must therefore be considered.

2) However, the observed occurrence within the MMSD gauging network of two apparently low probability events within two years is not, in the absence of supporting evidence, an unambiguous

Table 22

MAXIMUM RECURRENCE INTERVALS
AUGUST 1986, JUNE 1997, AND AUGUST 1998

Storm Duration (hours)	August 6, 1986 Storm[a] Maximum Rainfall Amount (inches)	August 6, 1986 Storm[a] Approximate Recurrence Interval[c] (years)	June 20-21, 1997 Storm Maximum (inches)	June 20-21, 1997 Storm Gauge of Maximum[b]	June 20-21, 1997 Storm Approximate Recurrence Interval of Maximum Amount[c] (years)	August 6, 1998 Storm Maximum (inches)	August 6, 1998 Storm Gauge of Maximum[b]	August 6, 1998 Storm Approximate Recurrence Interval of Maximum Amount[c] (years)
1	3.06	165[c]	1.58	1210	6[c]	2.64	1210	68[c]
2	5.24	711[c]	2.74	1209	25[c]	4.64	1207	363[c]
3	5.73	--[d]	3.93	1218	--[d]	5.80	1219	--[d]
4	5.93	--[d]	4.68	1209	--[d]	6.32	1219	--[d]
6	6.24	--[d]	5.35	1209	--[d]	7.84	1219	--[d]
12	6.60	--[d]	6.53	1212	--[d]	8.27	1219	--[d]
24	6.84	216[c]	7.44	1212	335[c]	8.30	1219	599[c]

[a]Data for General Mitchell Field only.

[b]1207: 8414 W. Florist Avenue, City of Milwaukee
1209: 8463 N. Granville Road, City of Milwaukee
1210: 8800 W. Lisbon Avenue, City of Milwaukee
1212: 2647 N. Bartlett Avenue, City of Milwaukee
1218: W152 N8634 Margaret Road, Village of Menomonee Falls
1219: 13600 W. Juneau Boulevard, Elm Grove Village Hall

[c]Based on Milwaukee rainfall frequency relationship developed for the full period of record (1890s-1998).

[d]Cannot be directly estimated for the full period of record because data were not available at these durations for full period.

Source: Rodgers and Potter, Camp Dresser & McKee, and SEWRPC.

demonstration of changing climate, nor does it indicate that the precipitation quantile estimates derived for General Mitchell Field are unrepresentative of regional climate. The primary reason is that these three recent events were not measured at a common location, but at different locations throughout a 200-square-mile area. The probability of three events exceeding a given magnitude (e.g., the estimated 100-year, x-hour rainfall) at at least one gauge within a 200-square-mile network area is much greater than that of observing three events of such magnitude at a single location such as General Mitchell Field. In deriving point precipitation intensity-duration-frequency relationships, it is not assumed that the gauging location is measuring the maximum accumulation for each regional storm event. This is particularly true in regions such as Southeastern Wisconsin where the highest-intensity precipitation is produced by summer convective thunderstorms, which are organized over relatively small areas.

Karl defines extreme rainfall more broadly than does this study. His definition includes events of more than two inches in 24 hours. Thus, his lower threshold is a relatively frequent event with an estimated recurrence interval of less than two years. The study presented herein is concerned with assigning frequencies to much larger "extreme" events. Therefore, Karl's results do not necessarily indicate an increase in extreme storm depths of the magnitude addressed herein.

Any study examining the time series stationarity of precipitation in a region should include an analysis of the time series behavior of regional stream discharges because streams are spatial integrators of precipitation. Caution must be exercised in the selection of stream gauging records for such an analysis, however, because stream discharge records are subject to several potential sources of time-series nonstationarity which do not affect precipitation records. These include the effects of changes in storage, detention, abstraction, and discharges (e.g., cooling water and sewer outfall) within the watershed and, most applicable to Milwaukee

Table 23

MAJOR STORM RAINFALL

	Peak 7-Hour Period			Peak 10-Hour Period			Peak 24-Hour Period			Peak 26-Hour Period		
Station	6/20-21/97	8/6/98	Difference	6/20-21/97	8/6/98	Difference	6/20-21/97	8/6/98	Difference	6/20-21/97	8/6/98	Difference
1201	2.85	0.45	-84%	3.46	0.45	-87%	3.93	0.54	-86%	4.01	0.54	-87%
1202	4.54	2.01	-56	4.78	2.71	-43	5.38	2.89	-46	5.89	3.08	-48
1203	4.72	0.86	-82	4.79	0.87	-82	5.61	1.07	-81	5.77	1.13	-80
1204	4.69	2.06	-56	4.78	2.09	-56	5.71	2.67	-53	6.16	2.70	-56
1205	5.62	5.20	-7	5.85	6.83	17	6.82	7.17	5	7.55	7.47	-1
1206	5.26	1.51	-71	5.33	1.60	-70	5.97	1.79	-70	6.58	1.96	-70
1207	4.79	5.95	24	5.12	6.15	20	5.63	6.47	15	6.16	6.50	6
1208	3.78	1.12	-70	3.85	1.57	-59	4.45	1.66	-63	4.66	1.67	-64
1209	5.60	2.92	-48	5.82	3.38	-42	6.74	3.64	-46	7.41	3.68	-50
1210	5.40	5.75	6	5.47	5.99	10	6.00	6.47	8	6.66	6.51	-2
1212	6.29	1.44	-77	6.45	1.56	-76	7.44	2.12	-72	8.11	2.49	-69
1213	3.87	0.06	-98	3.95	0.08	-98	4.36	0.14	-97	4.41	0.14	-97
1216	3.32	0.00	-100	3.43	0.00	-100	3.98	0.00	-100	4.06	0.00	-100
1217	4.52	1.18	-74	4.65	1.22	-74	6.00	1.53	-75	6.06	1.66	-73
1218	5.52	2.93	-47	5.56	2.95	-47	6.32	3.10	-51	7.05	3.18	-55
1219	4.95	8.27	67	5.01	8.27	65	5.49	8.28	51	5.97	8.29	39
1220	3.09	0.58	-81	3.56	0.61	-83	3.96	0.91	-77	4.00	0.92	-77
1221	4.45	1.76	-60	4.46	2.34	-48	5.66	2.53	-55	6.04	2.57	-57
1222	4.24	0.05	-99	4.32	0.07	-98	4.81	0.10	-98	4.86	0.10	-98
Gen. Mitchell	3.74	0.32	-91	3.86	0.33	-91	4.24	0.40	-91	4.24	0.41	-90

NOTE: City of Milwaukee Gauge Locations:

1202 5335 N. Teutonia Ave
1203 245 W. Lincoln Ave.
1204 300 S. 84th St,
1205 6945 N. 41st St
1206 3626 W. Fond du Lac Ave.
1207 8414 W. Florist Ave.
1208 3715 W. Lincoln Ave.
1209 8463 N. Granville Rd.
1210 8800 W. Lisbon Ave.
1212 2647 N. Bartlett Ave.
1213 6074 S. 13th St.
1216 3563 s. 97th St.

MMSD Gauge Locations:

1201 South Shore Plant, 8500 S. 5th Ave., City of Milwaukee
1217 502 N. Harbor Dr., City of Milwaukee
1218 W152 N8634 Margaret Rd., Village of Menomonee Falls
1219 13600 W. Juneau Blvd., Village of Elm Grove
1220 5635 S. New Berlin Rd., Village of Hales Corners
1221 1223 N. 25th St., City of Milwaukee
1222 6060 S. 13th St., City of Milwaukee

Source: National Weather Service, City of Milwaukee, Milwaukee Metropolitan Sewerage District, and SEWRPC.

County, changes in the watershed condition: increasing urbanization, with accompanying increases in impervious surfaces. For this reason, the USGS has identified and designated a subset of the national stream gauging network as the Hydroclimatic Data Network, suitable for the study of climatic variation (Slack and Landwehr, 1992) HCDN gauges are selected on the basis of length, completeness and accuracy of records, and unimpaired basin conditions. The Milwaukee River, gauged at Milwaukee (04087000), is included in the HCDN.

The Milwaukee River drains 696 square miles at the Milwaukee gauge site, and although significant development has occurred in the lower portions of its catchment over the last several decades, it remains a predominantly agricultural watershed. The basin location is sufficiently close to the Milwaukee precipitation gauging location(s), and the period of record (1915-1998) is of sufficient duration to provide a supplementary analysis of the behavior of regional climate. The annual peak discharge series, depicted in Figure 33, can be viewed as a proxy measure for extreme precipitation events in the watershed, although the size of the catchment limits the analysis to precipitation events with durations of 24 hours or longer. Although the peak of record occurred on June 21, 1997 (coin-

Table 24

IMPLIED RECURRENCE INTERVALS FOR AUGUST 1986 MILWAUKEE EVENT

Duration	Number of Observations	August 1986 Precipitation (inches)	Probability Distribution Function Ordinate	Recurrence Interval (years)
Period of Record				
5 Minutes	96	0.83	0.996	266
10 Minutes	96	1.12	0.984	64
15 Minutes	92	1.29	0.976	42
30 Minutes	92	1.60	0.946	19
60 Minutes	102	3.06	0.994	165
120 Minutes	96	5.24	0.999	711
1440 Minutes	108	6.84	0.995	216
1940-1998				
5 Minutes	53	0.83	0.997	287
10 Minutes	53	1.12	0.985	65
15 Minutes	53	1.29	0.977	43
30 Minutes	53	1.60	0.947	19
1 Hour..................	59	3.06	0.992	129
2 Hours................	59	5.24	0.997	336
3 Hours................	59	5.73	0.997	376
4 Hours................	59	5.93	0.997	292
6 Hours................	59	6.24	0.995	217
12 Hours..............	59	6.60	0.994	176
24 Hours..............	59	6.84	0.992	124
48 Hours..............	59	6.84	0.990	103
72 Hours..............	59	6.84	0.990	98
120 Hours............	59	7.06	0.991	117
240 Hours............	59	7.50	0.973	37

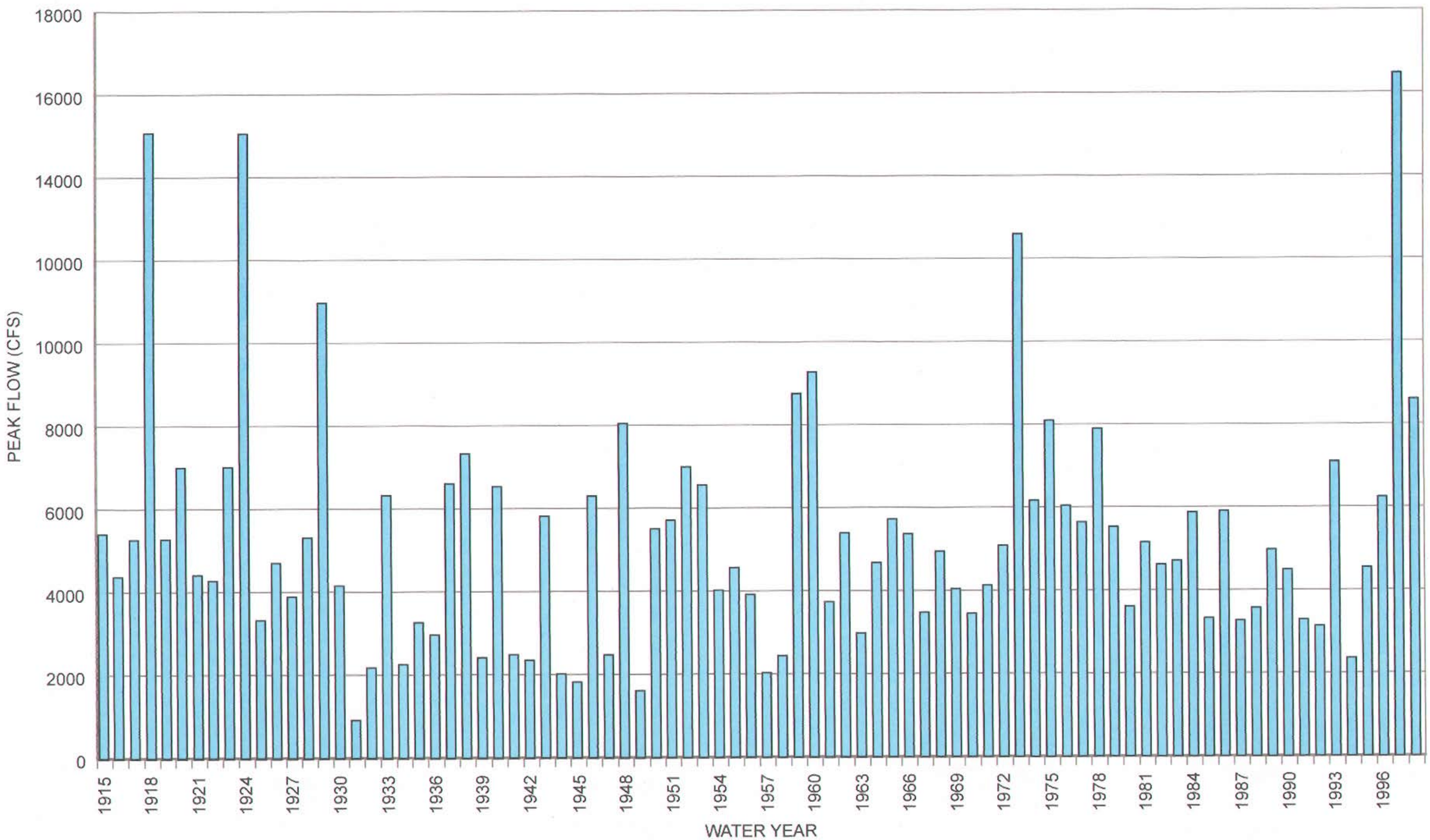
Source: Rodgers and Potter.

cident with the large Milwaukee precipitation event), no trend is observed in the data, and formal tests find no evidence of trend.

In summarizing the evidence revealed by the analysis of data assembled for this study, no statistically significant trend in either precipitation or streamflow data is noted which provides a sufficient basis to reject the hypothesis of a stationary climate within the study area. Care must be exercised, however, not to construe these results as proof of a stationary climate. It is in general not possible to prove stationarity, only to reject challenges to this hypothesis at a chosen level of statistical significance. In addition, even a climate that is known or assumed to be stationary over centuries or even millennia can exhibit episodic behavior. An apparent clustering of large events during a particular period, such as may have occurred recently in Southeastern Wisconsin, can thus be a genuine and observable phenomenon while not fundamentally at odds with the concept of a stationary climate.

Figure 33

ANNUAL SERIES PEAK FLOWS
MILWAUKEE RIVER AT RICHARDS STREET



Source: U.S. Geological Survey and Rodgers and Potter.

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Chapter V

TEMPORAL DISTRIBUTION OF RAINFALL

MOTIVATION AND PURPOSE

Some applications of design rainfall depths require definition of a time distribution for the rainfall pattern. The frequency analysis presented in Chapter IV provides no information regarding the appropriate time distribution of the rain. Also, it is not obvious what type of rainfall distribution provides the best hydrologic design standard. This section presents the results of investigations concerning the appropriate time distributions for extreme rainfalls. These investigations include:

- Review of rainfall distributions in current use.
- Assessment of actual, recorded rainfall distributions from extreme storms.
- Evaluation of the median distribution of real storms and typical deviations from the median.
- Comparison of hydrologic simulation results using several design storm methods (Appendix E).

The selection of a storm distribution depends on the objective of the particular engineering application. The intended purpose here is for development of design storm data to be used in hydrologic models that will provide flows and volumes for sizing stormwater and floodland management facilities and/or for determining flood hazard areas.

A simple case is a small watershed that is one hundred percent impervious. In such a watershed, the rainfall frequency and flow frequency are exactly equal when the storm duration and time of concentration are also equal. In this case, a uniform rainfall distribution would produce a peak flow with the same frequency as the rainfall that is applied. In larger, more complex watersheds with pervious surfaces, there is no rigorous method to relate rainfall frequency to flow frequency. The presence of storage, interception, and infiltration will always cause the runoff rate to be less than the peak rainfall rate. It may be necessary to distribute the rainfall nonuniformly in order to compensate for the reductions in flow rate caused by natural storage in channels and ponding areas. Rainfall early in the event fulfills the initial abstraction and wets surfaces so that the pervious areas behave more like impervious surfaces during the latter part of the storm. Nonuniform distributions can overestimate flows when there is a lack of system storage because the peak intensity in the modeled storm is greater than the intensity suggested by the rainfall frequency distribution.

One type of nonuniform distribution is the "nested" distribution. This is a rainfall pattern that usually covers 24 hours and includes periods with intensities that are appropriate to shorter duration storms. The intent of a nested distribution is to incorporate a full range of storm durations with only one execution of the hydrologic model. The storm is constructed so that the most intense hour corresponds to the appropriate one-hour storm volume and the most intense two-hour period equals the two-hour storm volume and so forth. The widely used SCS Type II storm distribution (USDA, 1992) is based on this approach. Experience with this distribution has shown that, in some applications, flows based on SCS Type II are higher than flows developed by other methods and can be excessively conservative. This is because the distribution pushes the envelope of plausible coincident frequency. While no part of the event has a higher intensity than dictated by the frequency analysis, it represents the most nonuniform possible rainfall pattern that satisfies the frequency data.

DISTRIBUTIONS IN CURRENT USE IN SOUTHEASTERN WISCONSIN

SCS (NRCS) Distributions

In 1964, the United States Department of Agriculture - Soil Conservation Service (SCS, now the Natural Resources Conservation Service or NRCS) published several nested distributions for use in various parts of the United States. The Type II distribution was proposed for most of the United States, including all of Wisconsin. As discussed previously, the objective of this distribution was to incorporate a range of storm durations into a single 24-hour event. It is unlikely that there has been any effort to justify the distribution as either a recreation of natural rainfall or as an appropriate means to establish risk-based design. Instead, the SCS distributions were developed to permit obtaining a critical duration analysis in a single model run. This was certainly a consideration prior to the development of low cost, high speed desktop computers in the early 1990s. Over the years, the SCS distributions have become widely used standards for floodplain management and design throughout the United States. The usually conservative flows have provided a built-in factor of safety for projects designed using these distributions.

The SCS Type II rainfall distribution is shown in Figure 34. As shown, the pattern is nearly symmetrical with the highest intensity during the twelfth hour. The reason for centering the distribution is unclear. The distribution could be constructed with the high intensity hours at either the start or end of the storm and still preserve the nested property of the storm.

Huff Distributions

Floyd A. Huff, a hydrologist with the Illinois State Water Survey (ISWS), has conducted a series of in-depth rainfall studies. Key products include his publications *Time Distribution of Rainfall in Heavy Storms* (1967) and *Time Distribution of Heavy Rainfall in Illinois* (1990). In the latter document, Huff provides four distributions which are derived from recorded rainfall for hundreds of storms that occurred in Illinois. Each "Huff distribution" has the most intense part of the storm concentrated in a different quarter of the overall storm duration. These are termed the first, second, third, and fourth quartile storm distributions. The four Huff distributions for point rainfall are shown in Figure 35.

DISTRIBUTION OF REAL STORMS IN SOUTHEASTERN WISCONSIN

Huff claimed that extreme storms have a tendency toward a particular distribution and that this distribution changes with the duration of the storm. There is some meteorological support for this theory, but it applies mainly to convective thunderstorms which often have an intense squall line along the leading edge (Ludlum, 1990). Storms of more than about three hours in duration either consist of several thunderstorms or are of frontal construction. Intuitively, these longer storms will have completely random distributions (that is, each possible arrangement of rainfall within the time period is just as likely as any other). In this purely random event distribution, the median distribution would be a uniform distribution.

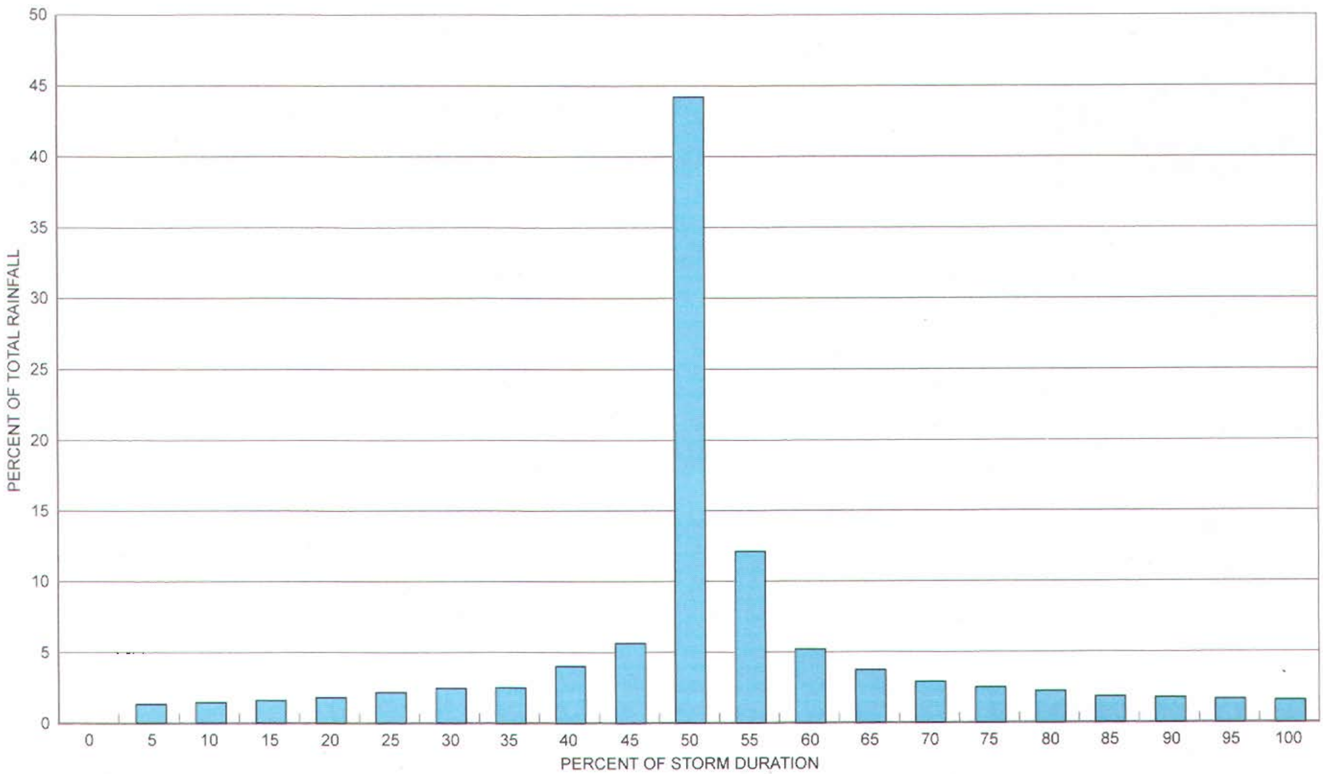
These points are illustrated in Figures 36 through 39. In Figure 36, distributions of 24-hour storms recorded at five sites in southeastern and south central Wisconsin are plotted. The plots in Figure 36 represent the cumulative rainfall distributions of 93 storms selected for this analysis. Each storm contained at least 0.8 inches of rain and has been normalized by dividing by the total rainfall. The dates, locations, and rainfall totals of the storms analyzed are set forth in Appendix C.[1]

The distributions shown in Figure 36 indicate a random variation of the cumulative distribution of real rainfall. The rainfall pattern varies across a wide range with a strong central tendency. A random process that is defined on the range of 0 to 1 is known as a beta distribution. All normalized rainfall distributions are realizations of a beta distribution. The uniform distribution is a special case where the probability density function is a horizontal line and the cumulative distribution function is a straight line with a slope of

[1]*Some small biases may have been introduced to this analysis because of the procedures used to screen and prepare the storms. First, storms were required to last at least 21 hours between the beginning and end of rainfall, although intervening hours of zero rainfall were allowed. Therefore some of the storms (31 of them) had hours of zero rainfall at the beginning or end of the storm. These storms were centered to maintain the proper midpoint in Figure 36. Storms of 21 and 23 hours duration can not be centered exactly and were shifted one half hour to the right when they were centered. This process creates a slight bias in the overall analysis.*

Figure 34

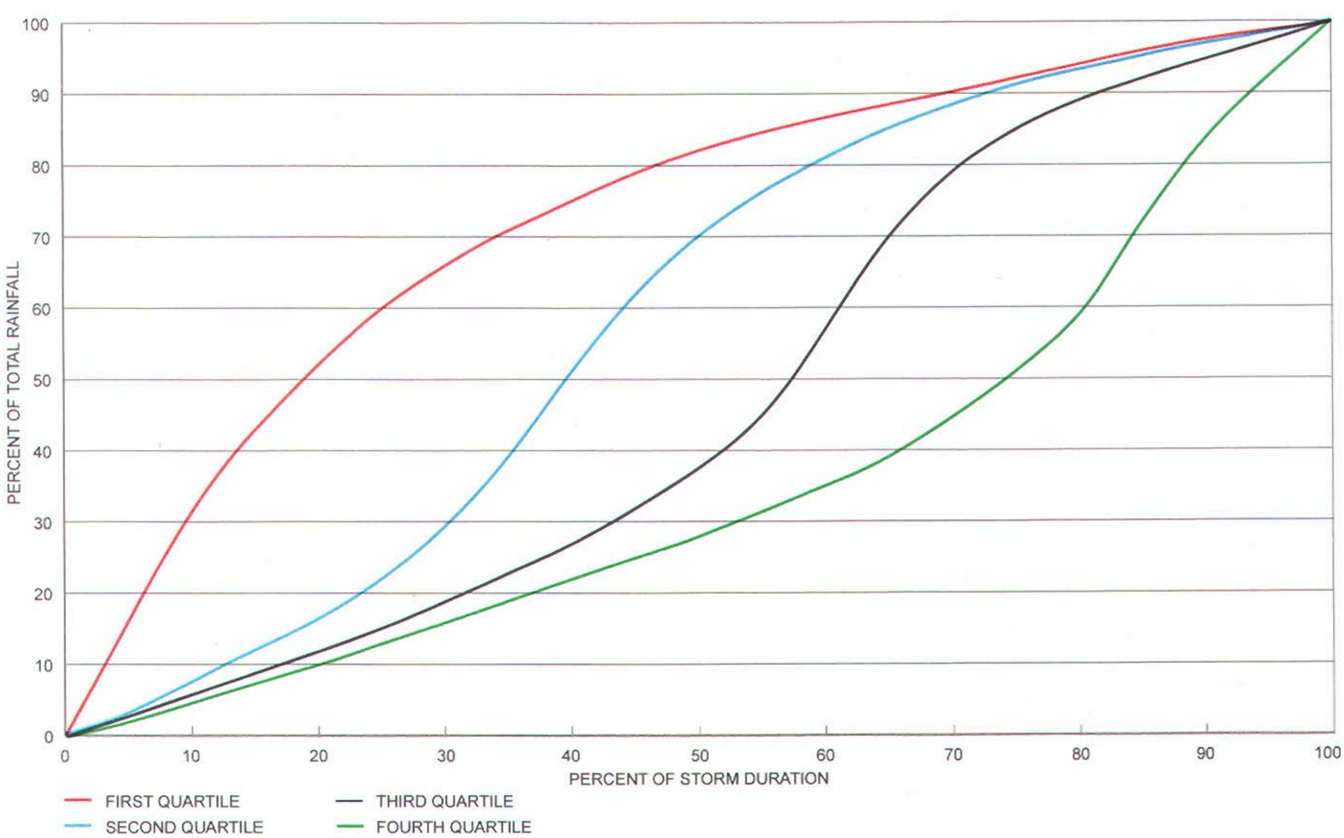
SCS TYPE II RAINFALL DISTRIBUTION



Source: U.S. Natural Resources Conservation Service and Camp, Dresser & McKee.

Figure 35

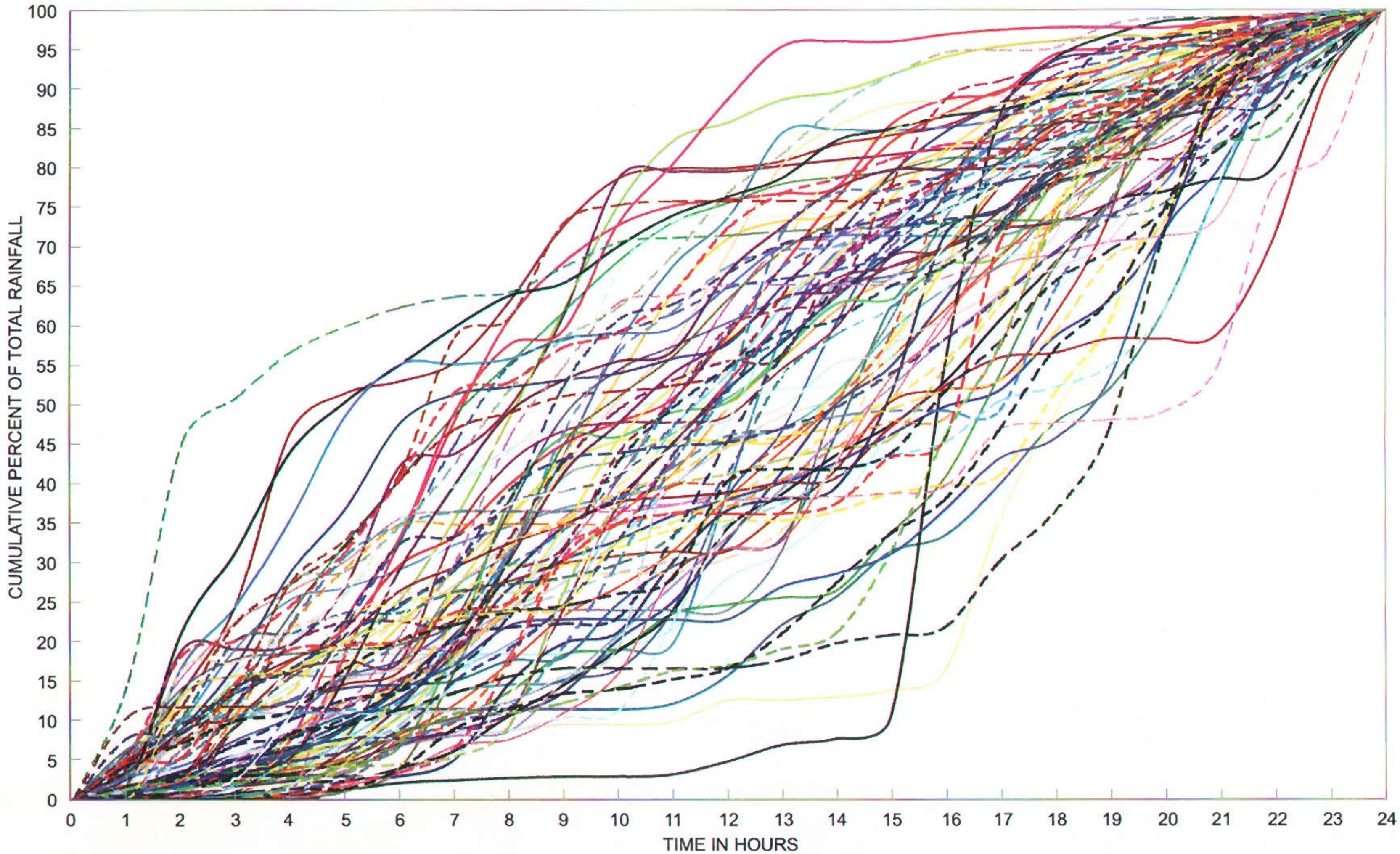
HUFF DISTRIBUTIONS FOR RAINFALL AT A POINT



Source: Illinois State Water Survey and Camp, Dresser & McKee, Inc..

Figure 36

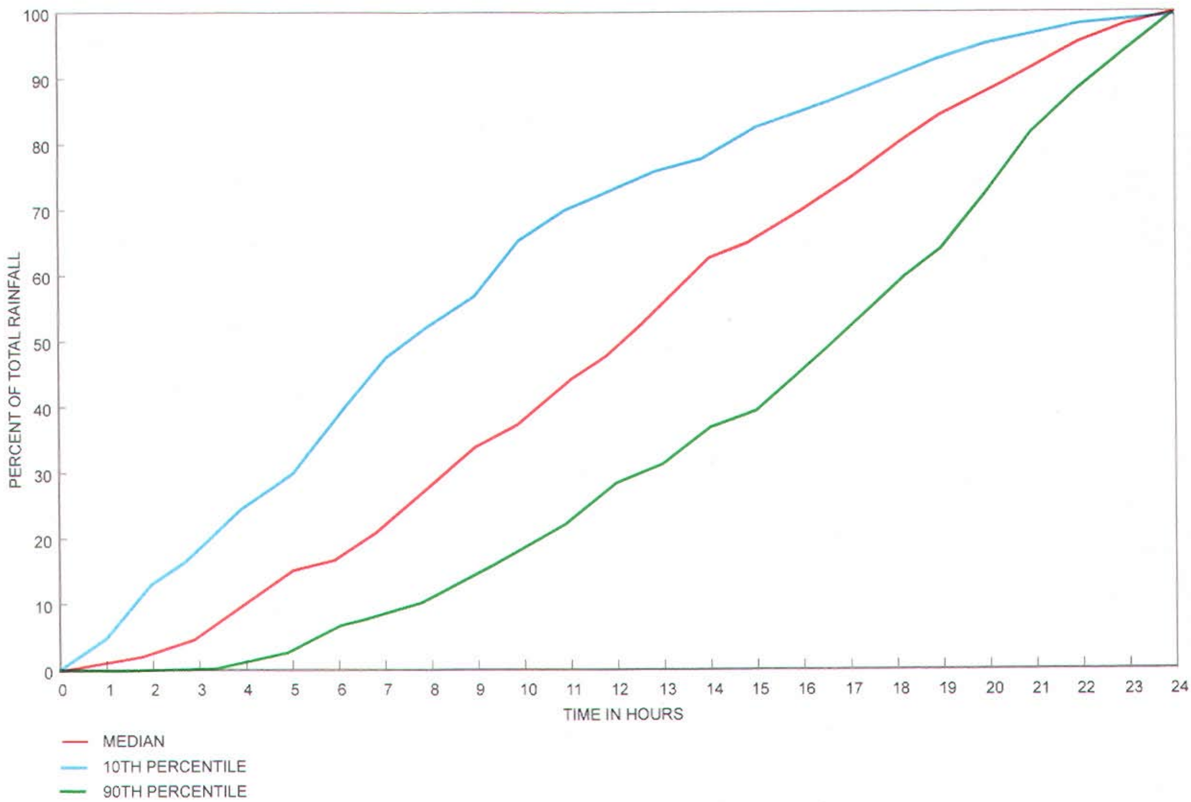
NORMALIZED DISTRIBUTION OF 93 EXTREME 24-HOUR STORMS



Source: Camp, Dresser & McKee, Inc.

Figure 37

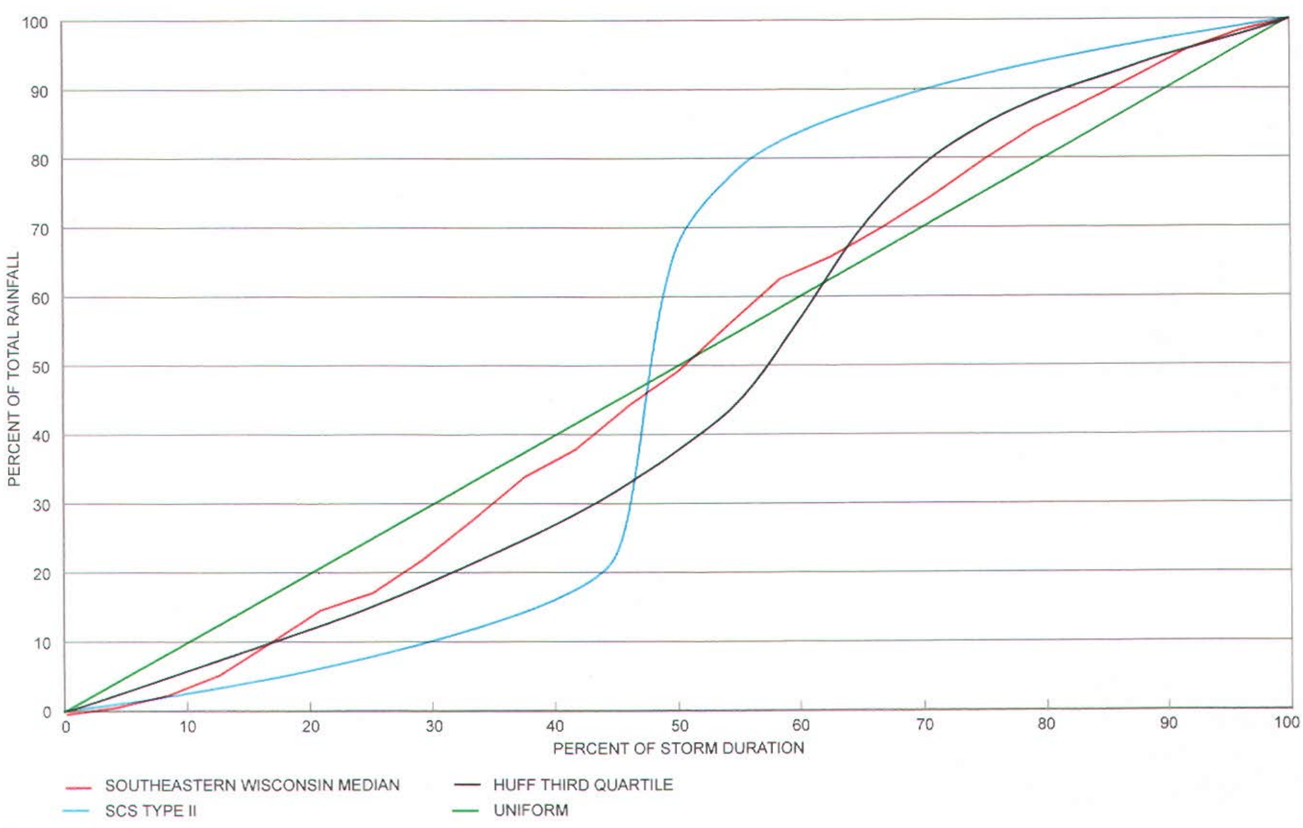
MEDIAN AND 10TH AND 90TH PERCENTILE DISTRIBUTIONS OF EXTREME 24-HOUR STORMS



Source: Camp, Dresser & McKee, Inc.

Figure 38

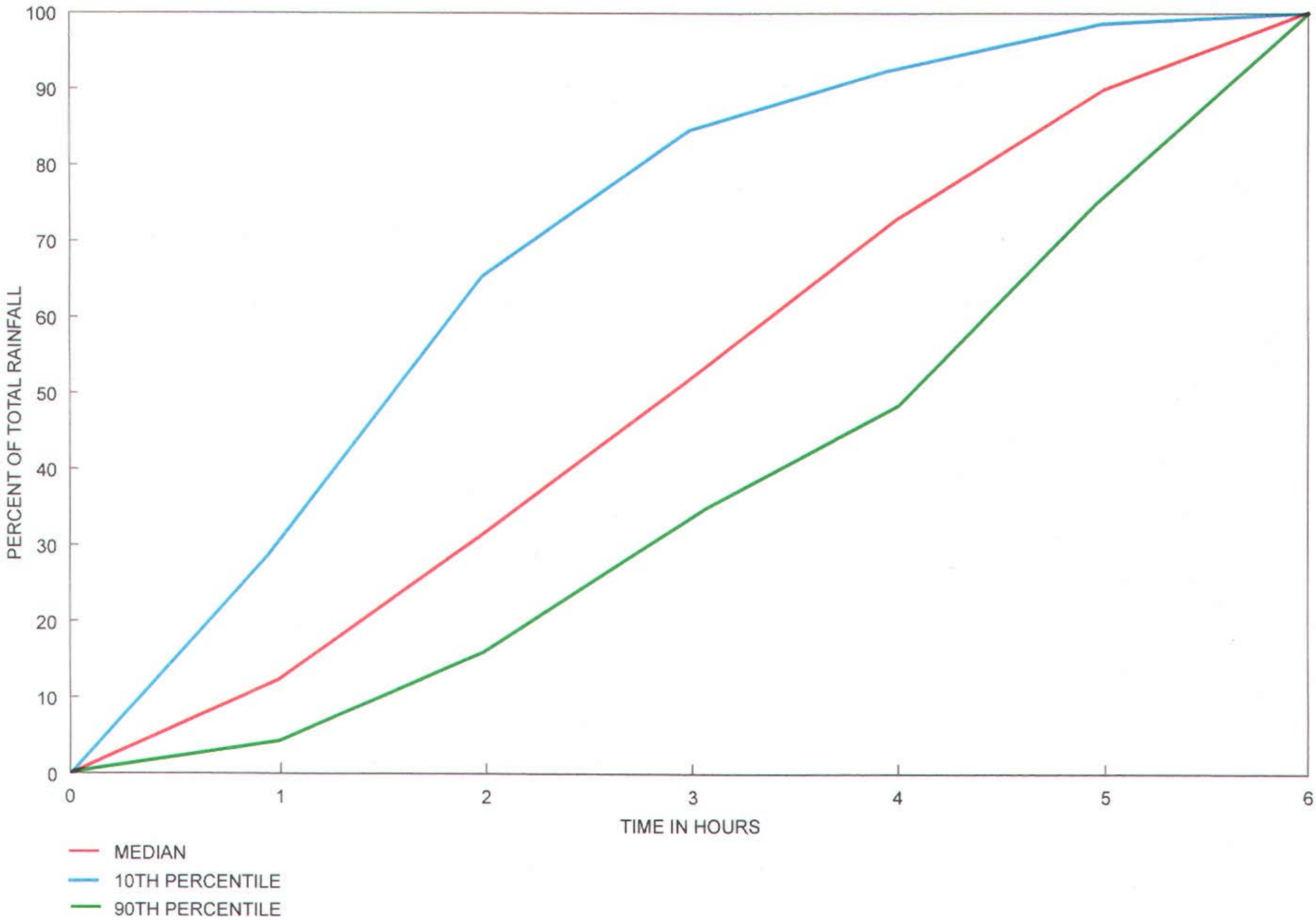
COMPARISON OF RAINFALL DISTRIBUTIONS



Source: Camp, Dresser & McKee, Inc.

Figure 39

MEDIAN AND 10TH AND 90TH PERCENTILE DISTRIBUTIONS OF EXTREME SIX-HOUR STORMS



Source: Camp, Dresser & McKee, Inc.

1 to 1. The distributions plotted in Figures 35 through 39 are in the form of cumulative beta distributions.

Figure 37 presents the median distribution of the 93, 24-hour storms recorded in southeastern and south central Wisconsin. This figure indicates that the median distribution is nearly a uniform distribution. A completely uniform distribution would be represented by a straight line on this plot. The envelope that defines the 10th percentile to 90th percentile range for cumulative rainfall in each hourly period is also shown. Eighty percent of the recorded storms operate within this range. A comparison of the median distribution to other rainfall distributions is in Figure 38. As shown, the median distribution nearly follows a uniform distribution.

Historical six-hour storms were also evaluated. The 113 storms employed in this analysis, and listed in Appendix D, all lasted exactly six hours. The median storm distribution is shown in Figure 39. As with the 24-hour events, the central tendency for the distribution of six-hour storms is also nearly uniform. The envelope of the 10th to 90th percentile range for six-hour storms is also shown in Figure 39.

General conclusions that can be drawn from the data are the following:

1) Real distributions of rainfall within a storm vary over a wide range of possible patterns.

Table 25

SEWRPC 10TH AND 90TH PERCENTILE RAINFALL DISTRIBUTIONS

Hour	Cumulative Percent of Total Storm Rain 10th Percentile Distribution	Cumulative Percent of Total Storm Rain 90th Percentile Distribution
0	0.0	0.0
1	7.6	0.3
2	15.0	0.9
3	22.0	1.9
4	28.7	3.2
5	35.2	4.9
6	41.3	7.0
7	47.1	9.4
8	52.6	12.2
9	57.9	15.3
10	62.8	18.8
11	67.4	22.7
12	71.8	26.9
13	75.8	31.5
14	79.5	36.4
15	83.0	41.7
16	86.1	47.4
17	88.9	53.4
18	91.4	59.8
19	93.7	66.5
20	95.6	73.6
21	97.2	81.1
22	98.6	87.8
23	99.6	94.5
24	100.0	100.0

Source: Camp, Dresser & McKee, Inc.

2) Rainfall distributions appear to have a strong central tendency that is also nearly symmetrical.

3) The central or median distribution of all real storms is a uniform distribution.

Good candidates for a real distribution to use in design are the median distribution or either the 10th or 90th percentile extreme distributions (see Table 25). It is expected that the uniform distribution will generate results that tend to underestimate the intended flow frequency. As discussed previously, the uniform rainfall is exactly correct for impervious watersheds where the rainfall duration exactly matches the watershed time of concentration, otherwise the peak flow prediction will be low. The 90th percentile distribution provides an opportunity to use a distribution based on real storm data while offering a more conservative rainfall intensity than does the uniform distribution. The 90th percentile storm is selected over the 10th percentile because it would generally be expected to produce higher peak flows since the highest intensity occurs later in the storm after a period of lighter rainfall has been used to satisfy the initial abstraction of the watershed.

COMPARISON OF DESIGN STORM APPROACHES

A comparison of the following three design storm methods is set forth in Appendix E of this report:

- Twenty-four hour rainfall depth from National Weather Service Technical Paper No. 40 (TP 40) with the SCS Type II distribution.
- Rainfall depths from Illinois State Water Survey Bulletin 71, with the appropriate Huff distribution.
- SEWRPC 2000 rainfall depths with the Southeastern Wisconsin 90th percentile distribution presented herein.

RECOMMENDATION

Based on analyses performed to date and presented in this report, the recommended rainfall distribution for hydrologic model studies and design in the Southeastern Wisconsin Region is the 90th percentile distribution as listed in Table 26 and plotted in Figure 40. This distribution was selected for the following reasons:

- It is based on recorded rainfall patterns in Southeastern Wisconsin.
- In combination with the SEWRPC 2000 rainfall depths, it produces flood flows that agree well with those computed based on analysis of long-term USGS stream gauge records or long-term continuous simulation of streamflow for relatively large watersheds.

Table 26

SEWRPC RECOMMENDED 90TH PERCENTILE RAINFALL DISTRIBUTION

Percent of Total Storm Time	Cumulative Percent of Total Storm Rain
0	0.0
5	0.4
10	1.3
15	2.7
20	4.6
25	7.0
30	9.9
35	13.4
40	17.4
45	21.9
50	26.9
55	32.4
60	38.5
65	45.1
70	52.2
75	59.8
80	67.9
85	76.6
90	85.1
95	93.2
100	100.0

Source: Camp, Dresser & McKee, Inc. and SEWRPC.

- For intermediate- and small-size subwatersheds, when combined with the SEWRPC 2000 rainfall depths, it produces flood flows that are similar to other design storm methods commonly applied in the Region.

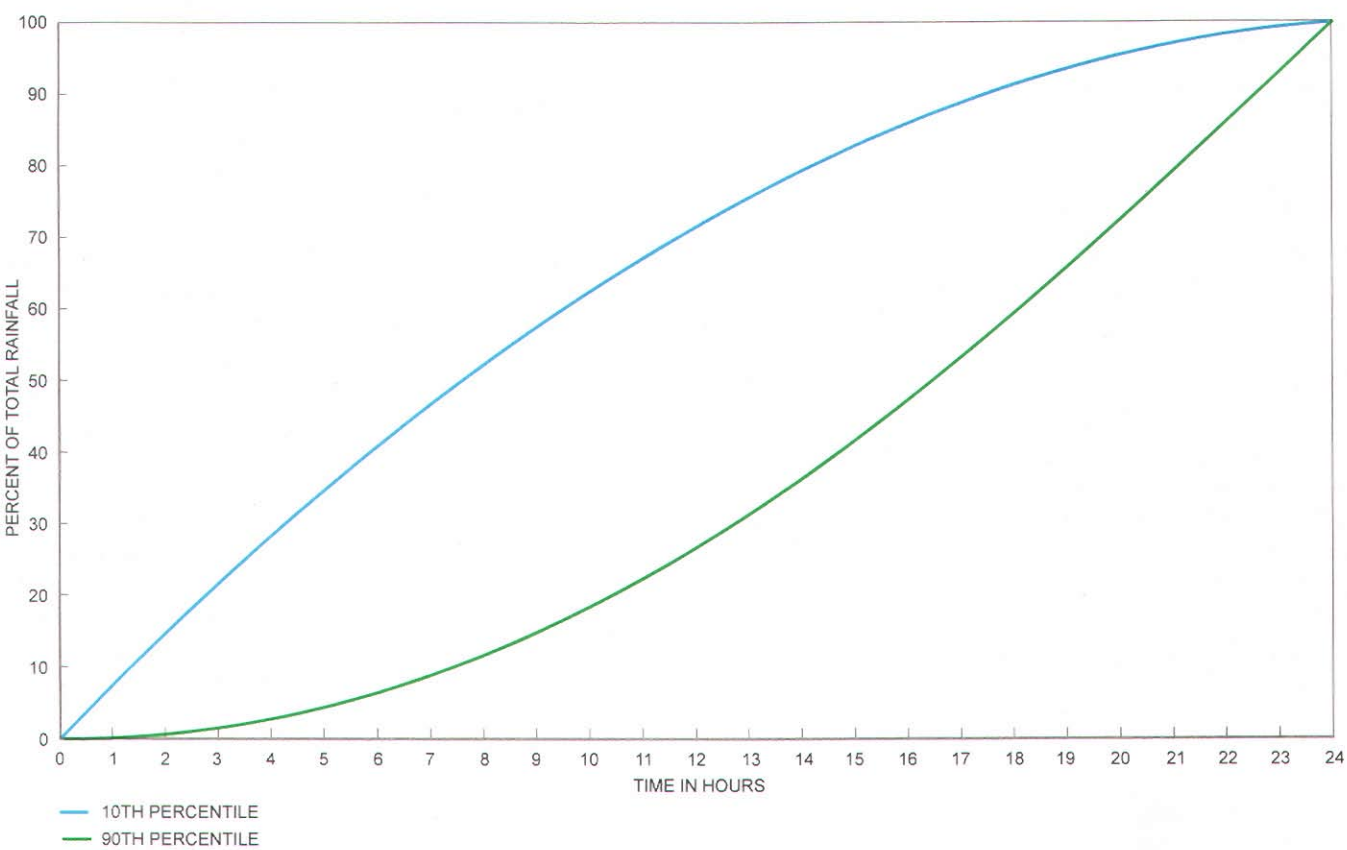
- Based on the analyses set forth in Appendix E, the 90th percentile distribution is considered to be the most appropriate to be used in combination with the SEWRPC 2000 rainfall depth-duration data, which are recommended to be applied in the Southeastern Wisconsin Region.

- The 90th percentile distribution provides conservative design values for peak flow and volume that are not excessively conservative.

The recommendation to apply the 90th percentile distribution with SEWRPC 2000 rainfall depths is adopted for design and planning purposes at this time. The Regional Planning Commission intends to conduct further studies to expand on the comparisons between flood flows determined for gauge sites and those determined using design storm methods. Such studies could result in refinement of the recommended temporal distribution of rainfall to be used with the SEWRPC 2000 rainfall depths.

Figure 40

SMOOTHED 10TH AND 90TH PERCENTILE RAINFALL DISTRIBUTIONS



Source: Camp, Dresser & McKee, Inc.

APPENDICES

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Appendix A

GENERAL MITCHELL INTERNATIONAL AIRPORT RAINFALL GAUGE HISTORY

Table A-1

MILWAUKEE MITCHELL INTERNATIONAL AIRPORT

Date Begun	Date Ended	Latitude/ Longitude	Elevation (meters/feet)	COOP ID	WBAN	Call Sign	WMO ID	Type
Milwaukee Mitchell International Airport								
01 Jul 1995	Present	42°57′N/87°54′W	204.8m/671.7′	475479	14839	MKE	72640	ASOS-NWS
Milwaukee General Mitchell Field								
01 Jan 1995	01 Jul 1995	42°57′N/87°54′W	204.8m/671.7′	475479	14839	MKE	72640	- -
01 Jan 1982	01 Jan 1995	42°57′N/87°54′W	204.8m/671.7′	475479	14839	MKE	72640	- -
01 Jan 1973	31 Dec 1981	42°57′N/87°54′W	204.8m/671.7′	475479	14839	MKE	72640	WSO
01 Jan 1969	01 Jan 1973	42°57′N/87°54′W	204.8m/671.7′	475479	14839	MKE	72640	WBAS
30 Nov 1961	01 Jan 1969	42°57′N/87°54′W	214.9m/704.9′	475479	14839	- -	- -	WBAS
01 Nov 1961	30 Nov 1961	42°57′N/87°54′W	214.9m/704.9′	475479	14839	- -	- -	WBAS
28 Feb 1960	01 Nov 1961	42°57′N/87°54′W	214.9m/704.9′	- -	14839	- -	- -	WBAS
01 Feb 1960	28 Feb 1960	42°57′N/87°54′W	214.9m/704.9′	475479	14839	- -	- -	WBAS
01 Jan 1955	01 Feb 1960	42°57′N/87°54′W	214.9m/704.9′	475479	14839	- -	- -	WBAS
31 Jan 1948	01 Jan 1955	42°57′N/87°54′W	210.9m/691.8′	475479	14839	- -	- -	WBAS
01 Jan 1948	31 Jan 1948	42°57′N/87°54′W	210.9m/691.8′	475479	14839	- -	- -	WBAS
01 Jan 1939	01 Jan 1948	42°57′N/87°54′W	210.9m/691.8′	- -	14839	- -	- -	WBAS
01 Jan 1933	01 Jan 1939	42°57′N/87°54′W	210.9m/691.8′	- -	14839	- -	- -	CAA
01 Jan 1931	01 Jan 1933	42°57′N/87°54′W	210.9m/691.8′	- -	14839	- -	- -	WBAS
01 Jan 1929	01 Jan 1931	42°57′N/87°54′W	205.1m/672.7′	- -	14839	- -	- -	WBO
01 Jul 1928	01 Jan 1929	42°57′N/87°54′W	205.1m/672.7′	- -	14839	- -	- -	A
- -								
01 Jan 1928	01 Jul 1928	Unknown	Unknown	- -	- -	- -	- -	A

NOTE: Description of Acronyms:

- A: Aviation and Cooperative
- ASOS: Automated Surface Observation Station
- CAA: Civilian Aeronautics Administration
- WBAN: Weather Bureau-Army-Navy
- WBAS: Weather Bureau Airport Station
- WBO: Weather Bureau Office
- WMO: World Meteorological Organization
- WSO: Weather Service Office

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Appendix B

VALUES OF MILWAUKEE AT-SITE, REAL-SPACE GEV PARAMETERS

Appendix B contains statistics summarizing the Milwaukee Mitchell Field precipitation data used as the basis for precipitation quantile estimates, and associated distribution parameters. The estimated parameters for the Generalized Extreme Value (GEV) distribution are referred to as shape (κ), scale (α) and location (ξ), respectively. The cumulative distribution function (cdf) for the GEV is:

$$F(x) = \exp\left\{ -\left[1 - \frac{\kappa(x-\xi)}{\alpha} \right]^{\frac{1}{\kappa}} \right\}$$

The cdf can be interpreted in this instance as the probability that annual maximum precipitation over the chosen duration will not exceed x (inches). The annual exceedance probability p for a given precipitation intensity (x) is thus 1-$F(x)$, and the recurrence interval in years is equal to the reciprocal of the exceedance probability ($1/p$). Precipitation quantiles, or intensities associated with a specific exceedance probability or recurrence interval in years, are obtained by inverting the cdf to obtain:

$$x(F) = x(1-p) = \xi + \frac{\alpha\left[1-(-\ln(F))^{\kappa}\right]}{\kappa}$$

Results for durations from five minutes through 10 days, and for both Period-of-Record and Period 1940-1998 precipitation data appear in Table B-1. The method used for calculating GEV parameters from the time series of annual maximum n-minute is described in J. M. R. Hosking, J. R. Wallis and E. F. Wood, "Estimation of the Generalized Extreme-Value Distribution by the Method of Probability-Weighted Moments," *Technometrics*, Vol. 27 No. 3, August, 1985.

Table B-1

SUMMARY OF MILWAUKEE PRECIPITATION STATISTICS AND ESTIMATED GEV PARAMETERS

Duration	Number of Observations	Minimum	Maximum	Mean	Standard Deviation	Skewness Coefficient	GEV Parameters		
							κ	α	ξ
All Observations, Entire Period of Record									
5-Minute	96	0.20	0.83	0.373	0.120	1.185	0.011	0.094	0.320
10-Minute	96	0.27	1.12	0.589	0.187	0.897	-0.003	0.147	0.504
15-Minute	92	0.32	1.34	0.754	0.232	0.610	0.098	0.203	0.654
30-Minute	92	0.42	1.86	0.994	0.328	0.688	0.025	0.271	0.844
60-Minute	102	0.48	3.06	1.239	0.457	1.391	-0.082	0.321	1.026
120-Minute	96	0.65	5.24	1.499	0.623	2.764	-0.139	0.374	1.224
1440-Minute	108	0.95	6.84	2.476	0.928	1.904	-0.155	0.572	2.043
All Observations, 1940-Current									
5-Minute	53	0.20	0.83	0.379	0.123	1.120	0.044	0.101	0.325
10-Minute	53	0.27	1.12	0.604	0.192	0.691	0.060	0.163	0.519
15-Minute	53	0.32	1.34	0.756	0.240	0.457	0.156	0.222	0.658
30-Minute	53	0.42	1.69	0.982	0.331	0.637	0.027	0.275	0.831
60-Minute	59	0.48	3.06	1.264	0.477	1.681	-0.109	0.315	1.044
2-Hour	59	0.65	5.24	1.503	0.686	3.114	-0.202	0.364	1.203
3-Hour	59	0.67	5.73	1.644	0.741	3.182	-0.195	0.394	1.323
4-Hour	59	0.68	5.93	1.767	0.774	2.975	-0.210	0.413	1.422
6-Hour	59	0.84	6.24	1.952	0.838	2.611	-0.220	0.455	1.565
12-Hour	59	0.94	6.60	2.259	0.925	2.135	-0.192	0.541	1.822
24-Hour	59	0.95	6.84	2.600	1.041	1.691	-0.162	0.649	2.102
48-Hour	59	1.12	6.84	2.999	1.151	1.191	-0.042	0.856	2.468
72-Hour	59	1.24	6.84	3.208	1.137	1.004	-0.011	0.883	2.688
120-Hour	59	1.54	7.06	3.589	1.174	0.654	0.086	1.020	3.081
240-Hour	59	2.05	7.50	4.431	1.350	0.404	0.106	1.221	3.843

Source: Rodgers and Potter.

Appendix C

DATA DESCRIBING 24-HOUR STORMS USED IN ANALYSIS OF STORM DISTRIBUTIONS

Table C-1

24-HOUR STORM DATA
CUMULATIVE HOURLY RAINFALL

Storm Number	1	2	3	4	5	6	7	8	9	10	11
Location	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell
Start Time (24-hour)	09/12/1944 15:00	05/02/1945 7:00	06/14/1949 3:00	03/30/1949 19:00	07/19/1950 5:00	04/24/1951 12:00	04/12/1952 7:00	06/02/1954 21:00	01/20/1959 19:00	01/11/1960 21:00	09/13/1961 2:00
Total Precipitation (inches)	1.25	1.21	2.28	1.37	3.3	1.43	1.95	2.78	1.25	1.71	2.65
Hour											
1	0.00	0.01	0.00	0.03	0.15	0.02	0.03	0.08	0.04	0.07	0.04
2	0.00	0.03	0.00	0.26	0.45	0.05	0.07	0.12	0.09	0.15	0.06
3	0.01	0.05	0.00	0.26	0.82	0.08	0.10	0.21	0.13	0.23	0.06
4	0.06	0.06	0.02	0.27	1.54	0.11	0.13	0.29	0.18	0.34	0.10
5	0.23	0.10	0.12	0.37	1.70	0.15	0.19	0.43	0.23	0.45	0.16
6	0.41	0.20	0.24	0.58	1.75	0.16	0.25	0.49	0.23	0.56	0.18
7	0.60	0.32	0.31	0.60	1.83	0.16	0.36	0.62	0.23	0.68	0.21
8	0.76	0.43	0.33	0.68	2.08	0.16	0.52	0.87	0.23	0.76	0.23
9	0.85	0.51	0.34	0.84	2.40	0.16	0.59	1.21	0.23	0.81	0.25
10	0.91	0.55	0.43	1.08	2.60	0.16	0.64	1.60	0.24	0.84	0.25
11	0.94	0.55	0.45	1.09	2.64	0.17	0.70	1.88	0.27	0.87	0.26
12	0.95	0.55	0.89	1.09	2.64	0.22	0.74	2.05	0.35	0.87	0.33
13	0.96	0.55	1.34	1.10	2.67	0.31	0.78	2.35	0.39	0.89	0.33
14	0.97	0.62	1.58	1.11	2.74	0.36	0.83	2.36	0.46	0.90	0.34
15	1.07	0.70	1.64	1.12	2.78	0.44	0.90	2.36	0.58	0.95	0.36
16	1.11	0.82	1.77	1.13	2.82	0.47	0.97	2.37	0.66	1.10	0.43
17	1.12	0.98	1.90	1.13	2.91	0.56	1.01	2.40	0.74	1.15	0.93
18	1.18	1.07	1.91	1.13	2.96	0.67	1.14	2.48	0.80	1.21	1.28
19	1.19	1.11	1.95	1.14	3.02	0.73	1.23	2.50	0.90	1.24	1.58
20	1.21	1.14	2.02	1.18	3.08	0.87	1.40	2.54	1.00	1.24	1.94
21	1.24	1.15	2.15	1.25	3.12	1.09	1.73	2.62	1.04	1.25	2.38
22	1.24	1.16	2.26	1.30	3.21	1.29	1.90	2.68	1.10	1.26	2.48
23	1.24	1.18	2.27	1.34	3.24	1.38	1.92	2.71	1.18	1.49	2.55
24	1.25	1.21	2.28	1.37	3.30	1.41	1.95	2.78	1.25	1.71	2.65

Table C-1 (continued)

Storm Number	12	13	14	15	16	17	18	19	20	21	22
Location	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell
Start Time (24-hour)	01/06/1962 7:00	05/17/1969 11:00	03/18/1971 11:00	04/09/1973 2:00	03/29/1974 15:00	04/02/1975 0:00	04/24/1976 7:00	02/20/1976 20:00	01/25/1978 16:00	01/12/1979 21:00	04/14/1980 4:00
Total Precipitation (inches)	1.17	1.29	1.63	1.84	1.46	1.3	3.11	1.31	0.97	1.34	1.01
Hour											
1	0.00	0.08	0.02	0.06	0.00	0.05	0.10	0.01	0.00	0.02	0.00
2	0.01	0.20	0.03	0.13	0.00	0.13	0.26	0.02	0.00	0.03	0.00
3	0.02	0.29	0.07	0.20	0.01	0.25	0.46	0.03	0.01	0.04	0.04
4	0.04	0.34	0.13	0.28	0.01	0.33	0.51	0.10	0.08	0.05	0.06
5	0.09	0.39	0.19	0.35	0.05	0.35	0.62	0.20	0.12	0.07	0.08
6	0.14	0.46	0.25	0.42	0.12	0.38	0.79	0.29	0.14	0.11	0.19
7	0.19	0.47	0.30	0.50	0.15	0.42	1.11	0.38	0.18	0.16	0.23
8	0.23	0.47	0.40	0.60	0.18	0.45	1.50	0.47	0.23	0.23	0.37
9	0.29	0.47	0.51	0.77	0.22	0.48	1.93	0.57	0.29	0.31	0.49
10	0.42	0.47	0.66	0.93	0.24	0.50	2.35	0.70	0.35	0.36	0.55
11	0.55	0.48	0.84	1.06	0.35	0.52	2.60	0.84	0.40	0.42	0.58
12	0.63	0.50	1.02	1.27	0.56	0.59	2.67	0.93	0.48	0.51	0.61
13	0.73	0.52	1.14	1.48	0.68	0.61	2.76	0.96	0.54	0.59	0.64
14	0.80	0.56	1.16	1.57	0.88	0.67	2.79	0.97	0.60	0.67	0.66
15	0.85	0.65	1.21	1.62	1.04	0.77	2.86	1.04	0.64	0.75	0.67
16	0.92	0.79	1.25	1.63	1.09	0.84	2.93	1.08	0.68	0.83	0.69
17	0.98	0.87	1.29	1.64	1.14	0.88	2.97	1.14	0.76	0.92	0.74
18	1.02	0.89	1.33	1.65	1.22	0.97	2.99	1.18	0.83	1.00	0.79
19	1.06	0.91	1.40	1.72	1.25	1.03	3.01	1.20	0.87	1.08	0.83
20	1.09	0.92	1.45	1.74	1.26	1.12	3.01	1.21	0.90	1.17	0.88
21	1.12	0.95	1.49	1.76	1.31	1.17	3.02	1.24	0.93	1.25	0.91
22	1.15	1.13	1.54	1.77	1.37	1.23	3.04	1.27	0.95	1.29	0.94
23	1.16	1.23	1.60	1.79	1.43	1.28	3.07	1.29	0.96	1.32	0.98
24	1.17	1.29	1.63	1.84	1.46	1.30	3.11	1.31	0.97	1.34	1.01

Table C-1 (continued)

Storm Number	23	24	25	26	27	28	29	30	31	32	33
Location	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell	Mitchell
Start Time (24-hour)	04/02/1982 12:00	04/01/1983 23:00	02/02/1983 8:00	04/22/1984 8:00	08/05/1986 20:00	04/13/1987 21:00	07/19/1989 0:00	03/03/1989 6:00	11/01/1992 6:00	04/14/1993 21:00	03/31/1993 5:00
Total Precipitation (inches)	1.79	2.06	1.23	1.27	6.84	1.85	2.68	1.11	1.82	1.47	1.38
Hour											
1	0.09	0.02	0.08	0.02	0.01	0.00	0.01	0.03	0.03	0.03	0.00
2	0.24	0.06	0.11	0.27	0.01	0.00	0.23	0.10	0.04	0.08	0.04
3	0.28	0.10	0.17	0.40	0.01	0.17	0.28	0.19	0.04	0.13	0.17
4	0.28	0.13	0.29	0.56	0.03	0.23	0.43	0.32	0.04	0.25	0.24
5	0.28	0.19	0.40	0.64	0.08	0.27	0.47	0.41	0.04	0.40	0.30
6	0.31	0.30	0.50	0.70	0.14	0.30	0.47	0.53	0.07	0.48	0.41
7	0.48	0.43	0.60	0.76	0.16	0.47	0.90	0.57	0.11	0.59	0.46
8	0.56	0.58	0.68	0.81	0.18	0.51	1.14	0.58	0.19	0.68	0.55
9	0.73	0.71	0.76	0.83	0.19	0.55	1.25	0.59	0.26	0.77	0.62
10	0.77	0.79	0.84	0.89	0.19	0.57	1.28	0.60	0.34	0.85	0.66
11	0.83	0.93	0.90	0.94	0.21	0.58	1.28	0.62	0.43	0.95	0.70
12	0.91	1.07	0.93	0.97	0.32	0.58	1.30	0.64	0.62	0.97	0.81
13	1.00	1.19	0.96	1.00	0.46	0.67	1.46	0.72	0.70	1.02	0.93
14	1.17	1.31	0.97	1.06	0.51	0.77	1.60	0.79	0.79	1.04	1.05
15	1.18	1.42	0.98	1.08	0.69	0.93	1.84	0.88	0.86	1.05	1.15
16	1.29	1.50	1.00	1.10	3.75	0.96	1.87	0.94	0.96	1.13	1.20
17	1.30	1.54	1.00	1.11	5.93	0.98	2.08	0.98	1.10	1.17	1.24
18	1.30	1.61	1.01	1.13	6.42	1.13	2.28	1.04	1.23	1.23	1.26
19	1.41	1.65	1.04	1.14	6.62	1.36	2.36	1.05	1.37	1.38	1.28
20	1.51	1.76	1.06	1.14	6.75	1.76	2.38	1.06	1.40	1.43	1.32
21	1.60	1.88	1.10	1.15	6.77	1.82	2.43	1.06	1.43	1.46	1.33
22	1.68	1.98	1.12	1.17	6.79	1.84	2.54	1.06	1.45	1.46	1.35
23	1.75	2.03	1.17	1.22	6.80	1.84	2.67	1.07	1.69	1.46	1.37
24	1.79	2.06	1.23	1.27	6.84	1.85	2.68	1.11	1.82	1.47	1.38

Table C-1 (continued)

Storm Number	34	35	36	37	38	39	40	41	42	43	44	45
Location	Mitchell	Mitchell	Mitchell	Eagle	Eagle	Eagle	Eagle	Eagle	Eagle	Eagle	Eagle	Eagle
Start Time (24-hour)	06/23/1994 7:00	01/13/1995 12:00	02/20/1997 16:00	07/19/1950 2:00	06/11/1955 3:00	01/11/1960 21:00	09/13/1961 1:00	08/08/1965 9:00	01/12/1966 4:00	01/03/1971 5:00	04/02/1982 10:00	10/31/1985 19:00
Total Precipitation (inches)	1.61	1.04	1.34	3.3	1.54	1.7	3.61	1.37	0.98	1.26	2.34	2.04
Hour												
1	0.00	0.00	0.00	0.00	0.03	0.06	0.05	0.01	0.00	0.00	0.03	0.06
2	0.00	0.00	0.00	0.01	0.26	0.15	0.11	0.04	0.00	0.00	0.04	0.16
3	0.00	0.01	0.01	0.07	0.38	0.24	0.12	0.04	0.00	0.02	0.22	0.20
4	0.03	0.06	0.07	0.25	0.55	0.30	0.12	0.04	0.00	0.03	0.29	0.26
5	0.07	0.08	0.10	0.75	0.75	0.35	0.18	0.04	0.01	0.08	0.33	0.31
6	0.11	0.08	0.14	1.10	0.85	0.45	0.31	0.04	0.04	0.15	0.34	0.34
7	0.31	0.09	0.24	1.62	0.85	0.50	0.37	0.07	0.16	0.25	0.35	0.41
8	0.61	0.11	0.33	1.90	0.86	0.55	0.49	0.20	0.30	0.38	0.41	0.49
9	0.74	0.14	0.46	1.96	0.90	0.59	0.66	0.27	0.44	0.52	0.42	0.56
10	0.74	0.21	0.61	2.41	0.91	0.64	0.69	0.29	0.50	0.60	0.58	0.67
11	0.79	0.26	0.70	2.66	0.92	0.65	0.85	0.41	0.55	0.68	0.69	0.81
12	0.81	0.34	0.78	2.93	1.00	0.66	0.89	0.50	0.62	0.73	0.74	0.91
13	0.91	0.43	0.85	3.15	1.08	0.68	0.92	0.52	0.68	0.80	0.77	0.99
14	1.01	0.52	0.92	3.17	1.10	0.69	0.95	0.54	0.72	0.81	1.08	1.04
15	1.02	0.57	1.02	3.17	1.10	0.80	1.21	0.70	0.77	0.85	1.46	1.17
16	1.09	0.66	1.10	3.20	1.10	0.89	1.47	0.98	0.79	0.88	1.63	1.24
17	1.11	0.75	1.14	3.22	1.10	0.95	1.94	1.02	0.83	0.91	1.70	1.31
18	1.26	0.83	1.22	3.23	1.13	0.96	2.43	1.08	0.84	0.92	1.82	1.37
19	1.41	0.88	1.25	3.23	1.14	0.99	2.72	1.15	0.85	0.95	1.87	1.44
20	1.50	0.92	1.30	3.23	1.20	0.99	3.11	1.18	0.86	1.00	2.02	1.63
21	1.54	0.97	1.31	3.25	1.35	1.00	3.31	1.20	0.88	1.11	2.18	1.75
22	1.56	1.00	1.33	3.27	1.39	1.20	3.41	1.21	0.92	1.20	2.29	1.84
23	1.59	1.02	1.33	3.29	1.44	1.55	3.52	1.36	0.96	1.25	2.32	1.97
24	1.61	1.04	1.34	3.30	1.54	1.70	3.61	1.37	0.98	1.26	2.34	2.04

Table C-1 (continued)

Storm Number	46	47	48	49	50	51	52	53	54	55	56	57
Location	Eagle	Green Bay	Green Bay	Green Bay	Green Bay	Green Bay	Green Bay	Green Bay	Green Bay	Green Bay	Green Bay	Green Bay
Start Time (24-hour)	10/08/1985 20:00	03/30/1949 22:00	04/12/1952 18:00	02/19/1953 16:00	04/05/1957 3:00	05/06/1960 7:00	04/29/1960 16:00	05/01/1964 11:00	09/19/1965 14:00	06/25/1968 21:00	05/27/1973 10:00	04/15/1973 13:00
Total Precipitation (inches)	1.63	1.63	1.29	1.51	0.88	2.43	1.2	1.23	2.5	2.31	3.28	0.88
Hour												
1	0.10	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.02	0.00	0.05
2	0.23	0.02	0.01	0.02	0.02	0.03	0.00	0.02	0.22	0.08	0.00	0.10
3	0.29	0.03	0.02	0.02	0.05	0.08	0.00	0.05	0.27	0.16	0.00	0.10
4	0.30	0.04	0.04	0.03	0.06	0.13	0.00	0.07	0.27	0.23	0.02	0.12
5	0.31	0.06	0.06	0.04	0.07	0.38	0.02	0.11	0.27	0.29	0.07	0.20
6	0.32	0.11	0.09	0.05	0.08	0.71	0.04	0.17	0.27	0.32	0.11	0.22
7	0.37	0.13	0.11	0.08	0.13	0.97	0.08	0.21	0.28	0.47	0.21	0.23
8	0.39	0.14	0.14	0.20	0.21	1.19	0.09	0.27	0.31	0.50	0.56	0.26
9	0.39	0.24	0.31	0.35	0.29	1.29	0.13	0.28	0.39	0.51	1.00	0.26
10	0.39	0.34	0.48	0.58	0.31	1.35	0.19	0.28	0.48	0.53	1.18	0.28
11	0.39	0.44	0.58	0.72	0.35	1.38	0.34	0.28	1.10	0.76	1.40	0.30
12	0.39	0.54	0.68	0.83	0.42	1.62	0.38	0.28	1.20	1.04	1.73	0.31
13	0.51	0.64	0.78	0.97	0.54	1.76	0.39	0.33	1.24	1.29	1.98	0.31
14	0.81	0.75	0.85	1.05	0.63	1.88	0.51	0.35	1.38	1.49	2.22	0.32
15	0.99	0.85	0.87	1.07	0.64	1.94	0.64	0.38	1.43	1.63	2.40	0.34
16	1.20	0.95	0.90	1.11	0.66	1.94	0.72	0.45	1.71	1.80	2.58	0.35
17	1.32	1.04	0.96	1.17	0.69	1.96	0.88	0.53	1.72	1.98	2.69	0.36
18	1.42	1.13	1.04	1.20	0.73	2.08	0.96	0.56	1.78	2.06	2.77	0.45
19	1.49	1.22	1.05	1.22	0.76	2.09	1.00	0.65	2.20	2.20	2.91	0.53
20	1.52	1.31	1.07	1.23	0.79	2.19	1.05	0.88	2.33	2.22	3.03	0.69
21	1.56	1.40	1.12	1.28	0.83	2.30	1.08	0.98	2.35	2.24	3.13	0.76
22	1.59	1.49	1.19	1.41	0.85	2.34	1.12	1.12	2.39	2.25	3.21	0.84
23	1.61	1.58	1.24	1.50	0.86	2.38	1.17	1.18	2.47	2.27	3.24	0.86
24	1.63	1.63	1.29	1.51	0.88	2.43	1.20	1.23	2.50	2.30	3.28	0.88

Table C-1 (continued)

Storm Number	58	59	60	61	62	63	64	65	66	67	68	69
Location	Green Bay	Green Bay	Green Bay	Green Bay	Green Bay	Green Bay	Green Bay	Green Bay	Hartford	Hartford	Hartford	Hartford
Start Time (24-hour)	04/01/1977 19:00	07/01/1978 17:00	03/03/1979 12:00	01/15/1980 18:00	10/31/1985 23:00	03/03/1989 6:00	03/01/1991 8:00	06/17/1996 1:00	10/20/1951 17:00	04/12/1952 7:00	06/20/1954 21:00	04/23/1955 21:00
Total Precipitation (inches)	1.26	1.64	1.43	1.14	2.3	1.35	1.16	1.61	2.29	1.15	2.25	2.21
Hour												
1	0.08	0.03	0.06	0.04	0.11	0.04	0.00	0.02	0.00	0.00	0.00	0.03
2	0.11	0.04	0.17	0.12	0.22	0.07	0.00	0.09	0.00	0.00	0.00	0.03
3	0.15	0.20	0.32	0.23	0.31	0.14	0.00	0.26	0.08	0.02	0.00	0.11
4	0.28	0.32	0.39	0.24	0.38	0.17	0.02	0.34	0.24	0.05	0.02	0.19
5	0.39	0.37	0.46	0.27	0.48	0.21	0.08	0.42	0.39	0.08	0.42	0.26
6	0.44	0.37	0.58	0.27	0.57	0.27	0.09	0.57	0.53	0.11	0.43	0.46
7	0.46	0.37	0.67	0.30	0.68	0.34	0.10	0.64	0.70	0.20	0.44	0.66
8	0.46	0.54	0.70	0.31	0.90	0.40	0.10	0.71	0.75	0.27	0.56	1.01
9	0.46	0.70	0.73	0.32	0.99	0.46	0.12	0.83	0.80	0.30	0.80	1.21
10	0.48	0.81	0.74	0.34	1.01	0.55	0.13	1.08	0.91	0.33	0.83	1.39
11	0.53	0.87	0.75	0.38	1.03	0.68	0.26	1.18	1.05	0.35	0.84	1.41
12	0.58	0.91	0.78	0.47	1.04	0.80	0.40	1.19	1.25	0.40	0.85	1.44
13	0.59	0.92	0.91	0.61	1.08	0.91	0.52	1.19	1.59	0.43	0.86	1.44
14	0.61	1.11	1.05	0.67	1.14	0.96	0.59	1.20	1.83	0.47	0.86	1.44
15	0.62	1.21	1.11	0.71	1.24	1.02	0.65	1.20	1.94	0.50	0.87	1.44
16	0.62	1.30	1.13	0.77	1.34	1.03	0.75	1.20	1.99	0.52	0.89	1.46
17	0.62	1.31	1.17	0.82	1.46	1.07	0.85	1.27	2.02	0.58	1.05	1.54
18	0.81	1.32	1.20	0.89	1.59	1.17	0.93	1.28	2.03	0.60	1.07	1.60
19	0.95	1.33	1.25	0.96	1.69	1.20	0.98	1.29	2.05	0.63	1.08	1.79
20	1.11	1.33	1.28	1.01	1.82	1.22	1.04	1.33	2.08	0.71	1.10	1.94
21	1.18	1.35	1.28	1.06	1.94	1.26	1.09	1.34	2.11	0.89	1.23	2.06
22	1.20	1.50	1.35	1.10	2.07	1.28	1.12	1.36	2.25	1.09	1.74	2.16
23	1.22	1.59	1.41	1.13	2.17	1.29	1.15	1.43	2.27	1.10	1.84	2.20
24	1.26	1.64	1.43	1.14	2.30	1.35	1.16	1.61	2.29	1.15	2.25	2.21

Table C-1 (continued)

Storm Number	70	71	72	73	74	75	76	77	78	79	80	81
Location	Hartford	Hartford	Hartford	Hartford	Hartford	Hartford	Hartford	Hartford	Hartford	Hartford	Hartford	Hartford
Start Time (24-hour)	10/23/1957 0:00	04/05/1957 5:00	05/06/1960 3:00	09/13/1961 0:00	01/03/1971 6:00	04/23/1976 21:00	03/04/1976 4:00	03/27/1977 1:00	05/12/1978 21:00	01/25/1978 23:00	08/07/1980 5:00	04/02/1982 9:00
Total Precipitation (inches)	1.15	0.91	1.94	3.86	0.86	2.7	1.84	1.1	3.8	1.17	3.75	2.54
Hour												
1	0.02	0.00	0.11	0.05	0.00	0.05	0.00	0.00	0.01	0.02	0.56	0.11
2	0.19	0.01	0.20	0.10	0.00	0.07	0.00	0.07	0.25	0.04	1.70	0.18
3	0.20	0.03	0.20	0.15	0.00	0.29	0.00	0.11	0.52	0.08	1.91	0.25
4	0.25	0.10	0.21	0.16	0.01	0.59	0.01	0.17	1.04	0.09	2.13	0.28
5	0.27	0.20	0.22	0.16	0.04	0.79	0.04	0.21	1.10	0.12	2.25	0.42
6	0.30	0.30	0.24	0.17	0.12	0.94	0.14	0.27	1.32	0.16	2.34	0.51
7	0.30	0.41	0.40	0.21	0.19	0.94	0.18	0.32	1.62	0.19	2.39	0.56
8	0.30	0.50	0.60	0.36	0.27	0.94	0.33	0.41	1.97	0.27	2.41	0.60
9	0.32	0.53	0.90	1.01	0.30	0.94	0.58	0.43	2.22	0.37	2.53	0.62
10	0.33	0.54	1.10	1.44	0.33	0.94	0.64	0.45	2.37	0.50	2.65	0.66
11	0.33	0.56	1.20	1.54	0.35	0.98	0.73	0.52	2.62	0.58	2.67	0.71
12	0.35	0.59	1.31	1.59	0.38	1.00	0.74	0.60	2.92	0.64	2.68	1.02
13	0.39	0.60	1.35	1.66	0.39	1.09	0.83	0.64	3.11	0.69	2.70	1.06
14	0.49	0.61	1.36	1.72	0.40	1.20	0.93	0.70	3.34	0.71	2.71	1.06
15	0.67	0.63	1.43	1.76	0.42	1.29	1.08	0.77	3.49	0.76	2.72	1.11
16	0.78	0.69	1.51	2.11	0.44	1.30	1.42	0.84	3.60	0.79	2.74	1.31
17	0.82	0.71	1.56	2.46	0.45	1.54	1.58	0.95	3.61	0.85	2.75	1.47
18	0.90	0.74	1.57	2.80	0.50	2.00	1.61	1.01	3.62	0.94	2.75	1.66
19	0.95	0.80	1.60	3.05	0.58	2.30	1.62	1.03	3.73	0.99	2.76	1.76
20	1.00	0.81	1.62	3.29	0.62	2.55	1.63	1.05	3.77	1.04	2.83	1.89
21	1.08	0.81	1.71	3.49	0.77	2.60	1.64	1.07	3.77	1.08	3.11	2.09
22	1.10	0.82	1.85	3.62	0.82	2.62	1.70	1.09	3.78	1.13	3.16	2.21
23	1.13	0.86	1.91	3.77	0.84	2.68	1.82	1.09	3.79	1.15	3.47	2.40
24	1.15	0.91	1.94	3.86	0.85	2.70	1.84	1.10	3.80	1.17	3.75	2.54

Table C-1 (continued)

Storm Number	82	83	84	85	86	87	88	89	90	91	92	93
Location	Madison	Madison	Madison	Madison	Madison	Madison	Madison	Madison	Madison	Madison	Madison	Madison
Start Time (24-hour)	04/12/1952 8:00	04/23/1955 20:00	05/06/1960 2:00	09/12/1961 9:00	05/10/1967 4:00	05/12/1978 20:00	10/22/1979 4:00	02/02/1983 0:00	02/04/1986 0:00	04/21/1987 15:00	03/31/1993 2:00	06/23/1994 3:00
Total Precipitation (inches)	0.97	2.15	2.58	3.57	1.59	2.68	1.69	1.48	1.47	1.6	1.6	2.33
Hour												
1	0.00	0.11	0.27	0.28	0.00	0.02	0.08	0.01	0.01	0.00	0.09	0.00
2	0.01	0.16	0.30	0.30	0.00	0.03	0.09	0.02	0.03	0.21	0.29	0.00
3	0.03	0.31	0.30	0.51	0.01	0.07	0.25	0.03	0.06	0.25	0.32	0.01
4	0.08	0.59	0.30	0.58	0.02	0.29	0.32	0.04	0.07	0.26	0.39	0.03
5	0.09	0.71	0.30	0.82	0.02	0.55	0.33	0.05	0.09	0.32	0.50	0.06
6	0.11	0.89	0.39	1.16	0.06	0.75	0.34	0.11	0.13	0.36	0.65	0.16
7	0.13	1.26	0.49	1.19	0.14	0.88	0.40	0.16	0.22	0.37	0.82	0.23
8	0.15	1.31	0.73	1.35	0.18	1.00	0.42	0.16	0.28	0.38	0.84	0.27
9	0.16	1.57	0.82	1.87	0.21	1.05	0.51	0.18	0.36	0.39	0.91	0.45
10	0.16	1.62	1.13	2.17	0.22	1.11	0.59	0.21	0.48	0.52	0.94	0.70
11	0.16	1.63	1.30	2.24	0.24	1.19	0.61	0.24	0.64	0.56	1.02	0.99
12	0.16	1.63	1.54	2.38	0.26	1.33	0.61	0.25	0.76	0.61	1.15	1.22
13	0.17	1.63	1.60	2.51	0.33	1.44	0.61	0.28	0.89	0.67	1.22	1.67
14	0.19	1.63	1.65	2.57	0.43	1.57	0.63	0.31	0.99	0.75	1.25	1.79
15	0.20	1.63	2.01	2.64	0.53	1.68	0.73	0.46	1.06	0.81	1.29	1.80
16	0.21	1.69	2.29	2.74	0.60	1.88	0.77	0.68	1.08	0.89	1.32	1.85
17	0.29	1.76	2.35	2.79	0.74	2.12	1.19	0.85	1.10	1.00	1.33	1.95
18	0.35	1.85	2.40	2.84	0.90	2.22	1.32	1.08	1.17	1.20	1.39	2.07
19	0.45	1.87	2.45	2.93	1.00	2.28	1.45	1.24	1.25	1.31	1.42	2.16
20	0.69	1.88	2.47	3.09	1.18	2.36	1.54	1.32	1.31	1.40	1.45	2.21
21	0.89	1.97	2.50	3.17	1.40	2.49	1.63	1.37	1.39	1.47	1.50	2.25
22	0.95	2.03	2.55	3.29	1.54	2.62	1.65	1.45	1.43	1.53	1.52	2.29
23	0.96	2.08	2.57	3.43	1.58	2.66	1.67	1.47	1.45	1.57	1.54	2.32
24	0.97	2.15	2.58	3.57	1.59	2.68	1.69	1.48	1.47	1.60	1.59	2.33

Source: National Weather Service and Camp,Dresser & McKee, Inc.

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Appendix D

DATA DESCRIBING SIX-HOUR STORMS USED IN ANALYSIS OF STORM DISTRIBUTIONS

Table D-1

MITCHELL FIELD CUMULATIVE SIX-HOUR STORM DATA

Date/Time	Storm Number	1	2	3	4	5	6	Total
6/22/1940 02:00	1	0.30	1.12	2.18	2.97	2.97	3.24	3.24
6/12/1940 03:00	2	0.05	0.24	0.50	0.64	0.73	0.80	0.80
9/07/1941 21:00	3	0.34	0.90	1.33	2.06	2.66	2.85	2.85
11/06/1943 19:00	4	0.11	0.30	0.69	1.14	1.52	1.81	1.81
3/15/1943 11:00	5	0.34	0.50	0.62	0.73	0.76	0.99	0.99
1/27/1944 08:00	6	0.08	0.11	0.34	0.56	0.72	0.73	0.73
9/27/1945 15:00	7	0.18	0.73	1.15	1.57	1.72	1.79	1.79
5/14/1945 01:00	8	0.15	0.24	0.50	0.81	0.99	1.16	1.16
5/04/1946 02:00	9	0.05	0.25	0.55	0.68	0.73	0.84	0.84
1/09/1946 02:00	10	0.11	0.20	0.33	0.38	0.50	0.57	0.57
9/21/1947 03:00	11	0.64	1.09	1.48	1.73	2.01	2.26	2.26
9/04/1947 22:00	12	0.47	0.91	0.96	0.96	0.96	1.99	1.99
6/28/1948 16:00	13	0.01	0.01	0.09	0.62	1.38	1.51	1.51
2/27/1948 13:00	14	0.14	0.30	0.50	0.73	1.02	1.05	1.05
7/26/1949 16:00	15	0.26	1.35	1.52	1.57	1.59	1.64	1.64
6/14/1949 14:00	16	0.44	0.89	1.13	1.19	1.32	1.45	1.45
3/30/1949 23:00	17	0.10	0.31	0.33	0.41	0.57	0.81	0.81
6/12/1950 23:00	18	0.01	0.12	2.38	2.75	2.96	3.06	3.06
4/23/1950 19:00	19	0.16	0.30	0.47	0.75	0.98	1.06	1.06
9/12/1951 16:00	20	0.53	1.36	1.44	1.44	1.47	1.48	1.48
4/28/1951 22:00	21	0.59	0.90	1.06	1.26	1.31	1.32	1.32
4/25/1951 04:00	22	0.09	0.20	0.26	0.40	0.62	0.82	0.82
7/18/1952 00:00	23	0.17	0.45	0.86	1.92	2.07	2.31	2.31
4/12/1952 23:00	24	0.04	0.17	0.26	0.43	0.76	0.93	0.93
7/31/1953 22:00	25	0.13	1.28	1.59	2.36	2.41	3.09	3.09
5/17/1953 08:00	26	0.04	0.05	0.15	0.28	0.44	0.59	0.59
7/06/1954 13:00	27	1.27	1.73	1.73	1.73	1.74	2.03	2.03
6/03/1954 04:00	28	0.25	0.59	0.98	1.26	1.43	1.73	1.73
4/23/1955 23:00	29	0.14	0.37	0.72	0.81	0.96	1.19	1.19
4/27/1956 02:00	30	0.33	0.69	1.04	1.10	1.29	1.51	1.51
6/13/1957 10:00	31	0.02	0.25	0.47	0.94	1.15	1.23	1.23
5/11/1957 01:00	32	0.04	0.07	0.10	0.14	0.44	0.55	0.55
5/09/1957 23:00	33	0.18	0.28	0.43	0.47	0.50	0.52	0.52
10/08/1958 23:00	34	0.40	1.51	1.81	1.96	2.11	2.14	2.14
9/24/1958 01:00	35	0.17	0.34	0.47	0.64	1.15	1.16	1.16
5/30/1958 18:00	36	0.40	0.73	0.85	0.88	0.91	0.95	0.95
7/17/1959 22:00	37	0.78	1.64	1.72	1.95	2.76	3.15	3.15
4/27/1959 20:00	38	0.08	0.20	0.28	0.45	0.50	0.58	0.58
3/30/1960 09:00	39	0.26	0.58	0.72	0.93	1.16	1.30	1.30
3/29/1960 20:00	40	0.04	0.68	0.95	0.95	1.18	1.22	1.22
9/13/1961 18:00	41	0.50	0.85	1.15	1.51	1.95	2.05	2.05
7/02/1962 07:00	42	0.07	0.17	0.34	0.54	1.00	1.26	1.26
4/29/1963 21:00	43	0.07	0.23	0.52	0.79	0.94	1.01	1.01
7/18/1964 04:00	44	0.80	1.48	1.88	2.31	2.32	2.38	2.38
7/01/1964 17:00	45	1.42	1.42	1.42	1.42	1.46	2.11	2.11
3/04/1964 23:00	46	0.13	0.29	0.53	0.79	1.04	1.20	1.20
5/23/1965 01:00	47	0.14	0.22	0.60	1.11	1.23	1.37	1.37
3/17/1965 04:00	48	0.03	0.18	0.31	0.45	0.53	0.60	0.60
3/21/1966 19:00	49	0.17	0.21	0.89	1.09	1.10	1.24	1.24
1/12/1966 12:00	50	0.14	0.28	0.44	0.58	0.72	0.84	0.84
6/28/1967 03:00	51	0.18	0.50	0.97	1.26	1.40	1.45	1.45
6/10/1967 14:00	52	0.28	0.84	0.95	1.06	1.27	1.35	1.35

Table D-1 (continued)

Date/Time	Storm Number	1	2	3	4	5	6	Total
6/26/1968 02:00	53	0.48	0.59	0.71	0.73	1.48	1.60	1.60
6/29/1969 17:00	54	0.01	0.35	1.67	1.91	1.96	1.97	1.97
4/17/1969 11:00	55	0.29	0.39	0.67	0.74	0.85	0.95	0.95
9/23/1970 20:00	56	0.62	0.63	0.63	1.19	1.42	1.45	1.45
6/01/1970 21:00	57	0.19	0.23	0.40	0.66	1.06	1.19	1.19
5/12/1970 21:00	58	0.28	0.64	0.81	0.88	0.93	0.96	0.96
3/18/1971 18:00	59	0.10	0.21	0.36	0.54	0.72	0.84	0.84
2/18/1971 16:00	60	0.07	0.20	0.43	0.52	0.55	0.57	0.57
9/18/1972 00:00	61	0.28	1.52	1.67	1.67	1.73	1.74	1.74
9/12/1972 22:00	62	0.14	0.63	1.30	1.38	1.40	1.41	1.41
4/20/1973 23:00	63	0.20	0.41	0.87	1.82	2.28	2.44	2.44
4/09/1973 09:00	64	0.10	0.27	0.43	0.56	0.77	0.98	0.98
3/13/1973 23:00	65	0.05	0.14	0.22	0.28	0.47	0.67	0.67
7/10/1974 05:00	66	0.03	0.05	0.24	0.93	1.36	1.44	1.44
4/13/1974 21:00	67	0.09	0.58	0.68	0.89	1.16	1.22	1.22
4/28/1975 01:00	68	0.24	1.30	1.44	1.48	1.59	1.70	1.70
2/23/1975 20:00	69	0.08	0.19	0.34	0.56	0.71	0.81	0.81
1/10/1975 00:00	70	0.05	0.16	0.38	0.47	0.51	0.70	0.70
5/05/1976 14:00	71	0.08	0.19	1.09	1.48	1.85	2.03	2.03
4/24/1976 12:00	72	0.17	0.49	0.88	1.31	1.73	1.98	1.98
3/26/1976 19:00	73	0.18	0.79	1.32	1.47	1.70	1.87	1.87
7/17/1977 22:00	74	0.44	0.92	1.05	1.43	1.81	2.23	2.23
5/12/1978 21:00	75	0.22	0.68	1.11	1.27	1.41	1.90	1.90
4/18/1978 03:00	76	0.05	0.20	0.36	0.55	0.71	0.78	0.78
4/06/1978 07:00	77	0.09	0.14	0.20	0.40	0.54	0.62	0.62
4/25/1979 19:00	78	0.16	0.40	0.66	1.03	1.27	1.59	1.59
4/11/1979 17:00	79	0.03	0.06	0.13	0.38	0.82	1.20	1.20
5/17/1980 16:00	80	0.05	0.40	0.62	0.70	0.75	0.81	0.81
4/14/1980 09:00	81	0.11	0.15	0.29	0.41	0.47	0.50	0.50
4/08/1981 15:00	82	0.20	0.27	0.52	0.75	0.86	0.89	0.89
6/25/1982 10:00	83	0.07	0.44	0.49	0.82	0.92	0.93	0.93
8/16/1983 22:00	84	0.53	0.63	1.26	1.33	2.46	3.00	3.00
4/09/1983 05:00	85	0.12	0.46	0.64	0.78	0.94	1.00	1.00
10/18/1984 17:00	86	0.21	0.34	0.57	0.78	0.97	1.41	1.41
7/10/1984 17:00	87	0.17	1.03	1.13	1.18	1.26	1.27	1.27
5/25/1984 02:00	88	0.27	0.47	0.55	0.75	1.13	1.21	1.21
9/08/1985 07:00	89	0.15	0.32	0.54	0.54	0.54	1.33	1.33
5/26/1985 16:00	90	0.06	0.62	0.70	0.98	1.15	1.23	1.23
8/06/1986 10:00	91	0.18	3.27	5.47	5.96	6.16	6.29	6.29
6/27/1986 02:00	92	1.37	2.05	2.15	2.20	2.28	2.32	2.32
5/17/1986 15:00	93	0.19	0.39	0.72	0.77	0.82	0.83	0.83
8/16/1987 07:00	94	0.56	0.60	0.66	0.70	1.03	1.22	1.22
1/19/1988 15:00	95	0.22	0.40	0.52	0.78	1.13	1.39	1.39
9/09/1989 04:00	96	0.15	0.20	0.90	1.20	1.26	1.29	1.29
3/28/1989 06:00	97	0.18	0.30	0.32	0.44	0.74	0.76	0.76
5/10/1990 00:00	98	0.22	0.64	0.95	1.19	1.24	1.49	1.49
5/09/1990 15:00	99	0.15	0.32	0.46	0.73	0.85	0.97	0.97
3/26/1991 02:00	100	0.05	0.23	0.51	0.57	0.75	0.84	0.84
6/04/1992 22:00	101	0.05	0.33	0.57	1.01	1.09	1.17	1.17
3/09/1992 12:00	102	0.13	0.19	0.21	0.26	0.37	0.54	0.54
4/19/1993 14:00	103	0.30	0.57	0.70	1.01	1.15	1.36	1.36
3/22/1993 22:00	104	0.12	0.19	0.26	0.37	0.56	0.68	0.68
1/20/1993 23:00	105	0.07	0.15	0.27	0.37	0.46	0.59	0.59

Table D-1 (continued)

Date/Time	Storm Number	1	2	3	4	5	6	Total
2/19/1994 22:00	106	0.08	0.14	0.52	0.64	0.83	1.00	1.00
5/08/1995 21:00	107	0.15	0.22	0.29	0.46	0.74	0.86	0.86
4/18/1995 04:00	108	0.05	0.15	0.30	0.38	0.55	0.61	0.61
6/17/1996 02:00	109	0.10	0.24	0.24	0.24	1.18	1.27	1.27
4/14/1996 23:00	110	0.10	0.24	0.42	0.62	0.77	0.94	0.94
6/21/1997 04:00	111	0.12	0.56	1.60	2.45	3.04	3.08	3.08
6/15/1997 22:00	112	0.09	0.30	0.62	0.89	1.18	1.29	1.29
4/30/1997 15:00	113	0.15	0.36	0.60	0.67	0.72	0.83	0.83

Source: National Weather Service and Camp Dresser & McKee, Inc.

Appendix E

COMPARISON OF DESIGN STORM APPROACHES

EVALUATION OF DESIGN STORM METHODS USING HYDROLOGIC MODELS OF ACTUAL WATERSHEDS

The performance of three candidate design storm methods was evaluated by performing hydrologic model simulations using each method. Flood hydrographs resulting from 100-year recurrence interval storms were computed using the following design storm approaches:

- Twenty-four hour rainfall depth from National Weather Service Technical Paper No. 40 (TP 40) with the U.S. Soil Conservation Service (SCS, now the U.S. Natural Resources Conservation Service) Type II distribution.

- Rainfall depths from Illinois State Water Survey Bulletin 71, with the appropriate Huff distribution.

- SEWRPC 2000 rainfall depths as set forth in Table 18 of this report, with the 90th percentile distribution from Table 26 of this report.

Watersheds Analyzed

The analyses used three different hydrologic models, with flood flows being developed for a range of watershed land uses, including predominantly rural, predominantly urban, and combinations of rural and urban uses. In addition, a range of tributary areas was analyzed to enable comparison of design storm results for 1) smaller areas that might be considered for stormwater management applications or for flood hazard analyses in headwater areas, and 2) larger areas for which model results would be applied for floodland management or flood hazard area delineation purposes. Information on the subwatersheds and watersheds analyzed is provided in Table E-1. The watersheds and hydrologic models are described below:

- **Calibrated U.S. Environmental Protection Agency (USEPA) HSPF model of the 111-square-mile Menomonee River watershed at U.S. Geological Survey (USGS) stream gauge No. 04087120 at N. 70th Street in the City of Wauwatosa.** This model was originally developed by the Southeastern Wisconsin Regional Planning Commission (SEWRPC) under the 1976 Menomonee River watershed study and was refined by SEWRPC under the 1990 stormwater drainage and flood control system plan for the Milwaukee Metropolitan Sewerage District (MMSD) and by Camp Dresser & McKee Inc. (CDM) under the ongoing MMSD watercourse system plan. The model condition used for this study assumed planned year 2020 land use in the watershed. Under those conditions, about 70 percent of the watershed would be expected to be developed in urban land uses and about 30 percent would be in rural uses.

- **U.S. Army Corps of Engineers (USCOE) HEC-1 model of the 682-square-mile Milwaukee River watershed at USGS stream gauge No. 040807000 near N. Richards Street in the City of Milwaukee.** This model was originally developed by the Wisconsin Department of Natural Resources under the 1991 Federal

Table E-1

RESULTS OF DESIGN STORM ANALYSES

Watershed or Subwatershed	Drainage Area at Location of Interest (square miles)	Hydrologic Model	Peak 100-Year Recurrence Interval Flood Flow based on Analysis of USGS Gauge Record (cfs)	100-Year Recurrence Interval Flood Flows (cfs)			Ratio of SEWRPC 2000 Design Storm Peak Flow to TP-40/SCS II Peak Flow	Ratio of SEWRPC 2000 Design Storm Peak Flow to Bulletin 71/Huff Peak Flow
				TP-40 Rainfall, SCS Type II Distribution	ISWS Bulletin 71 Rainfall, Huff Distribution	SEWRPC 2000 Rainfall, 90th Percentile Distribution		
Milwaukee River	682	HEC-1	13,500[a]	15,300[b]	16,900[c]	14,900[d]	0.97	0.88
Cedar Creek	125	HEC-1	- -	5,480[b]	6,990[c]	6,170[d]	1.13	0.88
Menomonee River	111	HSPF	12,800[e] 14,300[f]	14,300[g]	12,200[h]	14,900[i]	1.04	1.22
Lincoln Creek	20.8	SWMM	- -	6,780[j]	6,760[k]	8,010[l]	1.18	1.18
Lincoln Creek	18.4	SWMM	- -	5,800[j]	5,890[k]	5,960[l]	1.03	1.01
Kewaskum Creek	11.1	HEC-1	- -	2,400[j]	2,260[m]	2,200[m]	0.92	0.97
North Creek	1.49	HEC-1	- -	700[j]	490[o]	710[p]	1.01	1.45
Kettle View Creek	1.07	HEC-1	- -	840[j]	510[q]	680[r]	0.81	1.33
Bishops Woods Tributary	0.53	XP-SWMM	- -	540[j]	420[s]	500[r]	0.93	1.19

[a] *Based on 82 years of record (1915-1996).*

[b] *24-hour storm duration. Areal reduction factor of 0.91 applied as recommended in NWS TP-40. Rainfall depth is 5.00 inches with reduction factor applied.*

[c] *24-hour storm duration. Areal reduction factor of 0.91 applied as recommended in ISWS Bulletin 71. Rainfall depth is 5.68 inches with reduction factor applied.*

[d] *24-hour storm duration. Areal reduction factor of 0.91 applied as recommended in ISWS Bulletin 71. Rainfall depth is 5.35 inches with reduction factor applied.*

[e] *Based on 35 years of record (1962-1997).*

[f] *Based on continuous simulation of 58 years of record (1940-1997).*

[g] *24-hour storm duration. Areal reduction factor of 0.92 applied as recommended in NWS TP-40. Rainfall depth is 5.06 inches with reduction factor applied.*

[h] *Critical storm duration is six hours. Areal reduction factor of 0.88 applied as recommended in ISWS Bulletin 71. Rainfall depth is 4.12 inches with reduction factor applied.*

[i] *Critical storm duration is two hours. Areal reduction factor of 0.83 applied as recommended in ISWS Bulletin 71. Rainfall depth is 3.02 inches with reduction factor applied.*

[j] *24-hour storm duration. No areal reduction factor applied. Rainfall depth is 5.50 inches.*

[k] *Critical storm duration is three hours. No areal reduction factor applied. Rainfall depth is 3.99 inches.*

[l] *Critical storm duration is three hours. No areal reduction factor applied. Rainfall depth is 3.89 inches.*

[m] *Critical storm duration is 12 hours. No areal reduction factor applied. Rainfall depth is 5.43 inches.*

[n] *Critical storm duration is eight hours. No areal reduction factor applied. Rainfall depth is 4.88 inches.*

[o] *Critical storm duration is three hours. No areal reduction factor applied. Rainfall depth is 3.99 inches.*

[p] *Critical storm duration is six hours. No areal reduction factor applied. Rainfall depth is 4.70 inches.*

[q] *Critical storm duration is two hours. No areal reduction factor applied. Rainfall depth is 3.62 inches.*

[r] *Critical storm duration is two hours. No areal reduction factor applied. Rainfall depth is 3.64 inches.*

[s] *Critical storm duration is one hour. No areal reduction factor applied. Rainfall depth is 2.93 inches.*

Source: Camp Dresser & McKee and SEWRPC.

Emergency Management Agency flood insurance study for Ozaukee County. Refinements and corrections to this model were made by CDM under the MMSD watercourse system plan. This model also includes the 125-square-mile Cedar Creek subwatershed. At the USGS gauge site, land use in the Milwaukee River watershed is about 75 percent rural and 25 percent urban. As noted in the frequency analysis section of this report, this stream gauge site is part of the USGS Hydroclimatic Data Network. The sites in that network have a complete and accurate long-term streamflow record and reasonably unchanged basin conditions when considered within the context of the entire watershed area. Thus, flood frequency analyses made using the entire gauge record can be compared to hydrologic model results that reflect approximate existing conditions in the watershed. Such a comparison is made later in this Appendix.

- **XP-SWMM model of the highly urbanized, 20.8-square-mile, ungauged Lincoln Creek subwatershed at its confluence with the Milwaukee River in the City of Milwaukee.** This model was developed by CH2M Hill, Inc. for the November 1996 *Lincoln Creek Flood Control Management Plan* prepared for MMSD. The model was subsequently refined by CDM and converted to a U.S. Environmental Protection Agency SWMM model during the flood control project design phase.

- **USCOE HEC-1 model of the predominantly rural, ungauged Kettle View Creek, North Creek, and Kewaskum Creek subwatersheds of the Milwaukee River watershed in Washington County in the Village and Town of Kewaskum.** This model was developed by SEWRPC under the 1997 land use and street system plan for the Village of Kewaskum. For purposes of comparison, flood flows were determined for Kettle View Creek at Kettle View Drive, 0.9 mile upstream of the mouth (tributary area of 1.07 square miles); North Creek just downstream of its confluence with Knights Creek, and 0.8 mile upstream of the mouth (tributary area of 1.49 square miles); and Kewaskum Creek at its mouth (tributary area of 11.1 square miles). The planned year 2010 land use condition was modeled. Under that condition, the portion of the Kettle View Creek subwatershed that was considered was assumed to still be completely rural and the portions of the North and Kewaskum Creek subwatersheds were assumed to be more than 90 percent rural.

- **XP-SWMM model of the ungauged, 0.53-square-mile Bishops Woods Tributary subbasin of the Underwood Creek subwatershed in the City of Brookfield and the Village of Elm Grove.** This model was developed by Ruekert & Mielke, Inc. and the SEWRPC staff under the 1999 stormwater and floodland management plan for the Dousman Ditch and Underwood Creek subwatersheds. This subbasin was analyzed for planned buildout land use conditions under which about 85 percent of the subbasin would be in urban uses and 15 percent would be in rural uses.

The SCS Type II distribution is designed to include the full range of critical durations within a single 24-hour, or longer, storm distribution. Thus, all design storm analyses using that distribution were made for a 24-hour storm. When applying the Huff and SEWRPC 90th percentile distributions, the critical storm duration for the tributary area was determined by computing flood hydrographs for storms of various durations and selecting the critical duration as that which yielded the largest peak flow.[1] Critical storm durations are listed in Table E-1. As can be seen from that table, the critical storm duration is a function of both watershed size and the type of storm distribution that is applied.

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[1] *There are different Huff distributions for storms of different durations. As specified in Huff's publications, the Huff first quartile distribution was applied for storm durations of six hours or less; the second quartile distribution was used for durations greater than six hours, but less than or equal to 12 hours; and the third quartile distribution was used for durations greater than 12 hours, but less than or equal to 24 hours. Huff has published specific distributions for small, medium and large watersheds which were also used as required.*

Comparison of Design Storm Results

Results of this analysis are shown in Table E-1, which lists the maximum flows resulting from distribution of the 100-year rainfall depths according to the three procedures.

Comparison of the SEWRPC 2000 Rainfall and Distribution Approach With the TP-40/SCS II Approach

This comparison indicates that application of the SEWRPC 2000 design storm generally yields peak flows that are similar to, or somewhat less than, those determined using the TP-40/SCS II approach. For the Milwaukee and Menomonee River watersheds, the two methods yield peak 100-year flows within 4 percent of each other. This agreement would be expected for larger, more complex watersheds where the effects of floodwater storage and hydrograph timing tend to damp out differences in rainfall intensity. For the Cedar Creek subwatershed, the SEWRPC method yields flood flows that are 13 percent greater than the TP-40/SCS II approach.

For smaller subwatershed areas, such as those of 20.8 square miles and less in Table E-1, the SEWRPC design storm generally yields peak flows that are similar to, or less than, those determined using the TP-40/SCS II approach. The exception to this is the outlet of the Lincoln Creek subwatershed where the SEWRPC 2000 peak flow is about 18 percent greater than the TP-40/SCS II peak flow.[2].

Comparison of the SEWRPC 2000 Rainfall and Distribution Approach With the Bulletin71/Huff Approach

This comparison indicates that application of the SEWRPC 2000 design storm generally yields peak flows that are similar to, or somewhat less than, those determined using the Bulletin 71/Huff approach for tributary areas of about 11 square miles and greater. However, for Lincoln Creek at its mouth and for the Menomonee River watershed, the SEWRPC method yields flood flows that are 18 and 22 percent greater, respectively, than the Bulletin 71/Huff approach.

For smaller subwatershed areas, such as those of 1.5 square miles and less in Table E-1, the SEWRPC design storm yields peak flows that are about 20 to 45 percent greater than those determined using the Bulletin 71/Huff approach. This difference can be attributed to the location of the most intense rainfall period within each storm distribution. The SEWRPC 2000 90th percentile distribution places the most intense rainfall period in the second half of the storm, after the initial losses have been satisfied and infiltration loss rates have decreased. The Huff distribution that is recommended to be applied for storms with durations of six hours or less, such as would be critical for smaller subbasins, places the most intense rainfall period in the first quarter of the storm. Thus, with the first quartile Huff distribution, the initial losses are at least partially satisfied during the most intense period of the storm, and the intense period also occurs when infiltration capacities are greater than later in the storm. This situation would tend to reduce the peak rate of runoff relative to that computed for the SEWRPC 2000 90th percentile distribution.

Comparison of the SEWRPC 2000 Rainfall and Distribution Approach With Flood Frequency Analyses of Gauged Sites

As stated previously, the USGS stream gauge on the Milwaukee River in the City of Milwaukee at N. Richards Street is part of the USGS Hydroclimatic Data Network. Watershed conditions in areas tributary to gauge sites in that network have not changed enough over time to significantly alter the hydrologic characteristics of the watershed at

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[2] The modeled flows for Lincoln Creek at W. Villard Avenue in the City of Milwaukee (drainage area of 18.4 square miles) agree closely for all three design storm methods. The 18 percent difference in peaks at the mouth between the SEWRPC 2000 method versus the other two methods is due to timing characteristics of the hydrographs for the Lincoln Creek main stem and Crestwood Creek, which flows into the main stem downstream from W. Villard Avenue. Because the 90th percentile distribution has the most intense rainfall near the end of the storm period, the peak flow in Crestwood Creek occurs near the end of the storm. In this case, the Crestwood Creek peak flow nearly coincides with the peak flow in the Lincoln Creek main stem. For theTP-40/SCS Type II and Huff/Bulletin 71 methods, the peaks on the two streams are more separated in time, and the combined peak on the main stem is not as large as with the SEWRPC 2000 method.

the site. Thus, it is possible to directly compare the flood frequency relationship derived from the historic gauge record with the flows modeled using the design storm approaches. The SEWRPC 2000 design storm produces a peak 100-year recurrence interval flood flow that is about 10 percent greater than that determined from log Pearson Type III analysis of the 82 years of historic record at the USGS stream gauge on the Milwaukee River in the City of Milwaukee at N. Richards Street. The TP-40/SCS Type II and Bulletin 71/Huff design storms produce 100-year flood flows that are about 13 percent and 25 percent higher, respectively, than that determined from the gauge record.

The record at the USGS stream gauge on the Menomonee River in the City of Wauwatosa at N. 70th Street is not statistically stationary (that is, the record exhibits an increasing trend over time). This nonstationarity can be attributed to changes that have occurred in the watershed over time as rural lands were converted to urban uses and as the drainage system was altered. Therefore, statistical analysis of the 35 years of record at the gauge does not adequately determine the 100-year flood flow at the gauge. A better determination can be made through continuous simulation of the streamflow record for a relatively long period of time using a calibrated model of the watershed. Such a model was originally developed by SEWRPC under the 1976 Menomonee River watershed study and has been refined and updated at several times in the intervening years, as described above. That model, which simulates a 58-year period of record, yields a 100-year recurrence interval flood flow of 14,300 cfs for the Menomonee River at N. 70th Street under planned year 2020 land use conditions. That flow is equal to the TP-40/SCS Type II method peak flow, within 4 percent of the SEWRPC 2000 method peak flow, and within 15 percent of the Bulletin 71/Huff method peak flow.

Comparison of SEWRPC 2000 Rainfall Distributed According to the SCS Type II Procedure With the TP-40/SCS II Approach

The appropriateness of applying the SCS Type II distribution to the SEWRPC 2000 rainfall depths was investigated for the USGS stream gauge site on the Milwaukee River near Richards Street in the City of Milwaukee. As noted above, that USGS stream gauge is included in the Hydroclimatic Data Network and, although development has occurred in the watershed, hydrologic conditions have not been altered enough to create evidence of an increasing trend in streamflows over time.

Distributing the SEWRPC 2000 100-year, 24-hour rainfall amount using the SCS Type II approach and applying the resultant design storm over the Milwaukee River watershed yields a peak flood flow of 16,700 cfs. That flow is about 24 percent greater than the 100-year flood flow of 13,500 cfs determined from statistical analysis of the long-term gauge record; about 12 percent greater than the flood flow of 14,900 cfs determined based on application of the SEWRPC 2000 100-year, 24-hour rainfall amount using the 90th percentile distribution; and about 9 percent greater than the flood flow of 15,300 cfs based on application of the TP-40/SCS II approach. Thus, application of the SEWRPC 2000 rainfall with the SCS Type II distribution yields a 100-year flood peak greater than the peaks based on both the TP-40/SCS II design storm approach and analysis of the gauge record. That result indicates that application of the SEWRPC 2000 rainfalls with the SCS Type II distribution would be inappropriate for large storms. However, as noted above, application of the SEWRPC 2000 rainfalls with the 90th percentile distribution, as recommended in this report, does produce peak 100-year flood flows that agree well with those determined from statistical analyses of long-term measured or simulated flows.

Conclusions

Based on the foregoing, it can be concluded that:

- Both the TP-40/SCS Type II method and the SEWRPC 2000 method produce 100-year flood flows that agree well with flows computed based on analyses of long-term USGS stream gauge records or long-term continuous simulation of streamflow for relatively large watersheds.

- For two intermediate-size subwatersheds in the set analyzed) the rural 11.1-square-mile Kewaskum Creek subwatershed and the urban 18.4-square-mile portion of the Lincoln Creek subwatersheds), the three design storm methods used produce similar results. For the third intermediate-size subwatershed (the 20.8-square-mile Lincoln Creek subwatershed at its mouth), the SEWRPC 2000 Method produced a peak flow that is 18 percent greater than the peaks computed with either of the other two methods.

- For two of the smaller subwatersheds with areas of 1.5 square miles or less, the SEWRPC 2000 design storm method produced 100-year flood flows that fall between those of the other two methods. For the third smaller subwatershed, the TP-40/SCS Type II method and the SEWRPC 2000 method produced similar peak flows that are greater than that determined using the Bulletin 71/Huff method.

- It is more appropriate to apply the SEWRPC 2000 rainfall depths with the 90th percentile distribution, than to use them with the SCS Type II distribution.

EVALUATION OF DESIGN STORM METHODS IN MODELS OF A HYPOTHETICAL, SMALL SUBBASIN

An additional investigation was conducted to evaluate the effect of rainfall distribution on detention basin design for a hypothetical 160-acre development using land cover typically found in suburban areas. Again, the TP-40/SCS Type II, Bulletin 71/Huff, and the SEWRPC 2000 design storm methods were used to conduct the analysis.

The hypothetical detention basin design is based on a 160-acre drainage area with a pre-development NRCS runoff curve number of 70 and a post-development curve number of 83. Two release rate rules were employed to determine the storage requirements. The procedures for computing post-development 100-year release rates were:

- Match to pre-development 100-year peak flow for a range of storm durations and determine the critical maximum detention volume.[3]

- Match to pre-development two-year peak flow for the critical storm duration and determine the critical maximum detention volume.

The pre-development and post-development peak two- and 100-year storm flows determined using the TP-40/SCS Type II, Bulletin 71/Huff, and SEWRPC 2000 methods are shown in Table E-2. Peak two- and 100-year storm flows computed for each design storm method and for several storm durations are also shown in that table.

Computed pre-development peak flows range from 153 cfs using the Bulletin 71/Huff method to 167 cfs when the SEWRPC 2000 method is applied. Computed post-development unregulated flows range from 290 cfs using the TP-40/SCS Type II method to 366 cfs when the Bulletin 71/Huff method is applied. Thus, application of the SEWRPC 2000 design storm method yielded peak flows that are in the mid- to high-range for the three methods considered.

The results shown in Table E-3 indicate that the design storage volume needed to match the post-development 100-year storm peak flow to the critical pre-development 100-year peak is similar for all three methods. The design storage volume needed to match the post-development 100-year storm peak flow to the critical pre-development two-year peak is similar for the Bulletin 71/Huff and the SEWRPC 2000 methods, but approximately 30 percent less for the TP-40/SCS Type II method. Thus, depending on the release rate criterion that is applied, use of the SEWRPC design storm method would result in the provision of a maximum detention storage volume that is approximately equal to that determined for the Bulletin 71/Huff method and equal to, or greater than, that determined for the TP-40/SCS Type II method.

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[3] *When the approach of matching pre- and post-development peak flows is applied, flows are generally matched across a range of recurrence intervals that would typically include two, 10, and 100 years. For illustrative purposes, only the 100-year storm is examined here.*

Table E-2

PEAK FLOWS FOR HYPOTHETICAL 160-ACRE SUBBASIN

Storm Duration (hours)	TP-40 Rainfall, SCS Type II Distribution			ISWS Bulletin 71 Rainfall, Huff Distribution			SEWRPC 2000 Rainfall, 90th Percentile Distribution		
	Two-Year Pre-Development Flow (cfs)	100-Year Pre-Development Flow (cfs)	100-Year Post-Development Flow (cfs)	Two-Year Pre-Development Flow (cfs)	100-Year Pre-Development Flow (cfs)	100-Year Post-Development Flow (cfs)	Two-Year Pre-Development Flow (cfs)	100-Year Pre-Development Flow (cfs)	100-Year Post-Development Flow (cfs)
1	--	--	--	6	117	366	4	110	355
2	--	--	--	15	152	364	9	167	347
3	--	--	--	17	153	325	13	157	274
6	--	--	--	20	138	240	16	131	182
12	--	--	--	13	85	133	13	82	105
24	27	157	290	14	73	98	9	49	61

Source: Camp,Dresser & McKee, Inc..

Table E-3

DETENTION STORAGE ANALYSIS FOR HYPOTHETICAL 160-ACRE SUBBASIN

Storm Duration (hours)	TP-40 Rainfall, SCS Type II Distribution				ISWS Bulletin 71 Rainfall, Huff Distribution				SEWRPC 2000 Rainfall, 90th Percentile Distribution			
	Storage to Match Two-Year Critical Pre-Development Flow		Storage to Match Corresponding 100-Year Pre-Development Flow		Storage to Match Two-Year Critical Pre-Development Flow		Storage to Match Corresponding 100-Year Pre-Development Flow		Storage to Match Two-Year Critical Pre-Development Flow		Storage to Match Corresponding 100-Year Pre-Development Flow	
	Storage (ac-ft)	Outflow (cfs)	Storage (ac-ft)	Outflow (cfs)	Storage (ac-ft)	Outflow (cfs)	Storage (ac-ft)	Outflow (cfs)	Storage (ac-ft)	Outflow (cfs)	Storage (ac-ft)	Outflow (cfs)
1	--	--	--	--	17	20	12	153	16	16	11	167
2	--	--	--	--	25	20	17	153	24	16	18	167
3	--	--	--	--	28	20	18	153	28	16	19	167
6	--	--	--	--	35	20	18	153	37	16	16	167
12	--	--	--	--	38	20	--	--[a]	42	16	--	--[b]
24	32	27	19	157	44	20	--	--[a]	47	16	--	--[b]

[a]*Peak post-development flow is less than critical peak pre-development flow of 153 cfs. Therefore, detention storage is not needed to control the peak flow.*

[b]*Peak post-development flow is less than critical peak pre-development flow of 167 cfs. Therefore, detention storage is not needed to control the peak flow.*

Source: Camp,Dresser & McKee, Inc. and SEWRPC.

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