INTERACTIONS OF GROUNDWATER AND SURFACE WATER RESOURCES

Phase I: Potential Hydraulic Connections Between Bedrock Aquifers and Surface Water in the Twin Cities Metropolitan Region

Metropolitan Council Environmental Services: Water Supply Planning
St. Paul, MN

METROPOLITAN
COUNCIL

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Abbreviations and Acronyms

Barr	Barr Engineering Co.
Council	Metropolitan Council
ft/day	feet per day
GIS	geographic information system
HDR	HDR Engineering, Inc.
MCES	Metropolitan Council Environmental Services
MDH	Minnesota Department of Health
mg/L	milligram per liter
MGS	Minnesota Geological Survey
MN DNR	Minnesota Department of Natural Resources
MPCA	Minnesota Pollution Control Agency
NRCS	Natural Resources Conservation Service
NWI	National Wetland Inventory
PWI	Public Waters Inventory
TCMA	Twin Cities Metropolitan Area (11-county)
TM	technical memorandum
TU	tritium unit
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey

1 Introduction

The Twin Cities Metropolitan Area (TCMA) includes over one thousand lakes, three major rivers, and several streams, springs, and fens of ecological and cultural importance. Some of these surface waters are hydraulically connected to underlying bedrock aquifers and some are not, but all surface waters are dependent on inputs from some combination of rainfall, runoff, and shallow groundwater. In areas where upwelling groundwater serves an important ecological role (fens, trout streams, springs, etc.) and where lakes and wetlands overlie highly transmissive sediments, surface waters can experience impacts related to their physical connection with groundwater.

Connection between groundwater and surface water is conditional and based on a variety of factors. Some of these factors can influence one another (i.e. changing climate and weather patterns, land use changes, and groundwater pumping) and vary through time. Other factors (i.e. surficial geology, lake bathymetry) are different from place to place but remain relatively static through time. Determining which factors, or combination of factors, are driving observable changes is challenging and requires in-depth understanding of local geology and individual surface waters.

Recent attention has been paid to groundwater-surface water interactions because, in-part, some surface waters in the region have experienced changes that have had consequences for the people and communities that rely on them for social, cultural, and economic activities. In areas where significant groundwater pumping intersects with hydraulically connected surface water features, there is the potential for negative impacts to both groundwater and surface water. For example, the water level in White Bear Lake has been lowered, in-part, due to groundwater pumping, thereby affecting the communities that surround the lake (Minnesota Department of Natural Resources, 2018a). Other concerns related to hydraulic connection of surface water and groundwater include loss of ecological function in trout streams and groundwater-dependent wetlands, and contamination of drinking water resources, particularly in areas where pollutants can move rapidly through the surficial geology.

The goal of this study is to understand where in the TCMA there is potential for hydraulic connection between surface waters and groundwater through an examination of hydrogeologic conditions and water chemistry observations. The study is not intended to assess the hydraulic connection of individual surface waters. Rather, this assessment characterizes the surficial geologic landscape within the study area where, based on available data, there may be a higher (or lower) potential for surface waters to be hydraulically connected to the regional aquifer system. The findings of this assessment are intended to inform groundwater and surface water monitoring efforts, regional and local groundwater modeling activities, and future analyses that examine the interactions of groundwater and surface water resources.

2 Scope of the Assessment

Previous work by Barr Engineering Co. (Barr) in 2010 for the Metropolitan Council (Council) provided a regional evaluation of groundwater-surface water interactions based on an assessment of the regional water table, physiographic characteristics of surface water features, and shallow geology. In the 2010 report, a permeability scoring system was devised to identify surface water features that are likely discharging water to or receiving water from the regional groundwater system. That report also goes on to make monitoring recommendations based on the type of groundwater connection.

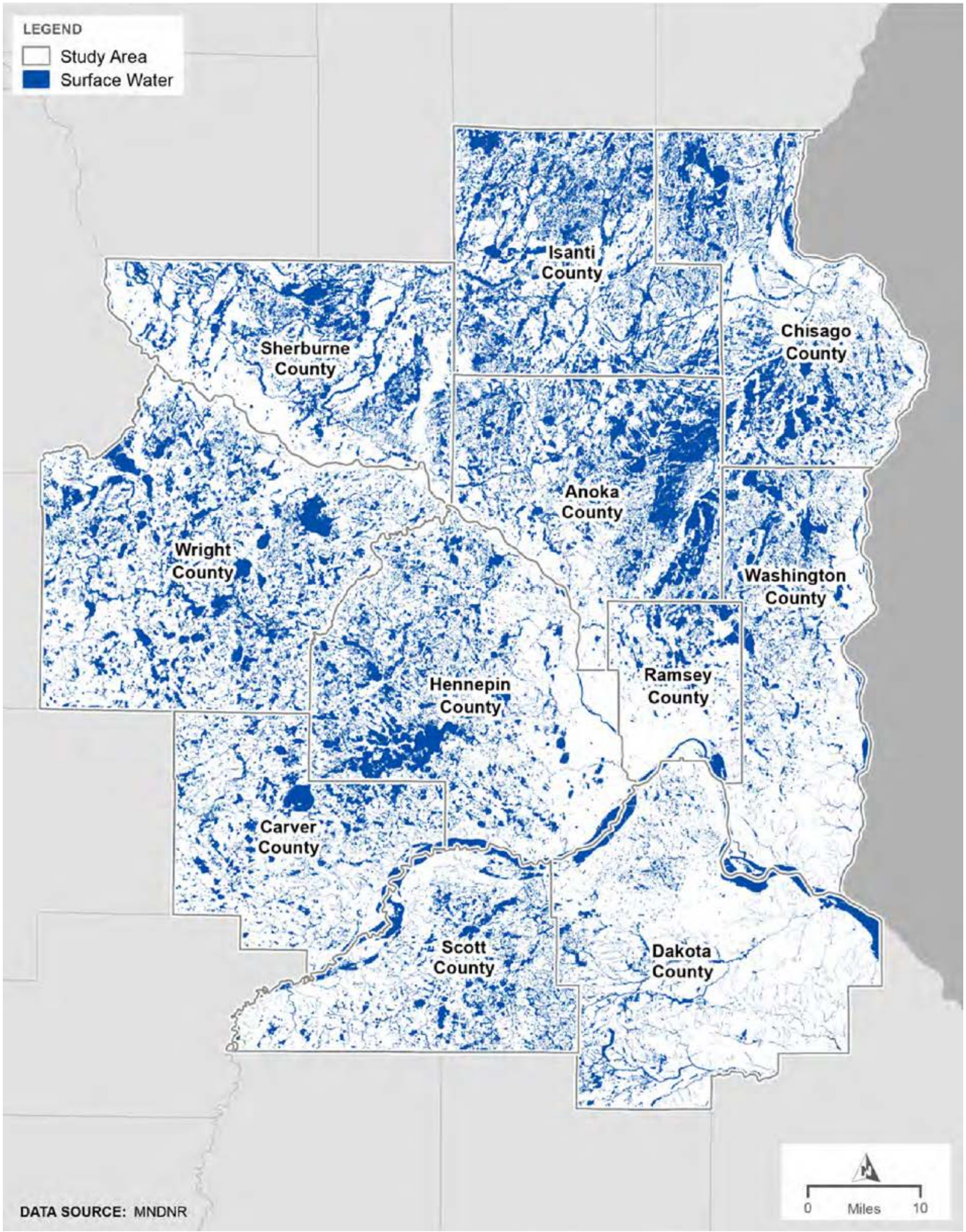
Since the completion of the Barr (2010) study, the Minnesota Geologic Survey (MGS) and the Minnesota Department of Natural Resources (DNR) have updated the hydrogeologic data in several of the county geologic atlases that identify and map surficial and bedrock geology. The DNR has also conducted a statewide water table evaluation (Adams, 2016). This study incorporates the updated geologic and water table data with current scientific understanding of groundwater-surface water connection to broadly map surficial hydrogeologic conditions for the region, to estimate permeabilities, and infer rates of vertical groundwater movement.

This study also uses available groundwater quality data. Groundwater chemistry can be assessed to understand the relative age of groundwater, and subsequently can be used to infer hydraulic connection (Pfannkuch, 1998). These data were obtained from local, regional, and state agencies that monitor the impact of contaminants on water resources and human health. These agencies evaluate the concentration of analytes in well water, including those that can be traced to human activity, and use the data to aid in resource planning, develop mitigation strategies, and introduce best management practices to prevent contamination. In this assessment, chemistry-based groundwater age serves as a check on our estimates of travel time through surficial sediments.

The assessment does not identify the status of groundwater connectedness for individual surface waters and assumes that all surface waters have the potential to be influenced by groundwater conditions to a greater or lesser degree. The study addresses the question: Where are surficial geologic conditions favorable for groundwater – surface water connectedness in the TCMA?

This report summarizes an assessment of the potential for hydraulic connections between bedrock aquifers and surface water in the TCMA. The study area covers 4,765 square miles and includes Anoka, Carver, Chisago, Dakota, Hennepin, Isanti, Ramsey, Scott, Sherburne, Washington, and Wright Counties. The study area is shown on Figure 2-1.

Figure 2-1. Twin Cities Metropolitan Area



3 Geologic Setting

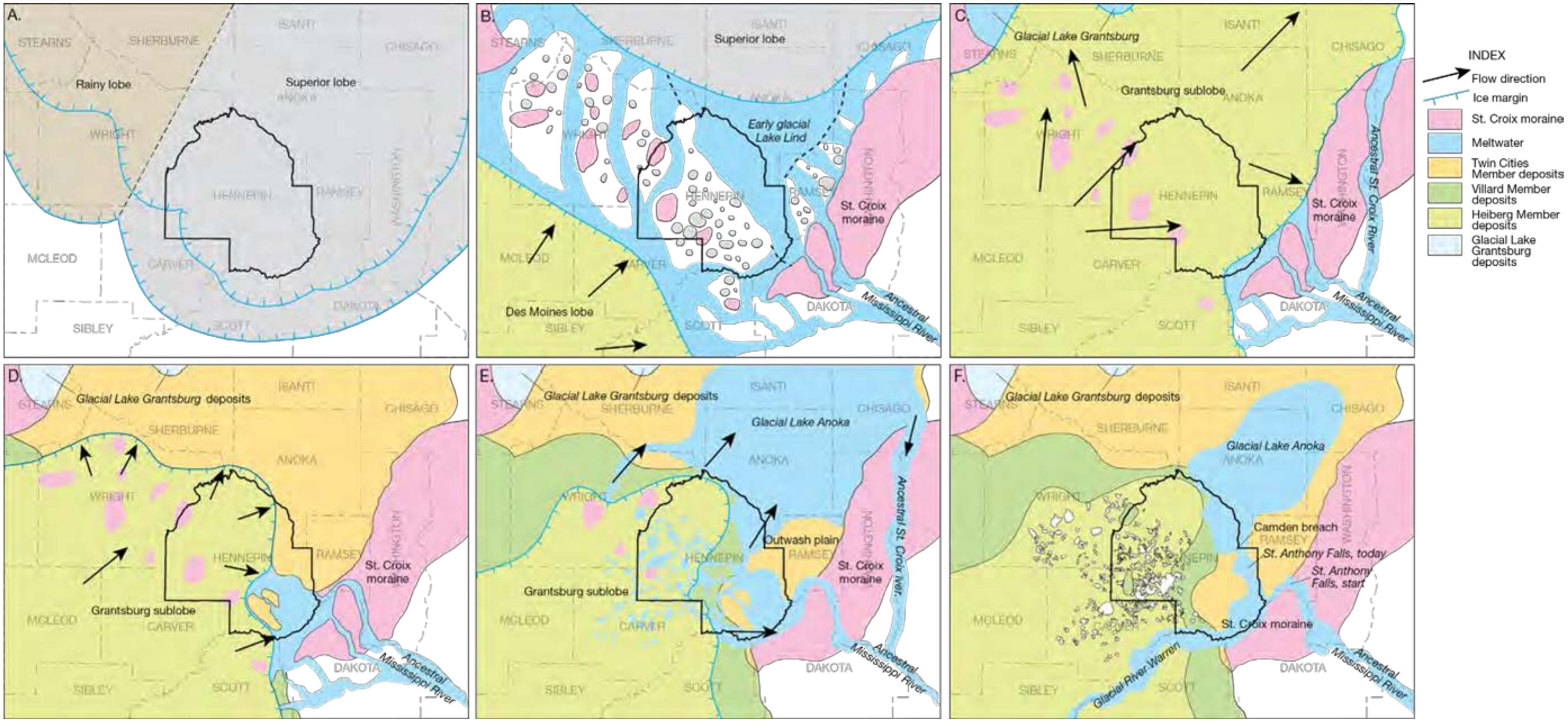
This study focuses on the surficial sediments of the eleven-county TCMA, because these deposits form the pathway for water moving between surface water features and underlying glacial and bedrock aquifers. The TCMA experienced up to eleven episodes of glaciation during the Quaternary Period (2.58 million – 11.7 thousand years ago). These continental glaciation events had a profound effect not only on the region's climate but on the land surface. Ice sheets originating in multiple areas of present-day Canada dramatically modified the sediments and bedrock of the region. In areas of the present-day metro where bedrock aquifers are inconsistent or unreliable water sources and glacial deposits are productive and easier to access, near-surface aquifers are important sources of water used for industry, irrigation, and drinking water supply.

The current land surface is predominantly made up of deposits altered by ice movement, and left behind after the last several Wisconinan-age glacial advances, including the Superior lobe, Des Moines lobe, and Grantsburg sublobe of the Des Moines lobe (Figure 3-1). Each of these glacial advances, and subsequent retreats from the region, left behind mixtures of till, outwash, and lacustrine sediments, resulting in such landforms as the St. Croix moraine, the Anoka sand plain, and outwash terraces along the Minnesota and Mississippi Rivers. Each glacial lobe's deposits reflect the bedrock geology over which the ice advanced, with resulting Superior lobe tills generally consisting of coarser materials (more sand) and Des Moines lobe tills consisting of more fine textured deposits (more clay). Outwash materials are generally sandy, while lacustrine deposits associated with glacial lakes are clayey.

Each ice advance extended over earlier glacial deposits, those older sediments became incorporated in the flowing ice, resulting in mixing of glacial materials. The subsequent collection of Quaternary sediments in the TCMA are highly variable and range from less than 10 feet to over 300 feet thick, with individual stratigraphic units ranging from very localized to extending across several counties. This complexity means that any regional assessment of water movement through these deposits cannot necessarily capture localized conditions that could result in preferential flow paths or perched conditions. However, by using a combination of hydrogeologic interpretation and chemistry data, we can have confidence in our regional interpretations of groundwater travel times through glacial deposits.

Throughout this report, the terms Quaternary, surficial, and glacial deposits, till, or sediments refer to the unconsolidated materials that overlie bedrock in the TCMA, not including soils.

Figure 3-1. Wisconsinan-age Glacial Deposition in the Twin Cities Metropolitan Area



Source: Steenberg, J. R., et al, 2018.

4 Assessment Approach and Methods

The hydrogeologic properties of surficial sediments fundamentally determine the potential for hydraulic connection between surface water resources and groundwater aquifers. However, whether or not any particular surface water or groundwater resource may be impacted (positively or negatively) by their interactions is based on a complicated set of local variables including the location and physical properties of surface water features, acute weather conditions and chronic climate patterns, and a variety of anthropogenic (human) activities. This assessment generalizes surficial hydrogeologic patterns within the TCMA and does not attempt to parse-out the specific factors that drive the hydraulic connectivity of individual surface water features. This examination attempts to understand the regional surficial geologic landscape, and points to areas where assumptions regarding bedrock groundwater-surface water connections are more or less well-understood.

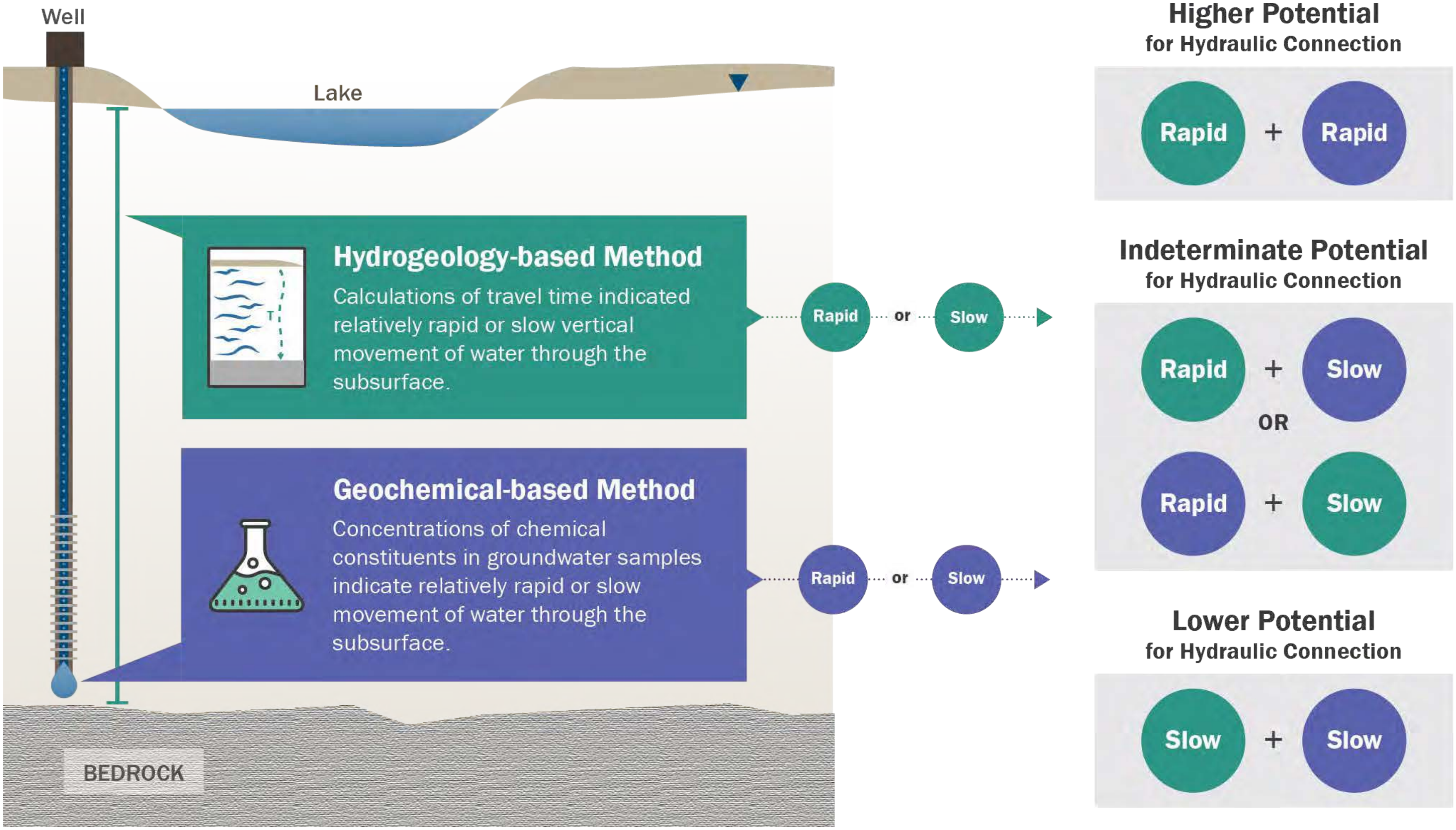
Two assessment methods were used to understand water movement through surficial sediments in the TCMA. The first method was a hydrogeologic assessment, which uses county geologic atlas data to estimate how easily water moves vertically through mapped Quaternary sediments. The second method was a geochemical assessment in which groundwater chemistry data from well testing databases was used to infer relative groundwater age. A comparison of the travel time from the hydrogeologic assessment, with the apparent groundwater age from the geochemical assessment, was used to characterize the surficial geologic landscape as having higher, lower, or indeterminate potential for hydraulic connection between surface waters and the uppermost bedrock aquifer. The two methods and assessment approach are summarized on Figure 4-1.

The methodology can be summarized by the following steps:

1. Collection of existing regional-scale hydrogeologic and geochemical datasets;
2. Estimation of vertical groundwater travel times based on hydrogeology;
3. Evaluation of the presence of anthropogenic, chemical indicators in groundwater using geochemical datasets and estimation of groundwater age to infer groundwater travel times;
4. A comparison of the hydrogeology-based and geochemical-based travel time assessments, resulting in a characterization of the surficial geologic landscape of the TCMA, and an assessment of the potential for groundwater-surface water hydraulic connection.

These steps are described in more detail below. The resulting characterization of the potential for hydraulic connection is described in Section 5.

Figure 4-1. Depiction of the Assessment Approach and Potential for Hydraulic Connection Characterization Process



Hydrogeology-based Method

Calculations of travel time indicated relatively rapid or slow vertical movement of water through the subsurface.

Geochemical-based Method

Concentrations of chemical constituents in groundwater samples indicate relatively rapid or slow movement of water through the subsurface.

4.1 Data Collection

Data used in this assessment included updates to information used in Barr (2010) as well as new geology and groundwater geochemical datasets. Datasets were obtained from the Minnesota Department Health (MDH), DNR, MGS, and United States Geological Survey (USGS). If needed, data were converted to a format suitable for processing with geographic information system (GIS) software. In addition to the datasets, staff from the agencies were interviewed to better understand the data provided.

A group of technical experts was convened with representatives from state and federal agencies, county staff, watershed districts, and Council staff in June 2018 to discuss the project and proposed methodology. Representatives who attended the meeting are listed in Appendix A. The work group meeting resulted in refinement and confirmation of the proposed methods, and the identification of additional data resources to be shared with the project team that would be essential to the assessment.

A summary of the datasets used in the assessment is listed below. Additional details and references are shown in Appendix B.

- Hydrogeologic data:
    - Quaternary geology from county geologic atlases and supplemented by data from MGS personnel;
    - Bedrock surface elevation;
    - Water table elevation and bedrock aquifer potentiometric surface elevation;
- Groundwater chemistry data, including sample results for tritium, nitrate, chloride, and bromide, which can be considered anthropogenic indicators; and
- Surface water features, including lakes, wetlands, fens, springs, streams (including trout streams), and rivers

4.2 Estimation of Hydrogeologic Vertical Groundwater Travel Time

This method uses the Darcy flux calculation to evaluate vertical groundwater travel time from an estimated regional water table, through surficial geologic deposits, to the uppermost bedrock aquifer. The water table and uppermost bedrock aquifer were selected as the vertical bounds for the calculation and are described as follows:

- Water table surface:
    - The water table used in this analysis is from Adams (2016) who developed a statewide water table from water levels contained in well construction records, water-surface elevations in the statewide 30-meter digital elevation model, and saturated soil information from Natural Resources Conservation Service

    (NRCS) soil surveys. This is a single, generalized water table surface and does not reflect how the water table can vary seasonally. In Minnesota, water tables are typically higher in the spring and early summer when snow and ice melt are occurring, and precipitation is greatest. Water tables are usually lower during the late summer and early fall when there is less precipitation and high evapotranspiration. The Adams (2016) water table represents average water table conditions based on the data used in their assessment.

    - Adams (2016) assumes that surface water features (i.e. lakes and streams) represent the water table, even if some happen to be perched above the water table. This assumption treats all surface water features equally in that regard.

- Uppermost bedrock aquifer:

    - The uppermost bedrock aquifer was the focus of this analysis because it is frequently used groundwater source in the TCMA. In much of the Central, Eastern and Southern TCMA, the uppermost bedrock aquifers are relatively shallow and highly productive. Most often the Prairie du Chien and Jordan aquifers are relied upon by municipalities, irrigators, and industries. The Prairie du Chien and Jordan aquifers become more inconsistent or absent as you move from East to West in the TCMA. In some area they are covered by relatively low permeability bedrock units..

    - In the Western and Northern TCMA, the uppermost bedrock aquifer is generally deeper and overlain by a greater thickness of glacial deposits. In these areas, where the Prairie du Chien and Jordan cannot be easily accessed, both Quaternary sediments and bedrock aquifers may be relied upon for drinking water supplies. Because pumping from wells in Quaternary sediments is closer to the surface, it may have more influence on potential hydraulic connections between surface and ground water than pumping from deeper bedrock aquifers in these areas.

- Bedrock Potentiometric Surface:

    - The bedrock potentiometric surface is the elevation water rises to in wells that penetrate the bedrock unit. When the potentiometric surface is above the top of the bedrock aquifer it means the aquifer is under pressure and is typically called a confined, or artesian, aquifer. The potentiometric surface of the uppermost bedrock aquifer affects the ability of water to travel from the water table to that aquifer. For example, a high potentiometric surface means the aquifer is under high pressure and is therefore more difficult to get water into, resulting in a longer vertical travel time.

    - The potentiometric surface used in this analysis is from Tipping

(2012), which used groundwater levels collected in March of 2008. Spring potentiometric surface levels are typically higher than other times of the year due to reduced groundwater pumping in the winter and spring. This adds a high-bias to calculated travel times.

In this simplified assessment, the movement of groundwater through Quaternary sediments is determined by two factors. The first factor is the distance between the water table elevation and the bedrock potentiometric surface. Where the water table is at a higher level than the potentiometric surface, groundwater movement will be downward. Where the potentiometric surface is above the water table an upward gradient exists. The second factor is the overall permeability, or hydraulic conductivity of the Quaternary stratigraphy. The bulk, or composite, vertical hydraulic conductivity is derived by calculating a mean hydraulic conductivity from the individual sedimentary units in the saturated zone within the Quaternary deposits.

These factors are expressed in the equation:

$$v_v = \frac{K_v(\varphi_{br} - \varphi_{wt})}{nL}$$ Equation 1

Where,

v_v is the vertical groundwater rate of movement in feet per day (ft/day),

K_v is the composite vertical hydraulic conductivity of Quaternary sediments in ft/day,

φ_{br} is the elevation of potentiometric surface in bedrock in feet (NAVD88),

φ_{wt} is the water table elevation in feet (NAVD88),

n is the overall effective porosity (unitless), and

L is the distance from the water table to the bedrock surface in feet.

Using an average regional water table, bedrock potentiometric surface, and composite hydraulic conductivities the rate of vertical groundwater movement through Quaternary sediments can be reasonably estimated. By including the thickness of saturated sediments an estimated travel time from the water table to the uppermost bedrock unit can be calculated. This can be expressed by the equation:

$$T_v = \frac{L}{v_v} = \frac{nL^2}{K_v\Delta\varphi)}$$ Equation 2 (Tipping 2012)

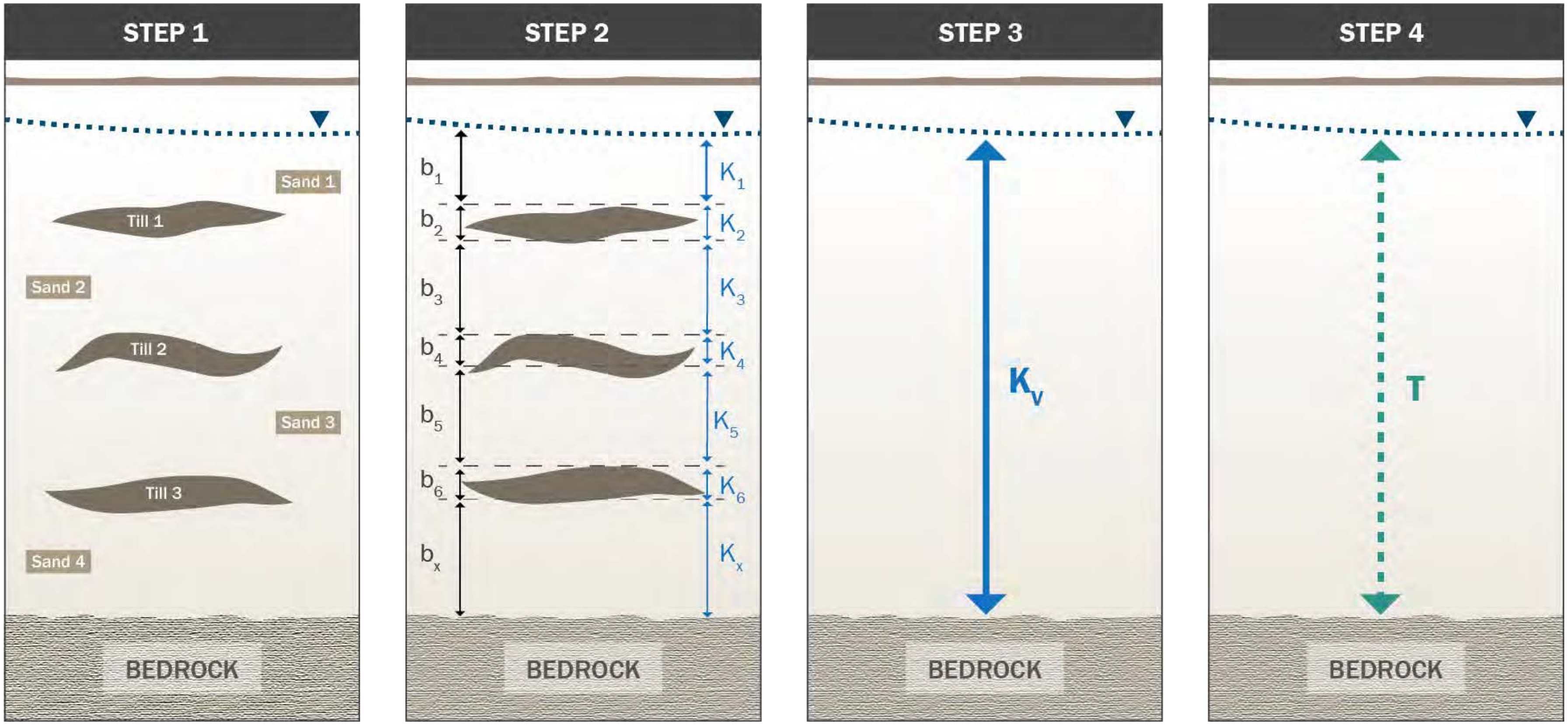
Where,

$\Delta\varphi$ is the difference in elevation between the water table and bedrock potentiometric surfaces in feet.

T_v is the vertical travel time through the Quaternary saturated zone in days, and

Figure 4-2 demonstrates the vertical travel time calculation process. The inputs to Equation 2, and the resulting vertical groundwater travel time, are described in the following subsections.

Figure 4-2. Depiction of the Vertical Travel Time Calculation Process



Identify the geologic layers between the water table and the bedrock surface.

Calculate the thickness (b) of each layer; assign hydraulic conductivity (K) value to each.

Calculate aggregate vertical hydraulic conductivity (K_V) using the weighted harmonic mean.

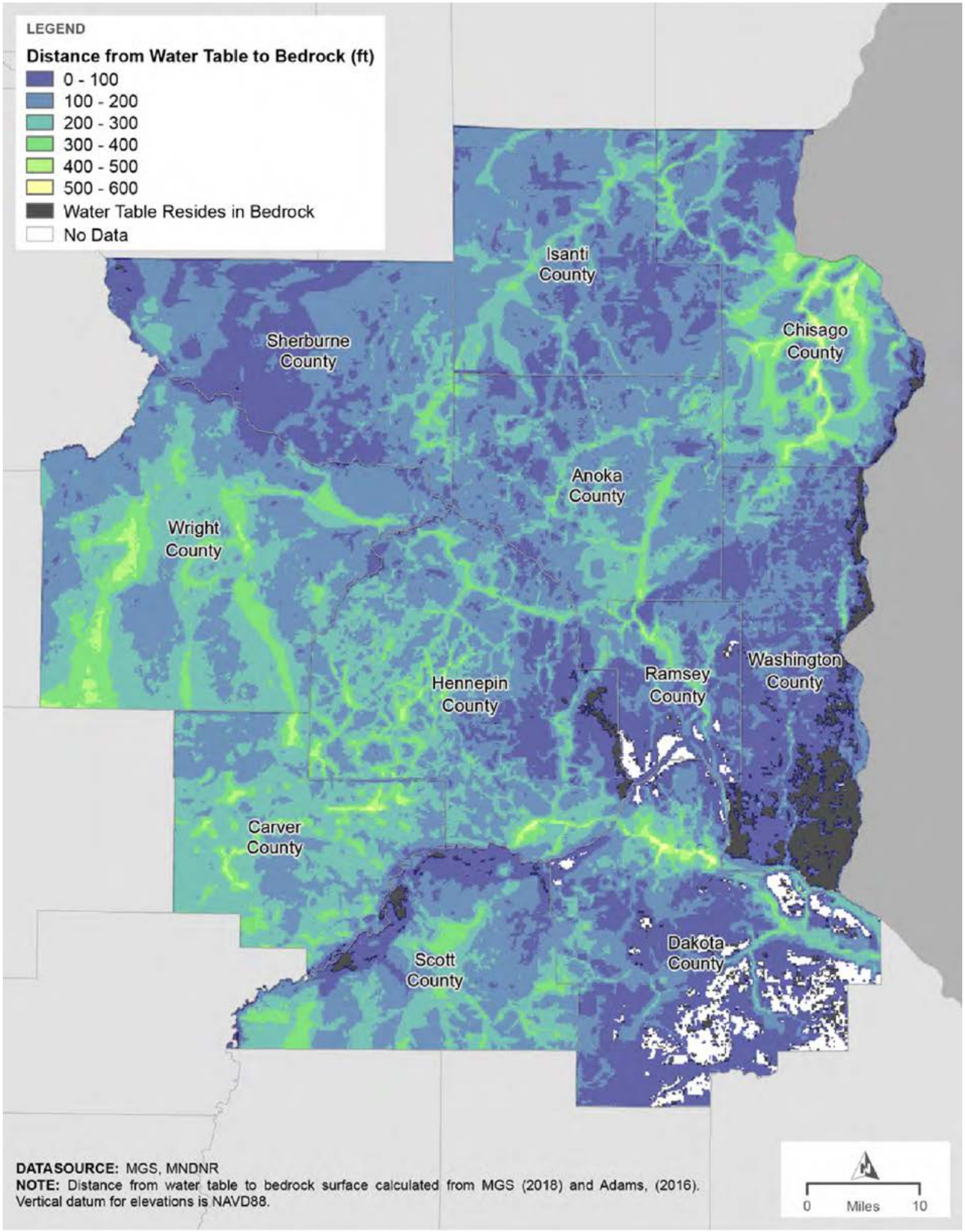
Calculate travel time (T) from the water table to the first bedrock aquifer.

4.2.1 Distance from Water Table to Bedrock Surface

Water table and bedrock surface are raster datasets, each in units of elevation (NAVD88 vertical datum), provided by Adams (2016) and MGS (2018) are described in Appendix B. These raster datasets were imported into GIS and subtracted to obtain a distance (in feet) between the regional water table and uppermost bedrock surface across the TCMA. A map showing the distance from the water table to the bedrock surface is included on Figure 4-3. Areas where the water table resides in bedrock (where the water table elevation is below the bedrock surface elevation) were assigned null values. These areas are most common in southern Washington County, and along some areas of the three rivers in the region.

Appendix C contains maps of the data sources used to calculate the distance from the water table to the bedrock surface, including a map of the water table surface (Figure C-1) and map of the bedrock surface (Figure C-2). A bedrock geology map is included on Figure C-3 in Appendix C for reference.

Figure 4-3. Distance from Water Table to Bedrock Surface



DATASOURCE: MGS, MNDNR
NOTE: Distance from water table to bedrock surface calculated from MGS (2018) and Adams, (2016). Vertical datum for elevations is NAVD88.

4.2.2 Composite Vertical Hydraulic Conductivity

The study area was divided into a grid 30 x 30-meter cells for all counties with recent Geologic Atlas updates. Where Geologic Atlas data is older and detailed surficial geologic data is lacking (Dakota and Ramsey counties), a 250 x 250-meter grid from Tipping (2011) was used. A composite vertical hydraulic conductivity value for the Quaternary sediments was calculated for each cell. This composite vertical hydraulic conductivity value represents the rate at which water can move downward through the sum of all sediments within each grid cell, between the water table and the bedrock surface. This operation was not performed for locations where the water table resides in the bedrock. The composite (or bulk) vertical hydraulic conductivity was calculated using the weighted harmonic mean of the individual sedimentary layers (Equation 3), for each vertical column in the study area grid.

$$K_v = \frac{\sum_{i=1}^{n} b_i}{\sum_{i=1}^{n} \frac{b_i}{K_i}} \qquad \text{Equation 3}$$

Where,

K_v is the composite vertical hydraulic conductivity of Quaternary sediments in ft/day,

b_i is the layer thickness in feet, and

K_i is the layer hydraulic conductivity in ft/day.

The process of calculating the composite vertical hydraulic conductivity is depicted in steps 1-3 on Figure 4-2. The Quaternary geology source datasets (see Appendix B), which cover different counties, do not share the same structure; therefore, different processing was required for each dataset in order to estimate the sediment material layer thicknesses and hydraulic conductivity values that would eventually be incorporated into Equation 3. Processing of the datasets was performed using GIS and is described below.

<u>Dakota and Ramsey Counties:</u>

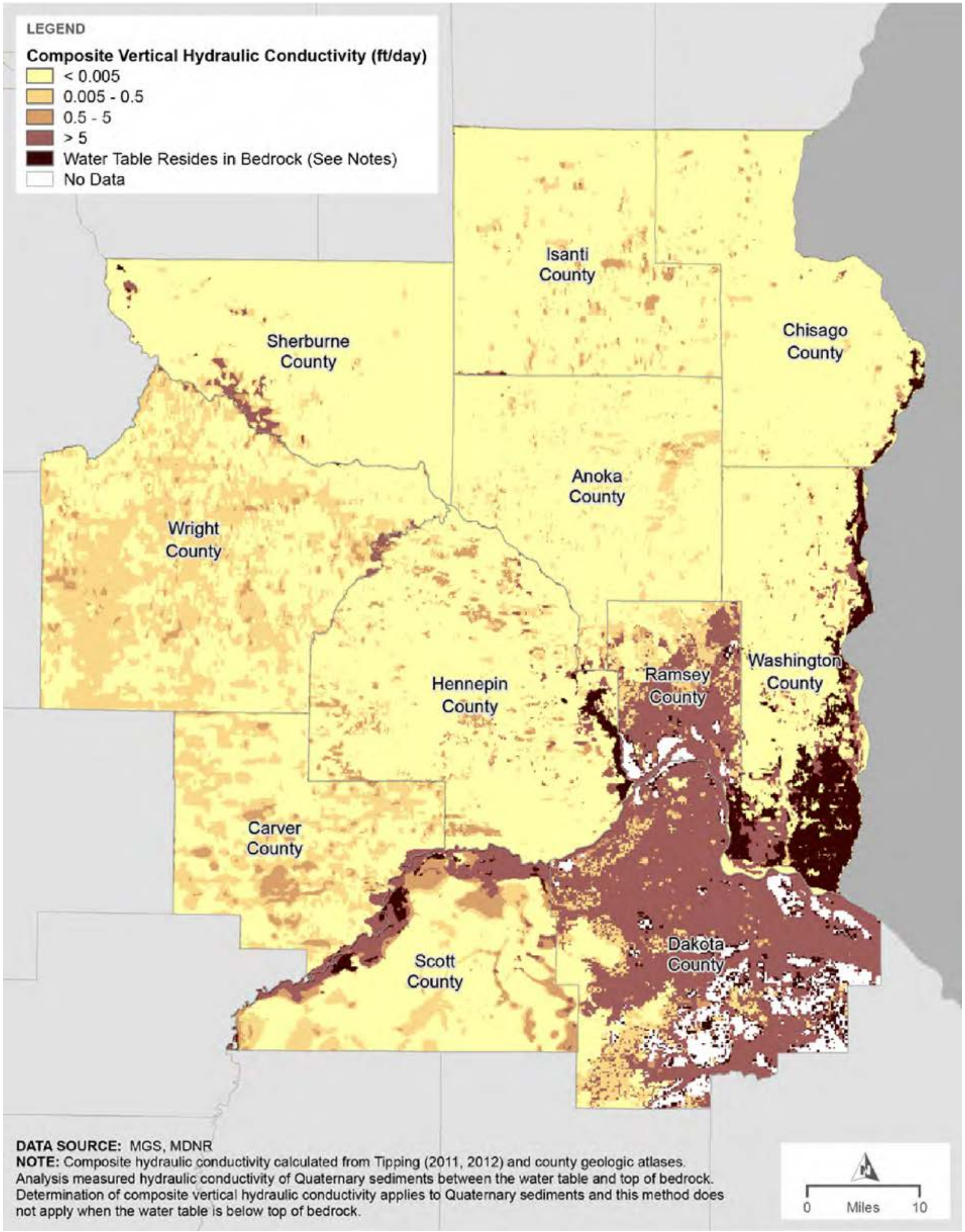
1. Surficial geologic layers above the water table elevation (Adams, 2016) were removed, and the remaining layers below the water table were used to complete the assessment.
2. Tipping (2011) assigned hydraulic conductivity estimates to each 20-foot thick ‘slice’ of Quaternary sediments, on a 250-meter grid for these two counties. Those assigned values were not changed for this assessment.
3. The thickness of each layer (in this case a fixed value of 20 feet) was divided by the hydraulic conductivity of that layer, followed by a calculation of the composite vertical hydraulic conductivity (Equation 3) for each column in the grid.

<u>Anoka, Carver, Chisago, Hennepin, Isanti, Scott, Sherburne, Washington, and Wright Counties:</u>

1. Surficial geologic units above the water table elevation (Adams, 2016) were removed, and the remaining layers below the water table were used to complete the assessment.
2. The geologic atlas for each of these nine counties (Appendix B) includes raster surfaces representing the top and bottom elevation of individual Quaternary units based on sediment textures, on a 30-meter grid. The thickness of each unit was calculated by subtracting the base elevation from the top elevation.
3. Hydraulic conductivity values from Tipping et al. (2010) were assigned to each of the over 200 mapped Quaternary sedimentary units in the geologic atlases. Tipping et al. (2010) summarizes hydraulic conductivity values calculated from a variety of test methods (e.g. lab permeameter, slug tests, aquifer pumping tests). Several test runs were completed to assess the sensitivity of the analysis to the assignment of various horizontal and vertical test values. Ultimately hydraulic conductivity values were selected by the analysis team based on tests that had a vertical component (when available), including vertical laboratory permeameter tests and aquifer pumping tests. A total of seven vertical hydraulic conductivity values, ranging from 1.55×10^{-4} ft/day for silt and clay to 7.04 ft/day for sand and gravel, were assigned to the various mapped units in the geologic atlases. A table of hydraulic conductivity values developed for this assessment is provided in Appendix E.
4. The thickness of each layer was divided by the hydraulic conductivity assigned to that layer, followed by a calculation of the composite vertical hydraulic conductivity (Equation 3) for each column in the grid.
5. Comparing the composite vertical hydraulic conductivity for these nine counties with the results from Dakota and Ramsey Counties illustrated some anomalies, such as sharp changes (generally at county boundaries). These anomalies likely indicate differences in mapping methods in certain counties and/or the dominance by a few, thick units, in our calculations. MCES worked with MGS staff to explore these anomalies and adjust the mapped sediment textures and hydraulic conductivity assignments for these nine counties. These adjustments were made through considerable effort by MGS personnel and resulted in a dataset that is more consistent across these nine counties (excluding Dakota and Ramsey Counties, which were derived from Tipping [2011]). The adjusted hydraulic conductivity assignments are tabulated in Appendix E.

Figure 4-4 shows a map of calculated composite vertical hydraulic conductivity values for the Quaternary sediments between the water table and bedrock surface. Areas where the water table resides in bedrock were assigned null values and are indicated on Figure 4-4. These areas include southern Washington County and areas along the three major rivers in the region.

Figure 4-4. Composite Vertical Hydraulic Conductivity of Quaternary Sediments



DATA SOURCE: MGS, MDNR

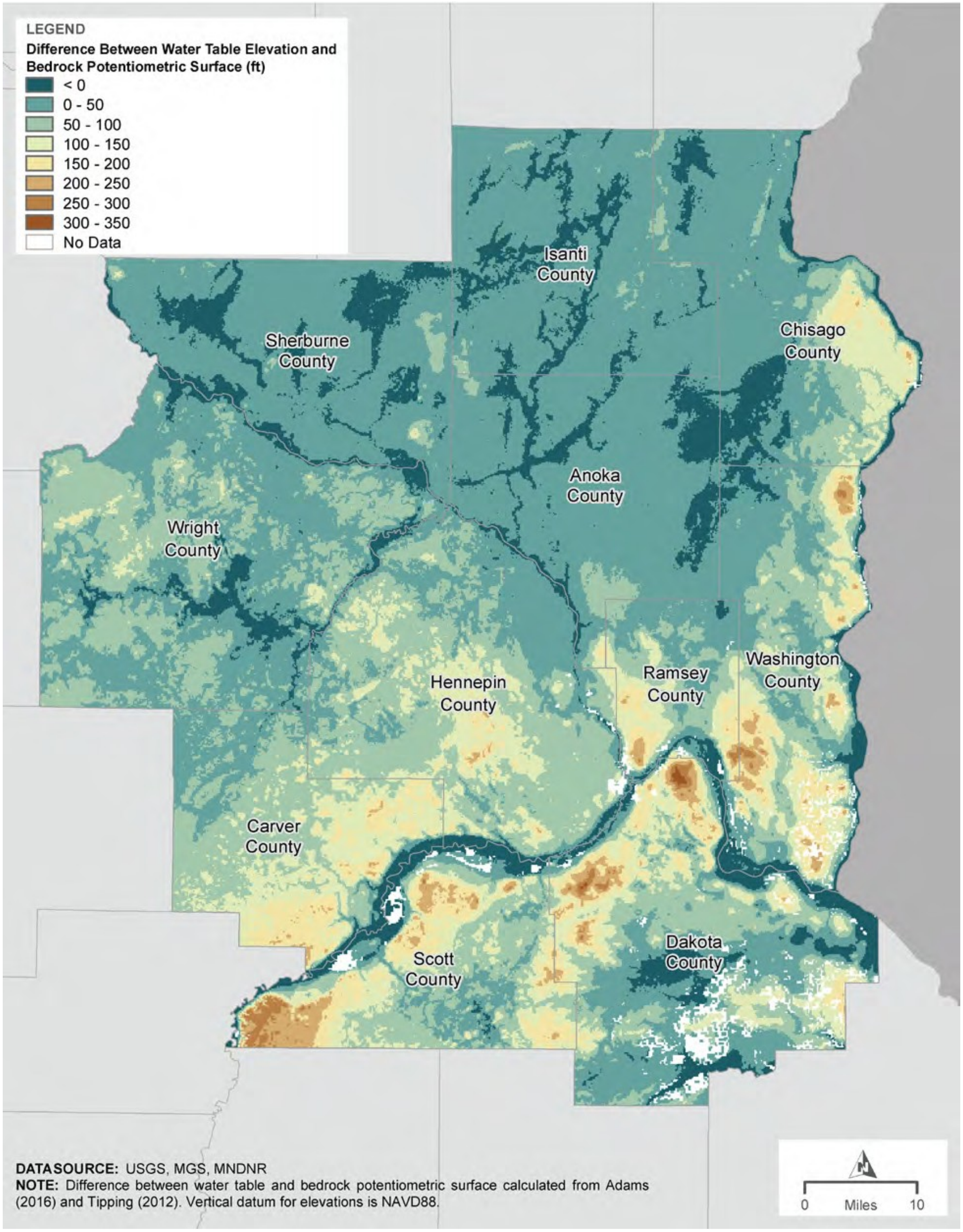
NOTE: Composite hydraulic conductivity calculated from Tipping (2011, 2012) and county geologic atlases. Analysis measured hydraulic conductivity of Quaternary sediments between the water table and top of bedrock. Determination of composite vertical hydraulic conductivity applies to Quaternary sediments and this method does not apply when the water table is below top of bedrock.

4.2.3 Difference in Elevation between Water Table and Bedrock Potentiometric Surface

The water table elevation and (uppermost) bedrock potentiometric surfaces are raster datasets provided by Adams (2016) and Tipping (2012), as described in Appendix B. Potentiometric surface data for the Prairie du Chien-Jordan Group were used, supplemented by potentiometric surface data for the uppermost bedrock aquifer where the Prairie du Chien-Jordan Group is absent. The water table and bedrock potentiometric surfaces were subtracted using GIS. Figure 4-5 shows the resulting difference in feet between the water table and bedrock potentiometric surface. Areas where the bedrock potentiometric surface is higher than the water table are designated as less than zero on Figure 4-5.

Appendix C contains maps of the source data used to calculate the difference in elevation between the water table and bedrock potentiometric surface, including a map of the water table surface (Figure C-1) and map of the bedrock potentiometric surface (Figure C-4).

Figure 4-5. Difference in Elevation between Water Table and Bedrock Potentiometric Surface



DATASOURCE: USGS, MGS, MNDNR
NOTE: Difference between water table and bedrock potentiometric surface calculated from Adams (2016) and Tipping (2012). Vertical datum for elevations is NAVD88.

4.2.4 Effective Porosity

Effective porosity was universally set equal to 0.20 after Tipping (2012), which is considered a reasonable average value for the variety of Quaternary sediments present in the TCMA.

4.2.5 Vertical Groundwater Travel Time

Vertical groundwater travel time between the water table and the uppermost bedrock aquifer was calculated by applying Equation 2 to the study area using GIS rasters. Raster grid sizing for the calculations was governed by the source data (250 meters for Dakota and Ramsey counties, and 30 meters for the remaining nine counties).

A map of the calculated vertical groundwater travel time between the water table and bedrock surface is shown on Figure 4-6. The lower the estimated bulk hydraulic conductivity and/or the less difference between the water table and bedrock potentiometric levels, the slower the vertical movement of groundwater.

Areas where the bedrock potentiometric surface is above the water table result in a calculation of negative vertical travel time. These areas are shown on Figure 4-6 as 'negative travel time' and indicate areas where there is an upward groundwater gradient between the bedrock groundwater and the water table[1]. Similarly, areas where there is higher bulk hydraulic conductivity and/or a greater difference between the water table and bedrock potentiometric levels there is relatively rapid vertical groundwater movement. The less distance, or thickness of Quaternary sediments, the less time is necessary for water to move to the bedrock surface, and therefore lowering travel time, as can be seen in the South and East TCMA on Figure 4-6.

The vertical groundwater travel times displayed in Figure 4-6 reflect some broadly accepted interpretations of Quaternary sediments in the TCMA. For example, studies have shown that glacial till can contain pockets of coarser-grained materials, which result in isolated areas of relatively rapid groundwater movement within broader areas of generally longer travel time. This is evident in some areas of western Hennepin County. Likewise, the relatively rapid vertical travel time seen across much of Dakota and Ramsey counties relates to the coarse and thin Quaternary deposits in those areas. Other areas that are known for having relatively rapid groundwater movement near the surface may also have relatively longer travel times due to deep, less permeable sediments, high potentiometric surface elevations, and overall thicker Quaternary deposits.

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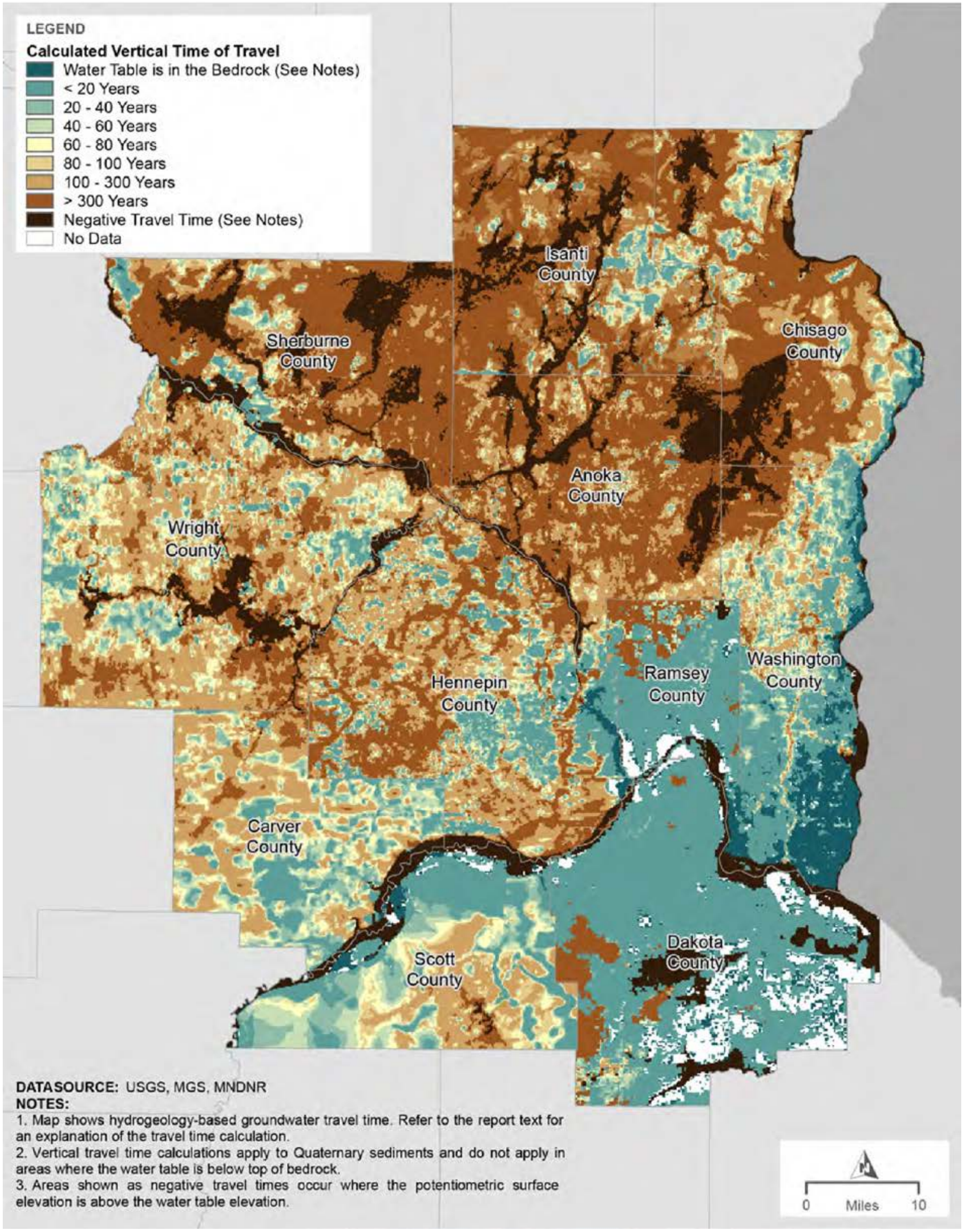
[1] In this assessment areas with an upward groundwater gradient have longer travel times. Areas with negative travel time are places where artesian conditions can be expected. Long travel times and slow vertical groundwater movement do not imply that surface waters are disconnected from groundwater, as is the case with certain surface water features such as springs and fens.

Figure 4-6. Vertical Time of Travel from Water Table to First Bedrock Aquifer



DATASOURCE: USGS, MGS, MNDNR

NOTES:

1. Map shows hydrogeology-based groundwater travel time. Refer to the report text for an explanation of the travel time calculation.
2. Vertical travel time calculations apply to Quaternary sediments and do not apply in areas where the water table is below top of bedrock.
3. Areas shown as negative travel times occur where the potentiometric surface elevation is above the water table elevation.

4.3 *Estimating Groundwater Age with Anthropogenic, Chemical Indicators*

Concentrations of chemical compounds known to be deposited at the surface and detected in groundwater can provide reasonable estimates of groundwater age at the point of measurement. Groundwater chemistry data from laboratory analytical reports (referenced in Appendix B was used to assess the presence or absence of various human activity-related constituents, which can be traced to relatively recent periods of use. These compounds, if present above certain concentrations, infer relatively young groundwater, which in turn indicates a relatively rapid groundwater travel time. Conversely, the absence of anthropogenic indicators may indicate relatively old groundwater and slow groundwater travel time[2].

Geochemical data from groundwater quality monitoring studies conducted by MDH, USGS, MN DNR, and MGS were compiled. The following qualifications were established for selecting which chemical compounds to use in the evaluation:

1. Compounds that have seen widespread application across all or large portions of the TCMA.
2. Anthropogenic (i.e. human-related) compounds, which, if present, can point to an approximate age of groundwater.
3. Compounds that are conservative ‘tracers’ that tend to persist in the environment, and generally have little retardation, attenuation, or biodegradation as they move through the subsurface.
4. Compounds that have been tested for in groundwater across all or large portions of the TCMA.

Selected compounds that generally meet the above requirements include tritium, nitrate, chloride, and bromide. Each of these compounds also exists naturally, although for the purposes of this assessment it is assumed that the anthropogenic forms of the compounds are identifiable above certain thresholds. A description of the selected compounds, and the background thresholds established for each compound are provided below.

- Tritium: Tritium, an isotope of hydrogen, is generated during atmospheric testing of nuclear bombs, which began in the 1950s and peaked in the 1960s, making it a relatively new element in the environment. Tritium reaches the earth’s surface through precipitation and has the rare quality of having been introduced relatively globally compared to other anthropogenic compounds. Tritium is also produced naturally with solar radiation sources, although this process results in a trace amount compared to anthropogenic tritium. For this report, it was assumed that a detection of tritium in groundwater, at or above the laboratory reporting limit of 0.8 tritium units (TU), implies the presence of groundwater that is relatively young, less than 60 years old.

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[2] It should be noted that while the absence of some constituents (i.e. tritium) in groundwater samples can be used to infer relatively old groundwater, the absence of others may simply reflect an absence of use of these substances in some locations.

- Nitrate: Nitrate is a component of crop fertilizers and saw widespread use in the TCMA by the 1970s. Nitrate also occurs naturally in groundwater. A background threshold concentration of 1 milligram per liter (mg/L) was established for this evaluation after Tipping (1994). Nitrate concentrations at or above 1 mg/L indicate an anthropogenic nitrate source, representing relatively young groundwater.
- Chloride: Anthropogenic sources of chloride include the application of road salt and some fertilizers, and discharge from water softeners; giving chloride a widespread presence in the TCMA. Road salt use in the TCMA was extensive by the 1960s coinciding with suburban and exurban development trends. Chloride also occurs naturally in groundwater. A background threshold concentration of 2 mg/L was established for this evaluation after Tipping (1994)[3]. Chloride concentrations at or above 2 mg/L indicate anthropogenic chloride, representing relatively young groundwater.
- Chloride/Bromide ratio: Anthropogenic sources of bromide include pesticides, flame retardants, and wastewater from coal-fired power plants. Bromide also occurs naturally in groundwater. The Minnesota Pollution Control Agency (MPCA) has shown that high chloride/bromide ratios in groundwater indicate the presence of anthropogenic chloride (Kroening and Ferrey 2013). A chloride/bromide ratio of 200:1 was used as a background threshold ratio for this evaluation after Kroening and Ferrey (2013) and Tipping (2012), indicating relatively young groundwater.

A regional groundwater chemistry dataset was developed by combining state agency datasets, removing duplicate data points, keeping the most recent sampling results for each location, and filtering out null values and erroneous data. Groundwater chemistry data from wells that have open intervals within 20 feet above and below the bedrock surface were carried forward in the evaluation. This zone (within 20 feet of the bedrock surface) was selected to represent the interface between the first bedrock surface and overlying surficial sediments. Groundwater pumping from this zone is more likely to influence surface water features than, for example, pumping from lower bedrock aquifers. This processing resulted in a point data set containing sampling well locales, and the measured concentrations of groundwater chemical analytes sampled at each well.

In order to compare apparent groundwater ages derived from groundwater chemistry data to the estimated vertical travel time data, spatial interpretation of the geochemical point data set was required. To interpolate between well locations, the *inverse distance weighted* method of interpolation was used in GIS to produce polygons of relative groundwater age for each chemical analyte. In some locations, where there are few samples or a large distance between samples, this method may

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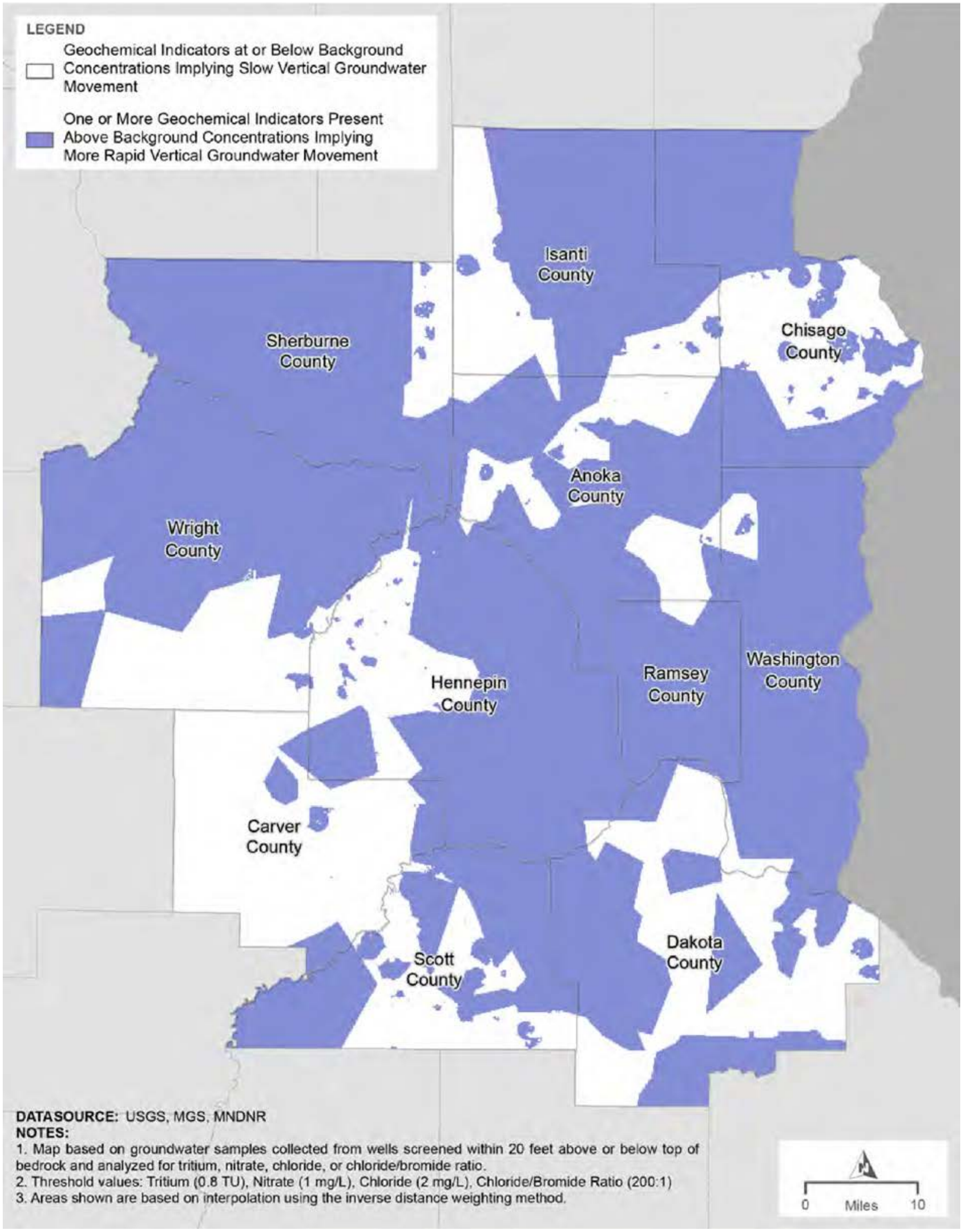
[3] Tipping (2012) notes that high concentrations (>2 mg/L) of naturally-occurring chloride may be associated with upwelling of old groundwater along fault zones. These fault zones, and the number of water samples from within the zones, are relatively sporadic in the TCMA and were not incorporated into this evaluation.

present a visual over-interpretation of the data. Other interpolation methods may be better suited to demonstrate confidence in the groundwater chemistry data.

Maps showing tritium, nitrate, and chloride concentrations, and the chloride/bromide ratio in groundwater, within 20 feet of the bedrock surface, are shown on Figures D-1 through D-4, respectively, in Appendix D. These maps show groundwater sample locations and interpolated areas where each anthropogenic, chemical indicator is estimated to be present or absent, above or below a threshold. It should be noted that interpolation is highly dependent on the number and distribution of data points, with a greater concentration of data and more even distribution of measurements, we can assume a more accurate interpolation. Where geochemical data are more sporadic the shortcomings of interpolation become apparent in the form of large patches of similarly-classified data. This is also seen near the edges of the TCMA, where the interpolation extends from a data point to the boundary of the study area, as this analysis did not include data points outside the TCMA to interpolate to.

Each of the four maps (Appendix D) of geochemical indicators were overlain to show areas of relatively young groundwater within 20 feet of the bedrock surface. For this assessment, the presence of any one of the four indicators above background concentrations infers relatively young groundwater, indicating a relatively rapid vertical groundwater travel time (< 60 years) to the first bedrock surface. The absence of all four anthropogenic indicators infers relatively old groundwater and slow vertical groundwater travel time (> 60 years) to the first bedrock surface. The results of the geochemical travel time evaluation and the spatial distribution of anthropogenic, chemical indicators of groundwater age are shown on Figure 4-7.

Figure 4-7. Geochemical Indicators in Groundwater within 20 ft. of Uppermost Bedrock Surface



DATASOURCE: USGS, MGS, MNDNR

NOTES:

1. Map based on groundwater samples collected from wells screened within 20 feet above or below top of bedrock and analyzed for tritium, nitrate, chloride, or chloride/bromide ratio.
2. Threshold values: Tritium (0.8 TU), Nitrate (1 mg/L), Chloride (2 mg/L), Chloride/Bromide Ratio (200:1)
3. Areas shown are based on interpolation using the inverse distance weighting method.

5 Potential Hydraulic Connections Between Surface Waters and Bedrock Aquifers

This assessment provides a regional-scale characterization of the permeability of surficial tills and sands, the hydraulic gradient between the regional water table and bedrock potentiometric surface, and the potential for vertical groundwater movement and transport through Quaternary sediments in the TCMA. The inclusion of geochemical data as a second assessment method provides evidence that either supports or contradicts the theoretical hydrogeological conditions using observed groundwater conditions.

This hydrogeologic assessment of travel time was performed using raster datasets in GIS and was informed by previous studies and reports by the MGS and MN DNR, as well as other local and regional experts. Assigning meaningful hydraulic conductivity values to Quaternary deposits that reasonably represent highly complex surficial sediments is a significant challenge. For example, tills in the TCMA have a wide range of textures, and hydraulic conductivities of tills have a range of four orders of magnitude (see Appendix E). The inherent variability of these sediments means that it is not possible to capture and display the entire range of permeabilities in a regional-scale analysis, and points to the need for local study when evaluating individual water resources. However, by providing estimations of mean hydraulic conductivity for each mapped surficial sediment, the study identifies broad patterns of the potential ease in which water can travel to bedrock from the surface.

During this study the analysis team worked closely with MGS Quaternary mapping staff to evaluate hydraulic conductivities and mapped surficial sediments, particularly along county borders. It was also determined that horizontal conductivity measurements were heavily skewing the results of the analysis, resulting in very rapid travel times throughout much of the TCMA. By eliminating horizontal conductivity measurements from the mean conductivity calculations, more reasonable travel times were determined. However, it is likely that the assessment does not fully capture localized preferential flow paths. The resulting hydrogeologically-derived travel times provide a generalized understanding of water movement from a regional water table, through glacial sediments, to the first bedrock surface.

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[4] For purposes of this assessment, areas with a negative travel time (shown on Figure 4-6) were incorporated into the ‘more than 60 years’ travel time category since downward groundwater movement into bedrock is slow in these areas; conversely, areas where the water table resides in bedrock (shown on Figure 4-6) were incorporated into the ‘less than 60 years’ travel time category.

Because tritium is the most universally dispersed geochemical constituent analyzed in this assessment, and its deposition age is the oldest and most well understood, groundwater age was characterized as either greater than or less than 60 years, or relative to the time since atmospheric nuclear testing. Significant use and deposition of other chemical constituents was assumed to be less than 60 years. Therefore groundwater travel times were characterized as relatively rapid or relatively slow based on the greater than or less than 60 years since tritium deposition cut-off, respectively4. This breakpoint (60 years) provides consistency when comparing the hydrogeologic assessment with the geochemical assessment, but should be considered as relative and not an absolute measure.

The results of the hydrogeologic and chemical travel time comparison can be divided into three scenarios, which form the basis for characterizing the hydraulic connection potential of the TCMA surficial geologic landscape:

1. When hydrogeologic travel time indicates relatively rapid (< 60 years) vertical groundwater movement to the bedrock surface, and is supported by the presence of one or more geochemical indicators. These areas are characterized as having a higher potential for hydraulic connection.

2. When the hydrogeologic travel time indicates relatively slow (> 60 years) vertical groundwater movement, and is supported by a lack of geochemical indicators. These areas are characterized as having lower potential for hydraulic connection.

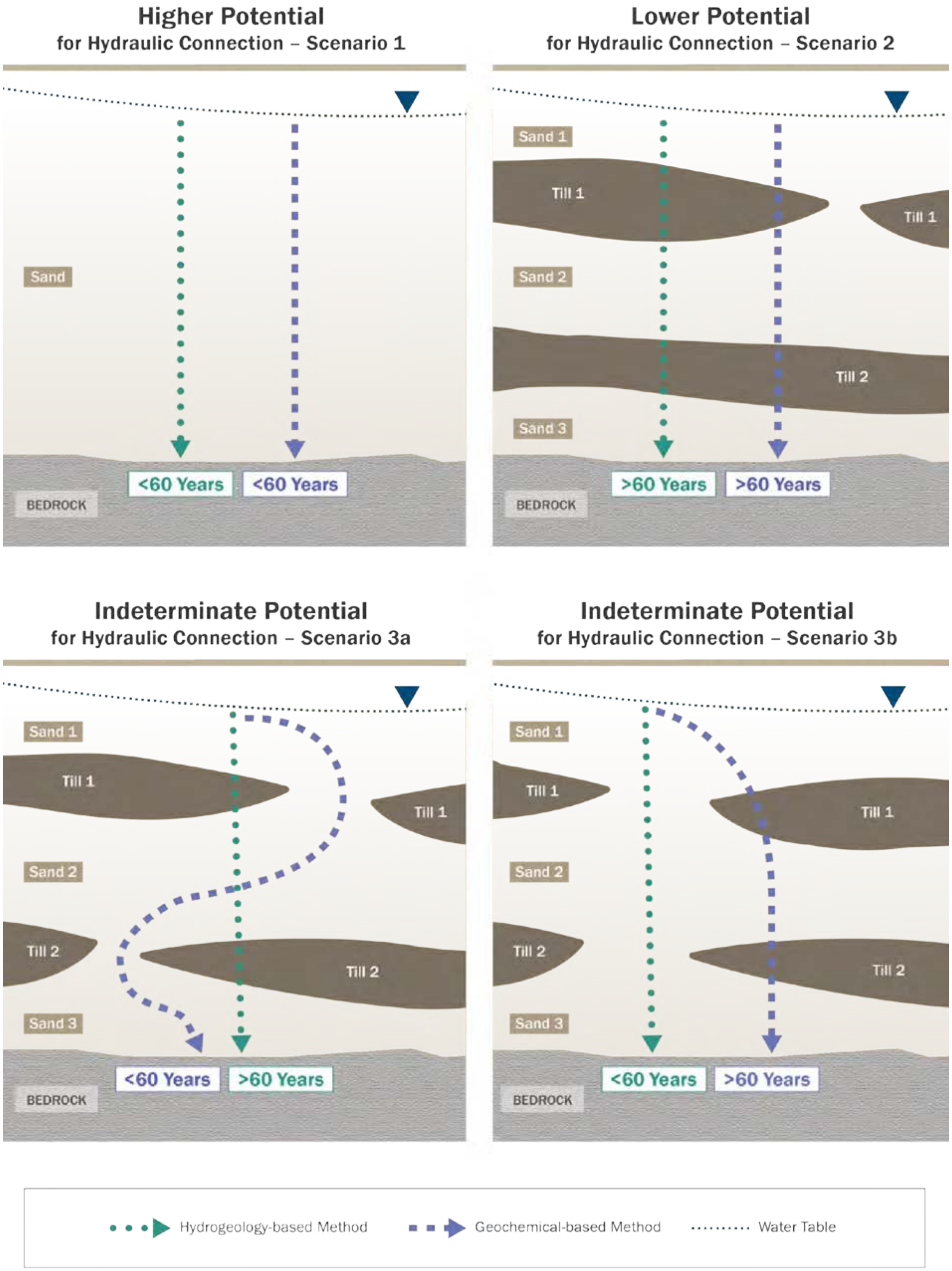
3. When the two assessment methods differ. This can occur when anthropogenic, chemical indicators have been detected in areas where the hydrogeologic data suggest slow vertical travel time, or, alternately, where hydrogeologic data suggest rapid vertical travel time, but there is a lack of geochemical evidence. These areas are characterized as indeterminate potential for hydraulic connection. In areas classified as indeterminate it is likely that the analysis is not capturing preferential flow paths or that there is a lack of surficial geologic and geochemical data, or both. Conversely, in areas that have agreement between the hydrogeologic-based travel time calculation and the observed geochemical conditions, there is a higher confidence in the data and the characterization of the potential for hydraulic connection.

The assessment results and corresponding characterizations are summarized in Table 5-1. Figure 4-1 shows the assessment and characterization process. The various scenarios depicting the assessment results are illustrated on Figure 5-1.

Table 5-1. Potential Hydraulic Connection Scenarios

Potential Hydraulic Connection Scenarios	Hydrogeologic and Geochemical Assessment Results	Hydrogeologic Vertical Groundwater Travel Time	Geochemical based Travel Time
1. Higher Potential for Hydraulic Connection	Hydrogeologic and geochemical assessments agree, indicating relatively rapid travel time.	Relatively **rapid** travel time (≤ 60 years)	Relatively **rapid** travel time (≤ 60 years)
2. Lower Potential for Hydraulic Connection	Hydrogeologic and geochemical assessments agree, indicating relatively slow travel time.	Relatively **slow** travel time (>60 years)	Relatively **slow** travel time (> 60 years)
3a. **Indeterminate Potential** for Hydraulic Connection	Hydrogeologic and geochemical assessments differ regarding travel time.	Relatively **slow** travel time (> 60 years)	Relatively **rapid** travel time (≤ 60 years)
3b. **Indeterminate Potential** for Hydraulic Connection	Hydrogeologic and geochemical assessments differ regarding travel time.	Relatively **rapid** travel time (≤ 60 years)	Relatively **slow** travel time (> 60 years)

Figure 5-1. Potential Hydraulic Connection Scenarios



A TCMA map showing the potential for hydraulic connection between the regional water table and first bedrock surface is depicted on Figure 5-2. The potential hydraulic connection areas shown on Figure 5-2 are discussed below.

Higher Potential for Hydraulic Connection

In areas of higher potential for hydraulic connection, the rates of downward groundwater movement are relatively rapid. In these areas, groundwater resources may be more vulnerable to land use changes and contamination, and may reflect changes to the quality and amount of infiltrating water relatively quickly. Additionally, the increased use of groundwater in these areas, and the potential for increased drawdown of the bedrock potentiometric surface can more quickly result in increased downward movement of groundwater through surficial sediments. This can result in a decline of the water table in nearby areas, which in turn can result in the decline of water levels in lakes, streams, and wetlands. Examples of these areas are seen in much of the Eastern and Southeastern TCMA.

Lower Potential for Hydraulic Connection

In areas of lower potential for hydraulic connection, the rates of downward groundwater movement through the Quaternary sediments are relatively slow. Effects of the increased use of groundwater and the development of increased drawdown of the bedrock potentiometric surface will initially be buffered by the overall low hydraulic conductivities of the Quaternary deposits, delaying the potential effects on the water table and surface water features. However, if significant groundwater use persists, without enough recharge to replenish the system, the drawdown effects can eventually result in impacts to surface water features. Examples of these areas are seen in much of the North and West TCMA.

Indeterminate Potential for Hydraulic Connection

There are several possible explanations for why the two assessment methods may not agree, resulting in areas where the potential for hydraulic connection is classified as indeterminate. In some cases, the indeterminate characterization of these areas may be related to the regional scale of the datasets used in the analysis, and an inability, given the scale, to fully represent the variability in hydrogeologic or anomalous conditions that may exist locally across the study area. Other cases may be related to the coverage of the geochemical datasets, or a lack of anthropogenic, chemical deposition at the surface. Potential explanations for discrepancies in assessment results are further described below.

- Hydrogeologic data are often derived from boring logs, the accuracy of which depends on the drilling, logging, and reporting methods used. For example, thin clay lenses may be present but not noted in the boring log, leading to hydrogeologic data that indicate greater permeability of surficial sediments than exists. Inaccurate or over-generalized boring logs can lead to areas represented by fewer mapped units and fewer hydraulic conductivity values that can skew the composite hydraulic conductivity.

- There could be interconnected lenses of highly permeable material (e.g. sand and gravel) and fractured low permeability sediments, that lead to vertical short-circuiting, and allow groundwater to move downward more quickly than the composited hydraulic conductivity data suggest. This could result in young groundwater present in an area where longer travel times were calculated, as illustrated in Figure 5-1 (Scenario 3a).

- Groundwater moves laterally, sometimes through highly permeable sediments, resulting in the detection of young groundwater in areas where the calculated travel time indicates slow vertical movement, or resulting in the detection of old groundwater in an area where travel time is expected to be rapid, as illustrated in Figure 5-1 (scenario 3b).

- Sporadic spatial coverage of geochemical data result in interpolated groundwater age over large areas of the study area. This is particularly apparent in Dakota County, and near the outer edges of counties where there are no additional data points to interpolate to. As a result, the interpolation may be an inaccurate estimation of groundwater age in some areas and may not agree with the hydrogeology-based assessment.

- Gaps in geochemical data measurements, as well as imbalances in the geographic coverage of nitrate, chloride, tritium, and chloride/bromide applications may lead to an over-representation of old groundwater. For example, in areas where nitrate was applied to the land surface, but there are no other chemical data available to further characterize the apparent groundwater age, denitrification may have decreased the original nitrate concentrations below the groundwater age threshold making relatively young groundwater appear older. In other areas, there may have been limited or no application of chlorides making it difficult to confirm relatively rapid groundwater travel times as indicated by the hydraulic properties of mapped surficial sediments.

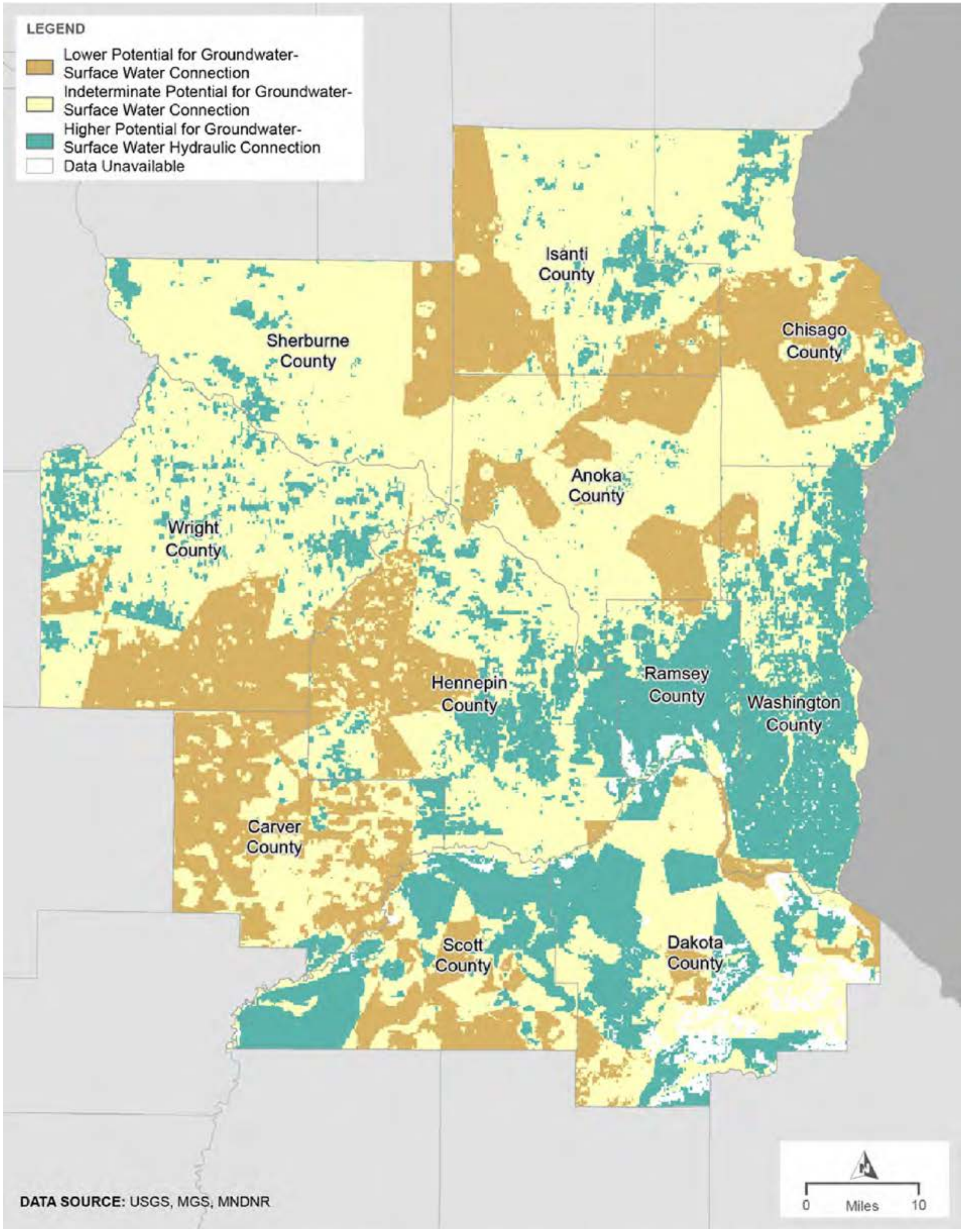
Examples of areas that are classified as indeterminate potential for hydraulic connection include the following.

- In southwestern Anoka County the vertical groundwater travel time was calculated to be slow while the geochemical evaluation showed the presence of young groundwater. This could indicate the presence of short-circuiting horizontal or vertical groundwater flow paths. It could also be due to sporadic geochemical measurements in this area resulting in an interpolation that may have skewed the classification of groundwater as relatively young.

- In south-central Carver County the hydrogeologic vertical groundwater travel time was calculated to be rapid but the geochemical evaluation indicated old groundwater based on numerous nitrate data (and few, but corroborating, tritium and chloride data). Uneven application and distribution of chemical constituents or oversimplified hydrogeologic characterization due to the scale of the datasets are possible explanations for this discrepancy.

Additional study and interpretation are needed in areas to more fully understand the potential for hydraulic connection between surface waters and bedrock aquifers in areas where the calculated groundwater travel time and the groundwater age estimation do not agree. Further examination of the hydrostratigraphy or inclusion of additional geochemical sampling data could result in refined datasets that improve the overall density of data and help to lessen areas of discrepancy. More information on recommendations for additional study is included in Section 7.

Figure 5-2. Potential Hydraulic Connection Areas



DATA SOURCE: USGS, MGS, MNDNR

5.1 Characterizing the TCMA by Hydraulic Connection Potential

Figure 5-2 portrays the TCMA by hydraulic connection potentials. The hydraulic connection designations (higher, lower, and indeterminate) broadly describe water movement through surficial sediments. but do not necessarily reflect local groundwater and surface water conditions. Although this characterization of the surficial geologic landscape is a simplified approach, that generalizes local groundwater flow characteristics, the combination of hydrogeologic and groundwater chemistry data provides information that can inform local and regional water resource planning and management decisions.

Within the study area, the hydraulic connection characterizations offer context when considering the interactions between surface water and groundwater resources. For those surface water features and aquifers in areas of higher potential for hydraulic connection, they may be more likely to rapidly reflect chronic and acute changes to either resource. For those water resources in areas of lower potential for hydraulic connection, they may be indirectly influenced or take longer to reflect changes. However, surface water and groundwater resources in both higher and lower potential hydraulic connection landscapes are often ecologically dependent on one another irrespective of the rate of water movement through the regional surficial geology.

Where the potential for hydraulic connection is characterized as indeterminate there is less confidence in the understanding of water movement through surficial sediments. Local monitoring of water level fluctuations of surface water features and underlying groundwater systems or other technical evaluations may illuminate, with time, a clearer understanding of the potential for hydraulic connections between water resources.

6 Conclusions

This study provides a regional-scale characterization of the potential for hydraulic connection between surface waters and the uppermost bedrock aquifers. The results point to areas where data indicate complexities that require a more refined assessment to fully interpret; it also identifies areas where there is relatively high confidence in the estimates of travel times through surficial sediments. This study does not examine the hydraulic connectedness of specific surface water with bedrock aquifers, nor does it evaluate the likelihood that surface water features will experience changes due to groundwater pumping in the TCMA.

Recent, detailed mapping of the Quaternary sediments in all but two counties of the study area through the County Geologic Atlas program made possible the development of maps of composite vertical hydraulic conductivity, and well testing programs of water agencies at many political levels provided this study with reliable groundwater chemistry data. The use of anthropogenic, chemical indicators as confirmation of hydrogeologically-derived travel times has resulted in a simplified but reasonable assessment of groundwater flow characteristics through the Quaternary sediments of the TCMA. These results can be used for improved mapping and modeling of groundwater flow systems and their interactions with area surface waters.

By comparing two different lines of inquiry, the regional maps compiled for this report advance our understanding of where observable changes due to groundwater and surface water resources may occur in the TCMA. These maps, and the data that were used to generate them, can aid communities and agencies in their water resource and drinking water management decisions.

While this study advances our understanding of the relationship between surface water features and near surface bedrock aquifers, there are limitations to its applicability based on the availability and nature of hydrogeologic and groundwater chemistry data. The compilation of hydraulic conductivity information in Tipping et al. (2010), while containing thousands of values, does not include many measurements of vertical hydraulic conductivity, which may limit the precision of our composite estimates. Also, the use of chemical, anthropogenic indicators could be further enhanced by the incorporation of more specific historical usage patterns and transformation kinetics, such as the half-life of tritium and denitrification processes. There are also additional databases of geochemical information that could lessen the sparseness and unevenness of the data in some areas. Taken together, these maps are regional- scale depictions that should be re-evaluated more closely at a local scale, when making decisions about local water resources.

This report and the associated data can help inform local and regional water planning decisions. The analysis gives communities and organizations information that can help to prioritize resource management or water monitoring efforts, while considering the interactions of groundwater and surface water systems. Planners and resource managers can incorporate the findings of this study into their decisions by combining this information with other localized data and plans such as water use and resource maps, water infrastructure maps, source water protection plans, and proposed land use changes. The maps and data presented in this report demonstrate that the complexity and physical properties of the surficial geologic landscape are important considerations when assessing potential impacts associated with groundwater and surface water interactions.

7 Recommendations for Further Study

Factors that can vary spatially and temporally (i.e. seasonal water table, increases in groundwater pumping, land use changes), and their relationships with physiographic factors (i.e. permeability of surficial sediments and bedrock, physiographic characteristics of surface water features) ultimately determine the sensitivity of groundwater and surface water resources to potential impacts. Further study, including assessment of other physiographic factors, such as lakeshed to lake area ratios and lake bathymetry, could inform a vulnerability assessment of specific areas, surface water features, or groundwater resources in the region. Understanding risk, especially within areas that have a higher potential of hydraulic connection, will help to provide more detailed information for making local water resource and supply planning decisions.

In addition to further evaluation of potential impacts and vulnerability in the region, several specific assumptions and data limitations were identified which, if addressed, could help to refine the regional characterization of hydraulic connection potential.

1. Dakota and Ramsey Counties have older Part A county atlases, and Hennepin and Isanti Counties have Part B county atlases in process. Inclusion of these counties' atlases would appreciably enhance the characterization of the TCMA's Quaternary geology and groundwater resources. Incorporating the new Dakota and Ramsey County atlases into the assessment would also allow for the same method of processing hydrogeologic data to be used as the other nine counties. Similarly, counties adjoining the 11-county TCMA provide useful context of the bordering areas; completion of Kanabec and Meeker Counties' Part B county atlases would benefit the hydrogeologic depictions.
2. Additional measurements of vertical hydraulic conductivities of Quaternary sediments would improve the representative values for different units. Additional sources of this data include the Minnesota Department of Agriculture, Minnesota Department of Transportation, MPCA, and the USGS. With additional values it may eventually be possible to develop lobe-specific estimates of Quaternary units' hydraulic characteristics.
3. Additional existing data on geochemical anthropogenic indicators used in this study could be incorporated. Further sources of such information include the Minnesota Department of Agriculture, Minnesota Department of Transportation, MPCA, and the TCMA counties. Also, data on geochemical environmental indicators should be collected for the adjacent counties to improve on characterization of border areas.
4. Additional environmental indicators could be added to the analysis to enhance insight into travel times and chronologies. Such indicators may include per- and polyfluoroalkyl substances (PFAS), priority pollutants, and viruses.

5. The use of the geochemical, anthropogenic indicators can be refined to include time series analyses for wells with multiple observations, tritium half-lives, denitrification, and county-by-county chloride use.

6. The most recent synoptic well study in the region is Tipping (2012). An updated regional synoptic study could provide valuable insight into current, seasonal potentiometric surface changes, and offer an up-to-date estimate of average conditions.

8 How to Request Datasets

GIS raster and shapefiles and associated metadata were generated for all datasets produced during the assessment of groundwater-surface water hydraulic connection for the 11-county TCMA will be made available through the Metropolitan Council.

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Appendix A. Technical Work Group Representatives

Organization [1]
Carver County Watershed Management Organization
Legislative Water Commission
Dakota County
Metropolitan Council Environmental Services (MCES)
Minnehaha Creek Watershed District
Minnesota Department of Agriculture
Minnesota Department of Health (MDH)
Minnesota Department of Natural Resources (MN DNR)
Minnesota Geological Survey (MGS)
United States Geological Survey (USGS)

[1] These organizations participated in a technical advisory group meeting to provide their expertise and perspective regarding this project’s proposed methodology. Their input was incorporated into this study. Their participation does not imply their acceptance or agreement with this report.

Appendix B. Assessment Datasets

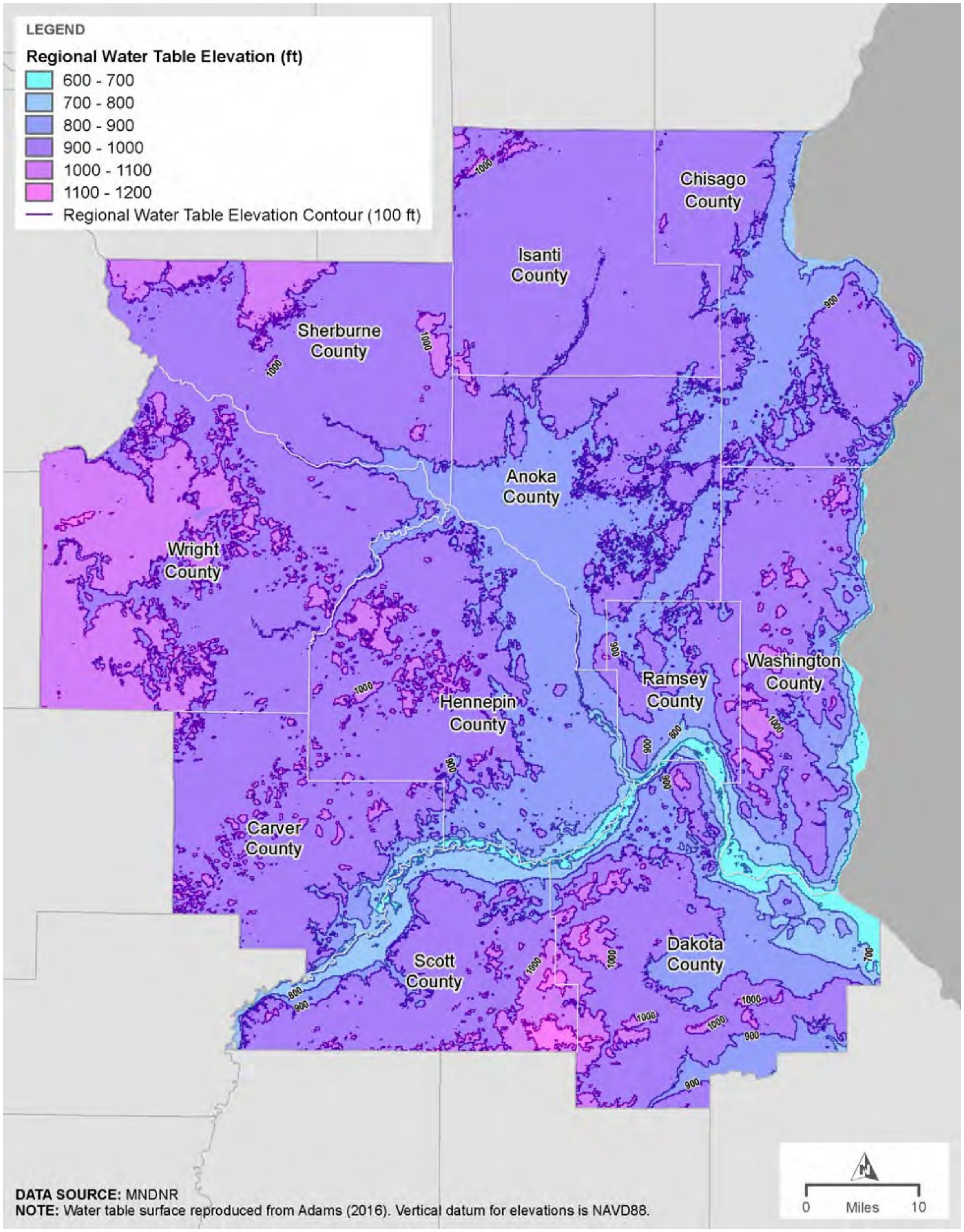
Appendix B. Assessment Datasets.

Dataset	Description	Source	Comments
Hydrogeologic Data			
Quaternary Geology	Point datasets (250-meter grid spacing) defining hydrogeologic properties of the Quaternary geology in Ramsey and Dakota counties.	Tipping (2011)	Supplemental data for out-of-date County Geologic Atlas Part A for Ramsey and Dakota counties.
Quaternary Geology, County Geologic Atlas Part A	Raster datasets (30-meter grid spacing) defining top and bottom of Quaternary geologic layers for Anoka, Carver, Chisago, Isanti, Scott, Sherburne, Washington, and Wright counties.	Setterholm (2013), Bauer (2014), Setterholm (2010), Chandler et al. (2017), Setterholm (2006), Lusardi (2013), Bauer (2016), Tipping (2013)	Updated County Geologic Atlas data for eight metro area counties.
Quaternary Geology, County Geologic Atlas Part A	Raster datasets (30-meter grid spacing) defining top and bottom of geologic layers for Hennepin County.	Lively (2018)	Draft County Geologic Atlas data for Hennepin County.
Quaternary Geology, Hydraulic Conductivity Values	Summary of hydraulic conductivity values obtained from laboratory analysis of sediment samples, field slug tests, and aquifer pumping tests.	Tipping et al. (2010)	
Bedrock Elevation	Raster dataset defining the elevation on the top of bedrock for the 11-county metro area.	MGS (2018)	
Water Table Elevation	Statewide raster dataset of the elevation of the water table. Uses the same methodology as the County Geologic Atlas Part B analysis.	Adams (2016)	
Potentiometric Surface in Bedrock	Raster dataset defining potentiometric surfaces in selected bedrock aquifers from spring of 2008 for the 11-county metro area.	Tipping (2012)	
Groundwater Geochemical Data			
Laboratory Analyses	Point dataset which includes monitoring data from 1965 to 2018 for tritium, nitrate, chloride, and bromide.	MDH (2018a), MDH (2018b)	

Dataset	Description	Source	Comments
Laboratory Analyses	Point dataset which includes monitoring data from 2010 to 2017 for tritium, nitrate, chloride, and bromide.	MN DNR (2018b)	
Laboratory Analyses	Point dataset including monitoring data from 1936 to 2018 for the 11-county metro area (more than 1,000 analytes).	USGS (2018a), USGS (2018b)	Analyte data were filtered to evaluate tritium, nitrate, chloride, and bromide.
Laboratory Analyses	Point dataset including monitoring data from the 11-county metro area (more than 50 analytes).	Tipping (2012)	Analyte data were filtered to evaluate tritium, nitrate, chloride, and bromide.
Surface Water Features			
Surface Water Features	Polygon dataset of surface water features including lakes, wetlands, streams which compile the USFWS National Wetland Inventory (NWI) and the MN DNR Public Waters Inventory (PWI).	Barr (2010)	
National Wetlands Inventory (NWI)	Polygon dataset defining wetlands through aerial image processing.	MN DNR (2017)	Supplemental data to update Barr (2010) surface water features.

Appendix C. Travel Time Assessment Figures

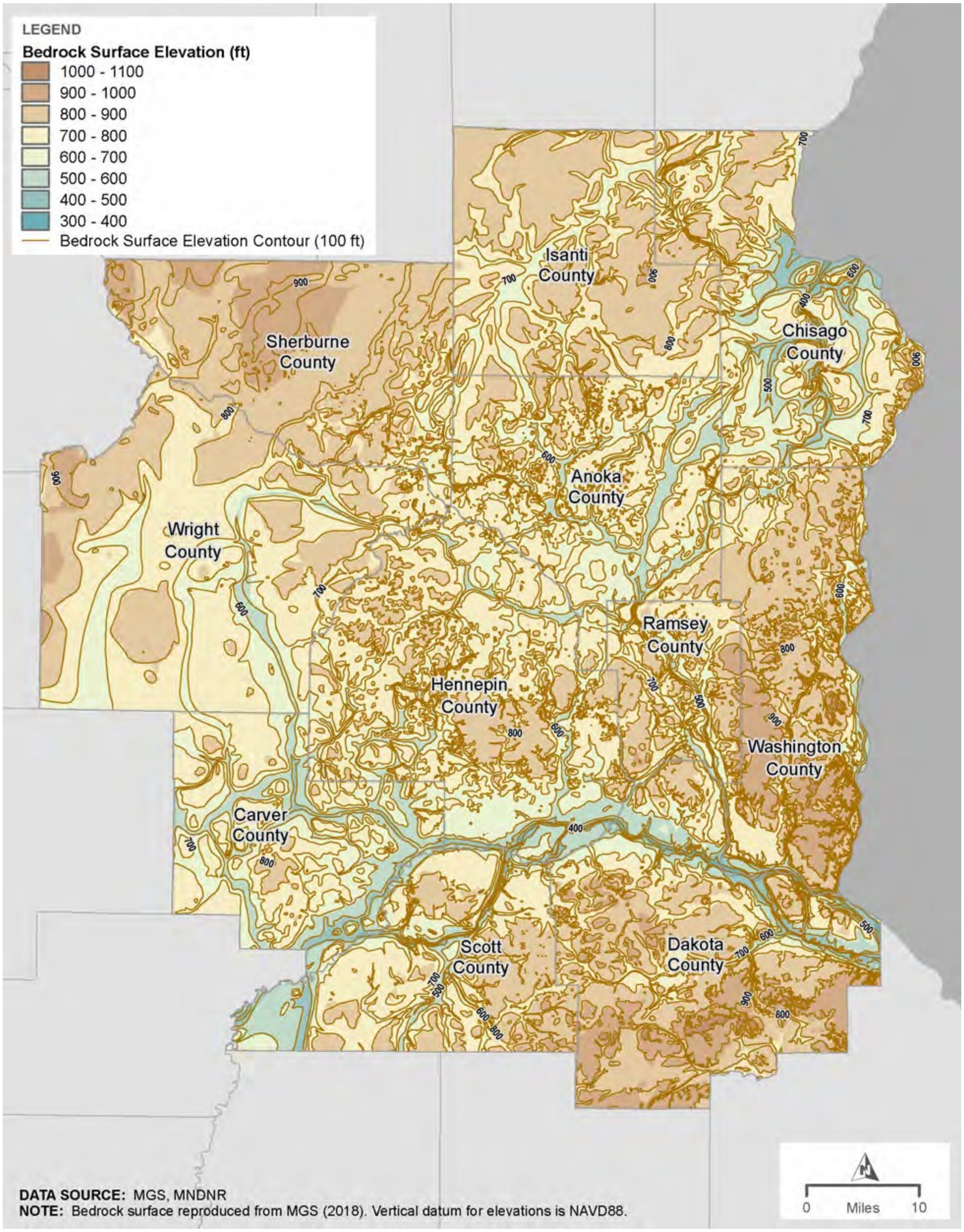
Figure C-1. Water Table Surface



DATA SOURCE: MNDNR

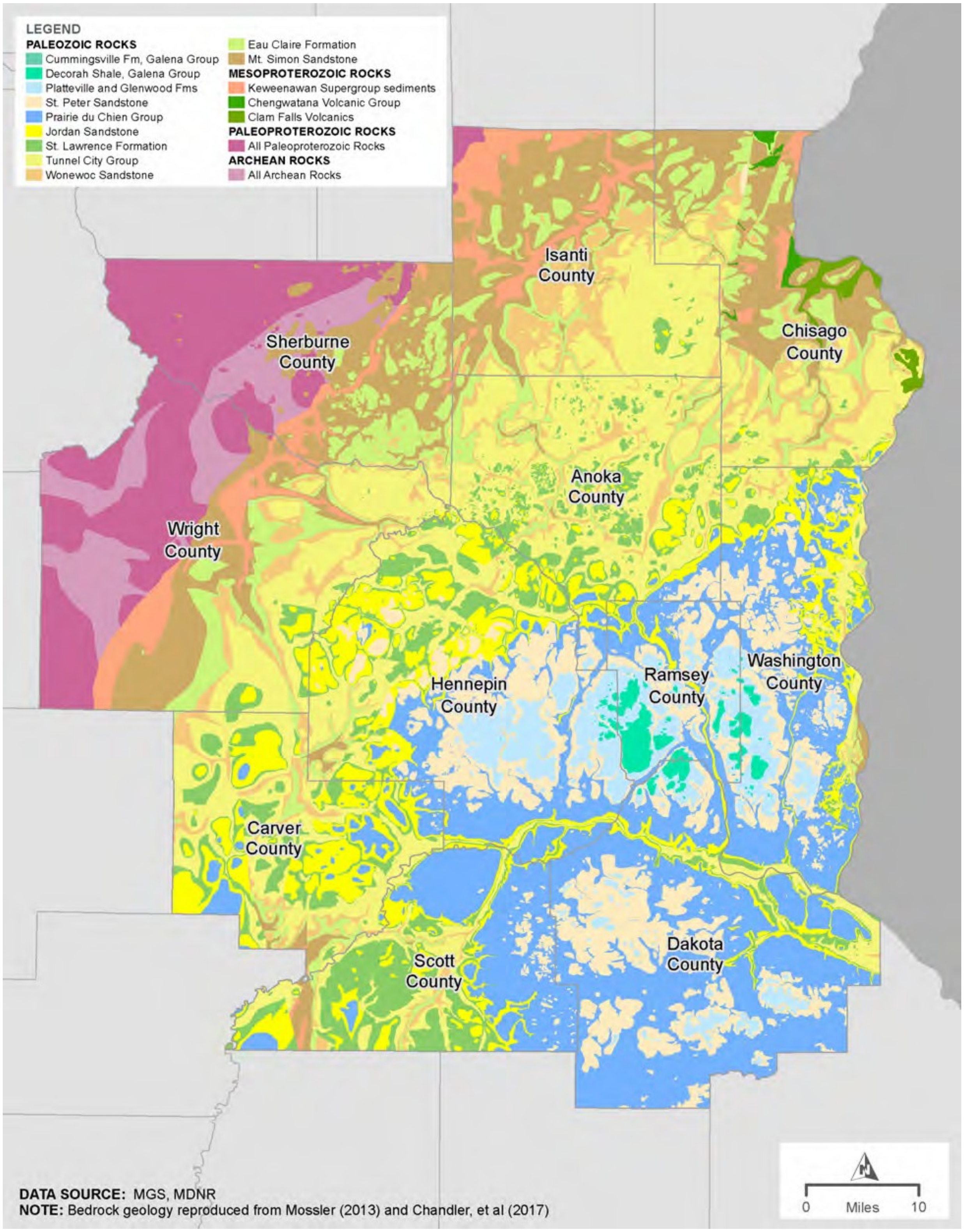
NOTE: Water table surface reproduced from Adams (2016). Vertical datum for elevations is NAVD88.

Figure C-2. Bedrock Surface



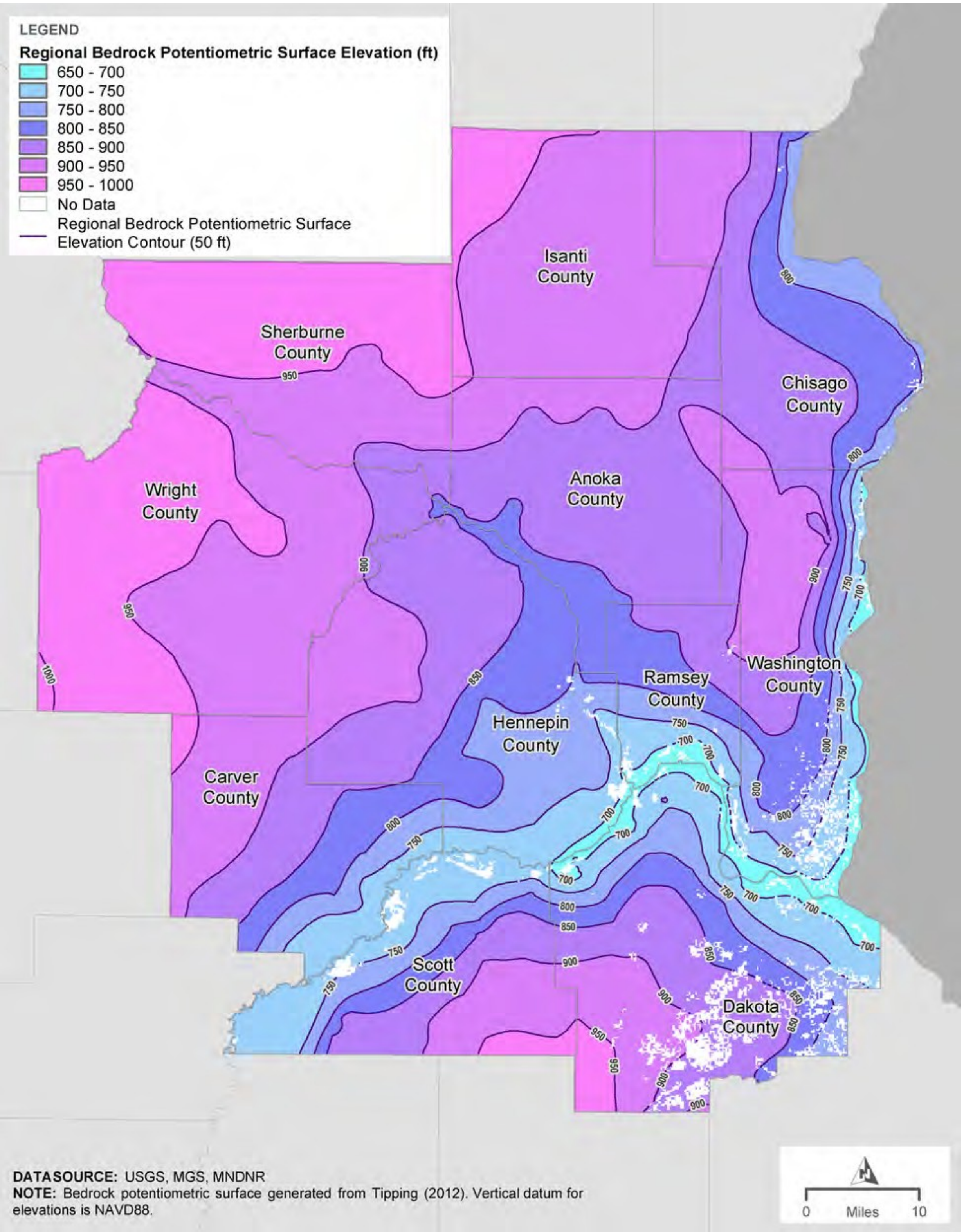
DATA SOURCE: MGS, MNDNR
NOTE: Bedrock surface reproduced from MGS (2018). Vertical datum for elevations is NAVD88.

Figure C-3. Bedrock Geology



DATA SOURCE: MGS, MDNR
NOTE: Bedrock geology reproduced from Mossler (2013) and Chandler, et al (2017)

Figure C-4. Bedrock Potentiometric Surface

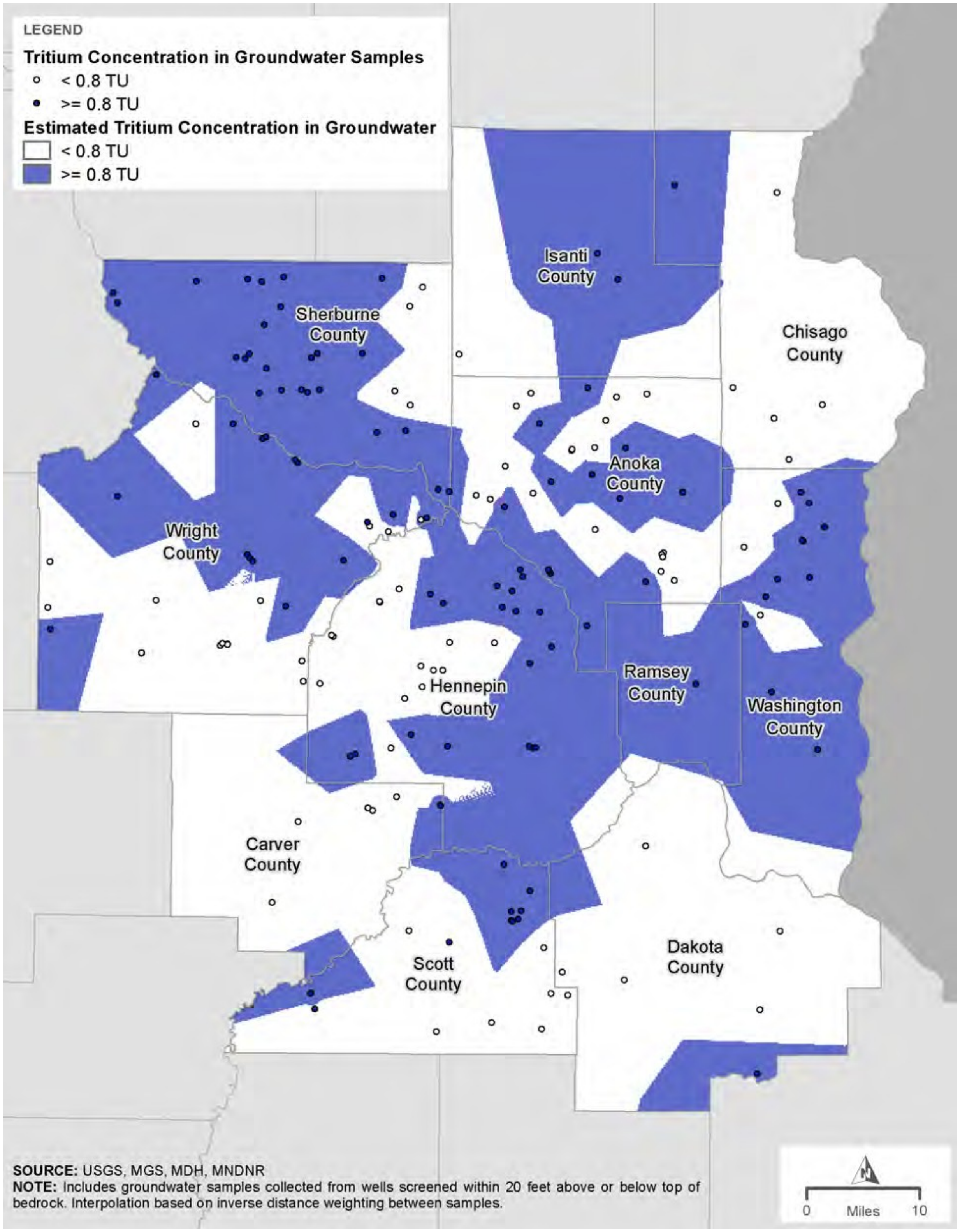


DATASOURCE: USGS, MGS, MNDNR

NOTE: Bedrock potentiometric surface generated from Tipping (2012). Vertical datum for elevations is NAVD88.

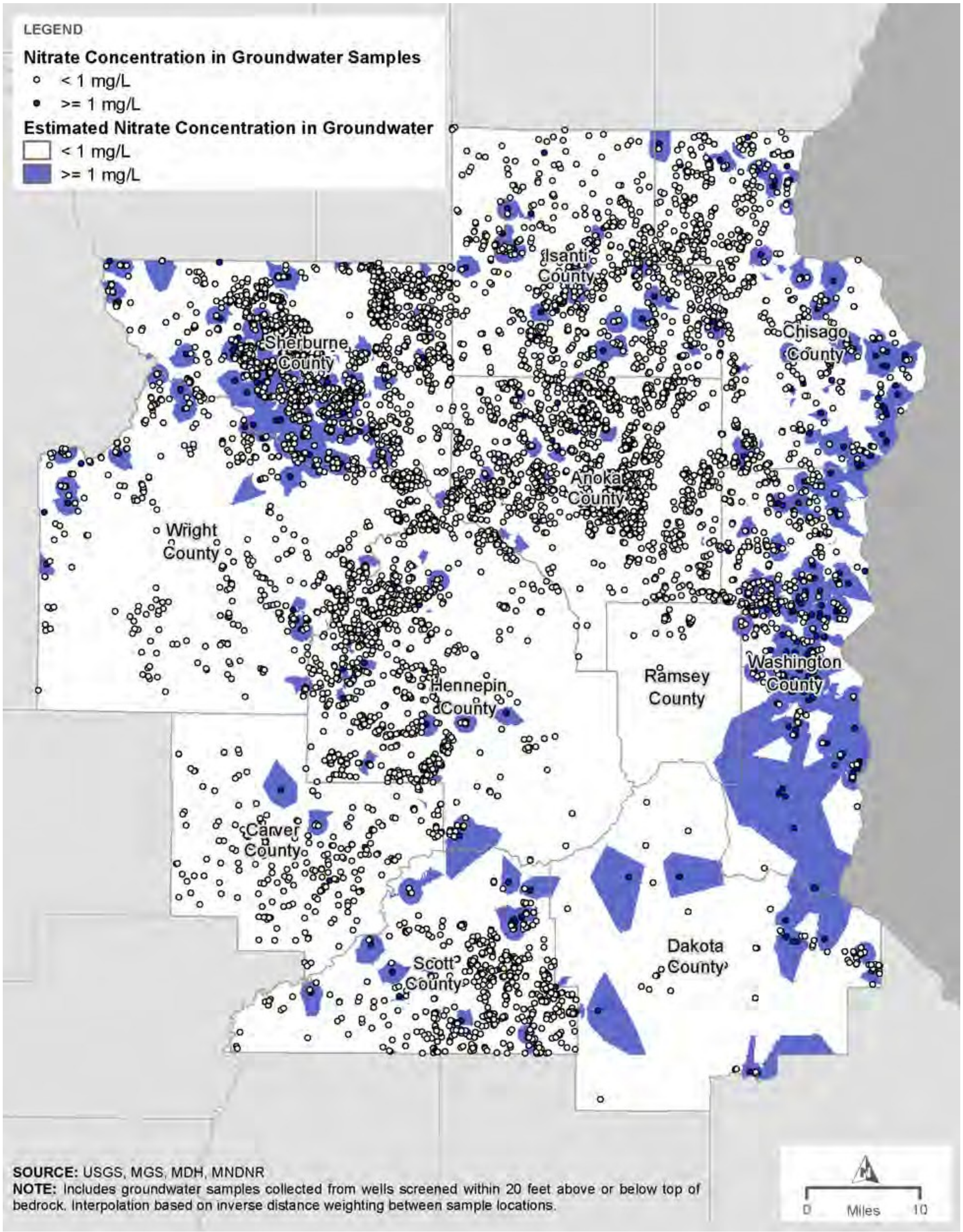
Appendix D. Geochemical Evaluation Figures

Figure D-1. Tritium in Groundwater



SOURCE: USGS, MGS, MDH, MNDNR
NOTE: Includes groundwater samples collected from wells screened within 20 feet above or below top of bedrock. Interpolation based on inverse distance weighting between samples.

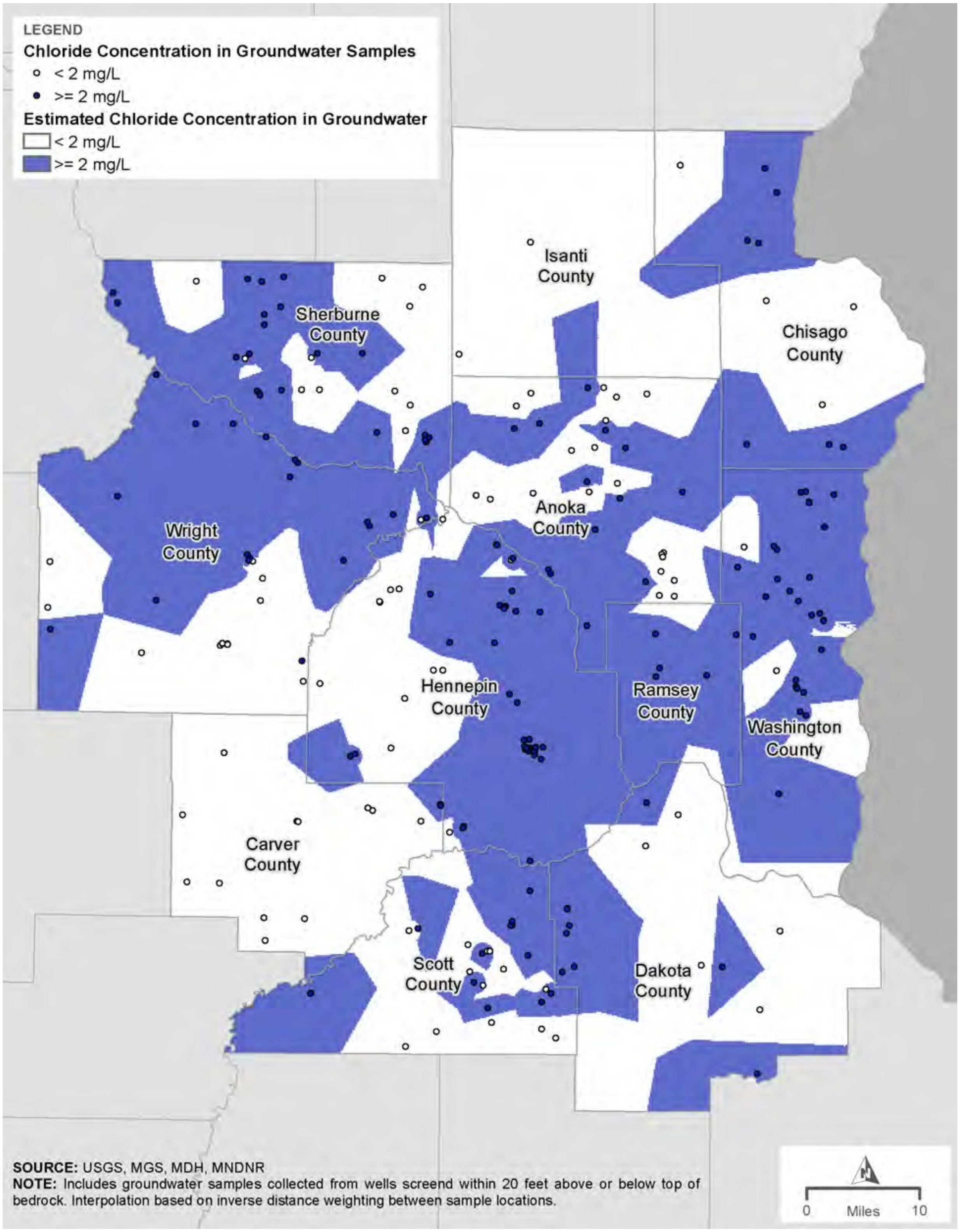
Figure D-2. Nitrate in Groundwater



SOURCE: USGS, MGS, MDH, MNDNR

NOTE: Includes groundwater samples collected from wells screened within 20 feet above or below top of bedrock. Interpolation based on inverse distance weighting between sample locations.

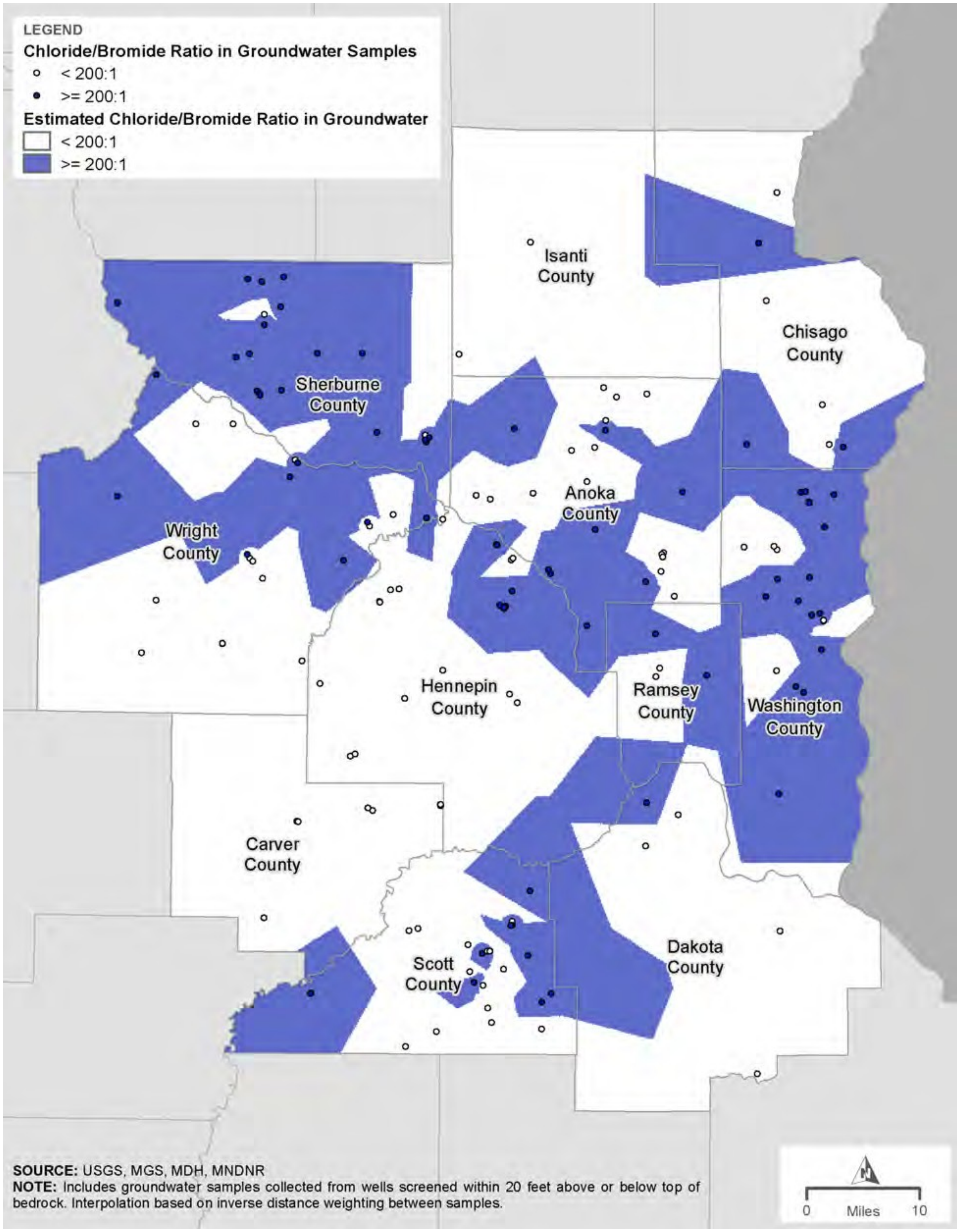
Figure D-3. Chloride in Groundwater



SOURCE: USGS, MGS, MDH, MNDNR

NOTE: Includes groundwater samples collected from wells screend within 20 feet above or below top of bedrock. Interpolation based on inverse distance weighting between sample locations.

Figure D-4. Chloride/Bromide Ratio in Groundwater



SOURCE: USGS, MGS, MDH, MNDNR

NOTE: Includes groundwater samples collected from wells screened within 20 feet above or below top of bedrock. Interpolation based on inverse distance weighting between samples.

Appendix E. Mean Hydraulic Conductivity Values Developed for Quaternary Sediments in the TCMA

Appendix E. Mean Hydraulic Conductivity Values Developed for Quaternary Sediments in the TCMA

County	Material Code (County Geologic Atlas)	Assigned Hydraulic Conductivity (ft/day) (Tipping et al. 2010)[1]	Description (County Geologic Atlas)	Soil Type (County Geologic Atlas)	2018 Revised Soil Type (MGS, MCES)[2]
Anoka	CE	9.81E-04	Sandy till, primarily from SupLobe Emerald Phase	SyLm	SyLm
Anoka	CR	9.81E-04	Sandy till primarily from SupLobe-St.Croix Phase	SyLm	SyLm
Anoka	FS	1.55E-04	Lk Henry/St Francis Fms sand & gravel	GyS	**CyM***
Anoka	LC	1.02E+00	Lacustrine clay & silt &/or clayey to sandy till	CyM	**Lm***
Anoka	NU	9.81E-04	Till to sandy till (NB Fm)	SyLm	**SyLm-Lm***
Anoka	P	4.73E-04	Peat and muck	Pt	Pt
Anoka	PT	1.02E+00	Loam till of Winnipeg provenance	Lm-CyLm	Lm-CyLm
Anoka	RT	9.81E-04	Sandy till of Superior provenance	SyLm	SyLm
Anoka	SC	7.04E+00	Sand and gravel	GyS	GyS
Anoka	SE	7.04E+00	Sand and gravel	GyS	GyS
Anoka	SL	7.04E+00	Sand and gravel (NewUlm & Cromwell Fms)	GyS	GyS
Anoka	SP	7.04E+00	Sand and gravel (from SupLob; also Winnipeg prov.)	GyS	GyS
Anoka	SR	7.04E+00	Sand and gravel (from SupLob & Winnipeg prov.)	GyS	GyS
Anoka	SS	9.72E-01	sandy surface sediments	GyS	**S***
Anoka	SU	9.81E-04	Undifferentiated sediment - sand & gravel	GyS	**SyLm***
Anoka	SV	7.04E+00	Sand and gravel (from SupLob; also Winnipeg prov.)	GyS	GyS
Anoka	SX	7.04E+00	Sand and gravel	GyS	GyS

County	Material Code (County Geologic Atlas)	Assigned Hydraulic Conductivity (ft/day) (Tipping et al. 2010)[1]	Description (County Geologic Atlas)	Soil Type (County Geologic Atlas)	2018 Revised Soil Type (MGS, MCES)[2]
Anoka	VT	9.81E-04	Sandy till of Superior provenance	SyLm	SyLm
Anoka	XT	1.02E+00	Pre-Wisc till of Winnipeg provenance	Lm	Lm
Carver	BT	1.02E+00	Glacial till - loam to clay loam	Lm-CyLm	**Lm***
Carver	DTH	1.02E+00	Glacial till - loam to clay loam	Lm-CyLm	**Lm***
Carver	DTV	1.02E+00	Glacial till: loam to clay loam	Lm-CyLm	**Lm***
Carver	GT	1.02E+00	Glacial till - Loam to sandy loam	Lm-SyLm	**Lm***
Carver	RT	9.81E-04	Glacial till - sandy loam	SyLm	SyLm
Carver	SB	7.04E+00	Sand and gravel	GyS	GyS
Carver	SDO	7.04E+00	outwash and alluvial sands and gravelly sands	GyS	GyS
Carver	SDV	7.04E+00	Sand and gravel	GyS	GyS
Carver	SG	7.04E+00	Sand and gravel	GyS	GyS
Carver	SR	7.04E+00	Sand and gravel	GyS	GyS
Carver	SU	7.04E+00	Undifferentiated sediment	GyS	GyS
Carver	SX	7.04E+00	Sand and gravel	GyS	GyS
Carver	UPS	1.02E+00	Undifferentiated sediment	Lm	Lm
Carver	XT	9.81E-04	Pre-Wisconsin loam till	MyLm	MyLm
Chisago	CE	9.81E-04	Cromwell Fm, Emerald Phase sandy till	SyLm	SyLm
Chisago	CR	9.81E-04	Cromwell Fm sandy till	SyLm	SyLm

County	Material Code (County Geologic Atlas)	Assigned Hydraulic Conductivity (ft/day) (Tipping et al. 2010)[1]	Description (County Geologic Atlas)	Soil Type (County Geologic Atlas)	2018 Revised Soil Type (MGS, MCES)[2]
Chisago	LC	1.02E+00	Cromwell Fm lacustrine clay & silt, to till	MyC	**Lm***
Chisago	NT	1.02E+00	New Ulm Fm loamy till	Lm	Lm
Chisago	NT1	1.02E+00	New Ulm Fm loamy till	Lm	Lm
Chisago	PEAT	4.73E-04	Peat & muck	MyC	**Pt***
Chisago	RT	9.81E-04	Pre-Wisconsin sandy till	SyLm	SyLm
Chisago	UPS	9.81E-04	Undifferentiated sediment	Lm	**SyLm***
Chisago	XT	1.02E+00	???	Lm ??	**Lm***
Chisago	QSC	7.04E+00	Cromwell Fm sand & gravel	GyS	GyS
Chisago	QSE	7.04E+00	Cromwell Fm sand & gravel	GyS	GyS
Chisago	QSL	7.04E+00	New Ulm & Cromwell Fms sand & gravel	GyS	GyS
Chisago	QSP	7.04E+00	Pre-Wisconsin sand & gravel	GyS	GyS
Chisago	QSR	7.04E+00	Pre-Wisconsin sand & gravel	GyS	GyS
Chisago	QSX	7.04E+00	Cromwell Fm, Emerald Phase sand & gravel	GyS	GyS
Chisago	SURF	9.72E-01	SURFACE SAND; some gravel but mostly fine sand	(None assigned)	**S***
Hennepin	AFSI	9.81E-04	(?) artificial fill, Superior provenance	MyS	MyS
Hennepin	AFTCI	1.02E+00	(?) artificial fill, TC Mbr provenance	CyS	CyS
Hennepin	QAFHL	9.81E-04	(?) alluvium	MyS	MyS
Hennepin	QAG	7.04E+00	near Crow R & Miss R: S & G	GyS	GyS

County	Material Code (County Geologic Atlas)	Assigned Hydraulic Conductivity (ft/day) (Tipping et al. 2010)[1]	Description (County Geologic Atlas)	Soil Type (County Geologic Atlas)	2018 Revised Soil Type (MGS, MCES)[2]
Hennepin	QAS	9.81E-04	MN R valley floodplain deposits: MyCLm-LmyfS	(None assigned)	**LmyfS***
Hennepin	QAT	7.04E+00	terrace deposits: S & G	GyS	GyS
Hennepin	QC	9.81E-04	Colluvium: LmS & G	GyS	**LmS**
Hennepin	QCA	1.02E+00	Cromwell Fm till: Lm-SyLm	Lm	Lm
Hennepin	QCE	9.81E-04	Emerald-phase till: SyLm-L	SyLm	SyLm
Hennepin	QCL	9.81E-04	Cromwell Fm lacustrine deposits: MLm-MyS	SyM	SyM
Hennepin	QCS	9.81E-04	Cromwell Fm till: SyLm-Lm	SyLm	SyLm
Hennepin	QEO	7.04E+00	Elmdale Fm outwash: fS-SyG	GyS	GyS
Hennepin	QET	1.02E+00	Elmdale Fm till: CLm-SyLm	Lm	Lm
Hennepin	QF1	7.04E+00	St.Francis Fm outwash: fS-SyG	GyS	GyS
Hennepin	QF2	7.04E+00	St.Francis Fm outwash: fS-SyG	GyS	GyS
Hennepin	QH1	7.04E+00	L.Henry Fm-Saulk Ctr Mbr outwash: fS-SyG	GyS	GyS
Hennepin	QH2	7.04E+00	L.Henry Fm-Meyer L. Mbr outwash: fS-SyG	(None assigned)	**GyS***
Hennepin	QHI	9.72E-01	Heiberg Mbr ice-contact deposits: LmyS-GyS	S	S
Hennepin	QHL	9.81E-04	Heiberg Mbr lacustrine deposits: MyCLm-MLm	MyLm	MyLm
Hennepin	QHT	1.02E+00	Heiberg Mbr till: Lm-CLm	CyM	**Lm***
Hennepin	QL	1.55E-04	lacustrine fS, M, & C with organic deposits	C and CyM	C and CyM
Hennepin	QLT	1.55E-04	Slackwater lacustrine deposits: MyCLm-MyC	MyC	MyC

County	Material Code (County Geologic Atlas)	Assigned Hydraulic Conductivity (ft/day) (Tipping et al. 2010)[1]	Description (County Geologic Atlas)	Soil Type (County Geologic Atlas)	2018 Revised Soil Type (MGS, MCES)[2]
Hennepin	QML	4.73E-04	L.Henry-Meyer L Mbr till: CLm-Lm	CLm	CLm
Hennepin	QMS	9.81E-04	Moland Mbr lacustrine Sand	S	**LmyS***
Hennepin	QMT	9.81E-04	Moland Mbr till: SyLm	SyLm	SyLm
Hennepin	QNB	9.72E-01	New Brighton Fm dep'd in L.Anoka: vf-mS	f-mS	f-mS
Hennepin	QND	7.04E+00	Grantsburg meltwater flow into L.Anoka: S & G	GyS	GyS
Hennepin	QNO	7.04E+00	along Crow R: fS to G	S	**GyS***
Hennepin	QOST	9.81E-04	Superior Lobe till: SyLm	SyLm	SyLm
Hennepin	QS1	7.04E+00	Cromwell Fm subsurface outwash: S-GyS	GyS	GyS
Hennepin	QS2	7.04E+00	Cromwell Fm outwash: S-SyG	GyS	GyS
Hennepin	QS3	7.04E+00	Emerald-phase outwash: S-SyG	GyS	GyS
Hennepin	QSC	1.02E+00	L.Henry Fm-Saulk Ctr Mbr till: CyLm-Lm	Lm	Lm
Hennepin	QSF1	9.81E-04	St.Francis Fm till: SyLm-L	Lm	**SyLm***
Hennepin	QSF2	9.81E-04	St.Francis Fm till: SyLm	SyLm	SyLm
Hennepin	QSH	9.81E-04	Lacustrine MLm, SyLm, & LmyS&G	SyLm	SyLm
Hennepin	QSI	9.72E-01	Cromwell Fm ice-contact deposits: LmyS-SyG	S	**LmyS&G***
Hennepin	QST	1.02E+00	TC Mbr stagnation deposits: MyCLm-SyLm	Lm	Lm
Hennepin	QSU	7.04E+00	Unknown provenance: fS-SyG	GyS	GyS
Hennepin	QTC	1.02E+00	TC Mbr colluvium: MyCLm-LmyS	Lm	Lm

County	Material Code (County Geologic Atlas)	Assigned Hydraulic Conductivity (ft/day) (Tipping et al. 2010)[1]	Description (County Geologic Atlas)	Soil Type (County Geologic Atlas)	2018 Revised Soil Type (MGS, MCES)[2]
Hennepin	QTI	9.81E-04	TC Mbr ice-contact deposits: MyC-LmyS	LmyS	LmyS
Hennepin	QTL	4.53E-02	TC Mbr lacustrine deposit: MyC-MLm	CyLm	**MyLm***
Hennepin	QTS	9.72E-01	TC Mbr outwash: S-Gy	S	S
Hennepin	QTS1	9.81E-04	TC Mbr S above lacustrine deposit: S-GyS	S	**LmyS***
Hennepin	QTS2	9.72E-01	TC Mbr S	S	S
Hennepin	QTT	9.81E-04	TC Mbr till: Lm-SyLm	Lm	**SyLm***
Hennepin	QU	1.55E-04	Undifferentiated sediment: C,M,S,&G	MyS	
Hennepin	QVO	7.04E+00	Superior Lobe outwash: fS-SyG	GyS	GyS
Hennepin	QVS	7.04E+00	Villard Mbr Sand: S-GyS	GyS	GyS
Hennepin	QVT	1.02E+00	Villard Mbr Till: Lm-SyLm	MyS	**Lm***
Hennepin	QWO	7.04E+00	Rainy Lobe outwash: fS-SyG	GyS	GyS
Hennepin	QWT	9.81E-04	Rainy Lobe till: SyLm-Lm	Lm	**SyLm***
Isanti	CSA	7.04E+00	New Ulm/Cromwell Fms sand & gravel	GyS	GyS
Isanti	CSE	7.04E+00	Cromwell Fm sand & gravel	GyS	GyS
Isanti	CSR	7.04E+00	Cromwell Fm sand & gravel	GyS	GyS
Isanti	CTA	1.02E+00	Cromwell Fm sandy till	SyLm	**Lm***
Isanti	CTE	9.81E-04	Cromwell Fm sandy till	SyLm	SyLm
Isanti	CTR	9.81E-04	Cromwell Fm sandy till	SyLm	SyLm

County	Material Code (County Geologic Atlas)	Assigned Hydraulic Conductivity (ft/day) (Tipping et al. 2010)[1]	Description (County Geologic Atlas)	Soil Type (County Geologic Atlas)	2018 Revised Soil Type (MGS, MCES)[2]
Isanti	FS1	7.04E+00	Lk Henry/St Francis Fms sand & gravel	GyS	GyS
Isanti	FS2	7.04E+00	Lk Henry Fm, Meyer Lk Mbr sand & gravel	GyS	GyS
Isanti	FT1	9.81E-04	Lk Henry/St Francis Fms sandy till	SyLm	SyLm
Isanti	FT2	9.81E-04	St Francis Fm sandy till	SyLm	SyLm
Isanti	MLS	7.04E+00	Lk Henry/St Francis Fms, Meyer Lk Mbr sand & gravel	GyS	GyS
Isanti	MLT	1.02E+00	Lk Henry Fm, Meyer Lk Mbr loamy to silty till	Lm-MyLm	Lm-MyLm
Isanti	NT	1.02E+00	New Ulm Fm loamy to silty to sandy till	Lm	Lm
Isanti	RS	7.04E+00	Cromwell Fm sand & gravel	SyG	SyG
Isanti	RT	9.81E-04	Henderson Fm sandy till	SyLm	SyLm
Isanti	SC	1.55E-04	Sand and gravel	GyS	**CyM***
Isanti	SCS	7.04E+00	Henderson/Lk Henry Fms sand & gravel	SyG	SyG
Isanti	SCT	1.02E+00	Lk Henry Fm, Sauk Centre Mbr loamy till	Lm	Lm
Isanti	SS	9.72E-01	sandy surface sediments	GyS	**S***
Isanti	UPS	9.81E-04	Undifferentiated sediment	Lm	**SyLm***
Isanti	USS	7.04E+00	Undifferentiated sand & gravel	GyS	GyS
Isanti	WRS	7.04E+00	St Francis Fm sand & gravel	GyS	GyS
Isanti	WRT	9.81E-04	Mulligan Fm sandy till	SyLm	SyLm
Scott	RIV	7.04E+00	river vally alluvium???	(None assigned)	**GyS***

County	Material Code (County Geologic Atlas)	Assigned Hydraulic Conductivity (ft/day) (Tipping et al. 2010)[1]	Description (County Geologic Atlas)	Soil Type (County Geologic Atlas)	2018 Revised Soil Type (MGS, MCES)[2]
Scott	S1	7.04E+00	Outwash	S-GyS	**GyS***
Scott	S2	7.04E+00	Outwash	S-GyS	**GyS***
Scott	S3	7.04E+00	Outwash	S-GyS	**GyS***
Scott	S4	7.04E+00	???	S-GyS ??	**GyS***
Scott	T1	1.02E+00	NW provenance till	SyLm-CLm	**Lm***
Scott	T2	9.81E-04	mixed provenance mixed till	Lm-SyLm	**Lm***
Scott	T3	1.02E+00	pre-Wisconsin age NW provenance till	Lm	Lm
Sherburne	CSA	7.04E+00	Cromwell Fm, Automba Phase sand & gravel	GyS	GyS
Sherburne	CSE	7.04E+00	Cromwell Fm, Emerald Phase sand & gravel	GyS	GyS
Sherburne	CSR	7.04E+00	Cromwell Fm, St. Croix Phase sand & gravel	GyS	GyS
Sherburne	CTA	9.81E-04	Cromwell Fm, Automba Phase till	Lm	**SyLm***
Sherburne	CTE	9.81E-04	Cromwell Fm, Emerald Phase till	Lm	**SyLm***
Sherburne	CTR	9.81E-04	Cromwell Fm, St. Croix Phase till	Lm	**SyLm***
Sherburne	FS1	7.04E+00	St. Francis Fm sand & gravel	GyS	GyS
Sherburne	FS2	7.04E+00	St. Francis Fm sand & gravel	GyS	GyS
Sherburne	FT1	9.81E-04	St. Francis Fm till	Lm	**SyLm***
Sherburne	FT2	9.81E-04	St. Francis Fm till	Lm	**SyLm***
Sherburne	MLS	7.04E+00	Lk Henry Fm, Meyer Lk Mbr sand & gravel	GyS	GyS

County	Material Code (County Geologic Atlas)	Assigned Hydraulic Conductivity (ft/day) (Tipping et al. 2010)[1]	Description (County Geologic Atlas)	Soil Type (County Geologic Atlas)	2018 Revised Soil Type (MGS, MCES)[2]
Sherburne	MLT	1.55E-04	Lk Henry Fm, Meyer Lk Mbr till	Lm	**MyLm**
Sherburne	NBS	9.72E-01	New Brighton Fm sandy glacial lake deposits	S	S
Sherburne	NS	7.04E+00	New Ulm Fm sand & gravel	GyS	GyS
Sherburne	NT	9.81E-04	New Ulm Fm till	Lm	**SyLm***
Sherburne	SC	1.55E-04	fine-grained surface sediments	CyM	**MyC***
Sherburne	SCS	7.04E+00	Lk Henry Fm, Sauk Centre Mbr sand & gravel	GyS	GyS
Sherburne	SCT	1.55E-04	Lk Henry Fm, Sauk Centre Mbr till	Lm	**SyLm***
Sherburne	SS	7.04E+00	sandy surface sediments	GyS	GyS
Sherburne	SUU	7.04E+00	Unknown sand & gravel	GyS	GyS
Sherburne	UPS	1.02E+00	Undifferentiated Pleistocene sediment	Lm	Lm
Washington	QCE	9.81E-04	Cromwell Fm sandy till & sand	SyLm-S	**SyLm***
Washington	QCR	9.81E-04	Cromwell Fm sandy till	SyLm	SyLm
Washington	QLC	1.02E+00	Cromwell Fm till	Lm	Lm
Washington	QNT	9.81E-04	Grantsburg Sublobe till	SyLm-Lm	SyLm-Lm
Washington	QPT	4.73E-04	Early Pleistocene Pierce Fm. Till	Lm	**Lm-CyLm***
Washington	QR1	9.81E-04	Henderson/River Falls Fm sandy till	SyLm	SyLm
Washington	QR2	9.81E-04	St. Francis/River Falls Fm	Lm	**Lm-SyLm***
Washington	QR3	9.81E-04	St. Francis/River Falls Fm very sandy till	MyS	**SyLm***

County	Material Code (County Geologic Atlas)	Assigned Hydraulic Conductivity (ft/day) (Tipping et al. 2010)[1]	Description (County Geologic Atlas)	Soil Type (County Geologic Atlas)	2018 Revised Soil Type (MGS, MCES)[2]
Washington	QS1	7.04E+00	Cromwell Fm gravelly sand	GyS	GyS
Washington	QS2	7.04E+00	Henderson/River Falls Fm loamy sand & gravel	MyS	**GyS***
Washington	QS3	7.04E+00	St. Francis/River Falls Fm sand	m-cS	**GyS***
Washington	QSC	7.04E+00	Sand and gravel	GyS	GyS
Washington	QSE	7.04E+00	Cromwell Fm gravelly sand	GyS	GyS
Washington	QSL	7.04E+00	Cromwell Fm loamy sand and gravel	MyS	**GyS***
Washington	QSP	7.04E+00	St. Francis/River Falls Fm loamy sand till	LmyS	**GyS***
Washington	QSU	7.04E+00	Superior provenance sand and gravel	GyS	GyS
Washington	QSV	7.04E+00	Sand and gravel (from SupLob; also Winnipeg prov.)	GyS	GyS
Washington	QSX	7.04E+00	Lk Henry Fm gravelly sand	GyS	GyS
Washington	QU	9.81E-04	Undifferentiated sediment: C,M,S,&G	MyS	**SyLm***
Washington	QVT	9.81E-04	Superior provenance loamy till	Lm	**SyLm***
Washington	QXT	1.02E+00	Meyer Lk Mbr, Lk Henry Fm loamy till	Lm	Lm
Washington	SC	1.55E-04	Sand and gravel	GyS	**CyM***
Washington	SC1	1.55E-04	Sand and gravel	GyS	**CyM***
Washington	SC2	1.55E-04	Sand and gravel	GyS	**CyM***
Washington	SL	9.81E-04	Sand and gravel (NewUlm & Cromwell Fms)	GyS	**SyLm***
Washington	SS	7.04E+00	sandy surface sediments	GyS	GyS

County	Material Code (County Geologic Atlas)	Assigned Hydraulic Conductivity (ft/day) (Tipping et al. 2010)[1]	Description (County Geologic Atlas)	Soil Type (County Geologic Atlas)	2018 Revised Soil Type (MGS, MCES)[2]
Washington	SS1	7.04E+00	sandy surface sediments	GyS	GyS
Washington	SS2	7.04E+00	sandy surface sediments	GyS	GyS
Wright	CG	7.04E+00	Cromwell Fm outwash	GyS	GyS
Wright	CG1	7.04E+00	Cromwell Fm outwash	GyS	GyS
Wright	CT	9.81E-04	Cromwell Fm sandy loam till	SyLm	SyLm
Wright	CT1	9.81E-04	Cromwell Fm sandy loam till	SyLm	SyLm
Wright	HA	7.04E+00	alluvium - sand and pebbly sand w/silt & clay	S-MyS	**GyS***
Wright	HBT	1.02E+00	New Ulm Fm, Heiberg Mbr - loam till	Lm	Lm
Wright	HL	1.55E-04	modern lake sediment - silt, clay, org'cs, & sand	MyS-MyC	**MyS-MyC***
Wright	HS	7.04E+00	Hewitt Fm outwash	GyS	GyS
Wright	HWT	9.81E-04	Hewitt Fm sandy loam till	SyLm	SyLm
Wright	MLS	7.04E+00	Lk Henry Fm, Meyer Lk Mbr - sand & gravel	GyS	GyS
Wright	MLT	1.02E+00	Lk Henry Fm, Meyer Lk Mbr - loam till	Lm	Lm
Wright	MS	7.04E+00	New Ulm Fm, Moland Mbr outwash	GyS	GyS
Wright	MT	9.81E-04	New Ulm Fm, Moland Mbr sandy loam till	SyLm	SyLm
Wright	NHS	7.04E+00	New Ulm Fm, Heiberg Mbr - sand & gravelly sand	GyS	GyS
Wright	NLC	4.53E-02	New Ulm Fm, Villard Mbr glacial lake sediment	CyM	**SyLm***
Wright	NLS	4.53E-02	glaciolacustrine sediment - silt, clay, & fine sand	MyS-MyC	**SyLm***

County	Material Code (County Geologic Atlas)	Assigned Hydraulic Conductivity (ft/day) (Tipping et al. 2010)[1]	Description (County Geologic Atlas)	Soil Type (County Geologic Atlas)	2018 Revised Soil Type (MGS, MCES)[2]
Wright	NT	1.02E+00	New Ulm Fm, Villard Mbr - loam till	Lm	Lm
Wright	NTS	7.04E+00	New Ulm Fm, Villard Mbr outwash	GyS	GyS
Wright	PRS	7.04E+00	Superior provenance - sand & gravel	GyS	GyS
Wright	PRT	1.02E+00	Superior provenance - loam till	Lm	Lm
Wright	PSU	7.04E+00	Undifferentiated sand & gravel	GyS	GyS
Wright	PU	1.02E+00	Undifferentiated sand, gravel, & lake sediments	MyS	**Lm***
Wright	PWS	7.04E+00	Winnipeg & Rainy provenance - sand & gravel	GyS	GyS
Wright	PWT	1.55E-04	Winnipeg & Rainy provenance - loam till	SyLm-CyLm	SyLm-CyLm
Wright	SCS	7.04E+00	Lk Henry Fm, Sauk Centre Mbr - sand & gravel	GyS	GyS
Wright	SCT	1.02E+00	Lk Henry Fm, Sauk Centre Mbr - loam till	Lm	Lm
Wright	WMT	7.04E+00	Mississippi R terrace - sand & gravelly sand	S-GyS	S-GyS
Wright	ZUS	7.04E+00	Basal sand & gravel	GyS	GyS
(various)	tct	1.02E+00	Twin Cities Fm.-till	(None assigned)	**Lm***
(various)	tco	7.04E+00	Twin Cities Fm. - sand and gravel	(None assigned)	**GyS***

Table Notes:

[1] Assigned hydraulic conductivity (K) values are means of values obtained from primarily vertical test methods (e.g. lab permeameter, aquifer test). A summary of the ranges of individual K values from test methods used in this assessment, as well as a summary of individual K values from all available test methods (horizontal and vertical) in Tipping et al. (2010) is provided below:

[2] Mapped sediments and hydraulic conductivity assignments were revised during this assessment by MCES with input from MGS personnel after anomalies such as sharp cut-offs (generally along county boundaries) were observed in the data, which indicate differences in mapping methods and/or the dominance by a few, thick units. The resulting dataset is more consistent across these nine counties; excluding Dakota and Ramsey Counties, which were derived from Tipping (2011).

* Sedimentary textures that were revised by MGS and MCES for this assessment are marked with an asterisk and shown in **boldface**.

Assigned K Value (ft/day)	Range of Individual K Values Used in Assigned K Value (ft/day)	Range of Individual K Values from All Available Horizontal and Vertical Test Methods in Tipping et al. (2010) (ft/day)
1.55E-04	6.80E-05 to 3.97E-04	6.80E-05 to 3.35E+00
4.73E-04	2.83E-06 to 2.83E+00	2.83E-06 to 5.45E+00
9.81E-04	1.98E-05 to 3.40E+00	1.98E-05 to 4.30E+01
4.53E-02	9.35E-06 to 5.67E+00	9.35E-06 to 1.50E+02
9.72E-01	2.53E-01 to 1.90E+00	5.84E-05 to 3.69E+01
1.02E+00	8.85E-02 to 3.42E+00	8.85E-02 to 3.42E+00
7.04E+00	4.82E-05 to 1.11E+02	4.82E-05 to 5.40E+02

C and CyM	Clay and Clayey Silt	LmS	Loam and Sand	Pt	Peat
CLm	Clay Loam	Lm-SyLm	Loam to Sandy Loam	S	Sand
CyM	Clayey Silt	LmyfS	Loamy Fine Sand	S-GyS	Sand to Gravelly Sand
CyS	Clayey Sand	LmyS	Loamy Sand	S-MyS	Sand to Silty Sand
f-mS	Fine to Medium Sand	LmyS&G	Loamy Sand and Gravel	SyG	Sandy Gravel
GyS	Gravelly Sand	MyC	Silty Clay	SyLm	Sandy Loam
Lm	Loam	MyLm	Silty Loam	SyLm-CyLm	Sandy Loam to Clayey Loam
Lm-CyLm	Loam to Clayey Loam	MyS	Silty Sand	SyLm-Lm	Sandy Loam to Loam
Lm-MyLm	Loam to Silty Loam	MyS-MyC	Silty Sand to Silty Clay	SyM	Sandy Silt