UNIVERSITY OF MINNESOTA

# Minnesota Geological Survey

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# DISTRIBUTION OF VERTICAL RECHARGE TO UPPER BEDROCK AQUIFERS TWIN CITIES METROPOLITAN AREA

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TABLE OF CONTENTS

**Executive summary**

This report summarizes work performed by the Minnesota Geological Survey (MGS) in partial fulfillment of work as described under contract 10I021 between the University of Minnesota and the Metropolitan Council. The goal of this investigation was to provide datasets that would assist the Metropolitan Council with regional ground water planning. Specifically, vertical travel times were calculated from a regional water table surface to bedrock in order to gain a better understanding of recharge to upper bedrock aquifers in the extended Twin Cities Metropolitan Area (TCMAx). A focus of this investigation, therefore, was on the permeability of unconsolidated sediments overlying the bedrock surface, and the regional distribution of vertical hydraulic gradient.

Permeability of unconsolidated deposits was estimated based on subsurface textures linked to measured permeabilities compiled in an earlier study (Tipping et al., 2010). The distribution of unconsolidated deposits of variable permeability was mapped by Quaternary geologists, or estimated by interpolation of water well driller's records. To accommodate both types of data, a regional matrix of regularly spaced datapoints from the land surface to the bedrock surface was constructed, with horizontal dimensions of 250 meters, and vertical spacing of 20 feet. Texture attributes were added to each datapoint based on its position relative to subsurface mapping and interpolation results. Regional distribution of hydraulic gradient was determined by building a bedrock potentiometric surface based on synoptic measurements (Sanocki et al., 2009) and water well records, and subtracting it from a regional water table surface (Barr, 2010). The difference in hydraulic head was then divided by distance from the regional water table to the bedrock surface to obtain hydraulic gradient.

Vertical travel time was calculated using a Darcy-flux based approach, using harmonic means of vertical hydraulic conductivity for each matrix horizontal (XY) location, hydraulic gradient, and a effective porosity value of 20 percent. Results were compared to distribution of recent waters (Tipping et al., 2010) in order to test the validity of this method.

The distribution of recent waters in the TCMAx upper bedrock aquifers broadly supports groundwater recharge rates calculated in this investigation. In general, recent waters are found at depth in areas with large vertical gradients and coarse, relatively high permeability material over bedrock. Furthermore, chemical results support the premise that water most impacted by activities at the landsurface – "manageable waters" – occur at elevations controlled by regional discharge to the major rivers, permeability of glacial deposits and high capacity pumping from upper bedrock aquifers.

At local and regional scales, project deliverables improve groundwater model calibration by helping to refine conceptual models of groundwater flow. Residence time data, reflected in the distribution of vertical recharge to upper bedrock aquifers, can be used to guide interpretation of calibration results as an alternative to calibration strictly by head values alone. These steps can result in a more realistic distribution of hydraulic conductivity parameters in numeric models.

## Introduction

This report summarizes work performed by the Minnesota Geological Survey (MGS) in partial fulfillment of work as described under contract no. 10I021 between the University of Minnesota and the Metropolitan Council. The goal of this investigation was to provide information on recharge to bedrock aquifers in the extended Twin Cities Metropolitan Area (TCMAx) (Figure 1). This report focuses on vertical movement of groundwater through unconsolidated deposits to bedrock aquifers; a second, complementary report focuses on the hydraulic conductivity and hydrostratigraphy of the Platteville Formation (Runkel et al., this study).

Resource managers make decisions which hinge on questions related to groundwater such as *What's the groundwater quality in my area? Is the groundwater getting worse or better? If we increase our use of the groundwater, what are the consequences*? Efficient management of groundwater resources requires better information on how these aquifers recharge. The distribution of overlying glacial materials clearly effects recharge to bedrock aquifers in the Twin Cities Metropolitan Area. However, residence times and pathways of groundwaters through these deposits are not well characterized.

While groundwater pathways through glacial deposits can be complex, two fundamental components of this flow system can be addressed: 1.) what is the composition, spatial distribution and hydraulic characteristics of unconsolidated materials overlying bedrock aquifers?, and 2.) what is the spatial distribution of vertical gradient that drives the downward movement of groundwater through these deposits? This investigation uses subsurface glacial mapping through parts of the TCMAx in addition to recent regional mapping of both water table and potentiometric surfaces of major TCMAx bedrock aquifers to calculate vertical flux of groundwater from the water table to the bedrock surface. Estimated travel times are then compared with the chemical and isotopic composition of TCMAx groundwaters to test the validity of this method.

**Background and data sources**

Focus on the downward flux of groundwater as a means of assessing groundwater recharge through glacial deposits is not a new approach. Larson-Higdem et al., 1975, applied similar methods to look at downward leakage to the Prairie du Chien – Jordan aquifer system in the Twin Cities metropolitan area; their work was incorporated into a more recent evaluation of recharge to Twin Cities unconfined bedrock aquifers (Ruhl et al., 2002). In a more general application, vertical flux of groundwater is the fundamental part of ground water sensitivity mapping (Minnesota Department of Natural Resources, 1991). In all cases, the complex pathways of groundwater movement through unconsolidated materials are simplified by considering the vertical component of groundwater flow only.

While the vertical movement of groundwater is conceptually clear, its calculation is dependent on estimates of vertical hydraulic conductivity that are highly variable and difficult to measure. Most aquifer tests are designed to estimate horizontal hydraulic conductivity, based on the premise that ground water flow to a pumping well is primarily horizontal. Direct measurements of vertical hydraulic conductivity are largely limited to laboratory experiments; field based values are typically based on leakage estimates derived from deviations from typical water level response curves to pumping. Notwithstanding scale effects that account for increases in hydraulic conductivity due to scale of measurement - lab to field to regional – it is assumed that a reasonable regional scale estimate of vertical hydraulic conductivity falls within the broad range of measured horizontal hydraulic conductivities for a given geologic material. For this investigation, mean horizontal hydraulic conductivity values from an earlier investigation for the Metropolitan Council (Tipping et al., 2010) were used as estimates of vertical hydraulic conductivity. Expected ranges of hydraulic conductivity for given textures of unconsolidated deposits used in this study are provided in Appendix A.

The most complete data on the distribution of subsurface materials comes from areas where Quaternary stratigraphic mapping has taken place (Figure 1). In the TCMAx, Quaternary subsurface mapping occurred first in Washington County as part of a county project (Meyer and Tipping, 1998), was included as part of a hydrogeologic investigation of the northwestern metropolitan area (Meyer and Tipping, 2007) and has been part of more recent county atlases in Scott, Carver and Chisago Counties (Lusardi and Tipping, 2006; Lusardi and Tipping, 2009; Meyer, 2010). In areas not covered subsurface mapping, subsurface texture distributions were estimated from data in the state water well database County Well Index (CWI), as described in the methods section of this report.

Data on vertical hydraulic gradients comes from two sources. Water table elevations were taken from a regional investigation on groundwater surface-water interaction (Barr, 2010). Bedrock potentiometric surfaces are based primarily on synoptic measurements of the Prairie du Chien and Jordan aquifers (Sanocki et al., 2009), augmented with data from CWI where these rocks are absent. Based on bedrock hydrostratigraphy, elevation of bedrock units and elevation of regional discharge (Mississippi, St. Croix and Minnesota Rivers), horizontal groundwater flux is assumed to be greatest within Prairie du Chien Group and Jordan Sandstone. It is expected that this flux drops off significantly below the St. Lawrence Formation. By combining synoptic measurements from the Prairie du Chien and Jordan aquifers, with CWI data for upper-most bedrock units beyond the extent of the Prairie du Chien and Jordan, the resultant bedrock potentiometric surface is meant to provide generalized base hydraulic head data for flow systems most directly connected to activities at the land surface.

Sources of historic water chemistry data collected as part of a previous investigation (Meyer and Tipping, 2007) for the Metropolitan Council are: the U.S. Geological Survey National Water Inventory System (U.S. Geological Survey, 2010); the Minnesota Department of Health; the Minnesota Pollution Control Agency GWMAP program—both ambient groundwater monitoring and land-use studies (Minnesota Pollution Control Agency, 2010); University of Minnesota graduate studies (Tipping, 1992; Nemetz, 1993; Burman, 1995); Dakota County Environmental Management (2006); Anoka County Community Health and Environmental Services (Marsh, 1996, 2001); and samples from 27 wells in northwestern Hennepin County where there were limited existing data. Additional data include earlier historic data from both regional (Hall et al., 1911; Maderak, 1963; Sabel, 1985; Lively et al., 1992) and local studies (Alexander and Ross, 2003; Andrews et al., 2005), along with tritium and strontium isotope analyses from northwestern Hennepin County (Tipping and others 2010).

## Methods

### *Distribution and hydraulic characteristics of unconsolidated subsurface materials*

In this investigation, vertical hydraulic conductivity values for unconsolidated materials are based on their textural distribution from the land surface to the bedrock surface. Subsurface mapping of unconsolidated deposits is not continuous across the Twin Cities metropolitan area (Figure 1). As a result, the compilation of subsurface Quaternary textures presented here is a hybrid of detailed subsurface mapping based on cross sections, and interpolation of textures from CWI.

Although the methods for detailed subsurface mapping have changed with time, the basic approach is the same. Subsurface materials are mapped in three dimensions by evaluating well records and cuttings, rotosonic core and textural analyses, within the context of stratigraphic order and conditions of deposition. To clarify textural descriptions in this report, the term *fine-grained materials* is used to describe clay loam to sandy loam basal tills, but can include lacustrine deposits composed of laminated fine sand, silt and clay; the term *coarse-grained* *materials* is used to describe sand and gravel glacio-fluvial deposits, including ice contact, valley train, subglacial and outwash deposits; the term *mixed fine and coarse-grained materials* is used to describe textures found in ice stagnation zones and other conditions resulting in a complex mixture of the two. Digital elevation models of the tops and bottoms of stratigraphic units produced by subsurface mapping were used in this investigation to delineate subsurface textures in these mapped areas shown on Figure 1.

Within the TCMAx, areas with no Quaternary subsurface mapping include Dakota, Ramsey, Isanti and portions of Hennepin County. Subsurface mapping is currently underway as part of the Wright and Sherburne geologic atlases, but are not completed at this time. In order to determine the distribution of subsurface textures in these areas, interpolation methods were used modified from those earlier geologic atlases were used (e.g. Meyer et al., 1995). With this approach, stratigraphic records from water wells are coded based on primary lithology into three generalized textural categories of fine-grained, coarse-grained, or a mixture of fine and coarse-grained. In driller's records, these intervals are typically referred to as clay, sand/gravel, and sandy clay/clayey sand. The stratigraphic record is then resampled into equal 10 foot elevation intervals. Two-dimensional interpolation using ordinary kriging is used to determine the likelihood of each category for a given elevation interval.

Two-dimensional, rather than three-dimensional interpolation is used, based on the premise that glacial deposits have undergone minimal structural deformation since their deposition, and that correlation is optimized by evaluating data at equal elevations. Interpolated results for each elevation interval are merged to into a single dataset to create a three-dimensional model for each of the three textural types (see Figures 2, 3 and 4).

In order to combine textural datasets from subsurface mapping and the interpolated model, a matrix of points between the land surface and bedrock surface was created, spaced 250 meters apart in the horizontal direction and 20 feet apart in the vertical direction, herein referred to as gridpoints. The size was chosen to cover the TCMAx at a scale that can be reasonably managed on a desktop computer. A range of vertical hydraulic conductivities (Kv) were assigned each gridpoint, based on its location within mapped Quaternary stratigraphic layers. Where subsurface mapping does not exist, a range of values were assigned based on interpolated model results. If neither of these sources were available for a given gridpoint, a null value was assigned. A final adjustment to assigned Kv values was made based on depth. If the gridpoint is within 20 feet of the land surface (upper-most gridpoint) it texture-derived hydraulic conductivity was assigned based on the current 1:200,000 scale surfical geologic map of the Twin Cities metropolitan region (Meyer, 2007). If the gridpoint is greater than 60 feet in depth from the land surface, its assigned range of hydraulic conductivity is two orders of magnitude less than the values assigned to a similar texture in the upper 60 feet. Textures and assigned ranges of hydraulic conductivities are included in Appendix A., Table 1. These estimates are based on a regional compilation of hydraulic conductivity measurements for glacial deposits, conducted at a wide range of scales (Tipping et. al., 2010). Methods for gridpoint assignment are illustrated on Figure 5.

In addition to hydraulic conductivities, gridpoints contain attributes on texture, texture source (subsurface mapping or interpolated model), Quaternary stratigraphic unit if mapped, surficial map unit, and unique identifiers for the six neighboring points. The latter is included to facilitate finite difference modeling.

For travel time calculations, a single "composite" Kv was assigned to each gridpoint based on the following hierarchy. If no other texture estimate was available, Kv was assigned based on texture from interpolated model. These Kv's were replaced by texture-based Kv's from subsurface mapping, which in turn were replaced by texture-based Kv's from the surficial map (upper 20 feet only). After these assignments were made, if a single column of gridpoints from the land surface to the bedrock surface had texture-derived Kv's for more than 40 percent of its points, the remaining blanks were assigned an intermediate value 10.05 ft/day; if less than 40 percent had texture-derived Kv's, the remaining blanks had no value assigned.

A second dataset was created to summarize subsurface conditions for each XY location within gridpoints, herein referred to as XY locations. This dataset contains information on: what percent of the subsurface is represented, either by subsurface and surface mapping or interpolation, by a texture attribute and associated K value; regional water table surface elevation; bedrock potentiometric surface elevation; and top of bedrock elevation.

For each XY location with greater than 40 percent of its subsurface gridpoint textures represented by mapping or interpolation, arithmetic, geometric and harmonic mean Kv values were calculated. This calculation was done both for points from water table elevation to the bedrock surface and from the water table elevation to the land surface, and are referred to as "Kv_sat" and "Kv_unsat" respectively in dataset XY locations. Kv_sat values based on harmonic mean of each composite Kv for a given XY location are shown on Figure 6. Field descriptions for datasets gridpoints and XY locations are included in Appendix D.

*Hydraulic Gradient*

Hydraulic head differences used to establish a hydraulic gradient between the water in upper, unconsolidated deposits and water in bedrock aquifers were determined using raster calculations. The regional water table raster surface was constructed to help evaluate the impact of pumping on surface water bodies at a regional scale (Barr, 2010). By design, it is well suited for this investigation, by providing generalized regional elevations of saturated conditions, without including zones of perched groundwater systems. Main sources of data sources for the regional water table surface are Minnesota Department of Natural Resources observation well network for water table wells, the County Well Index (CWI), and data from site specific studies. Results from regional groundwater flow models and surface-water elevations for reaches of some streams known to be gaining were also used as a control, particularly where data from other sources were sparse (Barr, 2010).

The regional bedrock potentiometric raster surface is a combination elevations from contoured synoptic water level measurements in the Prairie du Chien Group and Jordan Sandstone (Sanocki et al., 2009) and contoured water levels from the County Well Index for upper-most bedrock aquifers where the Prairie du Chien and Jordan are not present. The resultant bedrock potentiometric surface is meant to provide generalized bedrock hydraulic head data for flow systems most directly connected to activities at the land surface.

The regional water table and bedrock potentiometric surfaces are generalized surfaces both spatially and temporally. Both surfaces are based, in part, on measurements from CWI, taken most often at the date of installation, spanning all seasons over many decades. Filtering and data processing and final cross-validation of the water table CWI dataset resulted in values dropped with absolute residuals 20 feet or greater (Barr, 2010). Error for both regional water table surface and the bedrock potentiometric surface elevations are estimated to be at a minium +/- 20 feet in areas based solely on data from CWI.  Water table data from the DNR's observation well network are based on reliable measurements, but are subject to seasonal variations not included in this model. Bedrock water level data from 2008 synoptic water level measurements provide data that is temporally consistent across the metro area. Measurements were taken in March and August of 2008, and provide information on seasonal changes in hydraulic head within bedrock aquifers.

Subtracting the bedrock potentiometric surface from the regional water table surface produced negative values over much of the TCMAx. Many of these areas were focused on the major rivers, where upward discharge of bedrock aquifers is reflected in expected negative values. In other areas, it is less clear whether actual artesian conditions exist, or where uncertainty in the surface values produces overlap. For the purposes of travel time calculations, areas with negative values near major discharge areas, or areas where CWI records indicate flowing (artesian) bedrock wells were identified and are shown on the vertical recharge map. Outside of these areas, bedrock potentiometric surface elevations greater than the regional water table were lowered to one-half foot below the regional water table.

Subtraction of the adjusted bedrock potentiometric surface from the regional water table surface reveals seasonal changes in bedrock hydraulic head (Figure 7). Synoptic measurements taken in August 2008 show a broadening and deepening of hydraulic head in the central metropolitan area when compared to March 2008 measurements. The cause of this change is likely increased high capacity pumping in response to increased summer demand.

The hydraulic gradient between the regional water table and bedrock aquifers was determined by dividing the difference in hydraulic head by the vertical distance from the water table to the bedrock surface (Figure 8). Perched conditions in the central metropolitan area are present within and above the Plattville Formation; in places, the St. Peter Sandstone is partially unsaturated below it. These conditions invalidate the use of a Darcy flux- based calculation to estimate travel time from the water table to the Prarie du Chien Group and Jordan Sandstones. Although unsaturated conditions within glacial sediment are known to occur under the regional water table surface, the unconsolidated deposits below the regional water table were considered to be fully saturated for the travel-time calculation.

*Calculation of vertical travel times*

Vertical travel times for both saturated and unsaturated conditions were calculated for each XY location as follows:

$$T = L/((Kv*365* grad\_h)/n)$$

T = vertical time of travel in years

L

for saturated conditions: distance from regional water table to bedrock surface, in feet
for unsaturated conditions: distance from land surface to the regional water table, in feet

Kv = bulk vertical hydraulic conductivity in feet/day

for saturated conditions: mean value of gridpoints from water table to bedrock surface
for unsaturated conditions: mean value gridpoints from land surface to the water table

grad_h

for saturated conditions: difference in elevation between regional water table and bedrock poteniometric surfaces, divided by L, in feet
for unsaturated conditions: set equal to 1

n = effective porosity, set equal to 0.20

Time of travel estimates were calculated for arithmetic, geometric and harmonic means for both saturated and unsaturated conditions, and are included in the XY location dataset.

*Groundwater chemical and isotopic composition*

To evaluate vertical travel time estimates, three ground water chemical types, or hydrochemical facies, were mapped at the regional scale (Tipping et al., 2010): 1. *Recent waters* were distinguished by: a.) the presence of detectable tritium in water well samples. Elevations of these tritium detections were mapped as the land surface elevation minus casing depth; b.) areas within 50 feet of the land surface where the uppermost geologic unit is NW provenance till associated with the Des Moines lobe; c.) areas with sand and gravel at the land surface to a depth not greater than 30 feet below local elevations of the Mississippi and Minnesota Rivers. Conditions (b) and (c) are based on literature values (e.g. Schilling and Tassier-Surine 2006) and site-specific data (Tipping, et. al., 2010) generalized to broad regions having limited chemical data. These criteria resulted in a composite generalized contour map showing the elevation above mean sea level where recent water would be expected to be found (Figure 9). Other indicators of recent water such as the presence of elevated chloride, nitrate, or anthropogenic compounds generally fit within these contours. It should be noted that within the center part of the basin, contours show a bowl shaped presence of recent waters to an elevation of 475 feet. Vintage waters have been found above this elevation within the upper Prairie du Chien Group where it is covered by the Platteville and Glenwood Formations (see Figure 19, cross section F-F'). This condition of younger water underlying older water is expected to be present elsewhere within the TCMAx under similar hydrogeologic conditions; 2. *Waters with distinct cation ratios* were distinguished by having strontium to calcium plus magnesium molar ratios greater than 0.001. These waters are predominantly in the western part of the metro area, with the exception of the Mt. Simon aquifer, where they extend to the central and southeastern parts of the basin

(Figure 10) Elevated strontium to calcium plus magnesium ratios may be associated with recharge through NW provenance tills, and are also considered to an indicator of longer residence time (Eckman and Alexander, 2002); and 3. *Waters with naturally elevated chloride* were distinguished by having chloride levels greater than 15 ppm and carbon 14 age dates greater than 1,000 years. These waters were mapped in the Mt. Simon aquifer only, but are thought to be present in shallow aquifers near major fault zones in the metro area, including the cities of Hastings, Anoka, and Belle Plaine (Figure 11).

**Results**

*Regional maps*

Calculated vertical travel times for saturated and unsaturated conditions range from less than a year to well over 500 years (Figures 12 and 13). Results show differences in near surface and deeper subsurface hydraulic conditions. Anoka County, for example, has short travel times to the regional water table through coarse-grained deposits at the land surface, and long vertical travel times to bedrock, through complex subsurface layering of NE and NW provenance till and sand (see Figure 15, cross section B-B'). Areas in the central metropolitan area with travel times that are faster in saturated conditions than unsaturated result from texture differences between shallow and deeper sediments, and distance differences from the land surface to the water table and water table to bedrock, and areas near the Plateville subcrop edges where the saturated vertical gradient is greater than 1.

Chemical results show recent waters in uppermost bedrock aquifers at elevations generally above 700 feet (Figure 14). Recent waters detected at lower elevations are most often found in high capacity wells and in wells near areas of high capacity pumping. Bedrock aquifers containing highest percentage of recent waters are stratigraphically above the St. Lawrence Formation (Figure 15).

*Regional cross sections*

Physical setting, hydraulic gradient and chemical data are summarized by cross section in Figures 16 through 22. A key for cross section symbols is included in Figure 25. Regional cross sections A-A' through E-E' show variation in chemical types with depth along the general direction of groundwater flow towards regional discharge areas (Minnesota, Mississippi and St. Croix Rivers. Local cross sections F-F' through I-I' illustrate hydrologic conditions that impact groundwater movement.

- Cross section A-A', Sherburne County to Mississippi River (Figure 16). Recent waters interpreted as present in the upper 50 feet of unconsolidated deposits, increasing with depth in the central part of the basin. Lowest elevation of recent waters occurs in the Jordan Sandstone. Carbon 14 dates for Mt. Simon are shown, indicating a sharp contrast in recharge rates for the upper and lower aquifer systems.
- Cross section B-B', St. Francis, Anoka County to Mississippi River (Figure 17). Recent waters interpreted as present in the upper 50 feet of unconsolidated deposits, increasing with depth in the central part of the basin. Lowest elevation of recent waters occurs in the Jordan Sandstone. Complexity of unconsolidated deposits over bedrock, below surficial sands is shown.
- Cross section C-C', Big Marine Lake, Washington County to Mississippi River near downtown St. Paul (Figure 18). Recent waters between Big Marine and White Bear Lake in the Prairie du Chien Group largely based on tritium measurements from samples west and east of the cross section line interpreted as mixed waters (TU between 1 and 10).

Recent water is found at depth towards downtown St. Paul, coincident with a larger downward gradient and coarse unconsolidated deposits over bedrock. Slight upward gradient at White Bear Lake; downward gradient near Big Marine possibly marking groundwater divide, with regional discharge west towards the St. Croix River. Vintage waters in the Mt. Simon aquifer

- Cross section D-D', western Dakota County to Mississippi River near Hastings (Figure 19). Limited data show presence of clay, based on the interpolated model, restrict the downward movement of water west of the South Branch of the Vermillion River. Remainder of the cross section is largely sand and gravel over Prairie du Chien Group. A large buried valley filled with sand and gravel is present west of Hastings. Recent waters within this valley on this cross section based on sampled wells within and on the edges of the valley to the southeast.
- Cross section E-E', southeastern Scott County to Minnesota River near Shakopee Figure 20. Anthropogenic waters absent below cover of alternating NW and NE provenance tills. Elevated strontium to calcium plus magnesium ratios are limited to bedrock valley in upper aquifers and to the Mt. Simon in the lower aquifer. Naturally elevated chloride present in the Mt. Simon at the northeast end of the cross section. Presence of recent water in the Jordan in this area based on sampled wells to the east and west of the cross section line. A strong upward gradient from the Jordan is present near the Minnesota River.

*Local cross sections*

- Cross section F-F' Edina area (Figure 21). Age inversion within the open hole of a single well is shown. Grab samples from the lower portion of the open hole had detectible tritium, while the uppermost sample, located within the Shakopee Formation – Prairie du Chien Group, did not (MDH, 2010). Flow logging from a nearby test well (MN unique well no. 748656) showed strong downflow from the lower Shakopee to the Jordan Sandstone, corresponding to stratigraphic position of detectible tritium in this well. Interpreted stagnation zone of older water illustrated as present underneath the central portion of the Platteville/Glenwood cap.

- Cross section G-G' Eastern Hennepin County (Figure 21). Recent water occurs at depth east of till cover. Flow logging east of Highway 169 showed strong upflow from fractures in the upper Jordan Sandstone to the upper Oneota Formation - Prairie du Chien Group (MN unique well no. 676445.)
- Cross section H-H', south central Washington County to Mississippi River (Figure 22). Stratification of perflourochemical (PFC) detections between Shakopee (upper Prairie du Chien Group) and Jordan samples is shown. Results infer separate flow systems, with possibly greater flux through the Shakopee Formation compared to the Jordan Sandstone.
- Cross section I-I', southeastern Washington County to St. Croix River (Figure 22). Downward gradient over a north-south trending bedrock valley in the center of the cross section, west of Manning Avenue. The valley, filled with primarily coarse-grained material, shows cluster of PFC detections. Occurrence of PFC's near the St. Croix River indicates movement of groundwater through fractures and fault blocks, crossing stratigraphic units with wide ranging permeability.

**Discussion**

The distribution of recent waters in the TCMAx upper bedrock aquifers broadly supports groundwater recharge rates calculated in this investigation. In general, recent waters are found at depth in areas with large vertical gradients and coarse material over bedrock. Furthermore, chemical results support the premise that waters most impacted by activities at the landsurface – "manageable waters" – occur at elevations controlled by regional discharge to the major rivers, and high capacity pumping from the Prairie du Chien and Jordan aquifers or other uppermost bedrock aquifers where these rocks are not present. (Figures 14 and 15).

In southern Washington and central to east central Dakota County, coarse sediments overlie the Prairie du Chien Group. Much of this area is less than 50 feet to bedrock and the water table is largely below the bedrock surface. A large bedrock valley west of Hastings is also filled with coarse sediments. In areas where sufficient data exists, calculated vertical travel times are generally less than a year. Vertical gradients are controlled largely by regional discharge, although high capacity pumping for public water supply, commercial use and irrigation enhance vertical gradients locally.

In central and northern Washington County, relatively recent recharge occurs in areas of sandy NE provenance till over bedrock. Calculated vertical travel times are generally less than one to greater than 50 years depending on the presence of fine-grained sediment in the subsurface. A groundwater divide runs north-south through this portion of the county as water moves either east towards the St. Croix River or southwest towards the Mississippi River. Vertical gradients are controlled largely by regional discharge. Recent waters are found at elevations below regional discharge in east central and southeastern Washington County, where high capacity pumping increases vertical gradients locally.

Northeastern Washington, western Chisago and eastern Anoka and Northern Ramsey Counties have calculated vertical travel times generally greater than 500 years, largely due to the presence of fine-grained NW provenance tills and lacustrine sediment in the subsurface combined with a low vertical gradient. In western Anoka County, calculated vertical travel times are less, where the subsurface is composed of a greater percentage of coarse-grained sediments. Further west into Sherburne County, predominantly coarse grained sediments over bedrock result in calculated vertical travel times of less than a year. Recent waters are generally found only at shallower depths. Elevated strontium to calcium plus magnesium waters are limited to deeper aquifers in the central metro area, indicating diminished NW provenance till signature in recharge waters within these counties.

Where sufficient data exists, western Hennepin, Wright, Carver and Scott Counties generally have calculated vertical travel times of greater than 500 years. In these areas, a thick succession of NW and NE provenance tills and minimal vertical gradient restrict the downward movement of groundwater to bedrock. Water samples from bedrock wells below these tills have no detectible tritium, low chloride, and elevated strontium to calcium plus magnesium ratios, all indicative of older water receiving minimal recharge from the land surface. In northeastern Hennepin County, water chemistry changes to more recent waters at depth, concomitant with a thinning and replacement of NW provenance till by coarse-grained terrace deposits along the Mississippi River. Calculated vertical travel times in the area are generally less than 50 years.

Eastern Hennepin and Southern Ramsey County generally have calculated vertical travel times of less than a year, with the exception of areas where fine-grained material is present in the subsurface. Recent waters are found at elevations below regional discharge where high capacity pumping increases vertical gradients locally. These areas have the largest downward vertical gradients in the metropolitan area, in large part due to the presence of the Platteville and

Glenwood Formations, along with remnants of Decorah Shale above them. Recognizing that much of the water table is perched within and above these formations, seasonal changes in the bedrock potentiometric surface based on synoptic measurements in March and August clearly demonstrate the influence of high capacity pumping on vertical gradient in these areas (Figure 7).

In eastern Hennepin and southern Ramsey County and elsewhere, recent waters are found at depth in areas with large vertical gradients and coarse material over bedrock. These areas are commonly located in bedrock valleys which provide important "windows" to lower aquifers where upper bedrock aquitards are absent. Data provided in this investigation show that not all bedrock valleys are filled with coarse material. Texture-based hydraulic conductivity estimates stored in a regular three dimensional grid format should help with groundwater modeling across these bedrock valleys.

Much effort has been dedicated over the past decade to characterize water bearing characteristics of aquifers and aquitards in the Paleozoic rocks found in the Twin Cities area and elsewhere (Bradbury and Runkel, 2011). While advances have been made in our understanding of horizontal fractures, we are just beginning to understand and document the role of vertical fractures in these systems (e.g. Meyer et al., 2008; Anderson et al., 2011; Runkel et. al, this study). Elevations of detectable tritium in the central part of the basin are lower than regional discharge elevations. Flow log and borehole video data provide evidence for rapid downward flow in multi-aquifer test wells located near municipal well fields. Less well documented, but likely just as important is downward flow through vertical fractures (Hart, 2006). In both cases, increased vertical gradients caused by hi-capacity pumping create conditions for rapid migration of water in the vertical direction. The implications of enhanced vertical recharge to the municipal recharge municipal wellfields are two-fold. Wells that are receiving enhanced vertical recharge can be expected to be good suppliers of water in the future because the aquifer recharges rapidly compared to wells that are primarily receiving lateral recharge. However these same wells are more susceptible to surface contamination within wellhead protection areas, at rates likely faster than those predicted by conventional groundwater modeling.

**Suggested use**

Project deliverables were designed to provide water planners with both regional and site specific data for understanding groundwater flow in a geographic information systems (GIS) environment. Distribution of subsurface textures in unconsolidated deposits and associated ranges of hydraulic conductivity are supplemented by site-specific hydraulic conductivity data collected over a wide range of scales provide information on permeability; Hydrochemical facies mapping supplemented with site specific analytical results provide information on groundwater flow paths and residence times. To illustrate these features, an example of suggested use is presented for a groundwater contamination site in central Hennepin County.

Trichloroethene (TCE) contaminant plumes for 1990 and 2009 at the Honeywell site along with site specific measurements of horizontal hydraulic conductivity are shown in Figure 23a (MACTEC, 2010). The change in plumes from 1990 to 2009 shows plume migration with time to the east. The same plumes are shown in Figure 23b, along with texture-based estimates of vertical hydraulic conductivity from the regional Quaternary subsurface dataset. In both figures, lower hydraulic conductivity values area shown in blue, intermediate values in green and higher values in yellow. Lower hydraulic conductivity values to the southeast are visible in both the site specific and regional data.

Regional subsurface data for unconsolidated deposits, expanded out from the site, show the distribution of subsurface textures in the broader context of regional geology. Low permeability clay loam sediments are present northwest of the site at the land surface, while layers of clay loam to sandy clay loam and sand are present southwest of the site in the subsurface (Figure 24a). Expanding further out from the site, the change from fine-grained textures to the west to coarse-grained textures, including a largely sand filled bedrock valley to the east is visible Figure 24b. The addition of hydrochemical facies shows the distribution of recent waters in this area (Figure 24c). Recent waters are found in the shallow subsurface to the northwest, extending deeper into the bedrock valley southwest of the site. Further details are provided both by gridpoints, where till textures are separated by provenance, and in site specific datasets for both hydraulic conductivity and water chemistry from individual measurements can be added as GIS layers (Tipping et al., 2010).

At local and regional scales, project deliverables improve groundwater model calibration by helping to refine conceptual models of groundwater flow. Residence time data, reflected in the distribution of vertical recharge to upper bedrock aquifers, can be used to guide interpretation of calibration results as an alternative to calibration strictly by head values alone. These steps can result in a more realistic distribution of hydraulic conductivity parameters in numeric models.

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Appendix A., Table 1 hydraulic conductivity values for subsurface textures.

Corresponds to field “K_composite” in gridpoint. code specifies range of expected hydraulic conductivity in feet/day. Reference to “deep” in codes 8-11 are for point depths greater than 60 feet from land surface, estimated to be 2 orders of magnitude lower hydraulic conductivity than equivalent textures in shallow settings:

| *code* | *Texture Description* | *Kmax (ft/day* | *Kmin (ft/day)* |
|---|---|---|---|
| 1 | loam to clay loam | 3.0E-3 | 1.0E-3 |
| 2 | loam to sandy loam | 2.0E+1 | 1.0E-1 |
| 3 | loam, silt rich; silt and clay | 2.0E-2 | 3.0E-4 |
| 4 | loam to sandy clay loam | 2.0E+1 | 1.0E-1 |
| 5 | sand and gravel | 5000 | 100 |
| 6 | fine sand | 30 | 0.3 |
| 7 | sandy silt | 3 | 0.1 |
| 8 | loam to clay loam - deep | 3.0E-5 | 1.0E-5 |
| 9 | loam to sandy loam - deep | 2.0E-1 | 1.0E-3 |
| 10 | loam, silt rich; silt and clay - deep | 2.0E-4 | 3.0E-6 |
| 11 | loam to sandy clay loam - deep | 2.0E-1 | 1.0E-3 |

Appendix A., Table 1 Comparison of hydraulic conductivity values for mid-continent tills at various scales.

| Source | Location/till | Texture | Lab (permeameter)tests | Slug tests | Larger scale |
|---|---|---|---|---|---|
| Hooyer and Mode (2008) | Winnebago co Wisc Green Bay Lobe | From Rodenbeck (1988)<br>Kirby Lk: S 28%, Sl 44%, Cl, 29%<br>Middle Inlet; S 18%, Sl 47%, Cl, 35% | $10^{-4}$ ft/day | $10^{-1}$ to $10^{-2}$ ft/day (suggests fractures) | |
| Simpkins and Bradbury (1992) | "southeastern Wisc till | average S 12%, Sl 53%, Cl, 35% | 1 to 2 orders magnitude less than slug test values | $10^{-3}$ ft/day (fractured) to<br>$10^{-5}$ ft/day (less fractured) | |
| Bradbury and Muldoon (1990) | Eastern wisc tills | UNKNOWN | $10^{-3}$ to $10^{-5}$ ft/day | $10^{-1}$ to $10^{-3}$ ft day | |
| Schilling and Tassier-Surine (2006) | Pre-Illinoian till, Linn County Iowa | average S 44%, Sl 37%, Cl, 19% | none | Geomean $10^{-2}$ ft/day oxidized till<br>Geomean $10^{-4}$ ft/day unoxidized till | |
| Cravens and Ruedisili (1987) | East-central S. Dakota till | average S 21%, Sl 51%, Cl 28% | none | Avg. $2.1\times10^{-2}$ ft/day (oxidized)<br>Avg. $1.1\times10^{-3}$ ft/day (unoxidized) | |
| McKay, Cherry, Gillham (1993) | SW Ontario Till | Greater than 25% clay | $10^{-5}$ to $10^{-6}$ ft/day | $10^{-5}$ to $8\times10^{-2}$ ft/day (fractured till)<br>(also summarize "other" Canadian sites with fractured tills as btw $10^{-3}$ to $10^{-1}$ ft/day) | Field trench 5m (deep) by 7m (wide)<br>~$6\times10^{-2}$ ft/day |
| Gerber et al. (2001) | Ontario till | "Sandy-silt" till | | ~$1.4 \times 10^{-4}$ ft/day | Water chemistry & modeling indicate Kh 1 to 2 orders magn. > than slug test K. Max.bulk vertical K estimate is $10^{-4}$ ft/day |
| Tipping el al. (2010) | Des Moines Lobe<br>11 county Twin Cities Metro | average S 42%, Sl 37%, Cl, 21% | Avg $8.6 \times10^{-2}$ ft/day<br>Geom $8 \times10^{-4}$ ft/day<br>n= 32 | Avg $4.2 \times 10^{-1}$ ft/day<br>Geom $5.3 \times10^{-2}$ ft/day<br>n= 17 | |
| Tipping et al., (2010) | Superior Lobe<br>11 county Twin Cities Metro | average S 62%, Sl 26%, Cl, 12% | Avg $2.3 \times10^{-2}$ ft/day<br>Geom $1.2 \times 10^{-3}$ ft/day<br>n= 21 | Avg $7.3 \times10^{-1}$ ft/day<br>Geom $1.6 \times 10^{-1}$ ft/day<br>n= 30 | |

Appendix A., Table 3 Summary of horizontal and vertical hydraulic conductivity values by method (Tipping et al., 2010)

Hydraulic Conductivity - horizontal (ft/day)

| *method/hydro_class* | | n | mean | min | max | geomean |
|---|---|---|---|---|---|---|
| **Grain size** | description | | | | | |
| 1 | loam to clay loam | 1155 | 2.37E-01 | 2.83E-05 | 5.45E+00 | 9.64E-02 |
| 2 | loam to sandy loam | 325 | 1.26E+00 | 2.78E-03 | 1.42E+01 | 5.70E-01 |
| 3 | loam, silt rich; silt and clay | 79 | 3.45E-01 | 8.57E-03 | 3.35E+00 | 1.39E-01 |
| 4 | loam to sandy clay loam | 37 | 1.35E+00 | 8.85E-02 | 3.42E+00 | 1.02E+00 |
| 5 | sand and gravel | 168 | 5.47E+01 | 2.83E-02 | 3.09E+02 | 1.92E+01 |
| 6 | fine sand | 32 | 4.81E+00 | 5.84E-05 | 3.69E+01 | 1.61E-01 |
| 7 | sandy silt | 38 | 5.65E-01 | 1.42E-04 | 1.13E+01 | 2.42E-02 |
| **Lab Permeameter** | | | | | | |
| 5 | sand and gravel | 3 | 2.34E+00 | 4.30E-01 | 4.50E+00 | 1.60E+00 |
| **Aquifer test** | | | | | | |
| 5 | sand and gravel | 118 | 1.17E+02 | 4.82E-01 | 4.15E+02 | 6.53E+01 |
| **Slug test** | | | | | | |
| 1 | loam to clay loam | 17 | 3.87E-01 | 5.67E-04 | 3.83E+00 | 2.80E-02 |
| 2 | loam to sandy loam | 34 | 2.27E+00 | 2.83E-03 | 4.30E+01 | 2.00E-01 |
| 3 | loam, silt rich; silt and clay | 7 | 1.43E-02 | 7.65E-05 | 9.35E-02 | 7.74E-04 |
| 5 | sand and gravel | 215 | 3.98E+01 | 5.00E-03 | 5.40E+02 | 8.07E+00 |
| 6 | fine sand | 14 | 3.91E+00 | 1.42E-03 | 2.61E+01 | 5.11E-01 |
| 7 | sandy silt | 18 | 2.49E+01 | 1.40E-01 | 1.50E+02 | 5.54E+00 |
| **Specific Capacity - excluding CWI** | | | | | | |
| 5 | sand and gravel | 17 | 40.7294 | 1.5 | 152 | 2.66E+01 |

Hydraulic Conductivity - vertical (ft/day)

| *method* | | n | mean | min | max | geomean |
|---|---|---|---|---|---|---|
| **Lab Permeameter - constant head** | | | | | | |
| 1 | loam to clay loam | 17 | 1.68E-01 | 6.24E-05 | 2.83E+00 | 7.26E-04 |
| 5 | sand and gravel | 51 | 7.79E+00 | 4.82E-05 | 1.11E+02 | 1.69E+00 |
| 6 | fine sand | 2 | 1.70E+00 | 1.50E+00 | 1.90E+00 | 1.69E+00 |
| 7 | sandy silt | 9 | 8.55E-01 | 8.50E-04 | 5.67E+00 | 8.88E-02 |
| **Lab Permeameter - falling head** | | | | | | |
| 1 | loam to clay loam | 37 | 7.14E-02 | 2.83E-06 | 1.98E+00 | 2.19E-04 |
| 2 | loam to sandy loam | 14 | 2.45E-01 | 1.98E-05 | 3.40E+00 | 9.81E-04 |
| 3 | loam, silt rich; silt and clay | 4 | 1.94E-04 | 6.80E-05 | 3.97E-04 | 1.55E-04 |
| 5 | sand and gravel | 4 | 4.27E-01 | 6.80E-03 | 1.13E+00 | 1.22E-01 |
| 6 | fine sand | 1 | 2.35E-01 | 2.35E-01 | 2.35E-01 | 2.35E-01 |
| 7 | sandy silt | 31 | 1.07E-01 | 9.35E-06 | 1.64E+00 | 1.73E-03 |
| **Aquifer test** | | 3 | | | | |
| 5 | sand and gravel | 3 | 6.76E+01 | 7.00E-01 | 1.01E+02 | 1.93E+01 |

**Appendix B.** Point data geodatabase structure.

**Geodatabase Name: PointData.mdb (personal geodatabase)**

*Spatially enabled data tables*

| **Name** | **Description** |
|---|---|
| C_complete | Water chemistry, complete dataset. 1 row for each sample event |
| C_indx | Water chemistry, index summary data, linked to subsets of C_complete (tables with name beginning 'Csub') by field "relate_date" |
| K_complete | Hydraulic conductivity, complete dataset. 1 row for each measurement |
| K_indx | Hydraulic conductivity, index summary data, linked to subsets of K_complete (tables with name beginning 'Ksub') by field "seqno" |

*Subset data tables*

| **Name** | **Description** |
|---|---|
| Csub_age | Subset of water chemistry containing interpreted age and supporting data |
| Csub_agency_program | Subset of water chemistry containing agency and program information associated with water sample |
| Csub_field_parameters | Subset of water chemistry containing field parameter data |
| Csub_goodchargebalance | Subset of water chemistry containing samples with charge balance error less than 5% |
| Csub_isotopes | Subset of water chemistry containing samples with stable or radiogenic isotope data |
| Csub_majorcations_anions | Subset of water chemistry containing major cation and anion data. Strontium, barium, and choride concentrations included here because of their use for data interpretation. |
| Csub_PFCs | Subset of water chemistry containing PFC data from Washington County and portions of Ramsey and Dakota County, assembled by the Minnesota Department of Health |
| Ksub_data | Subset of hydraulic conductivity containing summary information |
| Ksub_specific_capacity | Subset of hydraulic conductivity containing data used to calculate hydraulic conductivity from specific capacity data |
| Ksub_texture | Subset of hydraulic conductivity containing texture information, if available, associated with K measurement. |

*Lookup tables*

| **Name** | **Description** |
|---|---|
| xAGENCY | Corresponds to field "agency," code specifies agency or organization that administers progam under which data was collected or managed:<br>C02 Anoka County |

| | |
|---|---|
| | C19 Dakota County<br>C82 Washington County<br>DNR MN Department of Natural Resources<br>DOT MN Department of Transportation<br>MDA MN Department of Agriculture<br>MDH MN Department of Health<br>METC Metropolitan Council<br>MWCC Metropolitan Waste Control Commission<br>PCA Mn Pollution Control Agency<br>UMN University of Minnesota<br>USEPA U.S. Environmental Protection Agency<br>USGS United States Geological Survey |
| xAQUIFER_THCK_MC | Corresponds to field "aquifer_thck_ft_mc," code specifies method used to establish aquifer thickness, in feet – used to calculate horizontal hydraulic conductivity from transmissivity values:<br><br>OH equal to open hole/screen length<br>EST estimated from cross section or other |
| xDATA_REFERENCE | Corresponds to field "agency_prg," which is a concatenation of fields "agency" and "program." For water chemistry data, this field uniquely identifies source of agency/program that collected or managed the data: |
| xDEPTH_MC | Corresponds to field "depth_mc," code specifies method used to establish depth of borehole or well:<br>EST Estimated from cross section or other |
| xELEV_MC | Corresponds to field "elev_mc," code specifies method used to establish land surface elevation of sample/test location:<br><br>A Altimeter (+/- 1 foot)<br>G GPS (Global Positioning System / satellite)<br>H GPS >12M (> +- 40')<br>I GPS 3-12M (+- 10-40')<br>J GPS 1-3M |

| | |
|---|---|
| | K GPS <= 1M<br>RV report value<br>S Surveyed<br>T 7.5 minute topographic map (+/- 5 feet)<br>T2 Calc from DEM (USGS 7.5 min or equiv.)<br>T3 Calc from County 2 ft. DEM |
| xGCMCODE | Corresponds to field "gcm_code," code specifies method used to establish sample/test location:<br>A Digitized - scale 1:24,000 or larger<br>A** Digitized from Washington Co. 1/2 section maps, verified by County Survey GPS<br>B Digitized - scale 1:100,000 to 1:24,000<br>DS1 Digitization (Screen) - Map (1:24,000)<br>DS2 Digitization (Screen) - Map (1:12,000)<br>G3 GPS Differentially Corrected<br>G6A GPS SA On (averaged)<br>G6O GPS SA Off (averaged)<br>I GPS; accuracy 3 to 12 meters (+ 6 to 40 feet)<br>PQ6 Public Land Survey - QQQQQQ Section<br>RD From report description (estimated error +/- 1000 m)<br>SM digitized from georeferenced site map, accuracy unknown<br>SPL<br>UNK Unknown method |
| xPROGRAM | Corresponds to field "program," code specifies which program within a given agency collected the data:<br><br>*Program* *Agency* *Description*<br>ACHES C02 Anoka County Community Health And Environmental Services<br>CGA MGS Minnesota Geological Survey County Geologic Atlas Part A<br>CLF MPCA Pollution Control Agency Closed Landfill Program<br>CMTS_RA MGS MGS-UMN Mt. Simon Aquifer Radium Study<br>DNEM_MS UMN University Of MN - David Nemetz M.S. Thesis (1993)<br>DOW DNR Dept. of Natural Resources Division Of Waters<br>EM CO19 Dakota County Environmental Management<br>ES METC Metropolitan Council Environmental Services |

| | | | |
|---|---|---|---|
| | GU | MDOT | Dept. of Transportation Geology unit |
| | GWM_04-08 | MPCA | PCA Groundwater Monitoring & Assessment Program, Ambient Data 2004-2008 |
| | GWM_92-96 | MPCA | PCA Groundwater Monitoring & Assessment Program, Baseline Data 1992-1996 |
| | LCMROPDC | MGS | Sampling For LCMR Prairie Du Chien Hydrogeology Project |
| | LFS | MWCC | Metropolitan Waste Control Commission Landfill Study (MICA) |
| | LFS | C27 | Hennepin County Landfill Siting Study - 1980S |
| | METC_NW1 | MGS | Sampling For Metropolitan Council Phase I Study |
| | NAWQA | USGS | USGS National Water Quality Assessment Program |
| | PFC | MDH | Dept. of Health PFC Investigation |
| | PWS | MDH | Dept. of Health Public Water Supply |
| | RTIP_MS | UMN | University Of MN - Robert Tipping M.S. Thesis (1992) |
| | SBUR_MS | UMN | University Of MN - Sandeep Burman M.S. Thesis (1995) |
| | SCA_1 | UMN | University Of MN - Scott Alexander, MN Groundwater Age Data (MNGWAGE.XLS) |
| | SCA_2 | UMN | University Of MN - Scott Alexander, Washington County Data (WASHCODATA.XLS) |
| | SCA_3 | UMN | University Of MN - Scott Alexander, Dakota County Data (DAKOTA3D.XLS) |
| | SF | MPCA | Pollution Control Agency Superfund |
| | SW | MPCA | Pollution Control Agency Solid Waste |
| | T&S | MPCA | Pollution Control Agency Tanks And Spills |
| | UMORE | UMN | University Of MN - UMORE Park Groundwater Assessment June 30, 2009 |
| | WHP | MDH | Dept. of Health Wellhead Protection |
| xREPORT_REFERENCES | Corresponds to field "report_ref," contents specify author and year associated with data: | | |
| | Alexander, 2010a | | Alexander, S.C., 2010a, Minnesota groundwater age data, University of Minnesota Hydrogeochemistry Laboratory, written communication |
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| xSITE_CONDITIONS | Corresponds to field "site_conditions," contents specify structural or true thickness conditions | |
| | E | Indicates bedrock unit at site is considered “eroded” |
| | M | Indicates bedrock unit at site is on monocline |
| xSITE_NAME | Corresponds to field “site_name”, contents specify name of site from which K values were derived: | |
| | FMGW | Former Minneapolis Gas Works |
| | GMEH | General Mills/East Hennepin Avenue |
| | KC | Koppers Coke |
| | LTS | Lindbergh Terminal Station |
| | MEI | Minneapolis East Interceptor |
| | MLAC | Minnesota Library Access Center |
| | MPT | Minnehaha Park Tunnel |
| | ODS | Oakdale Disposal |
| | RTC | Reilly Tar and Chemical |
| | SP | Superior Plating |

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| | U of M University of Minnesota east and west bank monitor wells |
| xTDS_MC | Corresponds to field "tds_mc," contents specify method used to determine total dissolved solids:<br>EV residue on evaporation |
| xTEST_MC | Corresponds to field "test_mc," contents specify method used to measure transmissivity/hydraulic conductivity:<br><br>BD borehole dilution test<br>CH constant head<br>FLMC flowmeter inject/pump - constant head<br>FSFH field falling head slug test<br>FSRH field rising head, includes slug tests and baildown tests<br>FSU Field Slug Test Unspecified<br>GP Guelph permeameter<br>GSE grain-size estimate<br>GSE_A grain-size estimate assumed based on report<br>LBH laboratory backpressure or consolidometer, horizontal<br>LBU laboratory unspecified<br>LBV laboratory backpressure or consolidometer, vertical<br>LCH laboratory constant head, orientation unknown<br>LCHH laboratory constant head, horizontal<br>LCHV laboratory constant head, vertical<br>LFH laboratory falling head, orientation unknown<br>LFHH laboratory falling head, horizontal<br>LFHV laboratory falling head, vertical<br>LKG Leakage into excavation beneath Platteville<br>LRH laboratory rising head, orientation unknown<br>LRHH laboratory rising head, horizontal<br>LRHV laboratory rising head, vertical<br>MPDP Philip-Dunne permeameter<br>OTH other<br>PPPT packer pressure test – discrete interval<br>PTD pumping test - discrete interval |

| | | |
|---|---|---|
| | PTE | pumping test - entire open hole |
| | PTE_A | pumping test - entire open hole assumed |
| | SPC | calculated from specific capacity |
| | UNK | unknown |
| xUNIT_TESTED | Corresponds to field "unit_tested," contents specify unit tested, most often as described in report: | |
| | AE | aeolian (wind blown) |
| | Al, ? | Alluvium, and another unknown component |
| | Al, C | Alluvium, coarse |
| | Al, F | Allumvium, fine |
| | Al, F | Alluvium, fine, deeply buried |
| | Al, F/M | Alluvium, fine to medium |
| | Al, M | Alluvium, medium |
| | Al, M, Lac | Alluvium, medium, lacustrine |
| | Al, mixed | Alluvium, variable grain size |
| | CFRN | Franconia Formation (Tunnel City Group) |
| | CJDN | Jordan Sandstone |
| | CMTS | Mt. Simon Sandstone |
| | CSLF | St. Lawrence and Franconia (Tunnel City Group) Formations, undivided |
| | CR | Decorah Shale, Carimona Member |
| | CRMG | Carimona (Decorah Shale) and Magnolia (Platteville) members |
| | FLOAT | Large block of limestone within unconsolidated quaternary sediment |
| | GF | Glaciofluvial |
| | HF | Platteville Formation, Hidden Falls member |
| | HFL | Platteville Formation, Hidden Falls member, likely lower part |
| | HFMF | Platteville Formation, Hidden Falls and Mifflin members |
| | HFMFPC | Platteville Formation, Hidden Falls, Mifflin, and Pecatonica members |
| | HFMP | Platteville Formation, Hidden Falls, Mifflin, and possibly Pecatonica members |
| | IC | Ice contact (heterolithic) |
| | Lac | Lacustrine |
| | Lac/Ow? | Lacustrine and/or outwash |
| | Lac?/Ow | Lacustrine and/or outwash; move "buried" to secondary unit tested column |
| | ML in outwash | inorganic silt in outwash |
| | MF | Platteville Formation, Mifflin member |

| | | |
|---|---|---|
| | MFL | Platteville Formation, Mifflin member, likely lower part |
| | MFPC | Platteville Formation, Mifflin and Pecatonica members |
| | MFU | Platteville Formation, Mifflin member, likely upper part |
| | MG | Platteville Formation, Magnolia member |
| | MGHF | Platteville Formation, Magnolia and Hidden Falls members |
| | MGHFMP | Platteville Formation, Magnolia, Hidden Falls, Mifflin and possibly Pecatonica members |
| | MGL | Platteville Formation, Magnolia, likely lower part |
| | MP | Platteville Formation, Mifflin and possibly Pecatonica members |
| | OGWD | Glenwood Formation |
| | OPCJ | Prairie du Chien Group and Jordan Sandstone |
| | OPDC | Prairie du Chien Group |
| | OPDC, middle | Prairie du Chien Group, middle |
| | OPDC, shallow | Prairie du Chien Group, shallow |
| | OPDC, upper | Prairie du Chien Group, upper |
| | OPVL | Platteville Formation, undifferentiated |
| | OSTP | St. Peter Sandstone |
| | OSTP? | questionable St. Peter Sandstone |
| | Ow | Outwash |
| | Ow, surficial | Outwash, surficial unit |
| | Ow, buried | Outwash, buried by possible aquitard |
| | Ow, buried, and CSLF | Outwash, buried by possible aquitard, and St. Lawrence and Franconia (Tunnel City Group) Formations, undivided |
| | Ow, buried, and CSLF | Outwash, buried by possible aquitard, and St. Lawrence and Franconia (Tunnel City Group) Formations, undivided |
| | Ow, buried, lower | Outwash, buried by possible aquitard, referred to as lower at site |
| | Ow, buried, lowest | Outwash, buried by possible aquitard, referred to as lowest at site |
| | Ow, buried, upper | Outwash, buried by possible aquitard, referred to as upper at site |
| | Ow, IC | Outwash and ice contact |
| | Ow, lower | Outwash, referred to as lower at site |
| | Ow, ML lenses | Outwash and inorganic silt lenses |
| | Ow, Mo | Outwash and moraine |
| | Ow, surficial | Outwash, surficial unit |
| | Ow, surficial and T | Outwash, surficial unit and till |
| | Ow, surficial and T | Outwash, surficial unit and till |

| | | |
|---|---|---|
| | Ow, T | Outwash and till |
| | Ow, T, Ow | Outwash and till |
| | Ow, upper | Outwash, referred to as upper at site |
| | Ow, upper and Lac | Outwash, referred to as upper at site, and lacustrine |
| | Ow, upper and T | Outwash, referred to as upper at site, and till |
| | Ow, upper and Lac | Outwash, referred to as upper at site, and lacustrine |
| | Ow, upper and T | Outwash, referred to as upper at site, and till |
| | P | Peat |
| | Pal | Palustrine |
| | Peat | Peat |
| | SOIL | Soil |
| | Sw | Swamp |
| | T | Till |
| | T, lower | Till, referred to as lower at site |
| | T, middle | Till, referred to as middle at site |
| | T, Ow | Till and outwash |
| | T, Ow, buried | Till and outwash that is likely buried beneath aquitard |
| | T, Ow, middle | Till and outwash, referred to as middle at site |
| | T, reworked | Till that is reworked |
| | T, surficial | Till, surficial unit |
| | T, upper | Till, referred to as upper at site |
| | T/Ow | Till and or outwash |
| | T? | Questionable till |
| | TOP | Topsoil |
| | Ow, surficial | Outwash, surficial unit |
| | TV | Tunnel Valley deposits |
| | UNK | unknown |
| xUNIT_TESTED_ADDL | Corresponds to field "unit_tested_addl," contents specify additional information about tested interval: | |
| | DESM_M | Des Moines lobe sediment, from MGS Qstrat models |
| | SUP_M | Superior lobe sediment, from MGS Qstrat models |
| | deep glacial unit | as referred to in report |
| | Anoka SP | Anoka Sand Plain |

| | | |
|---|---|---|
| | at water table | at water table |
| | Bedrock St. Peter Sandstone | Bedrock is St. Peter Sandstone |
| | brown | brown |
| | Brown-Grey fine to coarse sand with gravel | Brown-gray fine to coarse sand with gravel |
| | Brown-Grey silty fine to coarse sand, some gravel | Brown-gray silty fine to coarse sand, some gravel |
| | Brown-Yellow Sandy silt trace gravel and clay | Brown-yellow sandy silt trace gravel and clay |
| | buried Lacustrine | buried refers to possible burial beneath aquitard |
| | buried to not buried | buried refers to possible burial beneath aquitard |
| | buried to not buried, SUP Ow | buried refers to possible burial beneath aquitard |
| | buried?? | buried refers to possible burial beneath aquitard |
| | Clay | Clay |
| | coarse to gravelly sand | coarse to gravelly sand |
| | cobbles | cobbles |
| | Des Moines Lobe Outwash | Des Moines lobe outwash |
| | DESM | Part of Des Moines lobe deposition |
| | DESM Red, Fine | Part of Des Moines lobe deposition, red, fine |
| | DESM, grey | Part of Des Moines lobe deposition, gray |
| | DESM/SUP mix | DESM= Mix of Des Moines and Superior lobe deposition |
| | DESM? Unit B1 | as referred to in report; part of Des Moines lobe deposition fine |
| | sand | fine sand |
| | fine-coarse sand | fine-coarse sand |
| | fine-med sand | fine-med sand |
| | Fridley Fm | as referred to in report |
| | G, S | Gravel and sand |
| | Grey | Gray |
| | Hillside sand | as referred to in report |
| | intermediate depth | as referred to in report |
| | just above bedrock | as referred to in report |
| | Lite Brown silty fine to coarse sand, little gravel | Lite brown silty fine to coarse sand, little gravel |
| | Loess? | Loess? |
| | Lower Aquifer | as referred to in report |
| | Lower Confining Unit; SUP till and Ow | as referred to in report; part of Superior lobe deposition Lower Old |
| | Gray Till | as referred to in report |
| | Lower Sand Aquifer unit | as referred to in report |

| | | |
|---|---|---|
| | LS, some G | Loamy sand?, gravel |
| | med sand, gravel | med sand, gravel |
| | med sand,gravel | med sand, gravel |
| | Middle Aquifer | as referred to in report |
| | most of OPDC is open-hole | most of OPDC is open-hole |
| | Old gray outwash horizon No. 1 / Upper old Gray Till/ Old Gray Outwash Horizon No. 2 | as referred to in report |
| | Old gray outwash Horizon no. 2 | as referred to in report |
| | Old Gray Outwash no. 4 | as referred to in report |
| | Old gray outwash no.1 / upper old gray till / Old gray outwash Horizon no. 2 | as referred to in report |
| | perhaps Till | perhaps till |
| | River Falls Outwash | as referred to in report |
| | S, LS, G | Sand, loamy sand, gravel |
| | S, minor LS | Sand, minor loamy sand |
| | S,G | sand, gravel |
| | S,G, some LS | sand, gravel, some loamy sand |
| | S,G,S-Cr | sand, gravel, coarse sand |
| | S-Cr | sand, coarse sand |
| | SL-F, G | fine loamy sand, gravel |
| | SM | silty sand |
| | SUP | part of Superior lobe deposition |
| | SUP mostly | mostly part of Superior lobe deposition |
| | SUP ow, Unit C | as referred to in report; part of Superior lobe deposition SUP, |
| | middle till | as referred to in report; part of Superior lobe deposition |
| | SUP, Unit B2 | as referred to in report; part of Superior lobe deposition |
| | Till Mantle Unit Tested | as referred to in report |
| | Twin Cities Fm | as referred to in report |
| | Upper Aquifer Unit | as referred to in report |
| | Upper Aquifer Unit, Anoka SP | as referred to in report; Anoka SP=Anoka Sand Plain |
| | Upper Confining Unit (DESM)/ Middle Aquifer | as referred to in report; part of Des Moines lobe deposition |
| | Upper Confining Unit; DESM | as referred to in report; part of Des Moines lobe deposition |
| | Upper Old Gray Till | as referred to in report |

| | |
|---|---|
| xUSCS_CODE | Corresponds to field "uscs_code," contents specify Unified Soil Classification System code:<br><br>CH inorganic clay, liquid limit greater than 50<br>CL inorganic clay, liquid limit less than 50<br>GC clayey gravel<br>GM silty gravel<br>GP poorly-graded gravel<br>GW well-graded gravel<br>MH inorganic silt, liquid limt greater than 50<br>ML inorganic silt, liquid limit less than 50<br>OH organic clay<br>OL organic silt<br>PT peat<br>SC clayey sand<br>SM silty sand<br>SP poorly graded sand<br>SW well-graded sand |
| xVALUE_MINMAX | Corresponds to field "minmax," contents specify if K value is a minimum or maximum value<br>< indicates K value is a maximum value<br>> indicates K value is a minimum value |

**Appendix C.** Water Chemistry and Hydraulic Conductivity field names and descriptions

**Geodatabase Name: PointData.mdb (personal geodatabase)**

***Water chemistry table: C_complete*** *(note: detection and uncertainty fields are not listed. Blank in fieldname_det - reported concentration is the measured value; "<" - reported concentration is the detection limit; Blank in fieldname_unc – uncertainty unknown. Unless otherwise noted, fieldname _unc reported in same units as fieldname, error estimate - larger of 1. Predicted standard deviation, 2. Measured standard deviation).*

| **Field Name** | **Description** |
|---|---|
| relateid | CWI unique identifier |
| unique_no | Minnesota unique well number |
| wellname | Well name. Info from CWI if available |
| alt_id | Alternate identifier, e.g. field sample number |
| mpca_ambient_id | MPCA Ambient Groundwater Monitoring Identifier |
| mpca_EDA_id | MPCA Environmental Data Access Identifier |
| mdh_PWSID | MDH Public Water Supply Identifier |
| agency | Agency |
| program_id | Agency program associated with sample event |
| sample_date | date of sample collection as text in format yyyymmdd where equivalent sample_date2 available |
| sample_date2 | date of sample collection as date/time field |
| cond_TC25 | specific conductance of sample corrected to 25 degrees Celsius and reported as microsiemens per centimeter |
| cond | specific conductance of sample reported as microsiemens per centimeter - may or may not be corrected for temperature. |
| temp_c | temperature in degrees Celsius, assumed to be at time of sampling unless noted otherwise in remarks |
| pH | Negative log of hydrogen concentration |
| ORP | Eh: oxidation-reduction potential referenced to standard hydrogen electrode, in millivolts |
| ORP2 | oxidation-reduction potential relative to the silver:silver chloride reference electrode, in millivolts |

| | |
|---|---|
| DO | dissolved oxygen concentration in milligrams per liter |
| DO_units | A few DO analyses reported as percent atmospheric, indicated by "%" in this column |
| TOC | total organic carbon in milligrams per liter |
| Ca | calcium concentration in milligrams per liter |
| Mg | magnesium concentration in milligrams per liter |
| Na | sodium concentration in milligrams per liter |
| K | potassium  concentration in milligrams per liter |
| Na_K | sodium plus potassium concentration in milligrams per liter - (used in Hall and others, 1911) |
| Fe | iron concentration in milligrams per liter |
| Mn | manganese concentration in milligrams per liter |
| Sr | strontium concentration in milligrams per liter |
| Ba | barium concentration in milligrams per liter |
| P | phosphorous concentration in milligrams per liter |
| Al | aluminum concentration in milligrams per liter |
| Si | silicon concentration in milligrams per liter as SIO2 - assumed |
| TOTS | Total sulfur concentration in milligrams per liter as sulfur |
| TOTP | total phosphorous concentration in milligrams per liter as phosphorous |
| Alk_CaCO3 | total alkalinity of the solution reported as calcium carbonate in milligrams per liter |
| Cl | chloride concentration in milligrams per liter |
| SO4 | sulfate concentration in milligrams per liter |
| S2O3 | thiosulfate concentration in milligrams per liter |
| Br | bromide concentration in milligrams per liter |
| F | fluoride concentration in milligrams per liter |
| NO3_N | nitrate concentration in milligrams per liter reported as nitrogen |
| NO2_NO2_asN | nitrite concentration in milligrams per liter reported as nitrogen |
| TOTN | Total nitrogen (nitrate + nitrite + ammonia + organic-N) in milligrams per liter |
| NH3_N | Ammonia concentration in milligrams per liter as nitrogen |

| | |
|---|---|
| NH3_OrgN_N | Ammonia plus organic nitrogen concentration in milligrams per liter reported as nitrogen |
| NH4 | Ammonium concentration in milligrams per liter |
| ORTHO_PO4_P | orthophosphate concentration in milligrams per liter reported as phoshorus |
| PO4_P | phosphate concentration in milligrams per liter reported as phosphorus |
| TOTAL_CATIONS | total cations in milli-equivalents per liter |
| TOTAL_ANIONS | total anions in milli-equivalents per liter |
| PERCENT_ERR | charge balance percent error |
| TDS | total dissolved solids in milligrams per liter |
| TDC_MC | Total dissolve solids method code, "EV" indicates residue on evaporation |
| deuterium | deuterium isotope (per mil) |
| oxygen_18 | oxygen 18 isotope (per mil) |
| sulfur_34 | sulfur 34 isotope (per mil) |
| Gross_Alpha | gross alpha concentration in picocuries per liter |
| Polonium | polonium concentration in picocuries per liter |
| Rn_det | |
| Rn | radon concentration in picocuries per liter |
| Ra226_det | |
| Ra226 | radium 226  concentration in picocuries per liter |
| Ra228_det | |
| Ra228 | radium 228  concentration in picocuries per liter |
| U_det | |
| U | uranium  concentration in micrograms per liter |
| U234_U238 | uranium 234 to uranium 238 activity ratio |
| U238_U234 | uranium 238 to uranium 234 activity ratio |
| H3_det | |
| tritium | tritium concentration in tritium units (TU) |
| H3_err | tritium error (precision) |
| C14_PMC | carbon-14 reported as percent modern carbon |
| C14_PMC_unc | reported one sigma counting error |

| | |
|---|---|
| C14_corr | carbon-14 corrected, reported as percent modern carbon |
| C14_corr_unc | |
| C13 | carbon-13 (per mil) |
| soil_dC13_C12 | |
| Methane_dC13_C12 | |
| SF6 | sulfur hexafluoride concentration in femtograms per kilogram |
| CFC | Chlorofluorocarbon |
| Years_modifier | modifier, less than (<) or greater than (>) |
| Years | Model estimated age in years |
| Years_unc | Model estimated age uncertainty in years |
| age_Model | Name of model used to estimate age (C14; H3/He; SF6; CFC; other) |
| age_class | age class |
| age_basis | basis for age class |
| PFOs_det | |
| PFOS | perfluorchemicals: perfluorooctonate sulfate concentration in micrograms per liter |
| PFOA_det | |
| PFOA | perfluorchemicals: perfluorooctanoic Acid concentration in micrograms per liter |
| PFBA_det | |
| PFBA | perfluorchemicals: perfluorooctanoic Acid concentration in micrograms per liter |
| PFBS_det | |
| PFBA | perfluorochemicals: perfluorobutanoic acid concentration in micrograms per liter |
| PFBS_det | |
| PFBS | perfluorochemicals: perfluorobutane sulfonate concentration in micrograms per liter |
| PFHxA_det | |
| PFHxA | perfluorochemicals: perfluorohexanoic acid concentration in micrograms per liter |
| PFHxS_det | |

| | |
|---|---|
| PFHxS | perfluorochemicals: perfluorohexanesulfonate concentration in micrograms per liter |
| PFPeA_det | |
| PFPeA | perfluorochemicals: perfluoropentanoic acid concentration in micrograms per liter |
| Acetate_det | |
| Acetate | organic acid: acetate concentration in milligrams per liter |
| Lactate_det | |
| Lactate | organic acid: lactate concentration in milligrams per liter |
| Chlorate_det | |
| Chlorate | organic acid: chlorate concentration in milligrams per liter |
| Formate_det | |
| Formate | organic acid: formate concentration in milligrams per liter |
| Oxalate_det | |
| Oxalate | organic acid: oxalate concentration in milligrams per liter |
| utme | Universal Transverse Mercator easting, UTM zone 15 extended, NAD83 |
| utmn | Universal Transverse Mercator northing, UTM zone 15 extended, NAD83 |
| gcm_code | geographic coordinate method code |
| geoc_src | geographic coordinate source |
| elevation | land surface elevation in feet above mean sea level. Info from CWI if available |
| elev_mc | elevation method code. Info from CWI if available |
| depth_comp | depth completed in feet. Info from CWI if available |
| case_depth | casing depth in feet. Info from CWI if available |
| depth2bdrk | depth to bedrock in feet. info from CWI if available |
| first_bdrk | upper most bedrock. info from CWI if available |
| ohtopunit | open hole top unit. info from CWI if available |
| ohbotunit | open hole bottom unit. info from CWI if available |
| ohtopelev | top of open hole elevation |
| ohbotelev | bottom of open hole elevation |
| depth_top | depth to top of sampled interval if different from casing depth |

| | |
|---|---|
| | (in feet) |
| depth_bot | depth to bottom of sampled interval if different from depth _completed (in feet) |
| grout | well grouted? (Y, N, U). Info from CWI if available |
| use_c | well use code. Info from CWI if available |
| file_src | name of source file(s) |
| agency_prg | unique agency-program ID: concatenation of agency and program_id fields |
| relate_date | sample event comparison field |
| duplicate | duplicate from same sample date, 1 = yes |
| remarks | comments on data in row |
| report_ref | report reference, if available |
| redox_cat | Redox category as assigned by Jurgens and others (2009) based on DO, NO3_N, Mn, Fe and SO4 concentrations |
| redox_process | Redox process as assigned by Jurgens and others (2009) based on DO, NO3_N, Mn, Fe and SO4 concentrations |
| sr_ca_mg_ratio | strontium to calcium plus magnesium molar ratio |
| cl_br_ratio | chloride to bromide ratio, mg/L |
| flg_goodchargebalance | data flag - good charge balance |
| flg_fieldparameters | data flag – 1 indicates field parameters/physical characteristics (cond, temp, pH, DO) |
| flg_stable_radio_isotope | data flag - 1 indicates stable and radiogenic isotopes |
| flg_nutrients | data flag - 1 indicates nutrient data (phosphorous, nitrogen compounds) |
| flg_pfc | data flag - 1 indicates PFC data |
| flg_trace_metals | data flag - 1 indicates trace metals |
| flg_other | data flag - 1 indicates major cations and anions, physical characteristics - no or poor charge balance |
| flg_age | data flag - 1 indicates age determination |
| flg_redox_condition | data flag - 1 indicates redox condition assigned |
| flg_swuds | data flag - 1 indicates unique number matched DNR SWUD |
| flg_metro | data flag - 1 indicates sample location within 11-county metro area plus 5000 meters |

| | |
|---|---|
| flg_deliver | data flag - 1 indicates deliver to met council |
| seqno | Unique row identifier |

***Hydraulic conductivity table: K_complete***

| **Field Name** | **Description** |
|---|---|
| seqno | Unique row identifer |
| relateid | Unique site identifier – either unique well number or "Q series" number assigned at MGS |
| unique_no | Minnesota unique well number |
| alternate_id | Alternate ID |
| mdh_testid | identifier for MDH Aquifer Test Information System |
| usgs_mdh_aquitest_recnum | sequential identifier in USGS-MDH Aquifer Properties Database (Aquitest) |
| dnr_aquitest_recnum | sequential identifier in DNR version or USGS-MDH Aquifer Properties Database (from Jay Frischman) |
| agency | agency |
| program_id | Agency program identifier |
| test_contact | Test contact person or organization |
| wellname_from_file | well name from file or report |
| wellname_CWI | well name from CWI |
| T_min | Transmissivity – minimum |
| T_min_units | T minimum units |
| T_min_test_method | T minimum test method |
| T_min_analytical_method | T minimum analytical method |
| T_max | Transmissivity - maximum |
| T_max_units | T maximum units |
| T_max_test_method | T maximum test method |
| T_max_analytical_method | T maximum analytical method |
| T | Transmissivity |
| T_units | Transmissivity units |

| | |
|---|---|
| T_test_method | Transmissivity test method |
| T_analytical_mc | Transmissivity analytical method |
| aquifer_thck_ft | estimated aquifer thickness in feet |
| aquifer_thck_mc | estimated aquifer thickness method code |
| Kh_min | K value – horizontal – minimum |
| Kh_max | K value – horizontal – maximum |
| Kh | K value – horizontal |
| Kv | K value – vertical |
| K_units | K (horizontal/vertical) units |
| minmax | specifies if K value is a minimum or maximum value |
| Kh_ftday | K value – horizontal in ft/day |
| Kv_ftday | K value – vertical in ft/day |
| test_method | K test method |
| analytical_method | K calculation method |
| meas_date | measurement date as text in format yyyymmdd where equivalent meas_date2 available |
| meas_date2 | Measurement date in date format |
| aquifer_test_use | Well use as part of aquifer test. Not known whether pumping or observation well |
| data_src | Data source |
| site_name | Site name |
| report_reference_primary | Primary report reference |
| report_reference_secondary | Secondary report reference |
| elevation | land surface elevation in feet above mean sea level. Info from CWI if available |
| elev_mc | elevation method |
| depth_comp | depth completed in feet, info from CWI if available |
| depth_mc | Depth method |
| case_diam | casing diameter in inches, info from CWI if available |
| case_depth | casing depth in feet, info from CWI if available |
| depth2bdrk | depth to bedrock in feet, info from CWI if available |
| first_bdrk | uppermost bedrock unit, info from CWI if available |
| ohtopunit | open hole top unit, info from CWI if available |

| | |
|---|---|
| ohbotunit | open hole bottom unit, info from CWI if available |
| aquifer | aquifer unit, info from CWI if available |
| soil_class | soil class |
| depth_top | depth to top of test interval in feet |
| depth_bot | depth to bottom of test interval in feet |
| ohtopelev | elevation, top of test interval, in feet |
| ohbotelev | elevation, bottom of test interval, in feet |
| utme | Universal Transverse Mercator easting, UTM zone 15 extended, NAD83 |
| utmn | Universal Transverse Mercator northing, UTM zone 15 extended, NAD83 |
| gcm_code | Geographic coordinates method |
| geoc_src | Geographic coordinates source |
| file_src | name of electronic source file, if available, or local file if entered from paper records at MGS |
| comments1 | comments, set 1 |
| comments2 | comments, set 2 |
| comments3 | Comments, set 3 |
| unit_tested_per_report | Unit tested as described in report |
| unit_tested | Interpreted unit tested |
| unit_tested_addl | Additional information on unit tested |
| site_conditions | specifies structural or true thickness conditions |
| tx_summary | texture summary soil class or qualitative description |
| tx_depth_top | depth to top of sample interval for texture data, in feet |
| tx_depth_bot | depth to bottom of sample interval for texture data, in feet |
| porosity_prc | porosity, measured as percent |
| prc_crse_grvl | percent coarse gravel |
| prc_med_grvl | percent medium gravel |
| prc_fine_grvl | percent fine gravel |
| prc_crse_sand | percent coarse sand |
| prc_med_sand | percent medium sand |
| prc_fine_sand | percent fine sand |
| prc_grvl | percent gravel |

| | |
|---|---|
| prc_sand | percent sand |
| prc_silt | percent silt |
| prc_clay | percent clay |
| prc_siltclay | percent silt and clay combined |
| prc100txt | materials making up weight percent denominator |
| D60_mm | D60 number, in millimeters |
| D30_mm | D30 number, in millimeters |
| D10_mm | D10 number, in millimeters |
| dryweight_g | dryweight of sample in grams |
| sv_3in | sieve weight retained in grams - 3 inch |
| sv_2in | sieve weight retained in grams - 2 inch |
| sv_1in | sieve weight retained in grams - 1 inch |
| sv_p75in | sieve weight retained in grams - 0.75 inch |
| sv_p375in | sieve weight retained in grams - 0.375 inch |
| sv_no4 | sieve weight retained in grams - number 4 sieve |
| sv_n10 | sieve weight retained in grams - number 10 sieve |
| sv_no18 | sieve weight retained in grams - number 18 sieve |
| sv_no40 | sieve weight retained in grams - number 40 sieve |
| sv_no70 | sieve weight retained in grams - number 70 sieve |
| sv_no100 | sieve weight retained in grams - number 100 sieve |
| sv_no200 | sieve weight retained in grams - number 200 sieve |
| sv_no230 | sieve weight retained in grams - number 230 sieve |
| swl | static water level in feet, info from CWI if available |
| pump_wl | pumping water level in feet, info from CWI if available |
| hours | number of hours pumped, info from CWI if available |
| gpm | pumping rate in gallons per minute, info from CWI if available |
| spc_strcoeff | storage coefficient used for specific capacity to hydraulic conductivity conversion |
| spc_wlcoeff | well loss coefficient used for specific capacity to hydraulic conductivity conversion |
| flg_metro | Data flag - 1 indicates test in 11 county metro area |
| flg_bdrk | Data flag - 1 indicates bedrock sample |

| | |
|---|---|
| flg_uncs | Data flag - 1 indicates unconsolidated sample |
| flg_texture | Data flag - 1 indicates texture data |
| flg_cwi_spcap | Data flag - 1 indicates specific capacity data from CWI |

**Appendix D.** Regional summary geodatabase structure and field names/descriptions.

**Geodatabase Name: RegionalData.gdb (file geodatabase)**

*Spatially enabled data table*

| Name | Description |
|---|---|
| gridpoints_Q | 3D collection of regularly spaced grid points with estimated range of K data for unconsolidated deposits. This version differs from gridpoints in Tipping et al., 2010 by having 250 meter horizontal resolution as opposed to 500 meter horizontal resolution |
| gridpoints_waterchem | 3D collection of regularly spaced grid points showing regional hydrochemical facies. Subset of Tipping et al., 2010, containing hydorchemical facies only |
| XY_locations | 2D collection of points regularly spaced points, summarizing subsurface conditions used for vertical travel time calculations, for each XY location in gridpoints_Q. |

*Field names and definitions: gridpoints_Q*



| Name | Description |
|---|---|
| elev | Elevation of point in feet above mean sea level |
| utme, utmn | Universal Transverse Mercator easting and northing for each point. North American Datum 83, zone 15 |
| loc_code | Unique identifier for each point – combination of text string values for utme, utmn and elevation (in feet) |
| Loc_codeXY | Identifier for XY location of each datapoint – combination of text string values for utme and utmn |
| nT, nB, nE, nW, nN, nS | Loc_codes of six neighboring points. Used to facilitate groundwater modeling |
| Kx, Ky, Kz, Ss, pH, R, Q, delta_h, h1, h2, b, sat | Place holder fields for hydraulic parameters. Used to facilitate groundwater modeling |
| sand_prob | Likelyhood that point texture is coarse-grained. Result of subsurface interpolation of water well data |
| mix_prob | Likelyhood that point texture is mixture of fine and coarse-grained. Result of subsurface interpolation of water well data in CWI |
| clay_prob | Likelyhood that point texture is fine-grained. Result of subsurface interpolation of water well data in CWI |
| grid_code | Quaternary subsurface map code |
| maplabel | |
| K_classM | Hydraulic conductivity class code for sub surface points, based on subsurface interpolation of water well data, see lookup table xK_CLASS |
| K_class | Hydraulic conductivity class code for near-surface points, based on subsurface Quaternary stratigraphy mapping, see lookup table xK_CLASS |
| K_classSG | Hydraulic conductivity class code for near-surface points, based on surficial geology map units, see lookup |

| | |
|---|---|
| | table xK_CLASS |
| K_class_composite | Heirachy of K class assignments for each point: K_classSG replaces K_class; K_class replaces K_classM – this field can be used to display textures only. Select by value = code as specified in table xK_CLASS |
| K_classNULL | Value of 1 indicates points with no K class designation due to insufficient data |
| K_composite | Composite K value based on K_class composite depth. With the exception of sand and gravel, values are taken as arithmetic mean for K_class ranges as specified in table xK_CLASS. Points with K_classNULL = 1 are assigned an intermediate value of 10.05 feet/day. Sand and gravel are assigned a value of 50 ft/day |

*Field names and definitions: gridpoints_waterchem*

| **Name** | **Description** |
|---|---|
| POINTID | Unique identifier for each point |
| GRID_CODE | Quaternary subsurface map code |
| ELEV | Elevation of point in feet above mean sea level |
| K_class | Hydraulic conductivity class code, see lookup table xK_CLASS |
| K_class_sgpg | Hydraulic conductivity class code for near-surface points, based on surficial geology map units, see lookup table xK_CLASS |
| nat_elev_cl | Data flag – 1 indicates waters likely to have elevated chloride concentrations (greater than 15 ppm) likely due to natural conditions – not anthropogenic inputs. |
| srcamg | Data flag – 1 indicates waters likely to have strontium to calcium plus magnesium molar ratios likely greater than 0.001 |
| recent | Data flag – 1 indicates water likely to contain some component less than 60 years old |



*Field names and definitions: XY_locations.*

| **Name** | **Description** |
|---|---|
| loc_codeXY | Unique identifier for each point |
| loc_codeMAXe | Gridpoints_Q loc_code for given XY with highest elevation (land surface gridpoint_Q point) |
| minimum_elev | Minimum gridpoint _Q elevation for given XY, in feet |
| maximum_elev | Maximum gridpoint_Q elevation for given XY, in feet |
| utme, umtn | Universal Transverse Mercator easting and northing for each point. North American Datum 83, zone 15, meters |
| count_loc_codeXY | Number of gridpoints_Q for given XY |
| count_KzU | Count of unassigned gridpoint_Q for given XY |
| count_KzM | Number of gridpoints_Q for given XY with assigned texture class from interpolated model |

| | |
|---|---|
| prnct_vertM | Percent of gridpoints_Q for given XY that have assigned texture texture class from interpolated model |
| prcnt_vert | Percent of gridpoints_Q for given XY with assigned texture class from either interpolated model, subsurface mapping or surficial map |
| maplabel | Map label from surficial geology map MGS Open-File Report 07-02 |
| K_class_sgpg | K_class assignment from surfical geology map |
| elev_WT | Regional water table elevation in feet |
| elev_bdrk | Bedrock elevation regional bedrock surface digital elevation model (feet above msl) |
| elev_opcjx_M08 | Regional bedrock potentiometric elevation, March 2008, in feet |
| elev_opcjx_A08 | Regional bedrock potentiometric elevation, August 2008, in feet |
| delta_h_M08 | Difference in hydraulic head, March 2008, in feet (elev_WT – elev_opcjx_M08) |
| delta_h_A08 | Difference in hydraulic head, August 2008, in feet (elev_WT – elev_opcjx_A08) |
| grad_h_M08 | Hydraulic gradient, March 2008 (delta_h_M08/distance) |
| grad_h_A08 | Hydraulic gradient, August 2008 (delta_h_A08/distance) |
| Kz_mean_sat | Arithmetic mean of gridpoint Q K_composite value for points below regional water table, in ft/day |
| Kz_gmean_sat | Geometric mean of gridpoint Q K_composite value for points below regional water table, in ft/day |
| Kz_hmean_sat | harmonic mean of gridpoint Q K_composite value for points below regional water table, in ft/day |
| Kz_mean_unsat | Arithmetic mean of gridpoint Q K_composite value for points above regional water table, in ft/day |
| Kz_gmean_unsat | Geometric mean of gridpoint Q K_composite value for points above regional water table, in ft/day |
| Kz_hmean_unsat | harmonic mean of gridpoint Q K_composite value for points above regional water table, in ft/day |
| distance | Vertical distance from regional water table to bedrock surface, in feet |
| distance_unsat | Vertical distance from land surface to regional water table, in feet |
| porosity | Porosity, used for time of travel calculations. Set to 0.2 for all records |
| travel_time_yrs_Kzg | Vertical travel time from regional water table to bedrock surface calculated using geometric mean, in years |
| travel_time_yrs_Kzh | Vertical travel time from regional water table to bedrock surface calculated using harmonic mean, in years |
| travel_time_yrs_Kzh_unsat | Vertical travel time from land surface to regional water table calculated using harmonic mean and a vertical gradient of 1, in years |
| eleven_co_metro | Set to 1 where point is within eleven county extended metropolitan area |
| qstrat_mapped | Set to 1 for areas where subsurface mapping has taken place |
| WT_above_bdrk | Set to 1 where water table is above bedrock |
| opgw_absent | Set to 1 where Plattville Formation is not present |

*Lookup tables*

| Name | Description |
|---|---|
| xGRIDCODE | Corresponds to field "GRID_CODE," code specifies Quaternary subsurface map code, unit description and corresponding mapping project name: |

| *code* | *Description* | *Project* | *Map Label* | *K_Class* |
|---|---|---|---|---|
| 1 | till - sandy to loamy; high to low relief (diamicton) | Washington County (Meyer and Tipping, 1998) | t1 | 1 |
| 2 | till, generally sandy textured (diamicton) | Washington County (Meyer and Tipping, 1998) | t2 | 2 |
| 3 | loam till, generally silt-rich, loam -textured | Washington County (Meyer and Tipping, 1998) | t3 | 3 |
| 4 | till, generally sandy textured (diamicton) | Washington County (Meyer and Tipping, 1998) | t4 | 4 |
| 5 | silt and clay (bedded) | NW Metro (Meyer and Tipping, 2007) | cl | 3 |
| 6 | till, generally sandy textured (diamicton) | NW Metro (Meyer and Tipping, 2007) | ct1 | 2 |
| 7 | till, generally sandy textured (diamicton) | NW Metro (Meyer and Tipping, 2007) | ct | 2 |
| 8 | till, generally loamy textured (diamicton) | NW Metro (Meyer and Tipping, 2007) | xt | 3 |
| 9 | till, generally sandy textured (diamicton) | NW Metro (Meyer and Tipping, 2007) | rt | 4 |
| 10 | till, generally loamy textured (diamicton) | NW Metro (Meyer and Tipping, 2007) | pt | 3 |
| 11 | till, generally sandy textured (diamicton) | NW Metro (Meyer and Tipping, 2007) | vt | 4 |
| 12 | undifferentiated sediment | NW Metro (Meyer and Tipping, 2007) | unk | -1 |
| 13 | loam to clay loam (diamicton) | Carver County (Lusardi and Tipping, 2009) | dth | 1 |
| 14 | clay loam to sandy loam (diamicton) | Carver County (Lusardi and Tipping, 2009) | dtv | 1 |
| 15 | sandy loam(diamicton) | Carver County (Lusardi and Tipping, 2009) | rt | 2 |
| 16 | loam (diamicton) | Carver County (Lusardi and Tipping, 2009) | bt | 3 |
| 17 | loam to sandy loam (diamicton) | Carver County (Lusardi and Tipping, 2009) | gt | 3 |
| 18 | loam (diamicton) | Carver County (Lusardi and Tipping, 2009) | xt | 3 |
| 19 | unknown | Carver County (Lusardi and Tipping, 2009) | ups | -1 |
| 20 | silt and clay | NW Metro (Meyer and Tipping, 2007) | nl | 1 |
| 21 | New Ulm till - sandy to loamy; high to low relief (diamicton) | NW Metro (Meyer and Tipping, 2007) | nt | 1 |
| 22 | sandy loam to clay loam (diamicton) - nw provenance | Scott County (Lusardi and Tipping, 2006) | t1 | 1 |
| 23 | loam to sandy loam (diamicton) - mixed provenance | Scott County (Lusardi and Tipping, 2006) | t2 | 1 |

| | | | | |
|---|---|---|---|---|
| 24 | loam (diamicton) - nw provenance | Scott County (Lusardi and Tipping, 2006) | t3 | 3 |
| 26 | silt and clay | Chisago County (Meyer, 2010) | nl | 1 |
| 27 | | Chisago County (Meyer, 2010) | nt1 | 1 |
| 28 | New Ulm till, includes lacustrine silt and clay at base to the north | Chisago County (Meyer, 2010) | qnu | 1 |
| 29 | lacustrine clay and silt to till | Chisago County (Meyer, 2010) | qlc | 3 |
| 30 | Cromwell, sandy till | Chisago County (Meyer, 2010) | qcr | 2 |
| 31 | sandy till, may be finer-textured towards the base in deep valleys | Chisago County (Meyer, 2010) | qce | 2 |
| 32 | loam till, generally silt-rich, loam -textured | Chisago County (Meyer, 2010) | qxt | 3 |
| 33 | Superior provenance - sandy till | Chisago County (Meyer, 2010) | qrt | 4 |
| 34 | undifferentiated sediment | Chisago County (Meyer, 2010) | qu | -1 |
| 50 | fine sand to gravel (bedded) | NW Metro (Meyer and Tipping, 2007 | co1 | 5 |
| 51 | fine sand to gravel (bedded) | NW Metro (Meyer and Tipping, 2007 | co | 5 |
| 52 | fine sand to gravel (bedded) | NW Metro (Meyer and Tipping, 2007 | no2 | 5 |
| 53 | fine sand to gravel (bedded) | NW Metro (Meyer and Tipping, 2007 | no | 5 |
| 54 | fine sand to gravel (bedded) | NW Metro (Meyer and Tipping, 2007 | po | 5 |
| 55 | fine sand to gravel (bedded) | NW Metro (Meyer and Tipping, 2007 | Ro | 5 |
| 56 | fine sand to gravel (bedded) | NW Metro (Meyer and Tipping, 2007 | terr | 5 |
| 57 | fine sand to gravel (bedded) | NW Metro (Meyer and Tipping, 2007 | vo | 5 |
| 58 | fine sand to gravel (bedded) | NW Metro (Meyer and Tipping, 2007 | xo | 5 |
| 60 | fine sand to gravel (bedded) | Chisago County (Meyer, 2010) | qsc | 5 |
| 61 | fine sand to gravel (bedded) | Chisago County (Meyer, 2010) | qse | 5 |
| 62 | fine sand to gravel (bedded) | Chisago County (Meyer, 2010) | qsl | 5 |
| 63 | fine sand to gravel (bedded) | Chisago County (Meyer, 2010) | qsr | 5 |
| 65 | fine sand to gravel (bedded) | Chisago County (Meyer, 2010) | qsx | 5 |
| 65 | fine sand to gravel (bedded) | Chisago County (Meyer, 2010) | qu | 5 |
| 67 | fine sand to gravel (bedded) | Chisago County (Meyer, 2010) | sp | 5 |
| 68 | fine sand to gravel (bedded) | Chisago County (Meyer, 2010) | sup | 5 |
| 70 | fine sand to gravel (bedded) | Carver County (Lusardi and Tipping, 2009) | sb | 5 |
| 71 | fine sand to gravel (bedded) | Carver County (Lusardi and Tipping, 2009) | sdo | 5 |
| 72 | fine sand to gravel (bedded) | Carver County (Lusardi and Tipping, 2009) | sdv | 5 |
| 73 | fine sand to gravel (bedded) | Carver County (Lusardi and Tipping, 2009) | sg | 5 |

| | | | | |
|---|---|---|---|---|
| 74 | fine sand to gravel (bedded) | Carver County (Lusardi and Tipping, 2009) | sr | 5 |
| 75 | fine sand to gravel (bedded) | Carver County (Lusardi and Tipping, 2009) | su | 5 |
| 76 | fine sand to gravel (bedded) | Carver County (Lusardi and Tipping, 2009) | sx | 5 |
| 80 | fine sand to gravel (bedded) | Scott County (Lusardi and Tipping, 2006) | s1 | 5 |
| 81 | fine sand to gravel (bedded) | Scott County (Lusardi and Tipping, 2006) | s2 | 5 |
| 82 | fine sand to gravel (bedded) | Scott County (Lusardi and Tipping, 2006) | s3 | 5 |
| 83 | fine sand to gravel (bedded) | Scott County (Lusardi and Tipping, 2006) | s4 | 5 |
| 84 | fine sand to gravel (bedded) | Scott County (Lusardi and Tipping, 2006) | riv | 5 |
| 90 | fine sand and gravel (areas unmapped by till surfaces) | Washington County (Meyer and Tipping, 1998) | | 5 |

**xMAPLABEL**

Corresponds to field "maplabel," code specifies map label and unit description from metro area surficial geology map, MGS Open-File Report 07-02 (Meyer and Tipping, 2007).

**xK_CLASS**

Corresponds to fields "K_class," and "K_class_sgpg," code specifies range of expected hydraulic conductivity in feet/day. Reference to "deep" in codes 8-11 are for point depths greater than 60 feet from land surface, estimated to be 2 orders of magnitude lower hydraulic conductivity than equivalent textures in shallow settings:

| *code* | *Texture Description* | *Kmax (ft/day)* | *Kmin (ft/day)* |
|---|---|---|---|
| 1 | loam to clay loam | 3.0E-3 | 1.0E-3 |
| 2 | loam to sandy loam | 2.0E+1 | 1.0E-1 |
| 3 | loam, silt rich; silt and clay | 2.0E-2 | 3.0E-4 |
| 4 | loam to sandy clay loam | 2.0E+1 | 1.0E-1 |
| 5 | sand and gravel | 5000 | 100 |
| 6 | fine sand | 30 | 0.3 |
| 7 | sandy silt | 3 | 0.1 |
| 8 | loam to clay loam - deep | 3.0E-5 | 1.0E-5 |
| 9 | loam to sandy loam - deep | 2.0E-1 | 1.0E-3 |
| 10 | loam, silt rich; silt and clay - deep | 2.0E-4 | 3.0E-6 |
| 11 | loam to sandy clay loam - deep | 2.0E-1 | 1.0E-3 |

**Appendix E.** Guide to database use.

*Travel time calculations*

Several choices were made that impact the time of travel calculations shown on Figures 12 and 13, and on the accompanying map:

1.) Harmonic mean of vertical hydraulic conductivity (Kv) values for set of gridpoints at each XY location was used, as opposed to arithmetic or geometric mean. The harmonic mean is influenced more by lower values than the geometric or arithmetic mean. It was chosen based on the premise that low conductivity layers have the greatest influence on ground water flowpaths.

2.) In places other than those identified as regional discharge zones, the bedrock potentiometric surface was lowered one-half foot below the regional water table surface in places where it was greater than the water table surface. (Note: gradients shown on cross sections were not changed). This allowed for travel time calculation over a broader area where adequate subsurface data was available.



3.) Effective porosity was set at 20% for all calculations based on literature values. It is expected that actual effective porosity varies substantially over a range of textures and depositional environments.

These choices result in *extremely* long travel times under certain conditions, such as very low gradients and low bulk Kv. Rather than replace these travel time values with a realistic number, they were left in to reflect the limitations of this type of method at depicting actual groundwater flow. The resulting map is a reasonable depiction of the relative rather than absolute differences in vertical travel times across the metropolitan area. It should also be noted that in areas identified as regional discharge zones – bedrock potentiometric surface higher than the regional water table – travel time values were set to null.

*Layer files*

The following ArcGIS layer files are included to assist with database display. Depending on processing speed of the desktop computer, it may be help to use the "Definition Query" tab under layer properties to display only subsets of the larger database.

*XY_locations feature class*

| **Name** | **Description** |
| --- | --- |

| | |
|---|---|
| travel_time_yrs_Kzh _sat.lyr | Use to display vertical travel time in years from the regional water table to the bedrock surface calculated using harmonic mean of composite vertical hydraulic conductivity |
| travel_time_yrs_Kzh_unsat.lyr | Use to display vertical travel time in years from land surface to regional water table calculated using harmonic mean of composite vertical hydraulic conductivity |

*gridpoints_Q  feature class – represents any occurrence from landsurface to bedrock*

| **Name** | **Description** |
|---|---|
| gridpoints_Q_K_classM.lyr | Use to display subsurface textures as determined by interpolated model – based on driller's descriptions |
| gridpoints_Q_K_class.lyr | Use to display subsurface textures as determined by stratigraphic mapping |
| gridpoints_Q_K_classSG.lyr | Use to display near surface textures as determined by surfical mapping |
| gridpoints_Q_K_class_composite.lyr | Use to display near surface and subsurface textures, as determined by hierarchy of K_classM superceded by K_class, superceded by K_classSG. |
| | |



*gridpoints_waterchem*

| **Name** | **Description** |
|---|---|
| gridpoints_waterchem_nat_elev_cl.lyr | Use to display subsurface distribution of naturally elevated chloride waters |
| gridpoints_waterchem_srcamg.lyr | Use to display subsurface distribution of elevated strontium to calcium plus magnesium waters |
| gridpoints_waterchem_recent.lyr | Use to display near subsurface distribution of recent waters |

**Figure 1**. Investigation covers the extended 11-county Twin Cities metropolitan area, Minnesota. Areas with mapped Quaternary stratigraphy are shaded (Meyer and Tipping, 1998; Lusardi and Tipping, 2006; Meyer and Tipping, 2007; Lusardi and Tipping, 2009; Meyer, 2010). Locations of cross section (Figures 14 through 20) are shown.

**Figure 2.** Regional map showing distribution of subsurface relatively coarse-grained sediments, based on interpolation from CWI. Color indicates occurrence at any depth from the land surface to bedrock, having a minimum thickness of 10 feet. See text for explanation of interpolation methods.

**Figure 3.** Regional map showing distribution of subsurface relatively mixed fine and coarse-grained sediment, based on interpolation from CWI. Color indicates occurrence at any depth from the land surface to bedrock, having a minimum thickness of 10 feet. See text for explanation of interpolation methods.

**Figure 4.** Regional map showing distribution of subsurface relatively fine-grained sediment, based on interpolation from CWI. Color indicates occurrence at any depth from the land surface to bedrock, having a minimum thickness of 10 feet. See text for explanation of interpolation methods.

**Figure 5.** Schematic drawing of Quaternary points model. Columns of points where less than 40 percent of the column can be assigned texture- and depth-based range of hydraulic conductivities are left out of the final time of travel calculation.

**Figure 6.** Regional map showing composite hydraulic conductivities at each gridpoint XY location. Harmonic mean for each column of values was chosen over arithmetic and geometric means, based on the assumption that low conductivity units have the biggest impact on groundwater flow.

**Figure 7.** Regional maps showing adjusted vertical change in hydraulic head for March (**A.**) and August (**B.**) 2008. Bedrock surfaces were adjusted to be one half foot below the water table surface except in areas of groundwater discharge (Mississippi, Minnesota, St. Croix, and portions of the Crow River). Constructed by subtracting the bedrock potentiometric surface from the water table surface, summer increases in hydraulic gradient are most visible in the central metropolitan area. These changes reflect increased drawdown in the bedrock potentiometric surface due to higher summer pumping rates from the Prairie du Chien Group and Jordan Sandstone.

**Figure 8.** Schematic drawing showing the time of travel calculation. Mean hydraulic conductivity is calculated for points that fall between the water table and the bedrock surface. Hydraulic gradient is calculated over this same distance. The presence of Decorah/Plattville/Glenwood Formations and the possibility of unsaturated St. Peter Sandstone below precludes the use of Darcy calculation for time of travel where these units area present.

**Figure 9.** Regional maps showing the distribution of recent waters. **A.**) Chloride concentrations from water wells. Concentrations greater than 5 mg/l considered to be indicator of recent recharge. **B.**) Tritium results from water wells. Well with tritium concentrations greater than 10 tritium units (TU) considered to be dominated by waters having entered the ground since 1960; wells with less than 1 TU considered to be dominated by waters having entered the ground prior to 1960; intermediate values from 1 to 10 TU considered a mixture of older and recent waters. Distribution of elevated chloride and tritium is broadly similar. **C.**) Contours of open hole top (casing bottom) elevation for wells with detectable tritium. **D.**) raster surface marking the base elevation for recent waters, constructed in part using the contours shown in C.

**Figure 10.** Regional map showing strontium vs calcium plus magnesium concentrations. **A.**) Strontium to calcium plus magnesium molar ratios for all wells with acceptable charge balance. Elevated ratios to the west and southwest. **B.**) Contours of open hole top (casing bottom) elevation for Quaternary wells with strontium to calcium plus magnesium ratios greater than 0.001. **C.**) Contours of open hole top (casing bottom) elevation for Jordan wells with strontium to calcium plus magnesium ratios greater than 0.001. **D.**) Contours of open hole top (casing bottom) elevation for Mount Simon wells with strontium to calcium plus magnesium ratios greater than 0.001. Elevated ratios may be associated with recharge through NW provenance tills and/or longer residence time.

**Figure 11.** Regional map showing naturally elevated chloride concentrations. **A.**) Chloride concentrations in mg/l for wells with carbon 14 – determined ages of greater than 1200 years. Also shown are chloride outliers from Hall et al., 1911. Blue contours show height of open hole bottoms above the pre-Cambrian bedrock surface; colored contours show elevation for elevated chloride in unconsolidated deposits in the Belle Plaine area, Scott County. Major metropolitan area bedrock faults are also shown. Old waters with elevated chloride are associated with fault zones, possibly due to upwelling of waters associated with pre-Cambrian bedrock. B.) Chloride to bromide ratios, all wells. Chloride to bromide ratios less than 200 considered to be indicator of chloride from bedrock as opposed to anthropogenic sources. Contours of recent water elevations from Figure 9 shown for comparison to chloride bromide ratios. Elevated ratios (greater than 1000) are generally found in shallow wells with recent waters.

**Figure 12.** Calculated vertical travel time from regional water table the bedrock surface (saturated conditions) travel times greater than 500 years calculated for much of the western metropolitan area, where a thick sequence of clay loam NW provenance till and sandy loam NE provenance tills overlie bedrock. Shorter residence times are present where relatively coarse sediment overlies bedrock and in areas of large hydraulic gradient.

**Figure 13.** Calculated vertical travel time from the land surface to the regional water table surface (unsaturated conditions). Differences from the saturated map are most visible where surfical geologic conditions is different from subsurface conditions.

**Figure 14.** Histogram comparing chloride concentrations to top-of-open-hole elevation in sampled wells. Elevated chloride in metropolitan area water well samples, indicative of recent waters, is typically found at elevations above 700 feet above mean sea level, approximate elevation of the Minnesota, Mississippi and St. Croix Rivers. **A.**) Y axis from 400 to 1000 feet. **B.**) Expanded Y axis from 600 to 900 feet.

**Figure 15.** Lithostratigraphic column showing distribution of residence time by open hole interval. Recent waters found most often in bedrock stratigraphically higher than the St. Lawrence Formation.

**Figure 16.** Regional cross section A-A', Sherburne County to Mississippi River. Recent waters interpreted as present in the upper 50 feet of unconsolidated deposits, increasing with depth in the central part of the basin. Lowest elevation of recent waters occurs in the Jordan Sandstone. Carbon 14 dates for Mt. Simon are shown, indicating a sharp contrast in recharge rates for the upper and lower aquifer systems.

**Figure 17.** Regional cross section B-B', St. Francis, Anoka County to Mississippi River. Recent waters interpreted as present in the upper 50 feet of unconsolidated deposits, increasing with depth in the central part of the basin. Lowest elevation of recent waters occurs in the Jordan Sandstone. Complexity of unconsolidated deposits over bedrock, below surficial sands is shown.

**Figure 18.** Regional cross section C-C', Big Marine Lake, Washington County to Mississippi River near downtown St. Paul. Recent waters between Big Marine and White Bear Lake in the Prairie du Chien Group largley based on tritium measurements from samples west and east of the cross section line interpreted as mixed waters (TU between 1 and 10). Recent water is found at depth towards downtown St. Paul, coincident with a downward gradient and coarse unconsolidated deposits over bedrock. Slight upward gradient at White Bear Lake; downward gradient near Big Marine possibly marking groundwater divide, with regional discharge west towards the St. Croix River. Vintage waters in the Mt. Simon aquifer.

**Figure 19.** Regional cross section D-D', western Dakota County to Mississippi River near Hastings. Limited data show presence of clay, based on the interpolated model, restrict the downward movement of water west of the South Branch of the Vermillion River. Remainder of the cross section is largely sand and gravel over Prairie du Chien Group. A large buried valley filled with sand and gravel is present west of Hastings. Recent waters within this valley based on sampled wells within and on the edges of the valley to the southeast.

**Figure 20.** Regional cross section E-E', southeastern Scott County to Minnesota River near Shakopee. Anthropogenic waters absent below cover of alternating NW and NE provenance tills. Elevated strontium to calcium plus magnesium ratios limited to bedrock valley in upper aquifers and to the Mt. Simon in the lower aquifer. Naturally elevated chloride present in the Mt. Simon at the northeast end of the cross section. Presence of recent water in the Jordan in this area based on sampled wells to the east and west of the cross section line. A strong upward gradient from the Jordan is present near the Minnesota River.

**Figure 21A.** Local cross section F-F' Edina area. Age inversion within the open hole of a single well is shown. Grab samples from the lower portion of the open hole had detectible tritium, while the uppermost sample, located within the Shakopee Formation – Prairie du Chien Group, did not (MDH, 2010b). Flow logging from a nearby test well (MN unique well no. 748656) showed strong downflow from the lower Shakopee to the Jordan Sandstone, corresponding to stratigraphic position of detectible tritium in this well. Interpreted stagnation zone of older water illustrated as present underneath the central portion of the Platteville/Glenwood cap.

**Figure 21B.** Local cross section G-G' Eastern Hennepin County. Recent water occurs at depth east of till cover. Flow logging east of Highway 169 showed strong upflow from fractures in the upper Jordan Sandstone to the upper Oneota Formation - Prairie du Chien Group (MN unique well no. 676445.

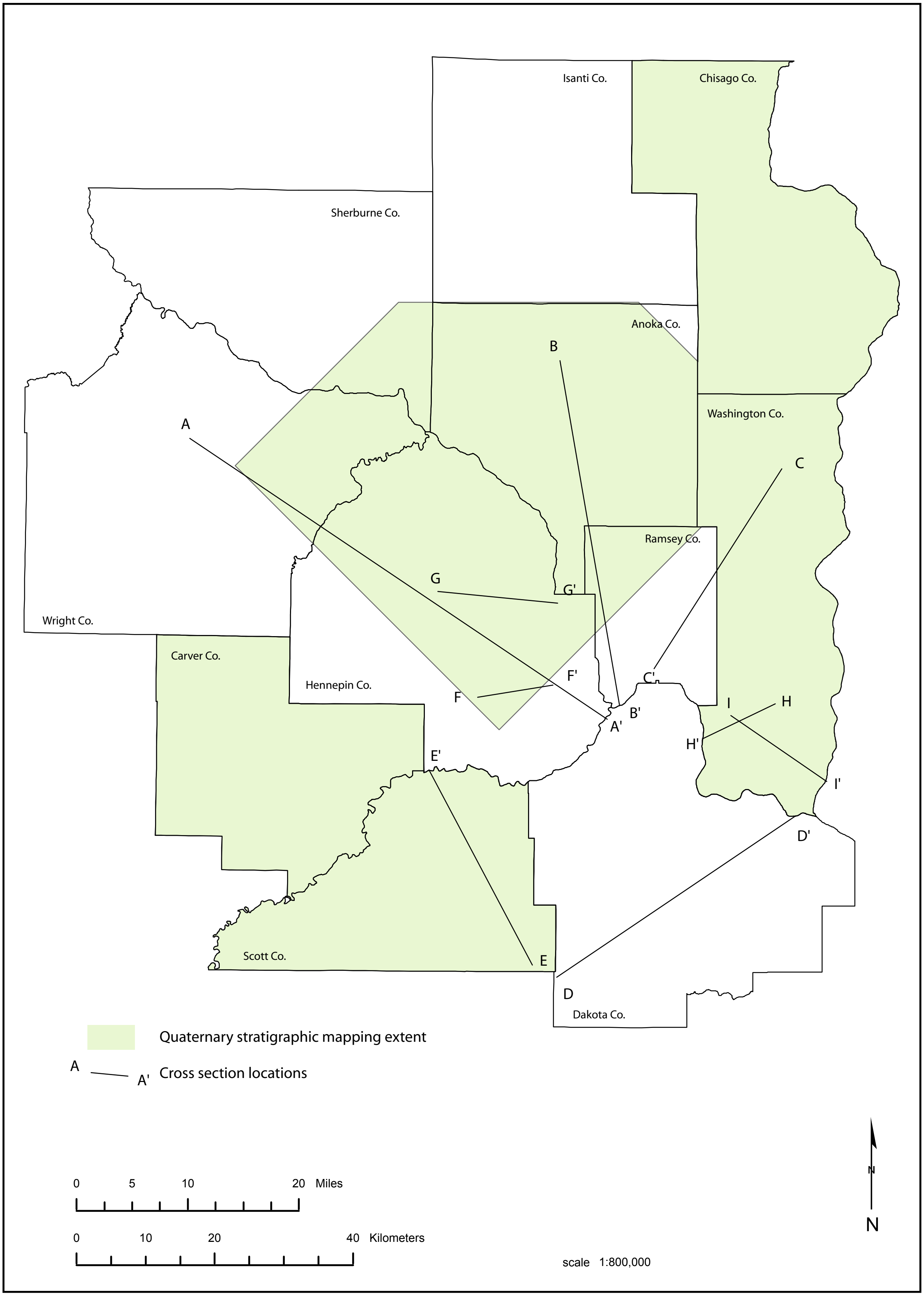
**Figure 22A.** Local cross section H-H', south central Washington County to Mississippi River. Stratification of perflourochemical (PFC) detections between Shakopee (upper Prairie du Chien Group) and Jordan samples is shown. Results infer separate flow systems, with possibly greater flux through the Shakopee Formation compared to the Jordan Sandstone.

**Figure 22B.** Local cross section I-I', southeastern Washington County to St. Croix River. Downward gradient over a north-south trending bedrock valley in the center of the cross section, west of Manning Avenue. The valley, filled with primarily coarse-grained material, shows cluster of PFC detections. Occurrence of PFC's near t he St. Croix River indicates movement of groundwater through fractures and fault blocks, crossing stratigraphic units with wide ranging permeability.

**Figure 23.** Honeywell contamination site, Golden Valley, Minnesota. **A.** ) TrichloroetheneTCE contaminant plumes for 1990 and 2009 at the Honeywell site along with site specific measurements of horizontal hydraulic conductivity are shown. Change in plumes from 1990 to 2009 shows plume migration with time to the east **B.**) 1990 and 2009 plumes, along with texture-based estimates of vertical hydraulic conductivity from the XY locations dataset. In both A and B, lower hydraulic conductivity values area shown in blue, intermediate values in green and higher values in yellow. Lower hydraulic conductivity values to the southeast are visible in both the site specific and regional data.

**Figure 24.** Honeywell contamination site, Golden Valley, Minnesota . perspective views from the southeast **A.** ) TCE contours indicate location of the site. Texture classes from gridpoint have been added, along with bedrock units. Low permeability clay loam sediments are present northwest of the site at the land surface, while layers of clay loam to sandy clay loam and sand are present southwest of the site in the subsurface **B.**) Perspective view extend back further. The change from fine-grained textures to the west to coarse-grained textures, including a largely sand filled bedrock valley to the east is visible. C.) Perspective view with distribution of recent waters added. Recent waters are found in the shallow subsurface to the northwest, extending deeper into the bedrock valley southwest of the site.

**Figure 25.** Cross section key for Figures 16 through 22.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Anoka Co.
Washington Co.
Ramsey Co.
Wright Co.
Carver Co.
Hennepin Co.
Scott Co.
Dakota Co.
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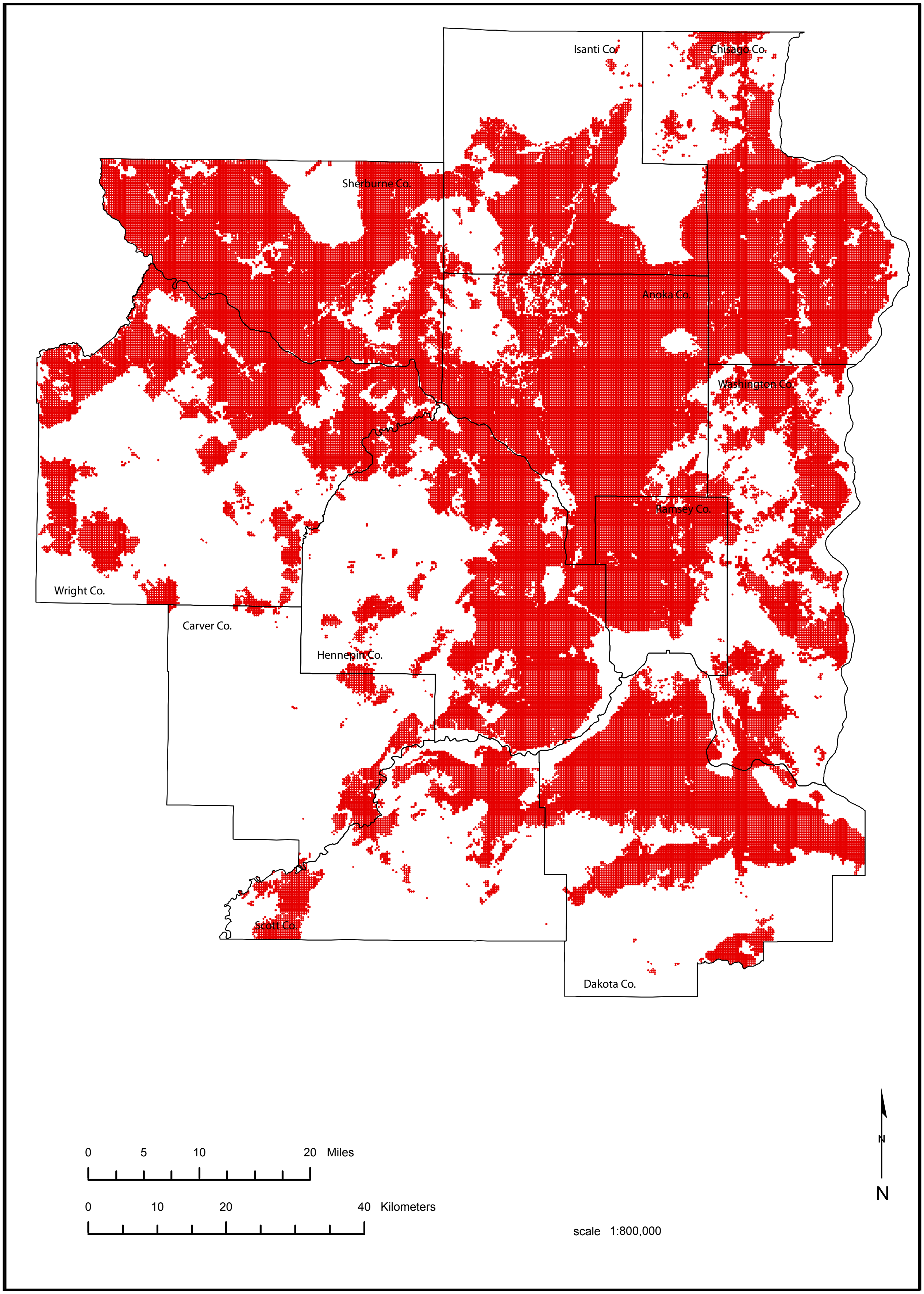
A'
B
B'
C
C'
D
D'
E
E'
F
F'
G
G'
H
H'
I
I'
Quaternary stratigraphic mapping extent
Cross section locations
0 5 10 20 Miles
0 10 20 40 Kilometers
scale 1:800,000
N

Figure 1



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Anoka Co.
Washington Co.
Ramsey Co.
Wright Co.
Carver Co.
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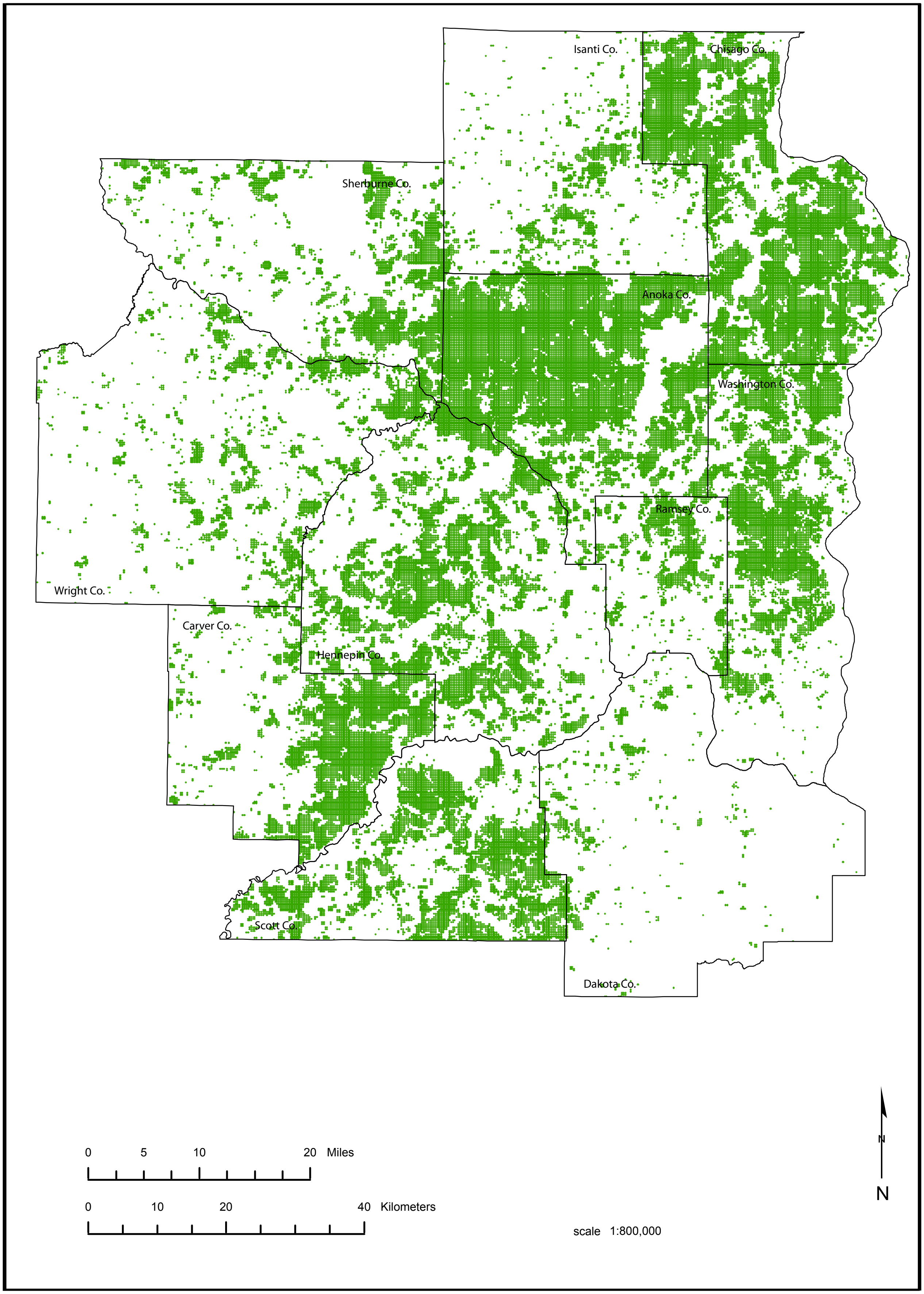
0 5 10 20 Miles
0 10 20 40 Kilometers
scale 1:800,000
N


Figure 2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Hennepin Co.
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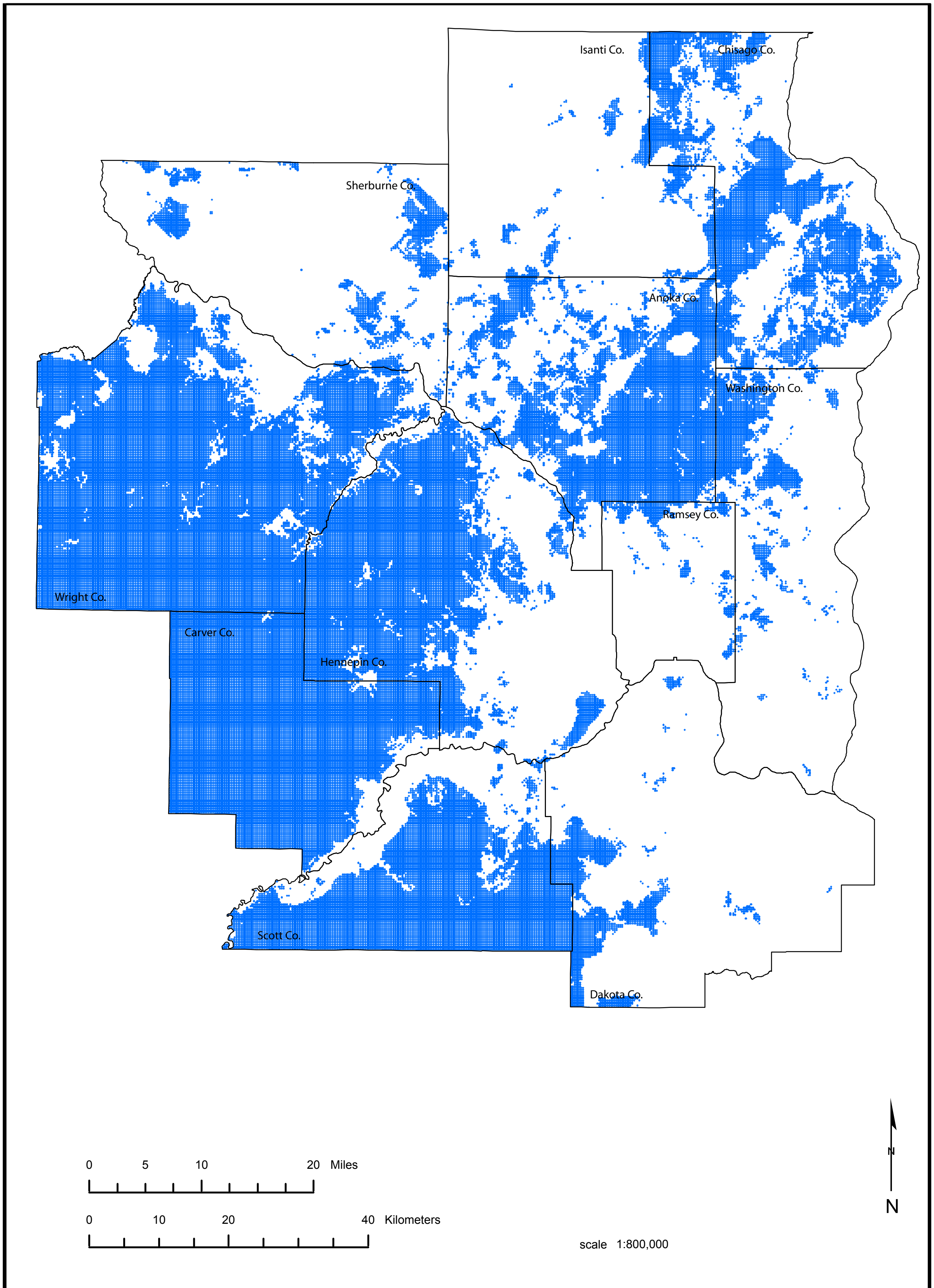
Dakota Co.
0 5 10 20 Miles
0 10 20 40 Kilometers
scale 1:800,000
N

Figure 3



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Dakota Co.
0 5 10 20 Miles
0 10 20 40 Kilometers
scale 1:800,000
N


Figure 4

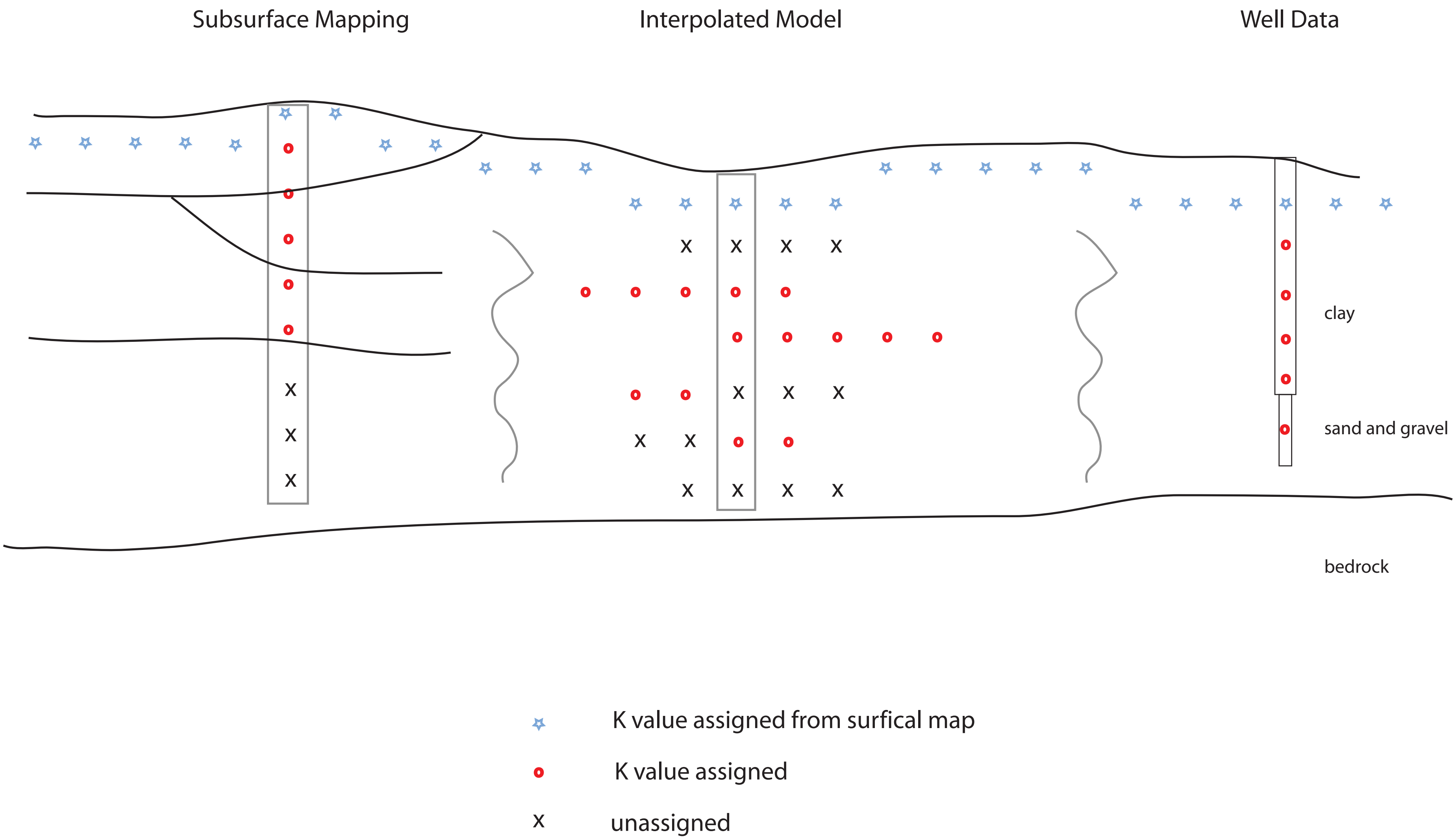
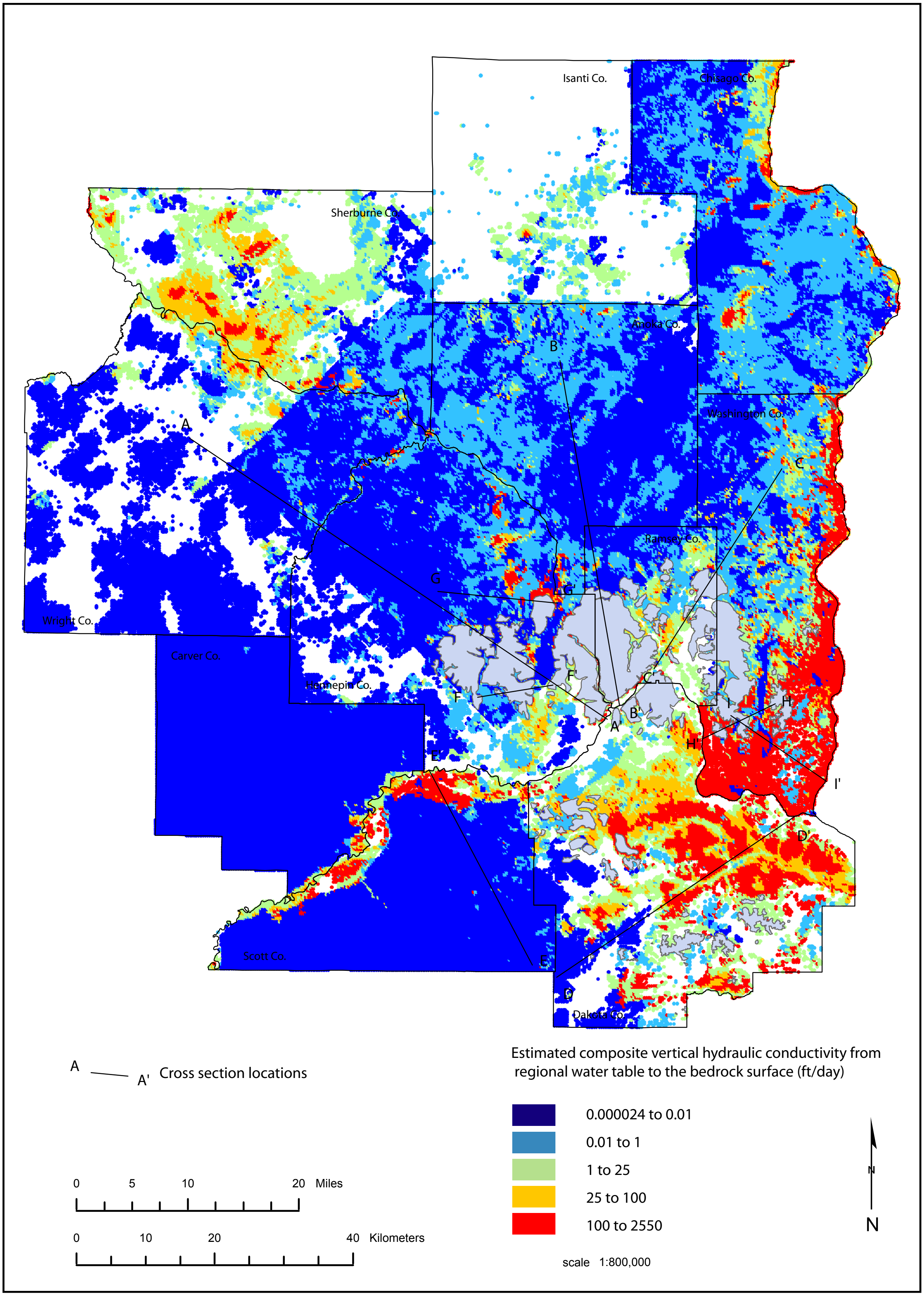

Subsurface Mapping
Interpolated Model
Well Data
clay
sand and gravel
bedrock
K value assigned from surfical map
K value assigned
x
unassigned

Figure 5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Wright Co.
Carver Co.
Hennepin Co.
Scott Co.
Dakota Co.
A
A'
B
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C
C'
D
D'
E
F
F'
G
G'
H
H'
I
I'
Cross section locations
Estimated composite vertical hydraulic conductivity from regional water table to the bedrock surface (ft/day)
0.000024 to 0.01
0.01 to 1
1 to 25
25 to 100
100 to 2550
0 5 10 20 Miles
0 10 20 40 Kilometers
N
scale 1:800,000

Figure 6

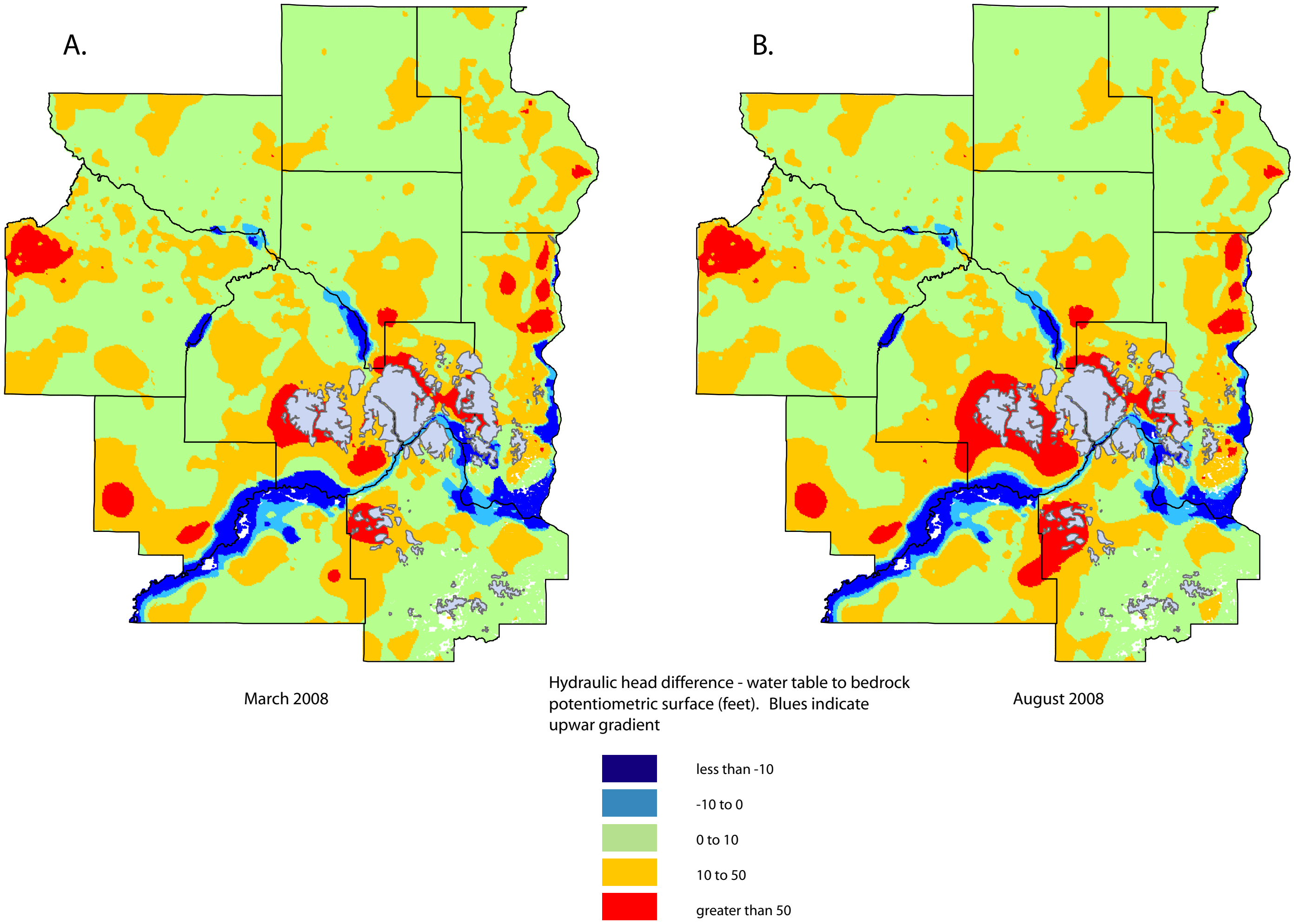

A.
B.
March 2008
August 2008
Hydraulic head difference - water table to bedrock potentiometric surface (feet). Blues indicate upwar gradient
less than -10
-10 to 0
0 to 10
10 to 50
greater than 50

Figure 7

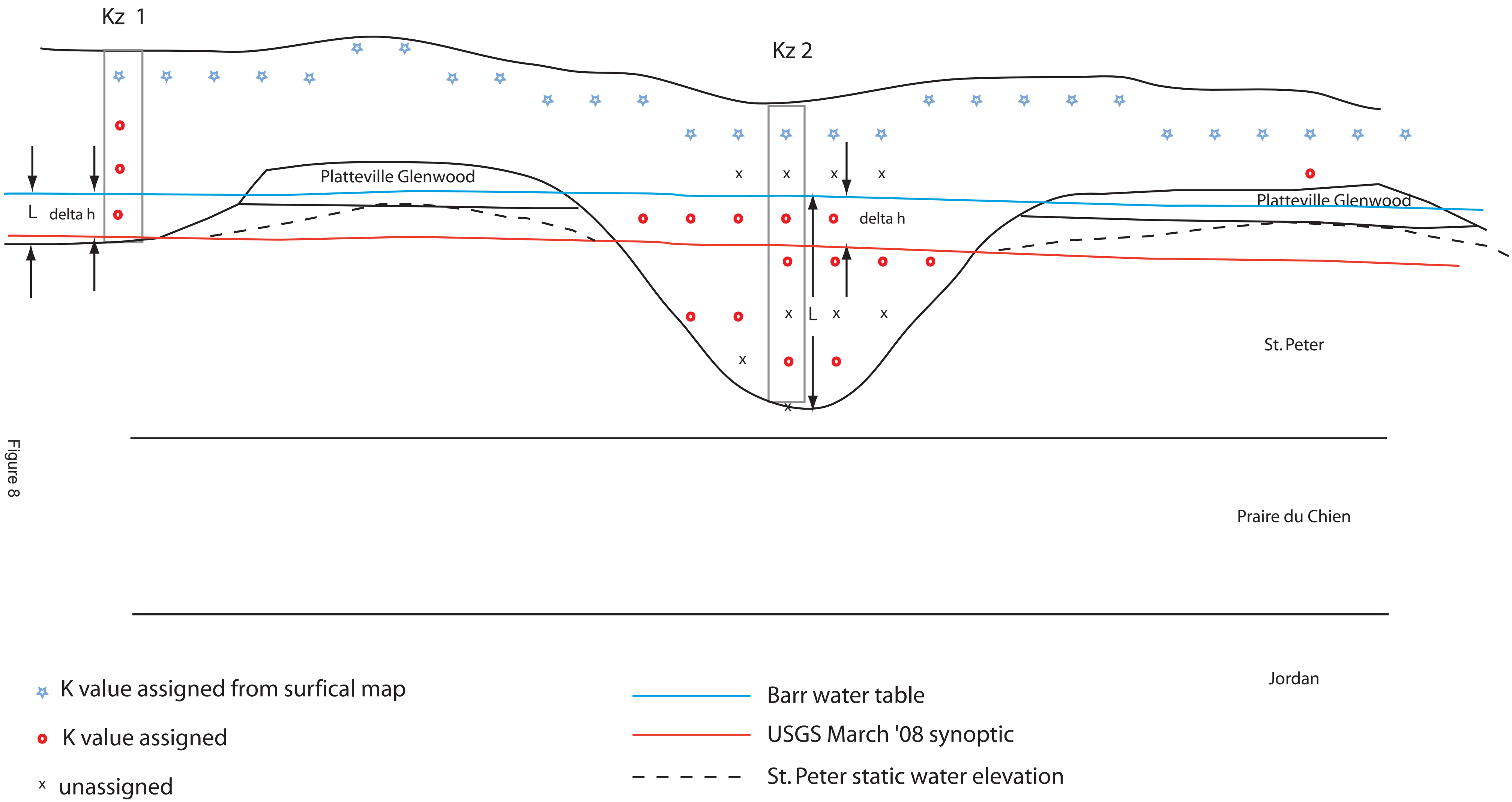



Figure 8

gradient = delta h / L

Kz saturated mean calculated only over distance L

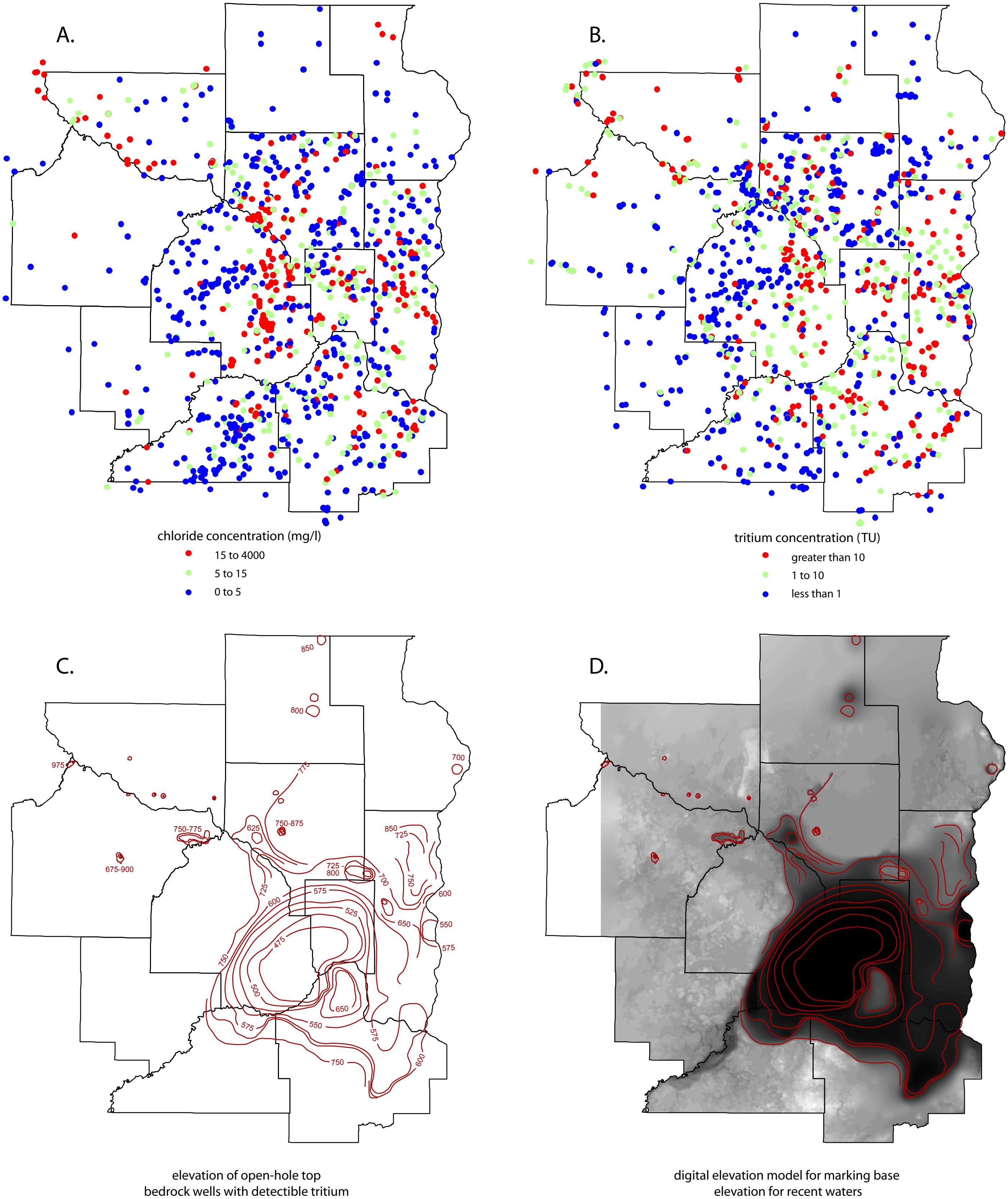
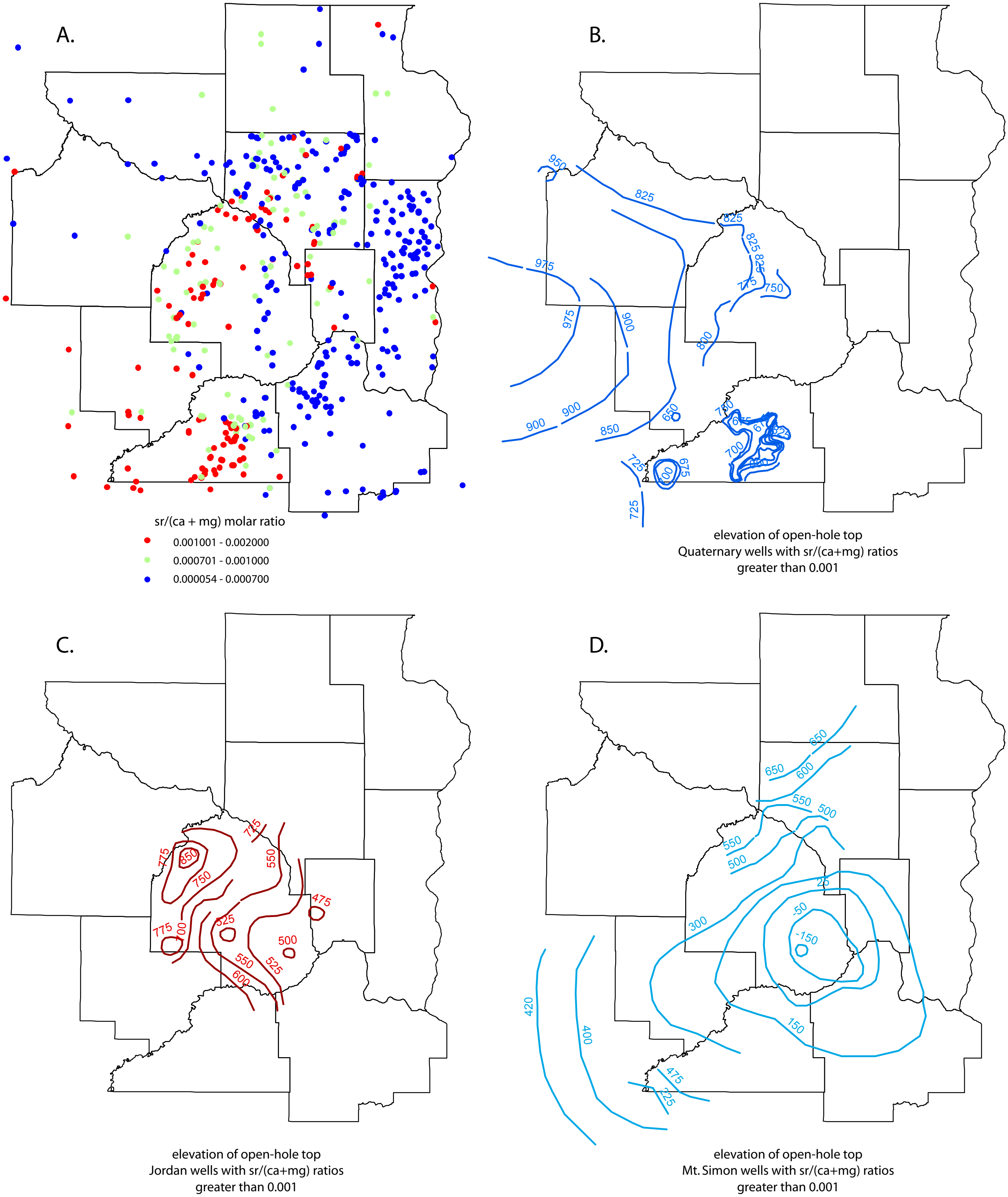

A.
chloride concentration (mg/l)
15 to 4000
5 to 15
0 to 5
B.
tritium concentration (TU)
greater than 10
1 to 10
less than 1
C.
elevation of open-hole top
bedrock wells with detectible tritium
D.
digital elevation model for marking base
elevation for recent waters

Figure 9



A.
sr/(ca + mg) molar ratio
0.001001 - 0.002000
0.000701 - 0.001000
0.000054 - 0.000700
B.
950
825
825
825
825
975
975
900
775
750
800
900
900
850
650
725
725
675
700
elevation of open-hole top
Quaternary wells with sr/(ca+mg) ratios
greater than 0.001
C.
775
850
750
775
550
475
775
700
525
500
550
525
600
elevation of open-hole top
Jordan wells with sr/(ca+mg) ratios
greater than 0.001
D.
650
650
600
550
500
550
500
25
-50
-150
300
420
400
150
475
225
elevation of open-hole top
Mt. Simon wells with sr/(ca+mg) ratios
greater than 0.001


Figure 10

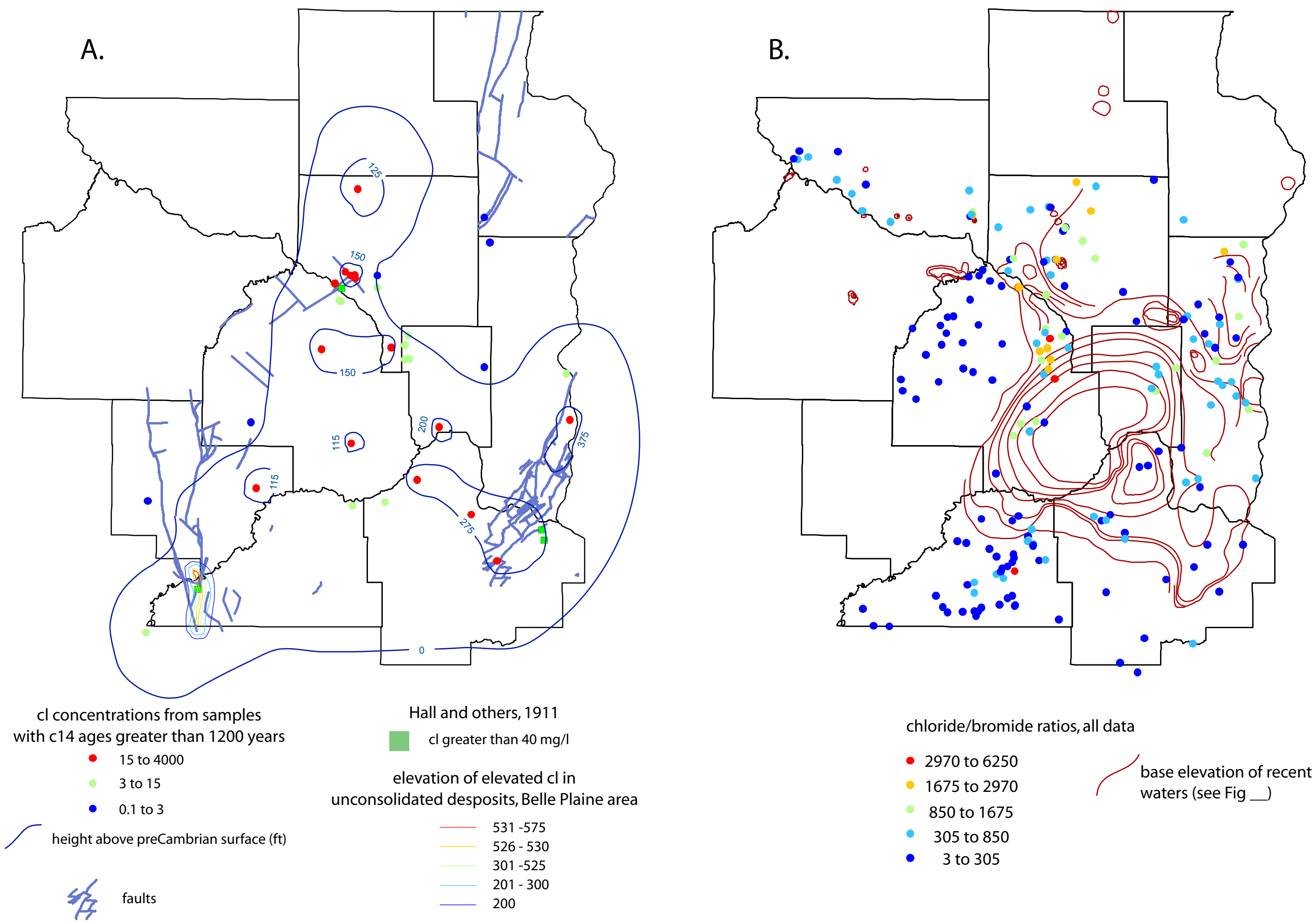

A.
125
150
150
115
200
115
375
275
0
cl concentrations from samples with c14 ages greater than 1200 years
15 to 4000
3 to 15
0.1 to 3
height above preCambrian surface (ft)
faults
Hall and others, 1911
cl greater than 40 mg/l
elevation of elevated cl in unconsolidated desposits, Belle Plaine area
531 -575
526 - 530
301 -525
201 - 300
200
B.
chloride/bromide ratios, all data
2970 to 6250
1675 to 2970
850 to 1675
305 to 850
3 to 305
base elevation of recent waters (see Fig __)

Figure 11

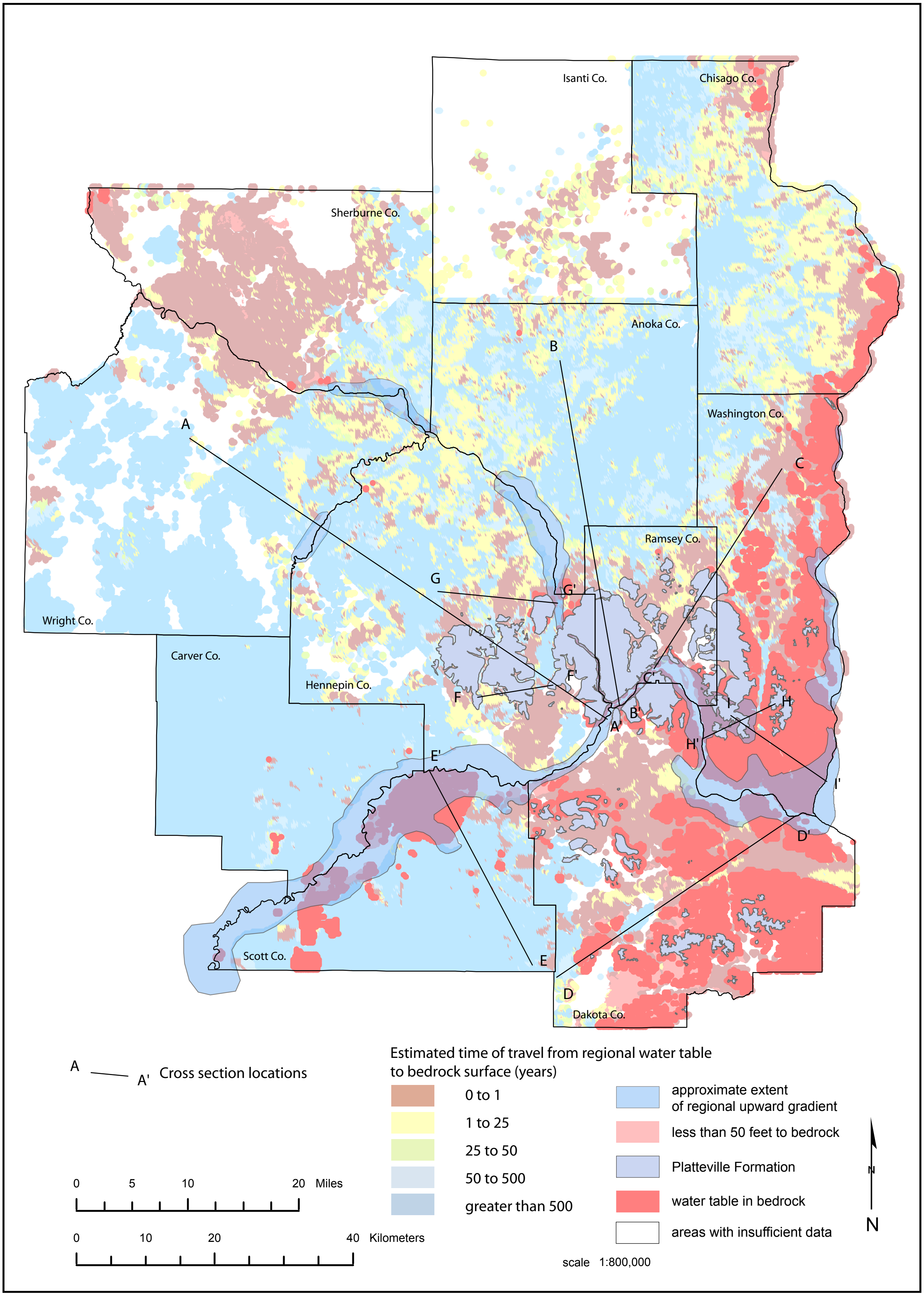
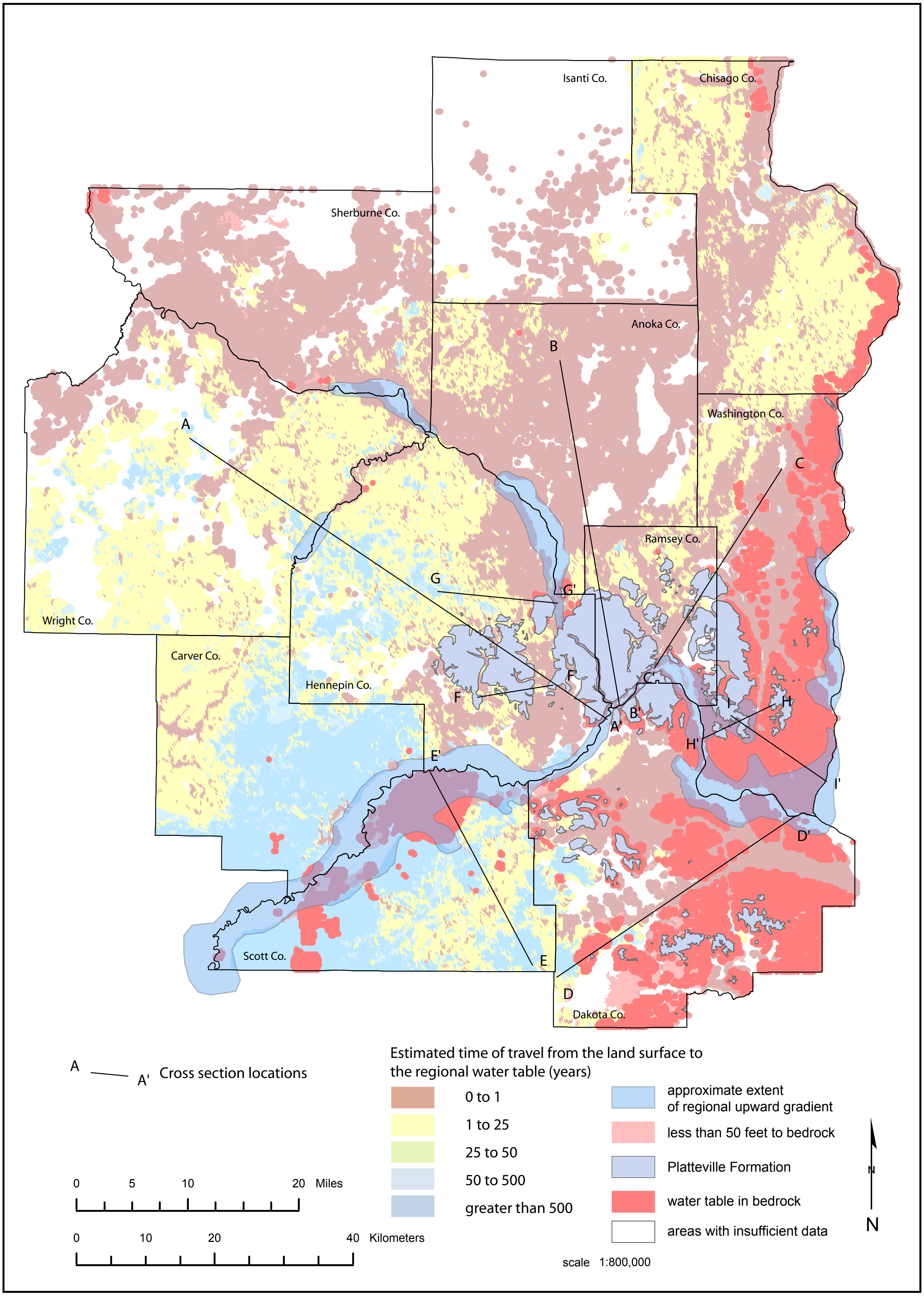
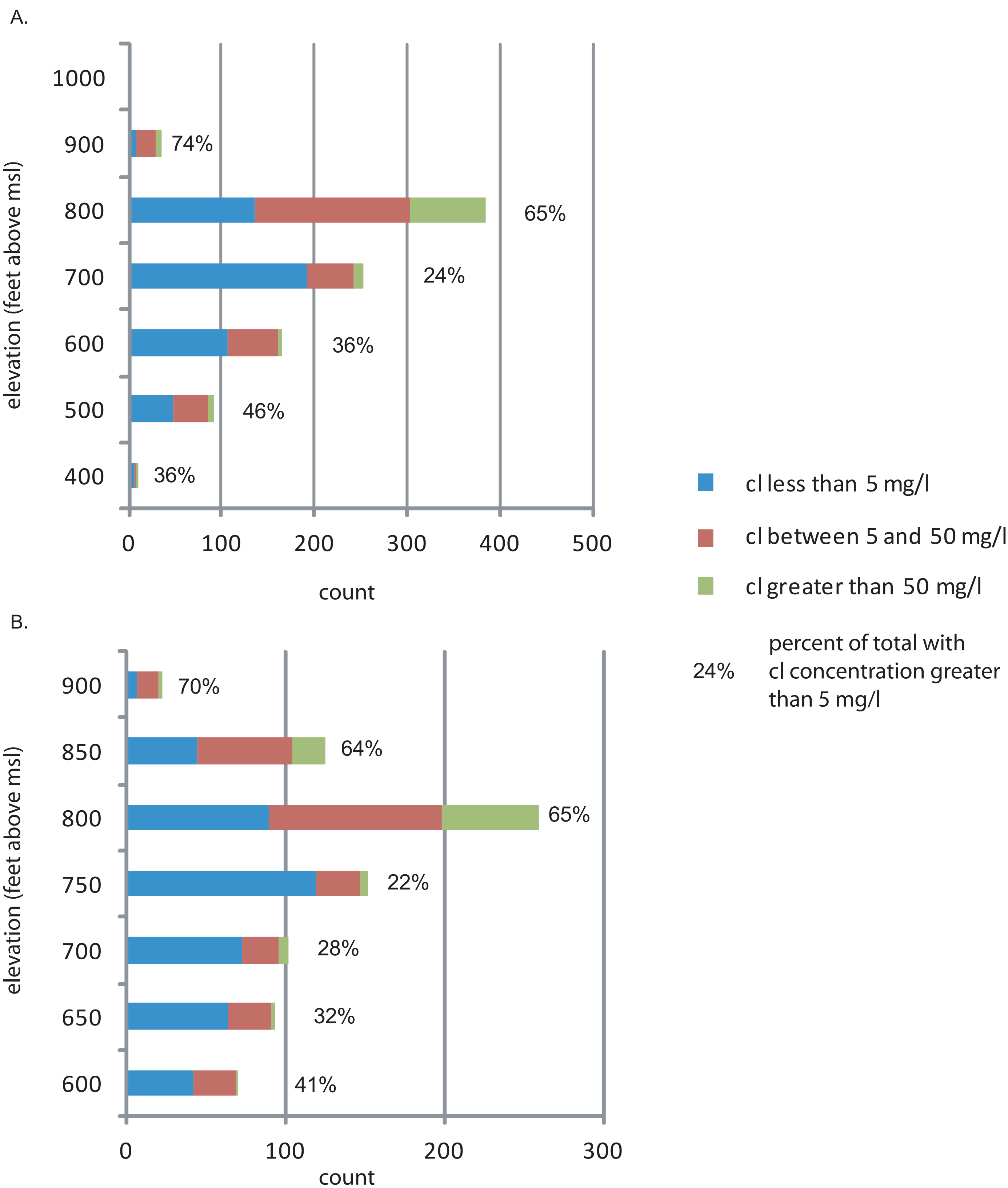

Isanti Co.
Chisago Co.
Sherburne Co.
Anoka Co.
Washington Co.
Ramsey Co.
Wright Co.
Carver Co.
Hennepin Co.
Scott Co.
Dakota Co.
A
A'
B
B'
C
C'
D
D'
E
E'
F
F'
G
G'
H
H'
I
I'
A — A' Cross section locations
Estimated time of travel from regional water table to bedrock surface (years)
0 to 1
1 to 25
25 to 50
50 to 500
greater than 500
approximate extent of regional upward gradient
less than 50 feet to bedrock
Platteville Formation
water table in bedrock
areas with insufficient data
0 5 10 20 Miles
0 10 20 40 Kilometers
scale 1:800,000
N

Figure 12



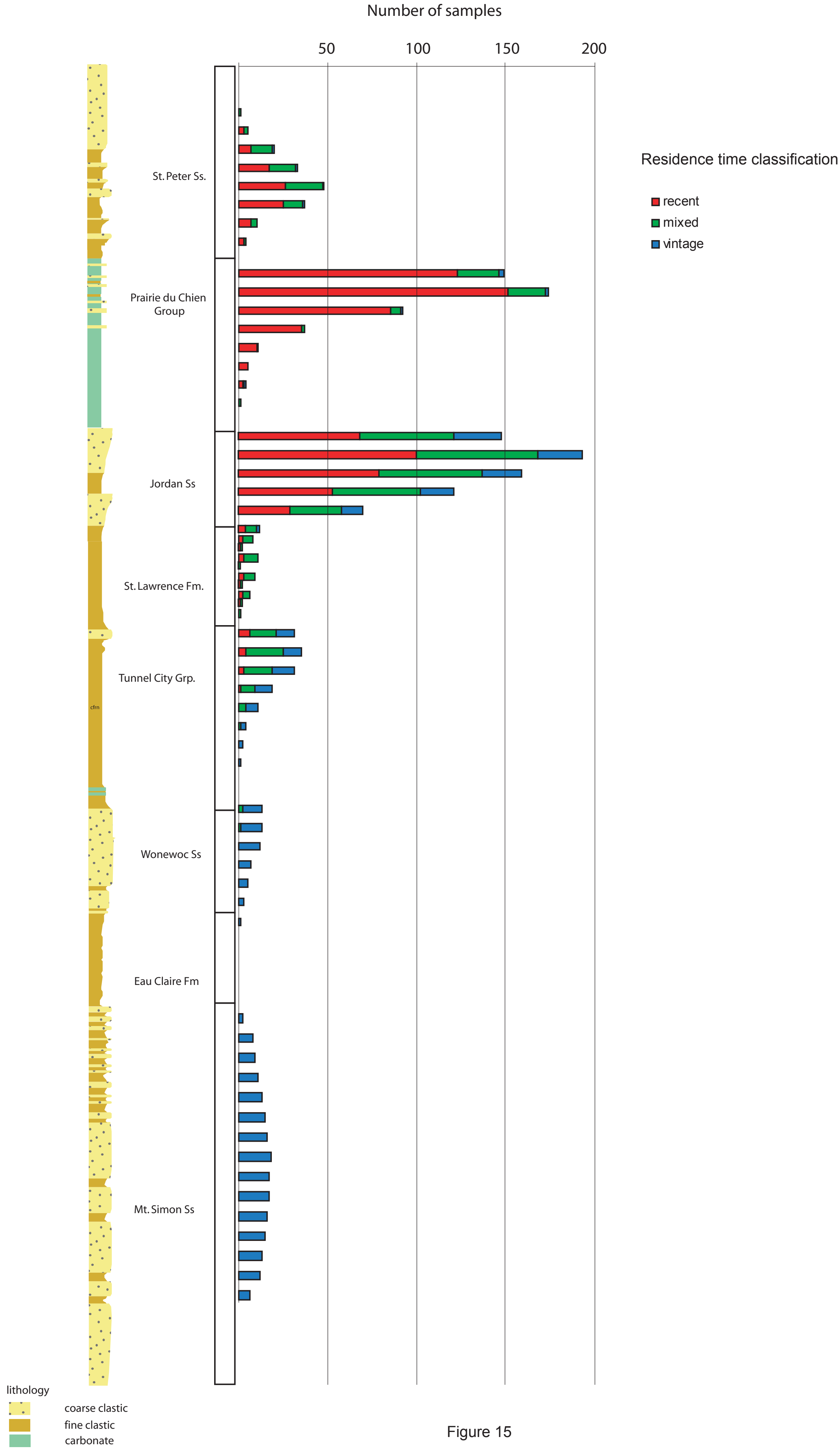
Isanti Co.
Chisago Co.
Sherburne Co.
Anoka Co.
Washington Co.
Ramsey Co.
Wright Co.
Carver Co.
Hennepin Co.
Scott Co.
Dakota Co.
A
A'
B
B'
C
C'
D
D'
E
E'
F
F'
G
G'
H
H'
I
I'
Cross section locations
Estimated time of travel from the land surface to the regional water table (years)
0 to 1
1 to 25
25 to 50
50 to 500
greater than 500
approximate extent of regional upward gradient
less than 50 feet to bedrock
Platteville Formation
water table in bedrock
areas with insufficient data
0 5 10 20 Miles
0 10 20 40 Kilometers
scale 1:800,000
N


Figure 13



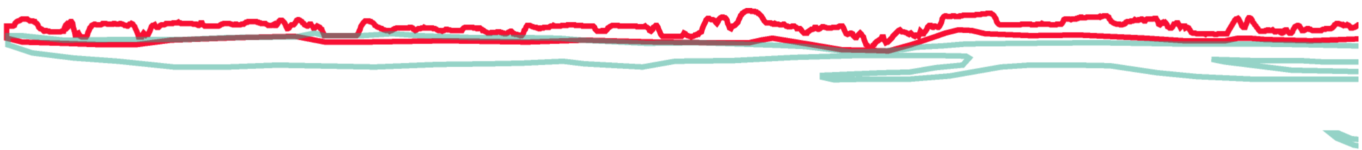
A.
1000
900
800
700
600
500
400
elevation (feet above msl)
74%
65%
24%
36%
46%
36%
0
100
200
300
400
500
count
B.
900
850
800
750
700
650
600
elevation (feet above msl)
70%
64%
65%
22%
28%
32%
41%
0
100
200
300
count
cl less than 5 mg/l
cl between 5 and 50 mg/l
cl greater than 50 mg/l
24%
percent of total with cl concentration greater than 5 mg/l

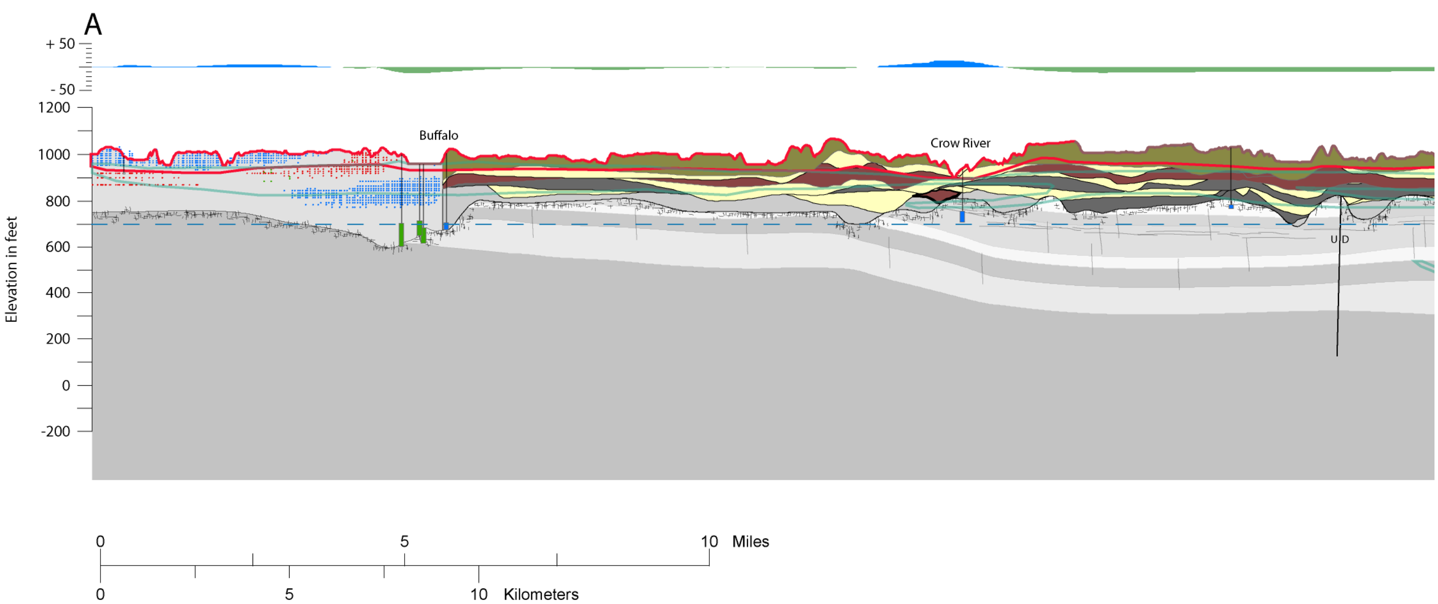

Figure 14



Number of samples
50
100
150
200
St. Peter Ss.
Prairie du Chien Group
Jordan Ss
St. Lawrence Fm.
Tunnel City Grp.
Wonewoc Ss
Eau Claire Fm
Mt. Simon Ss
Residence time classification
recent
mixed
vintage
lithology
coarse clastic
fine clastic
carbonate


Figure 15





A
+ 50
- 50
1200
1000
800
600
400
200
0
-200
Elevation in feet
Buffalo
Crow River
U D
0
5
10 Miles
0
5
10 Kilometers


Figure 16

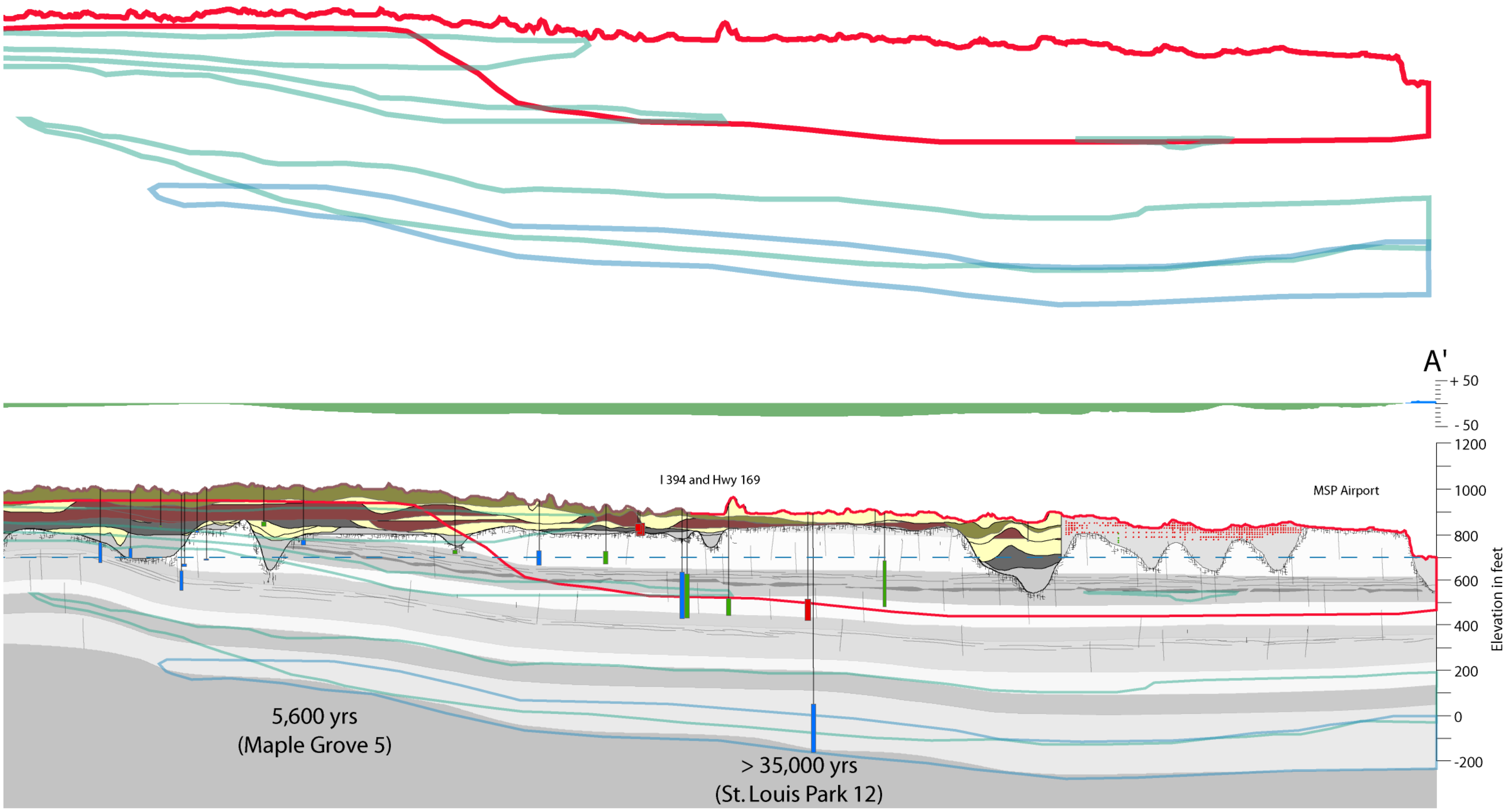
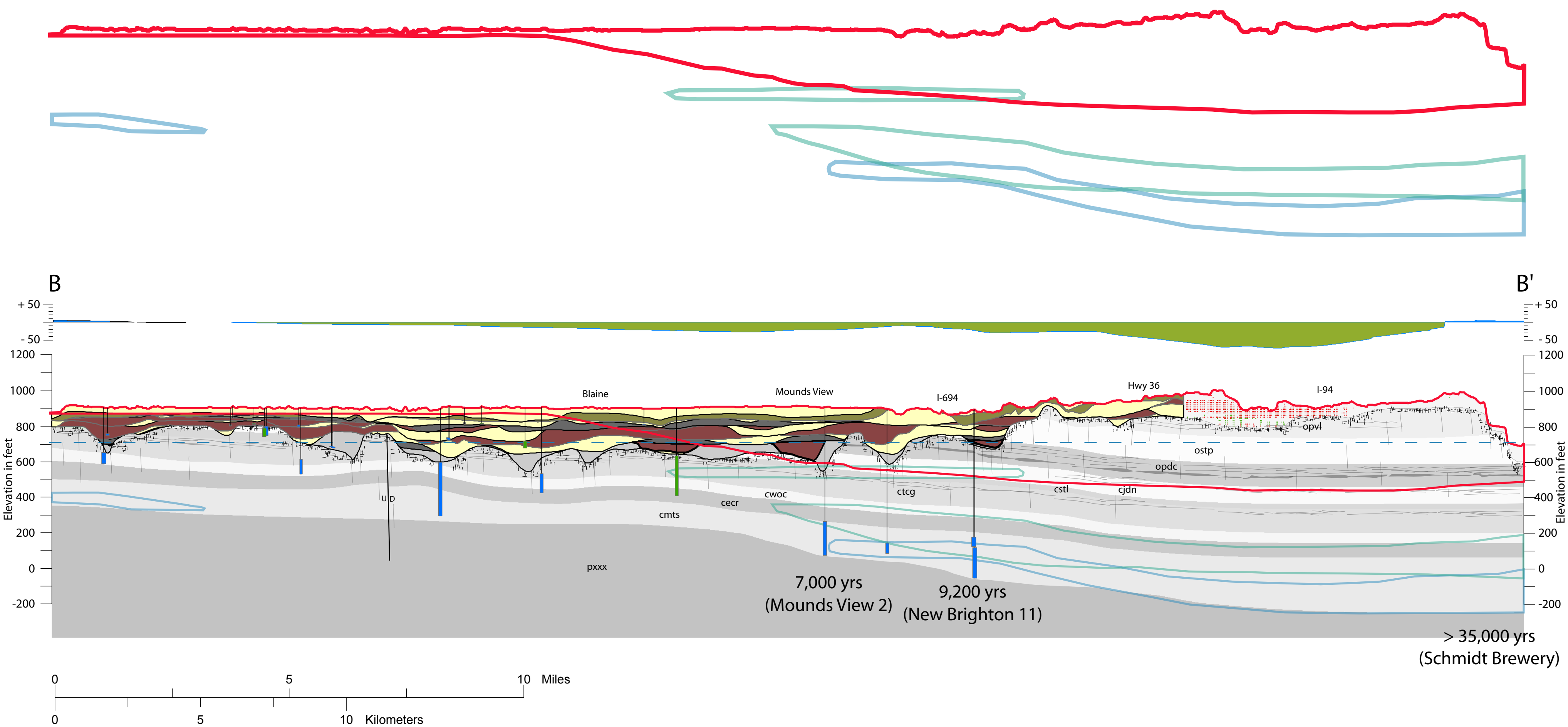
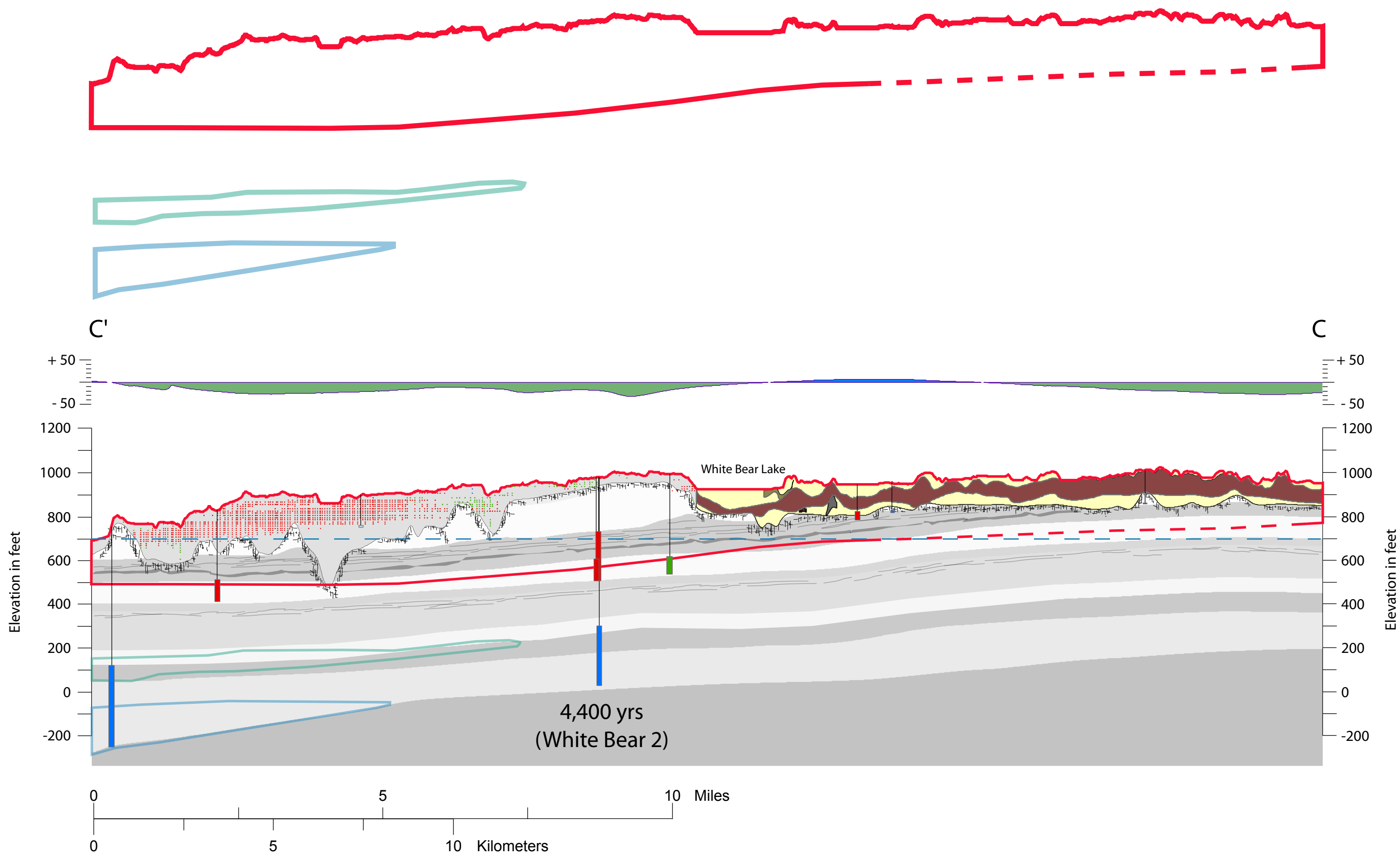



Figure 16 - continued



B
B'
+ 50
- 50
1200
1000
800
600
400
200
0
-200
Elevation in feet
Blaine
Mounds View
I-694
Hwy 36
I-94
opvl
ostp
opdc
cstl
cjdn
ctcg
cwoc
cecr
cmts
U D
pxxx
7,000 yrs
(Mounds View 2)
9,200 yrs
(New Brighton 11)
> 35,000 yrs
(Schmidt Brewery)
0
5
10
Miles
0
5
10
Kilometers


Figure 17



C'
C
+ 50
- 50
1200
1000
800
600
400
200
0
-200
Elevation in feet
White Bear Lake
4,400 yrs
(White Bear 2)
0
5
10
Miles
Kilometers


Figure 18

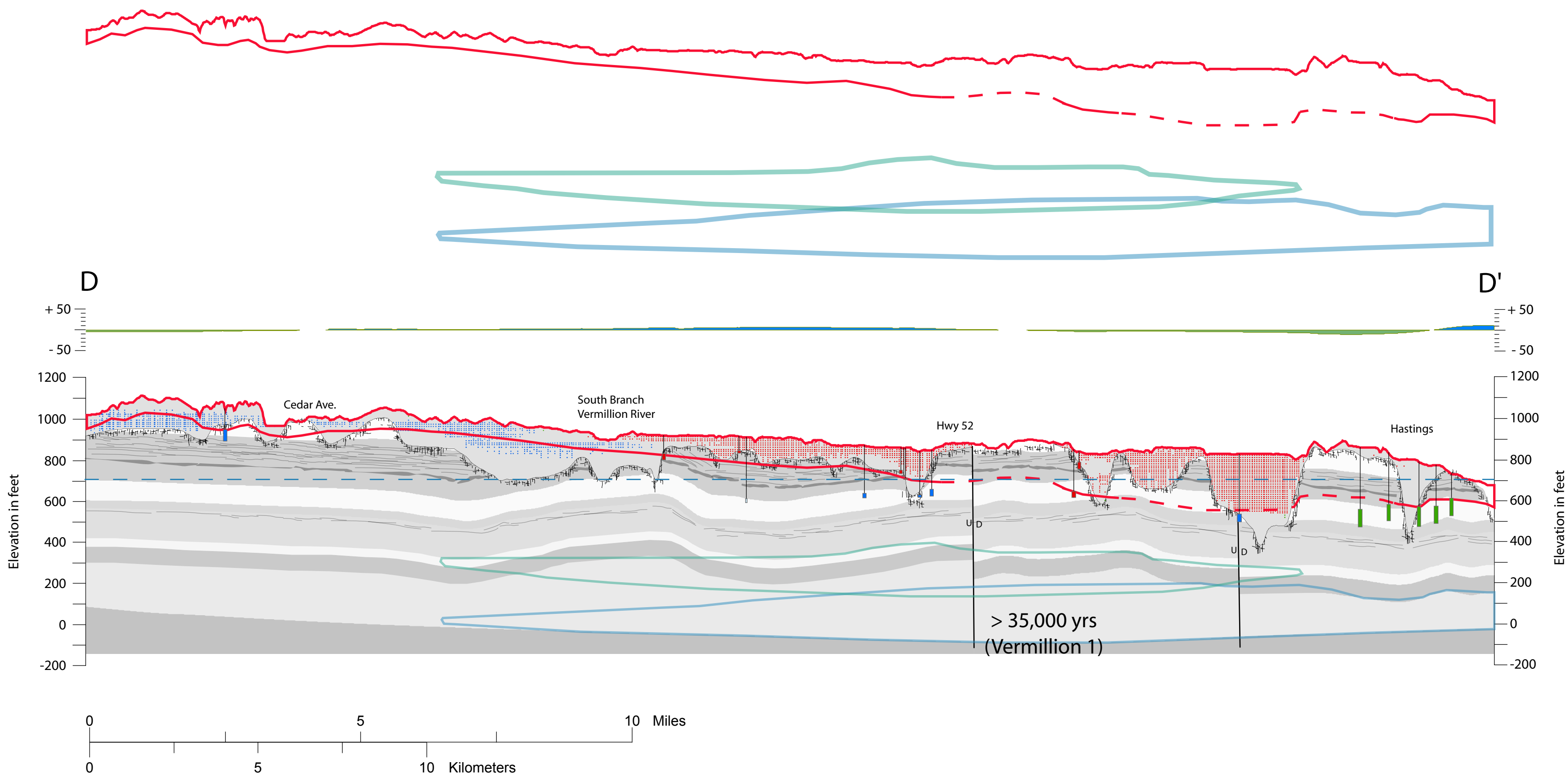

D
D'
+ 50
- 50
1200
1000
800
600
400
200
0
-200
Elevation in feet
Cedar Ave.
South Branch
Vermillion River
Hwy 52
Hastings
U D
U D
> 35,000 yrs
(Vermillion 1)
0
5
10 Miles
0
5
10 Kilometers

Figure 19

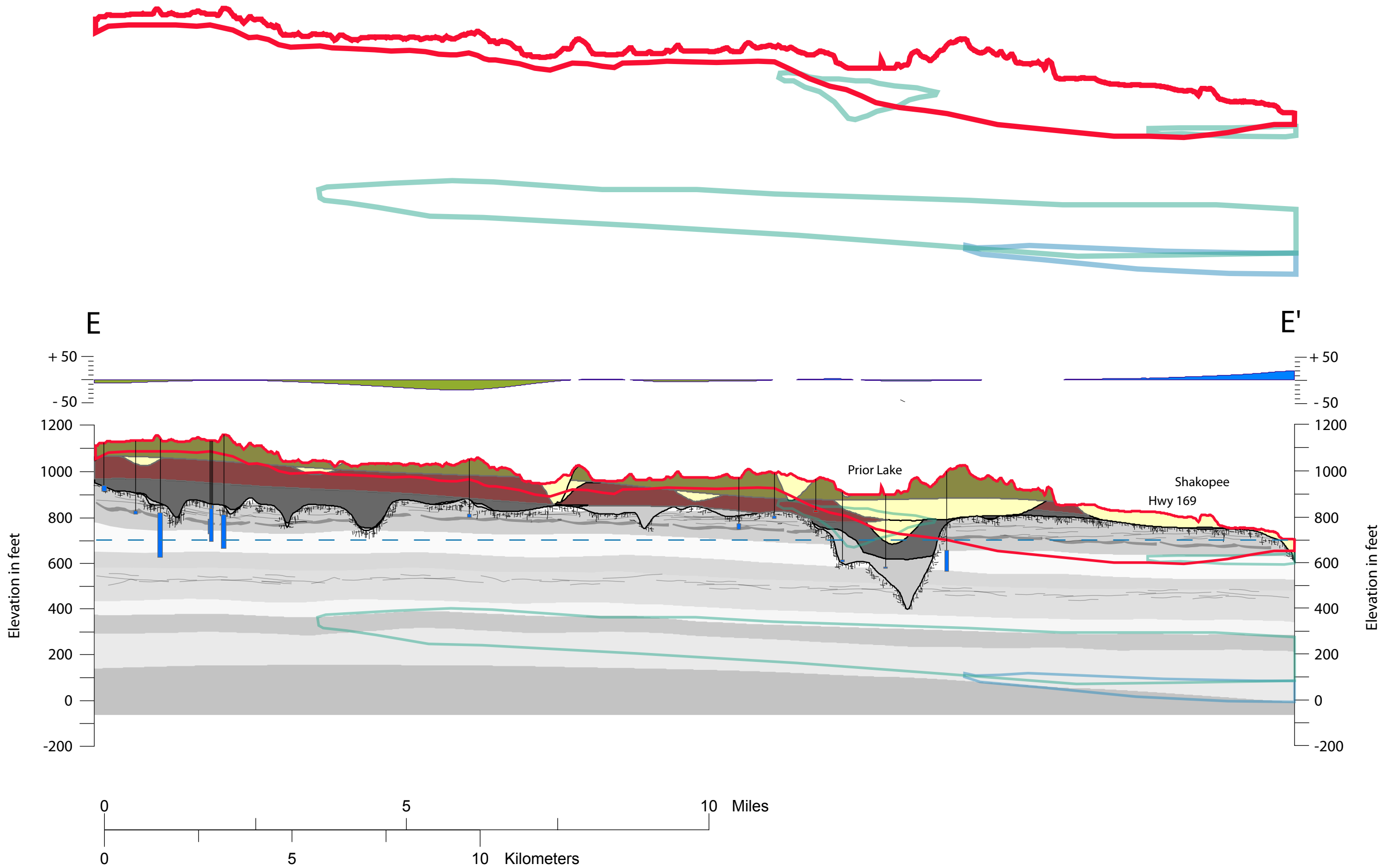
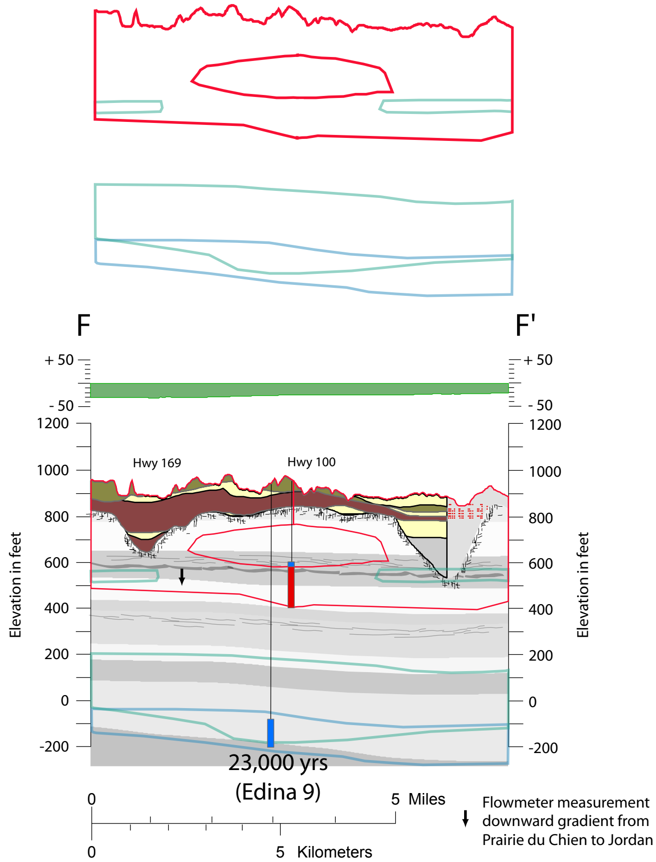
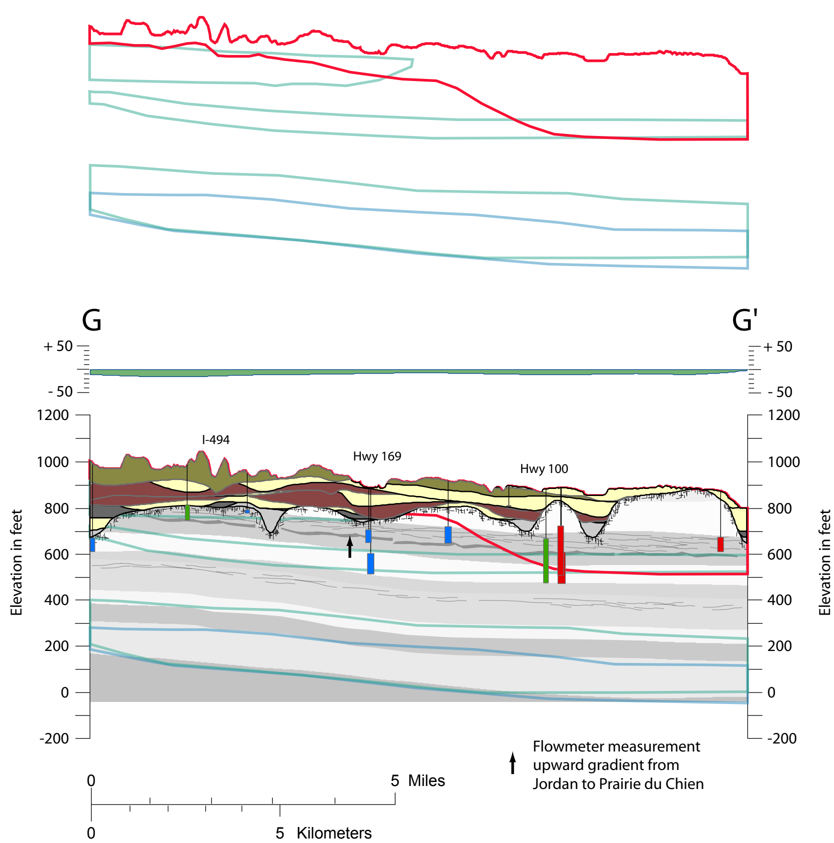

E
E'
+ 50
- 50
1200
1000
800
600
400
200
0
-200
Elevation in feet
Prior Lake
Shakopee
Hwy 169
0
5
10
Miles
Kilometers

Figure 20



F
F'
+ 50
- 50
1200
1000
800
600
400
200
0
-200
Elevation in feet
Hwy 169
Hwy 100
23,000 yrs
(Edina 9)
0
5 Miles
0
5 Kilometers
Flowmeter measurement
downward gradient from
Prairie du Chien to Jordan

G
G'
+ 50
- 50
1200
1000
800
600
400
200
0
-200
Elevation in feet
I-494
Hwy 169
Hwy 100
0
5 Miles
0
5 Kilometers
Flowmeter measurement
upward gradient from
Jordan to Prairie du Chien


Figure 21

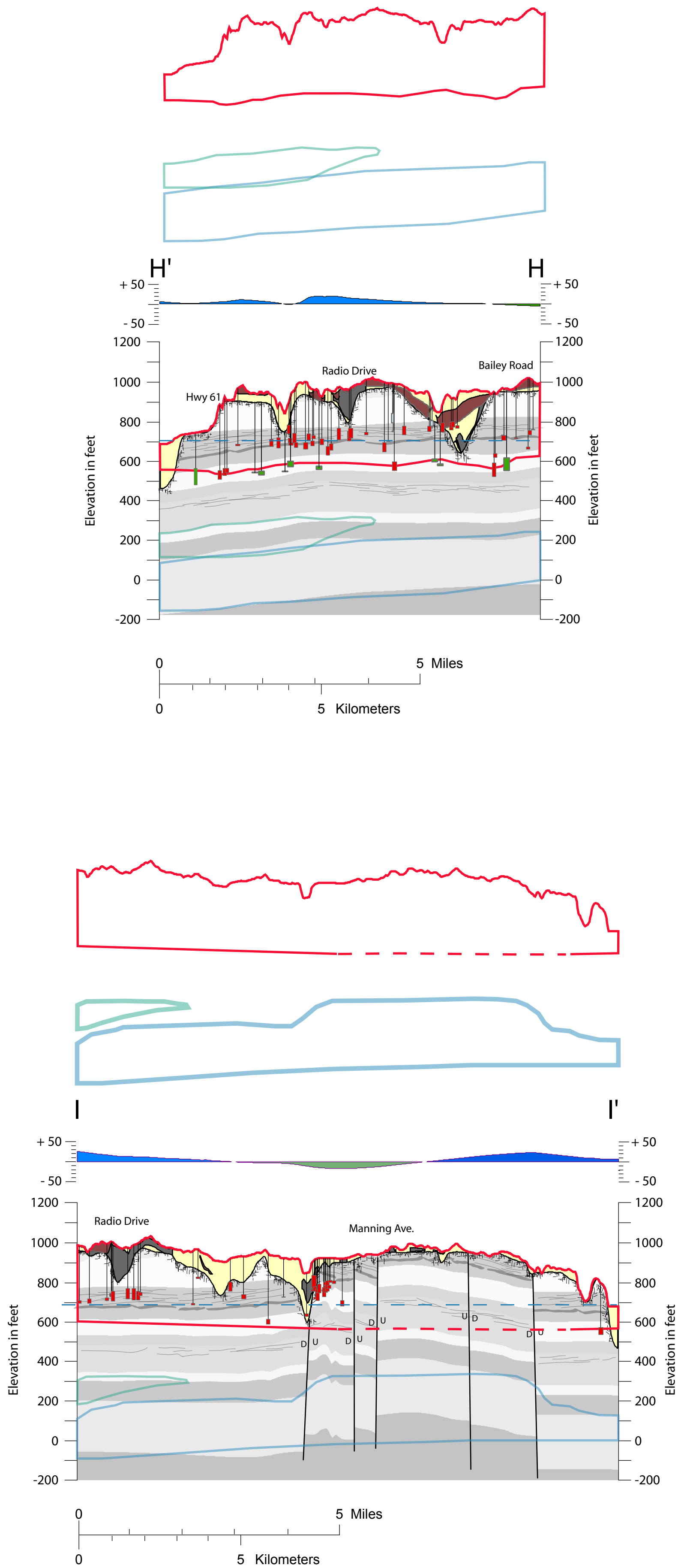
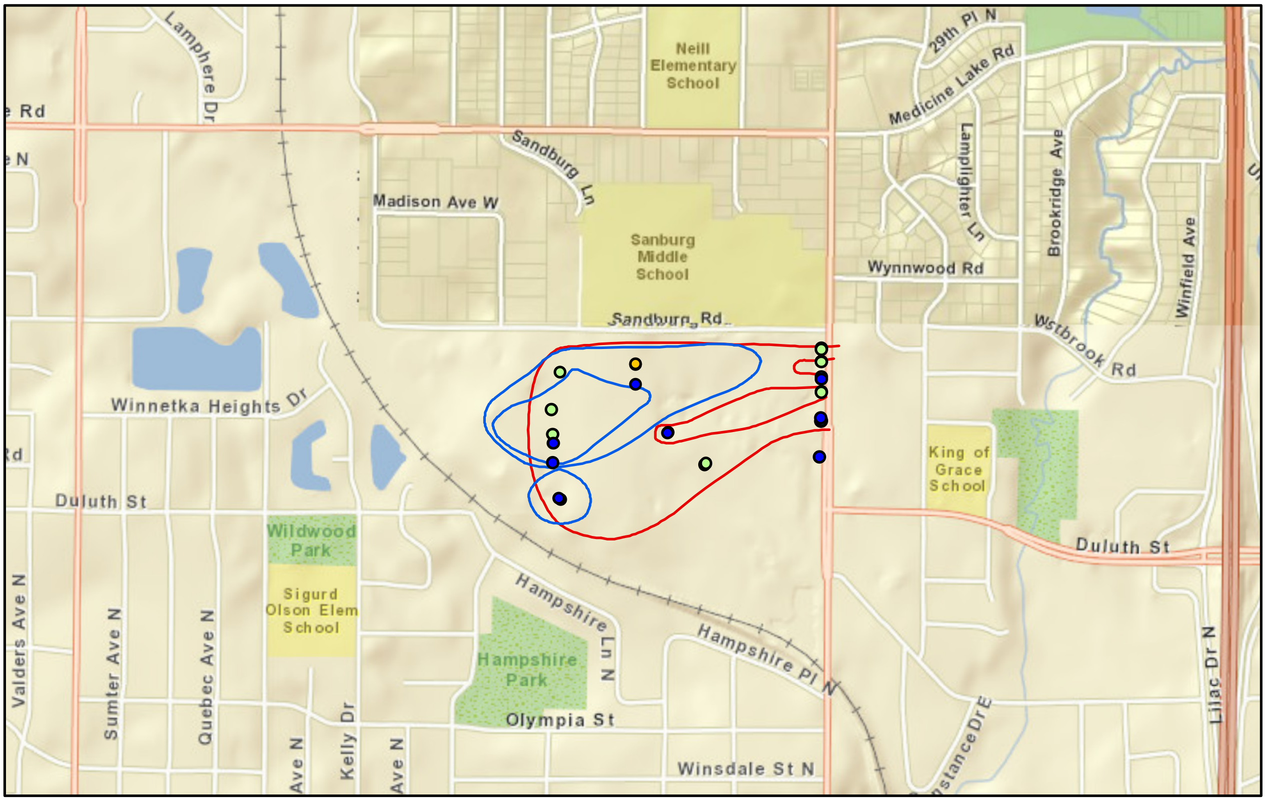
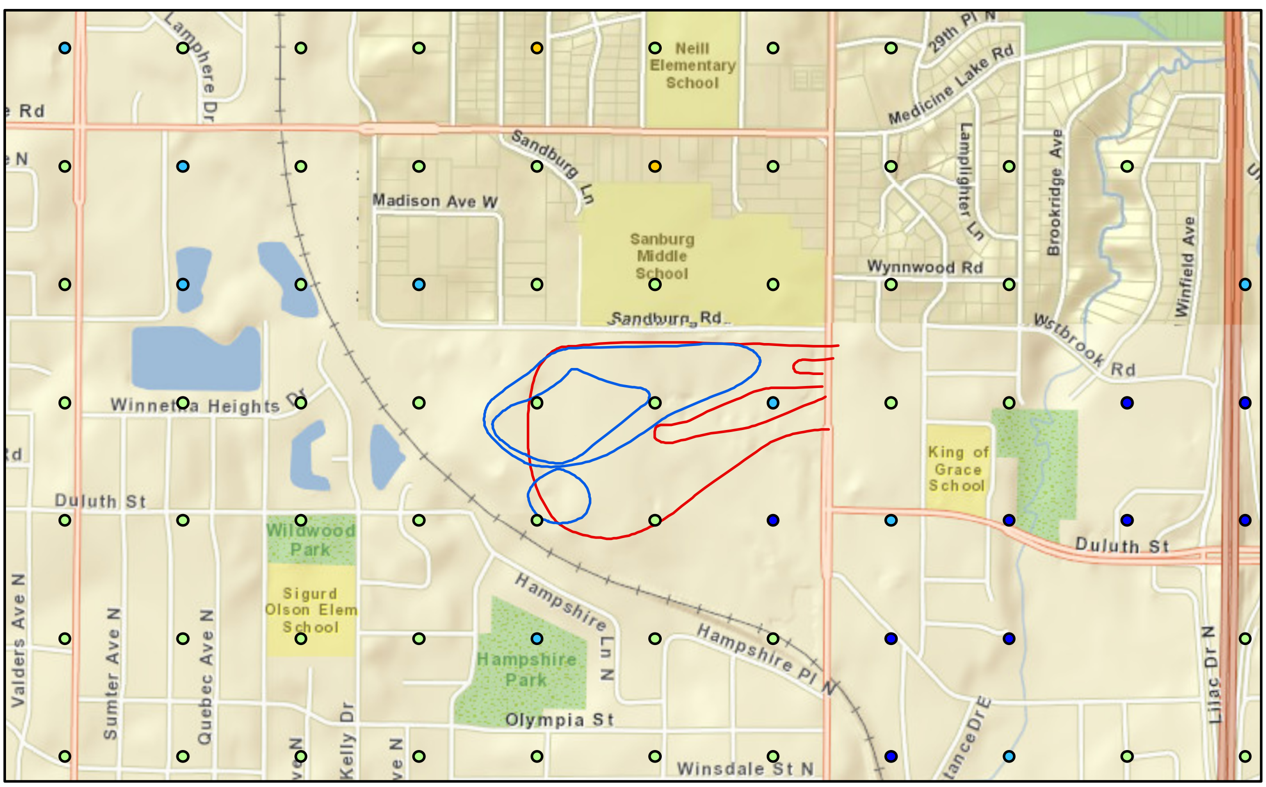

H'
H
+ 50
- 50
1200
1000
800
600
400
200
0
-200
Elevation in feet
Radio Drive
Bailey Road
Hwy 61
0
5 Miles
5 Kilometers
I
I'
Radio Drive
Manning Ave.
D U
U D
D U

Figure 22




A.

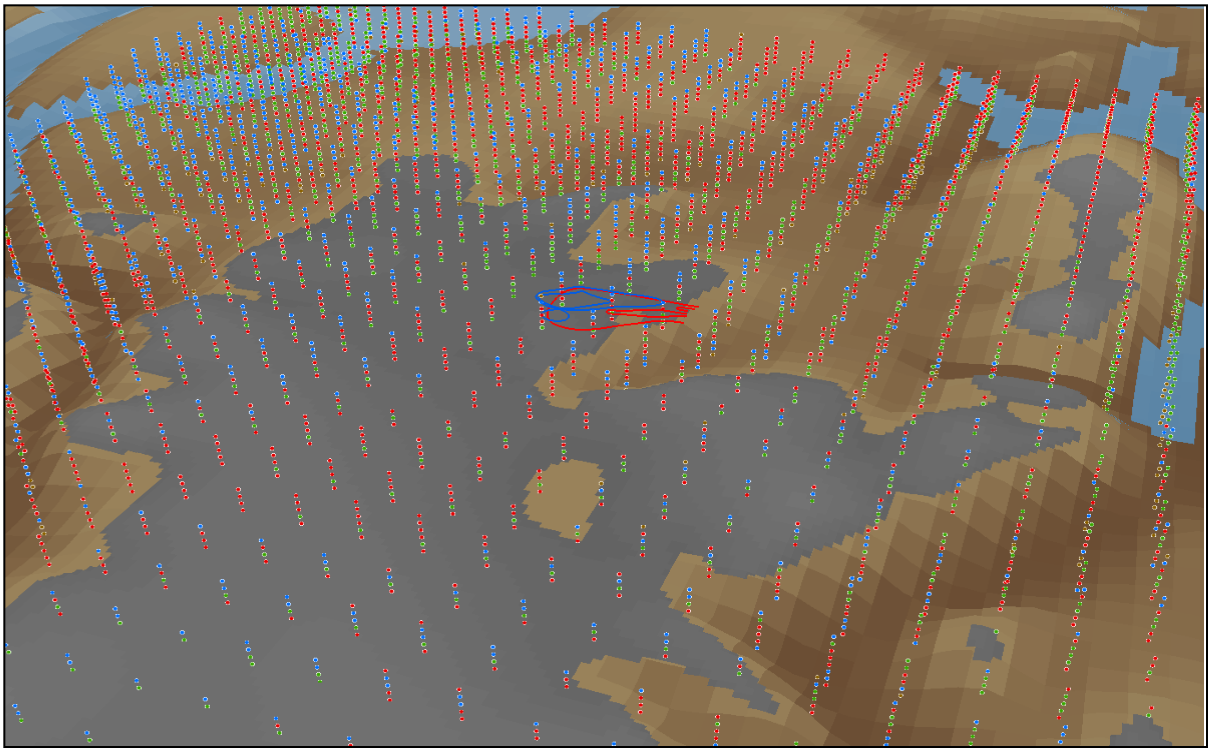



B.

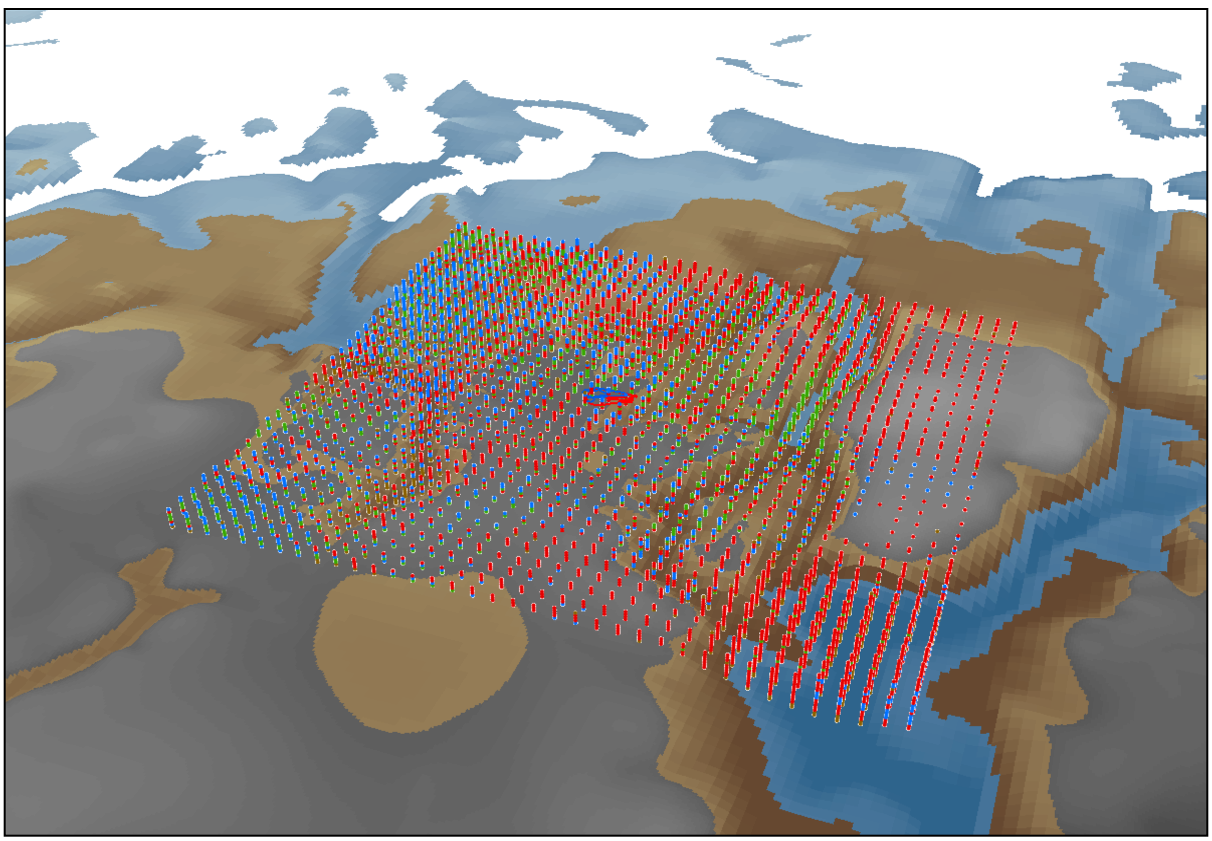
1990 plume

2009 plume

Figure 23



A.



B.

Generalized unconsilidated sediment textures. grid spacing 250 meters in horizontal, 20 feet in vertical

- coarse-grained
- coarse- to fine-grained
- fine-grained

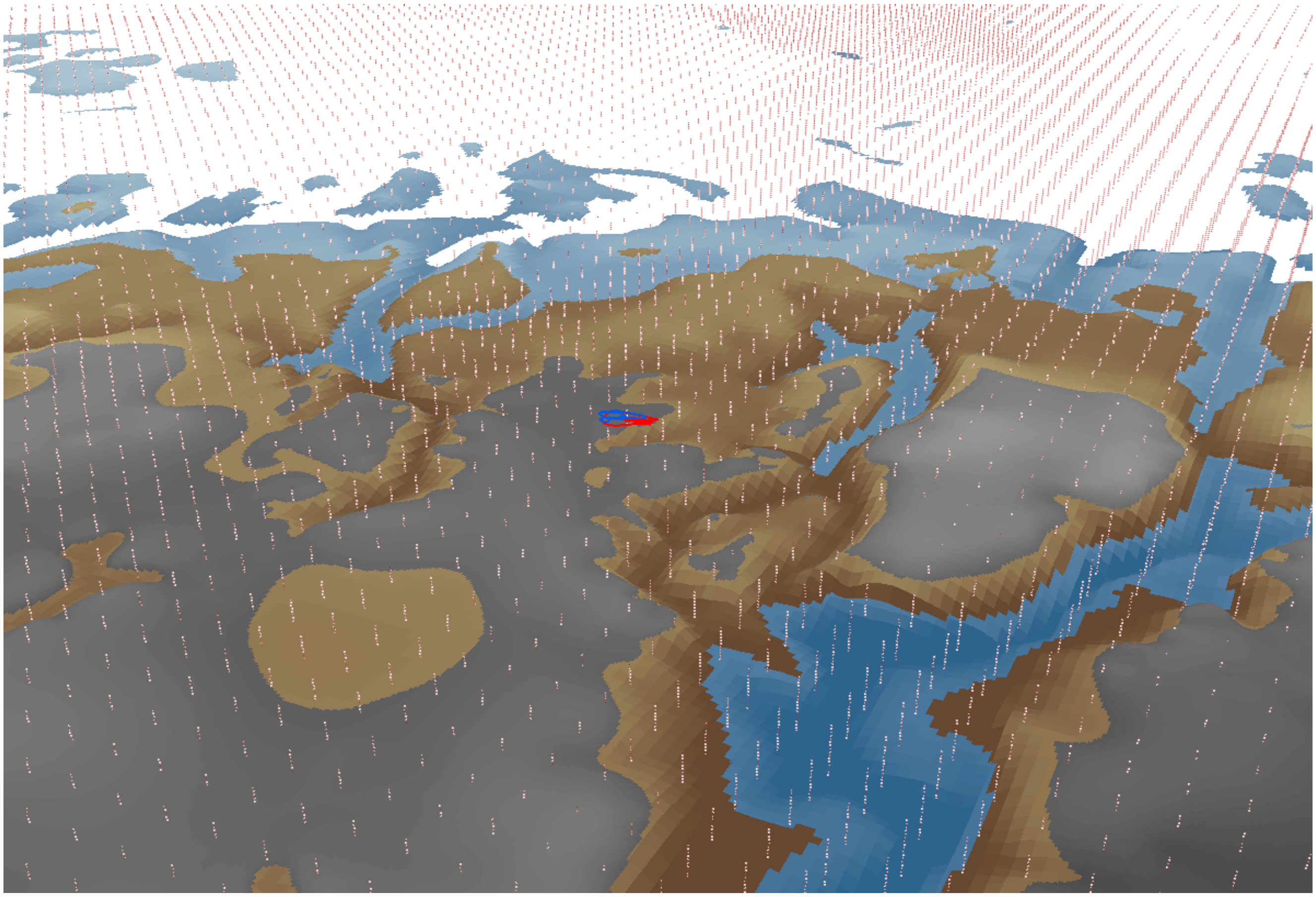
Bedrock

- Platteville Formation
- St. Peter Sandstone
- Prairie du Chien Group
- bedrock stratigraphically lower than the Pairie du Chien Group

1990 plume

2009 plume

Figure 24



C.

Regional distribution of recent waters.
grid spacing 500 meters in horizontal, 20 feet
in vertical

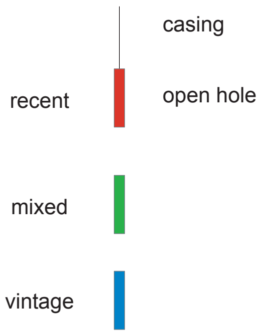
- gridpoint identifying recent waters, based on elevation of detectible tritium or anthropogenic contaminants

**hydrochemical facies**

*Recent/anthropogenic waters*:
waters distinguished primarily by the presence of detectible tritium. Other indicators of recent water such as elevated chloride, nitrate, or anthropogenic compounds generally also present.

*Elevated strontium to calcium plus magnesium ratios:*
waters distinguished by having strontium to calcium plus magnesium molar ratios greater than 0.001. Elevated strontium to calcium plus magnesium ratios may be associated with recharge through NW provenance tills, and are also considered to an indicator of longer residence time

*Naturally elevated chloride*:
waters distinguished by having chloride levels greater than 15 ppm and carbon 14 age dates greater than 1,000 years. Where data is available, these waters should also have chloride to bromide ratios less than 300.




Selected wells from the water chemistry database. Colors of open-hole intervals correspond to assigned qualitative age classes. Recent waters are dominated by waters having entered the ground since the late 1950s; Vintage water are dominated by waters having entered the ground prior to the late 1950's; Mixed waters are considered a combination of recent vintage waters. See text for discussion

5,600 yrs
(Maple Grove 5)

Mt. Simon Aquifer age determined from carbon-14 analysis; well name (Lively, etal., 1992) for wells not shown, location projected to cross section line.

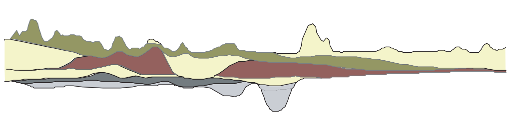
**hydraulic gradient**


Head difference between regional water table and bedrock potentiometric surface, in feet. Blue indicates upward gradient; green indicates downward gradient

flowmeter measuremt. errow indicates direction of ambient flow in an open borehole

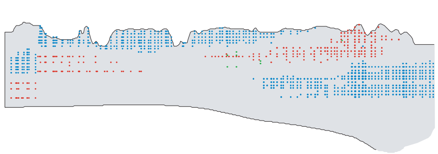
700 feet above msl line, marks regional discharge elevation as approximate elevation of the Mississippi, Minnesota and St. Croix Rivers

**mapped Quaternary stratigraphy**



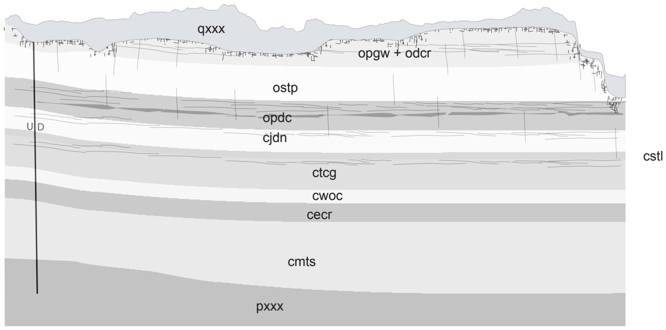
- sand and gravel
- loam to clay loam - generally NW provenance till
- loam to sandy loam - generally NE provenance till
- loam, silt rich; silt and clay - generally N provenance till; lacustrine deposits
- undifferentiated

**interpolated model**



- likelyhood of coarse-grained deposits > 40%
- likelyhood of coarse- to fine-grained deposits > 40%
- likelyhood of fine-grained material > 40%

Figure 25




| | |
|---|---|
| qxxx | Quaternary, undifferentiated |
| opgw + odcr | Plattville Fm., Glenwood Shale, Decorah Shale |
| ostp | St. Peter Sandstone |
| opdc | Prairie du Chien Group |
| cjdn | Jordan Sandstone |
| cstl | St. Lawrence Formation |
| ctcg | Tunnel City Group |
| cwoc | Wonewoc Sandstone |
| cecr | Eau Claire Formation |
| cmts | Mt. Simon Sandstone |
| pxxx | pre-Cambrian, undifferentiated |

near-surface fractures

hydraulically active bedding plane fractures and conduits

systematic vertical fractures

U D bedrock fault, indicating upthrown and downthrown sides

Figure 25 - continued