GEOLOGY IN SUPPORT OF GROUND-WATER MANAGEMENT FOR THE TWIN CITIES METROPOLITAN AREA

Metropolitan Council Water Supply Master Plan Development - Phase I

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Executive Summary

This report summarizes work by the Minnesota Geological Survey to provide the Metropolitan Council, as part of their Phase I Water Supply Master Plan, with reconnaissance information in the form of water chemistry data and Quaternary stratigraphy to help characterize recharge to metropolitan area bedrock aquifers. Major findings of the investigation are:

- Quaternary stratigraphy in Anoka County is a complex sequence of coarse and fine grained sediments, including multiple till layers, sand bodies and lacustrine deposits.
- Recharge to bedrock aquifers in the northwest and west-central parts of the metropolitan area appears to be largely localized due to a combination of high permeability zones in unconsolidated sediment and an induced gradient resulting from high capacity pumping. Ground-water flow models incorporating these localized pathways should improve estimates of ground-water flux in this region.
- Bedrock valleys filled with coarse-grained sediment also appear to be zones of localized recharge.
- Chloride is reliable tracer of recent water in the metropolitan area due to low background (pre-development) levels in most aquifers. The decrease in chloride concentrations downgradient effectively marks the limit of post-development water advance.
- Strontium/barium ratios help to distinguish water that has passed through the most recent northwest provenance glacial deposits (Des Moines lobe and Grantsburg

sublobe) from water that has passed through northeast provenance glacial deposits (Superior Lobe).

- Maintaining a water chemistry database connected to the County Well Index will help track changes in ground-water quality and flow paths over time.

Recommendations for additional work include the application of the datasets in this report for additional hypothesis testing and refinement of regional and local ground-water flow models. For example, no strontium and barium data was collected from municipal wells as part of this investigation; such data from municipal wells in eastern and south central Hennepin County might help test the conceptual model of localized recharge through windows in Des Moines Lobe till (unit nt) as presented in this report. If these wells have elevated strontium/barium ratios, then they are likely receiving water from underneath the Des Moines Lobe till, where ground-water samples taken had ratios that were more uniformly high.

The water chemistry data assembled as part of this investigation should also be used to look in more detail at the distribution of recent water in bedrock and adjacent valleys here and in other parts of the metro area. In general, no distinction was made in this report between water chemistry that came from bedrock wells from those completed in glacial deposits, as well-by-well analysis was beyond the scope of this investigation. Cation exchange data collected as part of this investigation (Appendix b) should help greatly in this regard. Geologic framework models of Quaternary deposits similar to the one created as part of this investigation exist for Washington and Scott Counties, both of which have extensive historic water chemistry and isotope data. Recently acquired perfluorochemical data for Washington and portions of Ramsey County by the Minnesota Department of Health provide a valuable tracing tool for both unconsolidated deposits and bedrock aquifers in that area. Dakota County also has extensive historic water chemistry data, some of which (pesticides and nitrates) were included in the database provided as part of this investigation. Analysis of major cations and anions, in addition to the construction of a geologic framework model for this portion of the metro area would also greatly improve understanding of groundwater flow and recharge in the southern metro area.

Finally, the temporal aspect of water quality data has not been addressed in this report, but is a valuable component of the dataset. There are only a few wells included in the dataset that have been sampled more than once, but clearly it would be useful to see how the spatial distribution of recent waters changes with time. It is expected that water chemistry data will help to iteratively refine ground-water flow modeling estimates by helping to identify zones of preferential flow.

Included on the accompanying CD are additional products of the investigation, including an electronic version of a new metro-area wide surficial geology map, water chemistry database and ESRI format grids associated with a geologic framework model of Quaternary deposits in the northwest metropolitan area.

Introduction

This report summarizes work by the Minnesota Geological Survey to provide the Metropolitan Council, as part of their Phase I Water Supply Master Plan, with information to help characterize recharge to metropolitan area bedrock aquifers. The Council requested a better understanding of the surface and subsurface distribution of unconsolidated deposits overlying bedrock, with the goal of identifying preferential water pathways from the land surface to bedrock. To this end, the Minnesota Geological Survey provided: 1.) a seamless surficial geology map of the greater Twin Cities metropolitan area; 2.) a collection of historic metro-wide water chemistry data used to prioritize areas for subsurface mapping – 27 new samples were collected in northwestern Hennepin County where data was sparse; and 3.) a three dimensional model of unconsolidated deposits from the land surface to bedrock for the northwest metropolitan area, hereafter referred to as the geologic framework model.

Data, methods and description of products

Surficial map

Regional information on surfical geology has been collected and mapped at various scales and areas throughout the metropolitan region, but a seamless compilation of these individual maps did not exist prior to this investigation. A new seven-county metropolitan area map was produced as part of this study (Meyer, 2007,see accompanying CD) .

The map contains information on the lithology and stratigraphy of Quaternary age deposits, landforms created by the movement of ice and melt water, as well as ice margin positions - both visible from the land surface and inferred. Updated versions of the Hennepin (Steffen, 2004), Sherburne (Jackson, 2002), and Wright (Jackson, 2004) County soil surveys, logs of recently located water wells and soil borings, and recent unpublished studies by the Minnesota Geological Survey were also used to compile the surficial geology.

Water chemistry database

Regional subsurface geology mapping of unconsolidated deposits is much less extensive than surficial mapping, with subsurface modeling existing in Washington and Scott Counties only. (Meyer and Tipping, 1998; Lusardi and Tipping, 2006). A metro area wide three-dimensional model of unconsolidated glacial deposits, although applicable to regional ground-water modeling efforts, was beyond the scope of this project. In order to prioritize an area for subsurface mapping, historic water chemistry data was collected with the goal that it might provide additional information on the spatial distribution of ground-water recharge to bedrock aquifers. The northwest metro study area (Figure 1) was chosen based on the density of data, and future projections of population growth and water demand (Metropolitan Council, 2001).

Water chemistry and isotopic data were used to help characterize ground-water flow paths and residence times. The Twin Cities metropolitan area has an abundance of historic water chemistry data that potentially provide a great deal of information on the the spatial and temporal distribution of ground-water flow. Sources of historic data collected as part of this investigation were: the United States Geological Survey NAQWA program along with additional data from the National Water Inventory System

(NWIS); the Minnesota Department of Health; the Minnesota Pollution Control Agency GWMAP program – both ambient ground-water monitoring and land-use studies; University of Minnesota graduate studies (Tipping, 1992; Nemetz, 1993; Burman, 1995); Dakota County Environmental Management (Jill Trescott, written communication); and Anoka County Community Health and Environmental Services (Marsh, 1996; Marsh 2001). Additional water chemistry data were collected as part of this investigation from 27 wells in northwestern Hennepin County where there was limited existing data. In all 37,559 analyses associated with 1915 sample events were assembled for located wells.

In addition to water chemistry field samples, cation exchange experiments were run on 47 samples of mostly fine-grained glacial deposits (Appendix b). Samples were chosen to best represent the units mapped as part of the subsurface geologic framework model, with the goal of "fingerprinting" different source area materials (i.e. Des Moines or Superior lobe tills) based on their exchangeable cations. Five grams of the less than 2 mm fraction of dried sample was combined with 100 ml 0.05 M ammonium acetate in Erlenmeyer flasks. Samples were twice shaken for 15 minutes and allowed to stand for 24 hours before 10 ml of filtered sample was taken from each flask. The filtered sample was acidified with 1 drop of 6 N hydrochloric acid and then submitted to University of Minnesota, Department of Geology and Geophysics to be analyzed for major cations, along with strontium and barium. Data from these experiments have not come back from the lab at the time of this report, but will be included as an addendum after the data are received and analyzed.

Data were compiled and interpreted in the context of the geologic framework model for the study area, considering such factors as distribution and thickness of glacial deposits, the distribution of bedrock valleys, and the distribution of high-capacity municipal pumping.

Geologic Framework Model

Compared to the bedrock geology of the Twin Cities metropolitan area, the glacial geology is extremely complex. The bedrock geology is relatively predictable in terms of extent and thickness of strata. However, the subsurface distribution of fine and coarse grained materials in Quaternary or glacial-related strata is not. This heterogeneity in glacial deposits is the result of many different depositional and erosional processes associated with glaciers, including subglacial, fluvial, and ice-collapse or other associated stagnation settings.

The primary data source for the glacial geologic framework model was water well records. Twenty-nine northwest to southeast cross sections were constructed, spaced 2 kilometers from one another (Figure 2.l). Universal Transverse Mercator coordinates (North American Datum 1983, Zone 15, utme, utmn) and elevation values were collected for each mapped unit. Elevation values were hand contoured at a 25 foot contour interval or finer scale where practical, and the contours were used to create digital elevation models (DEMs) for unit tops and bottoms (Figure 2.a-k). 18 units were mapped as part of the investigation (Appendix a). Derivative thickness grids for each unit were created based on unit DEMs.

The resulting geologic framework model clearly shows the complexity of unconsolidated deposits covering the bedrock of Anoka County. Commonly perceived as sand over bedrock, the Quaternary stratigraphy of this area is actually a complex sequence of coarse and fine grained sediments, including multiple till layers, sand bodies and lacustrine deposits. Unit CL in particular (Figure 2g), a subsurface lacustrine deposit in northeastern and east central Anoka County, is expected to be an important hydrologic unit because of its regional distribution and low permeability.

Discussion

Water chemistry and isotope data can provide useful information on ground-water pathways and residence times. In most of southeastern Minnesota, natural background chloride concentrations in bedrock aquifers are only a few parts-per-million (ppm). Because chloride is chemically un-reactive under conditions most often encountered in these aquifers and because chloride is often a component of near surface land use activities (ie. road salt, fertilizers, wastewater), concentrations above a few parts per million are a good indicator of water that was recently at the land surface. In this report, the term “recent” is used to describe waters that have entered the ground in the last 50 years (see discussion below). In areas where concentrations can be distinguished from background levels or other sources such as deep bedrock saline waters, decreases in chloride concentration downgradient effectively mark the limit of recent water advance (e.g. Edmunds and Smedley, 2000).

Tritium, like chloride, is chemically un-reactive in the subsurface, and, like chloride, is a good tracer of ground water movement because modern (post 1950’s) levels of tritium in the atmosphere are higher than they were prior to the atmospheric testing of nuclear weapons. Detectable tritium in ground-water indicates that some component of the water sampled entered the ground after the mid 1950s. This report follows the convention of Alexander and Alexander (1989) where “recent” water is used to describe water that predominantely entered the ground since since the 1950s, “vintage” water is used describe water that predominantly entered the ground before the 1950s, and “mixed” water used to describe a mixture of recent and vintage – understanding that all ground waters are mixtures to some degree.

Other useful residence time indicators on the time scale of decades include chemicals that were introduced into the environment that did not exist in these aquifers prior to development. Many of these, such as sulfur hexafluoride and chlorofluorocarbons (CFCs) have been combined with piston-flow conceptual models to calculate ground-water ages to within a few years. More often, the presence of these or other chemicals in the subsurface provide a qualitative assessement of the presence or absence of recent water for a given area. Examples include pesticides, herbicides and their breakdown products, and a host of other man-made compounds including caffeine, pharmaceuticals, and bug repellants.

The usefulness of water chemistry and isotope data as groundwater tracers is enhanced when the data are plotted in two and three dimensions, so they can be viewed in the context of regional geology and other data that may influence the direction and magnitude of ground-water flow. The locations of wells within the study area that have tritium data along with elevation and depth completion information are shown in Figure 3a. The locations have been color-coded based on their interpreted tritium age, with red indicating recent water (tritium concentration > 10 tritium units (TU)), blue indicating vintage water (tritium concentration below detection), and green indicating mixed water (tritium concentrations 1 to 10 TU). In Figure 3b, the locations have been plotted in three-dimensional space based on utm coordinates and bottom-of-hole elevations (well head elevation minus well depth). The variation in tritium concentrations with depth are somewhat apparent, with younger waters at higher elevations, but spatial variations are visible also, with predominantly vintage water in northwestern Hennepin County, recent to mixed water in eastern Hennepin County, and a heterogeneous distribution of recent, mixed and vintage water in Anoka County.

Contouring elevations of recent and mixed waters helps to identify spatial patterns in tritium concentrations (Figure 4). The uppermost red contours, indicating recent waters and spread through much of Anoka County are based on the bottom elevation of surfical sand units “no2” (surfcial outwash) and “terr” (terrace sands) from the geologic framework model (see Appendix a). Other contours were drawn to connect clusters of wells with similar bottom-of-hole elevations and tritium concentrations – red representing recent waters and green representing mixed waters. Viewing the contours at increasingly shallow angles relative to the horizon shows a distribution of recent waters at depth in eastern and south-central Hennepin County.

Recent waters at depth in the eastern and south-central portions of Hennepin County may be the result, in part, of an induced gradient in this area due to high-capacity pumping. Symbols used to show average location and bottom-of-hole elevations of municipal well fields on Figure 5a are graduated in size based on reported 2004 average daily pumping amounts, with larger symbols representing higher reported amounts (Metropolitan Council, 2007, written communication). The thickness and distribution of Des Moines Lobe till – unit nt from the geologic framework model, along with the contours of recent tritium concentrations have been added in Figures 5b-f. Thickness of unit nt is represented by gradational shades, with darker shades representing greater thickness. The elevation of unit nt thickness grid in the figure was set using the unit nt_top DEM. Viewing these data at increasingly shallow angles relative to the horizon suggest that recharge to these municipal pumping centers is localized through areas along the Mississippi River and into south-central Hennepin County where the Des Moines Lobe till is largely thin or absent. If water contributing to municipal wells in eastern and south-central Hennepin County was predominantly moving from west to east, then more recent water should be found at depth in western Hennepin County, fitting a previous conceptual model of regional flow in lower aquifers from western Hennepin County east and southeast towards the Mississippi and Minnesota Rivers.

Ground-water flow patterns within the study area can be further characterized through the use of strontium/barium ratios from ground-water chemistry data assembled as part of this investigation. The state-wide distribution of strontium/barium ratios in ground water show a clear pattern of higher ratios associated with Des Moines Lobe sediments (Figure 6). Within the study area, consistently higher values are found in northwest Hennepin County than in Anoka County, where values are more heterogeneous (Figure 7a.) When viewed with the distribution of Des Moines Lobe (unit nt) thickness and extent (Figure 7b), higher, more spatially uniform strontium/barium ratios are found in wells below thick unit nt in northwest Hennepin County, whereas ratios in Anoka County show an admixture of Des Moines Lobe and Superior Lobe signatures as defined by the state-wide distribution shown in Figure 6. Preliminary results from the cation exchange experiments conducted as part of this investigation support the observation from the water chemistry data that compared to Superior Lobe sediments, Des Moines

Lobe sediments are enriched in strontium relative to barium and that this signature is passed on to water moving through them by the process of cation exchange.

Chloride data support observations made from the tritium and strontium/barium ratio data that recharge is localized through areas where the Des Moines Lobe (unit nt) is thin or absent. Map and perspective views of chloride concentrations from wells with elevation and depth completed data are shown in Figure 8. Data points have been color coded according to interpreted age, with red representing recent waters (chloride concentrations greater than 8 ppm), green representing mixed waters (chloride concentrations between 3 and 8 ppm) and blue representing vintage waters (chloride concentrations less than 3 ppm). By viewing the datapoints at increasingly shallow angles with the horizon, a similar pattern to the tritium data emerges, with elevated chloride at depth in eastern and south-central Hennepin County. This similarity is highlighted by plotting recent tritium elevation contours along with the chloride concentrations (Figure 8c.). As observed with the tritium data, if water contributing to municipal wells in eastern and south-central Hennepin County was predominantly moving from west to east, then higher chloride concentrations should be found at depth in western Hennepin County, fitting a previous conceptual model of regional flow in lower aquifers from western Hennepin County east and southeast towards the Mississippi and Minnesota Rivers.

Chloride/bromide ratios can help to refine conceptual models of groundwater flow based on chloride data alone. Trend lines from Alexander, 2005 showing chloride bromide ratios from different source waters have been included on a plot of chloride versus bromide concentrations for the greater metropolitan area (Figure 9a) and within the study area (Figure 9b.) Both plots show a wide range of chloride/bromide ratios that may be useful in identifying source waters that are indistinguishable based on elevated chloride values alone. This is illustrated in Figure 10, where chloride/bromide ratios from northern Anoka County along with the bedrock surface are viewed obliquely from the southeast. Wells have been plotted according to their bottom-of-hole-elevation, using the color scheme used previously. Wells shown in red have chloride concentrations greater than 8 ppm are interpreted as recent water. Comparison of chloride/bromide ratios in these wells, however, shows an order of magnitude difference with depth, suggesting a different pathway for groundwater within a relatively small area. Map and perspective views of choride/bromide ratios shown in Figure 11 support a conceptual model of older water in bedrock aquifers below thick Des Moines Lobe sediments in northwestern Hennepin County, where chloride/bromide ratios are consistently low. In contrast, values in Anoka County are more heterogeneous, both horizontally and with depth.

The influence of bedrock valleys on the direction and magnitude of groundwater flow is variable depending on the lithology of the valley fill and presence or absence of a hydraulic gradient. The cities of Brooklyn Park and Maple Grove both have municipal wells finished in or near a prominent bedrock valley running sub parallel to the Mississippi River in northern Hennepin County (Figure 12). Sand thickness exceeds 150 feet in portions of the valley and the presence of recent waters at depth are interpreted as evidence for localized downward movement of water due to high capacity pumping.

Bedrock aquifers are found to have more secondary porosity in the form of horizontal and vertical fractures along and near bedrock valley walls (e.g. Ferguson, 1967). As such, bedrock wells completed near bedrock valleys may have a higher occurrence of recent water than wells located some distance from the valley. This conceptual model was tested qualitatively by digitizing the axes of the bedrock valleys within the study area, and then calculating the horizontal distance from the wells to the closest valley axis. Histograms of distance to bedrock valley axes for recent/mixed and vintage waters based on tritium concentrations are shown in Figure 13. There is no clear discernable difference between the histograms, although the patterns suggest a tendency for recent/mixed waters to be less likely found at distance from the valley than vintage waters. A more rigorous test would be to measure the distance from the open-hole interval to the bedrock surface. The occurrence of recent waters based on tritium and chloride levels deep within bedrock valleys and within bedrock units subcropping in the valley below known confining units suggests that bedrock valleys provide preferential pathways for water to move to lower aquifers.

Summary and recommendations for additional work

The major findings of this investigation are:

- Quaternary stratigraphy in Anoka County is a complex sequence of coarse and fine grained sediments, including multiple till layers, sand bodies and lacustrine deposits.
- Recharge to bedrock aquifers in the northwest and west-central parts of the metropolitan area appears to be largely localized due to a combination of high permeability zones in unconsolidated sediment and an induced gradient resulting from high capacity pumping. Ground-water flow models incorporating these localized pathways should improve estimates of ground-water flux in this region.

- Bedrock valleys filled with coarse-grained sediment also appear to be zones of localized recharge.
- Chloride is reliable tracer of recent water in the metropolitan area due to low background (pre-development) levels in most aquifers. The decrease in chloride concentrations downgradient effectively marks the limit of post-development water advance.
- Strontium/barium ratios help to distinguish water that has passed through the most recent northwest provenance glacial deposits (Des Moines lobe and Grantsburg sublobe) from water that has passed through northeast provenance glacial deposits (Superior Lobe).
- Maintaining a water chemistry database connected to the County Well Index will help track changes in ground-water quality and flow paths over time.

Recommendations for additional work include the application of the datasets in this report for additional hypothesis testing and refinement of regional and local ground-water flow models. For example, no strontium and barium data was collected from municipal wells as part of this investigation; such data from municipal wells in eastern and south central Hennepin County might help test the conceptual model of localized recharge through windows in Des Moines Lobe till (unit nt) as presented in this report. If these wells have elevated strontium/barium ratios, then they are likely receiving water from underneath the Des Moines Lobe till, where ground-water samples taken had ratios that were more uniformly high.

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Appendix a. Lithostratigraphic map unit descriptions and hydrologic properties, northwest metro area Quaternary geologic framework model

geologic framework model unit (surface)	map unit description	geologic framework model unit (sub-surface), in order from top to bottom	description
CO	Cromwell Fm; ice-contact dep	NO	fine sand to gravel (bedded)
	Cromwell Fm; outwash	CL	silt and clay (bedded)
CT1	Cromwell Fm; till	CT1	till, generally sandy textured (diamicton)
CT1 (or CO1 in a few places)	Cromwell Fm; till, sand cmplx	CO1	fine sand to gravel (bedded)
NL	NewBrightonFm silt&clay facies	CT	till, generally sandy textured (diamicton)
	New Ulm Fm; lake clay & silt	CO	fine sand to gravel (bedded)
	Langdon terr silt&clay facies	XT	till, generally loamy textured (diamicton)
	Richfield ter silt&clay facies	XO	fine sand to gravel (bedded)
NO2	New Brighton Fm sand & gravel	RT	till, generally sandy textured (diamicton)
	New Brighton Fm; sand facies	RO	fine sand to gravel (bedded)
	Till under sandy lake sediment	PT	till, generally loamy textured (diamicton)
	Eolian sand	PO	fine sand to gravel (bedded)
	Alluvial fan deposit	VT	till, generally sandy textured (diamicton)
	Lacustrine deposit	VO	fine sand to gravel (bedded)
	New Ulm Fm ice-contact deposit	UNK	unknown sediments above bedrock
	New Ulm Fm lake sand-DesMoines		
	New Ulm Fm outwash(Des Moines)		
NT	New Ulm Fm sandy till		
	New Ulm Fm loamtill low-relief		
	New Ulm Fm Twin Cities mbr		
	New UlmFm loamtill high-relief		
	New UlmFm till moderate relief		
TERR	Floodplain alluvium		
	Langdon terrace		
	Langdon Terr. over Cromwell Fm		
	Langdon ter. over New Ulm Fm		
	Langdon terrace;rock substrate		
	Langdon terr ovr red silt&clay		
	Richfield terrace		
	Richfield terr over Cromwell		
	Richfield terr over New Ulm Fm		
	Richfield terr; rock substrate		

Appendix b. Cation exchange experiment - sample collection (< 2mm fraction)

relateid	unique_no	sample_date	submit	sample_id	source	description	depth	depth interval (ft)	texture *grvl-sand-silt-clay*
0000685758	685758	6/25/2007		MCCE_01	Rotosonic Hole Mound TW	unoxidized till	45	43.5-47	
0000685758	685758	6/25/2007	x	MCCE_02	Rotosonic Hole Mound TW	coarse sand, Su	120	117-122	
0000256621	256621	6/25/2007		MCCE_03	Rotosonic Hole Waverly	unoxidized till	49	47-51	
0000251480	251480	7/6/2007		MCCE_04	Rotosonic Hole WR-2	reddish sandy ti	6	6	9-73-18-9
0000251480	251480	7/6/2007	x	MCCE_05	Rotosonic Hole WR-2	reddish sandy ti	8	8	8-65-24-11
0000251480	251480	7/6/2007	x	MCCE_06	Rotosonic Hole WR-2	red silty very fin	33	33	6-71-20-9
0000251480	251480	7/6/2007		MCCE_07	Rotosonic Hole WR-2	reddish loamy g	43	43	12-80-11-9
0000251480	251480	7/6/2007	x	MCCE_08	Rotosonic Hole WR-2	varigated coarse	46	46	10-81-10-9
0000251480	251480	7/6/2007	x	MCCE_09	Rotosonic Hole WR-2	silty fine sand, w	49	49	6-66-17-17
0000251480	251480	7/6/2007	x	MCCE_10	Rotosonic Hole WR-2	fine loamy till	63	63	2-48-28-24
0000251480	251480	7/6/2007	x	MCCE_11	Rotosonic Hole WR-2	fine loamy till	69	69	3-54-23-23
0000251480	251480	7/6/2007		MCCE_12	Rotosonic Hole WR-2	dark olive dense	78	78	2-35-34-31
0000251480	251480	7/6/2007		MCCE_13	Rotosonic Hole WR-2	dark olive dense	84	84	4-30-41-29
0000251480	251480	7/6/2007	x	MCCE_14	Rotosonic Hole WR-2	dark olive dense	96	96	1-27-45-28
0000251480	251480	7/6/2007	x	MCCE_15	Rotosonic Hole WR-2	dark olive dense	108	108	3-28-43-29
0000251480	251480	7/6/2007	x	MCCE_16	Rotosonic Hole WR-2	reddish poorly s	124	124	
0000251481	251481	7/6/2007	x	MCCE_17	Rotosonic Hole WR-3	gravelly sand	12	12	
0000251481	251481	7/6/2007	x	MCCE_18	Rotosonic Hole WR-3	red silty sandy ti	36	36	3-53-32-15
0000251481	251481	7/6/2007	x	MCCE_19	Rotosonic Hole WR-3	reddish v. sandy	55	55	8-77-19-4
0000251481	251481	7/6/2007	x	MCCE_20	Rotosonic Hole WR-3	reddish v. sandy	69	69	8-67-18-15
0000251481	251481	7/6/2007		MCCE_21	Rotosonic Hole WR-3	gray fine sandy	88	88	5-61-24-15
0000251481	251481	7/6/2007	x	MCCE_22	Rotosonic Hole WR-3	well sorted med	99	99	
0000251481	251481	7/6/2007	x	MCCE_23	Rotosonic Hole WR-3	gray fine loamy	110	110	2-33-42-25
0000251481	251481	7/6/2007		MCCE_24	Rotosonic Hole WR-3	gray fine loamy	125	125	4-39-36-25
0000251481	251481	7/6/2007	x	MCCE_25	Rotosonic Hole WR-3	gray fine loamy	140	140	9-41-35-24
0000251481	251481	7/6/2007	x	MCCE_26	Rotosonic Hole WR-3	interbedded and	173	173	
0000247130	247130	7/6/2007		MCCE_27	Rotosonic Shoreview RR-1	gray loamy till	49	49	3-49-34-17
0000247130	247130	7/6/2007	x	MCCE_28	Rotosonic Shoreview RR-1	gray loamy till	55	55	8-46-35-19
0000247130	247130	7/6/2007	x	MCCE_29	Rotosonic Shoreview RR-1	gray loamy till	58	58	7-46-34-20
0000247130	247130	7/6/2007	x	MCCE_30	Rotosonic Shoreview RR-1	medium sand, s	120	120	
0000247130	247130	7/6/2007	x	MCCE_31	Rotosonic Shoreview RR-1	sandy till, Super	146	146	5-56-33-11
0000247130	247130	7/6/2007		MCCE_32	Rotosonic Shoreview RR-1	dark gray clayey	164	164	4-30-44-26
0000247130	247130	7/6/2007	x	MCCE_33	Rotosonic Shoreview RR-1	dark gray clayey	167	167	1-34-41-25
0000247130	247130	7/6/2007		MCCE_34	Rotosonic Shoreview RR-1	dark gray clayey	194	194	2-30-48-22
0000247130	247130	7/6/2007	x	MCCE_35	Rotosonic Shoreview RR-1	dark gray clayey	197	197	5-31-48-21
0000247130	247130	7/6/2007		MCCE_36	Rotosonic Shoreview RR-1	compact dark gr	206	206	2-312-42-27
0000247130	247130	7/6/2007	x	MCCE_37	Rotosonic Shoreview RR-1	light brown loam	283.5	283.5	2-35-42-23
0000247206	247206	7/6/2007	x	MCCE_38	Rotosonic Isanti AR-1	sandy, somewha	95	95	11-68-21-11
0000247206	247206	7/6/2007		MCCE_39	Rotosonic Isanti AR-1	very dense, very	113	113	2-27-47-26
0000247206	247206	7/6/2007	x	MCCE_40	Rotosonic Isanti AR-1	same as above,	133	133	3-30-46-24
0000247206	247206	7/6/2007	x	MCCE_41	Rotosonic Isanti AR-1	same as above,	146	146	4-44--40-16
0000247206	247206	7/6/2007	x	MCCE_42	Rotosonic Isanti AR-1	wet till, loose an	210	210	5-78-14-8
0000247206	247206	7/6/2007	x	MCCE_43	Rotosonic Isanti AR-1	sandy till, loamy	220	220	6-80-15-5
0000247206	247206	7/6/2007		MCCE_44	Rotosonic Isanti AR-1	sandy red till	190	190	8-71-21-8
0000247206	247206	7/6/2007		MCCE_45	Rotosonic Isanti AR-1	sandy red till	200	200	4-75-15-10
0000247206	247206	7/6/2007		MCCE_46	Rotosonic Isanti AR-1	brownish gray sa	74	74	3-60-32-8
0000247206	247206	7/6/2007	x	MCCE_47	Rotosonic Isanti AR-1	sandy red till	180	180	
0000247206	247206	7/6/2007	x	MCCE_48	Rotosonic Isanti AR-1	dense gray loam	151	151	3-48-36-16
0000247206	247206	7/6/2007	x	MCCE_49	Rotosonic Isanti AR-1	dense gray loam	128	128	4-27-48-25
0000247206	247206	7/6/2007	x	MCCE_50	Rotosonic Isanti AR-1	thin gleyed zone	162	162	11-67-24-9
0000247130	247130	7/6/2007	x	MCCE_51	Rotosonic Shoreview RR-1	silty sand and gr	260	260	
0000247206	247206	7/6/2007	x	MCCE_52	Rotosonic Isanti AR-1	dense gray loam	117.5	117.5	2-18-45-27
0000251480	251480	7/6/2007		MCCE_53	Rotosonic Hole WR-2	red silty very fin	35	35'	
0000251480	251480	7/6/2007		MCCE_54	Rotosonic Hole WR-2	silty fine sand, w	52.5	52.5	
0000247206	247206	7/6/2007	x	MCCE_55	Rotosonic Isanti AR-1	sandy, somewha	96	96+	
0000		10/5/2007		MCCE_56	McLeod County Giddings 23823	unoxidized New	14	13-15	
0000		10/5/2007	x	MCCE_57	McLeod County Giddings 21670	unoxidized New	14	13-15	
0000		10/5/2007		MCCE_58	McLeod County Giddings 23826	unoxidized New	15	14.5-15	
0000256716	256716	10/5/2007		MCCE_59	Rotosonic Todd Co. TR-3 - 2567	unoxidized Des	35	35	
0000243178	243178	9/21/2007	x	MCCE_60	Anoka A-2 - 243178	silt, clayey silt, in	116	116	
0000243178	243178	9/21/2007	x	MCCE_61	Anoka A-2 - 243178	clay, ,clayey silt	67	67	4-36-60
0000243178	243178	9/21/2007		MCCE_62	Anoka A-2 - 243178	clay, clayey silt,	91	91	13-36-51
0000243177	243177	9/21/2007	x	MCCE_63	Anoka A-1 - 243177	clay, silty clay, la	65	65	7-34-59
0000243184	243184	9/21/2007	x	MCCE_64	Anoka A-8 - 243184	silty clay, lamina	85	approx 85	
0000243184	243184	9/21/2007		MCCE_65	Anoka A-8 - 243184	red clay, unit CL	69	approx 60	

Appendix C: Water chemistry data from northwestern Hennepin County collected Fall, 2006

	A1	A2	A3	A4	A5	A6	A7	A8
unique_no	445979	425079	424036	401396	438503	189605	426195	126414
depth (ft)	290	261	234	310	453	366	259	263
aquifer	cfrn	cjdn	cjdn	cfrn	cslf	cslf	cjdn	cjdn
date	2006-10-31	2006-10-31	2006-10-31	2006-10-31	2006-10-31	2006-10-31	2006-10-31	2006-10-31
temp (C)	9.8	9.7	9.3	9.9	9.3	9.3	9.8	9.6
pH	7.68	7.18	7.15	7.54	7.13	7.32	7.17	7.58
cond (umhos)	730	788	827	672	758	843	948	802
redox (mV)								
DO (ppm)								
Cations (ppm)								
Ca	86.88	92.17	99.85	76.95	99.33	105.00	113.80	64.12
Mg	37.69	41.31	44.27	25.17	37.85	33.72	52.70	40.48
Na	15.87	18.4	11.41	34.04	6.257	27.98	14.35	9.665
K	2.979	2.795	3.443	1.421	2.175	2.836	3.042	2.701
Al	0	0.01326	0.011115	0.0021305	0.005417	0.003956	0	0.003019
Fe	0.4082	0.58015	1.725	4.361	2.112	4.64	0.8524	3.776
Mn	0.33755	0.21945	0.57245	0.17725	0.0881	0.06042	0.09729	0.1044
Sr	0.35835	0.29615	0.4649	0.2141	0.3617	0.3293	0.3666	0.4148
Ba	0.08596	0.03663	0.1504	0.096265	0.1273	0.08742	0.07713	0.1375
Si	12.58	12.62	16.25	11.72	11.26	6.354	12.15	14.29
Anions (ppm)								
Alk_CaCO3	394	402	436	386	425	407	496	420
Cl	0.767	0.561	0.615	0.865	0.576	0.582	0.641	0.703
Br	0.023	0.024	0.026	0.016	0.011	0.016	0.027	0.015
NO2-N	<0.002	0.007	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
NO3-N	0.002	0.077	0.001	0.002	0.006	0.004	0.002	0.006
SO4	23.43	30.49	18.46	4.19	4.217	61.23	39.39	21.18
PO4-P	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
total P	67.44	278.68	362.2	307.85	0	0	0	0
F	0.204	0.226	0.237	0.183	0.188	0.232	0.119	0.251
charge balance								
cations (meq/kg)	8.23	8.89	9.24	7.44	8.41	9.32	10.73	7.04
anions (meq/kg)	8.40	8.70	9.13	7.84	8.61	9.44	10.76	8.87
% difference	1.05	1.04	0.60	2.62	1.18	0.68	0.16	11.56

Appendix C: Water chemistry data from northwestern Hennepin County collected Fall, 2006

	A9	A10	A11	A12	A13	A14	A15	A17
unique_no	419308	412209	178176	426189	105253	143514	404706	435801
depth (ft)	200	177	245	190	186	158	210	247
aquifer	ostp	cjdn	cfrn	cfrn	cfrn	cfrn	cjdn	cslf
date	2006-10-31	2006-10-31	2006-10-31	2006-11-01	2006-11-01	2006-11-01	2006-11-01	2006-11-01
temp (C)	9.8	9.5	9.2	9.9	8.4	9.5	9.9	9.7
pH	7.46	7.39	7.50	7.37	7.43	7.50	7.68	7.62
cond (umhos)	823	777	525	777	809	800	736	736
redox (mV)								
DO (ppm)								
Cations (ppm)								
Ca	84.64	97.23	70.66	97.12	105.70	97.25	73.95	72.51
Mg	42.84	40.00	24.19	39.75	40.62	42.41	44.96	46.73
Na	19.97	8.615	1.585	11.18	7.771	10.39	17.95	14.25
K	3.175	2.772	1.874	1.957	3.035	2.991	2.574	2.988
Al	0	0.002696	0.001752	0.004571	0	0	0.02007	0.000937
Fe	2.148	3.261	4.338	1.87	1.477	1.931	0.2465	2.071
Mn	0.06124	0.516	0.3256	0.5244	0.3232	0.4267	0.1375	0.2465
Sr	0.3645	0.3294	0.1079	0.2949	0.384	0.3726	0.3176	0.3843
Ba	0.1182	0.09013	0.05701	0.08405	0.1174	0.1072	0.05075	0.08566
Si	13.07	14.76	11.25	11.34	12.82	13.95	12.28	10.97
Anions (ppm)								
Alk_CaCO3	470	438	281	425	432	430	383	396
Cl	0.698	0.597	1.293	0.58	1.002	0.544	0.626	0.986
Br	0.025	0.018	0.028	0.021	0.052	0.018	0.018	0.02
NO2-N	<0.002	<0.002	<0.002	0.001	<0.002	<0.002	<0.002	<0.002
NO3-N	0.002	0.002	0.003	0.009	<0.001	<0.001	0.015	0.012
SO4	12.3	6.209	3.988	9.921	18.87	8.733	27.86	16.18
PO4-P	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
total P	417.9	131.3	210.1	0	198.2	305.9	253.6	0
F	0.215	0.166	0.16	0.132	0.222	0.149	0.242	0.232
charge balance								
cations (meq/kg)	8.71	8.62	5.65	8.68	9.06	8.90	8.25	8.18
anions (meq/kg)	9.69	8.91	5.75	8.73	9.07	8.81	8.27	8.30
% difference	5.30	1.70	0.87	0.28	0.10	0.52	0.13	0.72

Appendix C: Water chemistry data from northwestern Hennepin County collected Fall, 2006

	A18	A19	A20	A21	A22	A23	A25	A26
unique_no	159608	426300	197563	417017	187961	417065	156209	434305
depth (ft)	261	245	180	208	133	183	260	201
aquifer	cfrn	cslf	cslf	cslf	cjdn	cslf	cfrn	cjsl
date	2006-11-01	2006-11-01	2006-11-01	2006-11-01	2006-11-01	2006-11-01	2006-11-01	2006-11-01
temp (C)	9.5	9.8	9.7	9.4	9.8	9.9	11.2	9.4
pH	7.54	7.37	7.29	7.56	7.57	7.47	7.37	7.63
cond (umhos)	811	743	755	600	758	674	700	807
redox (mV)								
DO (ppm)								
Cations (ppm)								
Ca	99.07	95.72	99.23	70.00	89.27	78.05	85.12	99.32
Mg	44.03	38.33	38.51	31.59	41.25	33.64	35.98	41.03
Na	11.24	6.661	6.69	9.899	10.38	10.92	12.49	12.83
K	2.026	2.763	2.787	1.858	3.174	1.94	3.03	3.218
Al	0	0.015545	0.0068575	0.003859	0	0	0.001655	0
Fe	1.716	1.306	1.938	2.8045	5.948	2.2855	0.6287	2.459
Mn	0.4667	0.1986	0.7002	0.1106	0.779	0.2125	0.4211	2.602
Sr	0.3018	0.34475	0.38885	0.23705	0.39995	0.27825	0.3834	0.4265
Ba	0.07519	0.002542	0.068695	0.051335	0.06977	0.0656	0.08482	0.03403
Si	12.59	10.923	13.3	8.468	12.11	9.222	12.24	12.89
Anions (ppm)								
Alk_CaCO3	428	399	382	308	413	350	380	432
Cl	0.762	0.65	4.034	0.638	0.942	0.887	0.817	0.92
Br	0.018	0.017	0.038	0.01	0.018	0.015	0.032	0.024
NO2-N	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
NO3-N	<0.001	0.001	0.001	0.001	0.013	0.002	0.003	0.008
SO4	23.9	15.33	32.22	19.11	19.42	22.6	11.73	24.43
PO4-P	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
total P	132.9	14100	0	0	0	0	0	0
F	0.193	0.182	0.165	0.151	0.196	0.154	0.229	0.211
charge balance								
cations (meq/kg)	9.13	8.31	8.52	6.58	8.42	7.20	7.85	9.08
anions (meq/kg)	9.09	8.33	8.43	6.58	8.70	7.50	7.88	9.19
% difference	0.24	0.12	0.50	0.02	1.64	2.05	0.16	0.59

Appendix C: Water chemistry data from northwestern Hennepin County collected Fall, 2006

	A27	A27B	A28
unique_no	408683	146228	159332
depth (ft)	130	138	288
aquifer	cjdn	cjdn	cslf
date	2006-11-02	2006-11-02	2006-11-02
temp (C)	10.6	10.6	9.9
pH	7.50	7.68	7.93
cond (umhos)	1482	1070	526
redox (mV)			
DO (ppm)			
Cations (ppm)			
Ca	142.50	123.20	61.22
Mg	51.19	47.67	28.97
Na	72.77	18.56	3.813
K	3.729	2.454	1.335
Al	0.01445	0.003778	0
Fe	5.052	1.73	1.621
Mn	0.7771	0.62	0.4229
Sr	0.5192	0.4682	0.1414
Ba	0.266	0.1729	0.08336
Si	17.44	14.2	8.26
Anions (ppm)			
Alk_CaCO3	288	274	219
Cl	248.5	112.5	3.544
Br	0.063	0.046	0.034
NO2-N	0.002	<0.002	<0.002
NO3-N	0.003	0.003	0.002
SO4	96.3	116.2	62.19
PO4-P	<0.002	<0.002	<0.002
total P	0	0	0
F	0.149	0.176	0.198
charge balance			
cations (meq/kg)	14.63	10.98	5.66
anions (meq/kg)	14.78	11.08	5.79
% difference	0.52	0.48	1.10

Appendix D. Water chemistry data table structure and data dictionary

Name	Description
Data Tables	
c4wqr	Chemical analysis results
c4wqs	Water sample information
Look-up Tables	
CHEMICAL	Names of chemicals and water quality parameters, and unique chemical identifier numbers
LAB	Laboratory information
METHOD	Analysis methods
AGENCY	Agency or source of the data under which analysis was performed
PROGRAM	Program under which analysis was performed
UNITS	Units of measurement
SAMPLEEVENTS	Sampling name for regulary scheduled events or project identifier
DETECT	Detection code for parameter

Structure for table: **c4wqr**

Column Name	Type	Width
SAMPLE_NO	Numeric	
FLD_SAMPNO	Character	20
SAMPLE_EVENT	Character	10
LAB_NO	Character	9
RELATEID	Character	10
CHEM_NO	Character	10
LABCHEMNAM	Character	22
AN_DATE	Date	8
AN_METHOD	Character	10
DETECTCODE	Character	2
RPT_LIMIT	Numeric	
RESULT	Numeric	
UNITS	Character	10
RESULT_UNC	Numeric	
REMARK_R	Character	80
AGENCY	Character	7
PROGRAM_ID	Character	7
COLL_DATE	Date	
COLL_TIME	text	
REMARK_S	Character	25

Structure for table: **c4wqs**

Column Name	Type	Width
SAMPLE_NO	Numeric	
FLD_SAMPNO	Character	**20**
AN_DATE	Date	
RELATEID	Character	10
AGENCY	Character	50
PROGRAM	Character	50

Structure for table: **CHEMICAL**

Column Name	Type	Width
CHEM_NO	Character	10
NAME	Character	80
ABBREV	Character	10
SYNONYM	Character	65
CASNO	Character	10
STORET	Character	10
EPA_ID	Character	10

Structure for table: **METHOD**

Column Name	Type	Width
AN_METHOD	Character	10

DESC	Character	60

Structure for table: **DETECT**

Column Name	Type	Width
DETECTCODE	Character	2
DESC	Character	35

Structure for table: **UNIT**

Column Name	Type	Width
UNIT	Character	10
DESCRIPTION	Character	25

Structure for table: **SAMPLEEVENTS**

Column Name	Type	Width
CODE	Character	10
DESC	Character	80

Structure for table: **AGENCY**

Column Name	Type	Width
AGENCY	Character	7
NAME	Character	40

Structure for table: **PROGRAM**

Column Name	Type	Width
PROGRAM_ID	Character	7
AGENCY	Character	7
DESC	Character	50

Structure for table: **LAB**

Column Name	Type	Width
LAB_NO	Character	9
NAME	Character	50
ADDR1	Character	40

ADDR2	Character	40
CITY	Character	20
STATE	Character	2
ZIP	Character	10
CONTACT	Character	40
PHONE	Character	14
FAX	Character	14
E_MAIL	Character	40
CERT_NO	Character	10

Field description for table: **c4wqs**

SAMPLE_NO	Primary key, system generated
FLD_SAMPNO	Field sample number
AN_DATE	Analysis date
RELATEID	The unique and official identifier for the sample location – link to County Well Index
AGENCY	Agency under which sample was taken.
PROGRAM	Program under which sample was taken.

Field description for table: **c4wqr**

SAMPLE_NO	c4wqs table primary key
FLD_SAMPNO	Field sample number
SAMPLE_EVENT	User defined field for regularly scheduled sampling events or project identifier. Can be used for monitoring of requlatory compliance. (ie. FQ1996 - Fall Quartlerly Sampling for 1996)
LAB_NO	Laboratory number of laboratory where sample was analyzed, Field = field analysis. Usually the laboratory certification number from the U.S. EPA.
RELATEID	The unique and official identifier for the sample location – link to County Well Index
CHEM_NO	Chemical Abstract Services number for the chemical or modified identifier for water quality parameter (see CHEMICAL table).
LABCHEMNAM	chemical name
AN_DATE	1.)For analytes which have sample information; date on which analysis was

	competed for this parameter. 2.) For analytes without sample information; the date that the sample was taken.
AN_METHOD	Chemical analysis method.
DETECTCODE	Detection code for parameter. Valid codes are: < less than NA not analized NQ not quantified PP peak present PQ peak present but not quantified Null value indicates that result field is non-zero.
RPT_LIMIT	1.) For analytes (which have sample information) the reporting limit for parameter when different from method detection limit. Default value is the method detection limit. 2.) For analytes without sample information; the reporting limit is the same as the method detection limit and a null value indicates that no detection limit information is available for this result.
RESULT	Result of the analysis.
UNIT	Units of measure for the result.
RESULT_UNC	Result uncertainty, ±.
REMARK_R	Remarks - result
AGENCY	Agency under which sample was taken.
PROGRAM_ID	Program under which sample was taken.
COLL_DATE	Sample collection date (MM/DD/YY)
COLL_TIME	Sample collection time (HH:MM)

Field description for table: **CHEMICAL**

CHEM_NO	The unique identifier for a particular analyte or water quality parameter, usually the chemical abstract services registry number.
NAME	The full name of the analyte or water quality parameter.
ABBREV	The name or abbreviated name of the analyte or water quality parameter typically used on laboratory forms.
SYNONYM	Any synonym for the analyte that is commonly used, including trade names.
CASNO	The chemical abstract services registry number for an analyte.
STORET	STORET number for an analyte.
EPA_ID	EPA identifier for an analyte.

Field description for table: **METHOD**

AN_METHOD	Analysis method abbreviation.
DESC	Analysis method description

Field description for table: **DETECT**

DETECTCODE	Detection code for analyte. (i.e. < less than, NA not analyzed)
DESC	The detection code description.

Field description for table: **UNITS**

CODE	Units of measurement for the result.
DESC	The unit description.

Field description for table: **SAMPLEEVENTS**

CODE	User defined field for regularly scheduled sampling events or project identifier.
DESC	The description of the sample event.

Field description for table: **AGENCY**

AGENCY	agency or source of the data under which the analysis was performed
AGENCYNAME	The agency name.

Field description for table: **PROGRAM**

PROGRAM_ID	Bureaucratic program of the data under which the analysis was performed.
DESC	The description of the program.
AGENCY	The agency that administers the program.

Field description for table: **LAB**

LAB_NO	Laboratory number.
NAME	Name of laboratory.
ADDR1	First line of laboratory mailing address.
ADDR2	Second line of laboratory mailing address.
CITY	Laboratory city.
STATE	Laboratory state.
ZIP	Laboratory zip code.
CONTACT	Laboratory contact person name.
PHONE	Laboratory telephone number.
FAX	Laboratory fax machine telephone number

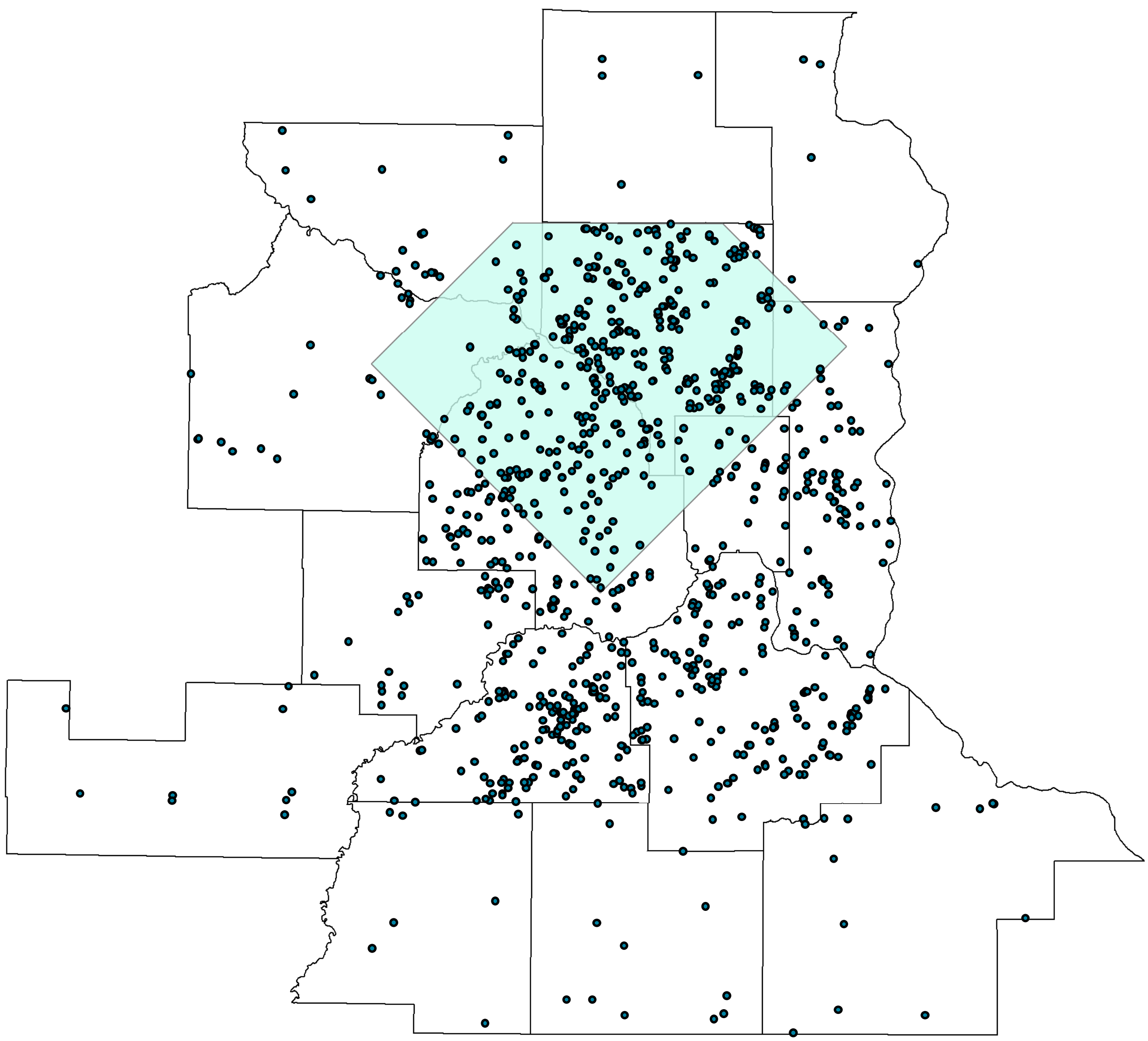

Figure 1. Map showing the greater Twin Cities metropolitan area, Minnesota and locations of wells with historic water chemistry data assembled as part of this investigation. Shaded area shows the extent of the Quaternary geologic framework model.