GEOLOGIC INVESTIGATION FOR PORTIONS OF THE TWIN CITIES METROPOLITAN AREA: I. Quaternary/Bedrock Hydraulic Conductivity, II. Groundwater Chemistry

Metropolitan Council Water Supply Master Plan Development

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Executive Summary

This report summarizes work performed by the Minnesota Geological Survey (MGS) in partial fulfillment of work as described under contract 091037 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, hydraulic conductivity data for both unconsolidated and bedrock materials, along with historic ground water chemical and isotopic data were assembled into spatial databases that can be used in a geographic information systems (GIS) format. Wherever possible, depth of the sampled or tested material was included along with location information, so the three-dimensional distribution of these data could be queried and compared to ongoing Metropolitan Council planning projects. For hydraulic conductivity data, the focus was on glacial-related Quaternary deposits, because these are the data most lacking for current ground-water modeling investigations. Hydrostratigraphic attributes of fine-grained materials were evaluated based on a comparison of measured values with texture, depth, and a literature review of other midcontinent tills. For water chemistry, the goal was to display the distribution of chemical types (hydrochemical facies) as a means to illustrate possible ground-water flowpaths. A sample acquisition date was included so the database could also be used to assess changes in chemical composition with time. For both hydraulic conductivity data and water chemistry, attributes were also assigned to a regional dataset of regularly spaced grid points to facilitate importing the data into groundwater modeling programs.

The individual point data geodatabase (PointData.mdb) provides access to hydraulic conductivity and chemical data for a specific site. Because much of the site information on

geologic setting comes from different consultant's reports, there is a lack of consistency in lithologic and stratigraphic attributes. In this way, PointData.mdb is best suited as a "what's in my neighborhood" type of dataset rather than for rigorous regional spatial analysis of hydraulic conductivity data. The grid design of regional summary data geodatabase (RegionalData.gdb) is meant to provide the means to readily import and adjust hydraulic conductivity and chemical data in ground water flow models, or for use as an additional layer for three-dimensional evaluation of model results. Use of regional summary data in these settings can aid in refining conceptual models of ground-water flow.

Introduction

The goal of this investigation was to provide datasets that would assist the Metropolitan Council with regional ground water planning. Specifically, hydraulic conductivity data for both unconsolidated and bedrock materials, along with historic ground water chemical and isotopic data were assembled into spatial databases that can be used in a geographic information systems (GIS) format. Data were assembled in both a point format to assess conditions at individual sites, and as regional summary data. The grid design of regional summary data provides the means to readily import and adjust hydraulic conductivity and chemical data in ground water flow models, or for use as an additional layer for three-dimensional evaluation of model results.

Methods

Data were acquired for the extended 11-county Twin Cities metropolitan area (Fig. 1). Sources of hydraulic conductivity data were the Minnesota Pollution Control Agency (MPCA) Superfund, Closed Landfill, Active Landfill, and Tanks-Leaks site files; Minnesota Department of Health (MDH) aquifer test database (Minnesota Department of Health, 2010); Minnesota

Department of Natural Resources (DNR) combined DNR/USGS aquifer test database (Minnesota Department of Natural Resources, 2010); private consultant firms; and various unpublished reports and documents on file at the Minnesota Geological Survey (MGS), most notably data from the Metropolitan Inter-County Association (MICA) regional landfill siting study (Metropolitan Inter-County Association, 1981). Based on our experience reviewing and compiling hydraulic conductivity data from these sources, we believe we compiled at most perhaps 20 to 30 percent of the total of such data for the 11 county Twin Cities Metro area that is accessible through public agencies. The bulk of such data likely is within archived site files at the MPCA. The highest volume and greatest spatial distribution of hydraulic conductivity data comes from values derived from the County Well Index (CWI) specific capacity data. Specific capacity data were converted to hydraulic conductivity data according to methods described in Bradbury and Rothschild (1985).

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 ground-water 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 added as part of this investigation include earlier historic data from both regional (Hall and others, 1911; Maderak, 1963; Sabel, 1985; Lively and others, 1992) and local studies (Alexander and Ross, 2003; Andrews and others, 2005). Newly acquired data as part of this study include tritium and strontium isotope analyses from northwestern Hennepin County.

Hydraulic conductivity and water chemistry data were assembled in ESRI "geodatabase" format, both as point data representing the location and depth of the test or collected sample, and as regional summary point data, where values were assigned to regularly spaced intervals both in horizontal and vertical dimensions across the study area. A detailed description of the database formats and their attributes are included in Appendices B-D.

Regional summary datasets are organized into gridpoints with 500-meter by 500-meter spacing in the horizontal dimension, 20-foot spacing in the vertical dimension for unconsolidated deposits, and 40-foot spacing in the vertical dimension for Paleozoic bedrock (Fig. 2). A mixture of metric and English customary units was used to accommodate basemap units (Universal Transverse Mercator—meter) and water well database (feet). Regional summary gridpoints for hydraulic conductivity data cover unconsolidated deposits only, extending in the vertical dimension from 350 to 1,210 feet above mean sea level. Points in unconsolidated sediments greater than 25 feet deep were assigned ranges of values based on their position relative to existing subsurface digital elevation models for Quaternary sediments (Fig. 1) and whether or not they are greater than 60 feet deep, where hydraulic conductivity values for fine grained sediments are expected to decrease from equivalent near surface textures. Points in unconsolidated sediments less than 25 feet deep were assigned values based on the metro area surficial geology map (Meyer, 2007) where they fall within the map area. The field “K_Class”in the regional summary dataset contains an integer value corresponding to a range of hydraulic conductivities listed in lookup table “xK_Class”. Areas outside of existing subsurface models or the surficial geology map were assigned values of "unknown".

Regional summary gridpoints of water chemistry data were assigned values based on interpreted hydrochemical facies, falling into three categories: 1. Recent/anthropogenic waters; 2. Naturally elevated chloride; and 3. Waters categorized by cation ratios of strontium to calcium plus magnesium. Category 3, based on cation ratios, spatially overlaps with categories 1 and 2, whereas recent and naturally elevated chloride waters are relatively distinct from one another. Specific steps for assigning hydrochemical facies data to grid points were to identify wells with water samples containing analyte of interest, contour the top-of-open-hole elevation for concentrations greater than a chosen cutoff value, create a gridded surface from the contours, and assign value based on position relative to the gridded surface.

Summary of product deliverables

Hydraulic conductivity data

Data collection focused mostly on unconsolidated materials, as these data are most needed for regional ground-water modeling investigations. Data were collected across the metro area (Fig. 3A) and include hydraulic conductivity values calculated on the basis of a wide range of measurement scales. In order of increasing volume of geologic material tested, the scales range from: laboratory permeameter tests; slug tests; values derived from specific capacity tests; and higher capacity aquifer tests. Higher capacity aquifer tests included in the dataset range from single hole tests with no observation wells, to multi-well tests that sample a still larger volume of sediment. Hydraulic conductivity (K) data collected as part of this investigation are consistent with published reports (for example Bradbury and Muldoon, 1990; Schulze-Makuch and others, 1999) that demonstrate measured K values are positively correlated with volume of sediment tested.

The published literature also suggests that the magnitude of increase in hydraulic conductivity with increasing volume tested will be greater for a heterogeneous compared with homogeneous aquifer (for example Schulze-Makuch and others, 1999). A relatively homogeneous aquifer will show only a modest increase in hydraulic conductivity as volume of sediment tested increases, whereas a more heterolithic aquifer will show a relatively large increase in hydraulic conductivity as volume of sediment tested increases. We could not confidently recognize this relationship in our dataset of hydraulic conductivities for Quaternary deposits, largely because our knowledge of the relative lithic heterogeneities within the aquifers is limited.

For finer-grained materials—those typically associated with tills (diamictons)—the range of volume tested is limited. This applies not only to our dataset, but to studies in the published literature as well. For horizontal conductivity (Kh), slug tests represent the upper limit of volume tested for fine-grained materials, because the response time of fine-grained materials to change in hydraulic conditions is so slow. Furthermore, monitoring wells in till are commonly designed for the express purpose of acquiring hydraulic conductivity data and provide no alternative use such as water supply or monitoring water quality over time. As such the expense of drilling and developing a test hole in till compared to a conventional well is a deterrent, and becomes increasingly so as costs rise with depth. For vertical hydraulic conductivity (Kv), estimates are based exclusively on laboratory testing (permeameter) or grain size analysis.

Based on the literature (for example Hendry, 1988; Simpkins and Bradbury, 1992; Schilling and Tassier-Surine, 2006; Hooyer and Mode, 2008) and a limited amount of information from our dataset, K will decrease in tills and other fine-grained Quaternary sediments with increasing depth of burial: horizontal hydraulic conductivity decreases one to two orders of magnitude down a depth of about 15 meters. A study of fine-grained Quaternary deposits in Wisconsin (Hooyer and Mode, 2008) indicated that hydraulic conductivity would be expected to decrease at a lesser rate below about 15 meters, decreasing another order of magnitude upon reaching a depth of about 60 meters. The relationship between depth and hydraulic conductivity demonstrated in these studies is attributable to decreasing development of macroporosity, especially fractures and other macropores that are most common and best connected in the upper 15 meters of an individual fine-grained unit, and to increasing consolidation of the material.

The Wood Lake landfill is the only site within our dataset where a potential relationship of decreasing hydraulic conductivity with increasing depth in individual till units was specifically tested (RMT, 1986). At this site, slug tests show decreasing K with depth. Trench observations at this site indicate that an oxidized upper few meters to about 15 meters depth was more highly fractured and had higher K values than an unoxidized, less fractured lower interval at greater depths. These results are consistent with observations by Quaternary scientists at MGS who note that in Minnesota, uppermost oxidized parts of till units are commonly more weathered and fractured than deeper, unweathered parts of the till units. An analysis of the combined data from all Twin Cities metro sites with till hydraulic conductivity values, however, shows a generally poor correlation between depth and K within our dataset. The strongest correlation (correlation coefficient = -0.42) of decreasing K with increasing depth was seen in a subset of slug test values calculated from tests between 0 and 20 feet depth.

Poor correlation of decreasing K with depth in tills, within our combined dataset for the metro area, could reflect several factors. Our slug test sample subset consists of K values collected almost entirely from depths of less than 80 feet (25 meters). Most of these tested till units may be uniformly fractured and/or heterolithic regardless of depth. The relatively high geometric mean and average K values for slug tests of tills in the metro area, compared to values from tills at other locations in midcontinent (Appendix A, Table 1), even though permeameter K values are generally similar, supports such an interpretation. In addition, at depths greater than approximately 15 meters, tests are commonly conducted on thin tills between sand and gravel deposits. These stratigraphic settings are unlike sites that are the basis for most published till K values, where thicker, commonly more homogeneous till units are tested over a greater range of depths. Furthermore, our dataset consists of values acquired from a wide range of till textures and relative heterogeneity, and therefore correlations between depth of sample and hydraulic conductivity may be obscured by a wide range in conductivity values that reflect these heterogeneities across the Twin Cities metro area. Finally, there are few slug tests in our database representing the shallowest depths of less than 5 meters, where published studies commonly show the greatest increase in K (for example McKay and others, 1993). Slug test data from MPCA leaky tank and spill sites could potentially fill this gap. We were not able to pursue these data as part of this project due to time constraints. Our conclusion, based on published studies and the somewhat limited Wood Lake investigation (RMT, 1986) as well as field observations by MGS Quaternary scientists, is that in a relatively homogeneous till sheet, K can be expected to decrease by approximately two orders of magnitude from the land surface to a depth of roughly 15 meters.

Estimating field scale K of tills for model input is difficult, given that the maximum volume of material tested from field data comes from slug tests. Literature review indicates that the arithmetic average or geomean of a number of slug test-derived K values are often regarded as generally appropriate. In these studies, such values are commonly consistent with, or within an order of magnitude of "field scale" values derived from modeling and/or flow velocities estimated from chemical tracers (for example Simpkins and Bradbury, 1992; McKay and others, 1993). Our compilation of slug test K values, summarized and compared to published values in Appendix A, Table 1, should be regarded as generally representative of tills where they are within 80 to 100 feet (25 to 30 meters) of the land surface. Calculating an average for a number of slug test derived K values should provide a user with the best-known estimate of field-scale K that takes equally into account both low conductivity matrix blocks, as well as values from wells with relatively high K where fractures and other high K heterogeneities are intercepted. In contrast, K values based on the geometric mean of slug test values are commonly one to two orders of magnitude lower than the arithmetic mean.

Where only lab permeameter K values are available, both the published literature and our database suggest that lab values can be scaled up to slug values by increasing approximately two orders of magnitude. For estimating K based on texture data alone within our dataset, methods are limited due to the limited amount of grain size distribution data it contains. The dataset does contain a relatively large amount of clay percent data, because it is used as a mapping tool for MGS projects. For that reason, we used the Puckett method (Puckett and others, 1985) because it depends on clay percent only.

$$\text{Puckett and others: } K_{(m/sec)} = 4.36\text{x}10^{-5} * e^{(-0.1975 * \%clay)}$$

%clay = percentage of the total sample finer than 0.002 mm (from Muldoon, 1987)

The average and geometric means of Puckett-derived K values favorably compare to the average and geometric means, respectively, of slug test values of tills (Appendix A, Table 2). For tills we have classified as loam to clay loam and loam to sandy loam, which are the majority of tills for which we have K values, the average and geometric mean of Puckett-derived values are the same order of magnitude as the average and geometric mean of slug test derived values. Puckett derived K values for tills classified as silt-rich loam differ from the average and geometric mean of slug-test derived values by as much as three orders of magnitude, indicating that the Puckett method may not be well suited for such tills, although this comparison is based on a relatively small number of slug tests for tills of such texture.

For coarser-grained materials—sands and gravels typically associated with fluvial deposits—the range of volume of material tested is wider. Kv and Kh tests come from lab permeameter testing, slug tests, values derived from specific capacity tests, and aquifer tests. Based on our analysis of values derived from individual sites in the metro area where K was measured using methods that range in volume of material tested, slug test K values for coarse-grained material are on the average six times greater than lab permeameter measured values from the same aquifer. Specific capacity derived values are about 3 times greater than slug test values, and aquifer test values are about 3 times specific capacity values.

Water chemistry data

Most data included in this investigation come from samples collected within the last 25 years with a few exceptions, including data collected in the 1960s (Maderak, 1963) and the 1910s (Hall and others, 1911). The core of this dataset is comprised of major cation and anion data with field parameters where available, along with an extensive collection of tritium data from the MDH source water protection program. Other significant datasets include perflourochemical (PFC) data for the east metro area from MDH and MPCA, and nitrate data from Dakota County Environmental Management (2006).

Water chemistry data were broken into subsets to facilitate use in a GIS environment. Subsets are 1. Good charge balance: samples having a charge balance error of less than 5 percent; 2. Oxidation-reduction (redox) condition: samples classified by redox state based on chemical composition using the methods of Jurgens and others (2009); 3. Field parameters: samples having data collected in the field, including temperature, conductivity, pH, eH, and dissolved oxygen; and 4. Indicators of ground water age: samples classified as "recent," "mixed," and "vintage" based on the model of Alexander and Alexander (1989). In this model, recent waters are samples whose chemical composition is indicative of waters having entered the ground in the last 60 years, vintage waters contain no admixture of recent waters, and mixed waters are some mixture of these end members, noting that all ground water is a mixture of different ages and chemical types.

Age classification of individual groundwater samples was based on several criteria. Samples classified as recent had some combination of detectable tritium, the presence of anthropogenic contaminants such as PFCs, or chloride concentrations greater than 5 parts per million (ppm) in areas thought not to have naturally elevated chloride levels. Waters classified as vintage meet none of the criteria listed for recent waters, whereas mixed waters contain small concentrations of these constituents. In all cases a specific age was included if carbon 14 or some other dating tool was available, along with the model used to calculate the age.

Three ground water chemical types, or hydrochemical facies, were mapped at the regional scale: 1. *Recent waters* were distinguished by A. The presence of detectable tritium—elevation mapped as the land surface elevation minus casing depth; B. Areas within 50 feet of the land surface where the uppermost geologic unit is from 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. 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. 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 St. Peter Sandstone where it is covered by the Platteville and Glenwood Formations. This condition of younger water underlying older water will be addressed in the next iteration of this dataset; 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; 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.

Discussion and suggested use

Hydraulic conductivity data

These data are highly scale-dependent. As such, we provide general "rules of thumb" from slug test to regional investigations. For fine-grained materials, measurement methods in order of increasing volume of geologic material tested are lab permeameter tests and field slug tests. For texture measurements, we found that the Puckett method applied to clay percent data provided hydraulic conductivities generally consistent with the average and geometric mean of slug test data. Results from lab permeameter tests can be scaled up to slug tests by increasing the measurement by approximately two orders of magnitude. Our slug test data for fine-grained materials are limited to measurements made at depths less than 80 feet. For till settings deeper than this, we suggest assigning values that are 1 to 2 orders of magnitude lower than these near-surface measurements.

For coarse-grained sediments, measurement methods in order of increasing volume of geologic material tested are texture analyses, lab permeameter, slug tests, specific capacity tests, and aquifer tests. There is a very limited amount of grain size distribution data contained in our dataset, restricting the application of Hazen (1893), Kozeny-Carmen, or other grain-size distribution based methods to these data. Results from lab permeameter tests on coarse-grained materials can be roughly scaled up to slug test values by a factor of 6. Hydraulic conductivity results derived from specific capacity data were on the average 3 times greater than slug test results. Finally, aquifer test values of hydraulic conductivity are approximately 3 times greater than specific capacity-derived values in our dataset.

Water chemistry data

These data are well suited for use as a tracer of ground water movement. In the absence of tritium, chloride concentrations can be used to map the three-dimensional distribution of recent waters. Low background concentrations (less than 5 ppm) in all aquifers stratigraphically higher than the Mt. Simon Sandstone provide a cutoff value to distinguish recently recharged ground water from ground water older than 60 years. Comparison of cation ratios across the metro area, specifically strontium to calcium plus magnesium concentrations, showed distinct patterns both in an east–west direction and with depth. The presence of anthropogenic compounds, best illustrated in the distribution of PFCs in the eastern metro area, point to the utility of using these data to show the distribution and approximate rate of movement of recent waters in the subsurface.

An example of the combined use of hydraulic conductivity and water chemistry data to assist in ground-water modeling is provided by a proposed infiltration basin investigation for the city of East Bethel in Anoka County (Braun Intertec Corporation, 2009). There, chemical data were compared to field and lab scale measurements of hydraulic conductivity. Average linear velocities (vertical) calculated from lab and field scale measurements predicted longer travel times than shown by the presence of elevated organic acids within the till. This disagreement between data was attributed in the report to secondary porosity and permeability. Fractures or other macropores were thought to provide conduits to deeper sand lenses to account for vertical and lateral distribution of recent waters within the till. Similarly, several other reports reviewed as part this project demonstrated the presence of relatively recent water within or beneath tills with low permeameter-derived K values, suggesting relatively rapid flow through heterogeneities such as fractures, macropores, or textural heterogeneities (for example sand dikes and lenticles; RMT, 1986; Donahue and Associates, 1990; Liesch and Associates, 1990; MACTEC, 2010).

The individual point data geodatabase (PointData.mdb) provides access to hydraulic conductivity and chemical data for a specific site. Because much of the site information on geologic setting comes from different consultant's reports, there is a lack of consistency in lithologic and stratigraphic attributes. In this way, PointData.mdb is best suited as a "what's in my neighborhood" type of dataset rather than for rigorous regional spatial analysis of hydraulic conductivity data. The grid design of regional summary data geodatabase (RegionalData.gdb) is meant to provide the means to readily import and adjust hydraulic conductivity and chemical data in ground water flow models, or for use as an additional layer for three-dimensional evaluation of model results. Use of regional summary data in these settings can aid in refining conceptual models of ground-water flow.

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Appendix A. Table 1. Comparison of hydraulic conductivity values for mid-continent tills at various scales with results from this study.

Source	Location/till	Texture	Lab (permeameter)tests	Slug tests	Larger scale
Hooyer and Mode (2008)	Winnebago County Wis. Green Bay lobe	From Rodenbeck (1988) Kirby Lk: S 28%, Sl 44%, Cl, 29% 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 Wis. till"	average S 12%, Sl 53%, Cl, 35%	1 to 2 orders magnitude less than slug test values	10^{-3} ft/day (fractured) to 10^{-5} ft/day (less fractured)	
Bradbury and Muldoon (1990)	Eastern Wis. 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 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. 2.1×10^{-2} ft/day (oxidized) Avg. 1.1×10^{-3} ft/day (unoxidized)	
McKay and others (1993)	SW Ontario Till	Greater than 25% clay	10^{-5} to 10^{-6} ft/day	10^{-5} to 8×10^{-2} ft/day (fractured till) (also summarize "other" Canadian sites with fractured tills as btw 10^{-3} to 10^{-1} ft/day)	Field trench 5m (deep) by 7m (wide) ~6×10^{-2} ft/day
Gerber and others (2001)	Ontario till	"Sandy-silt" till		~1.4×10^{-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
This project	Des Moines lobe 11 county Twin Cities Metro	average S 42%, Sl 37%, Cl, 21%	Avg 8.6×10^{-2} ft/day Geom 8×10^{-4} ft/day n= 32	Avg 4.2×10^{-1} ft/day Geom 5.3×10^{-2} ft/day n= 17	
This project	Superior lobe 11 county Twin Cities Metro	average S 62%, Sl 26%, Cl, 12%	Avg 2.3×10^{-2} ft/day Geom 1.2×10^{-3} ft/day n= 21	Avg 7.3×10^{-1} ft/day Geom 1.6×10^{-1} ft/day n= 30	

Appendix A. Table 2. Summary of horizontal and vertical hydraulic conductivity values by method, this study.

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: C02 Anoka County

	C19 Dakota County C82 Washington County DNR MN Department of Natural Resources DOT MN Department of Transportation MDA MN Department of Agriculture MDH MN Department of Health METC Metropolitan Council MWCC Metropolitan Waste Control Commission PCA Mn Pollution Control Agency UMN University of Minnesota USEPA U.S. Environmental Protection Agency 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: OH equal to open hole/screen length 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: 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: A Altimeter (+/- 1 foot) G GPS (Global Positioning System / satellite) H GPS >12M (> +- 40') I GPS 3-12M (+- 10-40') J GPS 1-3M

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

	BD borehole dilution test CH constant head FLMC flowmeter inject/pump - constant head FSFH field falling head slug test FSRH field rising head, includes slug tests and baildown tests FSU Field Slug Test Unspecified GP Guelph permeameter GSE grain-size estimate GSE_A grain-size estimate assumed based on report LBH laboratory backpressure or consolidometer, horizontal LBU laboratory unspecified LBV laboratory backpressure or consolidometer, vertical LCH laboratory constant head, orientation unknown LCHH laboratory constant head, horizontal LCHV laboratory constant head, vertical LFH laboratory falling head, orientation unknown LFHH laboratory falling head, horizontal LFHV laboratory falling head, vertical LRH laboratory rising head, orientation unknown LRHH laboratory rising head, horizontal LRHV laboratory rising head, vertical MPDP Philip-Dunne permeameter OTH other 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_per_report," 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
	GF	Glaciofluvial
	Ow, surficial	Outwash, surficial unit
	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
	FLOAT	Large block of limestone within unconsolidated quaternary sediment
	ML in outwash	inorganic silt in outwash
	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
	OPVL HF BPF	Platteville Formation, open to bedding plane fracture in Hidden Falls member
	OPVL Lower HF	Platteville Formation, lower Hidden Falls member
	OPVL lower Mag	Platteville Formation, lower Magnolia member
	OPVL lower MIFF	Platteville Formation, lower Mifflin member
	OPVL Mag	Platteville Formation, Magnolia member
	OPVL Mag, HF BPF	Platteville Formation, open to bedding plane fracture in Hidden Falls member
	OPVL MIFF	Platteville Formation, Mifflin member
	OPVL upper Mag	Platteville Formation, upper Magnolia member
	OPVL HF BPF	Platteville Formation, open to bedding plane fracture in Hidden Falls member
	OPVL HF BPF?	Platteville Formation, possibly open to bedding plane fracture in Hidden Falls member

	OPVL upper MIFF	Platteville Formation, upper Mifflin member
	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:	
	CH	inorganic clay, liquid limit greater than 50
	CL	inorganic clay, liquid limit less than 50
	GC	clayey gravel
	GM	silty gravel
	GP	poorly-graded gravel
	GW	well-graded gravel
	MH	inorganic silt, liquid limt greater than 50
	ML	inorganic silt, liquid limit less than 50
	OH	organic clay
	OL	organic silt
	PT	peat
	SC	clayey sand

	SM silty sand SP poorly graded sand SW well-graded sand

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
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
unit_tested_per_report	Unit tested as described in report
addl_unit_per_report	Additional information on unit tested
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	Z-aware collection of regularly spaced grid points with estimated range of K data for unconsolidated deposits and regional hydrochemical facies

Field names and definitions

Name	Description
POINTID	Unique identifier for each point
GRID_CODE	Quaternary subsurface map code
ELEV	Elevation of point in feet above mean sea level
qflg	Data flag – 1 indicates located within unconsolidated deposits
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
maplabel	Map label from metro area surficial geology map, MGS Open-File Report 07-02 (Meyer and Tipping, 2007). Applies to near-surface points, see lookup table xMAPLABEL
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

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	Washington County (Meyer and Tipping, 1998)	t1	1

	(diamicton)			
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
25	sand and gravel	Scott County (Lusardi and Tipping, 2006)	s4	5
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
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

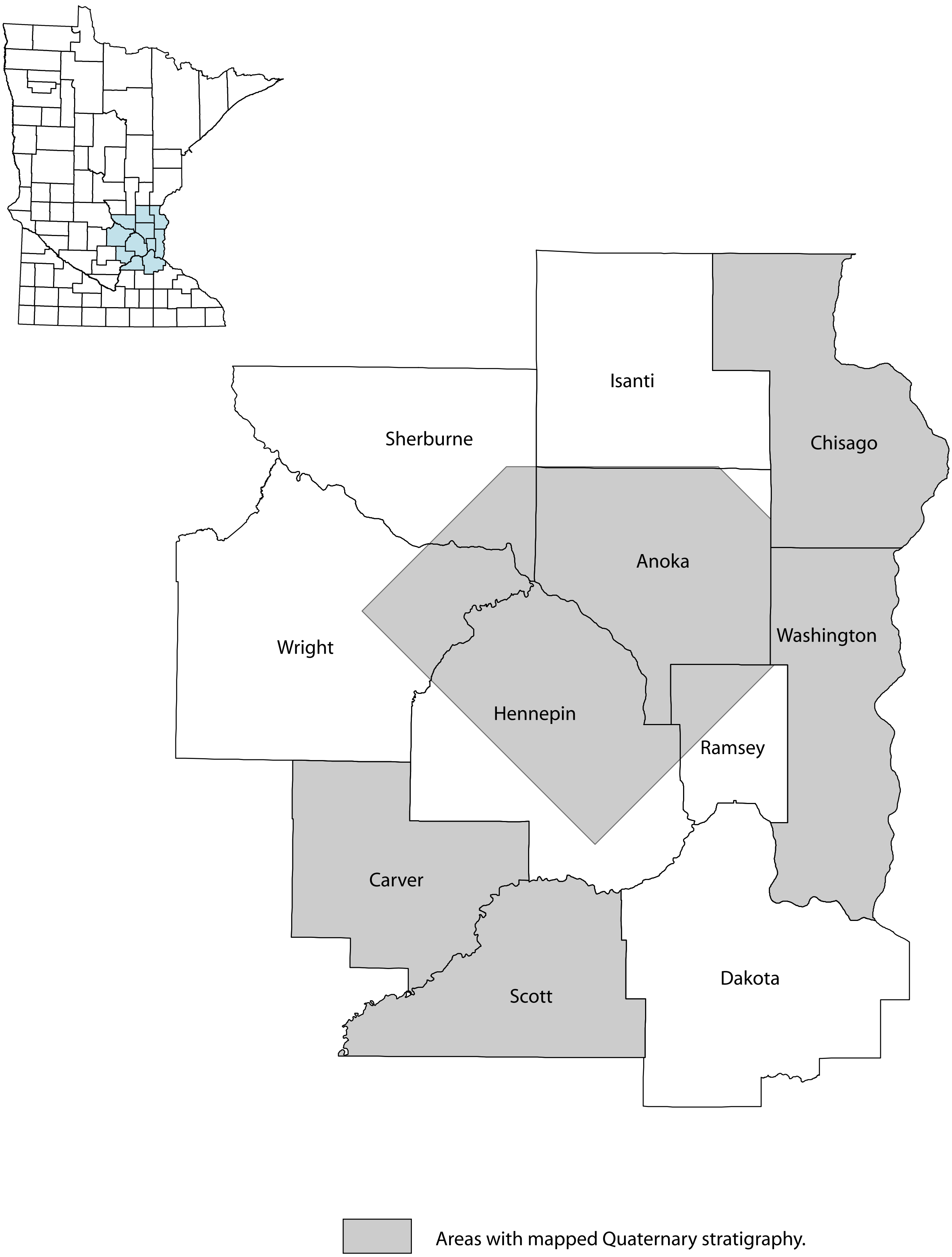
Figure 1. This investigation covers the extended 11-county Twin Cities metropolitan area, Minnesota. Areas with mapped Quaternary stratigraphy are shaded. Mapping in Wright, Anoka, and Sherburne Counties by the Minnesota Geological Survey, which will include Quaternary stratigraphy, is currently underway.

Figure 2. Distribution of regional gridpoint data. Blowup of regional points shown for northwestern Sherburne County; the density of points is too high to display regionally. Horizontal gridpoint spacing is 500 meters by 500 meters. Vertical spacing is 20 feet for unconsolidated material, and 40 feet for Paleozoic bedrock.

Figure 3. Distribution of point data. **A**. Locations with hydraulic conductivity data. The high density of points in the western and northern metro area are mostly hydraulic conductivity results derived from specific capacity data for wells completed in unconsolidated deposits. **B**. Locations with chemical and/or isotopic data.

Figure 4. Distribution of regional gridpoint data, Des Moines, and Superior lobe deposits. Des Moines lobe deposits, shown in green, are displayed as semi-transparent to show the distribution of of Superior lobe deposits below.

Figure 5. Distribution of regional gridpoint data, subsurface pre-Wisconsinan till with estimated hydraulic conductivity ranging from 1.4E-02 to 2.8E-04 ft/day. Locations in Dakota County, where Quaternary stratigraphy has not been mapped, were derived from the surfical geology map where the unit is at the land surface.



Isanti
Sherburne
Chisago
Anoka
Wright
Washington
Hennepin
Ramsey
Carver
Dakota
Scott
Areas with mapped Quaternary stratigraphy.

Figure 1

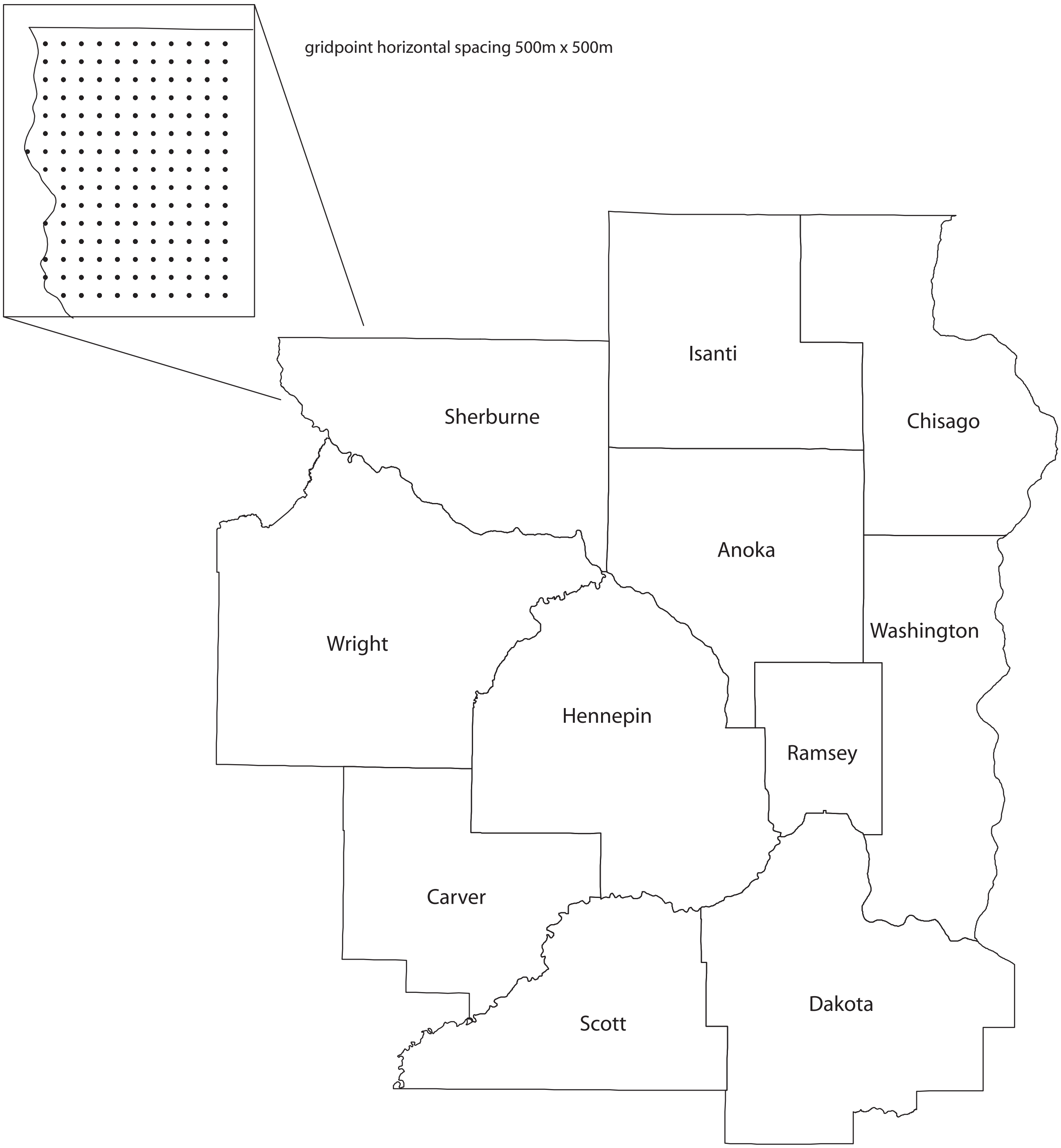
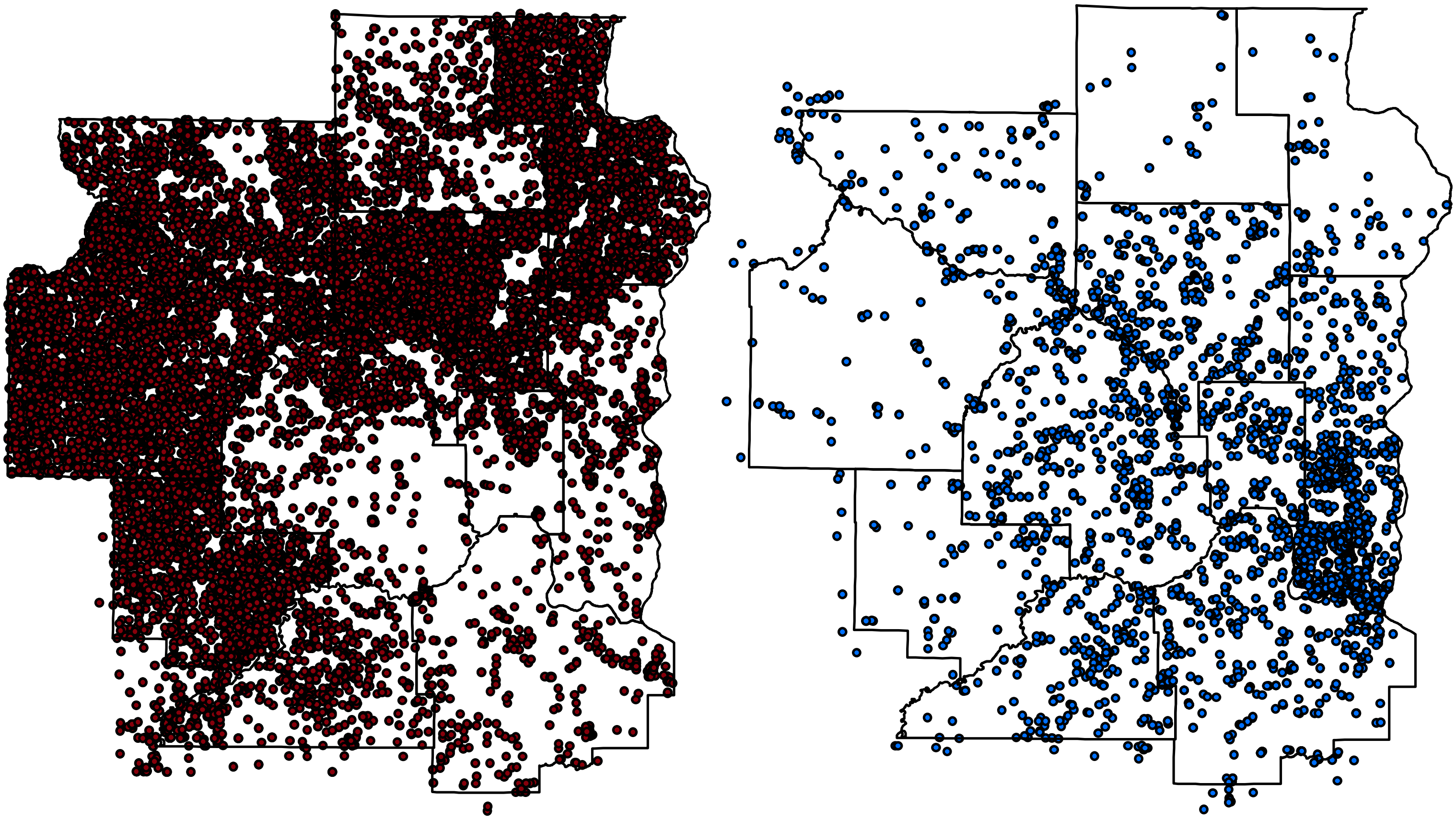

gridpoint horizontal spacing 500m x 500m
Isanti
Sherburne
Chisago
Anoka
Wright
Washington
Hennepin
Ramsey
Carver
Dakota
Scott

Figure 2



A. Locations with hydraulic conductivity data.

B. Locations with chemistry data.

Figure 3

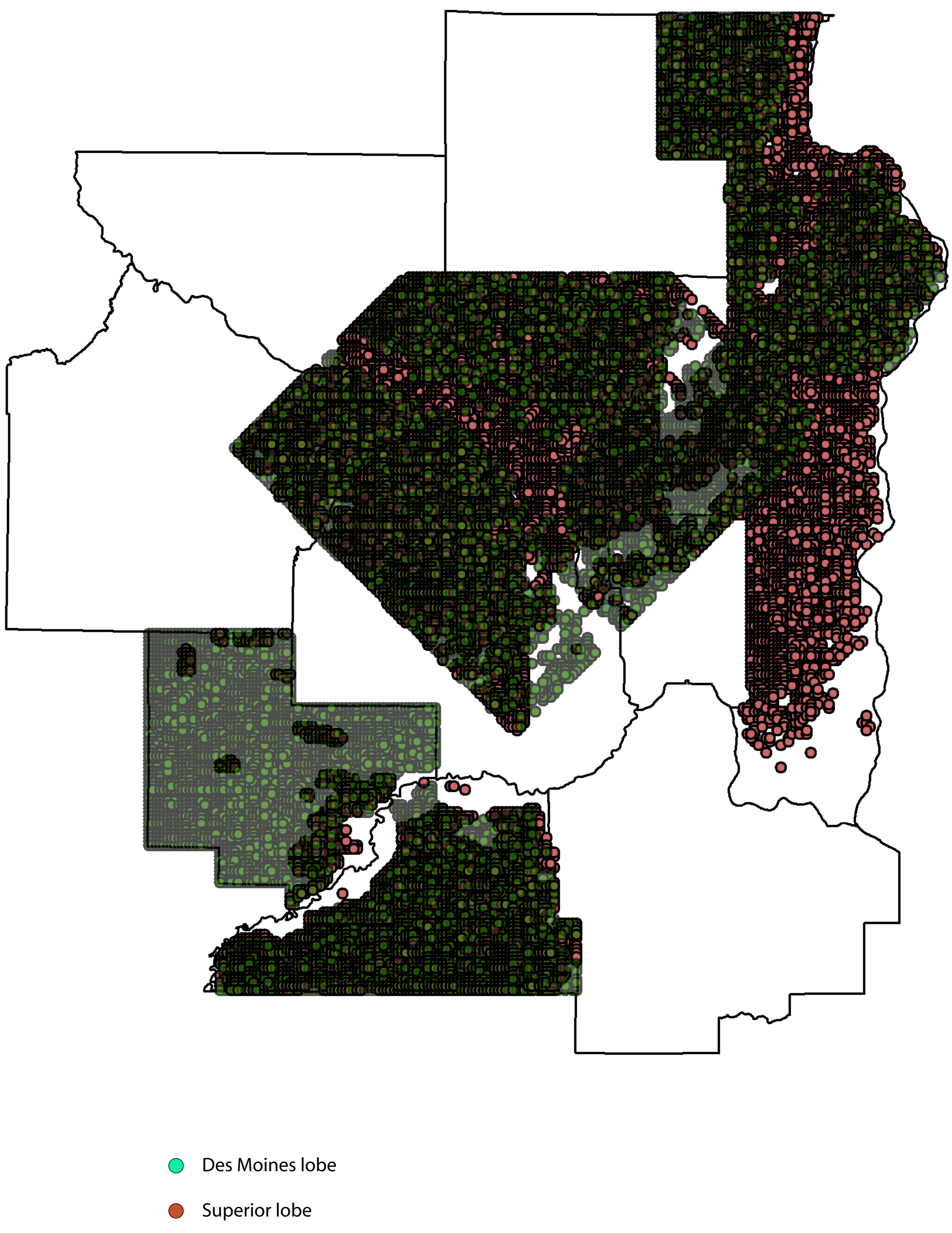


Figure 4

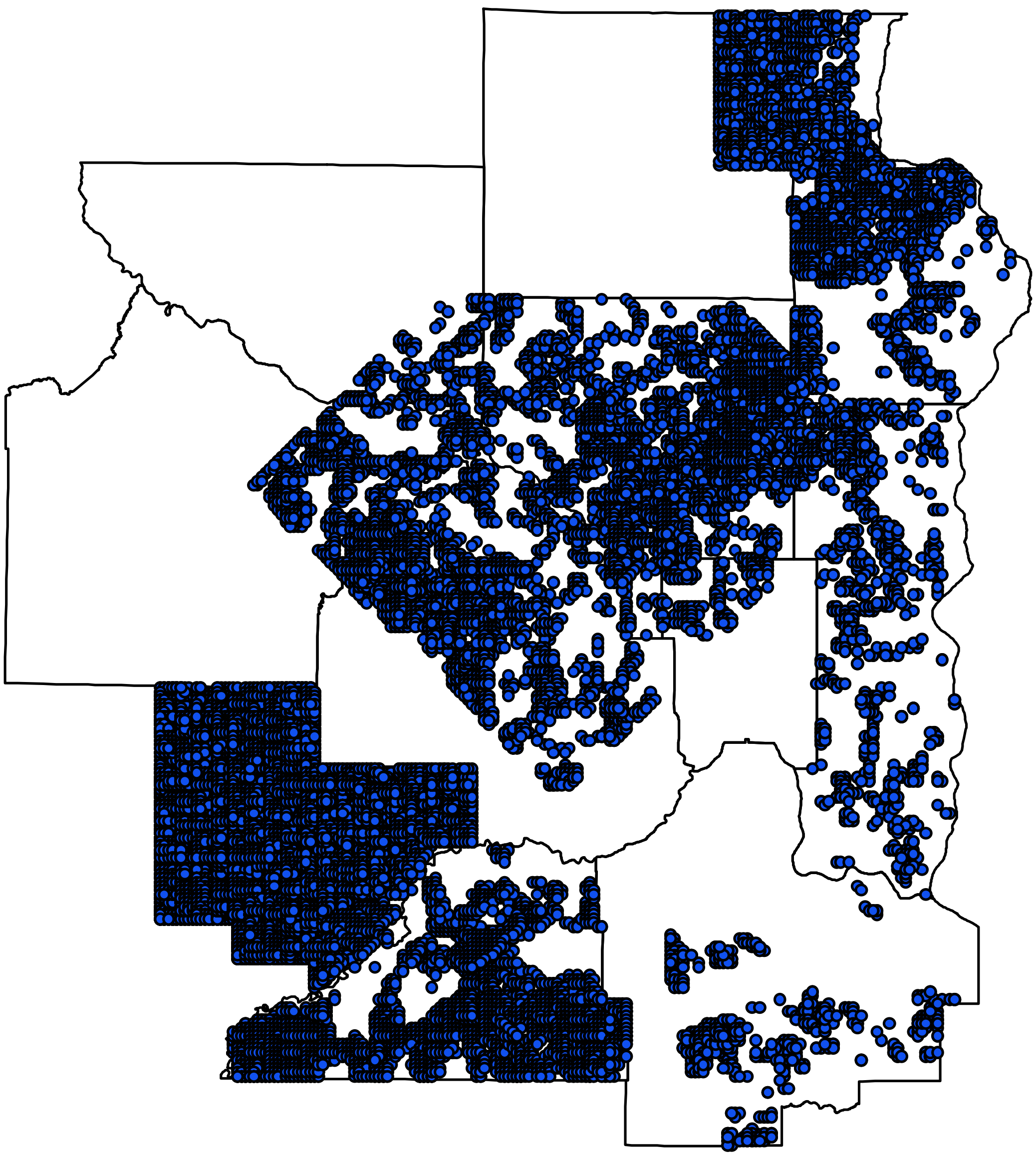


Figure 5