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CHLORIDE CONDITIONS AND TRENDS IN SOUTHEASTERN WISCONSIN

Chapter 6

CHLORIDE CONDITIONS AND TRENDS: GROUNDWATER

6.1 INTRODUCTION

This chapter will provide information on the Region's groundwater resources, sources and impacts of chloride to these resources, relevant regulatory standards, and chloride conditions and trends in the groundwater across the chloride study area. Analysis of conditions and trends is split between shallow groundwater and groundwater supplying public drinking water.

6.2 GROUNDWATER BACKGROUND

Groundwater is a dynamic, vital resource yet it is not visible for casual observation except where it discharges to surface water (e.g., springs and seeps). Precipitation is the ultimate source of essentially all of Southeastern Wisconsin's groundwater. Water that percolates into the land surface soils or into the bed of a waterbody and does not quickly return to the surface via evapotranspiration or by re-entering waterbodies is termed groundwater. The water elevation in the shallowest laterally extensive saturated strata is commonly referred to as the "water table."[1]

Even though groundwater is largely invisible, it is vitally important to the Region's ecology and human inhabitants. Private and public water supplies throughout inland portions of Southeastern Wisconsin

[1] *In some instances, saturated areas are created by water accumulating on impermeable layers buried in the subsurface soils. Such saturated areas can be underlain by unsaturated sediment and are termed "perched" water table aquifers.*

depend entirely upon groundwater, making it a natural resource crucial to modern human habitation. In general, the groundwater supplies in the study area adequately support growing human populations, agricultural demands, commerce, and diverse industrial uses. However, overexploitation and attendant water shortages may occur in areas of concentrated development, intensive landscape manipulation, inconducive geology, and/or intense human water demand. In addition to providing potable water for human needs, groundwater systems help attenuate runoff volumes, reducing flood risks along lake and stream corridors. Groundwater characteristics such as the amount available to wells and discharging to seeps and springs, as well as its ability to help moderate floods and support natural resource features, are controlled by a plethora of natural and human-induced factors such as precipitation, topography, soil permeability and structure, land use, potable water supply, and the water-bearing properties of sediments. Balancing growing human demands with long-term sustainability and ecosystem health necessitates careful, enlightened groundwater resource planning and management.

In addition to providing for human needs and desires, groundwater is vital to terrestrial and aquatic ecosystem health. Groundwater is often the only natural source of water to surface-water features during dry weather and is therefore critical to healthy stream ecology. Groundwater modulates flood, fair-weather, and drought stream flows by detaining water during wet weather and gradually releasing it to surface water features over extended time periods. Reduced flow volumes during wet weather help reduce erosion in uplands along watercourses, thereby contributing to improved water quality and ecosystem health. Water that reaches waterbodies via groundwater is commonly referred to as "baseflow." Baseflow can either directly enter large waterbodies, or it can discharge to small streams, ponds, springs, and seeps tributary to larger waterbodies. Baseflow sustains dry-weather lake elevations, wetlands, and the flow of rivers and streams. In comparison to surface water runoff, groundwater typically contains little to no sediment or phosphorus, has a more stable temperature regime, and commonly contains a lower overall pollutant load—all of which are favorable to aquatic life and the ecology of waterbodies. Groundwater-derived baseflow sustains waterbodies allowing them to maintain a diverse assemblage of plants and animals and enables them to provide unique ecological functions.

Aquifers

In southeastern Wisconsin, local precipitation is the source of most groundwater and groundwater is stored in and moves through the natural pore spaces and fractures found in unconsolidated sediment and bedrock. Sediment and rock units with significant porosity or fracturing can store large amounts of water. These units can supply useable amounts of water over prolonged periods and are referred to as "aquifers." Figure 6.1

shows that three main aquifers underlie southeastern Wisconsin. They are described below in order of increasing depth from the land surface.

- **Sand and gravel aquifer:** This aquifer is primarily found in porous, coarse-grained sand and gravel deposited by glacial action. Much of the water feeding this aquifer infiltrates through the local land surface. Its thickness and properties vary widely, but it is an important source of local water supply for many portions of the Southeastern Wisconsin Region. It is commonly highly vulnerable to contamination and over exploitation. The quality and quantity of water in this aquifer can be significantly influenced by changes in local land use. The sand and gravel aquifer is generally in good hydraulic communication with the underlying dolomite aquifer. The sand and gravel aquifer is critical for contributing baseflows to streams, rivers, lakes, and wetlands.

- **Dolomite aquifer:** Water in this aquifer is stored in and moves primarily through fractures in the bedrock. Much of the water found in this aquifer is derived from local infiltration through the sand and gravel aquifer above it. Although its water-bearing characteristics and thickness vary widely, it is a very important water supply aquifer. When located under a relatively thick layer of unconsolidated sediment, it is somewhat less vulnerable to contamination and overexploitation.

- **Sandstone aquifer:** The sandstone aquifer is commonly deeply buried and is found at depths well below the sand and gravel and dolomite aquifers. Water is stored in and moves through the rock's innate porosity and fractures in the rock. This aquifer is very thick, but the water bearing characteristics vary widely with depth. A layer of low permeability Maquoketa shale that overlies the sandstone aquifer extends over the eastern portion of the study area. This shale separates the sandstone aquifer from the dolomite and sand and gravel aquifers that lie above it and prevents water from percolating into the sandstone aquifer. Water recharging the sandstone aquifer infiltrates through the shallow sand and gravel and dolomite aquifers in western portions and to the west of the study area. While the sandstone aquifer is less vulnerable to pollution sources in areas where the Maquoketa shale is present, it is somewhat more vulnerable to contamination in its recharge area where it is hydrologically connected to the surface. The sandstone aquifer is an important source of municipal and industrial water supply.

Groundwater Recharge, Movement, and Discharge

The flow of groundwater in the subsurface is a complex three-dimensional process determined by several factors, including precipitation, topography, soil permeability and structure, land use, and the lithology and water-bearing properties of rock units. Water enters groundwater flow systems in recharge areas and moves through them toward discharge areas. In recharge areas, the flow of groundwater is downward; in discharge areas, the flow is upward. Between these two areas, groundwater flow is essentially horizontal. The idealized concept of groundwater flow in Figure 6.2 shows groundwater moving from recharge areas to discharge areas. One of the most significant differences between recharge areas and discharge areas is that the areal extent of discharge areas is generally much smaller than that of recharge areas. Regional recharge occurs primarily in upland areas or topographic high points, but local recharge can occur anywhere. Discharge from aquifers occurs at low points in the land surface such as rivers and lakes, or to wells. Recharge areas from which flow paths originate and diverge, are the locations of groundwater divides, across which there is no horizontal groundwater flow.

The pattern of groundwater flow from a recharge area to a discharge area constitutes a dynamic flow system, which incorporates several superimposed elements (see Figure 6.2). Depending on the drainage basin topography and the thickness of the aquifer system, groundwater flow systems may have local, intermediate, and regional components. If the surface topography has well-defined local relief, such as in many parts of the study area, a series of local shallow groundwater flow systems can form. If the aquifer systems are large and deep enough, deeper, intermediate, and regional flow systems may develop. There may be a series of local and intermediate flow systems between the regional recharge and discharge areas (see Figure 6.2). This idealized description of flow systems assumes steady-state flow, without extensive pumping of groundwater from deep wells. Groundwater flow systems can be altered both locally and regionally by well pumping.

The time it takes groundwater to move from a recharge area to a discharge area may range from a few days in the zone closest to the discharge area to thousands of years (millennia) for water that moves from the central part of a major recharge area through the deeper parts of the groundwater flow system. Flow paths that penetrate into the deepest portions of the aquifer system generally have the longest travel time from recharge to discharge areas (see Figure 6.2).

Much of the movement and discharge of groundwater in the Region occurs in local, unconfined, shallow flow systems within a few miles of points of recharge.[2] Depth of the local systems probably does not exceed 200 feet. Groundwater in semi-confined or confined aquifers moves in intermediate or regional flow systems

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[2] *H.L. Young,* Summary of Ground-Water Hydrology of the Cambrian-Ordovician Aquifer System in the Northern Midwest, United States, *U.S. Geological Survey Professional Paper 1405-A, 1992.*

within the bedrock, where the flow is deeper and slower, and crosses much longer distances from recharge areas to discharge points such as Lake Michigan or deep wells in the eastern part of the study area.

Groundwater supplies are generally replenished by precipitation soaking into the ground and entering aquifers. Water that infiltrates the land surface and enters aquifers is often referred to as “groundwater recharge.” Precipitation is the source of essentially all groundwater recharge, but recharge does not necessarily occur uniformly throughout the landscape, at the point where precipitation initially strikes the Earth, or uniformly throughout the year. Relatively flat undeveloped areas underlain by thick layers of granular permeable mineral soil are generally able to contribute more water to groundwater recharge and are identified as having high or very high groundwater recharge potential. On the other hand, hilly areas underlain with low permeability soils such as clay soils and drained by storm sewers are more likely to have low recharge potential. Water running off from areas less conducive to groundwater recharge can still flow to areas more permeable and infiltrate there, becoming a component of groundwater flow. Most groundwater recharge occurs during periods of low natural water demand such as times when plants are dormant or when precipitation or runoff are abundant. Little groundwater recharge occurs from small summer rains, even on good recharge areas, because higher uptake by plants and greater evaporation rates associated with warmer temperatures consume the incident precipitation, returning it to the atmosphere.

The relationship between surface waterbodies and groundwater is complicated. Because the sand and gravel and dolomite aquifers are hydrologically connected to surface waterbodies, water can move both from groundwater to a surface waterbody and from a surface waterbody to groundwater. As shown in the “Gaining Stream” panel of Figure 6.3, a waterbody gains water when groundwater elevations are higher than the adjacent waterbody. Conversely, a perennial waterbody loses water wherever the water table elevation is lower than the elevation of the waterbody. In such instances, water seeps into the underlying groundwater system (see Figure 6.3, “Losing Stream”). In some instances, such as ephemeral streams, the water table may not be in contact with the surface water feature. Stream reaches that receive groundwater discharge are called gaining reaches and those that lose water to the underlying aquifer are called losing reaches. The rate at which water flows between a stream and its adjoining aquifer depends on the hydraulic gradient between the two waterbodies and on the hydraulic conductivity of geologic materials that are located at the groundwater/surface water interface. For example, a clayey streambed will reduce the rate of flow between a stream and the adjacent aquifer as compared to a sandy or gravelly streambed. In the absence of surface water contributions, streamflow volume increases along gaining reaches and decreases along losing reaches. Streams along their length can have both gaining and losing reaches and the extent of these reaches may change based upon prevailing conditions. Since precipitation rates, evapotranspiration, water table elevations, and human-induced hydrologic stressors vary with time, a particular stream reach can switch from a gaining to a losing condition or from a losing to a gaining condition from one time period to the next.

Movements of Contaminants in Groundwater

Contamination of groundwater occurs when pollutants enter an aquifer. Some of the routes through which contaminants enter reflect the process of groundwater recharge and the hydraulic connections between groundwater and surface waterbodies. Recharge can carry contaminants land surface runoff through the soil into aquifers. Similarly, the connections between surface waterbodies and groundwater means that movement of water from surface water into groundwater will tend to carry contaminants contained in the water into groundwater. The ability of a contaminant to travel through soil or sediment and enter an aquifer depends on the chemical compositions of the contaminant and the materials comprising the soil, sediment, and aquifer. Because of its high solubility and mobility, chloride will generally travel with the water.

Contaminants in groundwater will often form plumes moving away from the source of contamination. This is shown in Figure 6.4. The general direction of contaminant movement follows the main flow of groundwater. If that were the only process influencing contaminant movement, the flow would look roughly like a solid tube moving through the groundwater. Two other processes cause the plume to spread out from the main route of flow. First, diffusion results in contaminant molecules dispersing away from the main line of groundwater movement. Second, contaminant molecules will be carried away from their source by local eddies around particles in the aquifer and by fractures through the rock. These processes act simultaneously and are independent of the main flow path through the aquifer. When dispersion of a contaminant plume occurs, it tends to decrease the contaminant concentration along the direction of groundwater flow, but contamination affects an increasingly larger volume of the aquifer with increasing distance from the contaminant source.[3]

Different contaminants may move through groundwater at different rates. The movement of some contaminants may be retarded due to chemical interactions with the material making up the aquifer. The result of this is that the movement of these contaminants may be slower than the linear rate of groundwater movement.

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[3] *L.R. Watson, E.R. Bayless, P.M. Buszka, and J.T. Wilson,* Effects of Highway Deicer Application on Ground-Water Quality of the Calumet Aquifer, Northwest Indiana, *U.S. Geological Survey Water-Resources Investigations Report No. 01-4260, 2001.*

Chloride ions will tend to move through groundwater at a rate near that of the groundwater movement. This is due to several properties of chloride ions including that they are highly soluble in water, they do not significantly participate in oxidation-reduction reactions, they are not readily adsorbed onto mineral surfaces, and they play few biochemical roles. Chloride ions tend to remain in solution through most processes that would remove other ions.[4] While chloride ions are highly mobile their movement in some compacted, fine-grained materials can be somewhat restricted by their relatively large size.

Sources of Groundwater Chloride

Chloride in groundwater can come from natural and anthropogenic sources. The predominant natural source of chloride in groundwater is from extraction of chloride-containing minerals in soil and bedrock. Concentrations of chloride can be particularly high in bedrock comprised of evaporites, which are types of sedimentary rocks formed through mineral precipitation due to water evaporation. These rocks, such as halite, gypsum, and anhydrite, are not common within southeastern Wisconsin bedrock. Consequently, natural concentrations of chloride in southeastern Wisconsin groundwater are quite low. A 1981 study of groundwater chloride concentrations found that across Wisconsin, the mean chloride concentrations were reported as 8.6 mg/l in the sand and gravel aquifer, 17 mg/l in Silurian dolomite aquifer, and 13 mg/l in the sandstone aquifer; these concentrations likely reflect natural concentrations in southeastern Wisconsin.[5] The chloride concentrations reported in this study for southeastern Wisconsin ranged from 0.5 to 510 mg/l, but the mean concentrations by County in each aquifer were generally low (see Table 6.1).[6]

Anthropogenic chloride entering groundwater generally comes through one of two paths (see Figure 6.5). Chlorides on the land surface can be carried through the soil into groundwater in conjunction with groundwater recharge. This is shown as path "Q" in Figure 6.5. Similarly, movement of water from surface water into groundwater will carry chloride from the surface waterbody into groundwater. This is shown as

[4] *J.D. Hem,* Study and Interpretation of the Chemical Characteristics of Natural Water (Third Edition), *U.S. Geological Survey Water Supply Paper No. 2254, 1989.*

[5] *P.A. Kammerer, Jr.,* Information Circular 39: Ground Water-Quality Atlas of Wisconsin*, United States Geological Survey and University of Wisconsin Geological and Natural History Survey, 1981.*

[6] *The Kenosha County sand and gravel aquifer mean chloride concentration as reported in the 1981 study was high at 164 mg/l, but this mean concentration was derived from two wells; one at 3.4 mg/l and the other at 325 mg/l. The wells with the higher concentrations in this dataset likely reflect impacts from anthropogenic sources of chloride instead of natural concentrations.*

path "U" in Figure 6.5. Chlorides originating from other sources generally pass through soil or surface water in order to enter groundwater.

Deicing salts, for example, may follow paths "A," "J," and "Q" in Figure 6.5 from the truck through impervious surface and soil to groundwater. After being applied to impervious areas such as highways, some of this salt will be moved to soil adjacent to the highway either through plowing of salt-laden snow to the roadside or through salt-containing runoff flowing onto roadside soils. Additional salt may bounce or roll onto soil adjacent to the highway during deicing operations. The salt will then infiltrate through soils near the road into groundwater. A statewide groundwater mapping study in Connecticut found that chloride concentrations in groundwater varied with proximity to highways and that concentrations increased with the increase in road application rates.[7] Similarly, a study of groundwater chloride concentrations in domestic wells in Vermont found that groundwater in wells closer to a paved road had substantially higher chloride concentrations than concentrations in wells that were farther away.[8]

Similarly, wastewater collection and treatment can contribute chlorides to soil which infiltrate to enter groundwater. Direct paths include discharge of effluent from WWTPs and onsite sewage treatment systems to soil and groundwater, as shown in paths "M" to "Q" and "N" to "Q," respectively, in Figure 6.5. A less direct route occurs through losses from sanitary sewers. Not all water and chloride entering a sewage collection system end up in receiving waters. Substantial amounts of exfiltration can occur from sanitary sewers. It has been estimated that about 10 to 30 percent of sanitary sewer pipes leak, providing water that can infiltrate into groundwater.[9] The amount of leakage can be substantial, on the order of 1 to 20 percent of dry-weather flow.[10] This route is also shown as path "M" to "Q" in Figure 6.5. Many other examples of pathways of chloride from sources major human are shown in Figure 6.5. Clearly, chloride can reach groundwater through numerous routes.

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[7] *J.P. Cassanelli and G.A. Robbins, "Effects of Road Salt on Connecticut's Groundwater: A Statewide Centennial Perspective,"* Journal of Environmental Quality, *42:737-748, 2013.*

[8] *J.P. Levitt and S.L. Larsen,* Groundwater Chloride Concentrations in Domestic Wells and Proximity to Roadways in Vermont, *U.S. Geological Survey Open-File Report No. 2019-1148, 2020.*

[9] *D.N. Lerner, "Identifying and Quantifying Urban Recharge—A Review,"* Hydrogeology Journal, *10:143-152, 2002.*

[10] *M. Rutsch, J. Riechermann, and P. Krebs, "Quantification of Sewer Leakage—A Review,"* Water Science and Technology, *54:134-144, 2006.*

Human activities unrelated to direct chloride applications may also lead to contamination of groundwater. Improperly abandoned wells provide a direct pathway from the land surface to the source aquifer for the well. If runoff carries salts to such wells, it can lead to rapid contamination of the aquifer. Pumping from wells located near surface waterbodies may induce flow from surface water into groundwater. An example of this occurred in the Blackstone River in Massachusetts. Hydrogeological investigations showed that pumping from several water supply wells induced flow from the river to the well through a highly transmissive layer of gravel.[11] During low flows, an upstream wastewater treatment plant is the main source of water to the Blackstone River near these wells. The induction of flow from the river into groundwater carried chloride and other contaminants to the well aquifer.

Some low-impact-development practices may also act as sources of chloride to groundwater. Stormwater management practices such as wet retention ponds, bioswales, and rain gardens are designed to capture and infiltrate runoff from surrounding impervious surfaces. These practices serve to recharge groundwater and limit direct runoff to surface waters. A study of stormwater ponds in Owings Mill, Maryland found greatly elevated specific conductance and chloride concentrations in groundwater under the ponds, indicating the ponds were a source of chloride to groundwater.[12] The widespread use of these stormwater best management practices could potentially accelerate chloride contamination of groundwater.

Chloride Accumulation in Aquifers

When salts are applied in a stream or river basin, some of the applied chloride will be removed by flow leaving the basin. The remaining chloride will be stored in soil and groundwater. Some of the chloride will be gradually moved to a river or stream system in baseflow and leave the basin in surface water flowing out. The effect on groundwater will depend on the relative magnitudes of chloride applications and losses over the course of time. If the amount of chloride being applied is greater than the amount leaving the basin through surface flow, chloride will accumulate in the groundwater and its concentration in the aquifer will increase. These increases will continue until the amount of chloride entering the groundwater due to applications equals the amount leaving through baseflow. At that point a steady state will be achieved with the chloride concentration and amount of chloride stored in groundwater achieving a stable level.

[11] *J.A. Izbicki,* Water Resources of the Blackstone River Basin, Massachusetts, *U.S. Geological Survey Water-Resources Investigations Report No. 93-4167, 2000.*

[12] *R.E. Casey, S.M. Lev, and J.W. Snodgrass, "Stormwater Ponds as a Source of Long-Term Surface and Ground Water Salinization,"* Urban Water Journal, *10:145-153, 2013.*

Storage of chloride in groundwater is likely happening in many areas (see Figure 6.2). This is indicated by the fact that increases in chloride concentrations in baseflow to urban streams has been reported in many locations.[13] These increases are at least partially due to chloride retention within the watershed soil and groundwater.[14]

Groundwater may act as both a sink and a source of chloride, which can result in complicated interactions with surface waterbodies. During the winter and spring, chloride concentrations in streams can be high due to the flushing of salts from impervious surfaces in their watersheds. Streams receiving groundwater discharges during winter may see mixing of higher salinity (salt content) surface water with lower salinity groundwater. In this case, the groundwater input will act to reduce chloride concentration in the stream. The opposite situation may occur during summer and fall months. If enough chloride is stored in groundwater, its concentration will be higher in groundwater than in the stream. Baseflow during these months will tend to increase chloride concentrations in the stream. This effect may be amplified during extended periods of drought.

The accumulation of chloride in groundwater and the long residence time of water in many aquifers suggests that if salt applications in a watershed are reduced, contributions of chloride in baseflow to surface waterbodies will continue for a considerable period of time, resulting in delays in ecological improvements. For example, a study of groundwater in an aquifer system in Southern Ontario that used a three-dimensional transport model projected that it would take decades to flush chlorides from groundwater in this system, even if road salt applications ceased.[15] This suggests that any evaluation of practices meant to reduce chloride contributions to groundwater must be conducted with the expectation that there could be a considerable time lag between the implementation of practices and improvements in groundwater chemistry.

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[13] *See, for example, S. Kaushal, P.M. Groffman, G.E. Likens, K.T. Belt, W.P. Stack, L.E. Band, and G.T. Fisher, "Increased Salinization of Fresh Water in the Northeastern United States,"* Proceedings of the National Academy of Sciences, *102:13,517-13,520, 2005 and S.R. Corsi, L.A. DeCicco, M.A. Lutz, and R.M. Hirsch, "River Chloride Trends in Snow-Affected Urban Watersheds: Increasing Concentrations Outpace Urban Growth Rate and Are Common Among All Seasons,"* Science of the Total Environment, *508:488-497, 2015.*

[14] *E.V. Novotny, A.R.A. Sander, O. Mohseni, and H.G. Stefan, "Chloride Ion Transport and Mass Balance in a Metropolitan Area Using Road Salt,"* Water Resources Research, *45: W12410, 2009.*

[15] *M.L. Bester, E.O. Frind, J.W. Molson, and D.L. Rudolph, "Numerical Investigation of Road Salt Impact on an Urban Wellfield,"* Groundwater, *44:165-175, 2006.*

Groundwater Standards for Chloride

Due to the recognized impacts of chloride on public health, Wisconsin has established groundwater quality standards in Chapter NR 140 of the *Wisconsin Administrative Code* to protect consumptive and non-consumptive groundwater uses.[16,17] Chapter NR 140 set a preventative action limit of 125 mg/l and an enforcement standard of 250 mg/l for chloride in groundwater. These standards affect facilities, practices, and activities that could impact groundwater quality and are regulated by the State of Wisconsin. Additionally, the U.S. Environmental Protection Agency has established a secondary maximum contaminant level of 250 mg/l, which was assigned due to potential aesthetic concerns such as change in taste. Additional discussion on groundwater standards can be found in Chapter 2 of this report.

6.3 DATA COMPILATION AND ORGANIZATION

Multiple data sources were used to assess the chloride conditions and trends in groundwater across the study area. These sources represent efforts from a variety of studies conducted by Federal, State, local agencies, and universities. The following section will describe sources of groundwater chloride data for the study area and how this data was retrieved, formatted, and aggregated for presentation in Section 6.4.

Data Sources

Major sources of groundwater chloride data for the study area included the Wisconsin Department of Natural Resources (WDNR), the United States Geological Survey (USGS), the Milwaukee Metropolitan Sewerage District (MMSD), and the University of Wisconsin – Stevens Point (UWSP) in collaboration with the University of Wisconsin – Extension. Chloride data from these sources was obtained through several databases, including the WDNR Groundwater Retrieval Network (GRN), the WDNR System for Wastewater Applications, Monitoring, and Permits (SWAMP), and the USEPA Water Quality Portal (WQP).[18] Groundwater chloride data from the SWAMP database was provided upon request from the WDNR in 2020 and UWSP in

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[16] *Wisconsin Department of Natural Resources Chlorides Workgroup, Recommendations on a Statewide Chloride Strategy, Report to the Water Initiatives Steering Committee, 2022. dnr.wisconsin.gov/sites/default/files/topic/Stormwater/WisconsinStatewideChlorideStrategy.pdf*

[17] Wisconsin Administrative Code *Chapter NR 140, Groundwater Quality, docs.legis.wisconsin.gov/code/admin_code/nr/100/140.*

[18] *The Water Quality Data Portal is a cooperative service sponsored by the USGS, USEPA, and the National Water Quality Monitoring Council. For the application in this Report, the Portal was used to retrieve chloride data from the USGS.*

2023. All groundwater chloride data obtained extends through 2022, with the exception of the data from the SWAMP database which extends through 2020.

The GRN database compiles data from WDNR drinking water data since 1970, private drinking water supply wells and studies since 1988, landfill monitoring well data from mid-1970s in the WDNR Groundwater and Environmental Monitoring System (GEMS) database, and monitoring well data from the mid-1970s in the WDNR SWAMP database.[19] Although data from SWAMP is included in the GRN database, Commission staff noted that a more complete dataset was provided by WDNR staff retrieving data directly from the SWAMP database. Consequently, SWAMP data in GRN was filtered out of this dataset so as not to duplicate data with the direct SWAMP download dataset.

Commission staff utilized the programming language R with the "dataRetrieval" package version 2.7.14 to query and download data from the WQP. The characteristic name "chloride" was used with the "readWQPdata" function in the R package to programmatically query all chloride across the SEWRPC member counties of Kenosha, Milwaukee, Ozaukee, Racine, Walworth, Washington, and Waukesha as well as adjoining Dodge, Fond du Lac, Jefferson, and Sheboygan Counties as these comprise the study area. Chloride observations were joined to information regarding the sample type and location, which allowed Commission staff to filter the data to only include groundwater chloride observations within the study area.

Data Formatting and Aggregation

All groundwater well chloride data downloaded was reported in either micrograms per liter (μg/l) or milligrams per liter (mg/l); data reported in micrograms per liter was converted to milligrams per liter. Data collection timestamps were represented in various formats across the different datasets. All timestamps were converted into a "Year-Month-Day" format. When reported, well depths were converted into feet. A unique "Well ID" was created by combining the name of dataset or, for data from SWAMP, the facility where the data was collected with a short descriptive label provided for each well. For example, wells in the GRN dataset were given well IDs such as "GRN-BR491," wells from the USGS dataset were given wells IDs such as "USGS-WI-USGS-423916088232701," and wells from the SWAMP dataset were given well IDs such as "ADELL SEWAGE COLLECTION SYSTEM-W-1."

Commission staff compiled the formatted groundwater well data from the WDNR, USGS, MMSD, and UWSP into one comprehensive dataset. This dataset, which encompassed groundwater chloride samples from all

[19] *For more information on the GRN database, see the following link: dnr.wisconsin.gov/topic/Groundwater/GRN.html.*

wells at any depth across the study area, was then split into separate analyses for shallow wells and municipal drinking water supply wells.

Shallow Wells

To assess shallow groundwater conditions within the study area, observations from wells with a depth of 300 feet or less were separated from the entire dataset for analysis. However, approximately 40 percent of the groundwater chloride observations were from wells without a reported depth (typically private wells). In these instances, wells utilized for private drinking water supplies as well as wastewater treatment facility monitoring wells without a reported depth were assumed to be "shallow" wells and were also retained in the shallow well dataset.

Chloride data was incorporated regardless of well type. The well types included in this analysis were identified in the comprehensive dataset as monitoring wells, piezometers, private potable wells, non-transient non-community wells, community other-than-municipal wells, transient non-community wells, community municipality wells, non-potable private wells, and groundwater extraction wells.

Wells associated with landfills or other permitted facilities were frequently labeled as either upgradient, side gradient, or downgradient from the landfill or facility. Upgradient and side gradient wells should essentially be capturing background conditions that are not influenced by that facility. Downgradient wells are effectively "downstream" of the facility in terms of typical groundwater flow paths, consequently, these wells would be influenced by any chloride discharge from the landfill or facility. The gradient position was used as-is in instances where it was provided. In instances where the wells were not labeled, Commission staff examined the well depths, coordinates, and resulting chloride concentrations to discern the upgradient and downgradient wells. For several monitoring wells, there was no information regarding the well gradient, depth, or coordinates that could be used to designate the gradient. Commission staff considered excluding downgradient wells from the shallow groundwater analysis due to potential direct influence from the landfill or facility. However, preliminary analyses of chloride concentrations in upgradient versus downgradient wells at the same landfill indicated that downgradient wells did not consistently have higher chloride concentrations than upgradient wells. Additionally, these downgradient wells were still capturing aspects of the groundwater chloride conditions even if the concentrations were higher than wells that are not influenced by chloride discharge. Consequently, Commission staff decided to keep all wells regardless of gradient position in the shallow groundwater analysis.

Duplicates and Outliers

As the shallow groundwater data was compiled from multiple sources, Commission staff examined the dataset to identify and remove duplicates present within and between the various datasets. Duplicate observations were identified via matching well descriptions and locations, sampling date, and chloride concentration. Only one copy of each duplicate observation was retained in the final dataset.

Similarly, Commission staff examined the data for each well to determine samples with exceedingly high or low chloride concentrations compared to the other samples collected at the same well. Some of these samples appeared to be potentially erroneous entries that were removed from the dataset while other samples were designated as outliers. Eight observations in the GRN database were reported as milligrams per liter but the reported concentrations, limits of detection, and limits of quantification appeared to be in micrograms per liter as concentrations were approximately 1,000 times higher than other observations for the same well. These eight observations were removed from the dataset entirely.

Commission staff also identified outlier observations in each well that had at least ten total observations (1,686 wells out of 5,938 total wells). For each well, Commission staff developed non-linear time series models to estimate average chloride concentrations over the period of record for which chloride data was available for that well.[20] Each observation was then compared to the estimated average for the sample date. Observations were flagged as outliers if they met all of the following three criteria: the absolute value of the difference between the sample and the estimated mean was greater than 90 percent of the mean, the difference in concentration between the sample and the estimated mean was at least 100 mg/l, and the difference between the sample and the preceding sample was at least 100 mg/l. Using this approach, Commission staff designated 360 out of 74,050 chloride observations (0.5 percent) as outliers (see Figure 6.6). These data were not incorporated into shallow groundwater chloride summary statistics or trend analyses.

Spatial Aggregation

Geographic information about the wells had to be estimated or aggregated at a coarse level. For SWAMP data, the coordinates for monitoring wells associated with landfills or permitted facilities were not always provided. In instances where the coordinates were missing, either the coordinates of the associated facility

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[20] *Local polynomial regressions were utilized for these models using the "loess" function from the "stats" package in the R programming language. Visual examinations of chloride time series data for individual wells indicated that many wells did not show monotonic increases or decreases, so linear regression models would not capture these variations over time.*

were utilized or well coordinates were determined based on staff knowledge of the facility in question. Due to security concerns, the exact locations of wells within the GRN database are not reported. Instead, the Public Land Survey System (PLSS) Section is reported for each well.[21] To combine this information with the chloride data from wells in other databases, the appropriate PLSS Section was assigned to each chloride observation. All spatial analyses were conducted using the PLSS Section to aggregate the groundwater chloride data. Since chloride data from wells up to 300 feet deep were utilized for analyses, summary statistics of chloride concentrations for each Section can be considered as representing up to 192,000 acre-feet or 0.057 cubic miles of aquifer volume.

In summary, the data acquisition, formatting, and aggregation for shallow groundwater chloride comprised the following steps.

- Acquiring available groundwater chloride data from the WDNR, MMSD, USGS, USEPA, and UW-SP datasets
- Keeping chloride data from "shallow" wells with reported depths of less than 300 feet or from private wells without reported depths
- Removing duplicate and potentially erroneous data
- Identifying and filtering outlier data
- Aggregating the chloride data to the appropriate PLSS Section for spatial analysis and mapping

Municipal Drinking Water Supply Wells

Commission staff also evaluated chloride conditions and trends in municipal drinking water supply wells. Most of this data was acquired from the WDNR GRN database, from which chloride observations were selected from wells with well uses labeled as Municipal Community (MC). The Commission also contacted public works directors from a subset of the municipalities in the Region requesting any additional data beyond what was retrieved through GRN. Unlike the shallow groundwater data, most of the wells in this dataset had reported well bottom depths, static water levels, casing depth, and casing diameters. Some of these wells are also included in the shallow groundwater analysis, as the shallowest municipal drinking water

[21] A PLSS section is approximately a square mile (640 acres) and designated as Township, Range, Section.

supply wells in the study area were 30 to 50 feet deep. However, this analysis also included deep wells (up to 2,266 feet) that were not in the shallow groundwater analysis.

6.4 CHLORIDE CONDITIONS IN SHALLOW GROUNDWATER

Chloride Conditions

Through the processes described in Section 6.3, the Commission compiled 73,690 non-outlier chloride concentrations for the shallow groundwater chloride conditions and trends analysis. Approximately 75 percent of the chloride observations were acquired from GRN data, followed by 21 percent from SWAMP and MMSD data, 3 percent from UWSP data, and 1 percent from USGS data. The earliest observations were collected in 1945 by the USGS while the latest observations included in this analysis were collected in 2022.

Across all non-outlier observations, chloride concentrations ranged from 0 to 6,310 mg/l, with a median concentration of 28.0 mg/l and a mean concentration of 88.7 mg/l.[22] Eighty-seven samples had a reported chloride concentration of 0 mg/l; most of these observations were from the GRN or UWSP datasets. Further analysis of these observations indicates that many of these samples were not truly 0 mg/l but were below the limit of detection, which was often between 1 to 3 mg/l. Ninety samples (about 0.1 percent) had reported chloride concentrations higher than 2,000 mg/l. These observations were collected from 25 wells, most of which were in Milwaukee County, with sample years ranging from 1976 to 2019. Several of these wells had consistently high chloride concentrations while others only had short periods or individual observations with high concentrations.

Chloride observations were acquired from 5,938 unique shallow wells across the study area. Just over half of the wells only have a single observation and 75 percent of the wells have data for less than ten years from the earliest to latest observation. Nearly all these wells with sparse information are from the UWSP, GRN, or USGS datasets. However, seventeen wells have chloride data ranging forty or more years and 74 wells have at least 100 samples; many of these 74 wells are owned by MMSD, the Lake Geneva wastewater treatment facility, or are monitoring wells for private food manufacturers. These wells and other wells with extensive records will be discussed in further detail in the "Chloride Trends" subsection later in this chapter. Just over half (55.2 percent) of the shallow wells with chloride data did not have a reported well depth, but

[22] The highest chloride concentration reported in the total dataset was 8,800 mg/l, but this observation was flagged as an outlier as it was more than ten times higher than any other observation from its well.

for the wells that did, the depth ranged from five to 300 feet with a median depth of 82.0 feet (see Figure 6.7).

Median shallow well chloride concentrations ranged from 0 to 5,425 mg/l. The overall mean of the well median concentrations was 66.10 mg/l and the overall median of the well median concentrations was 19 mg/l. Approximately half of the wells had median chloride concentrations of 20 mg/l or less, which is the highest concentration that may reflect natural conditions. Well depth alone did not appear to explain median well chloride concentrations, as both deep and shallow wells reported low and high median chloride concentrations.

As discussed in Section 6.3, PLSS Sections were used to spatially aggregate the groundwater chloride data due to security limitations with the GRN dataset. Of the 3,133 PLSS sections in the study area, 1,397 sections (44.5 percent) had at least one chloride observation in the shallow groundwater chloride dataset. Like the individual wells, many sections (509 sections or 36.4 percent) only had one observation to represent shallow wells in the study area. However, some sections had much more widespread data collection, with several sections containing over 1,000 chloride observations that extend over 25 years or more and were collected across dozens of wells. Median chloride concentrations by PLSS Section ranged from 0 to 1,490 mg/l with a mean of 39.4 mg/l and a median of 14.8 mg/l. Maps showing the Section mean and maximum chloride concentrations for the full dataset (1965 to 2022) are presented in Maps 6.1 and 6.2. Sections with the highest median and maximum chloride concentrations were spread across the study area, although these Sections were generally in more urbanized areas or contained facilities such as landfills, wastewater treatment facilities, and/or food manufacturers. However, some highly urban Sections still have generally low chloride concentrations, such as Section 072113 comprising Metcalfe Park in north-central Milwaukee and Section 072106 comprising northern Wauwatosa.[23] Many Sections generally had significant variability in chloride concentrations due to changes in each well over time as well as differences between wells with varying depths and soils and varying sources of chloride (see Figure 6.8).

Commission staff evaluated how many samples, wells, and Sections in the full dataset exceeded the highest expected natural concentration in groundwater (20 mg/l) as well as WDNR and USEPA groundwater quality standards (see Table 6.2). The majority (58.9 percent) of groundwater observations exceeded 20 mg/l and

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[23] *The wells in these Sections do not have reported well depths and were presumed to be shallow (less than 300 feet deep). It's possible that these low chloride observations characterize deeper groundwater strata, which may explain the low concentrations observed in these highly urban areas.*

nearly half of the wells and forty-two percent of the PLSS Sections with data had median concentrations that exceeded this natural threshold. Nineteen percent of the groundwater chloride observations exceeded the preventative action limit of 125 mg/l and nearly nine percent of observations exceeded the enforcement standard of 250 mg/l. These observations were spread relatively evenly throughout time, with observations exceeding the 250 mg/l standard as early as 1965. Two hundred and ninety-four wells had median chloride concentrations exceeding the 250 mg/l enforcement standard; however, 95 of these wells only had one chloride observation. Thirty-seven Sections had median chloride concentrations exceeding the 250 mg/l drinking water standard, but the chloride data in 13 of these Sections was only comprised of one sample.

Recent Conditions (2013-2022)

To better understand recent groundwater chloride conditions, Commission staff filtered the entire shallow groundwater chloride dataset to only include observations collected between January 1, 2013 and December 31, 2022. This recent condition dataset included 5,214 observations. As with the full dataset, most of these samples were from the GRN dataset; however, this count is influenced by the lack of MMSD and SWAMP data after 2020. Chloride observations were compiled from 1,287 individual shallow wells spanning 561 PLSS sections (18 percent of the study area). Concentrations ranged from 0 to 4,100 mg/l, with a median chloride concentration of 39.0 mg/l and a mean concentration of 96.7 mg/l for recent well conditions.

As with the full dataset, most of the shallow wells with recent chloride data only had one observation (979 wells or 76.1 percent). Of the 156 wells with at least ten chloride observations, the median chloride concentrations ranged from 1.3 to 1,600 mg/l, with an average of the median concentrations of 106.4 mg/l. Several of these wells with the highest median chloride concentrations were relatively shallow (less than 40 feet deep) wells in Milwaukee County, including the well with the highest median chloride concentration of 1,600 mg/l. Seventy-nine of the 1,287 shallow wells with chloride data have median concentrations greater than or equal to the 250 mg/l enforcement standard while 97 wells (7.5 percent) have maximum chloride concentrations that exceed it.

Of the 561 PLSS Sections with recent chloride data, a slight majority (282 wells or 50.3 percent) only had one chloride observation, and 310 Sections (55.3 percent) only had chloride data from one well. Recent median concentrations across all Sections ranged from 0 to 1,460 mg/l with an average of the Section median concentrations of 59.8 mg/l (see Map 6.3). As with the full dataset, Sections with the highest median chloride concentrations were spread across the study area but were generally comprised of urban land uses and/or contained facilities associated with chloride discharge. For the full recent dataset, 43 PLSS sections had wells with a mean concentration greater than or equal to 250 mg/l, with Section 052104 in southwestern Milwaukee County having the most wells exceeding this standard at 13 wells.

Chloride Trends

To better understand how groundwater chloride concentrations have changed over time, Commission staff filtered the non-outlier shallow groundwater chloride dataset to only include data from wells which met three criteria: at least 20 samples, the most recent samples was collected in 2000 or later, and the samples covered at least a 20 year period. A total of 338 wells met this criteria, which comprised 22,008 chloride observations across 46 PLSS sections (1.4 percent of the study area). Summary statistics from this population of chloride observations were similar to that of the full dataset, with chloride ranging from 0 to 4,100 mg/l, a median concentration of 30.0 mg/l, and a mean concentration of 91.2 mg/l. The earliest chloride observation included in this dataset was collected in 1972 while the most recent was in 2020. The 46 Sections were generally spread across the chloride study area, although there were fewer sections represented in the western portion of the study area than the eastern portion (see Map 6.4). Consequently, the trends exhibited in this subset of the data may be considered a weak representation of groundwater chloride trends across the study area.

Commission staff utilized the 22,008 chloride observations to develop linear regressions models of the chloride concentrations over time (as represented by the year) for each of the 338 wells that met the criteria for inclusion in the trends analysis. The alpha value, also referred to as threshold for statistical significance, for these linear regressions was 0.05, meaning that there would be a less than five percent chance of rejecting the null hypothesis when true. Wells where the linear regression slope was zero or the p-value, the "probability value" or the likelihood of observed effect occurring by chance, was greater than 0.05 were designated as "No Significant Trend". Wells with a positive regression slope and a p-value less than 0.05 were designated as "Significant Increase" while wells with a negative regression slopes and a p-value of less than 0.05 as "Significant Decrease." In total, 89 of the 338 wells (26.3 percent) were "No Significant Trend" while 156 wells (46.2 percent) were designated "Significant Increase" and 93 wells (27.5 percent) were designated "Significant Decrease." Examples of wells showing "Significant Increase", "No Significant Trend," and "Significant Decease" are illustrated in Figure 6.9. As this Figure shows, wells designated as "No Significant Trend" could either have relatively consistent chloride concentrations over time or could have fluctuating concentrations that lack a clear, monotonic direction.

Of the 46 Sections represented in this dataset, 20 Sections had at least 50 percent of their wells significantly increasing in chloride concentrations with eight Sections having 100 percent of their wells increasing (22 wells total) (see Map 6.4 and Table 6.3). Six Sections had at least 50 percent of their wells significantly decreasing with one Section having 100 percent of their wells decreasing (one well total). The remaining 20 Sections either had a majority of wells with "No Significant Trend" or were mixed between increasing, decreasing, and no trend wells.

Visual examination of wells in the trend dataset with long chloride time series shows that the chloride concentrations in many wells are quite dynamic. Some wells exhibit monotonic increases or decreases in chloride concentration while others show seasonal or multi-year fluctuations. These fluctuations may be driven by changes in chloride loading, well depth, dilution from increased water levels, or other factors. While it is beyond the scope of this study to examine patterns in individual wells, understanding the dynamic nature of shallow groundwater chloride concentrations helps inform the significant variability in the data across the study area as well as how quickly changes can occur. For example, the well with the most rapid decrease in chloride concentrations over time was a monitoring well for Cedar Valley Cheese, Inc., which decreased from 977 mg/l in 1990 to 12 mg/l in 2008. Other monitoring wells at this facility and some other facilities across the study area showed similar significant decreases in chloride over time which may represent operational changes. The well with the most rapid increase was GRN-926, a 13-foot deep well located in western West Allis in Milwaukee County. This well data increased from 210 mg/l in 1996 to 4,100 mg/l in 2014 before declining again to 430 mg/l in 2018. The three highest concentrations at this well were collected in March and April of 2013 through 2015, which may reflect seasonal pulses of chloride-laden water at the surface percolating into the very shallow groundwater.

Seasonality and Other Influences

Commission staff evaluated whether shallow groundwater chloride concentrations were impacted by seasonal effects, such as increased chloride inputs during winter (i.e., due to application of road salts and deicers) as well as changing water groundwater levels.[24] In this evaluation, the mean concentration for each month in each year for all data and the annual mean for each year in each well was calculated. These monthly means were then divided by their respective annual means to determine the percent by which chloride concentrations each month deviated from its year. This examination was performed using the entire shallow groundwater dataset as well as only for very shallow wells (less than 25 feet deep). No seasonal effects were noted for the entire dataset, but a weak seasonal effect may be evident for the very shallow wells (see Figure 6.10). The months of January, February, March, October, and December had mean concentrations

[24] *Commission staff had noted potential seasonal influences while evaluating chloride concentrations over time in individual wells, particularly in very shallow wells, which led to this larger examination.*

above their respective annual means while the other months had mean concentrations at or below their respective annual means. However, the weak influence may indicate that only a few shallow wells have a seasonal influence or that the dataset is not complete enough to detect these influences more fully.

Due to the lack of coordinate and well depth information for much of the available shallow groundwater dataset, Commission staff did not conduct a statistical examination of how groundwater chloride concentrations may be influenced by land use, soil characteristics, or the underlying geology. As described earlier in this Chapter, many of the wells and PLSS Sections that have high and/or increasing chloride concentrations were located in urban areas and/or near landfills, wastewater treatment facilities, and industrial facilities. There did not appear to be clear spatial distinctions that reflected underlying soil or geological characteristics. For example, a difference in chloride concentrations along an east-west gradient may indicate differences due to groundwater contamination susceptibility or changes in the depth of the sand and gravel aquifer (see Map 6.5). While these differences were not detected, this may reflect the spatially and temporally sparse dataset throughout much of southeastern Wisconsin as these differences would be expected to influence shallow groundwater chloride concentrations.

Shallow Groundwater Summary

Across the chloride study area, shallow groundwater chloride concentrations are highly variable with differences within wells over time, between wells within the same PLSS Section, and between PLSS Sections. However, most observations and monitored wells indicate that groundwater chloride concentrations have increased from natural conditions, with the highest observed concentration 315 times higher than the natural concentrations for southeastern Wisconsin. Additionally, more wells were designated as significantly increasing in chloride concentrations than either significantly decreasing or not showing a trend. These increases likely reflect inputs from anthropogenic chloride sources, such as road salts and deicers, wastewater treatment, fertilizers, and waste from industrial and food processing facilities. This general increase in shallow groundwater chloride concentrations across much of southeastern Wisconsin has likely affected surface water chloride concentrations, especially for waterbodies where groundwater is a main water source such as spring-fed lakes and stream baseflows.

Shallow groundwater chloride concentrations are dynamic and can show rapid changes at a given location. Extremely shallow groundwater may reflect seasonal differences in chloride loading to the environment, with higher concentrations during winter and early spring potentially indicative of road salt and deicer use. Chloride concentrations at some food manufacturers and industrial facilities has rapidly declined over the past two decades, likely reflecting changing practices at these facilities.

Due to the spatial limitations of the dataset, analysis of influences such as land use, soil, and geology on chloride concentrations was not feasible. However, shallow groundwater near urban areas as well as chloride-discharging facilities are more likely to have high chloride concentrations, particularly if the soils in these areas are highly susceptible to contamination (see Map 6.5). Monitoring efforts that could create a more comprehensive shallow groundwater chloride dataset would include:

- Consistently identifying the well depth in groundwater databases
- Finer-scale spatial locations for the well
- Regular chloride monitoring over time at wells not associated with an industrial or wastewater facility

6.5 CHLORIDE CONDITIONS IN PUBLIC DRINKING WATER SUPPLY WELLS

Municipal drinking water well data was reviewed in detail to better categorize the groundwater chloride levels in the study area. Data was taken from the WDNR GRN database for the "MC (Municipal Community)" category only, which represented municipal well data. For the study area a total of 46 municipalities had reported chloride levels in the database for the period 1977-2025. To note, many municipalities had only one or two well chloride measurements over the period, and those with multiple chloride datapoints having a sample about every 10 years.

Chloride Conditions

A depiction of the full municipal well dataset is included in Figure 6.11 and summarized in Table 6.4. This figure shows measured chloride levels versus the municipal well depth. Based on the observed chloride levels, shallow wells were determined to be those with depths less than or equal to 300 feet. Shallow well data was 46 percent of the total municipal well dataset with a median chloride level of 100 mg/l. Deep wells were determined based on very low chloride levels, which were those with depths greater than 700 feet. Deep wells were 33 percent of the dataset and exhibited a median chloride level of 8 mg/l. Only 11 percent of the deep well chloride measurements were above 20 mg/l. The difference between the median and mean chloride concentrations for the deep wells is only 1 mg/l, indicating a tight range of measured chloride levels. The municipal wells with depths between 300 feet and 700 feet accounted for 21 percent of the dataset and indicated the transition between shallow and deep well chloride levels. These mid depth wells had a median chloride concentration of 26 mg/l. This categorization of well depths aligns closely with the depiction of aquifers in Figure 6.1.

For the overall municipal well dataset (shown in Figure 6.11), shallow well chloride levels frequently exceed the groundwater preventative action limit of 125 mg/l, while a few of the mid depth well data exceed that limit. Shallow wells also show numerous chloride concentration exceedances above the drinking water enforcement standard of 250 mg/l.

Chloride Trends

To investigate the change in groundwater chloride levels over time, a review of individual well data by community was completed. Only a few of the 46 reporting communities in the study area had multiple chloride samples over the period of record (1977-2025). Commission staff reached out to municipalities that had longer datasets to see if additional raw water sampling had been completed beyond what was found in the GRN database. Only the Cities of Brookfield and West Bend and Village of Slinger provided additional well chloride data. The City of Whitewater and Village of Grafton confirmed no additional well chloride data was available beyond what is reported in GRN. Also, the City of Waukesha confirmed the municipality switched to a Lake Michigan water supply on October 9, 2023, thus all their wells have been offline and will be abandoned in the near future. The City of Waukesha well data prior to switching water supply was included in the full dataset evaluation above but will not be discussed in this section. Map 6.6 shows all the municipalities included in this analysis as well as those included in the detailed evaluation. Also shown on the map is the western extent of the Maquoketa Shale as a point of reference, which acts as a confining layer protecting the deep aquifer wells from the shallow ones.

Six communities were selected for a more detailed analysis of their drinking water well data. These included the Cities of Brookfield, West Bend, and Whitewater and the Villages of Grafton, Hartland, and Slinger. These communities were chosen based on their longer chloride dataset, range of well depths, and to provide good geographical coverage of the study area. In the figures by community, each well dataset is uniquely shown, with line and symbol types represent shallow, mid depth, and deep wells. Well depths are included in the legend along with each unique well identifier in GRN. To note, this detailed analysis did not drill down to exactly where each well is located within the community to determine if that was a factor in the observed chloride levels. It is anticipated that well location would especially influence the shallow well chloride levels.

The municipal well data for the City of Brookfield from 1991 to 2025 is included in Figure 6.12. This dataset is unique as the City has well data in each depth category. The four deep wells, which are all below 1,391 feet, show a level trend in chloride concentrations over time (chloride range of 4 and 29 mg/l over time), while the mid depth (range of 22 to 120 mg/l) and shallow wells (range of 68 to 360 mg/l) show an increasing trend in chloride concentrations over time. One exception is shallow well IZ385, which shows a steadier chloride concentration around 190 mg/l throughout the time range. Mid depth wells range from 350 feet to 400 feet deep, while the shallow wells range from 150 feet to 280 feet deep. Of the municipalities reviewed in detail, the City shallow wells are deeper than most of the wells reviewed. The three shallow wells have very high chloride levels in February 2025, ranging from 165 mg/l to 355 mg/l. For the City of Brookfield municipal wells, the mid depth and shallow well chloride data are trending above the full dataset median values shown in Table 6.4. Also, the shallow well chloride levels all exceed the preventative action limit of 125 mg/l, while two of them for the most recent sampling are above the enforcement standard of 250 mg/l.

The municipal well data for the Village of Grafton from 1992 to 2017 is included in Figure 6.13. This dataset includes six mid depth wells and one deep well. Unfortunately, the one deep well has only two datapoints from 1993 to 1999. The six mid depth wells, ranging from 518 to 580 feet, all exhibit an increasing trend in chloride concentrations over time. For the Village of Grafton municipal wells, four of the six mid depth wells are trending above the 26 mg/l median chloride concentration of the full municipal well dataset shown in Table 6.4. Furthermore, only one of the mid depth well chloride levels exceed the preventative action limit of 125 mg/l for the most recent 2017 sampling.

The Village of Hartland municipal well data from 1983 to 2020 is included in Figure 6.14. This dataset includes five shallow wells. The shallow wells, ranging from 82 to 122 feet deep, exhibit an overall increasing trend in chloride concentrations over time. Although three of the wells leveled out between 2017 and 2020, albeit at higher chloride concentrations of 110, 140, and 250 mg/l, for each well respectively. Well BH397 was showing a decreasing trend in chloride concentrations between 2016 and 2019, but rose again in 2020 to 140 mg/l. All Village have very high chloride levels in February 2025, ranging from 110 mg/l to 280 mg/l. For the Village of Hartland municipal wells, all of the shallow wells are trending above the 100 mg/l median chloride concentrations of the full municipal well dataset shown in Table 6.4. Also, all but one of the shallow well chloride levels exceed the preventative action limit of 125 mg/l for recent sampling, while two of them for the most recent 2020 sampling are above the enforcement standard of 250 mg/l.

The municipal well data for the Village of Slinger from 2008 to 2024 is included in Figure 6.15. This dataset includes two shallow wells and one mid depth well. All three wells, ranging from 78 to 317 feet deep, exhibit an overall increasing trend in chloride concentrations over time. Well BH264, which is the shallowest well at 78 feet deep, shows the greatest range of recent chloride levels of between 240 mg/l in 2017 and 192 mg/l in April 2024. All three of the wells show an increase between the last two measured chloride levels, which were completed in April 2024 and December 2024. For the Village of Slinger municipal wells, all three wells are trending above the median shallow (100 mg/l) and median mid depth (26 mg/l) chloride concentrations of the full municipal well dataset shown in Table 6.4. Also, the shallow well chloride levels both consistently exceed the preventative action limit of 125 mg/l, while one of them for the most recent 2024 sampling is above the enforcement standard of 250 mg/l.

The City of West Bend municipal well data from 1993 to 2024 is included in Figure 6.16. This dataset includes eight shallow wells and one mid depth well. The shallow wells, ranging from 71 to 275 feet deep, overall exhibit an increasing trend in chloride concentrations over time. In 2019 the City began taking more frequent well sampling, and an overall leveling out of chloride concentrations is observed. The one mid depth well at 380 feet had its highest chloride concentration of 16 mg/l in October 2024, which is below the full dataset median of 26 mg/l. Shallow well WQ162 appears to have a decreasing trend in chloride levels from a high data point of 676 mg/l in March 2019, but a leveling out to about 320 mg/l is observed in the most recent 2024 samples. This may mean the earliest high concentration was an outlier for this well. For the City of West Bend municipal wells, all but one of the shallow wells are trending above the 100 mg/l median shallow chloride concentration of the full municipal well dataset shown in Table 6.4. Furthermore, six of the shallow well chloride levels exceed the preventative action limit of 125 mg/l for recent sampling, while four of them for the most recent sampling are above the enforcement standard of 250 mg/l.

The final municipal well dataset reviewed was for the City of Whitewater from 1977 to 2020, which is included in Figure 6.17. This dataset includes one mid depth well and four deep wells. The deep wells range in depth from 800 to 1,019 feet, while the mid depth well is 657 feet deep. The Maquoketa Shale does not extend to the City (Map 6.6), therefore it makes sense that no shallow wells are used for municipal water supply. The mid depth well does show an increasing chloride concentration over time, although it is low at 17 mg/l in 2020. This is below the full dataset median trend for mid depth wells of 26 mg/l. All but one of the deep wells show a level trend over time, with an overall range of 1 mg/l to 24 mg/l. Deep well BH194 indicates an increasing trend in chloride concentration from 1993 (6 mg/l) to 2020 (24 mg/l). For the City of Whitewater municipal wells, all but one deep well are trending above the median deep (8 mg/l) chloride concentrations of the full municipal well dataset shown in Table 6.4. None of the deep well chloride levels are above the preventative action limit of 125 mg/l.

Municipal Water Supply Well Summary

Summary conclusions for the available municipal well dataset for the study area are listed below.

- Chloride concentrations in shallow wells (less than 300 feet deep) are increasing over time.

- Chloride concentrations in mid depth wells (300 to 700 feet deep) are increasing over time.

- Chloride concentrations in deep wells (greater than 700 feet deep) are low and holding steady over time. Due to the time scales involved in groundwater flow (see Figure 6.2), the observed chloride trends in shallow and mid depth wells are anticipated to produce future upward trends in the deep aquifer.

- Shallow municipal well chloride data is much more variable and dynamic than the mid depth and deep wells.

- Shallow well chloride levels often exceed the groundwater preventative action limit of 125 mg/l. Shallow well chloride levels also show occasional exceedances of the drinking water enforcement standard of 250 mg/l.

- Mid depth well chloride levels rarely exceeded the groundwater preventative action limit of 125 mg/l.

- Deep well chloride levels did not exceed the groundwater preventative action limit of 125 mg/l.

- Municipal well raw water sampling for chloride that is reported to GRN is occurring about once every 10 years. It is recommended for future investigations that sampling of municipal wells occur more frequently and at different times of the year. Perhaps once every three years, with a sample taken in winter/spring and another in summer/fall.

- Municipal well locations in GRN are only identified down to the section level. A more refined location description would also aid in chloride data review and analysis. Even something as simple as going down to the quarter section would be helpful.

Technical Report No. 63

CHLORIDE CONDITIONS AND TRENDS IN SOUTHEASTERN WISCONSIN

Chapter 6

CHLORIDE CONDITIONS AND TRENDS: GROUNDWATER

TABLES

Table 6.1
Reported Mean Chloride Concentrations in Southeastern Wisconsin

	Mean Chloride Concentration (mg/l) and (Number of Wells) by County						
Aquifer	Kenosha	Milwaukee	Ozaukee	Racine	Walworth	Washington	Waukesha
Sand and Gravel	164[a] (2)	5.7 (3)	6.2 (12)	4 (1)	8.1 (51)	6.3 (42)	29 (15)
Silurian Dolomite	7.5 (6)	10 (54)	15 (44)	2.9 (6)	3.9 (13)	20 (56)	32 (42)
Sandstone	29 (4)	16 (26)	12 (3)	37 (8)	3.2 (33)	42 (9)	7.6 (41)

Note: The chloride concentrations reported in this table were compiled as part of a 1981 study entitled "Ground-water-quality Atlas of Wisconsin" by the United States Geological Survey (USGS) in cooperation with the University of Wisconsin – Extension Geological and Natural History Survey.

[a] *This high mean concentration was derived from two wells: one at 3.4 mg/l and the other at 325 mg/l. The wells with the higher concentrations in this dataset likely reflect impacts from anthropogenic sources of chloride instead of natural concentrations.*

Source: USGS, WGNHS, and SEWRPC

#277866 – TR-63 (Chloride Study Conditions and Trends) Table 6.2 GW Thresholds
200-1100
JPP/mid
7/16/2025

Table 6.2
Comparison of Chloride Samples, Wells, and Sections to Existing Groundwater Thresholds: 1945-2022

Threshold	Observation Exceeds Threshold		Median Concentration Exceeds Threshold			
	Number of Observations	Percent of Observations	Number of Wells	Percent of Wells (of those with chloride data)	Number of Sections	Percent of Sections (of those with chloride data)[a]
Highest Natural Levels (20 mg/)	43,407	58.9	2,890	48.7	593	42.4
Preventative Action Limit (125 mg/l)	14,123	19.1	702	11.8	82	5.9
Enforcement Standard (250 mg/l)	6,384	8.7	294	5.0	37	2.6

[a] *Of the 3,133 PLSS Sections in the study area, only 1,397 Sections had groundwater chloride data.*

Source: MMSD, WDNR, UWSP, and SEWRPC

Table 6.3
Summary of Shallow Well Trend Dataset by Public Land Survey System Section

Section ID	Township	Range	Section	Median Chloride (mg/l)	Number of Observations	Year Range	Significant Increase		Significant Decrease		No Significant Trend	
							Number of Wells	Percent of Wells	Number of Wells	Percent of Wells	Number of Wells	Percent of Wells
						Kenosha County						
011905	01 N	19 E	05	110	595	1989-2020	3	42.9	3	42.9	1	14.3
012117	01 N	21 E	17	66	443	1988-2020	1	25.0	3	75.0	0	0.0
012233	01 N	22 E	33	167	286	1977-2009	1	16.7	3	50.0	2	33.3
012330	01 N	23 E	30	8.4	103	1988-2020	1	100.0	0	0.0	0	0.0
022132	02 N	21 E	32	1.96	1,100	1983-2020	0	0.0	1	10.0	9	90.0
						Milwaukee County						
052101	05 N	21 E	01	5.8	259	1995-2020	3	33.3	1	11.1	5	55.6
052103	05 N	21 E	03	26	134	1994-2019	3	100.0	0	0.0	0	0.0
052104	05 N	21 E	04	19	1,131	1976-2019	21	87.5	1	4.2	2	8.3
052131	05 N	21 E	31	5.8	489	1978-2013	4	57.1	0	0.0	3	42.9
052202	05 N	22 E	02	59	359	1979-2008	2	28.6	3	42.9	2	28.6
052236	05 N	22 E	36	8.2	372	1975-2010	3	50.0	1	16.7	2	33.3
062107	06 N	21 E	07	110	336	1996-2019	3	37.5	4	50.0	1	12.5
						Ozaukee County						
102102	10 N	21 E	02	23.4	498	1972-2016	4	36.4	2	18.2	5	45.5
102208	10 N	22 E	08	6.3	658	1978-2014	5	62.5	1	12.5	2	25.0
122111	12 N	21 E	11	105	321	1988-2020	0	0.0	3	60.0	2	40.0
122220	12 N	22 E	20	56.2	195	1999-2020	1	33.3	2	66.7	0	0.0
122222	12 N	22 E	22	62	660	1978-2020	2	20.0	6	60.0	2	20.0
122229	12 N	22 E	29	64.3	260	1999-2020	3	75.0	0	0.0	1	25.0
						Racine County						
021901	02 N	19 E	01	20	281	1991-2019	1	20.0	2	40.0	2	40.0
031929	03 N	19 E	29	106.5	39	1977-2006	1	100.0	0	0.0	0	0.0
032223	03 N	22 E	23	34.5	888	1985-2016	13	46.4	8	28.6	7	25.0
042201	04 N	22 E	01	12	730	1980-2009	2	18.2	7	63.6	2	18.2

Table continued on next page.

Table 6.3 (Continued)

Section ID	Township	Range	Section	Median Chloride (mg/l)	Number of Observations	Year Range	Significant Increase Number of Wells	Significant Increase Percent of Wells	Significant Decrease Number of Wells	Significant Decrease Percent of Wells	No Significant Trend Number of Wells	No Significant Trend Percent of Wells
						Walworth County						
021509	02 N	15 E	09	19.0	300	1978-2001	3	75.0	0	0.0	1	25.0
021532	02 N	15 E	32	52	965	1982-2020	3	30.0	5	50.0	2	20.0
021830	02 N	18 E	30	251.5	1,250	1986-2020	9	100.0	0	0.0	0	0.0
041815	04 N	18 E	15	34	944	1979-2011	10	66.7	2	13.3	3	20.0
041831	04 N	18 E	31	10	1,185	1987-2020	11	55.0	3	15.0	6	30.0
						Washington County						
091931	09 N	19 E	31	9.3	23	1995-2019	0	0.0	1	100.0	0	0.0
092036	09 N	20 E	36	6	294	1981-2001	1	25.0	2	50.0	1	25.0
122008	12 N	20 E	08	43	472	1985-2020	3	75.0	1	25.0	0	0.0
122021	12 N	20 E	21	34.6	33	1993-2019	1	100.0	0	0.0	0	0.0
						Waukesha County						
052018	05 N	20 E	18	62.7	427	1983-2010	3	60.0	1	20.0	1	20.0
052036	05 N	20 E	36	8.7	255	1986-2019	0	0.0	1	10.0	9	90.0
061901	06 N	19 E	01	78	1,196	1979-2010	11	78.6	2	14.3	1	7.1
062018	06 N	20 E	18	21.3	662	1981-2019	11	64.7	0	0.0	6	35.3
071822	07 N	18 E	22	24.6	182	1977-2020	4	100.0	0	0.0	0	0.0
071832	07 N	18 E	32	74.5	438	1988-2011	3	60.0	1	20.0	1	20.0
072020	07 N	20 E	20	155	151	1975-2001	0	0.0	2	100.0	0	0.0
081932	08 N	19 E	32	32.9	35	1993-2019	1	100.0	0	0.0	0	0.0
081933	08 N	19 E	33	60	27	1995-2020	0	0.0	1	100.0	0	0.0
081936	08 N	19 E	36	28.5	1,152	1982-2020	0	0.0	9	90.0	1	10.0
082001	08 N	20 E	01	75.5	87	1994-2020	2	100.0	0	0.0	0	0.0
082019	08 N	20 E	19	24.6	32	1995-2019	0	0.0	0	0.0	1	100.0
						Fond Du Lac County						
141924	14 N	19 E	24	2.8	257	1999-2020	1	20.0	1	20.0	3	60.0
						Sheboygan County						
132134	13 N	21 E	34	79	1,094	1980-2020	2	18.2	5	45.5	4	36.4
152031	15 N	20 E	31	220	410	1993-2020	0	0.0	1	25.0	3	75.0

Source: MMSD, WDNR, UWSP, and SEWRPC

#277382 – TR-63 (Chloride Study Conditions and Trends) Table 6.4 Municipal Well Data Summary
200-1100
LKH/mid
6/5/25

Table 6.4
Municipal Groundwater Wells – Chloride Data Summary

Parameter	Shallow Wells	Mid Depth Wells	Deep Wells
Well Depth (feet)	0-300	301-700	>700
Number of Chloride Samples	375	175	265
Minimum Observed Chloride Level (mg/l)	0	0	0
Maximum Observed Chloride Level (mg/l)	676	190	98
Median Chloride Level (mg/l)	100	26	8
Mean Chloride Level (mg/l)	138	41	9

Source: WDNR, SEWRPC, City of Brookfield, Village of Slinger, and City of West Bend

Technical Report No. 63

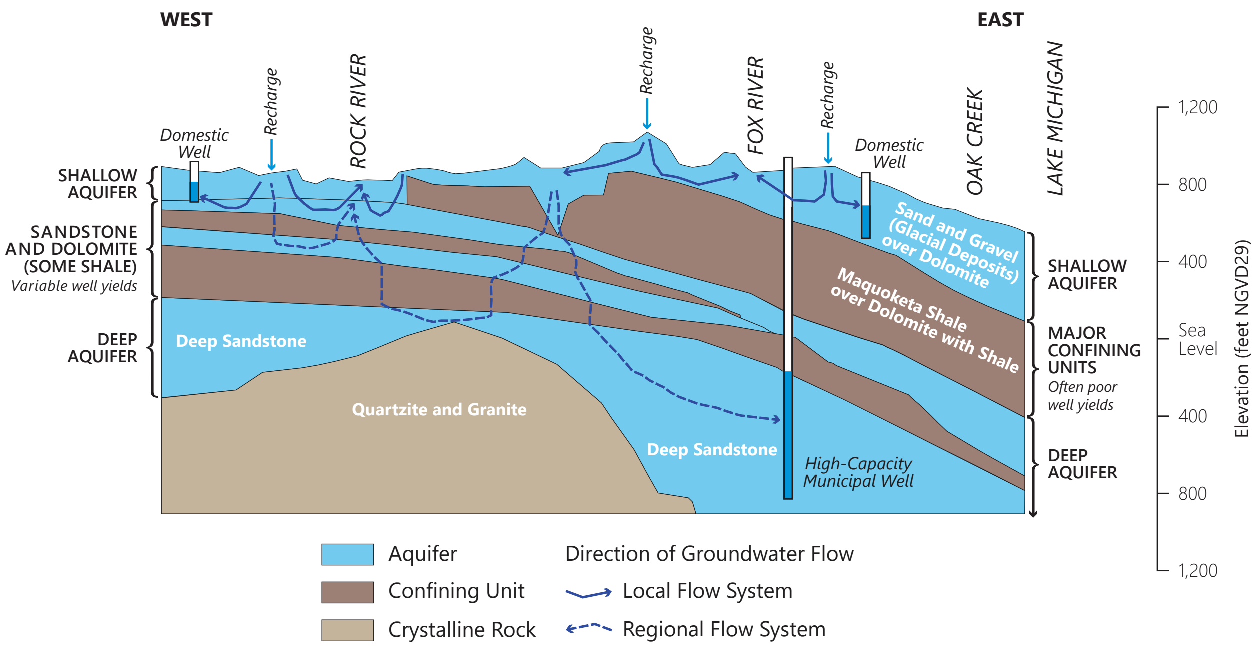
CHLORIDE CONDITIONS AND TRENDS IN SOUTHEASTERN WISCONSIN

Chapter 6

CHLORIDE CONDITIONS AND TRENDS: GROUNDWATER

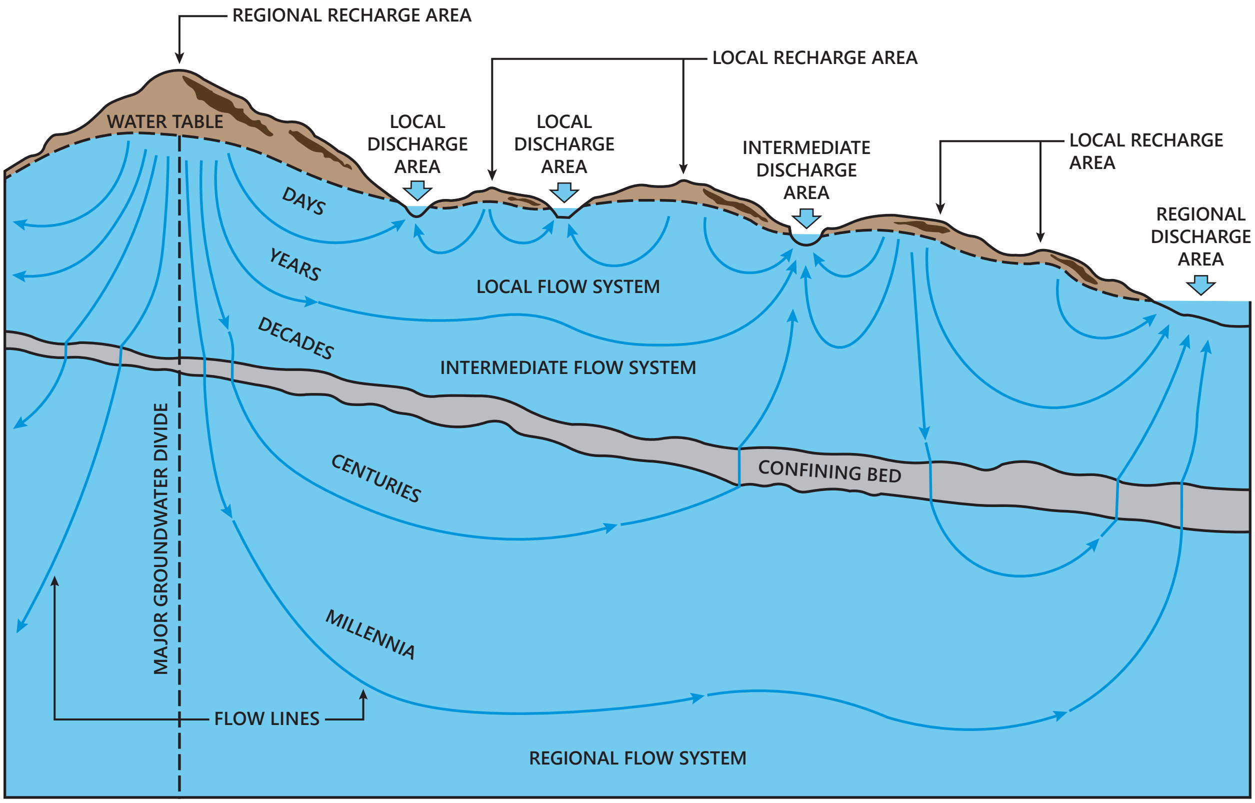
FIGURES

Figure 6.1
Aquifer Systems in Southeastern Wisconsin



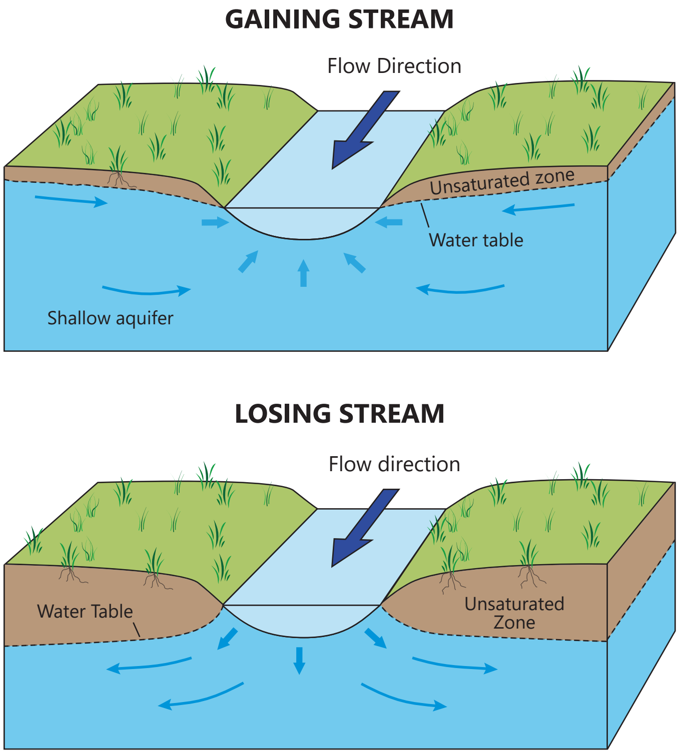
Source: U.S. Geological Survey, University of Wisconsin—Extension, and SEWRPC

Figure 6.2
Idealized Groundwater Flow Systems Under Steady State Conditions



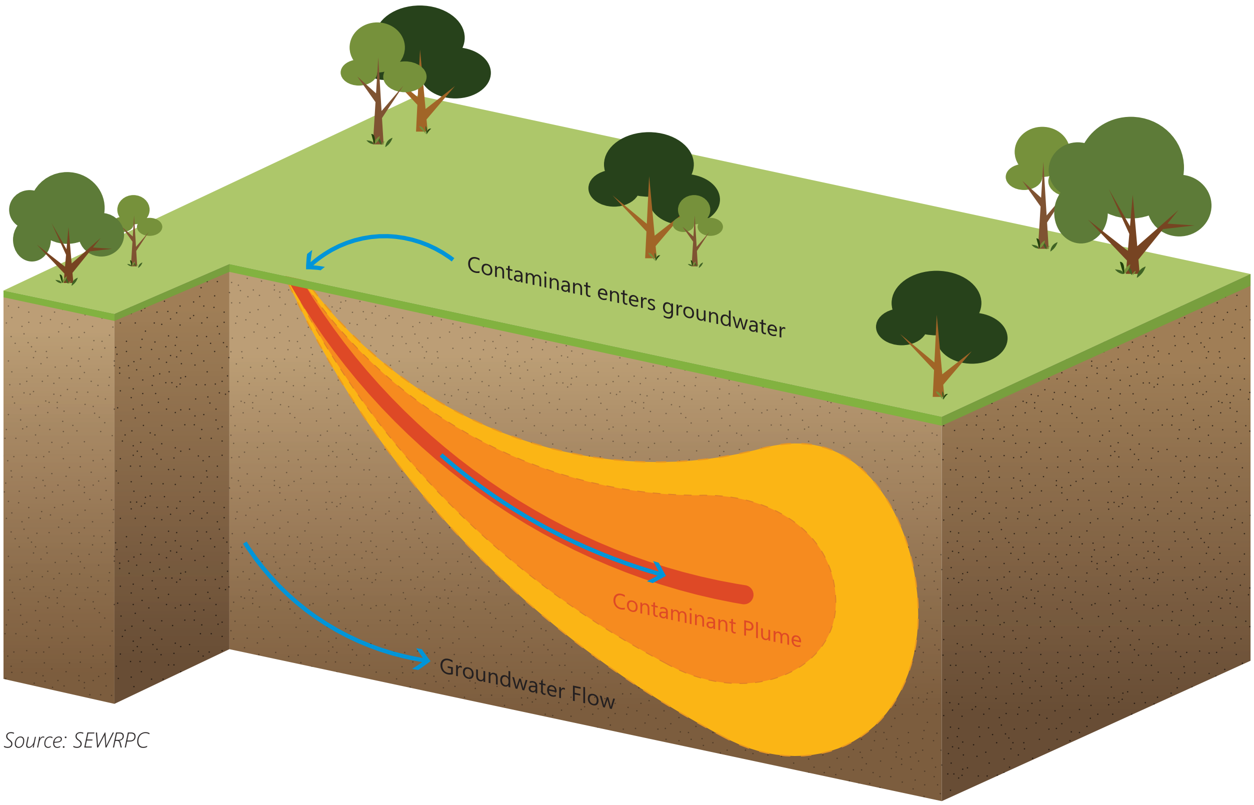
Source: Modified from A. Zaporozec in SEWRPC Technical Report No. 37, Groundwater Resources of Southeastern Wisconsin, *2002*

Figure 6.3
Interactions of Surface Water and Groundwater



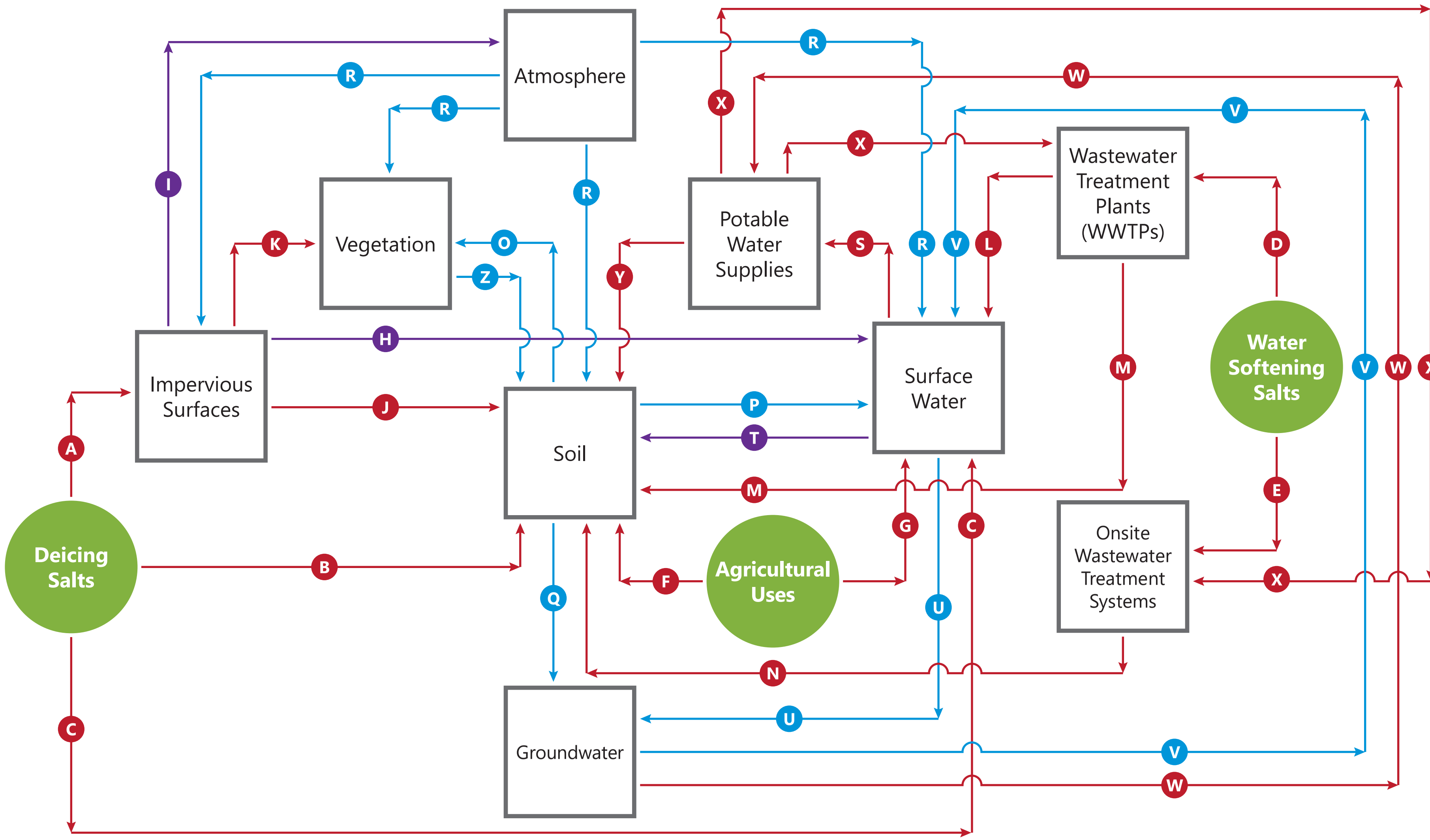
Source: Modified from T.C. Winter, J.W. Harvey, O.L. Franke, and W.M. Alley, Ground Water and Surface Water: A Single Resource, *U.S. Geological Survey Circular 1139, p. 9, 1998, and SEWRPC*

Figure 6.4
Plume Movement of Contaminants Through Groundwater



Source: SEWRPC

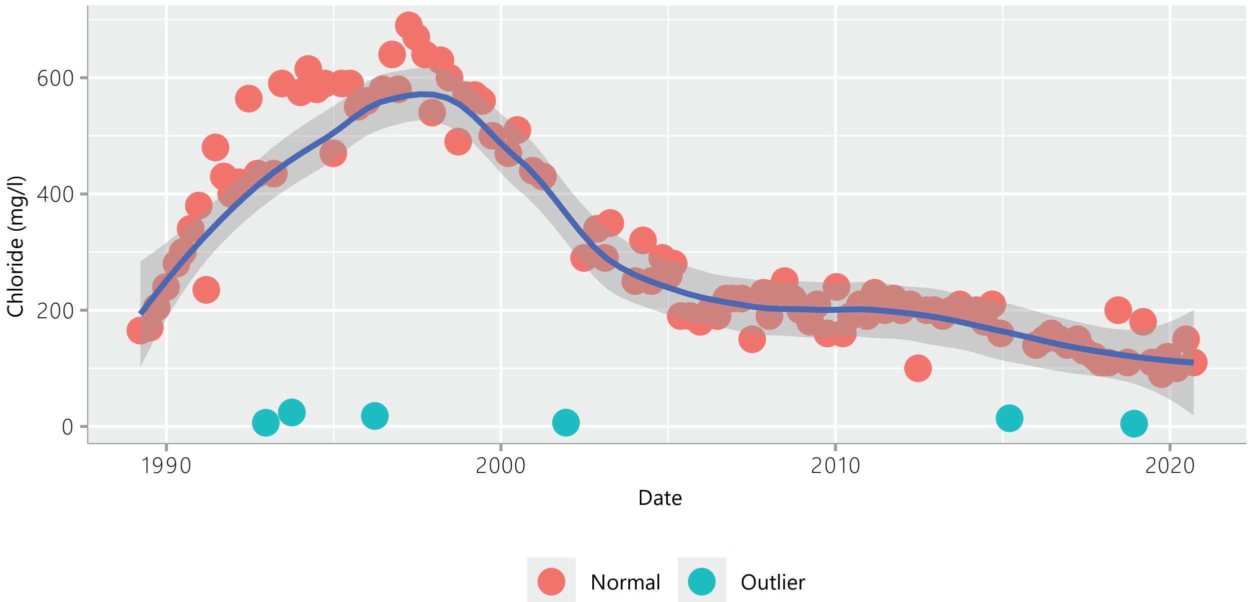
Figure 6.5
Pathways of Chloride Through the Environment



Note: Green circles indicates sources of chloride to the environment. Gray boxes indicate compartments in the environment. Blue arrows indicate paths that are natural processes. Red arrows indicated paths that are human activities. Purple arrows indicate paths that are a combination of natural processes and human activities.

Source: SEWRPC

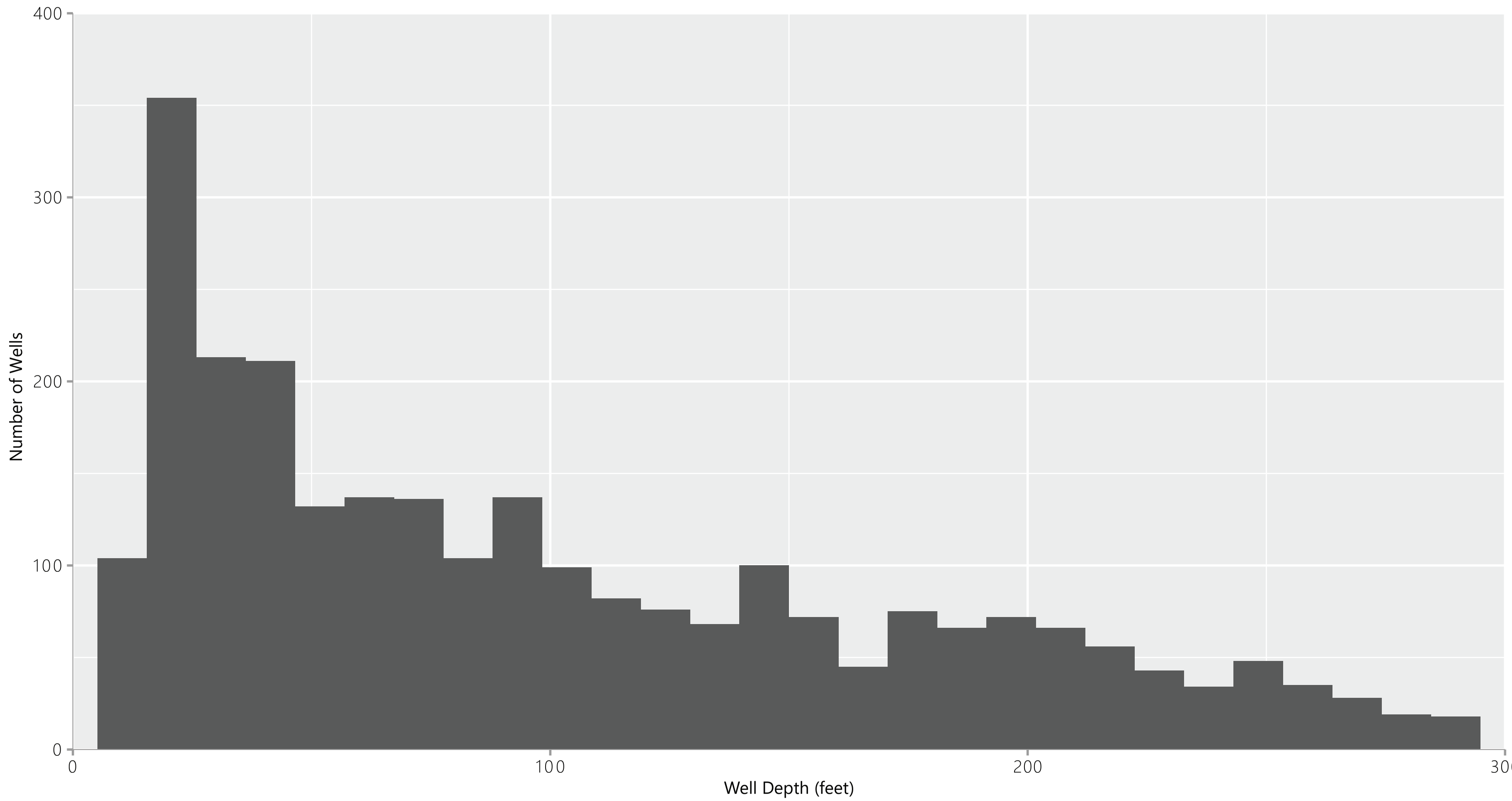
Figure 6.6
Example of Outlier Identification Process



Note: Blue line shows estimated mean chloride concentration determined using local polynomial regression of chloride across the time series.

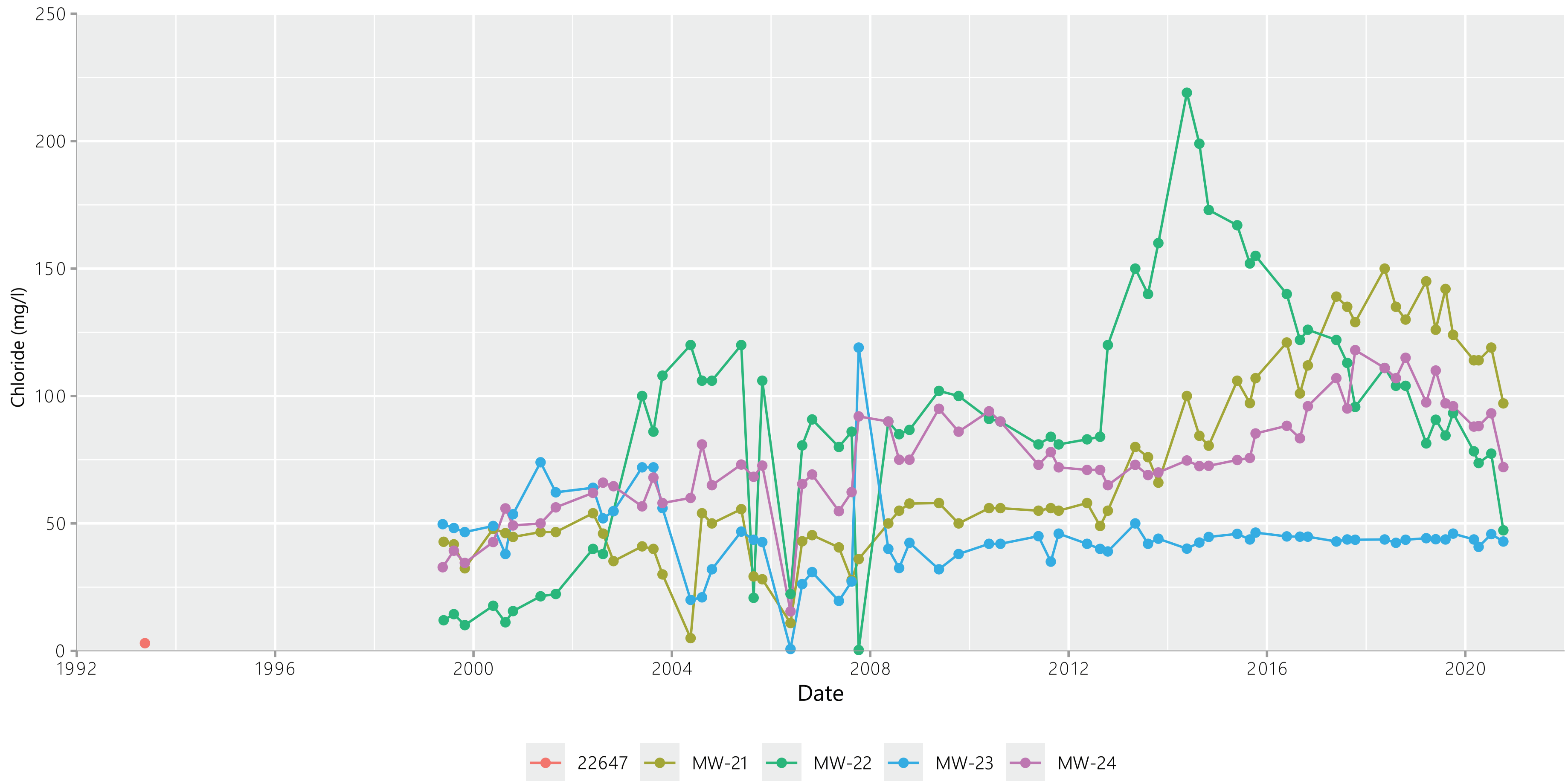
Source: WDNR and SEWRPC

Figure 6.7
Histogram of Well Depths for Wells with Chloride Observations and Reported Well Depths: 1945-2022



Source: WDNR, USGS, MMSD, UWSP, and SEWRPC

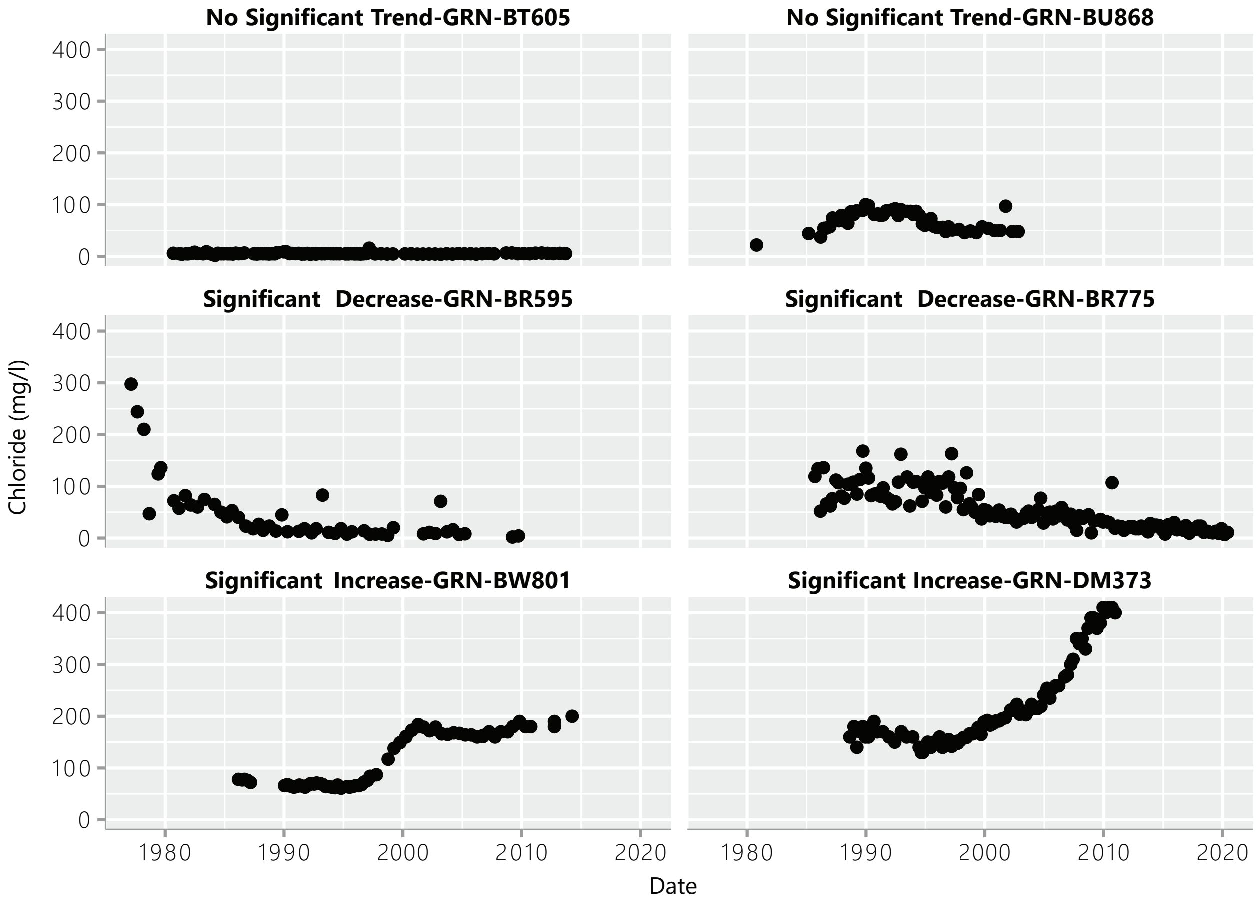
Figure 6.8
Example of Chloride Variability within a PLSS Section: Township 12, Range 22, Section 29



Note: Each line indicates chloride concentrations from a well within the Section.

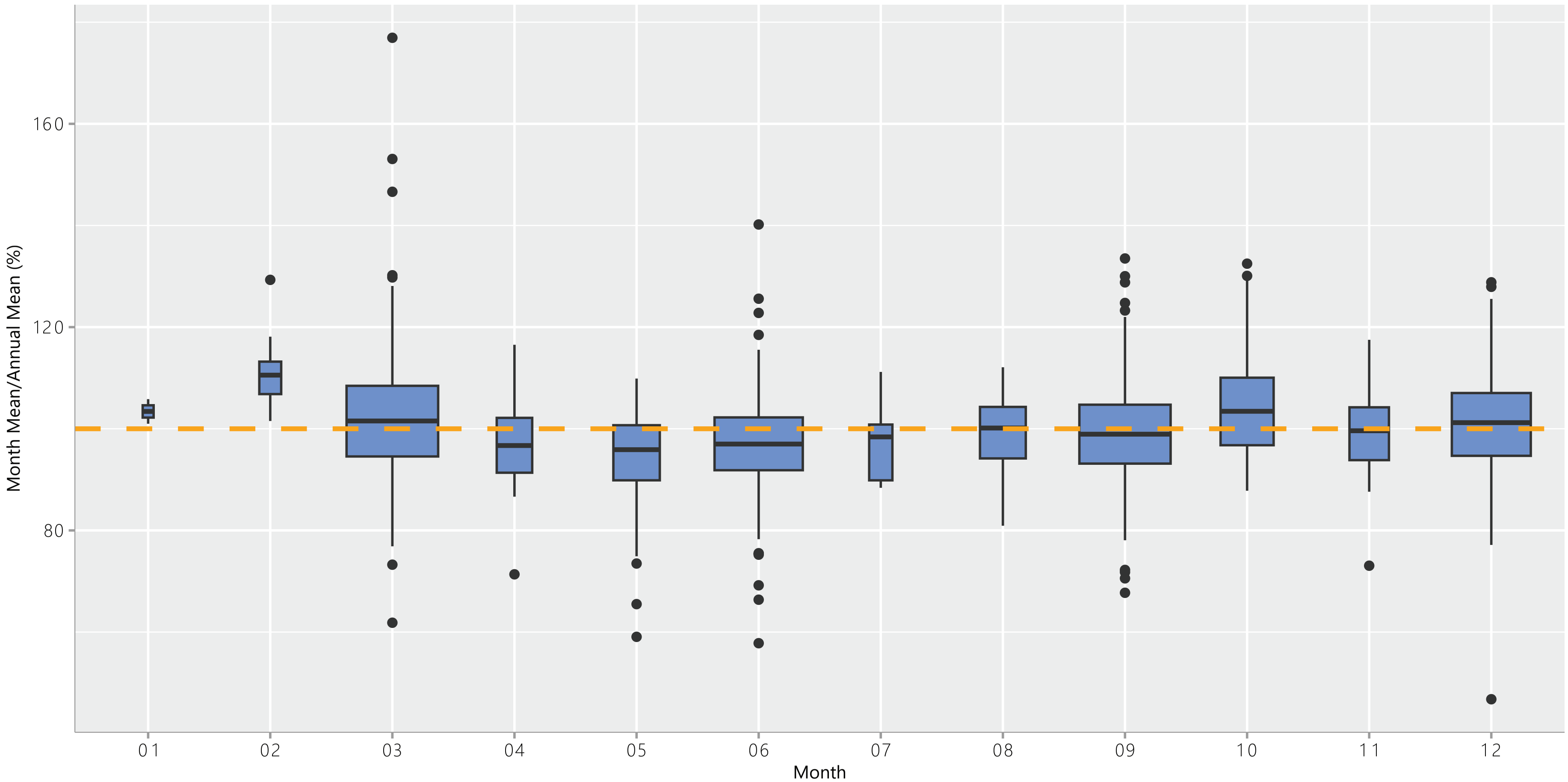
Source: WDNR, UWSP, and SEWRPC

Figure 6.9
Chloride Concentrations Over Time for Example Trend Wells



Source: WDNR, MMSD, USGS, UWSP, and SEWRPC

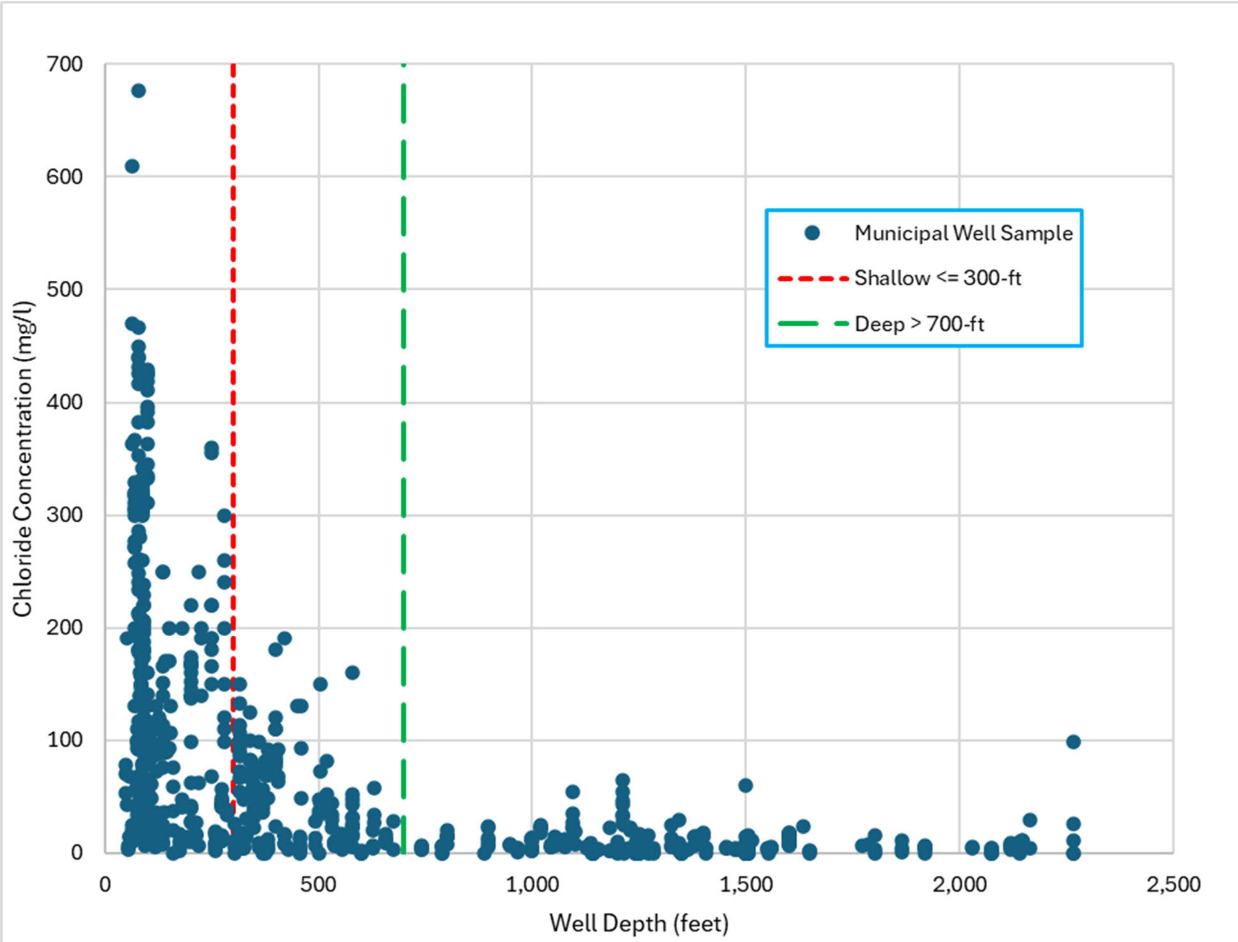
Figure 6.10
Monthly Mean Chloride Concentrations Compared to Annual Concentrations in Very Shallow Wells



Note: The boxplot width indicates the number of samples with a narrower box having fewer samples.

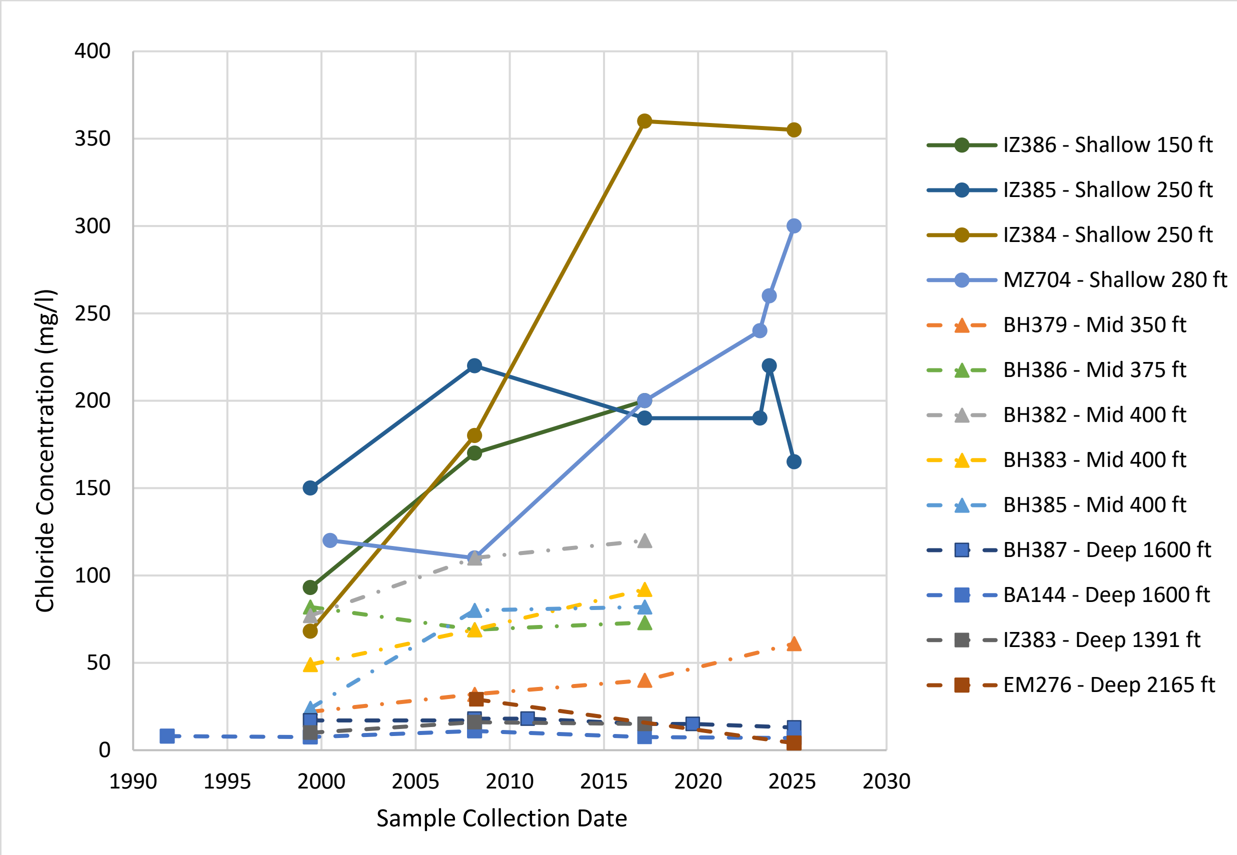
Source: WDNR, MMSD, USGS, UWSP, and SEWRPC

Figure 6.11
All Active Municipal Well Data: 1977-2025



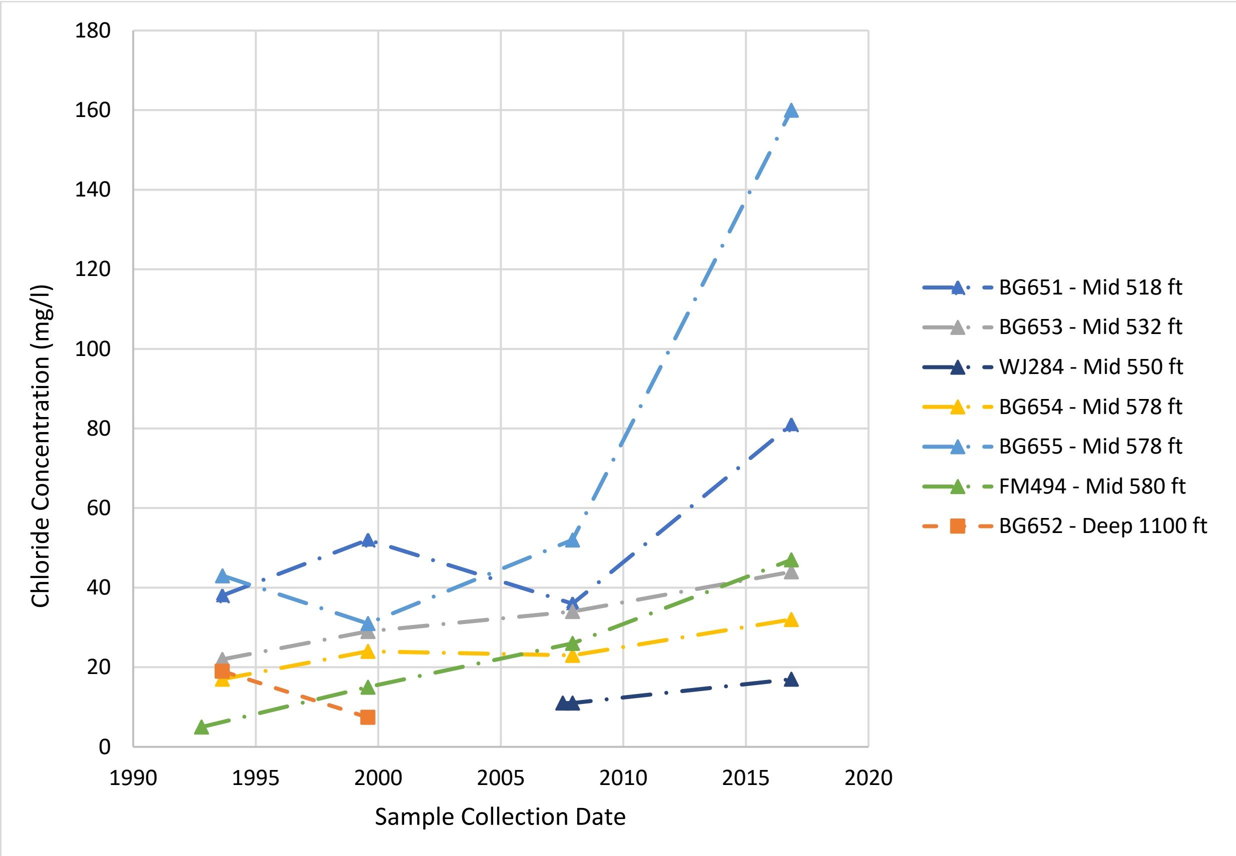
Source: WDNR, SEWRPC, City of Brookfield, Village of Slinger, and City of West Bend

Figure 6.12
Municipal Well Chloride Trend – City of Brookfield: 1991-2025



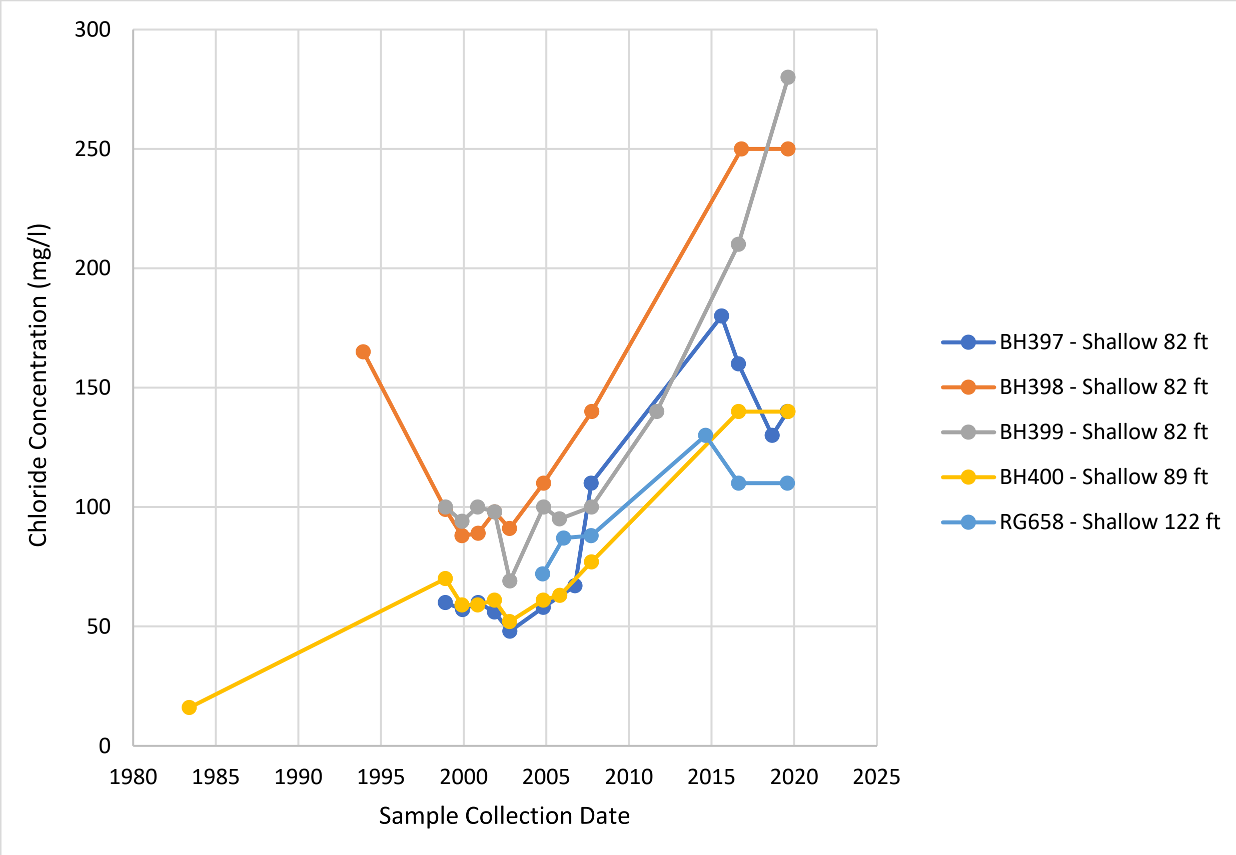
Source: WDNR, SEWRPC, City of Brookfield

Figure 6.13
Municipal Well Chloride Trend – Village of Grafton: 1992-2017



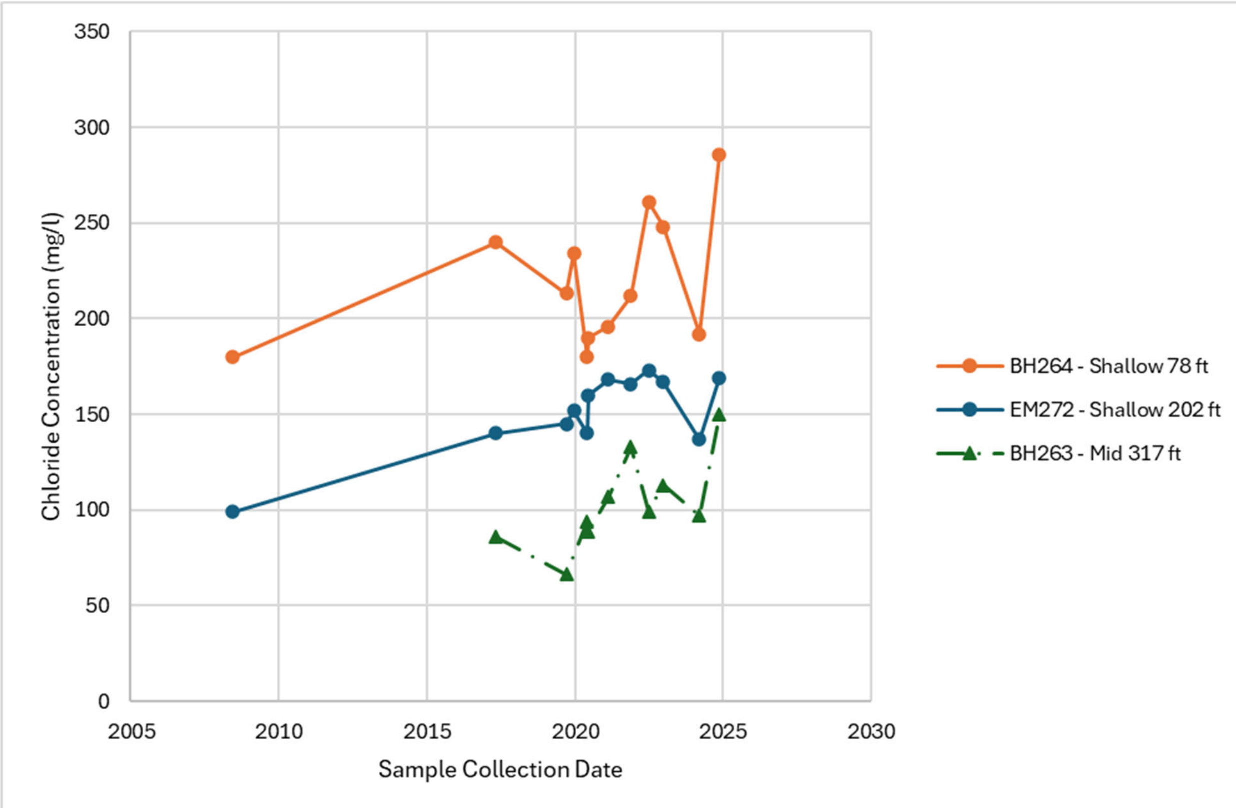
Source: WDNR, SEWRPC

Figure 6.14
Municipal Well Chloride Trend – Village of Hartland: 1983-2020



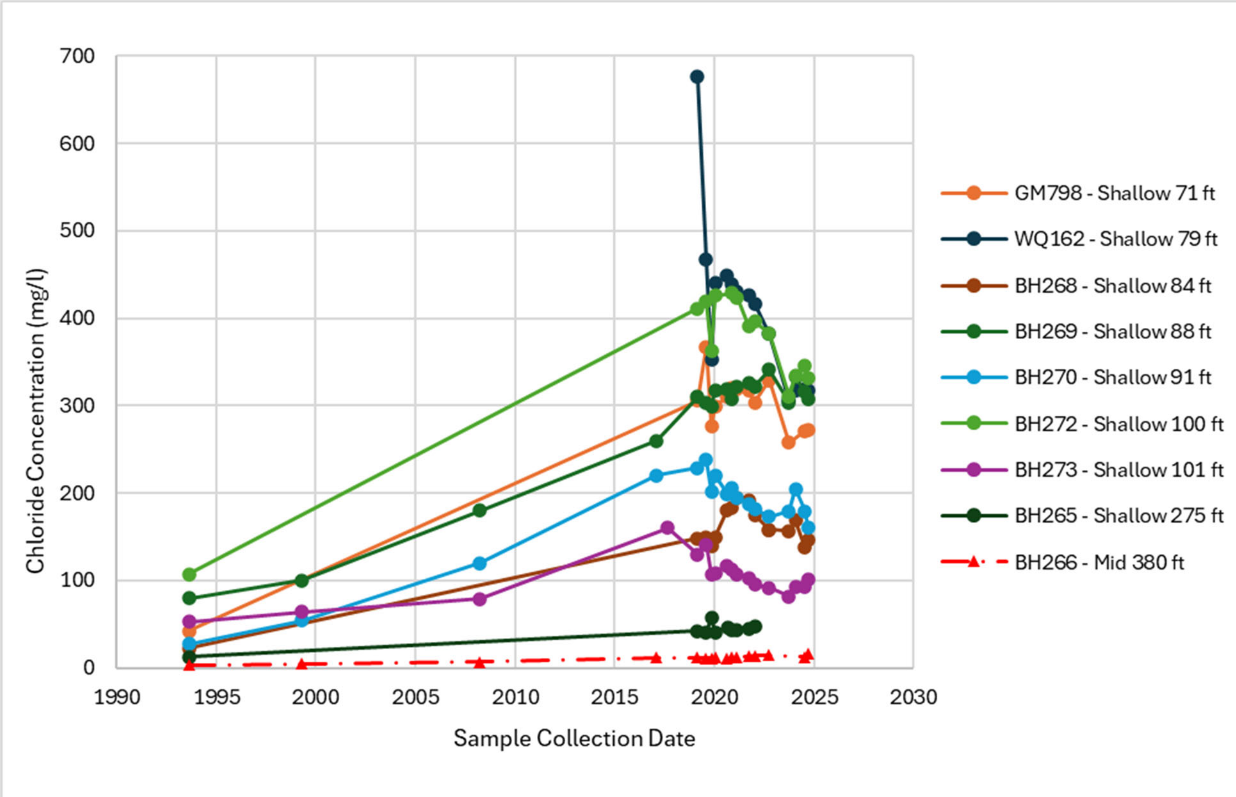
Source: WDNR, SEWRPC

Figure 6.15
Municipal Well Chloride Trend – Village of Slinger: 2008-2024



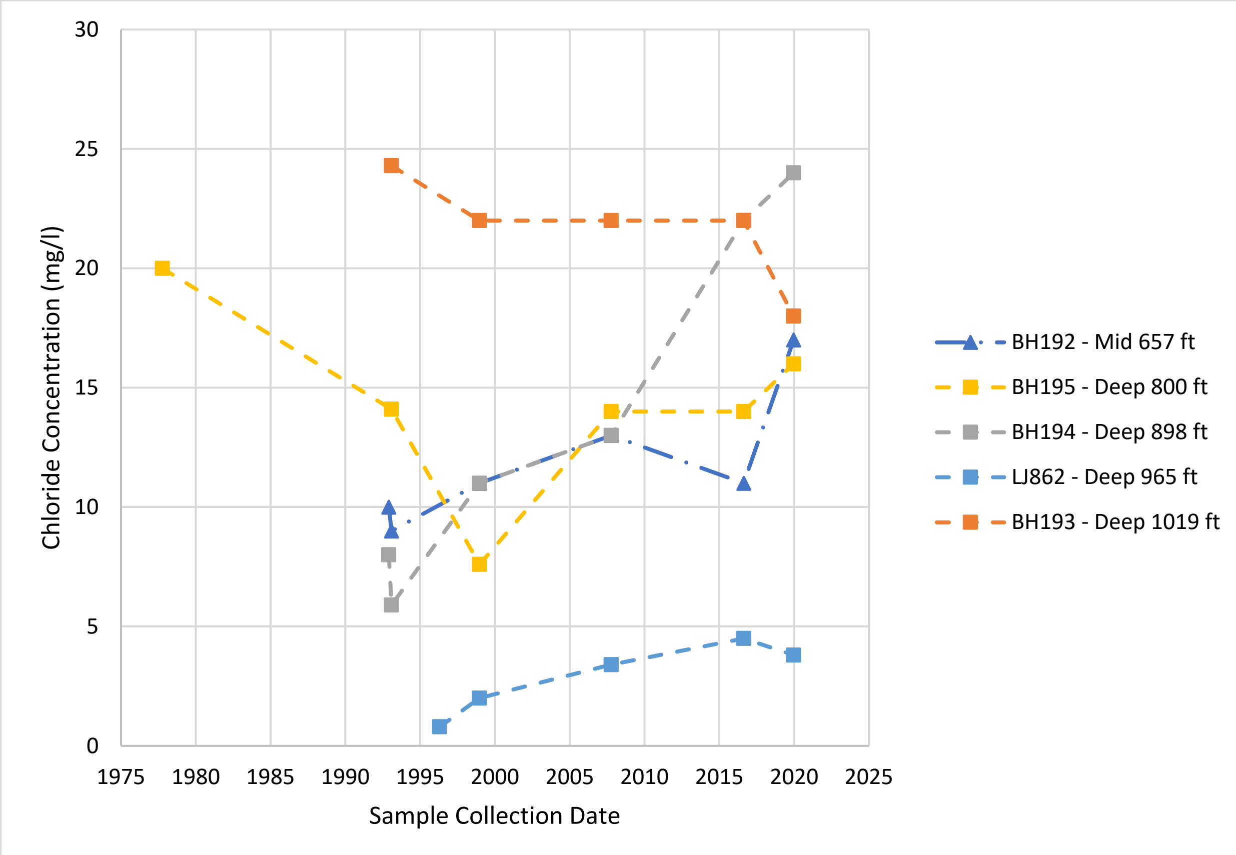
Source: WDNR, Village of Slinger, SEWRPC

Figure 6.16
Municipal Well Chloride Trend – City of West Bend: 1993-2024



Source: WDNR, SEWRPC, City of West Bend

Figure 6.17
Municipal Well Chloride Trend – City of Whitewater: 1977-2020



Source: WDNR, SEWRPC

Technical Report No. 63

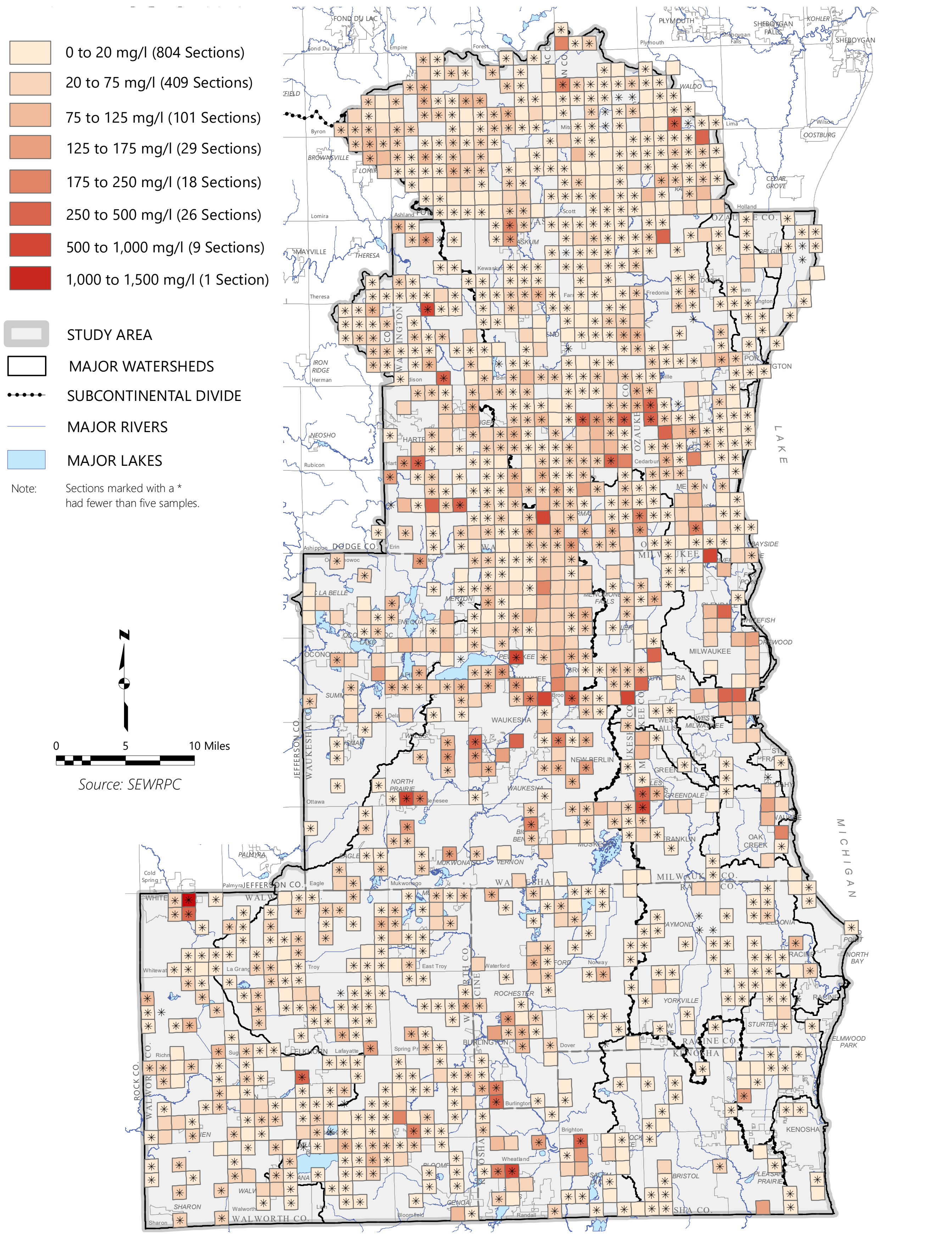
CHLORIDE CONDITIONS AND TRENDS IN SOUTHEASTERN WISCONSIN

Chapter 6

CHLORIDE CONDITIONS AND TRENDS: GROUNDWATER

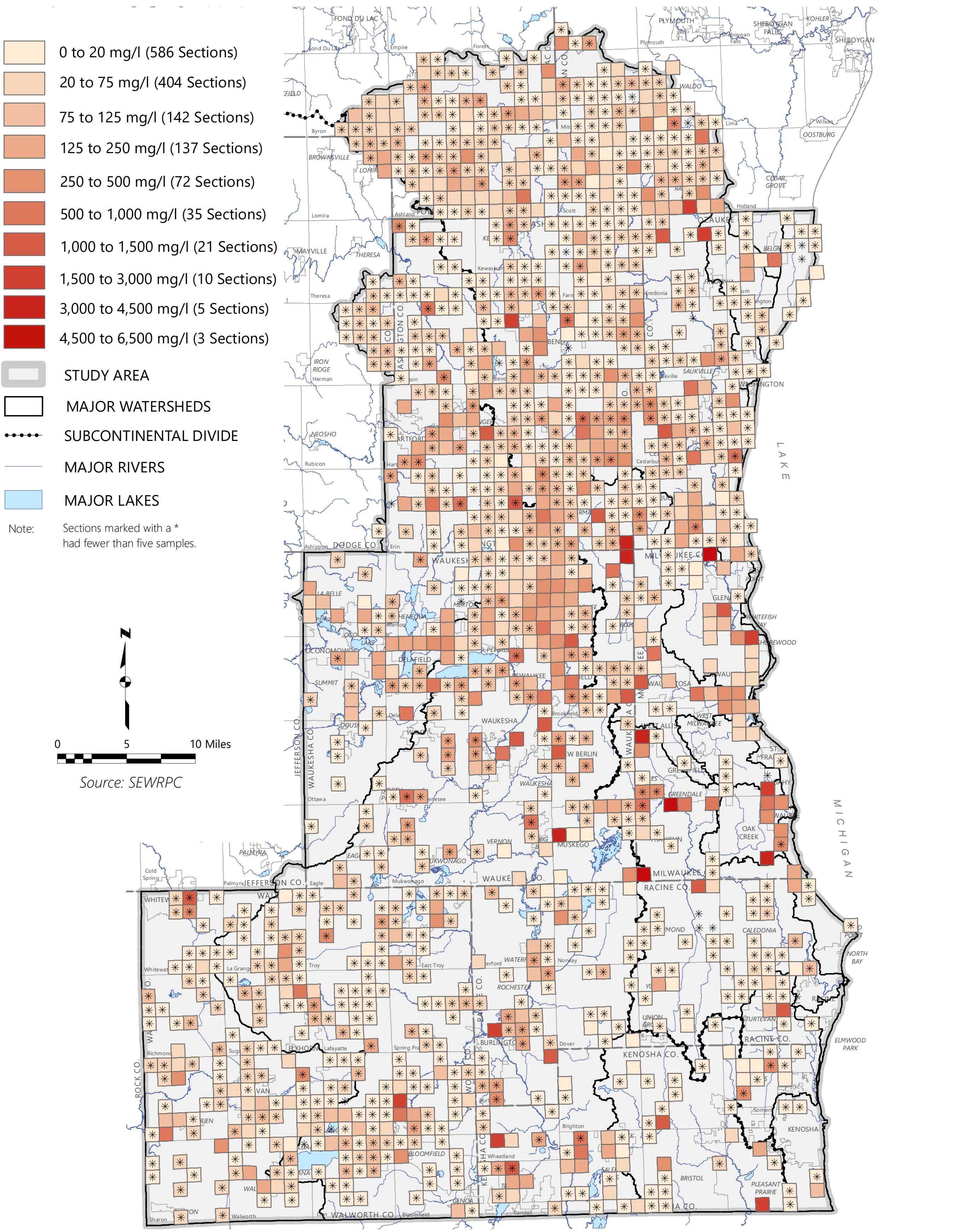
MAPS

Map 6.1
Median Shallow Groundwater Chloride Concentrations Among PLSS Sections: 1945 through 2022

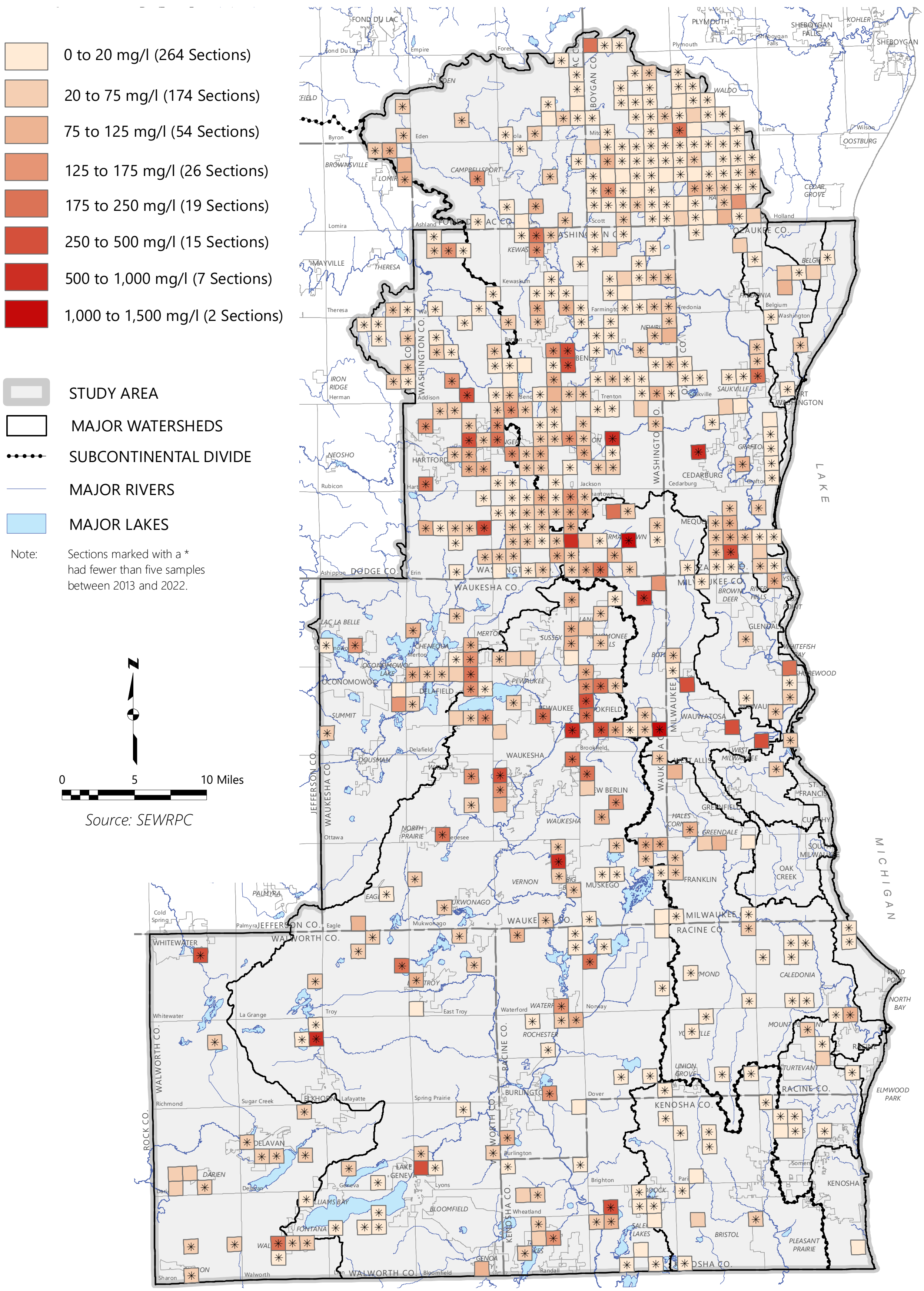


Source: SEWRPC

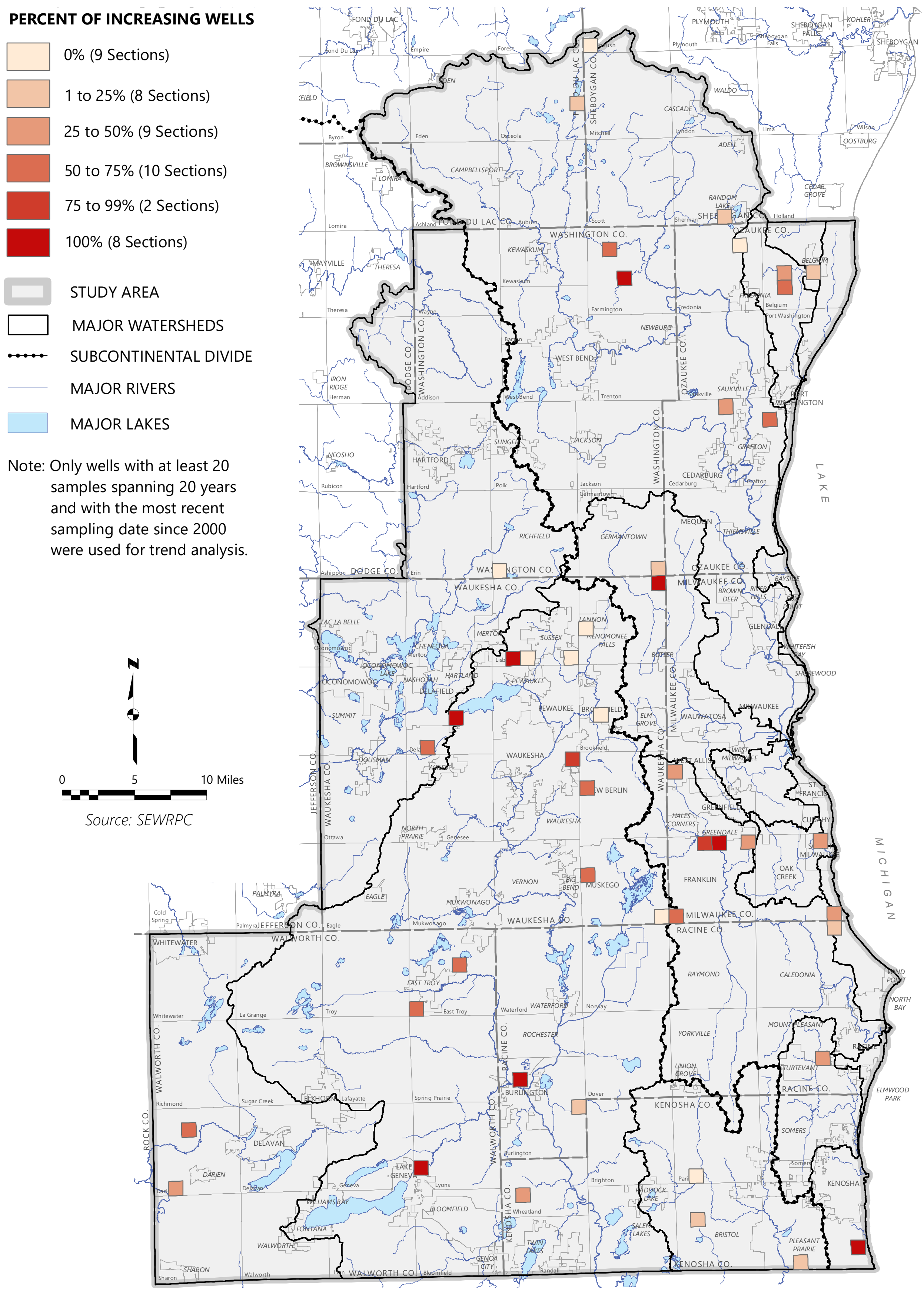
Map 6.2
Maximum Shallow Groundwater Chloride Concentrations Among PLSS Sections: 1945 through 2022



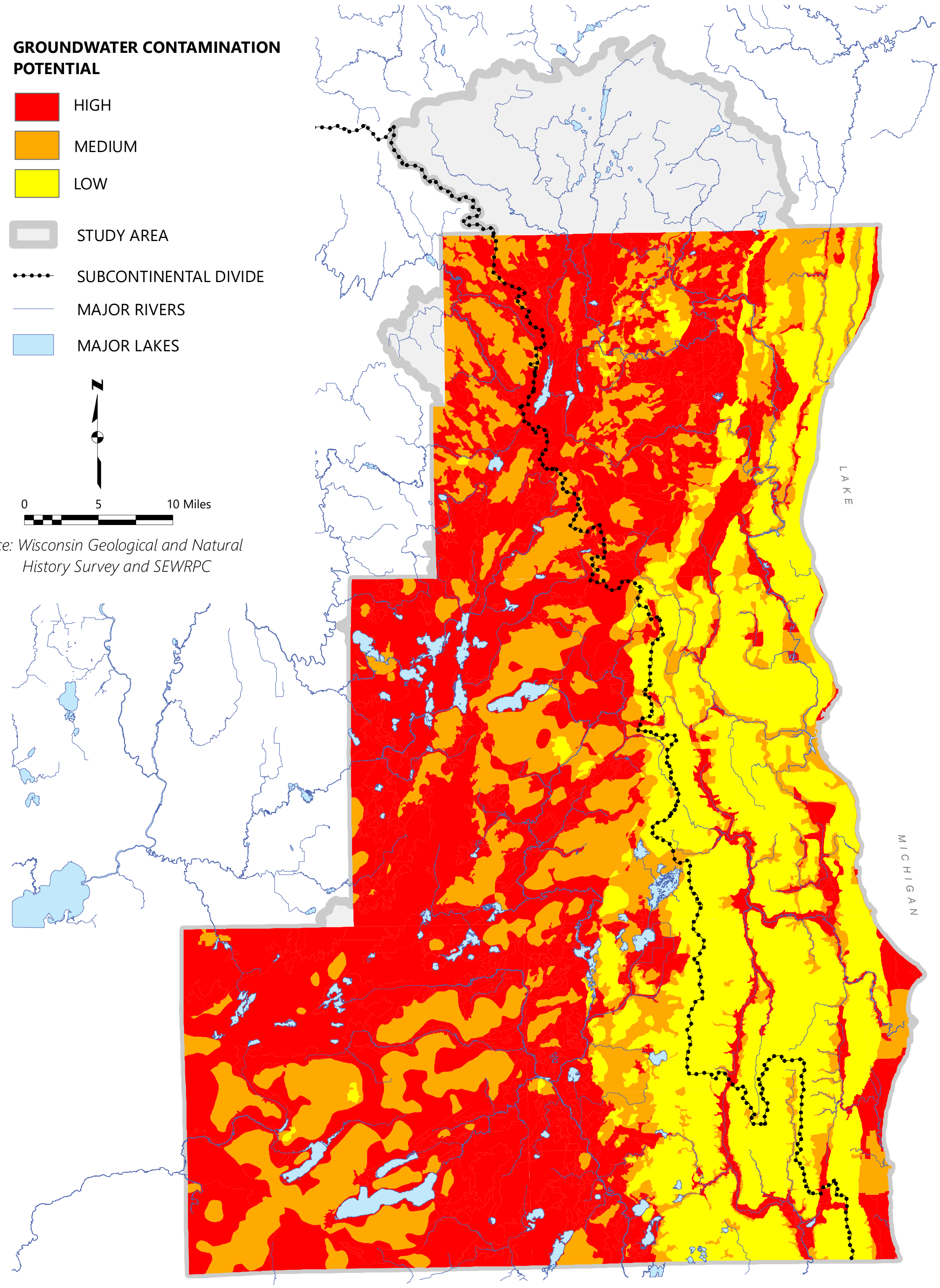
Map 6.3
Recent Shallow Groundwater Median Chloride Concentrations Among PLSS Sections: 2013 - 2022



Map 6.4
Percent of Shallow Wells in PLSS Sections with Increasing Chloride Concentrations: 1945 - 2022

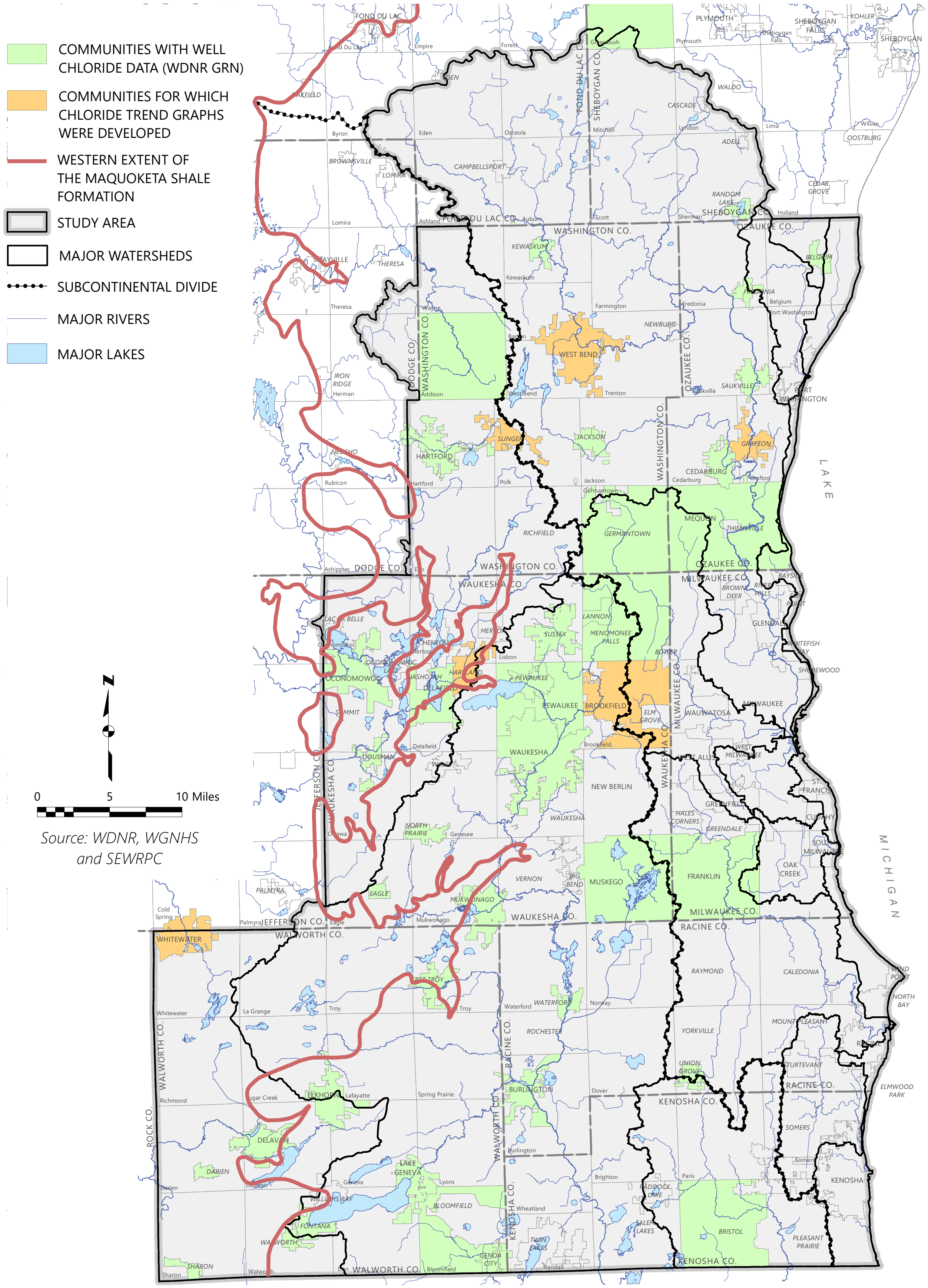


Map 6.5
Modeled Groundwater Contamination Potential in Southeastern Wisconsin



Source: Wisconsin Geological and Natural History Survey and SEWRPC

Map 6.6
Communities with Municipal Well Data



Source: WDNR, WGNHS and SEWRPC