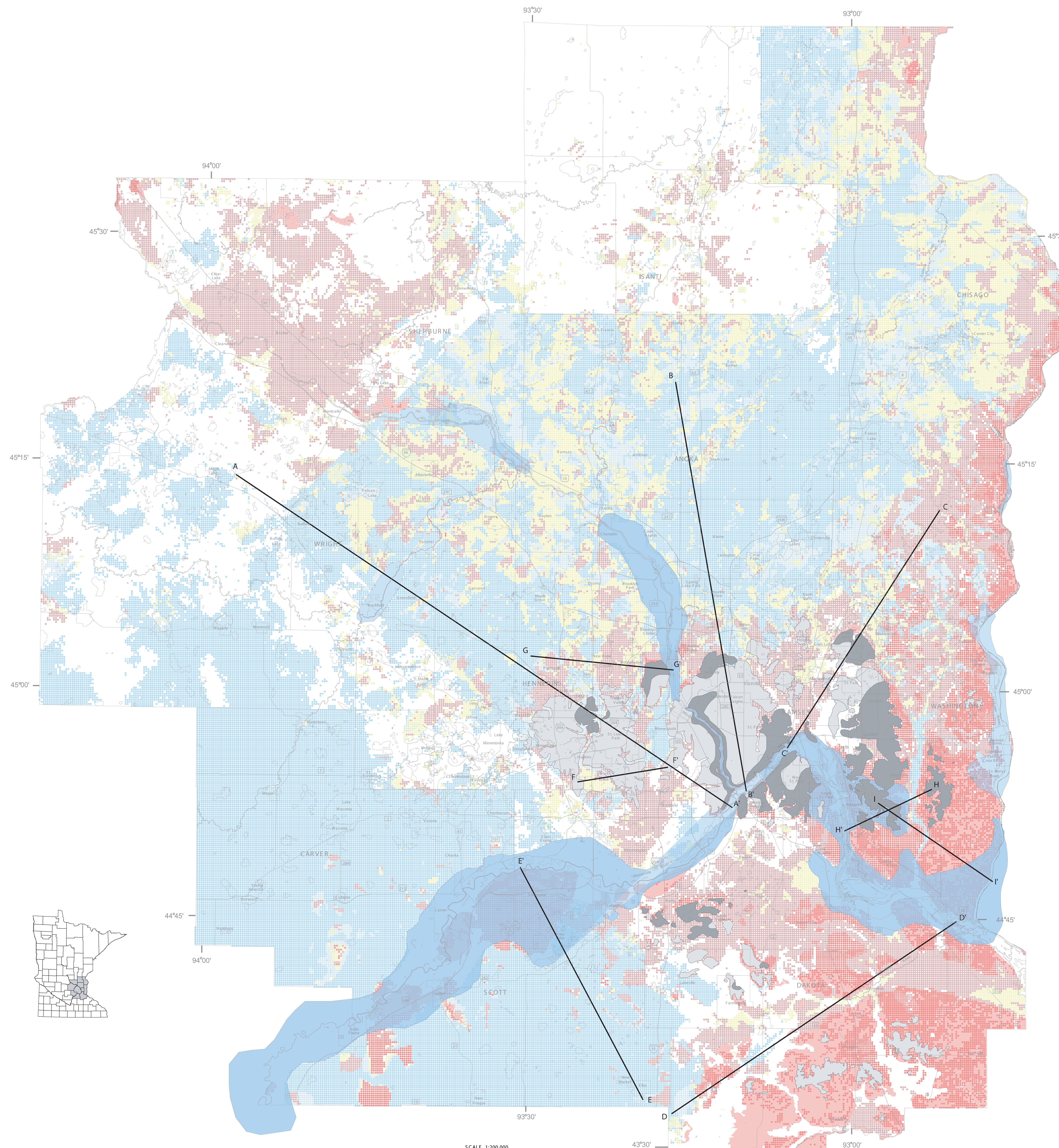
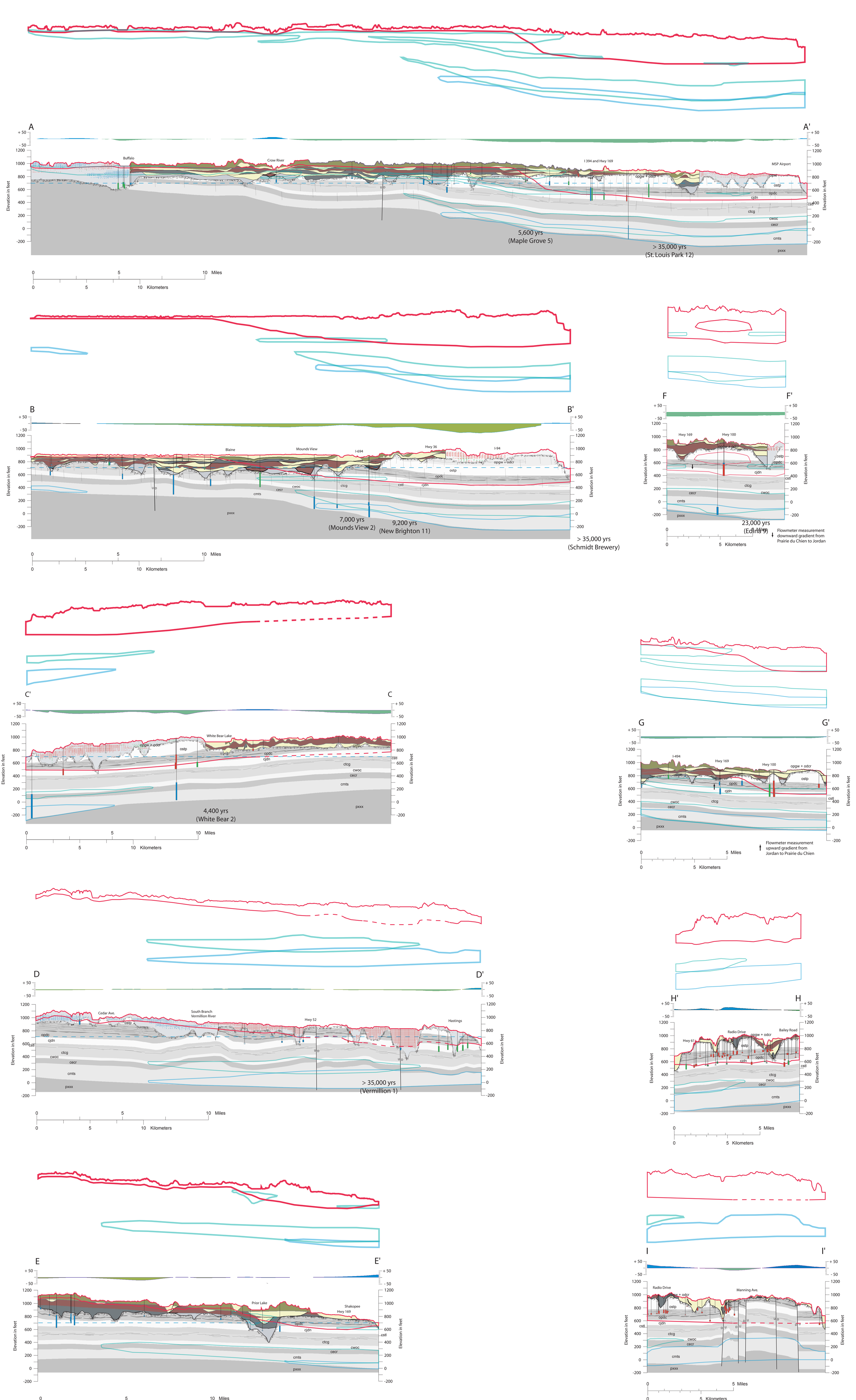
UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY
Harvey Thorleifson, Director

Prepared with the Support of
THE METROPOLITAN COUNCIL REGIONAL PLANNING AGENCY

DISTRIBUTION OF VERTICAL RECHARGE TO UPPER BEDROCK AQUIFERS TWIN CITIES METROPOLITAN REGION , MINNESOTA

Robert G. Tipping
2011





hydrochemical facies

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

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

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

casing
recent — open hole
mixed
vintage

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

5,600 yrs
(Maple Grove 5)

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

hydraulic gradient

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

flowmeter measurement. Arrow indicates direction of ambient flow in an open borehole

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

mapped Quaternary stratigraphy

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

interpolated model

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

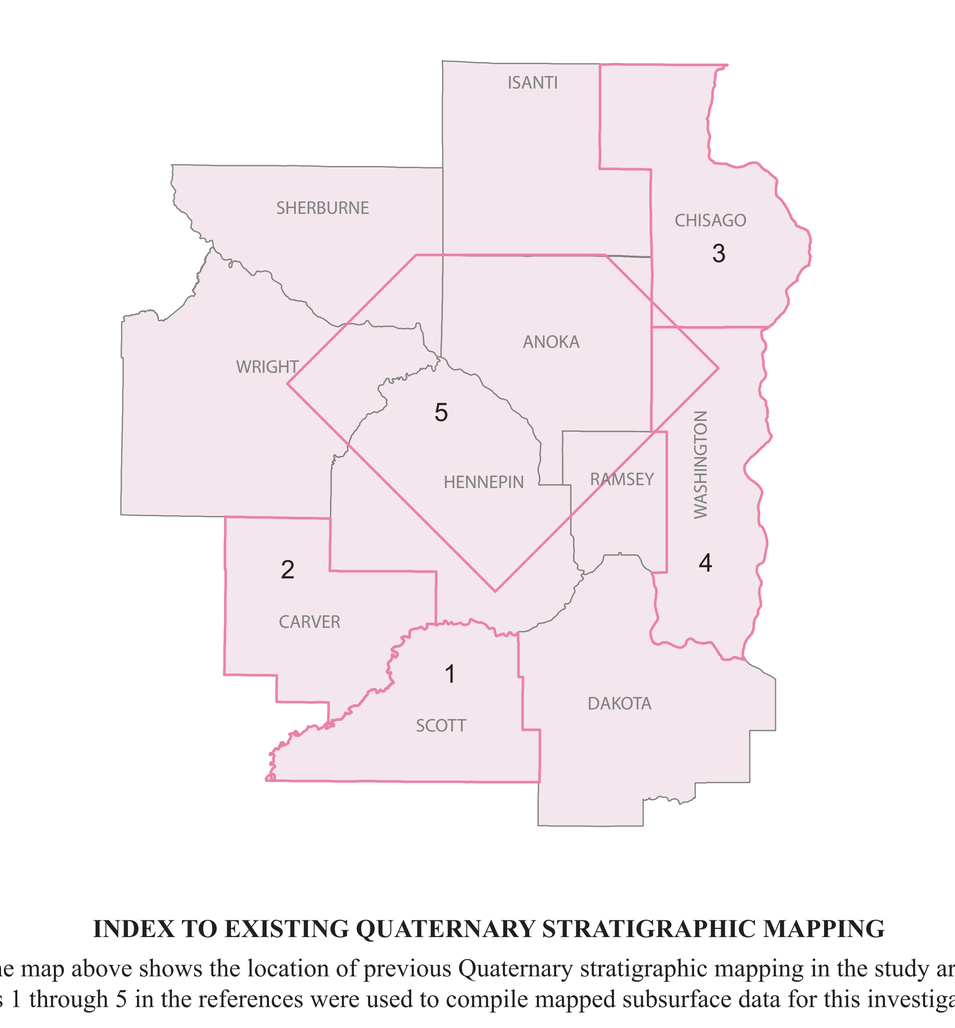
qxxx	Quaternary, undifferentiated
opgw + odcr	Plattville Fm., Glenwood Shale, Decorah Shale
ostp	St. Peter Sandstone
opdc	Prairie du Chien Group
cjdn	Jordan Sandstone
cstl	St. Lawrence Formation
ctcg	Tunnel City Group
cwoc	Wonewoc Sandstone
cecr	Eau Claire Formation
cmts	Mt. Simon Sandstone
pxxx	pre-Cambrian,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

near-surface fractures

hydraulically active bedding plane fractures and conduits

systematic vertical fractures

bedrock fault, indicating upthrown and downthrown sides



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

Table 1. code refers to field "K_class_composite" in gridpoints data set. 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 (Tipping et. al., 2010)

INDEX TO EXISTING QUATERNARY STRATIGRAPHIC MAPPING

The map above shows the location of previous Quaternary stratigraphic mapping in the study area. Citations 1 through 5 in the references were used to compile mapped subsurface data for this investigation.

DESCRIPTION OF MAP UNITS

Vertical travel time (years)

- 0 - 1
- 1 - 25
- 25 - 50
- 50 - 500
- > 500

Greater Twin Cities metropolitan area divided in a matrix of points 250 meters on center in the horizontal (XY) location, separated by 20 feet in the vertical (Z) direction from the land surface to the bedrock surface. Time of travel in the vertical direction calculated for each XY location from the regional water table to the bedrock surface. Estimate based on calculation of vertical Darcy flux divided by assumed effective porosity of 20%. Calculation not done for conditions where water table is at or below the bedrock surface, or in conditions where depth to bedrock is less than 50 feet. See text for discussion.

Platteville Formation

Estimated area of partially saturated conditions in underlying St. Peter Sandstone

Estimated area of fully saturated or unknown conditions in underlying St. Peter Sandstone

Saturated/unsaturated conditions in St. Peter determined by comparing static water elevation from CWI interpreted as St. Peter wells with modeled Plattville/Glenwood base elevation.

Depth to bedrock less than 50 feet

Area not within subcrop area of the Platteville Formation where bedrock is less than 50 feet from the land surface. Area determined by subtracting 30 meter DEM derived from current metropolitan area bedrock topography (Jirsa and others, 2011) from USGS 30 meter National Elevation Dataset (NED).

Water table in bedrock

XY point locations where water table elevation (Barr, 2010) is less than or equal to bedrock elevation

Regional discharge (upward gradient) from bedrock aquifers

Result of subtraction of regional bedrock poteniometric surface, created from contoured synoptic water elevations for the Prairie du Chien Group and Jordan Sandstone (Sanocki and others, 2009) and contours for uppermost bedrock water elevations from CWI, from regional water table surface (Barr, 2010).
Shows areas of upward gradient (negative values) for both March and August 2008 synoptic measurements.

Insufficient subsurface data to calculate vertical travel time

XY point locations where less than 40% of the subsurface gridpoints could be assigned texture values based on surface/subsurface mapping or interpolation. At these locations, bulk Kv estimates could not be determined.

Introduction

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

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

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

Methods

Distibution and hydraulic characteristics of unconsolidated subsurface materials

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

Within the TCMAx, areas with no Quaternary subsurface mapping include Dakota, Ramsey, Isanti and portions of Hennepin County. Subsurface mapping is currently underway as part of the Wright and Sherburne geologic atlases, but are not completed at this time. In order to determine the distribution of subsurface textures in these areas, interpolation methods modified from those of earlier geologic atlases were used (e.g. Meyer and others, 1995). With this approach, stratigraphic records from water wells are coded based on primary lithology into 3 textural categories of fine-grained, coarse-grained, or a mixture of fine and coarse-grained. In driller's records, these intervals are typically referred to as clay, sand/gravel, and sandy clay/clayey sand. The stratigraphic record is then resampled into equal 10 foot elevation intervals. Two-dimensional interpolation using ordinary kriging is used to determine the likelihood of each category for a given elevation interval. Two-dimensional, rather than three-dimensional interpolation is used, based on the premise that glacial deposits have undergone minimal structural deformation since their deposition, and that correlation is optimized by evaluating data at equal elevations. Interpolated results for each elevation interval are merged to into a single dataset to create a three-dimensional model for each of the three textural types.

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

For travel time calculations, a single "composite" Kv was assigned to each gridpoint in qgrdpoints_250 based on the following hierarchy. If no other texture estimate was available, Kv was assigned based on texture from interpolated model. These Kv's were replaced by texture-based Kv's from subsurface mapping, which in turn were replaced by texture-based Kv's from the surficial map (upper 20 feet only). After these assignments were made, if a single column of gridpoints from the land surface to the bedrock surface had texture-derived Kv's for more than 40 percent of its points, the remaining blanks were assigned an intermediate value 10.05 ft/day; if less than 40 percent had texture-derived Kv's, the remaining blanks had no value assigned.

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

For each XY location with greater than 40 percent of its subsurface gridpoint textures represented by mapping or interpolation, arithmetic, geometric and harmonic mean Kv values were calculated. This calculation was done both for points from water table elevation to the bedrock surface and from the water table elevation to the land surface, and are referred to as "Kv_sat" and "Kv_unsat" respectively in the XY location dataset.

Hydraulic Gradient

Hydraulic head differences used to establish a hydraulic gradient between the water in upper, unconsolidated deposits and water in bedrock aquifers were determined using raster calculations. The regional water table raster surface was constructed to help evaluate the impact of pumping on surface water bodies at a regional scale (Barr, 2010). By design, it is well suited for this investigation, by providing generalized regional elevations of saturated conditions. With exception of zones above the Platteville Formation, zones of perched groundwater systems are not included. Main sources of data sources for the regional water table surface are Minnesota Department of Natural Resources observation well network for water table wells, the County Well Index (CWI), and data from site specific studies. Results from regional groundwater flow models and surface-water elevations for reaches of some streams known to be gaining were also used as a control, particularly where data from other sources were sparse (Barr, 2010).

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

The regional water table and bedrock potentiometric surfaces are generalized surfaces both spatially and temporally. Both surfaces are based, in part, on measurements from CWI, taken most often at the date of installation, spanning all seasons over many decades. Filtering and data processing and final cross-validation of the water table CWI dataset resulted in values dropped with absolute residuals 20 feet or greater (Barr, 2010). Error for both regional water table surface and the bedrock potentiometric surface elevations are estimated to be at a minium +/- 20 feet in areas based solely on data from CWI. Water table data from the DNR's observation well network are based on reliable measurements, but are subject to seasonal variations not included in this model. Bedrock water level data from 2008 synoptic water level measurements provide data that is temporally consistent across the metro area. Measurements were taken in March and August of 2008, and provide information on seasonal changes in hydraulic head within bedrock aquifers. Subtracting the bedrock potentiometric surface from the regional water table surface produced negative values over much of the TCMAx. Many of these areas were focused on the major rivers, where upward discharge of bedrock aquifers is reflected in expected negative values. In other areas, it is less clear whether actual artesian conditions exist, or where uncertainty in the surface values produces overlap. For the purposes of travel time calculations, areas with negative values near major discharge areas, or areas where CWI records indicate flowing (artesian) bedrock wells were identified and are shown on this map. Outside of these areas, bedrock potentiometric surface elevations greater than the regional water table were lowered to one-half foot below the regional water table.

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

Calculation of vertical travel times

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

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

- T — vertical time of travel in years
- Kv — bulk vertical hydraulic conductivity in feet/day
  - for saturated conditions: mean value from water table to bedrock surface
  - for unsaturated conditions: mean value from water table to land surface
- grad_h
  - for saturated conditions: difference in elevation between regional water table and bedrock poteniometric surfaces, in feet
  - for unsaturated conditions: set equal to 1
- L
  - for saturated conditions: distance from water table to bedrock surface, in feet
  - for unsaturated conditions: distance from the land surface to the water table, in feet
- n — effective porosity, set equal to 0.20

Time of travel estimates were calculated for arithmetic, geometric and harmonic means of Kv for both saturated and unsaturated conditions. The map uses travel time estimates calculated using the harmonic mean because it best matched chemical and isotopic results.

Groundwater chemical and isotopic composition

To evaluate vertical travel time estimates, three ground water chemical types, or hydrochemical facies, were mapped at the regional scale (Tipping and others, 2010):
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 till associated with the Des Moines lobe; C. Areas with sand and gravel at the land surface to a depth not greater than 30 feet below local elevations of the Mississippi and Minnesota Rivers. Conditions (b) and (c) are based on literature values (e.g. Schilling and Tassier-Surine 2006) and site-specific data (Tipping, et. al., 2010) generalized to broad regions having limited chemical data. These criteria resulted in a composite generalized contour map showing the elevation above mean sea level where recent water would be expected to be found. Other indicators of recent water such as the presence of elevated chloride, nitrate, or anthropogenic compounds generally fit within these contours. It should be noted that within the center part of the basin, contours show a bowl shaped presence of recent waters to an elevation of 475 feet. Vintage waters have been found above this elevation within the upper Prairie du Chien Group where it is covered by the Platteville and Glenwood Formations (see cross section F-F'). This condition of younger water underlying older water is expected to be present elsewhere within the TCMAx under similar hydrogeologic conditions; 2. Waters with distinct cation ratios were distinguished by having strontium to calcium plus magnesium molar ratios greater than 0.001. These waters are predominantly in the western part of the metro area, with the exception of the Mt. Simon aquifer, where they extend to the central and southeastern parts of the basin. Elevated strontium to calcium plus magnesium ratios may be associated with recharge through NW provenance tills, and are also considered to an indicator of longer residence time (Eckman and Alexander, 2002; and 3. Waters with naturally elevated chloride were distinguished by having chloride levels greater than 15 ppm and carbon 14 age dates greater than 1,000 years. These waters were mapped in the Mt. Simon aquifer only, but are thought to be present in shallow aquifers near major fault zones in the metro area, including the cities of Hastings, Anoka, and Belle Plaine.

Results

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

Regional cross sections

* Cross section A-A', Sherburne County to Mississippi River. Recent waters interpreted as present in the upper 50 feet of unconsolidated deposits, increasing with depth in the central part of the basin. Lowest elevation of recent waters occurs in the Jordan Sandstone. Carbon 14 dates for Mt. Simon are shown, indicating a sharp contrast in recharge rates for the upper and lower aquifer systems.
* Cross section B-B', St. Francis, Anoka County to Mississippi River. Recent waters interpreted as present in the upper 50 feet of unconsolidated deposits, increasing with depth in the central part of the basin. Lowest elevation of recent waters occurs in the Jordan Sandstone. Complexity of unconsolidated deposits over bedrock, below surficial sands is shown.
* Cross section C-C', Big Marine Lake, Washington County to Mississippi River near downtown St. Paul. Recent waters between Big Marine and White Bear Lake in the Prairie du Chien Group largely based on tritium measurements from samples west and east of the cross section line interpreted as mixed waters (TU between 1 and 10). Recent water is found at depth towards downtown St. Paul, coincident with a downward gradient and coarse unconsolidated deposits over bedrock. Slight upward gradient at White Bear Lake; downward gradient near Big Marine possibly marking groundwater divide, with regional discharge west towards the St. Croix River. Vintage waters in the Mt. Simon aquifer
* Cross section D-D', western Dakota County to Mississippi River near Hastings. Limited data show presence of clay, based on the interpolated model, restrict the downward movement of water west of the South Branch of the Vermillion River. Remainder of the cross section is largely sand and gravel over Prairie du Chien Group. A large buried valley filled with sand and gravel is present west of Hastings. Recent waters within this valley based on sampled wells within and on the edges of the valley to the southeast.
* Cross section E-E', southeastern Scott County to Minnesota River near Shakopee. Recent waters absent below cover of alternating NW and NE provenance tills. Elevated strontium to calcium plus magnesium ratios limited to bedrock valley in upper aquifers and to the Mt. Simon in the lower aquifer. Naturally elevated chloride present in the Mt. Simon at the northeast end of the cross section. Presence of recent water in the Jordan in this area based on sampled wells to the east and west of the cross section line. A strong upward gradient from the Jordan is present near the Minnesota River.

Local cross sections

* Cross section F-F' Edina area. Age inversion within the open hole of a single well is shown. Grab samples from the lower portion of the open hole had detectible tritium, while the uppermost sample, located within the Shakopee Formation - Prairie du Chien Group, did not (MDH, 2010). Flow logging from a nearby test well (MN unique well no. 748656) showed strong downflow from the lower Shakopee to the Jordan Sandstone, corresponding to stratigraphic position of detectible tritium in this well. Interpreted stagnation zone of older water illustrated as present underneath the central portion of the Platteville/Glenwood cap.
* Cross section G-G' Eastern Hennepin County. Recent water occurs at depth east of till cover. Flow logging east of Highway 169 showed strong upflow from fractures in the upper Jordan Sandstone to the upper Oneota Formation - Prairie du Chien Group (MN unique well no. 676445.)
* Cross section H-H', south central Washington County to Mississippi River. Stratification of perflourochemical (PFC) detections between Shakopee (upper Prairie du Chien Group) and Jordan samples is shown. Results infer separate flow systems, with possibly greater flux through the Shakopee Formation compared to the Jordan Sandstone.
* Cross section I-I', southeastern Washington County to St. Croix River. Downward gradient over a north-south trending bedrock valley in the center of the cross section, west of Manning Avenue. The valley, filled with primarily coarse-grained material, shows cluster of PFC detections. Occurrence of PFC's near the St. Croix River indicates movement of groundwater through fractures and fault blocks, crossing stratigraphic units with wide ranging permeability.

Discussion

The distribution of recent waters in the TCMAx upper bedrock aquifers broadly supports groundwater recharge rates calculated in this investigation. In general, recent waters are found at depth in areas with large vertical gradients and coarse material over bedrock. In southern Washington and central to east central Dakota County, coarse sediments overlie the Prairie du Chien Group. Much of this area is less than 50 feet to bedrock and the water table is largely often the bedrock surface. A large bedrock valley west of Hastings is also filled with coarse sediments. In areas where sufficient data exists, calculated vertical travel times are generally less than a year. Vertical gradients are controlled largely by regional discharge, although high capacity pumping for public water supply, commercial use and irrigation enhance vertical gradients locally.

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

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

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

Eastern Hennepin and Southern Ramsey County generally have calculated vertical travel times of less than a year, with the exception of areas where fine-grained material is present in the subsurface. Recent waters are found at elevations below regional discharge where high capacity pumping increases vertical gradients locally. These areas have the largest downward vertical gradients in the metropolitan area, in large part due to the presence of the Platteville and Glenwood Formations, along with remnants of Decorah Shale above them. Recognizing that much of the water table is perched above these formations, seasonal changes in the bedrock potentiometric surface based on synoptic measurements in March and August clearly demonstrate the influence of high capacity pumping on vertical gradient in these areas.

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

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

REFERENCES

Anderson, J.R., Runkel, A.C., Tipping, R.G., Barr, K.D.L., and Alexander, E.C., Jr., 2011, Hydrostratigraphy of a fractured, urban aquitard, in Miller, J.D., Jr., Hudak, G.J., Wittkop, C., and McLaughlin, P.I., eds., Archean to Anthropocene: Field Guides to the Geology of the Mid-Continent of North America: Geological Society of America Field Guide 24, p. 457-475.

Barr Engineering, 2010, Evaluation of groundwater and surface-water interaction: guidance for resource assessment, Twin Cities Metropolitan Area, Minnesota. Prepared for Metropolitan Council, June 2010. 27 p. plus GIS files. http://www.metrocouncil.org/environment/WaterSupply/gwswinteractionevaluation.htm (Accessed August 17, 2011)

Bradbury, K.R. and Runkel, A.C., 2011, Recent advances in the hydrostratigraphy of Paleozoic bedrock in the Midwestern United States. GSA Today, v. 21, no. 9, pp 10-12

Eckman, J., and Alexander, S.C., 2002, Ground-water chemistry and residence time, Regional Hydrogeologic Assessment Ottertail Area, West-Central Minnesota, Minnesota Department of Natural Resources Regional Hydrologic Assessment Series RHA-5, technical appendix to part B, 15 p.

Hart, D.J., Bradbury, K.R., and Feinstein, D.T., 2006, The vertical hydraulic conductivity of an aquitard at two spatial scales. Ground Water, v. 44, no. 2, pp. 201-211

Larson-Higdem, D., Larson, S.P., Norvitch, R.F., 1975, Configuration of the water table and distribution of downward leakage to the Prairie du Chien-Jordan aquifer in the Minneapolis-St. Paul metropolitan area, Minnesota. United States Geological Survey Open-File Report 75-342, 33 p.

Lively, R.S., Jameson, R., Alexander, E.C., Jr., and Morey, G.B., 1992, Radium in the Mt. Simon-Hinckley aquifer, east-central and southeastern Minnesota: Minnesota Geological Survey Information Circular IC-36, 58 p.

(1) Lusardi, B.A. and Tipping, R.G., 2006, Quaternary Stratigraphy, pl 4 of Setterholn, D.R., project manager, Geologic Atlas of Scott County, Minnesota. Minnesota Geological Survey County Atlas C-17.

(2) Lusardi, B.A. and Tipping, R.G., 2009, Quaternary Stratigraphy and Sand Distribution Model, pl.4 of Bauer, E.J., project manager, Geologic Atlas of Carver County, Minnesota. Minnesota Geological Survey County Atlas C-21, Part A.

(3) Meyer, G.N., 2010, Quaternary Stratigraphy, pl 4 of Runkel, A.C., project manager, Geologic atlas of Chisago County, Minnesota. Minnesota Geological Survey County Atlas C-22, Part A.

Meyer, G.N., Knaeble, A.R., and Tipping, R.G., 1995, Quaternary Stratigraphy, pl 4 of Meyer, G.N.,project manager, Geologic atlas of Stearns County, Minnesota, Minnesota Geological Survey County Atlas C-10, Part A.

(4) Meyer, G. and Tipping, R.G., 1998, Digital elevation models of tops and bottoms of four tills within Washington County, Minnesota: Minnesota Geological Survey, Unpublished Manuscript Maps, Scale 1:50,000, eight digital files.

(5) Meyer, G.N. and R.G. Tipping, 2007, Geology in support of ground-water management for the Twin Cities Metropolitan Area, Metropolitan Council Water Supply Master Plan Development - Phase I. Minnesota Geological Survey Open File Report OF07-02.

Minnesota Deparment of Health, 2010, Sourcewater protection tritium data, Justin Blum, written Communication

Minnesota Department of Natural Resources, 1991, Criteria and Guidelines for Assessing Geologic Sensitivity of Ground Water Resources in Minnesota. St. Paul, Minnesota.

Ruhl, J.F., Kanivetsky, Roman, and Shmagin, Boris, 2002, Estimates of recharge to unconfined aquifers and leakage to confined aquifers in the seven-county metropolitan area of Minneapolis-St. Paul, Minnesota: U.S. Geological Survey Water-Resources Investigations Report 02-4092, 32 p.

Runkel, A.C., Anderson, J.R., and Tipping, R.G., 2011, Hydraulic conductivity and hydrostratigraphy of the Platteville Formation, Twin Cities Metropolitan Area, Minnesota. Report delivered to the Metropolitan Council for Metropolitan Council Water Supply Plan Development.

Sanocki, C.A., Langer, S.K., and Menard, J.C., 2009, Potentiometric surfaces and changes in groundwater levels in selected bedrock aquifers in the Twin Cities Metropolitan Area, March-August 2008 and 1988-2008. United States Geological Survey Scientific Investigations Report 2009-5226, 76 p.

Schilling, K., and Tassier-Surine, S., 2006, Hydrogeology of Pre-Illinoian till at the I-380 rest stop site, Linn County Iowa. Iowa Geological Survey Technical Information Series 51, Iowa Department of Natural Resources, 53 p.

Tipping, R.G., Runkel, A.C. and Gonzalez, C.M., 2010, Geologic investigation for portions of the Twin Cities Metropolitan Area: I. Quaternary/bedrock hydraulic conductivity, II. Groundwater chemistry. Informal report delivered to the Metropolitan Council for Metropolitan Council Water Supply Master Plan Development, 62 p.

DISTRIBUTION OF VERTICAL RECHARGE TO UPPER BEDROCK AQUIFERS, TWIN CITIES METROPOLITAN REGION , MINNESOTA

Map submitted as deliverable for contract between University of Minnesota and the Metropolitan Council for project entitled
"Geologic Investigations for portions of the Twin Cities Metropolitan area: Bedrock Aquifer Recharge and Contaminant Plume Mapping for Portions of the Twin Cities Metropolitan Area"
Review and editing of this map for eventual publication may result in changes to content. Produced for, and funded by, the Metropolitan Council.

Metropolitan Council