North Branch Water and Light Wellhead Protection Plan

Part 1:
Delineation of the Wellhead Protection Area (WHPA), Drinking Water Supply Management Area (DWSMA) and Assessments of Well and DWSMA Vulnerability

Prepared for:
North Branch Water and Light

August, 2012

BARR

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August 2012

I hereby certify that this plan, document, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Geologist under the laws of the state of Minnesota.

Signature:

John C. Greer

Date: August 7, 2012 Reg. No. 30347

Wellhead Protection Plan for North Branch Water and Light

Part I

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1.0 Introduction

Wellhead protection areas (WHPAs) and a Drinking Water Supply Management Area (DWSMA) were delineated for North Branch Municipal Water and Light (NBWL). This report summarizes the delineation of WHPAs and the DWSMA for NBWL as required by the Minnesota Wellhead Protection Rules.

NBWL has six municipal water supply wells including Well 1 (unique number 217922), Well 2 (unique number 112244), Well 3 (unique number 522767), Well 4 (unique number 706844), Well 5 (unique number 749383), and Well 6 (unique number 593584). Wells 1, 2, and 6 pump water from the Middle Proterozoic sedimentary aquifer and the Mount Simon – Hinckley aquifer. Well 3 and Well 5 pump water from the Mount Simon–Hinckley aquifer. Well 4 pumps from a buried Quaternary sand and gravel aquifer. Well locations are shown on Figure 1 and well construction data are presented in Appendix A.

Data elements used in preparation of the report are presented in Table 1.

2.0 Criteria for Wellhead Protection Area Delineation

The following criteria were used to ensure accurate delineation of the WHPA.

2.1 Time of Travel

A minimum ten-year time of travel criteria must be used to determine a WHPA (MN Rule 4720.5510) so there is sufficient reaction time to remediate potential health impacts in the event of contamination of the aquifer. A time of travel of ten years was considered in this study. As required by the Wellhead Protection Rules, the one-year time of travel was also determined for each well addressed in this study.

2.2 Aquifer Transmissivity

Per discussions with Minnesota Department of Health (MDH) staff during the Pre-Delineation Meeting (MDH, 2011a), aquifer transmissivity and hydraulic conductivity were determined as follows: 1) For the Mt. Simon – Hinckley aquifer a pumping test at NBWL Well 5 was used (Appendix B). Based on this test, the transmissivity was estimated to be 5,370 ft^2/day; using an aquifer thickness of 150 feet results in an estimated hydraulic conductivity of 35.8 ft/day (10.9 m/day). 2) The aquifer transmissivity of the Middle Proterozoic sedimentary aquifer was determined using a specific capacity test for NBWL Well 2 (Appendix B). Using the TGuess Method (Bradbury and Rothschild, 1985), the transmissivity of the Middle Proterozoic sedimentary aquifer is estimated to be 441 ft^2/day and the hydraulic conductivity is estimated to be 4.4 ft/day (1.3 m/day). 3) The aquifer transmissivity for the Quaternary sand and gravel aquifer was determined using a specific capacity test for NBWL Well 4. Using the Tguess Method the transmissivity of the Quaternary aquifer is estimated to be 1,728 ft^2/day, and the hydraulic conductivity is estimated to be 29 ft/day (8.8 m/day). This falls within the expected range based on regional data from the Minnesota Geological Survey and Metropolitan Council (Tipping et al., 2010) which indicates that the hydraulic conductivity of Quaternary aquifers in the North Branch area range from 4.6 ft/day to 221.4 ft/day with a geometric mean hydraulic conductivity of 20.3 ft/day (n=89).

2.3 Daily Volume of Water Pumped

Pumping data for NBWL for the period 2006 through 2010 is summarized in Table 2. The largest annual withdrawal for 2006-2010 was 239,353,000 gallons in 2007. The projected total withdrawal for 2015 is estimated to be 292,700,000 gallons. Projected pumping rates for 2015 were estimated for each well based on the percentage of the total volume that each well pumped from 2006-2010.

The pumping rate for Well 6 was adjusted based on an estimated total use of 21 Mgal/yr (17Mgal/yr for irrigation and 4 Mgal/yr for municipal peak demand) (Bonin, 2011). The pumping rates used for W in the delineation of the WHPA were the maximum of either the projected 2015 pumping rate, or those reported for 2006-2010. Table 2 summarizes the historical and projected distribution of the annual withdrawal among the NBWL municipal wells and the pumping rates used for delineation of the WHPA.

2.4 Conceptual Hydrogeologic Model

The conceptual hydrogeologic model is described in Barr (2005) and is repeated here with slight modifications for completeness.

2.4.1 Geologic History

North Branch is located in the northern part of a geologic feature called the *Hollandale Embayment* – a large bay in an ancient shallow sea were sediment was deposited as the seas waxed and waned to form what is now most of the major bedrock geologic units in eastern Minnesota. Before the deposition of what is now the Mt. Simon Sandstone, there was structural uplifting of Precambrian rocks that formed an uplifted block (called a "horst") that trends north-south. The western edge of this horst corresponds approximately with Interstate 35. Subsequent tectonic activities formed a structural basin (the Twin Cities basin), centered under what is now Minneapolis and St. Paul. Bedrock units generally dip southward toward the center of the Twin Cities basin. There may have been some reactivation of the Precambrian faults after deposition of younger rocks (Morey, 1972).

During the Quaternary (about the last two-million years), glacial advances eroded away higher relief bedrock units and deposited a mixture of glacially derived tills and outwash over the landscape. The combination of depositional history, structural faulting, and glaciation has resulted in the current geologic setting. Major bedrock aquifer units, such as the Prairie du Chien-Jordan aquifer, are not present in the North Branch area due to these processes. The Wonewoc Sandstone-Tunnel City Group aquifer is present to the west of North Branch but underneath North Branch (where the underlying horst feature is present), the uppermost bedrock unit is primarily the Mt. Simon Sandstone (and the upper portion of this unit has also been eroded).

2.4.2 Regional Bedrock Geology

The bedrock geology as interpreted by Runkel and Boerboom (2010) is shown on Figure 1. Locations of three geologic cross sections through the study area are also shown on Figure 1. Geologic cross section A-A' is a west to east cross section (Figure 2); cross section B-B' (Figure 3) and C-C' (Figure 4) are north to south cross sections.

The hydrostratigraphic units of importance for this study are described in more detail below.

Chengwatana volcanics

The Chengwantana volcanics consist of deeply dipping sequences of interlayered ophitic to weakly porphyritic basalt flows and coarse interflow conglomerate units. The western margin of this unit is juxtaposed against the Mt Simon-Hinckley sandstone along the Douglas Fault in the vicinity of North Branch (Runkel and Boerboom, 2010).

Mesoproterozoic Sedimentary Rocks

Mesoproterozoic sedimentary rocks consist of feldspathic sandstone, reddish-brown mudstone and siltstone, and minor shale units of the Keweenawan Supergroup (Runkel and Boerboom, 2010). Due to a limited number of borings and complexities associated with faulting in the area these units cannot be assigned to individual formations but are likely related to the Solar Church and/or Fond du Lac Formations. Of importance to this study is the informally defined St. Croix Horst Sandstone. This sandstone is present below most of North Branch with bedding that dips 50^o to 70^o from horizontal and is often cut by numerous thin, white veins of calcite (Boerboom, 2010).

Mt. Simon Sandstone

The Cambrian-aged Mt. Simon Sandstone consists of multiple beds of moderately-sorted to well-sorted quartz sandstone intermixed with thin beds of feldspathic sandstone, siltstone, and shale (Mossler and Tipping, 2000). The formation can be up to 250 feet thick in Chisago County (Runkel and Boerboom, 2010). East of the Douglas Fault the Mt. Simon Sandstone is often the uppermost bedrock. West of the Douglas Fault the Mt. Simon Sandstone is overlain by the Eau Claire Formation (a confining unit) and the Wonewoc Sandstone and Tunnel City Group.

Eau Claire Formation

The Cambrian-aged Eau Claire Formation is a siltstone, very fine feldspathic sandstone, and greenish-gray shale. Some sandstone beds are glauconitic. (Mossler and Tipping, 2000). The Eau Claire Formation gradually coarsens to the north in Chisago County and is dominantly a very fine- to fine-grained sandstone in the northern one-half of the county (Runkel and Boerboom, 2010).

Wonewoc Sandstone

The Cambrian-aged Wonewoc Sandstone is medium to very coarse-grained, quartzose sandstone and very-fine to fine-grained feldspathic sandstone, with scattered thin beds of shale (Mossler and Tipping, 2000).

Tunnel City Group

The Cambrian-aged Tunnel City Group is divided into two formations: the Mazomanie Formation and the Lone Rock Formation. The Mazomanie Formation is mostly a medium-grained friable, quartz sandstone. The Lone Rock Formation underlies the Mazomanie Formation and consists of fine grained glauconitic, feldspathic sandstone and siltstone (Runkel and Boerboom, 2010).

2.4.3 Recharge and Discharge of Groundwater

The primary mechanisms of recharge to the aquifer system in the region is infiltrating precipitation that moves below the root zone of plants and migrates downward by gravity to the water table. Recharge rates in east-central Minnesota are typically in the range of less than 1 inch per year to over 12 inches per year. A secondary source of recharge is seepage through the bottoms of lakes, wetlands, and some streams. Water supplying individual aquifers which NBWL wells tap is controlled by leakage from overlying confining units; either Quaternary clays, or the Eau Claire Formation where present.

Most groundwater flows southeast and east toward the St. Croix River, which is a regional discharge zone. Secondary discharge zones include smaller streams, some lakes and wetlands, evapotranspiration from plants, and wells.

2.4.4 Direction of Groundwater Flow

Regional groundwater flow for all bedrock aquifers is to the east and south, toward the St. Croix River. Differing directions of flow can be expected for the shallow aquifer (surficial deposits) near lakes and streams. Near high capacity wells, groundwater flow is typically toward the wells.

2.5 Model Description

To accurately delineate the WHPA, it is necessary to assess how nearby wells, rivers, lakes, and variations in geologic conditions affect groundwater flow directions and velocities in the aquifer. The finite difference code MODFLOW-96 (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) was used for this study to simulate groundwater flow in the hydrostratigraphic units from the Quaternary aquifer down to the Mesoproterozoic sedimentary rocks. MODFLOW is public domain software that is available at no cost from the United States Geological Survey. The pre- and post-processor Groundwater Vistas (version 6) (Environmental Simulations, Inc., 2011) was used to create the data files and evaluate the results.

The base finite difference model used in this study is the groundwater flow model developed for evaluation of future well locations for NBWL (Barr, 2005). Full description of this model is presented in Appendix E. A brief summary and discussion of changes made to the model for this project are presented below.

The groundwater flow model is a 5 layer model and includes all major hydrostratigraphic units in the North Branch Area. The model layers generally correspond to the following: Layer 1 – Quaternary sediments; Layer 2 – Tunnel City Group and Wonewoc Sandstone; Layer 3 – Eau Claire Formation; Layer 4 – Mt. Simon Sandstone; and Layer 5 – Proterozoic Sediments. In the North Branch area, where upper bedrock units are not present, the layers are represented as the Quaternary sediments. The model takes into account regional flow boundaries. The major flow boundary near North Branch is the St Croix River. To the west the model extends to the approximate extent of the Mt. Simon-Hinckley aquifer. Smaller streams and area lakes are also included in the model using constant head cells and the River Package of MODFLOW. In addition, high capacity pumping wells from the State Water Use Database System (SWUDS) are included in the model.

The model was modified in the vicinity of North Branch to better represent the local conditions. Changes made to the model for use in delineating the NBWL WHPAs included:

- Refining the model grid around NBWL municipal wells to a cell size of 10m x 10m;
- Modify the hydraulic conductivity zones and layer elevations to match recently mapped geology in the North Branch area (Boerboom, 2010; Runkel and Boerboom, 2010)
- Adjust the location of the faults in the North Branch area based on recently mapped geology (Runkel and Boerboom, 2010).
- Hydraulic conductivity values of the Mt. Simon-Hinckley aquifer, and Proterozic sediments adjusted based on values presented in Section 2.2.
- Incorporate a new hydraulic conductivity zone in model layer 5 to represent the Proterozoic sediments in an area of approximately 4 km^2 around NBWL Wells 1 and 2.
- Incorporate a new hydraulic conductivity zone to represent the Chengwantana volcanics.

- Incorporate a new hydraulic conductivity zone to represent the buried sand and gravel aquifer supplying Well 4. Review of Quaternary stratigraphy data indicated that this unit is consistent with unit qsx as mapped by Meyer (2010).
- Layer thicknesses to the west of North Branch in the vicinity of Isanti were adjusted based on updated information.

After these revisions were made to the model a check on model calibration to hydraulic heads was made. Calibration residuals for hydraulic head are presented in Appendix E.

Sensitivity of the model parameters was also evaluated and results are presented in Appendix E.

MODFLOW files for the calibrated model are included in Appendix G.

2.6 Groundwater Flow Field

Groundwater flow in the glacial aquifer and bedrock aquifers in the vicinity of North Branch is to the east toward the St. Croix River. The ambient direction of groundwater flow was estimated based on static water level data from well records obtained from the County Well Index. This flow direction is consistent with the flow direction determined using the groundwater flow model in this study.

3.0 Delineation of the Wellhead Protection Area

Delineation of the WHPA for the NBWL wells involved the evaluation of both porous media and fracture flow. First, the capture zones for each well were delineated based on porous media flow and then, because of extensive faulting in the area, the capture zones were also delineated according to the procedures described in the MDH guidance for WHPA delineations in fractured and solution-weathered bedrock (MDH, 2005). A composite WHPA was defined by combining the capture zones delineated using these two methods.

3.1 Porous Media Flow Evaluation

The groundwater flow model discussed above was used to simulate the groundwater flow field in the vicinity of North Branch. The WHPA for each of the NBWL wells was delineated using the software program MODPATH (Pollock, 1994) with the modeled groundwater flow field. A minimum of 300 particles were distributed vertically surrounding the open interval of each well. These particles were tracked backwards in time for both 1 and 10 years. When viewed in plan view, the areas encompassed by the particle traces were then outlined as the one- and ten-year porous medium time of travel zones for each well (Figure 5).

Porosity values used for the porous media evaluation were as follows: Quaternary sediments = 0.2, Wonewoc Sandstone and Tunnel City Group = 0.253, Eau Claire Formation = 0.1, Mt. Simon-Hinckley Sandstone = 0.233, Proterozic Sediments = 0.1 Proterozoic basalt = 0.01 (Norvitch et al., 1974, Schwartz and Zhang, 2003)

3.1.1 Sensitivity Analysis

A sensitivity analysis was performed for the model using the auto sensitivity option in Groundwater Vistas. The model was most sensitive to the horizontal hydraulic conductivity (K_x) of the Quaternary sediments (Zone 1 and Zone 8), and the horizontal and vertical hydraulic conductivities of the Tunnel City Group/Wonewoc Sandstone (Zone 3). Output from the sensitivity analysis is presented in Appendix E.

Multiple particle tracking simulations were conducted to account for uncertainty in the groundwater flow model. For these simulations, the hydraulic conductivity values for the most sensitive hydraulic conductivity zones (1, 3, and 8) were adjusted. The calibrated horizontal hydraulic conductivities of Zone 1 and Zone 8 (Quaternary sediments) are 24 m/day and 22 m/day, respectively. The hydraulic conductivities of these zones were adjusted to 1 m/day and 50 m/day based on the expected range in values for glacial sediments in the area. The calibrated horizontal and vertical hydraulic conductivities of zone 3 (Tunnel City Group/Wonewoc Sandstone) are 12.8 m/day and 0.02 m/day, respectively. The horizontal and vertical hydraulic conductivities of Zone 5 were adjusted plus and minus 50%. Particle traces from all simulations were combined to define a composite porous media flow capture zone as shown on Figure 5.

3.2 Fracture Flow Evaluation

The bedrock in the North Branch area is extensively faulted. Between NBWL Well 5 and Well 4 is the Douglas Fault zone. Across the Douglas Fault zone up to 200 feet of vertical displacement has occurred (Runkel and Boerboom, 2010). East of NBWL Well 6 is another unnamed fault where up to 100 feet of vertical displacement has occurred (Runkel and Boerboom, 2010). Between these mapped fault features it is likely that additional smaller faults or fault zones may be present but are difficult to define based on limited boring data. Because of the extensive faulting in the area, fracture flow capture zones were delineated for all wells. Delineation technique 1 from MDH (2005) was used for NBWL Wells 1 and 2. Delineation technique 2 (MDH, 2005) was used for NBWL Wells 3, 5, and 6. Well 4 is open to a Quaternary sand and gravel aquifer. However, as shown on Figure 2 this buried Quaternary aquifer is likely connected to the bedrock aquifer and may receive a significant amount of water from the Mt. Simon Sandstone which is subsequently faulted in the Douglas Fault zone. Also, the porous media flow evaluation indicated that particle traces originating from Well 4 extend into the Mt. Simon Sandstone along the fault zone. Because of this connection, delineation technique 4 (MDH, 2005) was used.

The fixed-radius fracture-flow capture zones defined for Well 3, Well 4, Well 5 and Well 6 were extended upgradient based on gradients from the groundwater flow model (Figure 5). A five year groundwater time of travel was used for the fixed radius capture zone and an additional five year time of travel was used for the upgradient extensions per direction from MDH (MDH, 2011b). Fixed radius capture zones were also extended along the orientation of faults in the area one mile from the well unless a geologic boundary such as a mapped fault was encountered in which case the extension was terminated at the geologic boundary. A summary of calculations used in the delineation of fracture flow capture zones is presented in Appendix D.

3.3 Other Groundwater Withdrawal

Potential interference from other high capacity wells in the area was incorporated by including wells from Minnesota DNR SWUDS database in the groundwater flow model. The base model (Barr,

2005) used average pumping rates for 2004 for these other high capacity wells. For wells within two miles of North Branch well pumping rates were updated to use the average from 2006-2010. For the fracture flow analysis, potential capture zones from other high capacity wells would not intersect the capture zones for the NBWL wells so they were not included in the delineation of fracture flow capture zones. Pumping from wells other than the NBWL wells was not adjusted to address future use.

4.0 Delineation of the Drinking Water Supply Management Areas

The NBWL DWSMA encompasses the WHPA with boundaries that correspond to geographically identifiable features (e.g., parcel boundaries, quarter section lines). Parcel boundaries where used as much as possible in the delineation of the DWSMA. Quarter section lines where used in limited areas where large parcels are intersected by quarter section lines. The DWSMA extends into North Branch Township and Isanti County to the west. The DWSMA that encompasses the 10-year groundwater time of travel zones is shown on Figure 6.

5.0 Well Vulnerability Assessment

MDH evaluated the vulnerability of NBWL municipal wells to contamination from contaminants released at the surface. The evaluation parameters include geology, well construction, pumping rate, and water quality. All NBWL wells are classified as being not vulnerable. Copies of the MDH well vulnerability scoring sheet for the NBWL wells are presented in Appendix C.

6.0 Drinking Water Supply Management Area Vulnerability Assessment

The vulnerability of the bedrock aquifers supplying NBWL Wells 1, 2, 3, 5, and 6 and the buried Quaternary sand and gravel aquifer supplying NBWL Well 4 were assessed. The vulnerability of the DWSMA associated with the NBWL wells was evaluated using geologic logs for wells located within and surrounding the DWSMA along with previous mapped data from the Minnesota Geological Survey.

Geologic logs listed in the Minnesota Geological Survey (MGS) County Well Index for wells in the vicinity of the DWSMA were reviewed and “L scores” based on the thickness of low permeability units at each well location were assigned to each well. (See MnDNR (1991) for a discussion of how to determine L scores). Aquifer vulnerability was further assessed using the geologic cross sections, bedrock geology map (Runkel and Boerboom, 2010), surficial geology (Meyer, 2010a), and the Quaternary stratigraphy model of Meyer (2010b). These data were used to construct three cross sections (Figure 2 through Figure 4). Locations of these cross sections are shown on Figure 1. The low levels of tritium (below the detection limit of 0.8 tritium units) in Well 3, Well 4, and Well 5 were also considered in assessing aquifer vulnerability.

The entire DWSMA is assigned a vulnerability rating of “low” indicating that water moving vertically from the surface will have several decades to a century to reach the aquifer(s). All NBWL wells have a geologic sensitivity rating of low to very-low due to thick confining units of glacial clay (Appendix E).

7.0 Supporting Data Files

The groundwater model can be reviewed using MODFLOW (Harbaugh and McDonald, 1996). MODPATH pathline files can be reviewed using MODPATH Version 3 (Pollock, 1994)

All coordinates in the modeling files are based on UTM NAD 83 Zone 15 N datum. Elevations are in meters above mean sea level (m MSL). Time units are days. Length units are meters.

GIS files are included in Appendix G. Descriptions are self-explanatory and some additional information is available in the associated metadata. Shapefiles files are in UTM NAD 83 Zone 15 N datum.

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Tables

Table 1
Assessment of Data Elements

Data Element	Present and Future Implications				Data Source
	Use of the Well s	Delineation Criteria	Quality and Quantity of Well Water	Land and Groundwater Use in DWSMA	
Precipitation					
Geology					
Maps and geologic descriptions	M	H	H	H	MGS, CWI
Subsurface data	M	H	H	H	MGS, MDH, CWI
Borehole geophysics	M	H	H	H	MGS
Surface geophysics	L	L	L	L	Not Available
Maps and soil descriptions					
Eroding lands					
Water Resources					
Watershed units					
List of public waters					
Shoreland classifications					
Wetlands map					
Floodplain map					
Land Use					
Parcel boundaries map	L	H	L	L	WSB and Associates
Political boundaries map	L	L	L	L	MNGEO
PLS map	L	H	L	L	DNR
Land use map and inventory					
Comprehensive land use map					
Zoning map					
Public Utility Services					
Transportation routes and corridors	L	M	L	L	MNDOT
Storm/sanitary sewers and PWS system map					
Oil and gas pipelines map					
Public drainage systems map/list					
Records of well construction, maintenance, and use	H	H	H	H	North Branch Water and Light, CWI, MDH files

Definitions Used for Assessing Data Elements:

High (H) - the data element has a direct impact
Moderate (M) - the data element has an indirect or marginal impact
Low (L) - the data element has little if any impact
Shaded - the data element was not required by MDH for preparing the WHP plan

CWI – Minnesota County Well Index
DNR – Minnesota Department of Natural Resource
MNGEO - Minnesota Geospatial Information Office
MDH – Minnesota Department of Health
MNDOT – Minnesota Department of Transportation
MPCA – Minnesota Pollution Control Agency
NRCS – Natural Resources Conservation Service
SSURGO – Soil Survey Geographic Database
USGS – United State Geological Survey

Table 1
Assessment of Data Elements (Continued)

Data Element	Present and Future Implications				Data Source
	Use of the Well s	Delineation Criteria	Quality and Quantity of Well Water	Land and Groundwater Use in DWSMA	
Surface Water Quantity					
Stream flow data					
Ordinary high water mark data					
Permitted withdrawals					
Protected levels/flows					
Water use conflicts	M	M	L	M	DNR
Groundwater Quantity					
Permitted withdrawals	H	H	H	H	DNR
Groundwater use conflicts	L	L	L	L	DNR
Water levels	H	H	H	H	CWI, MDH
Surface Water Quality					
Stream and lake water quality management classification					
Monitoring data summary					
Groundwater Quality					
Monitoring data	H	H	H	H	MDH
Isotopic data	H	H	H	H	MDH
Tracer studies	H	H	H	H	Not Available
Contamination site data	M	M	M	M	MPCA, MDH
Property audit data from contamination sites					
MPCA and MDA spills/release reports	M	M	M	M	MDH, MPCA

Definitions Used for Assessing Data Elements:

High (H) - the data element has a direct impact
Moderate (M) - the data element has an indirect or marginal impact
Low (L) - the data element has little if any impact
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CWI – Minnesota County Well Index
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USGS – United State Geological Survey

Table 2
Annual and Projected Pumping Rates for North Branch Wells

Unique Number	Well Name	Total Annual Withdrawal (gal/yr) 2006	2007	2008	2009	2010
217922	1	159,891,000	158,063,000	91,027,000	3,942,000	209,000
112244	2	36,396,000	50,106,000	12,814,000	350,000	0
522767	3	5,872,000	3,352,000	65,103,000	129,316,000	124,964,000
706844	4	28,112,000	27,832,000	43,557,000	81,604,000	74,783,000
749383	5	0	0	0	13,254,000	806,000
593584	6	0	0	0	0	15,390
	Totals	230,271,000	239,353,000	212,501,000	228,466,000	200,777,390

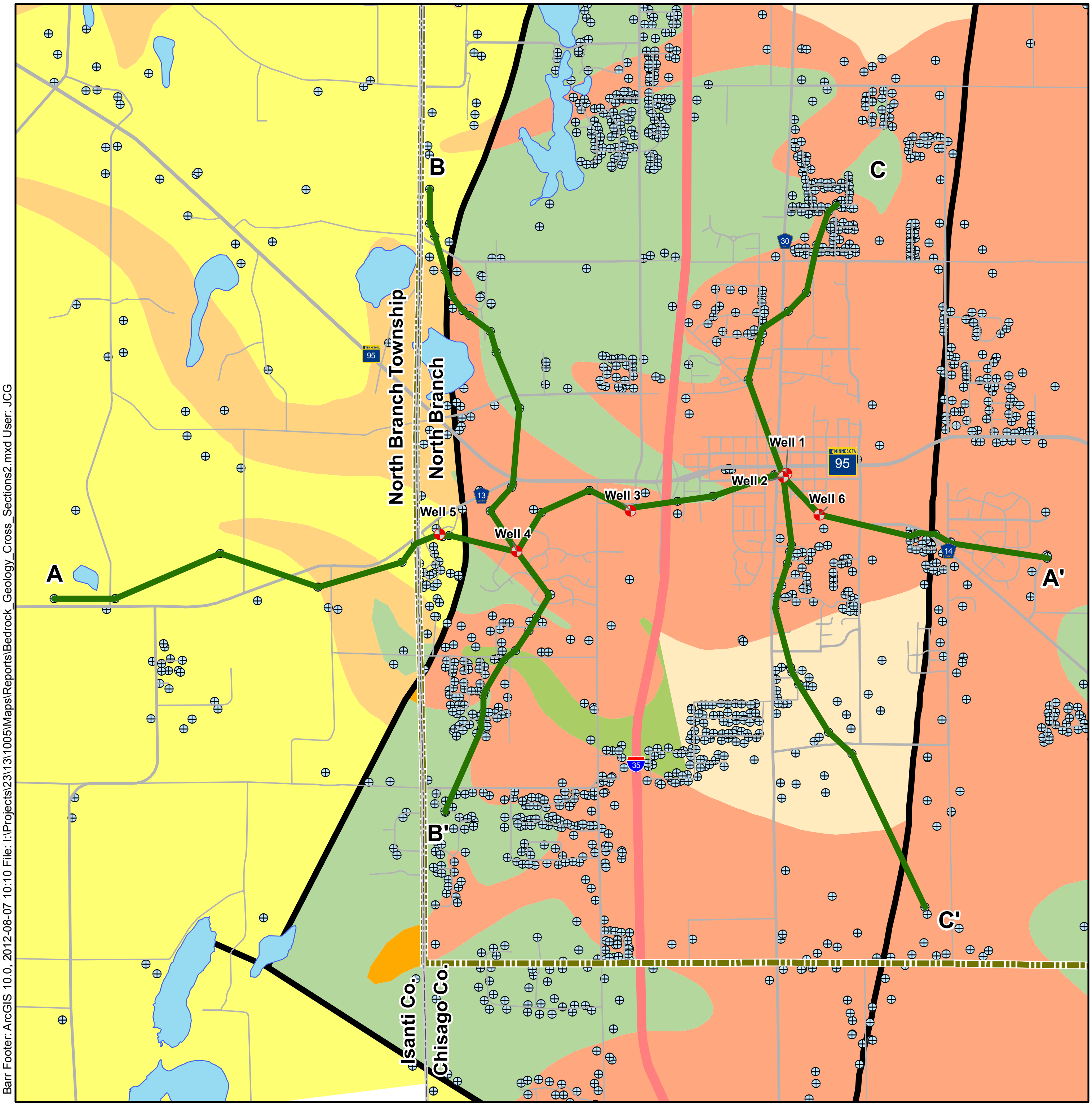
Source: MN DNR SWUDS Database

Unique Number	Well Name	Percentage of Annual Withdrawal 2006	2007	2008	2009	2010	Average Annual % of Withdrawal
217922	1	69.4%	66.0%	42.8%	1.7%	0.1%	36.0%
112244	2	15.8%	20.9%	6.0%	0.2%	0.0%	8.6%
522767	3	2.6%	1.4%	30.6%	56.6%	62.2%	30.7%
706844	4	12.2%	11.6%	20.5%	35.7%	37.2%	23.5%
749383	5	0.0%	0.0%	0.0%	5.8%	0.4%	1.2%
593584	6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

		Projected Water Use (2015)			Maximum Total Pumping for Model Input[2]		
Unique Number	Well Name	Total[1] (gal/yr)	% of Total Projected Water Use Well[1]	Projected Well Pumpage Based on % (gal/yr)	gal/yr	gal/day	m^3/day
217922	1		36.0%	105,372,000	159,891,000	438,058	1,658
112244	2		8.6%	25,172,200	50,106,000	137,277	520
522767	3		30.7%	89,858,900	129,316,000	354,290	1,341
706844	4		23.5%	68,784,500	81,604,000	223,573	846
749383	5		1.2%	3,512,400	13,254,000	36,312	137
593584	6		0.0%	0	21,000,000	57,534	218
	Totals	292,700,000		292,700,000	455,171,000	1,247,044	4,720

[1] Percentages for Wells 1 through 6 are based the average annual % of annual withdrawal for the period 2005 thorugh 20009.
[2] Well 6 rate of 21 mg/yr represents sum of estimated pumping for irrigation (17 mg/yr) and municipal peak demand (4 mg/yr) that was provided by WSB & Associates

Figures



Bedrock Geology

CAMBRIAN

- *Tunnel City Group*
- *Wonewoc Sandstone*
- *Eau Claire Formation*
- *Mt. Simon Sandstone*

MESOPROTEROZOIC

- *Sandstone, Siltstone, Shale (St. Croix Horst Sandstone)*
- *Chengwatana Volcanic Group*

- Geologic Cross Section
- North Branch Water & Light Well
- County Boundaries - Line.lyr
- Muncipal Boundary
- Water Body
- Well - County Well Index
- Fault

Miles
0 1

N

BARR

Figure 1

BEDROCK GEOLOGY
WHPP Part 1
North Branch Municipal
Water and Light
Chisago County, MN

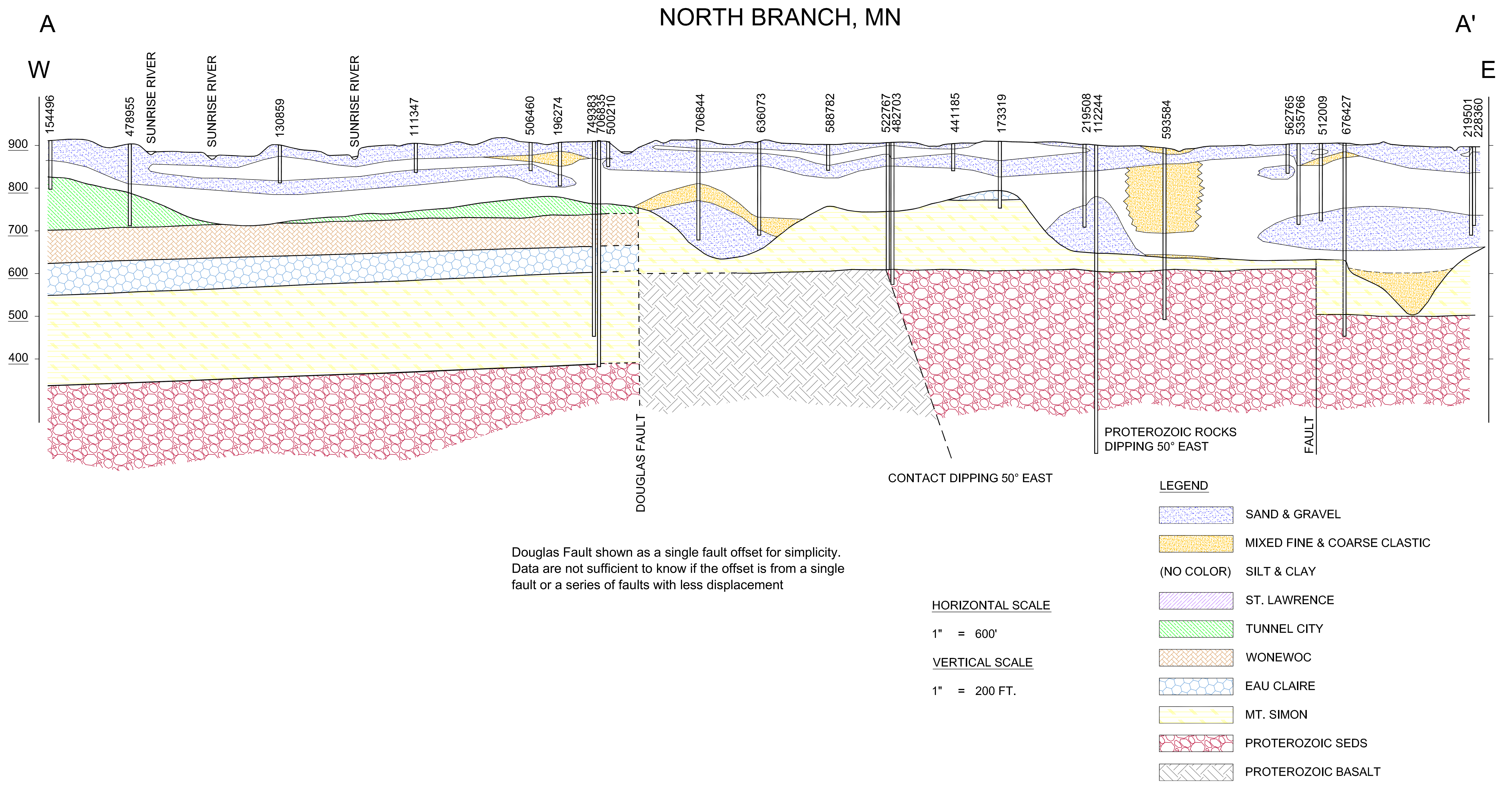
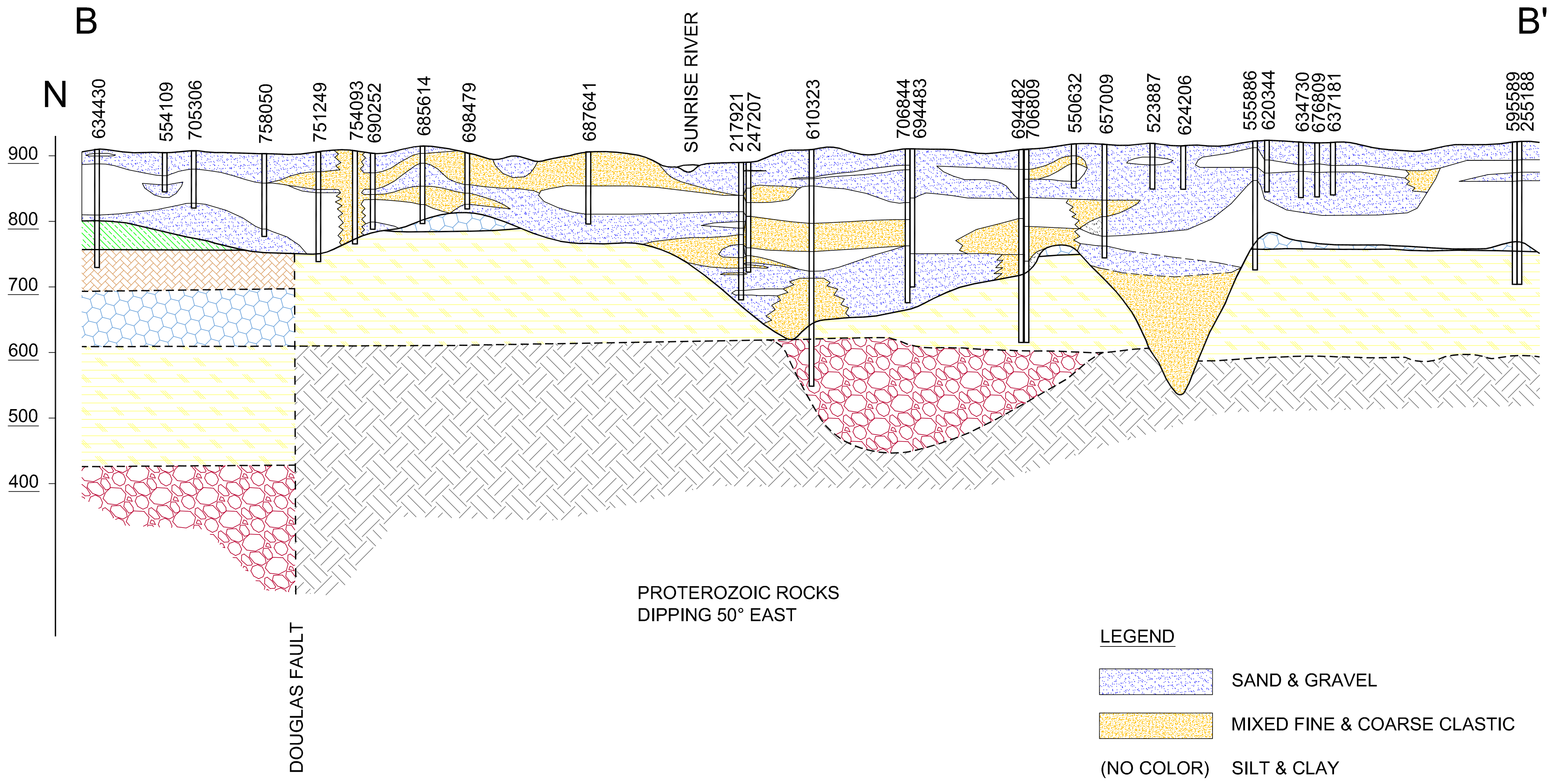


Figure 2

GEOLOGIC CROSS SECTION A-A'
WHPP Part 1
North Branch Municipal
Water and Light
Chisago County, MN

NORTH BRANCH, MN



Douglas Fault shown as a single fault offset for simplicity. Data are not sufficient to know if the offset is from a single fault or a series of faults with less displacement

HORIZONTAL SCALE

1" = 600'

VERTICAL SCALE

1" = 200 FT.

LEGEND

- SAND & GRAVEL
- MIXED FINE & COARSE CLASTIC
- (NO COLOR) SILT & CLAY
- ST. LAWRENCE
- TUNNEL CITY
- WONEWOC
- EAU CLAIRE
- MT. SIMON
- PROTEROZOIC SEDS
- PROTEROZOIC BASALT

Figure 3

GEOLOGIC CROSS SECTION B-B'
WHPP Part 1
North Branch Municipal
Water and Light
Chisago County, MN

NORTH BRANCH, MN

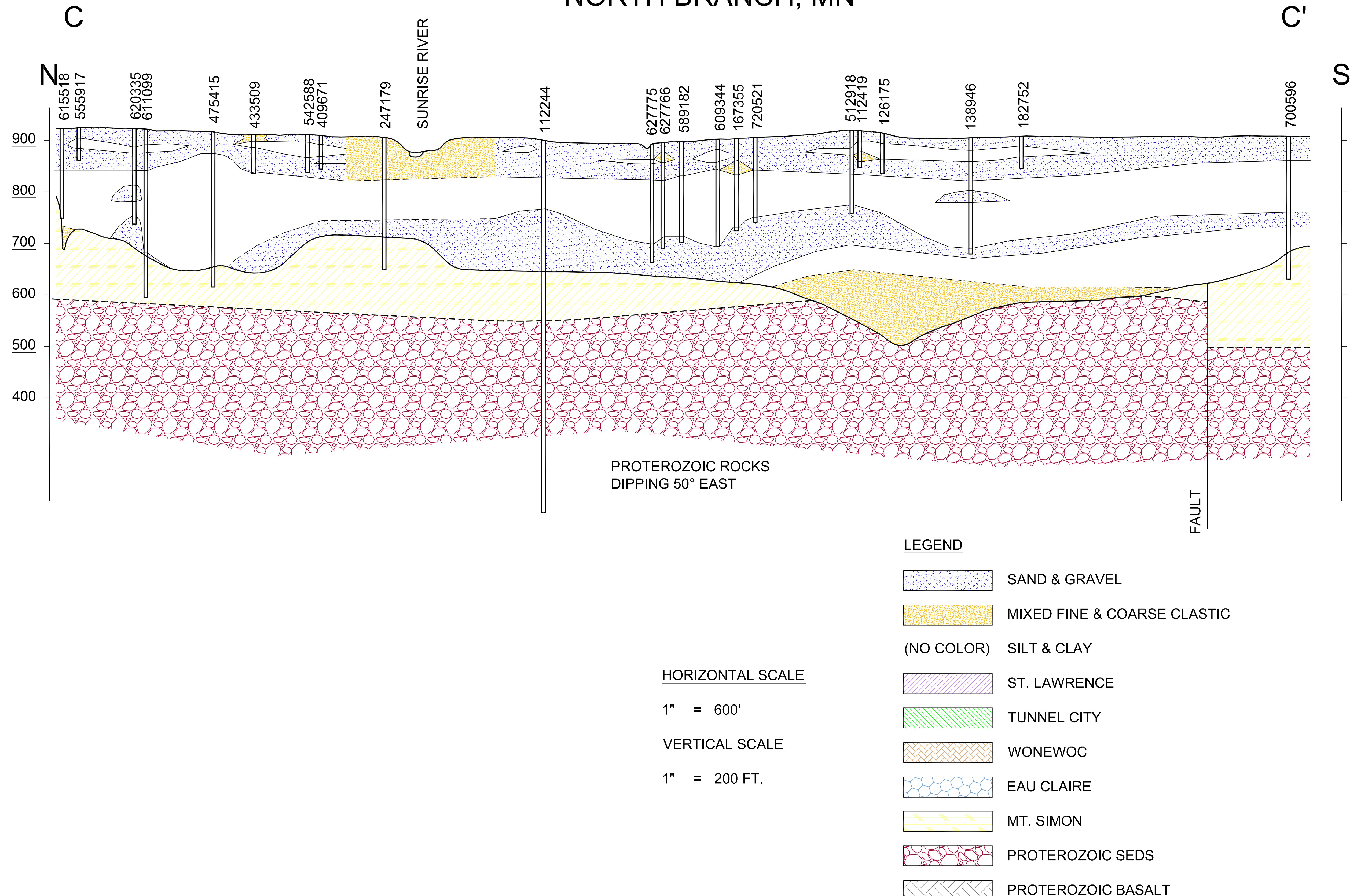


Figure 4

GEOLOGIC CROSS SECTION C-C'
WHPP Part 1
North Branch Municipal
Water and Light
Chisago County, MN

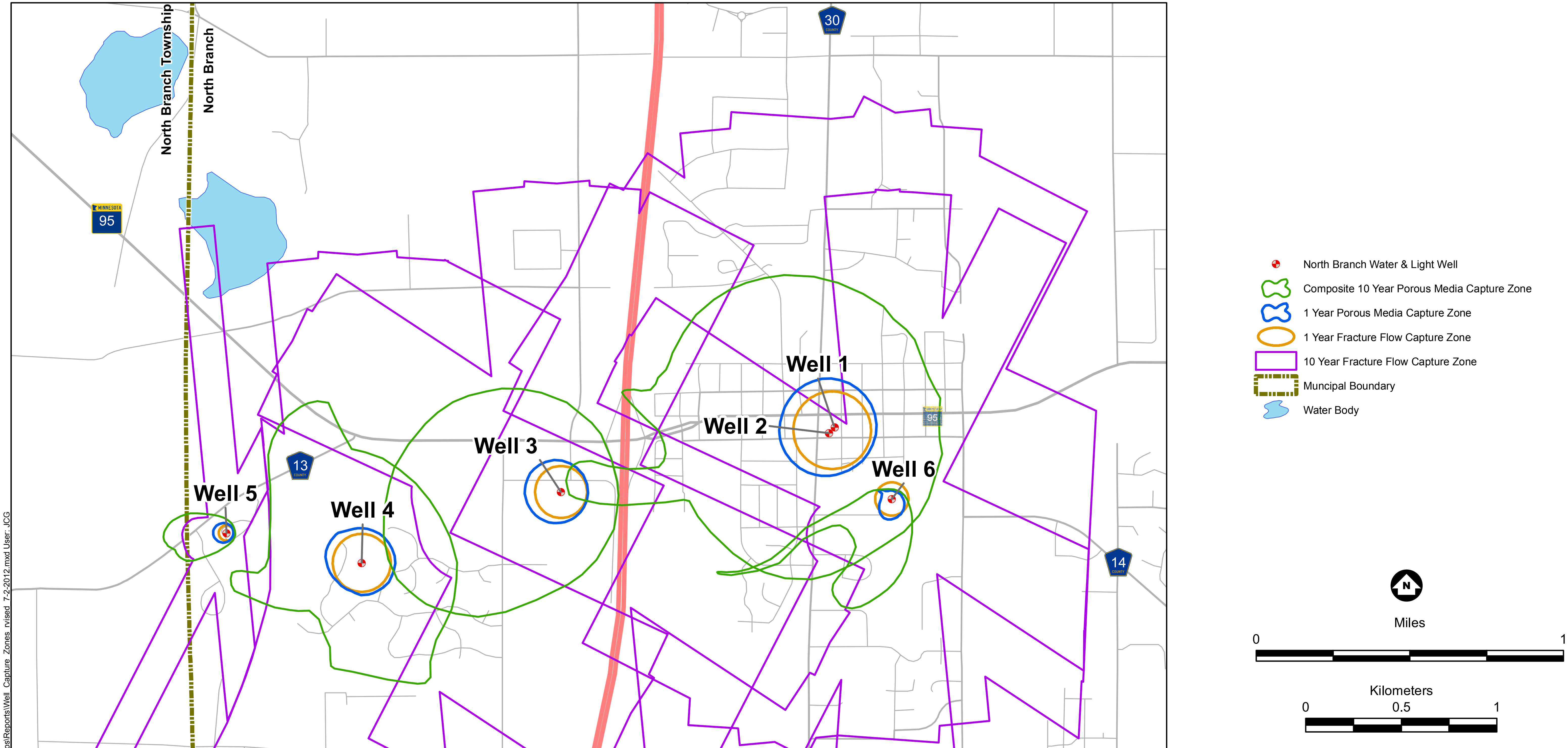


Figure 5

WELL CAPTURE ZONES
WHPP Part 1
North Branch Municipal
Water and Light
Chisago County, MN

BARR

Barr Footer: ArcGIS 10.0, 2012-07-26 13:11 File: I:\Projects\23\13\1005\Maps\Reports\Well Capture Zones rvised 7-2-2012.mxd User: JCG

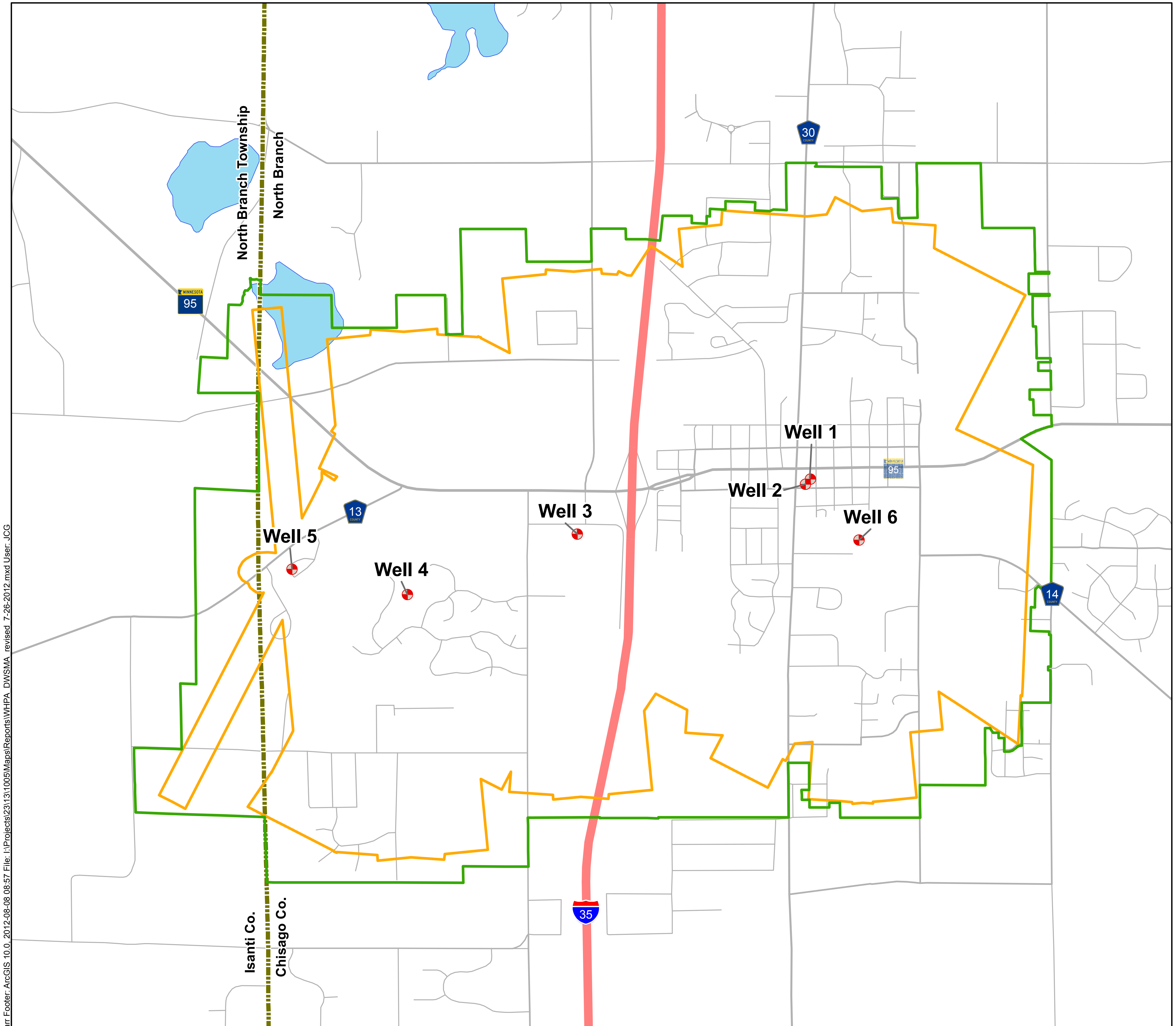


Figure 6

WHPA & DWSMA
WHPP Part 1
North Branch Municipal
Water and Light
Chisago County, MN

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Appendices

Appendix A

Well Construction Records

Unique Well Number	County Chisago	MINNESOTA DEPARTMENT OF HEALTH	Entry Date 1988/04/07
217922	Quad North Branch	**WELL AND BORING RECORD**	Update Date 2009/07/30
	Quad Id 151C	*MINNESOTA STATUTES CHAPTER 1031*	Received Date

Well Name NORTH BRANCH 1

Township	Range	Dir	Section	Subsection	Field Located	MGS
35	21	W	21	BBCDBA	Elevation	895.00 ft.

Well Depth	Depth Completed	Date Well Completed
762.00 ft	762.00 ft	1947/03/13

Well Address NORTH BRANCH 1

NORTH BRANCH MN 55056 Changed

Contact Address CITY OF NORTH BRANCH

NORTH BRANCH MN 55056

Drilling Method Cable Tool

Drilling Fluid

Well Hydrofractured? ☐ YES ☐ NO From ft. to

Use Community Supply

Casing Type Steel (black or low Drive Shoe? ☐ YES ☐ NO Hole Diameter (in.)
Diameter 12 Depth 263
12.00 in. from 0.00 to 263.00 ft. lbs/ft

Description	Color	Hardness	From	To (ft.)
SAND			0	68
CLAY			68	125
SAND & GRAVEL			125	256
SAND & GRAVEL			256	258
SILTSTONE	GREEN		258	275
SILTY SAND	GREEN		275	290
SANDY SILT	GREEN		290	295
SANDY SILT			295	315
SILT	RED		315	325
FINE SAND	GREEN		325	335
SILTSTONE	RED/GRN		335	495
NO RECORD			495	545
SHALE & CLAY	RED/GRN		545	762

Screen No

Make

Diamter Slot Length Set

Open Hole(ft.) From 263.0 **to** 762.0

Type

Static Water Level
31.00 ft. Land surface Date measured 1947/03/13

Pumping Level (below land surface)
37.00 ft. after hrs. pumping 350.00 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☐ Casing Protection ☐ 12 in. above grade
☐ At-grate (Environmental Wells and Borings ONLY) ☐ Basement offset

Grouting Information Well grouted? ☐ YES ☐ NO

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ YES ☐ NO

Pump
☐ Not Installed Date Installed 1947/00/00
Manufacture's name
Model number HP 25.00 Volts
Length of drop pipe Material Capacity g.p.m
Type Turbine

Abandoned Wells
Does property have any not in use and not sealed well(s)? ☐ YES ☐ NO

Variance
Was a variance granted from the MDH for this well? ☐ YES ☐ NO

Well Contractor Cerfication
Layne Well Co. 27010

License Business Name **Lic. or Reg No.**

Remarks
GAMMA LOGGED 4-22-1987. M.G.S. NO. 61. HIGH SPECIFIC CAP. SEEMS INCONGRUOUS UNLESS GRAVEL IN DRIFT CONTRIB.

First Bedrock CMTS Aquifer Mt.Simon-Fond du lac
Last Strat PMSU Depth to Bedrock 258.00 ft.

Name of Driller Date

Unique Well Number **217922**

County: Chisago
Quad: North Branch
Quad Id: 151C

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING RECORD
MINNESOTA STATUTES CHAPTER 1031

Entry Date: 1988/04/07
Update Date: 2009/07/30
Received Date:

Well Name	Township	Range	Dir	Section	Subsection	Depth Drilled	Depth Completed	Date Completed	Lic/Reg. No.	Driller Name
NORTH BRANCH 1	35	21	W	21	BBCDBA	762 ft	762 ft	1947/03/13	27010	

Elevation 895.00 **ft.** **Method** 7.5 minute topographic **Aquifer** Mt.Simon-Fond du lac **Depth to Bedrock** 258 **ft.** **Open Hole 263-762** **SWL** 31

Field Located Minnesota Geological Survey
Program
Uni No.Verified Information from owner
Geologic Interpretation Tony Runkel

Location Method GPS Code Measurements (Ps Universal Transverse Mercator(UTM) - NAD83 - Zone 15 - Meters
Input Source
Input Date 1999/07/26
Agency MGS

UTM Easting (X) 501632
UTM Northing (Y) 5039701
Interpretation Method Geologic study 1:24k to 1:100k

Geological Material	Color	Hardness	DEPTH From	DEPTH To	Thick	ELEVATION From	ELEVATION To	Stratigraphy	LITHOLOGY Primary	LITHOLOGY Secondary	LITHOLOGY Minor
SAND			0	68	68	895	827	Sand	Sand		
CLAY			68	125	57	827	770	Clay	Clay		
SAND & GRAVEL			125	256	131	770	639	Sand & larger	Sand	Gravel	
SAND & GRAVEL			256	258	2	639	637	Sand & larger	Soil	Gravel	
SILTSTONE	GREEN		258	275	17	637	620	Mt.Simon	Siltstone	Sandstone	
SILTY SAND	GREEN		275	290	15	620	605	Mt.Simon	Shale	Sandstone	
SANDY SILT	GREEN		290	295	5	605	600	Mt.Simon	Shale	Sandstone	
SANDY SILT			295	315	20	600	580	Mid.Proterozoic Sedimentary	Shale	Sandstone	
SILT	RED		315	325	10	580	570	Mid.Proterozoic Sedimentary	Siltstone		
FINE SAND	GREEN		325	335	10	570	560	Mid.Proterozoic Sedimentary	Sandstone		
SILTSTONE	RED/GRN		335	495	160	560	400	Mid.Proterozoic Sedimentary	Siltstone		
NO RECORD			495	545	50	400	350	Mid.Proterozoic Sedimentary	Shale	Sandstone	
SHALE & CLAY	RED/GRN		545	762	217	350	133	Mid.Proterozoic Sedimentary	Shale	Clay	

Unique Well Number **112244**

County Chisago
Quad North Branch
Quad Id 151C

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING RECORD
MINNESOTA STATUTES CHAPTER 1031

Entry Date 1988/04/07
Update Date 2009/07/30
Received Date

Well Name NORTH BRANCH 2

Township	Range	Dir	Section	Subsection	Field Located	MGS
35	21	W	21	BBCDCB	Elevation	896.00 ft.

Well Address NORTH BRANCH 2
NORTH BRANCH MN 55056 Changed

Contact Address CITY OF NORTH BRANCH
NORTH BRANCH MN 55056

Description	Color	Hardness	From	To (ft.)
SAND			0	72
CLAY	RED		72	132
GRAVEL & ROCK			132	165
SAND	RED		165	188
GRAVEL & ROCK			188	256
GRAVEL & ROCK			256	258
SHALE	GREEN	HARD	258	298
SHALE	GREEN	HARD	298	308
SHALE	RED	HARD	308	360
SHALE & SANDY MUD	RED		360	733

Well Depth 733.00 ft
Depth Completed 360.00 ft
Date Well Completed 1978/10/06

Drilling Method Cable Tool

Drilling Fluid

Well Hydrofractured? ☐ YES ☐ NO From ft. to

Use Community Supply

Casing Type Steel (black or low Drive Shoe? ☑ YES ☐ NO Hole Diameter (in.)
Diameter 16 Depth 261
24.00 in. from 0.00 to 74.00 ft. lbs/ft
16.00 in. from 0.00 to 261.00 ft. lbs/ft

Screen Yes
Open Hole(ft.) From to
Make JOHNSON Type stainless steel

Diamter	Slot	Length	Set			
10.00	35	52	259	ft. to	309	ft.
8.00	35	51	309	ft. to	360	ft.

Static Water Level
32.00 ft. Land surface Date measured 1978/10/02

Pumping Level (below land surface)
215.00 ft. after hrs. pumping 350.00 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☐ Casing Protection ☑ 12 in. above grade
☐ At-grate (Environmental Wells and Borings ONLY) ☐ Basement offset

Grouting Information Well grouted? ☑ YES ☐ NO
Material Neat Cement From 0.0 To 74.0 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☑ YES ☐ NO

Pump
☑ Not Installed Date Installed
Manufacture's name
Model number HP Volts
Length of drop pipe Material Capacity g.p.m
Type

Abandoned Wells
Does property have any not in use and not sealed well(s)? ☐ YES ☐ NO

Variance
Was a variance granted from the MDH for this well? ☐ YES ☐ NO

Well Contractor Cerfication
Bergerson-Caswell 27058
License Business Name Lic. or Reg No.
HENRICH, E.
Name of Driller Date

Remarks
GAMMA LOGGED 4-26-1978. M.G.S. NO. 1356. WELL BACK FILLED TO 360 FT.

First Bedrock CMTS Aquifer Mt.Simon-Fond du lac
Last Strat PMSU Depth to Bedrock 256.00 ft.

Unique Well Number **112244**

County: Chisago
Quad: North Branch
Quad Id: 151C

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING RECORD

MINNESOTA STATUTES CHAPTER 1031

Entry Date: 1988/04/07
Update Date: 2009/07/30
Received Date:

Well Name	Township	Range	Dir	Section	Subsection	Depth Drilled	Depth Completed	Date Completed	Lic/Reg. No.	Driller Name
NORTH BRANCH 2	35	21	W	21	BBCDCB	733 ft	360 ft	1978/10/06	27058	HENRICH, E.

Elevation 896.00 **ft.** **Method** 7.5 minute topographic **Aquifer** Mt.Simon-Fond du lac **Depth to Bedrock** 256 **ft.** **Screen 259-360** **SWL** 32

Field Located Minnesota Geological Survey
Program
Uni No.Verified Information from owner
Geologic Interpretation Tony Runkel

Location Method GPS Code Measurements (Ps Universal Transverse Mercator(UTM) - NAD83 - Zone 15 - Meters
Input Source
Input Date 1999/07/26
Agency MGS

UTM Easting (X) 501601
UTM Northing (Y) 5039670
Interpretation Method Geologic study 1:24k to 1:100k

Geological Material	Color	Hardness	DEPTH From	DEPTH To	Thick	ELEVATION From	ELEVATION To	Stratigraphy	LITHOLOGY Primary	LITHOLOGY Secondary	LITHOLOGY Minor
SAND			0	72	72	896	824	Sand	Sand		
CLAY	RED		72	132	60	824	764	Clay-red	Clay		
GRAVEL & ROCK			132	165	33	764	731	Gravel (+larger)	Gravel	Cobble	
SAND	RED		165	188	23	731	708	Sand-red	Sand		
GRAVEL & ROCK			188	256	68	708	640	Gravel (+larger)	Gravel	Cobble	
GRAVEL & ROCK			256	258	2	640	638	Mt.Simon	Sandstone	Shale	
SHALE	GREEN	HARD	258	298	40	638	598	Mt.Simon	Sandstone	Shale	
SHALE	GREEN	HARD	298	308	10	598	588	Mid.Proterozoic Sedimentary	Shale	Siltstone	
SHALE	RED	HARD	308	360	52	588	536	Mid.Proterozoic Sedimentary	Shale	Siltstone	
SHALE & SANDY MUD	RED		360	733	373	536	163	Mid.Proterozoic Sedimentary	Shale	Siltstone	Sandstone

Unique Well Number 522767

County Chisago
Quad North Branch
Quad Id 151C

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING RECORD
MINNESOTA STATUTES CHAPTER 1031

Entry Date 1993/08/18
Update Date 2007/05/15
Received Date

Well Name NORTH BRANCH 3

Township	Range	Dir	Section	Subsection	Field Located	MGS
35	21	W	20	BCDBDA	Elevation	907.00 ft.

Well and Contact Address BRANCH (TANGER NO.2)
FLINK AV
NORTH BRANCH MN 55056 Changed

Well Depth 304.00 ft **Depth Completed** 304.00 ft **Date Well Completed** 1993/00/00

Drilling Method Cable Tool

Drilling Fluid **Well Hydrofractured?** [ ] YES [ ] NO From ft. to

Use Community Supply

Casing Type Steel (black or low Drive Shoe? [✓] YES [ ] NO **Hole Diameter (in.)**
Diameter 18 Depth 186
18.00 in. from 0.00 to 186.00 ft. lbs/ft

Description	Color	Hardness	From	To (ft.)
SILTY SAND	BROWN	SOFT	0	4
SAND	BROWN	SOFT	4	13
SANDY CLAY	GRAY	MEDIUM	13	20
SANDY CLAY & GRAVEL	GRAY	MEDIUM	20	33
SAND	BROWN	SOFT	33	60
CLAY	RED/BRN	SOFT	60	89
SANDY CLAY	RED/BRN	MED-HRD	89	101
SANDY CLAY & GRAVEL	RED/BRN	MED-HRD	101	110
SAND & GRAVEL	BRN/GRY	MED-HRD	110	116
SAND & GRAVEL	BROWN	MED-HRD	116	130
SANDY GRAVEL	BRN/GRY	MED-HRD	130	150
SAND & GRAVEL	BROWN	MED-HRD	150	158
SAND, GRAVEL, SHALE	BRN/GRN	MED-HRD	158	163
SANDSTONE, GRAVEL	WHT/GRY	MEDIUM	163	169
SANDSTONE	WHITE	MEDIUM	169	169
SANDSTONE, SHALE	WHT/GRN	MEDIUM	169	183
SANDSTONE	WHITE	SOFT	183	240
SANDSTONE	WHITE	SOFT	240	248
SANDSTONE, PEBBLE	WHITE		248	254
SANDSTONE, SHALE	WHT/GRN	MEDIUM	254	259
SANDSTONE, SHALE	VARIED	SOFT	259	263
SANDSTONE, SHALE	WHT/GRN	SOFT	263	304

Screen No **Open Hole(ft.)** From 186.0 to 304.0
Make Type
Diamter Slot Length Set

Static Water Level
32.00 ft. Land surface Date measured 1993/00/00

Pumping Level (below land surface)
51.00 ft. after 24.00 hrs. pumping 500.00 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
[ ] Casing Protection [ ] 12 in. above grade
[ ] At-grate (Environmental Wells and Borings ONLY) [ ] Basement offset

Grouting Information Well grouted? [ ] YES [✓] NO

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? [✓] YES [ ] NO

Pump
[✓] Not Installed Date Installed
Manufacture's name
Model number HP Volts
Length of drop pipe Material Capacity g.p.m
Type

Abandoned Wells
Does property have any not in use and not sealed well(s)? [ ] YES [✓] NO

Variance
Was a variance granted from the MDH for this well? [ ] YES [ ] NO

Well Contractor Cerfication
Traut M.J. Well Co. 71536

License Business Name **Lic. or Reg No.**
TRAUT, T.

Name of Driller **Date**

Remarks
GAMMA LOGGED 3-12-1993. M.G.S. NO.3383.

First Bedrock CMTS Aquifer Mt.Simon
Last Strat CMTS Depth to Bedrock 163.00 ft.

Unique Well Number 522767

County Chisago
Quad North Branch
Quad Id 151C

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING RECORD
MINNESOTA STATUTES CHAPTER 1031

Entry Date 1993/08/18
Update Date 2007/05/15
Received Date

Well Name	Township	Range	Dir	Section	Subsection	Depth Drilled	Depth Completed	Date Completed	Lic/Reg. No.	Driller Name
NORTH BRANCH 3	35	21	W	20	BCDBDA	304 ft	304 ft	1993/00/00	71536	TRAUT, T.

Elevation 907.00 ft. **Method** 7.5 minute topographic **Aquifer** Mt.Simon **Depth to Bedrock** 163 ft. **Open Hole 186-304** **SWL** 32

Field Located Minnesota Geological Survey
Program
Uni No.Verified Information from owner
Geologic Interpretation Bruce Bloomgren

Location Method GPS Code Measurements (Ps Universal Transverse Mercator(UTM) - NAD83 - Zone 15 - Meters
Input Source
Input Date 1999/05/27
Agency MGS

UTM Easting (X) 500198 **UTM Northing (Y)** 5039362
Interpretation Method Geologic study 1:24k to 1:100k

Geological Material	Color	Hardness	DEPTH From	DEPTH To	Thick	ELEVATION From	ELEVATION To	Stratigraphy	LITHOLOGY Primary	LITHOLOGY Secondary	LITHOLOGY Minor
SILTY SAND	BROWN	SOFT	0	4	4	907	903	Sand & silt-brown	Sand	Silt	
SAND	BROWN	SOFT	4	13	9	903	894	Sand-brown	Sand		
SANDY CLAY	GRAY	MEDIUM	13	20	7	894	887	Clay & sand-gray	Clay	Sand	
SANDY CLAY & GRAVEL	GRAY	MEDIUM	20	33	13	887	874	Pebbly sand/silt/clay-gray	Clay	Sand	Gravel
SAND	BROWN	SOFT	33	60	27	874	847	Sand-brown	Sand		
CLAY	RED/BRN	SOFT	60	89	29	847	818	Clay	Clay		
SANDY CLAY	RED/BRN	MED-HRD	89	101	12	818	806	Clay & sand	Clay	Sand	
SANDY CLAY & GRAVEL	RED/BRN	MED-HRD	101	110	9	806	797	Pebbly sand/silt/clay	Clay	Sand	Gravel
SAND & GRAVEL	BRN/GRY	MED-HRD	110	116	6	797	791	Sand & larger	Sand	Gravel	
SAND & GRAVEL	BROWN	MED-HRD	116	130	14	791	777	Sand & larger-brown	Sand	Gravel	
SANDY GRAVEL	BRN/GRY	MED-HRD	130	150	20	777	757	Sand & larger	Gravel	Sand	
SAND & GRAVEL	BROWN	MED-HRD	150	158	8	757	749	Sand & larger-brown	Sand	Gravel	
SAND, GRAVEL, SHALE	BRN/GRN	MED-HRD	158	163	5	749	744	Pebbly sand/silt/clay	Sand	Gravel	Clay
SANDSTONE, GRAVEL	WHT/GRY	MEDIUM	163	169	6	744	738	Mt.Simon	Sandstone		
SANDSTONE	WHITE	MEDIUM	169	169	0	738	738	Mt.Simon	Sandstone		
SANDSTONE, SHALE	WHT/GRN	MEDIUM	169	183	14	738	724	Mt.Simon	Sandstone	Shale	
SANDSTONE	WHITE	SOFT	183	240	57	724	667	Mt.Simon	Sandstone		
SANDSTONE	WHITE	SOFT	240	248	8	667	659	Mt.Simon	Sandstone		
SANDSTONE, PEBBLE	WHITE		248	254	6	659	653	Mt.Simon	Sandstone		
SANDSTONE, SHALE	WHT/GRN	MEDIUM	254	259	5	653	648	Mt.Simon	Sandstone	Shale	
SANDSTONE, SHALE	VARIED	SOFT	259	263	4	648	644	Mt.Simon	Sandstone	Shale	
SANDSTONE, SHALE	WHT/GRN	SOFT	263	304	41	644	603	Mt.Simon	Sandstone	Shale	

Unique Well Number **706844**

County Chisago
Quad Stark
Quad Id 152D

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING RECORD
MINNESOTA STATUTES CHAPTER 1031

Entry Date 2005/03/10
Update Date 2008/10/31
Received Date 2005/02/14

Well Name NORTH BRANCH WATER & LIG

Township	Range	Dir	Section	Subsection	Field Located	MDH
35	21	W	19	DBCBAC	Elevation	914.00 ft.

Well Depth	Depth Completed	Date Well Completed
240.00 ft	220.00 ft	2004/02/10

Well Address NORTH BRANCH WATER & LIGHT

MN

Drilling Method Cable Tool

Drilling Fluid Bentonite

Well Hydrofractured? ☐ YES ☐ NO From ft. to

Use Community Supply

Casing Type Steel (black or low Drive Shoe? ☑ YES ☐ NO
Diameter 18 Depth 171
24.00 in. from 0.00 to 169.00 ft. 94.62 lbs/ft
18.00 in. from 0.00 to 171.00 ft. 70.59 lbs/ft

Hole Diameter (in.)
24.0(To 169.0
18.0(To 240.0

Description	Color	Hardness	From	To (ft.)
SAND	BROWN	SOFT	0	25
HARDPAN	VARIED	HARD	25	32
CEMENTED SAND	BROWN	HARD	32	82
CLAY & ROCKS	BROWN	MEDIUM	82	108
SANDY CLAY	BROWN	HARD	108	148
SAND ROCKS	BROWN	SOFT	148	225
FINE SAND	BROWN	SOFT	225	240

Screen Yes
Make JOHNSON Type
Diamter 12.00 Slot 30 Length 60 Set 158 ft. to 218 ft.

Open Hole(ft.) From to

Static Water Level
29.10 ft. Land surface Date measured 2005/01/27

Pumping Level (below land surface)
129.95 ft. after 8.00 hrs. pumping 350.00 g.p.m.

Wellhead Completion
Pitless adapter manufacturer PUMPHOUSE Model
☐ Casing Protection ☑ 12 in. above grade
☐ At-grate (Environmental Wells and Borings ONLY) ☐ Basement offset

Grouting Information Well grouted? ☑ YES ☐ NO
Material Neat Cement From To 169.0 ft. 7.50 Cubic yards

Nearest Known Source of Contamination
500 feet S Direction SEW Type
Well disinfected upon completion? ☑ YES ☐ NO

Pump
☑ Not Installed Date Installed
Manufacture's name
Model number HP Volts
Length of drop pipe Material Capacity g.p.m
Type

Abandoned Wells
Does property have any not in use and not sealed well(s)? ☐ YES ☑ NO

Variance
Was a variance granted from the MDH for this well? ☐ YES ☑ NO

Remarks
ELEVATION: 910.0 FT. MSGS QUAD: D-152 ENGINEER: WSB NANCY ZIEGLER (651)287-8316 ROGER E. RENNER, MGWC

First Bedrock Aquifer Quat. Buried Artes. Aquifer
Last Strat QFUB Depth to Bedrock ft.

Well Contractor Cerfication
Renner E.H. Well 71015
License Business Name Lic. or Reg No.
SAMPSON, J.
Name of Driller Date

Unique Well Number **706844**

County Chisago
Quad Stark
Quad Id 152D

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING RECORD
MINNESOTA STATUTES CHAPTER 1031

Entry Date 2005/03/10
Update Date 2008/10/31
Received Date 2005/02/14

Well Name	Township	Range	Dir	Section	Subsection	Depth Drilled	Depth Completed	Date Completed	Lic/Reg. No.	Driller Name
NORTH BRANCH WATER & LI(	35	21	W	19	DBCBAC	240 ft	220 ft	2004/02/10	71015	SAMPSON, J.

Elevation 914.00 **ft.** **Method** 7.5 minute topographic **Aquifer** Quat. Buried Artes. Aqui **Depth to Bedrock** **ft.** **Screen 158-218** **SWL** 29.1

Field Located Minnesota Department of Health
Program
Uni No.Verified
Geologic Interpretation Emily Bauer

Location Method Universal Transverse Mercator(UTM) - NAD83 - Zone 15 - Meters
Input Source
Input Date 2004/11/22
Agency MGS

UTM Easting (X) 499154
UTM Northing (Y) 5038991
Interpretation Method Geologic study 1:24k to 1:100k

Geological Material	Color	Hardness	DEPTH From	DEPTH To	Thick	ELEVATION From	ELEVATION To	Stratigraphy	LITHOLOGY Primary	LITHOLOGY Secondary	LITHOLOGY Minor
SAND	BROWN	SOFT	0	25	25	914	889	Sand-brown	Sand		
HARDPAN	VARIED	HARD	25	32	7	889	882	Pebbly sand/silt/clay	Hardpan		
CEMENTED SAND	BROWN	HARD	32	82	50	882	832	Sand-brown	Sand		
CLAY & ROCKS	BROWN	MEDIUM	82	108	26	832	806	Pebbly sand/silt/clay-brown	Clay	Cobble	
SANDY CLAY	BROWN	HARD	108	148	40	806	766	Clay & sand-brown	Clay	Sand	
SAND ROCKS	BROWN	SOFT	148	225	77	766	689	Sand & larger-brown	Sand	Cobble	
FINE SAND	BROWN	SOFT	225	240	15	689	674	Sand-brown	Sand		

Unique Well Number **749383**

County Chisago
Quad Stark
Quad Id 152D

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING RECORD
MINNESOTA STATUTES CHAPTER 1031

Entry Date 2007/07/02
Update Date 2009/06/17
Received Date

Well Name NORTH BRANCH 5

Township	Range	Dir	Section	Subsection	Field Located	MDH
35	21	W	19	CBBADA	Elevation	912.00 ft.

Well Depth 467.00 ft
Depth Completed 467.00 ft
Date Well Completed 2007/09/14

Well Address NORTH BRANCH 5
38420 WOOD DUCK LA
NORTH BRANCH MN 55056 Changed

Contact Address CITY OR NORTH BRANCH
6388 MAPLE ST
NORTH BRANCH MN 55056 Changed

Drilling Method Cable Tool

Drilling Fluid Bentonite

Well Hydrofractured? [ ] YES [✓] NO From ft. to

Use Community Supply

Casing Type Steel (black or low Drive Shoe? [✓] YES [ ] NO
Diameter 24 Depth 329
30.00 in. from 0.00 to 193.90 ft. 118.65 lbs/ft
24.00 in. from 0.00 to 329.00 ft. 94.62 lbs/ft

Hole Diameter (in.)
29.0(To 324.0
24.0(To 467.0

Description	Color	Hardness	From	To (ft.)
SAND, CLAY, STONES	BROWN	MEDIUM	0	155
FRANCONIA SANDSTONE	GREEN	MEDIUM	155	178
IRONTON-GALESVILLE	GRN/WHT	M.SOFT	178	252
EAU CLAIRE SHALE	GRN/BLU	HARD	252	315
MT. SIMON	TAN/WHT	MEDIUM	315	465
RED CLASTICS	RED	HARD	465	467

Screen No
Make
Diamter Slot Length Set

Open Hole(ft.) From 329.C to 467.0
Type

Static Water Level
15.00 ft. Land surface Date measured 2007/09/10

Pumping Level (below land surface)
56.90 ft. after 4.00 hrs. pumping 1200.00 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
[ ] Casing Protection [✓] 12 in. above grade
[ ] At-grate (Environmental Wells and Borings ONLY) [ ] Basement offset

Grouting Information Well grouted? [✓] YES [ ] NO
Material Neat Cement From To 329.0 ft. 21.00 Cubic yards

Nearest Known Source of Contamination
500 feet S Direction SEW Type
Well disinfected upon completion? [✓] YES [ ] NO

Pump
[✓] Not Installed Date Installed
Manufacture's name
Model number HP Volts
Length of drop pipe Material Capacity g.p.m
Type

Abandoned Wells
Does property have any not in use and not sealed well(s)? [ ] YES [✓] NO

Variance
Was a variance granted from the MDH for this well? [ ] YES [✓] NO

Well Contractor Cerfication
EH Renner and Sons, Inc. 1431

License Business Name **Lic. or Reg No.**
SIGAFOOS, R.

Name of Driller **Date**

Remarks
GAMMA LOGGED 6-15-2007. MG.S. NO. 4706. LOGGED BY JIM TRAEN.

First Bedrock CFRN Aquifer Mt.Simon
Last Strat PMSU Depth to Bedrock 155.00 ft.

Unique Well Number **749383**

County Chisago
Quad Stark
Quad Id 152D

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING RECORD
MINNESOTA STATUTES CHAPTER 1031

Entry Date 2007/07/02
Update Date 2009/06/17
Received Date

Well Name	Township	Range	Dir	Section	Subsection	Depth Drilled	Depth Completed	Date Completed	Lic/Reg. No.	Driller Name
NORTH BRANCH 5	35	21	W	19	CBBADA	467 ft	467 ft	2007/09/14	1431	SIGAFOOS, R.

Elevation 912.00 **ft.** **Method** 7.5 minute topographic **Aquifer** Mt.Simon **Depth to Bedrock** 155 **ft.** **Open Hole 329-467** **SWL** 15

Field Located
Program
Uni No.Verified Info/GPS from data source
Geologic Interpretation Tony Runkel

Location Method Digitization (Screen) - Map (1:: Universal Transverse Mercator(UTM) - NAD83 - Zone 15 - Meters
Input Source
Input Date 2007/07/02
Agency MGS

UTM Easting (X) 498446
UTM Northing (Y) 5039147
Interpretation Method Geologic study 1:24k to 1:100k

Geological Material	Color	Hardness	DEPTH From	DEPTH To	Thick	ELEVATION From	ELEVATION To	Stratigraphy	LITHOLOGY Primary	LITHOLOGY Secondary	LITHOLOGY Minor
SAND, CLAY, STONES	BROWN	MEDIUM	0	155	155	912	757	Pebbly sand/silt/clay-brown	Sand	Clay	Pebbles
FRANCONIA SANDSTONE	GREEN	MEDIUM	155	178	23	757	734	Franconia	Sandstone	Shale	Dolomite
IRONTON-GALESVILLE	GRN/WHT	M.SOFT	178	252	74	734	660	Ironton-Galesville	Sandstone		
EAU CLAIRE SHALE	GRN/BLU	HARD	252	315	63	660	597	Eau Claire	Shale	Sandstone	
MT. SIMON	TAN/WHT	MEDIUM	315	465	150	597	447	Mt.Simon	Sandstone		
RED CLASTICS	RED	HARD	465	467	2	447	445	Mid.Proterozoic Sedimentary	Shale		

Unique Well Number **593584**

County Chisago
Quad North Branch
Quad Id 151C

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING RECORD
MINNESOTA STATUTES CHAPTER 1031

Entry Date 1999/07/29
Update Date 2010/06/02
Received Date

Well Name NORTH BRANCH GOLF COURSE

Township	Range	Dir	Section	Subsection	Field Located	MGS
35	21	W	21	BDCCBA	Elevation	887.00 ft.

Well Depth 410.00 ft
Depth Completed 410.00 ft
Date Well Completed 1999/04/22

Well Address NORTH BRANCH GOL COURSE
NORTH BRANCH MN 55056 Changed

Contact Address CITY OF NORTH BRANCH
1356 MAIN ST
NORTH BRANCH MN 55056 Changed

Drilling Method Non-specified Rotary

Drilling Fluid Bentonite

Well Hydrofractured? ☐ YES ☐ NO From ft. to

Use Irrigation

Casing Type Steel (black or low Drive Shoe? ☑ YES ☐ NO
Diameter 10 Depth 300
10.00 in. from 0.00 to 300.00 ft. 40.48 lbs/ft

Hole Diameter (in.)
15.0(To 300.0
10.0(To 410.0

Description	Color	Hardness	From	To (ft.)
PEAT	BLACK	SOFT	0	5
SANDY CLAY	GRAY	MEDIUM	5	21
FINE SAND	GRAY	SOFT	21	46
LENSES CLAY/SAND	GRAY	MEDIUM	46	87
SANDY CLAY	RED/BRN	HARD	87	208
CLAY/BOULDERS	RED	HARD	208	258
CLAY/GRAVEL	RED/BRN	MEDIUM	258	264
SHALE	GREEN	MEDIUM	264	295
SANDSTONE	RED/BRN	MEDIUM	295	310
SANDSTONE	RED/BRN	MEDIUM	310	410

Screen No
Make
Diamter Slot Length Set

Open Hole(ft.) From 300.C to 410.0
Type

Static Water Level
24.00 ft. Land surface Date measured 1999/03/22

Pumping Level (below land surface)
58.50 ft. after 11.00 hrs. pumping 400.00 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☐ Casing Protection ☑ 12 in. above grade
☐ At-grate (Environmental Wells and Borings ONLY) ☐ Basement offset

Grouting Information Well grouted? ☑ YES ☐ NO
Material Neat Cement From 0.0 To 220.0 ft. 84.00 Sacks
Material Neat Cement From 220.0 To 300.0 ft. 60.00 Sacks

Nearest Known Source of Contamination
315 feet W Direction SDF Type
Well disinfected upon completion? ☑ YES ☐ NO

Pump
☐ Not Installed Date Installed 1999/06/00
Manufacture's name AMERICAN
Model number 8L30-3 HP 50.00 Volts 480
Length of drop pipe 108.(Material Capacity 325 g.p.m
Type Submersible

Abandoned Wells
Does property have any not in use and not sealed well(s)? ☐ YES ☑ NO

Variance
Was a variance granted from the MDH for this well? ☐ YES ☑ NO

Remarks
LOCATED: FOURTH AND PINE ST. GAMMA LOGGED 11-14-2006.
STRATIGRAPHY BAASED ON GAMMA & VIDEO LOGS.

Well Contractor Cerfication
Renner E.H. Well 71015
License Business Name Lic. or Reg No.
SCHAFFER, R.
Name of Driller Date

First Bedrock CMTS Aquifer Mid.Proterozoic Sedimentary
Last Strat PMSU Depth to Bedrock 264.00 ft.

Unique Well Number **593584**

County: Chisago
Quad: North Branch
Quad Id: 151C

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING RECORD

MINNESOTA STATUTES CHAPTER 1031

Entry Date: 1999/07/29
Update Date: 2010/06/02
Received Date:

Well Name	Township	Range	Dir	Section	Subsection	Depth Drilled	Depth Completed	Date Completed	Lic/Reg. No.	Driller Name
NORTH BRANCH GOLF COUR	35	21	W	21	BDCCBA	410 ft	410 ft	1999/04/22	71015	SCHAFFER, R.

Elevation 887.00 **ft.** **Method** 7.5 minute topographic **Aquifer** Mid.Proterozoic Sedime **Depth to Bedrock** 264 **ft.** **Open Hole 300-410** **SWL** 24

Field Located Minnesota Geological Survey
Program
Uni No.Verified Information from owner
Geologic Interpretation Tony Runkel

Location Method
Input Source
Input Date 2006/08/29
Agency MGS

Universal Transverse Mercator(UTM) - NAD83 - Zone 15 - Meters
UTM Easting (X) 501930
UTM Northing (Y) 5039325
Interpretation Method Inferred from geophysical log

Geological Material	Color	Hardness	DEPTH From	DEPTH To	Thick	ELEVATION From	ELEVATION To	Stratigraphy	LITHOLOGY Primary	LITHOLOGY Secondary	LITHOLOGY Minor
PEAT	BLACK	SOFT	0	5	5	887	882	Peat-black	Peat	Organic Deposits	
SANDY CLAY	GRAY	MEDIUM	5	21	16	882	866	Clay & sand-gray	Clay	Sand	
FINE SAND	GRAY	SOFT	21	46	25	866	841	Sand-gray	Sand		
LENSES CLAY/SAND	GRAY	MEDIUM	46	87	41	841	800	Clay & sand-gray	Clay	Sand	
SANDY CLAY	RED/BRN	HARD	87	208	121	800	679	Clay & sand	Clay	Sand	
CLAY/BOULDERS	RED	HARD	208	258	50	679	629	Pebbly sand/silt/clay-red	Clay	Obsidian	
CLAY/GRAVEL	RED/BRN	MEDIUM	258	264	6	629	623	Pebbly sand/silt/clay	Clay	Gravel	
SHALE	GREEN	MEDIUM	264	295	31	623	592	Mt.Simon	Shale		
SANDSTONE	RED/BRN	MEDIUM	295	310	15	592	577	Mt.Simon	Sandstone		
SANDSTONE	RED/BRN	MEDIUM	310	410	100	577	477	Mid.Proterozoic Sedimentary	Sandstone		

Appendix B

Aquifer Test Data and Analysis

MINNESOTA MDH DEPARTMENT OF HEALTH
Environmental Health Division
Drinking Water Protection Section
Source Water Protection Unit
P.O. Box 64975
St. Paul, Minnesota 55164-0975

Aquifer Test Plan

Public Water Supply ID:	130011	**PWS Name:**	North Branch Water and Light

Contact

Aquifer Test Contact:	**John Greer**
Contractor Name and Address:	**Barr Engineering**
	4700 West 77th Street
City, State, Zip:	**Minneapolis, MN 55435-4803**
Phone and Fax Number:	**952-832-2691 (phone) 952-832-2601 (fax)**

Proposed Aquifer Test Method

☐ 1) An existing pumping test that meets the requirements of wellhead protection rule part 4720.5520 and that was previously conducted on a public well in your water supply system.

☐ 2) An existing pumping test that meets the requirements of wellhead protection rule part 4720.5520 and that was previously conducted on another well in a hydrogeologic setting determined by the department to be equivalent.

☐ 3) A pumping test conducted on a new or existing public well in your water supply system and that meets the requirements for larger sized water systems (wellhead protection rule part 4720.5520).

☐ 4) A pumping test conducted on a new or existing public well in your water supply system and that meets the requirements for smaller sized water systems (wellhead protection rule part 4720.5530).

☐ 5) An existing pumping test that does not meet the requirements of wellhead protection rule part 4720.5520 and that was previously conducted on: 1) a public water supply well or 2) another well in a hydrogeologic setting determined by the department to be equivalent.

[X] 6) An existing specific capacity test or specific capacity test for the public water supply well.

☐ 7) An existing published transmissivity value.

- Include all pumping test data and the estimated transmissivity value when the aquifer test method proposed is one of those specified in Nos. 1, 2, 5, 6, or 7 listed above.

Test Description			
Pumped Well Unique No:	706844 (North Branch #4)	**Test Duration (Hours):**	24
Location (Township, Range, Section, Quarters):	T35 R21W Sec19 DBCBAC	**Pump Type:**	
		Discharge Rate:	325 gpm
Number of Observation Wells:	0	**Flow Rate Measuring Device Type:**	

[X] Confined [ ] Unconfined

- You must include a map showing the location of the pumping well and observation well(s).

Rational for Proposed Test Method

Briefly describe the rationale for method selected:

Specific capacity data for buried quaternary aquifer. Only known test data for the unit the well is open to.

Using the TGuess Method (Bradbury and Rothschild, 1985) the transmissivity of the aquifer is estimated to be 1728 ft^2/day, and a hydraulic conductivity of 29 ft/day.

Regional data from the MGS/MCES hydraulic conductivity database for buried Quaternary aquifers in the area has the following characteristics (n= 89):
Minimum K = 4.6 ft/day
Maximum K = 221.4 ft/day
Geometric Mean K = 20.3 ft/day

List all unique numbers of wells that this Aquifer Test Plan applies to:					
706844 (Well 4)					

Reviewed by:	**Approved:** [ ] **Yes** [ ] **No**	**Approval Date:**

Worksheet for Estimating Transmissivity and Hydraulic Conductivity from Specific Capacity Test Data

Explanation and notes attached.

Maximum iterations	100	
Error tolerance (as drawdown)	0.001	feet

Field Data								Estimated Parameters			Calculated Results							Diagnostics: Solution Integrity			Diagnostics: Sensitivity of T:		
Location	Well Diam.	Depth to Water: Initial	Depth to Water: Final	Test Duration	Mean Pumping Rate	Screened Interval: Depth to Top	Screened Interval: Depth to Bottom	Storage Coeff. (S)	Well loss Coeff. (C)	Aquifer Thickness (b)	Measured Drawdown (s_m)	Saturated Screen Length (L)	Well loss (s_w)	Partial Penetration Parameter (s_p)	Specific Capacity	**Transmissivity (T)**	**Conductivity (K)**	Calculated Drawdown	Error as Drawdown	Well Bore Storage Test	to S at ± 1 factor of 10	to s_w at 10% of s_m	to b at ± 25%
	inches	feet	feet	hours	gpm	feet	feet	-	sec^2/ft^5	feet	feet	feet	feet	-	gpm/ft	**sq ft/sec**	**ft/day**	feet			sq ft/sec	sq ft/sec	sq ft/sec
North Branch Well 4	18	33.0	78.0	24	325.0	158.0	218.0	0.001	0	60	45.00	60.0	0.0E+00	0.00	7.22	**2.0E-02**	**2.9E+01**	45.00	0.00%	pass	3.2E-03	2.4E-03	3.0E-03

References:

Bradbury, K.B., and E.R. Rothschild, 1985. A computerized technique for estimating the hydraulic conductivity of aquifer from specific capacity data: Ground Water vol. 23, No. 2, pp. 240-246.

ASTM International, 2004. Standard Test Method for Determining Specific Capacity and Estimating Transmissivity at the Control Well, Standard D 5472-93, in Annual Book of ASTM Standards, Vol. 04.08 pp. 1279-1282.

Worksheet for Estimating Transmissivity and Hydraulic Conductivity from Specific Capacity Test Data

Explanation

This spreadsheet estimates transmissivity and hydraulic conductivity following the method of Bradbury and Rothschild (1985). The method applies the Cooper-Jacob approximation of the Theis equation, with corrections for partial penetration and well loss, as indicated in equations 1-4.

Equation 1 is the modified Cooper-Jacob approximation of the Theis equation for transient radial flow to a well in a confined aquifer. Equation 2 calculates well loss, based on a correction factor (C), which must be estimated or determined by alternate test methods. Equation 3 calculates a unitless partial penetration correction factor (see assumptions below), employing the function G(L/b), approximated in Equation 4 with a polynomial best-fit.

The estimates of transmissivity and conductivity yielded by this method are imperfect, and presumed to be less realistic than the estimates that can be made from time/drawdown or distance/drawdown tests, if those data are available. This solution method includes several assumptions that should limit the confidence placed in its estimates:

a) the tested aquifer is confined, non-leaky, homogeneous and isotropic;
b) the storage coefficient of the aquifer is known;
c) the well loss is known;
d) the effective aquifer thickness is known.

In most cases, the storage coefficient, well loss, and aquifer thickness can only be estimated. The error introduced is non-negligible, but can be loosely bracketed. The diagnostic section of the worksheet includes a limited sensitivity analysis.

If the user has little control on well loss, or aquifer thickness, the well loss and partial penetration correction terms may be removed, respectively, by setting the well loss coefficient (C) equal to zero, and the aquifer thickness (b) equal to the saturated screen interval. Note that the partial penetration correction factor assumes isotropic conditions ($K_h = K_z$), and gives a value of T extrapolated from the screened interval to the full aquifer thickness. If the aquifer is anisotropic, this correction is inappropriate.

Eq. 1 $$T = \frac{Q}{4\pi(s_m - s_w)}\left[\ln\left(\frac{2.25Tt}{r_w^2 S}\right) + 2s_p\right]$$

Eq. 2 $$s_w = CQ^2$$

Eq. 3 $$s_p = \frac{1-L/b}{L/b}\left(\ln\frac{b}{r_w} - G(L/b)\right)$$

Eq. 4 $$G(L/b) = 2.948 - 7.363(L/b) + 11.447(L/b)^2 - 4.675(L/b)^3$$

b - aquifer thickness
C - well loss coefficient
L - screen length
Q - mean pumping rate
r_w - effective radius
s_m - measured drawdown
s_w - well loss
s_p - partial penetration parameter
S - storativity
T - transmissivity
t - pumping duration

Usage Notes

<u>Units</u>
The user may chose any combination of units for field data, estimated parameters and calculated results by changing the units shown in the column headers. Each of these cells has an embedded pull down list from which to chose. Only the listed options will work, because the embedded functions look for specific text strings. The units of the diagnostic columns are linked to the calculated results, and shouldn't be manually changed.

<u>Input</u>
Field data may be pasted in or entered directly. The units header should be changed to agree with the data. All depth values are assumed to be from a common reference point (e.g., ground surface).

<u>Calculated Results</u>
The calculated results cells all make use of user-defined functions written in Visual Basic for Applications. The functions and their arguments are listed to the right. The code may be viewed by opening Excel's Visual Basic Editor. Cells containing these functions may be drag-filled or copied down their respective columns to extend the table. Changing the units in the column header will automatically change the output units.

<u>Diagnostics</u>
The difference between calculated drawdown the measured drawdown is a metric for assessing the convergence of the solution. If the error is unacceptably high, the maximum iterations and error tolerance may be adjusted in the fields above the table. The well bore storage test checks that the specific capacity test rate and duration were adequate to negate the influence of water removed from the well casing on the measured drawdown. The test applies criterion that the test duration be longer than $25 * r_w^2/T$ (ASTM, 2004). Note that this check assumes well radius and riser radius are equal.

The worksheet assesses the sensitivity of transmissivity to variation in the storage coefficient (S), to the degree of well loss (s_w), and to the effective isotropic aquifer thickness (b). The resulting values shown indicate the variance of T from the actual estimate, when the target parameter is adjusted as indicated.

Functions and arguments employed in this workbook

CalcDD(TGuess(well diam., diam. units, t, t units, Q, Q units, S, s_w, s_w units, s_p, T, T units, output units)
Returns drawdown calculated from an estimated T.
Getdd(dtw initial, dtw initial units, dtw final, dtw final units, output units)
Returns drawdown calculated from measured depth to water (dtw)
GetK(T, T units, b, b units, output units)
Returns an estimate of hydraulic conductivity calculated by T/b.
Getloss(Q, Q units, C, C units, output units)
Returns the well loss correction factor (s_w).
Getsl(screen top depth, screen top depth units, screen bottom depth, screen bottom depth units, dtw init., dtw units, output units)
Returns the saturated screen length computed from field data.
GetSpCap(Q, Q units, s_m, s_m units, output units)
Returns specific capacity.
ppen(L, L units, b, b units, d, d units)
Returns the partial penetration correction factor (s_p).
TGuess(well diam., diam. units, s_m, s_m units, t, t units, Q, Q units, S, s_w, s_w units, s_p, error tolerance, error units, max. steps, output units)
Return an estimate of transmissivity.
wellstorage(well diam., diam. units, t, t units, T, T units)
Returns the text "pass" or "fail" based on a test for inappropriate effects of well bore storage.

References

1) Bradbury, K.B., and E.R. Rothschild, 1985. A computerized technique for estimating the hydraulic conductivity of aquifer from specific capacity data: Ground Water vol. 23, No. 2, pp. 240-246.
2) ASTM International, 2004. Standard Test Method for Determining Specific Capacity and Estimating Transmissivity at the Control Well, Standard D 5472-93, in Annual Book of ASTM Standards, Vol. 04.08 pp. 1279-1282.

Questions/Bugs, contact:
Michael Cobb, UW-Madison Department of Geology and Geophysics, cobb@geology.wisc.edu

Regional Hydraulic Conductivity Data
Burried Quaternary Aquifer, North Branch, MN area

Unique Number	T	T units	T analytical method	Aquifer Thickness (ft)	Kh (ft/day)	Test Method	Aquifer	UTM E	UTM N
196274	450	ft^2/day	TGUESS	40	11.25	Specific Capacity	QBAA	498226	5039058
635118	685	ft^2/day	TGUESS	25	27.39	Specific Capacity	QBAA	498518	5040055
592602	715	ft^2/day	TGUESS	40	17.88	Specific Capacity	QBAA	498632	5037652
582658	581	ft^2/day	TGUESS	47	12.37	Specific Capacity	QBAA	499032	5038335
558466	3011	ft^2/day	TGUESS	38	79.23	Specific Capacity	QBAA	498795	5037705
401041	418	ft^2/day	TGUESS	40	10.44	Specific Capacity	QBAA	497516	5038455
723636	1631	ft^2/day	TGUESS	33	49.42	Specific Capacity	QBAA	498304	5039972
634730	592	ft^2/day	TGUESS	40	14.79	Specific Capacity	QBAA	498850	5037506
609614	3330	ft^2/day	TGUESS	40	83.24	Specific Capacity	QBAA	498645	5038303
648862	528	ft^2/day	TGUESS	34	15.52	Specific Capacity	QBAA	498876	5037440
631243	427	ft^2/day	TGUESS	20	21.36	Specific Capacity	QBAA	498574	5037343
676809	715	ft^2/day	TGUESS	40	17.88	Specific Capacity	QBAA	498829	5037436
637970	3878	ft^2/day	TGUESS	40	96.94	Specific Capacity	QBAA	498460	5040333
598048	2872	ft^2/day	TGUESS	40	71.8	Specific Capacity	QBAA	498399	5038966
653760	578	ft^2/day	TGUESS	31	18.66	Specific Capacity	QBAA	498585	5037967
687641	230	ft^2/day	TGUESS	40	5.76	Specific Capacity	QBAA	499181	5040301
577029	901	ft^2/day	TGUESS	40	22.52	Specific Capacity	QBAA	500157	5040507
743250	133	ft^2/day	TGUESS	11	12.08	Specific Capacity	QBAA	498338	5038233
523887	6951	ft^2/day	TGUESS	47	147.89	Specific Capacity	QBAA	499146	5038080
548322	728	ft^2/day	TGUESS	40	18.21	Specific Capacity	QBAA	498736	5040221
694483	692	ft^2/day	TGUESS	89	7.78	Specific Capacity	QBAA	499159	5038980
431738	1530	ft^2/day	TGUESS	40	38.26	Specific Capacity	QBAA	500121	5040479
656439	424	ft^2/day	TGUESS	21	20.2	Specific Capacity	QBAA	498584	5037357
676819	332	ft^2/day	TGUESS	40	8.31	Specific Capacity	QBAA	499380	5038067
550632	248	ft^2/day	TGUESS	31	8	Specific Capacity	QBAA	499336	5038384
620344	454	ft^2/day	TGUESS	43	10.55	Specific Capacity	QBAA	498847	5037664
676821	164	ft^2/day	TGUESS	27	6.08	Specific Capacity	QBAA	498864	5037341
562762	1684	ft^2/day	TGUESS	34	49.54	Specific Capacity	QBAA	498821	5037974
598047	2872	ft^2/day	TGUESS	40	71.8	Specific Capacity	QBAA	498626	5038756
452262	236	ft^2/day	TGUESS	18	13.1	Specific Capacity	QBAA	498670	5040485
436594	976	ft^2/day	TGUESS	40	24.4	Specific Capacity	QBAA	499623	5040485
575644	604	ft^2/day	TGUESS	40	15.09	Specific Capacity	QBAA	498820	5037774
544275	1042	ft^2/day	TGUESS	40	26.05	Specific Capacity	QBAA	498817	5039546
588782	3330	ft^2/day	TGUESS	40	83.24	Specific Capacity	QBAA	499821	5039549
641068	581	ft^2/day	TGUESS	47	12.37	Specific Capacity	QBAA	498988	5037560
631543	728	ft^2/day	TGUESS	40	18.21	Specific Capacity	QBAA	498548	5037580
582657	604	ft^2/day	TGUESS	49	12.32	Specific Capacity	QBAA	499019	5038150
638933	319	ft^2/day	TGUESS	29	11.01	Specific Capacity	QBAA	498875	5037285
750853	505	ft^2/day	TGUESS	22	22.94	Specific Capacity	QBAA	499448	5038066
562384	1235	ft^2/day	TGUESS	40	30.87	Specific Capacity	QBAA	498863	5037929
631244	703	ft^2/day	TGUESS	26	27.05	Specific Capacity	QBAA	498630	5037387
648809	824	ft^2/day	TGUESS	40	20.61	Specific Capacity	QBAA	498604	5037295
448288	597	ft^2/day	TGUESS	30	19.89	Specific Capacity	QBAA	498572	5037908
701584	257	ft^2/day	TGUESS	40	6.42	Specific Capacity	QBAA	499775	5037594
648874	460	ft^2/day	TGUESS	39	11.79	Specific Capacity	QBAA	499063	5037503
562374	607	ft^2/day	TGUESS	40	15.17	Specific Capacity	QBAA	498866	5037859
706844	1441	ft^2/day	TGUESS	92	15.66	Specific Capacity	QBAA	499154	5038991
641069	581	ft^2/day	TGUESS	47	12.37	Specific Capacity	QBAA	498900	5037512
635113	268	ft^2/day	TGUESS	20	13.39	Specific Capacity	QBAA	498406	5040330
712512	308	ft^2/day	TGUESS	21	14.66	Specific Capacity	QBAA	499837	5037259
653108	184	ft^2/day	TGUESS	40	4.6	Specific Capacity	QBAA	499936	5040510
620424	8854	ft^2/day	TGUESS	40	221.35	Specific Capacity	QBAA	498424	5038694

Regional Hydraulic Conductivity Data
Burried Quaternary Aquifer, North Branch, MN area

Unique Number	T	T units	T analytical method	Aquifer Thickness (ft)	Kh (ft/day)	Test Method	Aquifer	UTM E	UTM N
537809	401	ft^2/day	TGUESS	40	10.03	Specific Capacity	QBAA	499392	5038339
650479	1173	ft^2/day	TGUESS	40	29.32	Specific Capacity	QBAA	498330	5038679
630000	1544	ft^2/day	TGUESS	40	38.59	Specific Capacity	QBAA	498422	5038389
714530	3115	ft^2/day	TGUESS	24	129.79	Specific Capacity	QBAA	500023	5038309
550817	304	ft^2/day	TGUESS	34	8.95	Specific Capacity	QBAA	498675	5037727
656440	852	ft^2/day	TGUESS	34	25.05	Specific Capacity	QBAA	498723	5037402
648810	606	ft^2/day	TGUESS	29	20.9	Specific Capacity	QBAA	498882	5037386
637166	390	ft^2/day	TGUESS	40	9.74	Specific Capacity	QBAA	499860	5037553
537762	285	ft^2/day	TGUESS	20	14.23	Specific Capacity	QBAA	498272	5039494
680158	373	ft^2/day	TGUESS	38	9.81	Specific Capacity	QBAA	499015	5037490
670616	367	ft^2/day	TGUESS	34	10.8	Specific Capacity	QBAA	498975	5037460
626935	870	ft^2/day	TGUESS	28	31.07	Specific Capacity	QBAA	498627	5040099
676482	246	ft^2/day	TGUESS	40	6.14	Specific Capacity	QBAA	498519	5038328
714544	7217	ft^2/day	TGUESS	49	147.28	Specific Capacity	QBAA	498999	5038008
642633	667	ft^2/day	TGUESS	46	14.51	Specific Capacity	QBAA	498934	5038396
164698	9941	ft^2/day	TGUESS	79	125.84	Specific Capacity	QBAA	499867	5037535
636073	1055	ft^2/day	TGUESS	40	26.38	Specific Capacity	QBAA	499382	5039347
720477	592	ft^2/day	TGUESS	40	14.81	Specific Capacity	QBAA	498359	5040097
656441	457	ft^2/day	TGUESS	29	15.77	Specific Capacity	QBAA	498664	5037347
542625	760	ft^2/day	TGUESS	40	19.01	Specific Capacity	QBAA	498670	5037893
626578	1434	ft^2/day	TGUESS	48	29.88	Specific Capacity	QBAA	499001	5038275
676820	901	ft^2/day	TGUESS	40	22.52	Specific Capacity	QBAA	498788	5037320
542591	568	ft^2/day	TGUESS	40	14.19	Specific Capacity	QBAA	498599	5037650
690008	528	ft^2/day	TGUESS	35	15.1	Specific Capacity	QBAA	498371	5040008
631224	791	ft^2/day	TGUESS	40	19.77	Specific Capacity	QBAA	498661	5037437
565325	1179	ft^2/day	TGUESS	22	53.61	Specific Capacity	QBAA	498713	5037906
577039	548	ft^2/day	TGUESS	29	18.9	Specific Capacity	QBAA	499980	5037164
644684	592	ft^2/day	TGUESS	40	14.79	Specific Capacity	QBAA	498674	5037578
720543	290	ft^2/day	TGUESS	40	7.24	Specific Capacity	QBAA	498281	5039497
653791	390	ft^2/day	TGUESS	40	9.74	Specific Capacity	QBAA	498751	5037495
569998	607	ft^2/day	TGUESS	32	18.96	Specific Capacity	QBAA	498812	5037909
657009	1231	ft^2/day	TGUESS	40	30.77	Specific Capacity	QBAA	499269	5038261
676808	901	ft^2/day	TGUESS	40	22.52	Specific Capacity	QBAA	498636	5037528
550631	279	ft^2/day	TGUESS	37	7.55	Specific Capacity	QBAA	499277	5038345
136128	1417	ft^2/day	TGUESS	40	35.43	Specific Capacity	QBAA	498116	5038075
582662	604	ft^2/day	TGUESS	49	12.32	Specific Capacity	QBAA	499024	5038074
614429	1212	ft^2/day	TGUESS	40	30.31	Specific Capacity	QBAA	498622	5038768

Min	**4.6**
Max	**221.4**
Average	**30.3**
Geomean	**20.3**

North Branch Water & Light

WELL # 4

2004

WELL DIA. 18" DEPTH 240 WELL: SCREEN X OPEN HOLE ______

ORIGINAL S.W.L. 33 ORIG. P.L. 78 ORIG. G.P.M. 325 ORIG.S.C ______

24 Hour Pump Test

DAY/TIME	WATER AT REST/SWL	GPM	PSI	AMPS	VOLTAGE	PUMPING WTR LVL	DRAW DOWN	SPECIFIC CAPACITY	WATER COLOR/ SAND CONTENT
9-4-07 1430	35	325	50	40		76	43		
9-6-07 9110	36	325	48	40		79	43		
9-6-07 1210	34	325	48	40		79	45		
9-6-07 1720	32.5	325	50	40		77.5	45.0		
9-7-07 8:30	34	325	48	40		78	44		

DATE COMMENTS

Example: Pumping Water Level minus Static Water Level equals X (PWL - SWL = X)
X = Draw Down in Feet
Gallons Per Minute divided by Draw Down equals Specific Capacity or Gallons of Water Pumped Per Foot of Draw Down (GPM ÷ Draw Down = Specific Capacity)

Information should be recorded a minimum of 10 to 15 minutes after start-up of pump.

BERGERSON-CASWELL, INC. 1-800-328-6188

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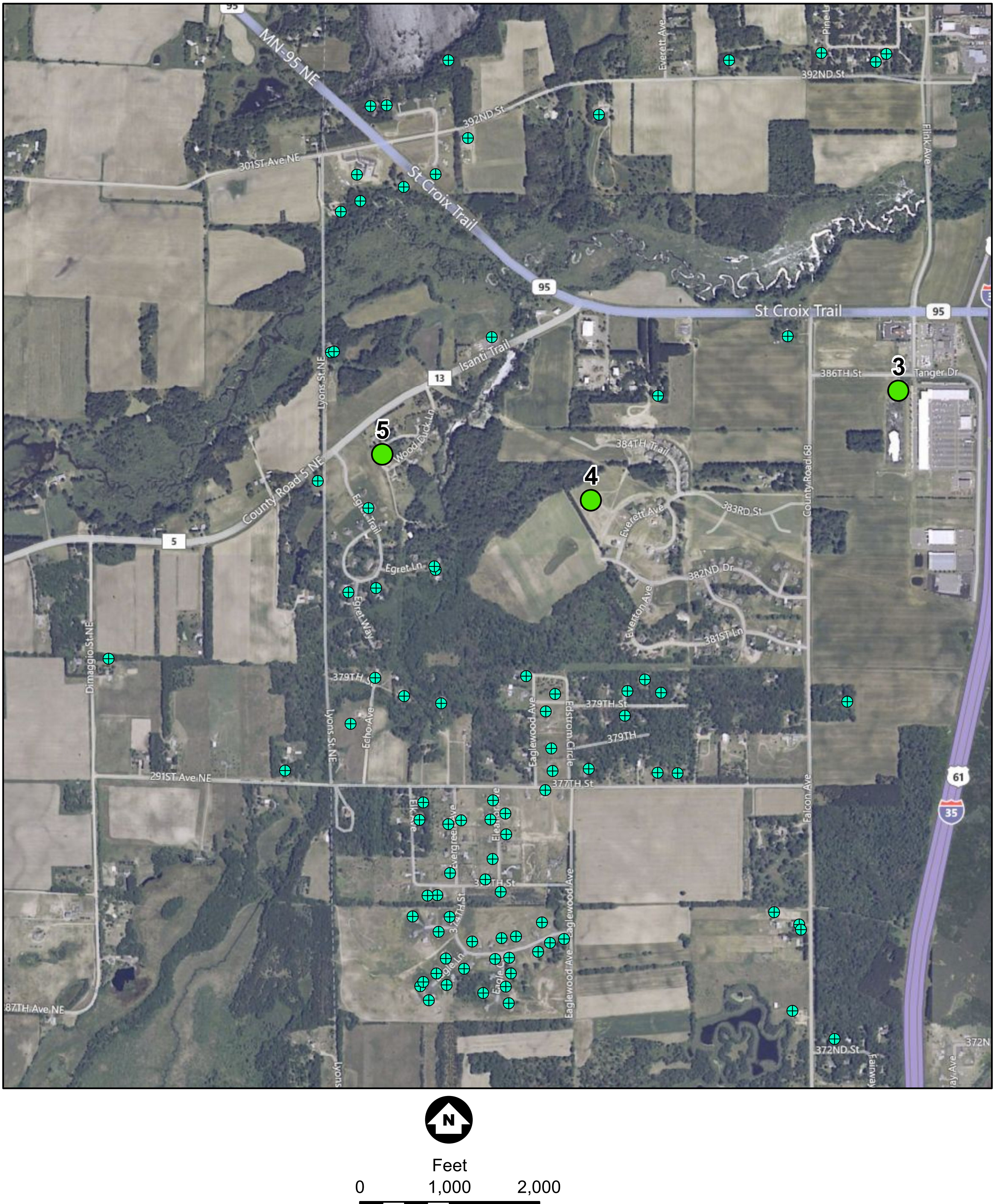


North Branch Wells

Quaternary Wells with Specific Capacity Data

Quaternary Wells with Specific Capactiy Data
North Branch Water and Light

MINNESOTA MDH DEPARTMENT OF HEALTH
Environmental Health Division
Drinking Water Protection Section
Source Water Protection Unit
P.O. Box 64975
St. Paul, Minnesota 55164-0975

Aquifer Test Plan

Public Water Supply ID:	130011	**PWS Name:**	North Branch Water and Light

Contact

Aquifer Test Contact:	**John Greer**
Contractor Name and Address:	**Barr Engineering**
	4700 West 77th Street
City, State, Zip:	**Minneapolis, MN 55435-4803**
Phone and Fax Number:	**952-832-2691 (phone) 952-832-2601 (fax)**

Proposed Aquifer Test Method

[X] 1) An existing pumping test that meets the requirements of wellhead protection rule part 4720.5520 and that was previously conducted on a public well in your water supply system.

[ ] 2) An existing pumping test that meets the requirements of wellhead protection rule part 4720.5520 and that was previously conducted on another well in a hydrogeologic setting determined by the department to be equivalent.

[ ] 3) A pumping test conducted on a new or existing public well in your water supply system and that meets the requirements for larger sized water systems (wellhead protection rule part 4720.5520).

[ ] 4) A pumping test conducted on a new or existing public well in your water supply system and that meets the requirements for smaller sized water systems (wellhead protection rule part 4720.5530).

[ ] 5) An existing pumping test that does not meet the requirements of wellhead protection rule part 4720.5520 and that was previously conducted on: 1) a public water supply well or 2) another well in a hydrogeologic setting determined by the department to be equivalent.

[ ] 6) An existing specific capacity test or specific capacity test for the public water supply well.

[ ] 7) An existing published transmissivity value.

- Include all pumping test data and the estimated transmissivity value when the aquifer test method proposed is one of those specified in Nos. 1, 2, 5, 6, or 7 listed above.

To request this document in another format, please call the Section Receptionist at (651) 201-4700 or Division TTY at (651) 201-5797.

HE-01555-01 (10/06)
IC #140-0606

Test Description			
Pumped Well Unique No:	749383 (North Branch #5)	**Test Duration (Hours):**	192 (Multiple-steps)
Location (Township, Range, Section, Quarters):	T35 R21W Sec19 CBBADA	**Pump Type:**	
		Discharge Rate:	Variable (0-2000 gpm)
Number of Observation Wells:	1 (TW10, 706835)	**Flow Rate Measuring Device Type:**	Bernoulli Tube

[X] Confined [ ] Unconfined

- You must include a map showing the location of the pumping well and observation well(s).

Rational for Proposed Test Method

Briefly describe the rationale for method selected:

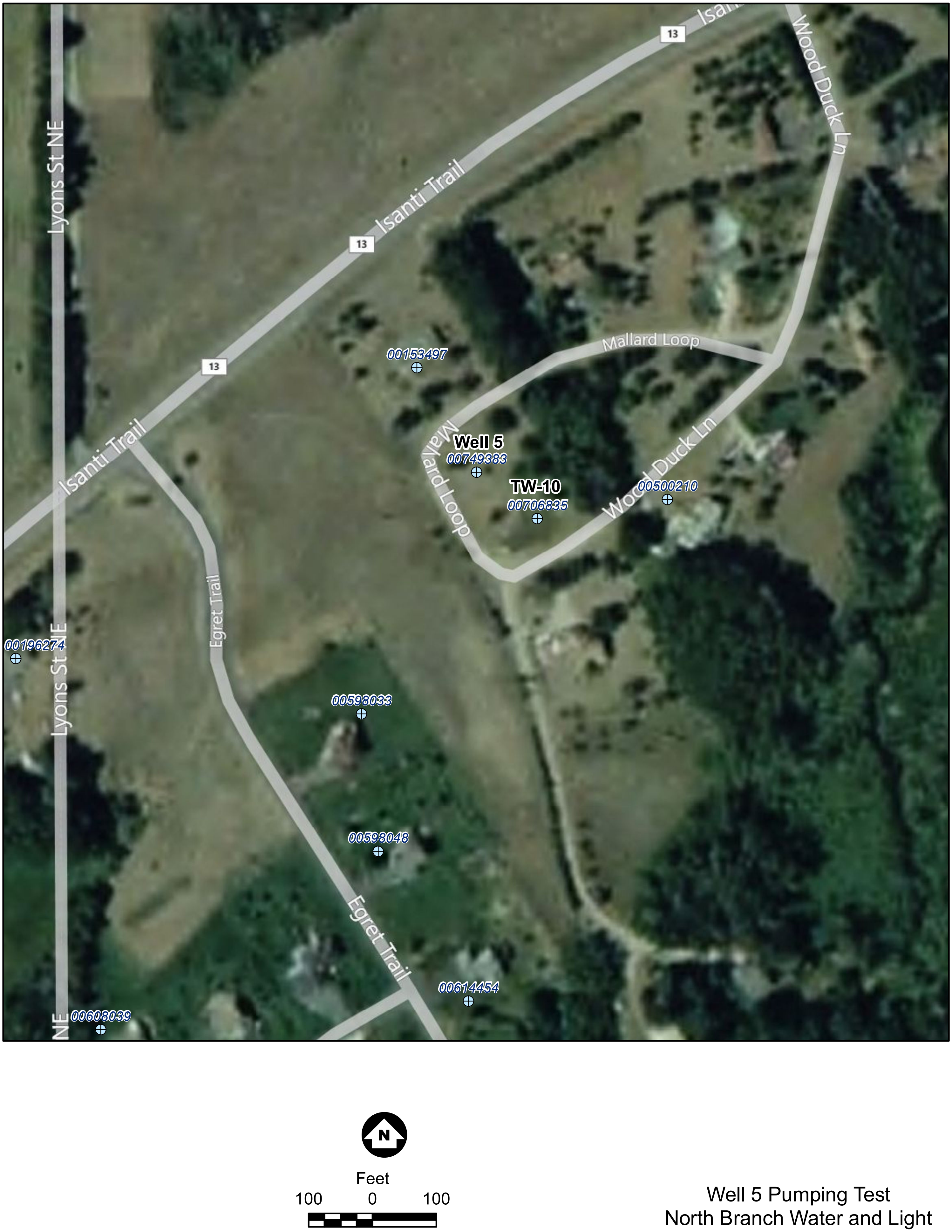
This pumping test has multiple steps with multiple recovery periods. The last step was 24 hours in length. Data was analyzed by MDH staff. This is the most complete and longest test available for the Mt Simon-Hinckley aquifer in the area. The monitoring well was also open to the Tunnel City – Wonewoc aquifer and allows for estimation of the leakage through the Eau Claire Formation.

Transmissivity as determined by MDH is 5370 ft^2/day
Using a aquifer thickness of 150 feet results in a hydraulic conductivity of 35.8 ft/day

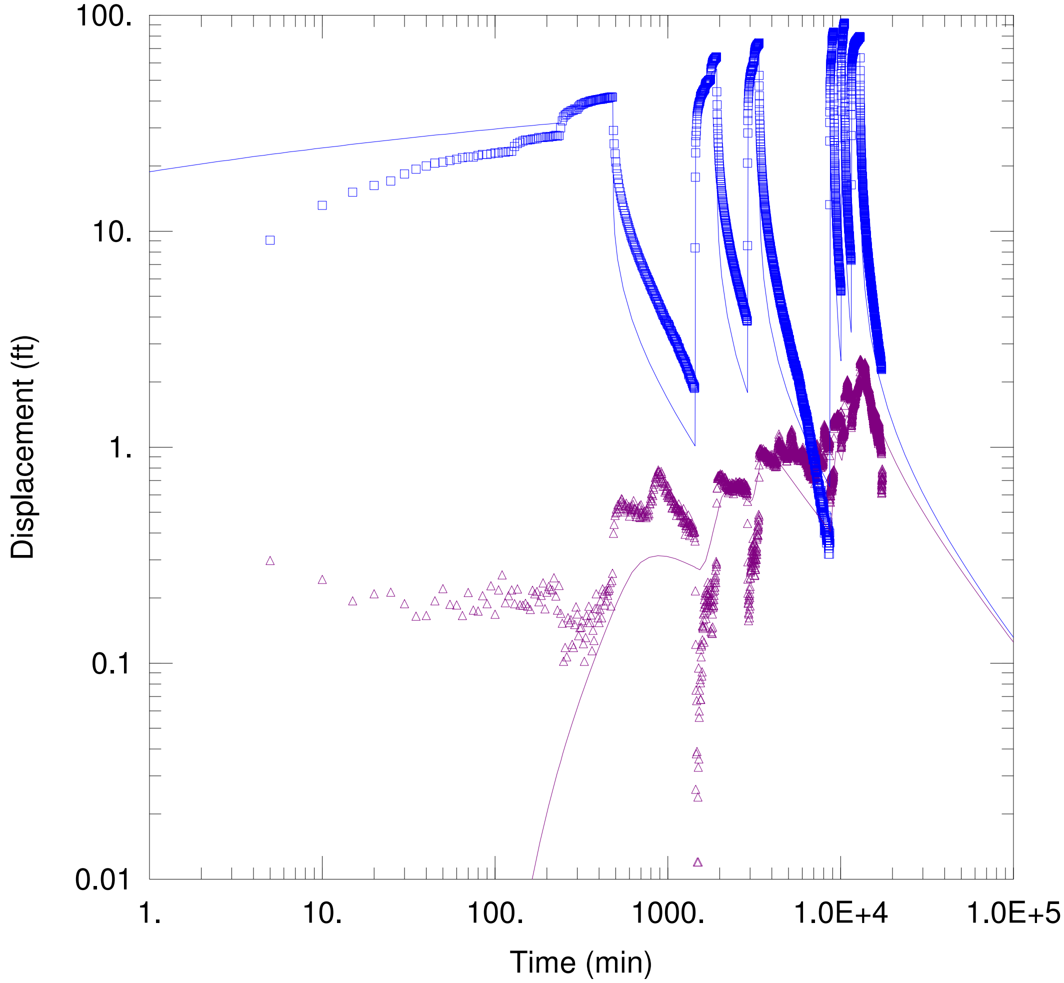
List all unique numbers of wells that this Aquifer Test Plan applies to:

522767 (Well 3)					
749383 (Well 5)					

Reviewed by:	**Approved:** [ ] **Yes** [ ] **No**	**Approval Date:**



Well 5 Pumping Test
North Branch Water and Light



WELL TEST ANALYSIS

Data Set: P:\...\North Branch Well 5 pumptest_test Aug - Sept 2007_MDH.aqt
Date: 11/17/11 Time: 12:33:04

PROJECT INFORMATION

Company: MDH
Location: North Branch
Test Well: Test Well 10
Test Date: Feb 10, 2006

AQUIFER DATA

Saturated Thickness: 146. ft
Anisotropy Ratio (Kz/Kr): 1.
Aquitard Thickness (b'): 20. ft
Aquitard Thickness (b"): 20. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Well 5	1635387.14	16532627.95

Observation Wells

Well Name	X (ft)	Y (ft)
△ Test Well 10	1635416.67	16532562.34
□ Well 5	1635387.14	16532627.95

SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 5371.2 ft^2/day
1/B = 0.0002008 ft^{-1}
T2 = 2034.1 ft^2/day
S = 0.002951
ß/r = 1.455E-5 ft^{-1}
S2 = 6.31E-5

MINNESOTA MDH DEPARTMENT OF HEALTH
Environmental Health Division
Drinking Water Protection Section
Source Water Protection Unit
P.O. Box 64975
St. Paul, Minnesota 55164-0975

Aquifer Test Plan

Public Water Supply ID:	130011	PWS Name:	North Branch Water and Light

Contact

Aquifer Test Contact:	**John Greer**
Contractor Name and Address:	**Barr Engineering**
	4700 West 77th Street
City, State, Zip:	**Minneapolis, MN 55435-4803**
Phone and Fax Number:	**952-832-2691 (phone) 952-832-2601 (fax)**

Proposed Aquifer Test Method

☐ 1) An existing pumping test that meets the requirements of wellhead protection rule part 4720.5520 and that was previously conducted on a public well in your water supply system.

☐ 2) An existing pumping test that meets the requirements of wellhead protection rule part 4720.5520 and that was previously conducted on another well in a hydrogeologic setting determined by the department to be equivalent.

☐ 3) A pumping test conducted on a new or existing public well in your water supply system and that meets the requirements for larger sized water systems (wellhead protection rule part 4720.5520).

☐ 4) A pumping test conducted on a new or existing public well in your water supply system and that meets the requirements for smaller sized water systems (wellhead protection rule part 4720.5530).

☐ 5) An existing pumping test that does not meet the requirements of wellhead protection rule part 4720.5520 and that was previously conducted on: 1) a public water supply well or 2) another well in a hydrogeologic setting determined by the department to be equivalent.

[X] 6) An existing specific capacity test or specific capacity test for the public water supply well.

☐ 7) An existing published transmissivity value.

- Include all pumping test data and the estimated transmissivity value when the aquifer test method proposed is one of those specified in Nos. 1, 2, 5, 6, or 7 listed above.

Test Description			
Pumped Well Unique No:	112244 (North Branch #2)	**Test Duration (Hours):**	Unknown
Location (Township, Range, Section, Quarters):	T35 R21W Sec21 BBCDBA	**Pump Type:**	
		Discharge Rate:	350 gpm
Number of Observation Wells:	0	**Flow Rate Measuring Device Type:**	

[X] Confined [ ] Unconfined

- You must include a map showing the location of the pumping well and observation well(s).

Rational for Proposed Test Method

Briefly describe the rationale for method selected:

Specific capacity data for the Fond du lac aquifer (Proterozoic sediments). The only other high capacity well in the area open to this aquifer is North Branch Well 1 (217922) and as noted on the well log the specific capacity for that well is incongruous.

Using the TGuess Method (Bradbury and Rothschild, 1985) the transmissivity of the aquifer is estimated to be 441 ft^2/day, and a hydraulic conductivity of 4.4 ft/day.

List all unique numbers of wells that this Aquifer Test Plan applies to:

217922 (Well 1)					
112244 (Well 2)					

Reviewed by:	**Approved:** [ ] **Yes** [ ] **No**	**Approval Date:**

Worksheet for Estimating Transmissivity and Hydraulic Conductivity from Specific Capacity Test Data

Explanation and notes attached.

Maximum iterations	100
Error tolerance (as drawdown)	0.001 feet

	Field Data							*Estimated Parameters*			*Calculated Results*							*Diagnostics*					
		Depth to Water				Screened Interval												*Solution Integrity*			*Sensitivity of T:*		
Location	Well Diam.	Initial	Final	Test Duration	Mean Pumping Rate	Depth to Top	Depth to Bottom	Storage Coeff. (S)	Well loss Coeff. (C)	Aquifer Thickness (b)	Measured Drawdown (s_m)	Saturated Screen Length (L)	Well loss (s_w)	Partial Penetration Parameter (s_p)	Specific Capacity	**Transmissivity (T)**	**Conductivity (K)**	Calculated Drawdown	Error as Drawdown	Well Bore Storage Test	to S at ± 1 factor of 10	to s_w at 10% of s_m	to b at ± 25%
	inches	feet	feet	hours	gpm	feet	feet	-	sec^2/ft^5	feet	feet	feet	feet	-	gpm/ft	**sq ft/sec**	**ft/day**	feet			sq ft/sec	sq ft/sec	sq ft/sec
North Branch Well 2	10	32.0	215.0	12	350.0	261.0	360.0	0.001	0	100	183.00	99.0	0.0E+00	0.03	1.91	**5.1E-03**	**4.4E+00**	183.00	0.00%	pass	8.4E-04	6.0E-04	1.2E-03

Note: Test duration assumed to be 12 hours

References:

Bradbury, K.B., and E.R. Rothschild, 1985. A computerized technique for estimating the hydraulic conductivity of aquifer from specific capacity data: Ground Water vol. 23, No. 2, pp. 240-246.

ASTM International, 2004. Standard Test Method for Determining Specific Capacity and Estimating Transmissivity at the Control Well, Standard D 5472-93, in Annual Book of ASTM Standards, Vol. 04.08 pp. 1279-1282.

Worksheet for Estimating Transmissivity and Hydraulic Conductivity from Specific Capacity Test Data

Explanation

This spreadsheet estimates transmissivity and hydraulic conductivity following the method of Bradbury and Rothschild (1985). The method applies the Cooper-Jacob approximation of the Theis equation, with corrections for partial penetration and well loss, as indicated in equations 1-4.

Equation 1 is the modified Cooper-Jacob approximation of the Theis equation for transient radial flow to a well in a confined aquifer. Equation 2 calculates well loss, based on a correction factor (C), which must be estimated or determined by alternate test methods. Equation 3 calculates a unitless partial penetration correction factor (see assumptions below), employing the function G(L/b), approximated in Equation 4 with a polynomial best-fit.

The estimates of transmissivity and conductivity yielded by this method are imperfect, and presumed to be less realistic than the estimates that can be made from time/drawdown or distance/drawdown tests, if those data are available. This solution method includes several assumptions that should limit the confidence placed in its estimates:

a) the tested aquifer is confined, non-leaky, homogeneous and isotropic;
b) the storage coefficient of the aquifer is known;
c) the well loss is known;
d) the effective aquifer thickness is known.

In most cases, the storage coefficient, well loss, and aquifer thickness can only be estimated. The error introduced is non-negligible, but can be loosely bracketed. The diagnostic section of the worksheet includes a limited sensitivity analysis.

If the user has little control on well loss, or aquifer thickness, the well loss and partial penetration correction terms may be removed, respectively, by setting the well loss coefficient (C) equal to zero, and the aquifer thickness (b) equal to the saturated screen interval. Note that the partial penetration correction factor assumes isotropic conditions ($K_h = K_z$), and gives a value of T extrapolated from the screened interval to the full aquifer thickness. If the aquifer is anisotropic, this correction is inappropriate.

Eq. 1 $$T = \frac{Q}{4\pi(s_m - s_w)}\left[\ln\left(\frac{2.25Tt}{r_w^{\,2} S}\right) + 2s_p\right]$$

Eq. 2 $$s_w = CQ^2$$

Eq. 3 $$s_p = \frac{1 - L/b}{L/b}\left(\ln\frac{b}{r_w} - G(L/b)\right)$$

Eq. 4 $$G(L/b) = 2.948 - 7.363(L/b) + 11.447(L/b)^2 - 4.675(L/b)^3$$

b - aquifer thickness
C - well loss coefficient
L - screen length
Q - mean pumping rate
r_w - effective radius

s_m - measured drawdown
s_w - well loss
s_p - partial penetration parameter
S - storativity
T - transmissivity
t - pumping duration

Usage Notes

Units
The user may chose any combination of units for field data, estimated parameters and calculated results by changing the units shown in the column headers. Each of these cells has an embedded pull down list from which to chose. Only the listed options will work, because the embedded functions look for specific text strings. The units of the diagnostic columns are linked to the calculated results, and shouldn't be manually changed.

Input
Field data may be pasted in or entered directly. The units header should be changed to agree with the data. All depth values are assumed to be from a common reference point (e.g., ground surface).

Calculated Results
The calculated results cells all make use of user-defined functions written in Visual Basic for Applications. The functions and their arguments are listed to the right. The code may be viewed by opening Excel's Visual Basic Editor. Cells containing these functions may be drag-filled or copied down their respective columns to extend the table. Changing the units in the column header will automatically change the output units.

Diagnostics
The difference between calculated drawdown the measured drawdown is a metric for assessing the convergence of the solution. If the error is unacceptably high, the maximum iterations and error tolerance may be adjusted in the fields above the table. The well bore storage test checks that the specific capacity test rate and duration were adequate to negate the influence of water removed from the well casing on the measured drawdown. The test applies criterion that the test duration be longer than $25 * r_w^2 / T$ (ASTM, 2004). Note that this check assumes well radius and riser radius are equal.

The worksheet assesses the sensitivity of transmissivity to variation in the storage coefficient (S), to the degree of well loss (s_w), and to the effective isotropic aquifer thickness (b). The resulting values shown indicate the variance of T from the actual estimate, when the target parameter is adjusted as indicated.

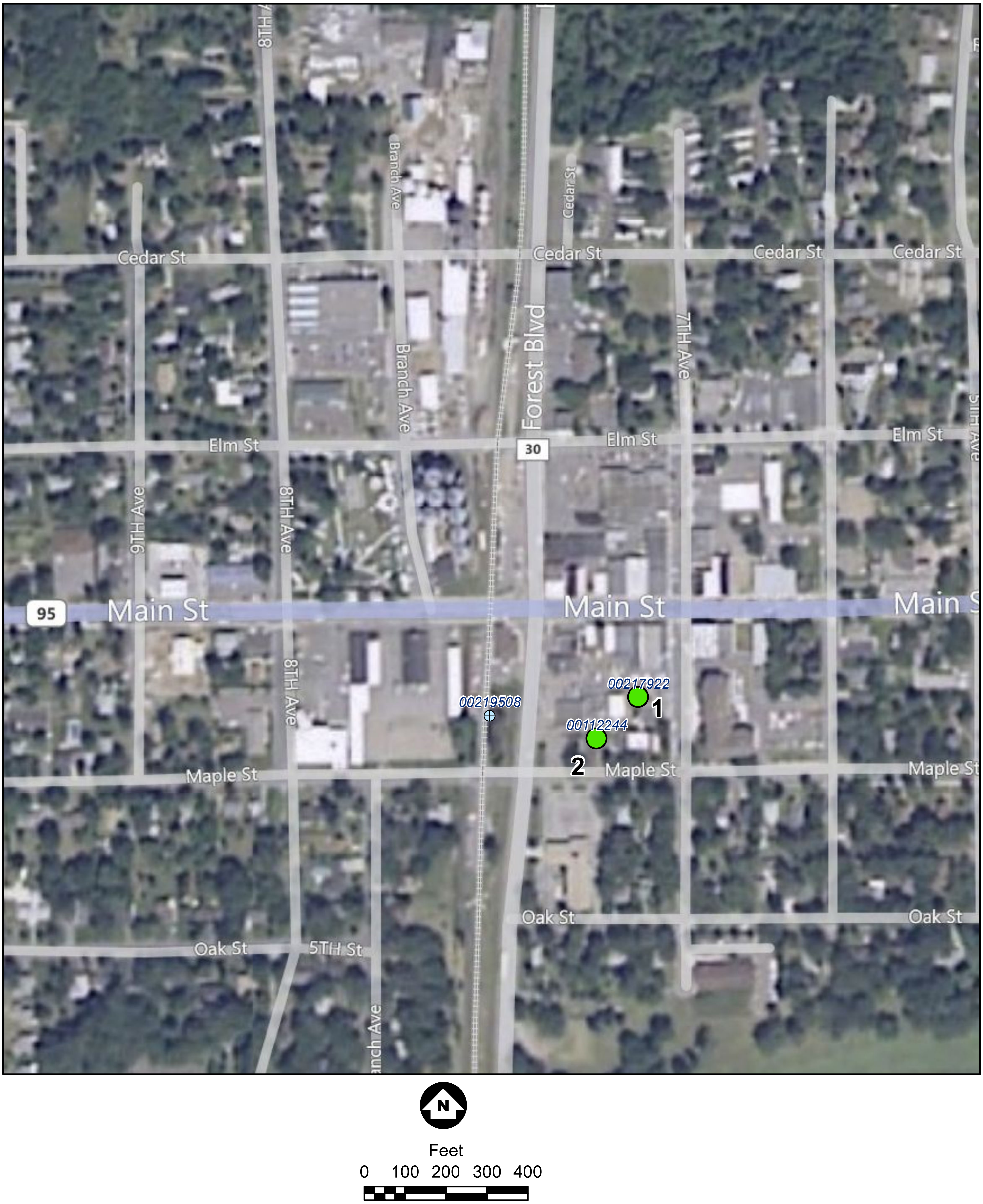
Functions and arguments employed in this workbook

CalcDD(TGuess(well diam., diam. units, t, t units, Q, Q units, S, s_w, s_w units, s_p, T, T units, output units)
Returns drawdown calculated from an estimated T.
Getdd(dtw initial, dtw initial units, dtw final, dtw final units, output units)
Returns drawdown calculated from measured depth to water (dtw)
GetK(T, T units, b, b units, output units)
Returns an estimate of hydraulic conductivity calculated by T/b.
Getloss(Q, Q units, C, C units, output units)
Returns the well loss correction factor (s_w).
Getsl(screen top depth, screen top depth units, screen bottom depth, screen bottom depth units, dtw init., dtw units, output units)
Returns the saturated screen length computed from field data.
GetSpCap(Q, Q units, s_m, s_m units, output units)
Returns specific capacity.
ppen(L, L units, b, b units, d, d units)
Returns the partial penetration correction factor (s_p).
TGuess(well diam., diam. units, s_m, s_m units, t, t units, Q, Q units, S, s_w, s_w units, s_p, error tolerance, error units, max. steps, output units)
Return an estimate of transmissivity.
wellstorage(well diam., diam. units, t, t units, T, T units)
Returns the text "pass" or "fail" based on a test for inappropriate effects of well bore storage.

References

1) Bradbury, K.B., and E.R. Rothschild, 1985. A computerized technique for estimating the hydraulic conductivity of aquifer from specific capacity data: Ground Water vol. 23, No. 2, pp. 240-246.
2) ASTM International, 2004. Standard Test Method for Determining Specific Capacity and Estimating Transmissivity at the Control Well, Standard D 5472-93, in Annual Book of ASTM Standards, Vol. 04.08 pp. 1279-1282.

Questions/Bugs, contact:
Michael Cobb, UW-Madison Department of Geology and Geophysics, cobb@geology.wisc.edu



North Branch Wells

Other Wells - County Well Index

Fond du Lac Aquifer Wells
North Branch Water and Light

Appendix C

MDH Well Vulnerability Assessments

625 Robert St. N. St. Paul MN 55155
P.O. Box 64975 St. Paul MN 55164 - 0975

MINNESOTA DEPARTMENT OF HEALTH
SECTION OF DRINKING WATER PROTECTION
SWP Vulnerability Rating

PWSID: 1130011 | TIER: 5
SYSTEM NAME: North Branch | WHP RANK:
WELL NAME: Well #1 | UNIQUE WELL #: 00217922

COUNTY: Chisago | TOWNSHIP NUMBER: 35 | RANGE: 21 W | SECTION: 21 | QUARTERS: BBCC

CRITERIA		DESCRIPTION	POINTS
Aquifer Name(s)	:	Mt.Simon-Fond Du Lac	
DNR Geologic Sensitivity Rating	:	Very low	15
L Score	:	5	
Geologic Data From	:	Well Record	
Year Constructed	:	1947	
Construction Method	:	Cable Tool/Bored	0
Casing Depth	:	263	5
Well Depth	:	762	
Casing grouted into borehole?		Unknown	0
Cement grout between casings?		Not applicable	0
All casings extend to land surface?		Yes	0
Gravel - packed casings?		No	0
Wood or masonry casing?		No	0
Holes or cracks in casing?		No	0
Isolation distance violations?			0
Pumping Rate	:	350	5
Pathogen Detected?			0
Surface Water Characteristics?			0
Maximum nitrate detected	:	<.4 07/11/1991	0
Maximum tritium detected	:	Unknown	0
Non-THMS VOCs detected?			0
Pesticides detected?			0
Carbon 14 age	:	M	0
Wellhead Protection Score	:		25
Wellhead Protection Vulnerability Rating	:		NOT VULNERABLE
Vulnerability Overridden	:		

COMMENTS
CMTS-PYFL

MINNESOTA DEPARTMENT OF HEALTH
SECTION OF DRINKING WATER PROTECTION
SWP Vulnerability Rating

625 Robert St. N. St. Paul MN 55155
P.O. Box 64975 St. Paul MN 55164 - 0975

PWSID: 1130011 — TIER: 5
SYSTEM NAME: North Branch — WHP RANK:
WELL NAME: Well #2 — UNIQUE WELL #: 00112244

COUNTY: Chisago — TOWNSHIP NUMBER: 35 RANGE: 21 W — SECTION: 21 QUARTERS: BBCC

CRITERIA		DESCRIPTION	POINTS
Aquifer Name(s)	:	Mt.Simon-Fond Du Lac	
DNR Geologic Sensitivity Rating	:	Very low	15
L Score	:	5	
Geologic Data From	:	Well Record	
Year Constructed	:	1978	
Construction Method	:	Cable Tool/Bored	0
Casing Depth	:	261	5
Well Depth	:	360	
Casing grouted into borehole?		Yes	0
Cement grout between casings?		Unknown	5
All casings extend to land surface?		Yes	0
Gravel - packed casings?		No	0
Wood or masonry casing?		No	0
Holes or cracks in casing?		No	0
Isolation distance violations?			0
Pumping Rate	:	350	5
Pathogen Detected?			0
Surface Water Characteristics?			0
Maximum nitrate detected	:	<.4 03/07/1989	0
Maximum tritium detected	:	Unknown	0
Non-THMS VOCs detected?			0
Pesticides detected?			0
Carbon 14 age	:	Unknown	0
Wellhead Protection Score	:		30
Wellhead Protection Vulnerability Rating	:		NOT VULNERABLE
Vulnerability Overridden	:		

COMMENTS
CMTS-PYFL

MINNESOTA MDH DEPARTMENT OF HEALTH

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MINNESOTA DEPARTMENT OF HEALTH
SECTION OF DRINKING WATER PROTECTION
SWP Vulnerability Rating

PWSID: 1130011 TIER: 5
SYSTEM NAME: North Branch WHP RANK:
WELL NAME: Well #3 UNIQUE WELL #: 00522767

COUNTY: Chisago TOWNSHIP NUMBER: 35 RANGE: 21 W SECTION: 20 QUARTERS: BCDA

CRITERIA		DESCRIPTION	POINTS
Aquifer Name(s)	:	Mt. Simon	
DNR Geologic Sensitivity Rating	:	Low	20
L Score	:	2	
Geologic Data From	:	Well Record	
Year Constructed	:	1993	
Construction Method	:	Cable Tool/Bored	0
Casing Depth	:	186	10
Well Depth	:	304	
Casing grouted into borehole?		No	0
Cement grout between casings?		Not applicable	0
All casings extend to land surface?		Yes	0
Gravel - packed casings?		No	0
Wood or masonry casing?		No	0
Holes or cracks in casing?		Unknown	0
Isolation distance violations?			0
Pumping Rate	:	500	5
Pathogen Detected?			NOT VULNERABLE
Surface Water Characteristics?			NOT VULNERABLE
Maximum nitrate detected	:	<.05 05/07/1997	NOT VULNERABLE
Maximum tritium detected	:	<.8 03/15/2006	NOT VULNERABLE
Non-THMS VOCs detected?			0
Pesticides detected?			0
Carbon 14 age	:	Unknown	0
Wellhead Protection Score	:		35
Wellhead Protection Vulnerability Rating	:		NOT VULNERABLE
Vulnerability Overridden	:		

COMMENTS
This well is classified as drawing from the CMTS and PMFL aquifers according to the MGS.

MINNESOTA DEPARTMENT OF HEALTH

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MINNESOTA DEPARTMENT OF HEALTH
SECTION OF DRINKING WATER PROTECTION
SWP Vulnerability Rating

PWSID: 1130011 TIER: 5
SYSTEM NAME: North Branch WHP RANK:
WELL NAME: Well #4 UNIQUE WELL #: 00706844

COUNTY: Chisago TOWNSHIP NUMBER: RANGE: SECTION: QUARTERS:

CRITERIA		DESCRIPTION	POINTS
Aquifer Name(s)	:	Quaternary Buried Artesian	
DNR Geologic Sensitivity Rating	:	Low	0
L Score	:	6	
Geologic Data From	:	Well Record	
Year Constructed	:	2004	
Construction Method	:	Cable Tool/Bored	0
Casing Depth	:	171	10
Well Depth	:	240	
Casing grouted into borehole?		Yes	0
Cement grout between casings?		Unknown	5
All casings extend to land surface?		Yes	0
Gravel - packed casings?		No	0
Wood or masonry casing?		No	0
Holes or cracks in casing?		Unknown	0
Isolation distance violations?			0
Pumping Rate	:	325	5
Pathogen Detected?			NOT VULNERABLE
Surface Water Characteristics?			NOT VULNERABLE
Maximum nitrate detected	:	<.05 05/22/2006	NOT VULNERABLE
Maximum tritium detected	:	<.8 03/08/2006	NOT VULNERABLE
Non-THMS VOCs detected?			0
Pesticides detected?			0
Carbon 14 age	:	Unknown	0
Wellhead Protection Score	:		20
Wellhead Protection Vulnerability Rating	:		NOT VULNERABLE
Vulnerability Overridden	:		

COMMENTS

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MINNESOTA DEPARTMENT OF HEALTH
SECTION OF DRINKING WATER PROTECTION
SWP Vulnerability Rating

PWSID: 1130011 | TIER: 5
SYSTEM NAME: North Branch | WHP RANK:
WELL NAME: Well #5 | UNIQUE WELL #: 00749383

COUNTY: Chisago | TOWNSHIP NUMBER: | RANGE: | SECTION: | QUARTERS:

CRITERIA		DESCRIPTION	POINTS
Aquifer Name(s)	:	Mt. Simon	
DNR Geologic Sensitivity Rating	:	Very low	15
L Score	:	7	
Geologic Data From	:	Other	
Year Constructed	:	2007	
Construction Method	:	Cable Tool/Bored	0
Casing Depth	:	329	5
Well Depth	:	467	
Casing grouted into borehole?		Yes	0
Cement grout between casings?		Yes	0
All casings extend to land surface?		Yes	0
Gravel - packed casings?		No	0
Wood or masonry casing?		No	0
Holes or cracks in casing?		No	0
Isolation distance violations?			0
Pumping Rate	:	1200	20
Pathogen Detected?			NOT VULNERABLE
Surface Water Characteristics?			NOT VULNERABLE
Maximum nitrate detected	:	Unknown	0
Maximum tritium detected	:	<.8 05/06/2009	NOT VULNERABLE
Non-THMS VOCs detected?			0
Pesticides detected?			0
Carbon 14 age	:	Unknown	0
Wellhead Protection Score	:		40
Wellhead Protection Vulnerability Rating	:		NOT VULNERABLE
Vulnerability Overridden	:		

COMMENTS

Used geology information from test well 706835. Previous tritium result of <0.8 TU on 12/4/2008.

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MINNESOTA DEPARTMENT OF HEALTH
SECTION OF DRINKING WATER PROTECTION
SWP Vulnerability Rating

PWSID: 1130011
SYSTEM NAME: North Branch
WELL NAME: Well #6

TIER: 5
WHP RANK:
UNIQUE WELL #: 00593584

COUNTY: Chisago TOWNSHIP NUMBER: RANGE: SECTION: QUARTERS:

CRITERIA		DESCRIPTION	POINTS
Aquifer Name(s)	:	Mid.Proterozoic Sedimentary	
DNR Geologic Sensitivity Rating	:	Medium	25
L Score	:	5	
Geologic Data From	:	Well Record	
Year Constructed	:	1999	
Construction Method	:	Rotary/Drilled	0
Casing Depth	:	300	5
Well Depth	:	410	
Casing grouted into borehole?		Yes	0
Cement grout between casings?		Not applicable	0
All casings extend to land surface?		Yes	0
Gravel - packed casings?		No	0
Wood or masonry casing?		No	0
Holes or cracks in casing?		Unknown	0
Isolation distance violations?			0
Pumping Rate	:	400	5
Pathogen Detected?			0
Surface Water Characteristics?			0
Maximum nitrate detected	:	Unknown	0
Maximum tritium detected	:	Unknown	0
Non-THMS VOCs detected?			0
Pesticides detected?			0
Carbon 14 age	:	Unknown	0
Wellhead Protection Score	:		35
Wellhead Protection Vulnerability Rating	:		NOT VULNERABLE
Vulnerability Overridden	:		

COMMENTS

Appendix D

Summary of Fracture Flow Capture Zone Calculations

Well 1 (unique #217922)

Calculation for Ratio of Well Discharge to the Discharge Vector (Q/Qs)

See: Appendix 2 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

If Q/Qs is less than 3000 m then delineation Technique 2 should be used: Calculated Fixed Radius with An Upgradient Extension

Input variables		Calculated Q/Qs (m)
Well Discharge, Q (gpm)	304	5623
Aquifer Thickness, H (ft)	200	
Aquifer Hydraulic Conductivity K (m/day)	1.3	
Hydraulic Gradient, i	0.0037191	

Equation listed in Appendix 2 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

$$Q/Qs = \frac{Q\left(\frac{1\,ft^3}{7.48\,gal}\right)\left(\frac{1440\min}{1\,day}\right)\left(\frac{0.0283\,m^3}{1\,ft^3}\right)}{(H)\left(\frac{0.3048\,m}{1\,ft}\right)(K)(i)}$$

Calculation for Fixed Radius with No Upgradient Extension

See method 1 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

Input Variables		Calculated Fixed Radius (m)	Volume (m^3)
Well Pumping Rate m^3/day	1657	562	60,493,520
Pumping Period (years)	10		
Effective porosity, n	0.1		
Thickness of saturated portion of aquifer, L (m)	61.0		

$$R = \sqrt{\frac{Q}{nL\pi}}$$

Where:

Q = Well Discharge (L^3/T)=(Well pumping rate)(pumping time period)

n = effective porosity

L = thickness of saturated portion of aquifer (L)   note: lesser of open borehole or 200 ft

Well 2 (unique #112244)

Calculation for Ratio of Well Discharge to the Discharge Vector (Q/Qs)

See: Appendix 2 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

If Q/Qs is less than 3000 m then delineation Technique 2 should be used: Calculated Fixed Radius with An Upgradient Extension

Input variables	
Well Discharge, Q (gpm)	95
Aquifer Thickness, H (ft)	99
Aquifer Hydraulic Conductivity K (m/day)	1.3
Hydraulic Gradient, i	0.0037191

Calculated Q/Qs (m)
3560

Equation listed in Appendix 2 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

$$Q/Qs = \frac{Q\left(\frac{1\,ft^3}{7.48\,gal}\right)\left(\frac{1440\,\min}{1day}\right)\left(\frac{0.0283m^3}{1\,ft^3}\right)}{(H)\left(\frac{0.3048m}{1\,ft}\right)(K)(i)}$$

Calculation for Fixed Radius with No Upgradient Extension

See method 1 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

Input Variables	
Well Pumping Rate m^3/day	519
Pumping Period (years)	10
Effective porosity, n	0.1
Thickness of saturated portion of aquifer, L (m)	30.2

Calculated Fixed Radius (m)	Volume (m^3)
447	18,957,217

$$R = \sqrt{\frac{Q}{nL\pi}}$$

Where:

Q = Well Discharge (L^3/T)=(Well pumping rate)(pumping time period)

n = effective porosity

L = thickness of saturated portion of aquifer (L)   note: lesser of open borehole or 200 ft

Well 3 (unique #522767)

Calculation for Ratio of Well Discharge to the Discharge Vector (Q/Qs)

See: Appendix 2 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

If Q/Qs is less than 3000 m then delineation Technique 2 should be used: Calculated Fixed Radius with An Upgradient Extension

Input variables	
Well Discharge, Q (gpm)	246
Aquifer Thickness, H (ft)	118
Aquifer Hydraulic Conductivity K (m/day)	10.9
Hydraulic Gradient, i	0.0023265

Calculated Q/Qs (m)
1470

Equation listed in Appendix 2 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

$$Q/Qs = \frac{Q\left(\frac{1\,ft^3}{7.48\,gal}\right)\left(\frac{1440\,\text{min}}{1\,day}\right)\left(\frac{0.0283\,m^3}{1\,ft^3}\right)}{(H)\left(\frac{0.3048\,m}{1\,ft}\right)(K)(i)}$$

Calculation for Fixed Radius with No Upgradient Extension

See method 1 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

Input Variables	
Well Pumping Rate m^3/day	1340
Pumping Period (years)	5
Effective porosity, n	0.233
Thickness of saturated portion of aquifer, L (m)	36.0

Calculated Fixed Radius (m)	Volume (m^3)
305	10,499,079

$$R = \sqrt{\frac{Q}{nL\pi}}$$

Where:

Q = Well Discharge (L^3/T)=(Well pumping rate)(pumping time period)

n = effective porosity

L = thickness of saturated portion of aquifer (L)   note: lesser of open borehole or 200 ft

Well 4 (unique #706844)

Calculation for Ratio of Well Discharge to the Discharge Vector (Q/Qs)

See: Appendix 2 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

If Q/Qs is less than 3000 m then delineation Technique 2 should be used: Calculated Fixed Radius with An Upgradient Extension

Input variables	
Well Discharge, Q (gpm)	155
Aquifer Thickness, H (ft)	60
Aquifer Hydraulic Conductivity K (m/day)	10.9
Hydraulic Gradient, i	0.0023265

Calculated Q/Qs (m)
1824

Equation listed in Appendix 2 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

$$Q/Qs = \frac{Q\left(\frac{1 ft^3}{7.48 gal}\right)\left(\frac{1440 \min}{1 day}\right)\left(\frac{0.0283 m^3}{1 ft^3}\right)}{(H)\left(\frac{0.3048 m}{1 ft}\right)(K)(i)}$$

Calculation for Fixed Radius with No Upgradient Extension

See method 1 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

Input Variables	
Well Pumping Rate m^3/day	846
Pumping Period (years)	5
Effective porosity, n	0.233
Thickness of saturated portion of aquifer, L (m)	18.3

Calculated Fixed Radius (m)	Volume (m^3)
340	6,625,374

$$R = \sqrt{\frac{Q}{nL\pi}}$$

Where:

Q = Well Discharge (L^3/T)=(Well pumping rate)(pumping time period)

n = effective porosity

L = thickness of saturated portion of aquifer (L)   note: lesser of open borehole or 200 ft

Well 5 (unique #749383)

Calculation for Ratio of Well Discharge to the Discharge Vector (Q/Qs)

See: Appendix 2 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

If Q/Qs is less than 3000 m then delineation Technique 2 should be used: Calculated Fixed Radius with An Upgradient Extension

Input variables	
Well Discharge, Q (gpm)	25
Aquifer Thickness, H (ft)	138
Aquifer Hydraulic Conductivity K (m/day)	10.9
Hydraulic Gradient, i	0.0007754

Calculated Q/Qs (m)
386

Equation listed in Appendix 2 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

$$Q/Qs = \frac{Q\left(\frac{1\,ft^3}{7.48\,gal}\right)\left(\frac{1440\,\min}{1\,day}\right)\left(\frac{0.0283\,m^3}{1\,ft^3}\right)}{(H)\left(\frac{0.3048\,m}{1\,ft}\right)(K)(i)}$$

Calculation for Fixed Radius with No Upgradient Extension

See method 1 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

Input Variables	
Well Pumping Rate m^3/day	137
Pumping Period (years)	5
Effective porosity, n	0.233
Thickness of saturated portion of aquifer, L (m)	42.1

Calculated Fixed Radius (m)	Volume (m^3)
90	1,076,083

$$R = \sqrt{\frac{Q}{nL\pi}}$$

Where:

Q = Well Discharge (L^3/T)=(Well pumping rate)(pumping time period)

n = effective porosity

L = thickness of saturated portion of aquifer (L)   note: lesser of open borehole or 200 ft

Well 6 (unique #593584)

Calculation for Ratio of Well Discharge to the Discharge Vector (Q/Qs)

See: Appendix 2 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

If Q/Qs is less than 3000 m then delineation Technique 2 should be used: Calculated Fixed Radius with An Upgradient Extension

Input variables	
Well Discharge, Q (gpm)	40
Aquifer Thickness, H (ft)	110
Aquifer Hydraulic Conductivity K (m/day)	1.3
Hydraulic Gradient, i	0.0034836

Calculated Q/Qs (m)
1433

Equation listed in Appendix 2 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

$$Q/Qs = \frac{Q\left(\frac{1\,ft^3}{7.48\,gal}\right)\left(\frac{1440\min}{1day}\right)\left(\frac{0.0283m^3}{1\,ft^3}\right)}{(H)\left(\frac{0.3048m}{1\,ft}\right)(K)(i)}$$

Calculation for Fixed Radius with No Upgradient Extension

See method 1 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

Input Variables	
Well Pumping Rate m^3/day	218
Pumping Period (years)	5
Effective porosity, n	0.1
Thickness of saturated portion of aquifer, L (m)	33.5

Calculated Fixed Radius (m)	Volume (m^3)
194	3,972,162

$$R = \sqrt{\frac{Q}{nL\pi}}$$

Where:

Q = Well Discharge (L^3/T)=(Well pumping rate)(pumping time period)

n = effective porosity

L = thickness of saturated portion of aquifer (L) note: lesser of open borehole or 200 ft

Wells 1 and 2

Calculation of Revised Volume for Overlapping Capture Zones

See: Section 5, Scenario 1 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

Well	Fixed Radius (m)	Open Hole (m)	Top of open hole (ft)	Bottom of open hole (ft)	Overlap
1	562	61	263	463	-
2	447	30.2	261	360	0.979798

Well 1 volume	60533213.96	m^3
Contributing Well 2 volume	18589508.06	m^3
Total Volume	79122722.03	m^3
Revised Radius	643	m

Wells 1,2 and 6

Calculation of Revised Volume for Overlapping Capture Zones

See: Section 5, Scenario 2 of Guidance for Delineating Wellhead Protection Area in Fractured and Solution-Weathered Bedrock in Minnesota (MDH, 2005)

Well	Fixed Radius (m)	Open Hole (m)
1,2	643	61
6	194	33.5

Overlap area	113041.88	m^2
Common Open Hole Interval	33.5	m
Overlap volume	3786903	m^3
Well 1,2 volume	79122722.03	m^3
Well 6 volume	3960938.867	m^3
1,2 Overlap	3606365.784	m^3
6 Overlap	180537	m^3
Revised Well 1,2 Volume	82729087.81	m^3
Revised Well 6 Volume	4141476	m^3
Revised Well 1,2 Radius	657	m
Revised Well 6 Radius	198	m

10 Year Fixed Radius Capture Zone Up Gradient Extensions

Well 3	**522767**				
Well Location				Center of extension	
X	500198			X	499728.5
Y	5039362			Y	5039269
Length of extension (1.57 * radius of fixed radius capture zone)	478.5769999			Center of extension +10 degrees	
Flow Direction	-101.2			X	499719.5
Flow Direction + 10 degrees	-91.2			Y	5039352
Flow Direction - 10 degrees	-111.2			Center of extension - 10 degrees	
				X	499751.8
				Y	5039189

Well 4	**706844**				
Well Location				Center of extension	
X	499154			X	498631
Y	5038991			Y	5038887
Length of extension (1.57 * radius of fixed radius capture zone)	533.1467837			Center of extension +10 degrees	
Flow Direction	-101.2			X	498621
Flow Direction + 10 degrees	-91.2			Y	5038980
Flow Direction - 10 degrees	-111.2			Center of extension - 10 degrees	
				X	498656.9
				Y	5038798

10 Year Fixed Radius Capture Zone Up Gradient Extensions

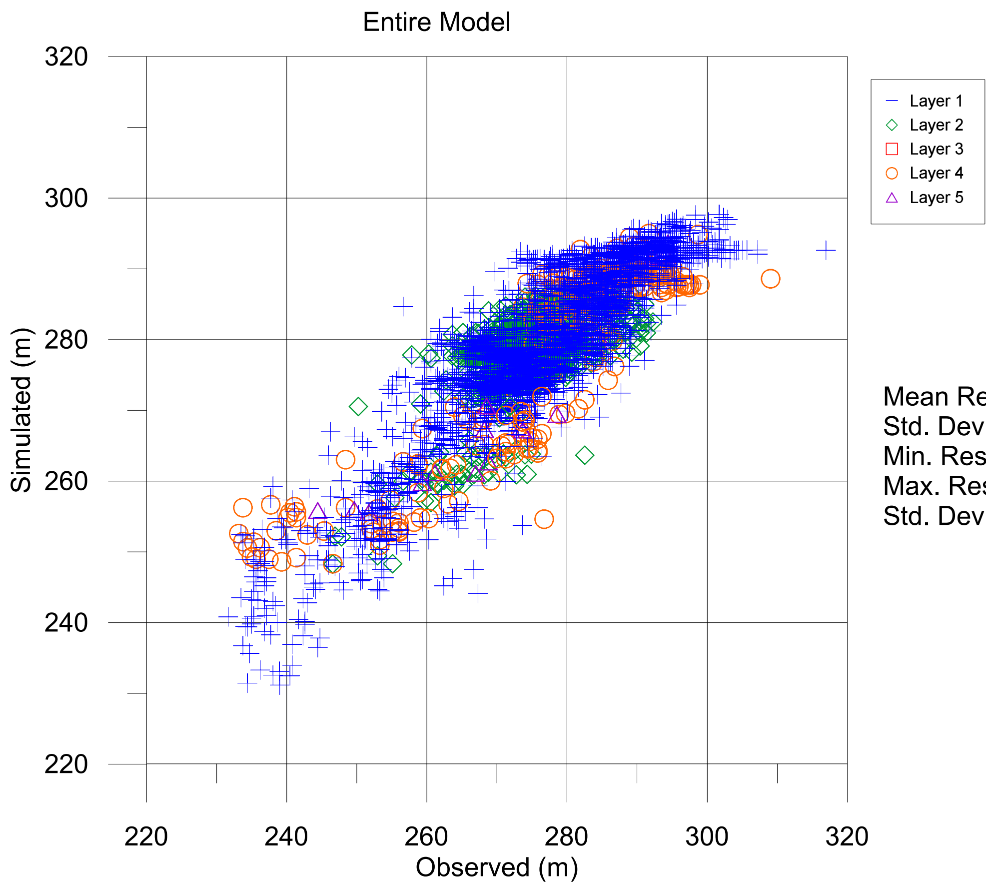
Well 5	**749383**				
Well Location				Center of extension	
X	498446			X	498308.7
Y	5039147			Y	5039112
Length of extension (1.57 * radius of fixed radius capture zone)	141.6774185			Center of extension +10 degrees	
Flow Direction	-104.2			X	498304.7
Flow Direction + 10 degrees	-94.2			Y	5039137
Flow Direction - 10 degrees	-114.2			Center of extension - 10 degrees	
				X	498316.8
				Y	5039089

Well 6	**593584**				
Well Location				Center of extension	
X	501930			X	501719.2
Y	5039325			Y	5039096
Length of extension (1.57 * radius of fixed radius capture zone)	311.4439439			Center of extension +10 degrees	
Flow Direction	-137.4			X	501682.6
Flow Direction + 10 degrees	-127.4			Y	5039136
Flow Direction - 10 degrees	-147.4			Center of extension - 10 degrees	
				X	501762.2
				Y	5039063

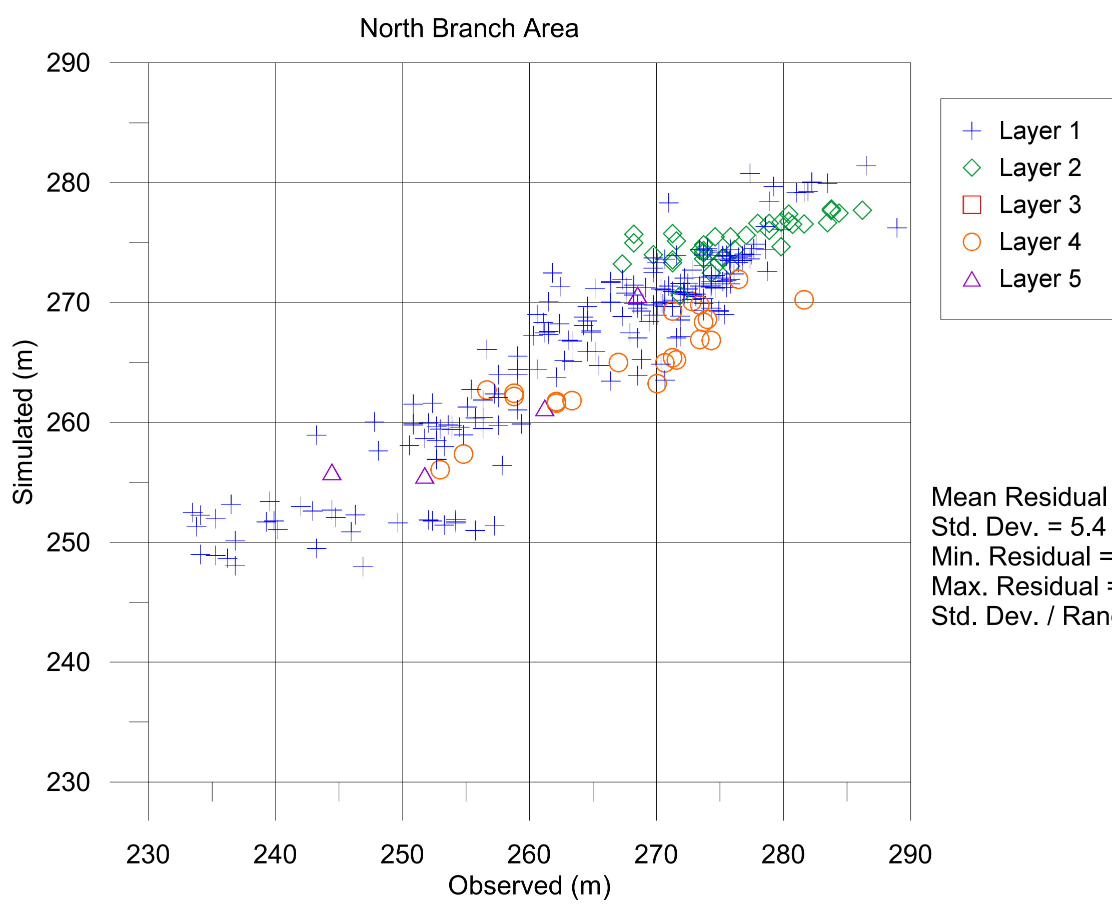
Appendix E

Groundwater Model

Figure E1
Observed vs Computed Hydraulic Head

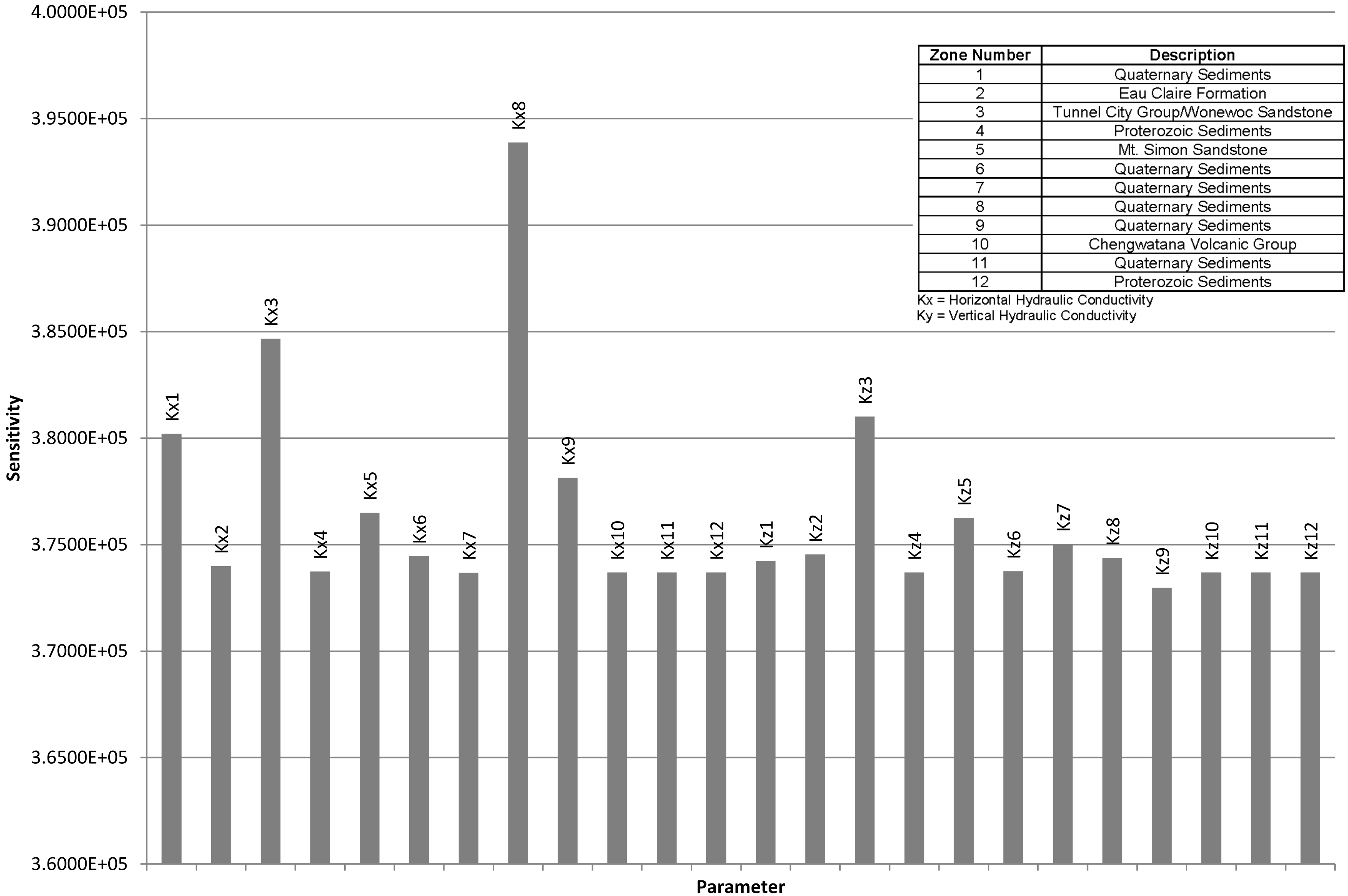


Mean Residual = -2.7 m
Std. Dev. = 5.3 m
Min. Residual = -28.0 m
Max. Residual = 24.4 m
Std. Dev. / Range = 0.1 m



Mean Residual = -1.2 m
Std. Dev. = 5.4 m
Min. Residual = -19.0 m
Max. Residual = 12.7 m
Std. Dev. / Range = 0.1 m

Figure E2
Parameter Sensitivities



Zone Number	Description
1	Quaternary Sediments
2	Eau Claire Formation
3	Tunnel City Group/Wonewoc Sandstone
4	Proterozoic Sediments
5	Mt. Simon Sandstone
6	Quaternary Sediments
7	Quaternary Sediments
8	Quaternary Sediments
9	Quaternary Sediments
10	Chengwatana Volcanic Group
11	Quaternary Sediments
12	Proterozoic Sediments

Kx = Horizontal Hydraulic Conductivity
Ky = Vertical Hydraulic Conductivity

Groundwater Modeling Evaluation of Future Wells for the North Branch Water and Light Commission

Prepared for:
WSB and Associates, Inc.

November 2005

Table of Contents

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List of Figures

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Introduction

1.1 Purpose and Scope

This report summarizes the results of a study to identify and predict the location of future water supply wells for the North Branch Water and Light Commission. Recent attempts within the City limits to install wells have been met with limited success, due mainly to the caving in of the open-hole section of the well. Previous evaluation of the geologic setting (Letter to Nancy Zeigler from Brian LeMon and John Greer, September 15, 2005) suggests that there is a Precambrian fault system underneath North Branch that uplifted the bedrock, causing significant thinning of the Mt. Simon-Hinckley aquifer and fracturing of the bedrock. That study, and supplemental work performed as part of this study, indicates that the fault system is likely underneath and parallel to Interstate 35.

This study suggests that just to the west of the City limit, the full section of the Mt. Simon-Hinckley aquifer, as well as the overlying Eau Claire Formation and the Franconia-Ironton-Galesville aquifer, should be present. The uplifted fault block (horst) is primarily east of the City's western limit. Therefore, new wells should be installed west of the City in the Mt. Simon-Hinckley aquifer and also possibly in the Franconia-Ironton-Galesville aquifer.

A regional three-dimensional groundwater flow model was developed to evaluate locations for five future wells, each pumping at 900 gallons per minute (gpm). Four to five additional wells should be able to supply future water demand. The groundwater flow model was calibrated and used to estimate the drawdown that would be caused by pumping of these wells.\

1.2 Summary of Findings

This study finds the following:

1. A new well field could be developed approximately two miles west of the City. Wells installed in the Mt. Simon-Hinckley aquifer and in the Franconia-Ironton-Galesville aquifer should be able to yield sufficient quantities of groundwater.

2. These new wells will cause regional drawdown, as expected. Some existing wells in the area might experience some drops in yield but it is likely that there would be no noticeable adverse impacts from pumping.

3. The fault system does not appear to adversely affect well yields, provided that the wells are installed sufficiently west of the City to encounter the Franconia-Ironton-Galesville aquifer and the full section of the Mt. Simon-Hinckley aquifer. While two miles west of the City limits should be sufficient, test drilling and pumping tests should be performed to verify this conclusion.

2 Groundwater Flow Model Development

2.1 What is a Groundwater Flow Model?

A groundwater flow model is a computer program that simulates the important conditions that control groundwater levels, flow to wells, and the interactions between geology and surface-water features. The computer program uses well-established mathematical equations that describe how water flows in aquifers and aquitards. The program is tailored to a particular area's geology and hydrology and is, most importantly, formulated to answer very specific problems.

For this study, the groundwater flow code MODFLOW was used (McDonald and Harbaugh, 1988). MODFLOW was developed by the U.S. Geological Survey and is the most widely used groundwater modeling code in the world. MODFLOW employs a finite-difference method of solving the differential equations that describe groundwater flow. It is capable of simulating three-dimensional flow in aquifers and aquitard, both in steady-state and transient modes.

Graphical user interfaces (GUIs) are almost always used with groundwater flow models. GUIs greatly assist in designing the model, entering the data, and post-processing the results. For this study, the GUI Groundwater Vistas, version 4 (ESI, 2004) was used.

2.2 Overview of Steps to Building and Using the Groundwater Flow Model

The groundwater flow model for this study was developed in the following steps:

1. The hydrogeology and data availability of the area was evaluated and summarized (Letter to Nancy Zeigler from Brian LeMon and John Greer, September 15, 2005). The most salient feature in the study area is fault block (horst) underneath the City of North Branch that has lifted up the Franconia-Ironton-Galesville aquifer and the Mt. Simon-Hinckley aquifer and subsequently eroded these units away (or thinned them considerably).

2. The problems that require a groundwater flow model were determined. In this case, the problem at hand is to determine where wells can be installed to the west of the City of North Branch in order to maximize well yields and meet future water demands.

3. A conceptual model of groundwater flow was developed. The conceptual model is a schematic representation of the major aquifers, aquitards, water sources, and water sinks in the area. The conceptual model is the basis for the computer model of groundwater flow.

4. The computer model was built using the following information:

    a. Elevations of the base of key hydrostratigraphic units from the Minnesota Geological Survey's County Well Index (CWI);

    b. Surface-water features, including lake stage elevation;

    c. Higher capacity wells (i.e. wells with groundwater appropriations permits), with pumping rates assigned on the basis of 2004 annual averages; and

    d. Geophysical data on the locations of fault zones.

5. The computer model is put through an exhaustive calibration procedure to "ground truth" the model and prepare it for predictive simulations. The calibration process involves automatically adjusting model parameters (e.g., aquifer and aquitard hydraulic conductivity and recharge from infiltrating precipitation) with expected ranges until the difference between groundwater levels measured in wells (from CWI) and the computer's simulation of groundwater levels is minimized in a least-squares sense. In other words, the calibration process ensures that the model is capable of reasonably reproducing current groundwater flow conditions.

The calibrated groundwater flow model becomes a tool for predicting the effects of future wells. The model can be used to predict the amount of drawdown induced by a given pumping rate for future well locations and thereby make some conclusions about well interference effects, potential yields, and optimal spacing between future wells. Thus, the groundwater flow model becomes the design tool for a new well field.

2.3 Conceptual Hydrogeologic Model

The conceptual hydrogeologic model defines the major aquifers, aquitards, geologic structures, and water sources/sinks that are important to the location *and* the problem for which the model is being developed. The conceptual model establishes how geologic units interact with hydrologic features to control the direction and rate of groundwater flow. The conceptual model also forms the basis for how aquifers and aquitards are represented in the computer model (i.e. how geologic units are lumped together or split apart for the purposes of the computer simulation.

2.3.1 Statement of Problem Evaluated

Different conceptual models may be necessary for a particular location, depending upon the nature of the problem(s) that the computer model is intended to evaluate. Once built, a compute model may be able to solve other problems for which it was not originally designed but often a new model with a different conceptual model may be necessary.

The problem for which this model was developed is stated as follows:

> *Locations for new public water supply wells for the North Branch Water and Light Commission will be evaluated with the model. The area of focus is immediately west of the City and west of a known fault zone. The primary aquifer of interest is the Mt. Simon-Hinckley aquifer. An aquifer of secondary interest is the Franconia-Ironton-Galesville (FIG) aquifer. The following questions may need addressing:*

1. *How close to the fault zone can a well be located before boundary effects impinge upon the well's yield?*
2. *What are reasonable expectations for well yield?*
3. *If wells are located to meet expected future demands, where should those wells be located (in particular, how far apart should these wells be located to minimize well interference effects)?*
4. *How much will groundwater levels be lowered in the area and what existing wells in the area might be affected by pumping of new municipal water supply wells?*

2.3.2 Geologic Conditions, Aquifers, and Aquitards

2.3.2.1 Geologic History

North Branch is located in the northern part of a geologic feature called the *Hollandale Embayment* – a large bay in an ancient shallow sea were sediment was deposited as the seas waxed and waned to form what is now most of the major bedrock geologic units in eastern Minnesota. Before the deposition of what is now the Mt. Simon Sandstone, there was structural uplifting of Precambrian rocks that formed an uplifted block (called a "horst") that trends north-south. The western edge of this horst corresponds approximately with Interstate 35. Subsequent tectonic activities formed a structural basin (the Twin Cities basin), centered under what is now Minneapolis and St. Paul. Bedrock units generally dip southward toward the center of the Twin Cities basin. There may have been some reactivation of the Precambrian faults after deposition of younger rocks (Morey, 1972).

During the Quaternary (about the last two-million years), glacial advances eroded away higher relief bedrock units and deposited a mixture of glacially derived tills and outwash over the landscape. The combination of depositional history, structural faulting, and glaciation has resulted in the current geologic setting. Major bedrock aquifer units, such as the Prairie du Chien-Jordan aquifer, are not present in the North Branch area, due to these processes. The Franconia-Ironton-Galesville aquifer is present to west of North Branch but underneath North Branch (where the underlying horst feature is present), the uppermost bedrock unit is the Mt. Simon Sandstone (and the upper portion of this unit has also been eroded).

2.3.2.2 Regional Bedrock Geology

A definitive published map of the uppermost bedrock in the North Branch area and surrounding region is not available. County Well Index data were evaluated to identify the uppermost bedrock unit in wells in the region. Differentiation between units, especially with respect to Mt. Simon Sandstone, Hinckley Formation, and Fond du Lac Formation is difficult in some locations, based on the drilling logs. An interpretation of the approximate extent of uppermost bedrock units is shown on Figure 1. Also shown on this figure is the approximate location of the horst, as interpreted from the Minnesota Geological Survey's aeromagnetic survey results (included as part of Letter to Nancy Zeigler from Brian LeMon and John Greer, September 15, 2005). The depth to bedrock is greatest in the vicinity of the horst feature underneath North Branch. The interpreted depth to bedrock, based on CWI data, is shown on Figure 2.

2.3.2.3 Hydrostratigraphy

Hydrostratigraphy refers to the geologic units that make up aquifers and aquitards. Aquifers transmit usable quantities of water, whereas aquitards do not. Aquitards typically separate one aquifer from another and are sometimes referred to as "confining beds".

Hydrostratigraphic units that are considered as part of the groundwater model in the evaluation of water supplies for North Branch include:

Geologic Unit	Hydrostratigraphic Unit	Comments
Quaternary glacial sediments	Surficial Aquifer	Locally variable; susceptible to contamination
Franconia Formation	Franconia-Ironton-Galesville (FIG) Aquifer	May have yields high enough for public water supplies
Ironton & Galesville Sandstones		
Eau Claire Formation	Eau Claire Aquitard	Significant regional aquitard
Mt. Simon and Hinckley Sandstones	Mt. Simon-Hinckley Aquifer	Moderately high yields where full section is present; may have high total dissolved solids
Fond du Lac Formation	Fond du Lac Aquifer	Moderate to poor yield; high total dissolved solids

2.3.2.4 Recharge and Discharge of Groundwater

The primary mechanisms of recharge to the aquifer system in the region is infiltrating precipitation that moves below the root zone of plants and migrates downward by gravity to the water table. Recharge rates in east-central Minnesota are typically in the range of less than 1 inch per year to over 12 inches per year. A secondary source of recharge is seepage through the bottoms of lakes, wetlands, and some streams.

Most groundwater flows southeast and east toward the St. Croix River, which is a regional discharge zone. Secondary discharge zones includes smaller streams, some lakes and wetlands, evapotranspiration from plants, and wells.

2.3.2.5 Direction of Groundwater Flow

Regional groundwater flow is to the east and south, toward the St. Croix River. Differing directions of flow can be expected for the shallow aquifer (surficial deposits) near lakes and streams. Near high capacity wells, groundwater flow is typically toward the wells.

2.3.3 Summary of Conceptual Hydrogeologic Model

The conceptual hydrogeologic model of groundwater flow in the region is depicted schematically in the cross section on Figure 2. The conceptual model consists of five hydrostratigraphic units (surficial aquifer; Franconia-Ironton-Galesville aquifer; Eau Claire aquitard; Mt. Simon-Hinckley aquifer; and Fond du Lac aquifer).

2.4 Groundwater Flow Model Construction

2.4.1 Model Domain and Horizontal Discretization

The domain (extent) of the groundwater flow model is shown on Figure 4. Also shown on Figure 4 is the finite-difference grid. The domain was selected to encompass an area sufficiently large enough to include the major hydraulic sources and sinks. The western boundary of the model represents the approximate western extent of the Mt. Simon-Hinckley aquifer. The eastern edge extends to the St. Croix River.

The model is approximately 94 km x 67 km. There are 103 rows and 148 columns, with 60,800 active grid cells. The maximum grid cell size is 1 km x 1 km (for far-field areas where model accuracy is not as important). The grid is refined in areas west of North Branch, were predictive simulations of future wells are performed. Grid cells in this area are a maximum of 250 m x 250 m, and are refined much smaller around hypothetical wells for predictive simulations.

2.4.2 Vertical Discretization

The model is divided into five computation layers. Layer 1 represents the glacial drift aquifer. Layer 2 is generally the Franconia-Ironton-Galesville aquifer. Layer 3 is generally the Eau Claire aquitard. Layer 4 is the Mt. Simon-Hinckley aquifer and Layer 5 is the Fond du Lac aquifer. Along the periphery of the model domain and where the Franconia-Ironton-Galesville aquifer and/or the Eau Claire aquitard are not present, Layers 2 and 3 also can represent portions of the Mt. Simon-Hinckley aquifer.

2.4.3 Layer Geometry and Base Elevations

Base elevations for the various layers were assigned using well log information in the County Well Index. These data were geostatistically assigned to grid cells in the model domain for the various layers. Cross sections through the model are shown on Figure 5, depicting the vertical discetization and the variation in model layers across the model domain. In the vicinity of North Branch, where faulting of the horst has increased the relative elevation of bedrock units, the model’s base is substantially higher and layers are thinner.

2.4.4 Hydraulic Conductivity Zonation

There is almost no regional data on hydraulic conductivity (permeability) values for the bedrock units in the model domain. Information from the Twin Cities area provides some guidance. The approach used in this study was to determine the aquifer parameter values through an *inverse optimization method* in the calibration process. This process lends itself to dividing up the model layers into zones where hydraulic conductivity values are likely to be similar. For example, in Layer 2, there are zones to delineate where the Franconia Ironton-Galesville is present, zones for where the Eau Claire Formation is present, and zones for glacial drift. Examples of zonation are shown on Figure 6. Each zone has both a horizontal and a vertical hydraulic conductivity value.

2.4.5 Faults

The fault system that is associated with the horst feature is represent in two ways: by varying the base elevation of the bottom of the Fond du Lac Formation and by including *horizontal wall* features that have lower values of hydraulic conductivity. The horizontal wall features hinder groundwater flow across the fault zone. They are included in all five layers of the model, at the location shown on Figure 7.

2.4.6 Lakes and Rivers

Major lakes and rivers are represented in the model using constant head cells, for which the average lake stage is assigned (in meters above mean sea level). Average lake stages were obtained from the Minnesota Department of Natural Resources Lakefinder web site. All lakes are in Layer 1, except portions of the St. Croix River, which are in both Layers 1 and 2.

2.4.7 Recharge

Recharge is applied to Layer 1. Recharge represents the average annual rate of water that infiltrates through the ground and reaches the water table. Recharge is divided into zones in the model for calibration. Recharge zones are shown on Figure 8. Recharge zones correspond approximately to hydraulic conductivity zones in Layer 1.

2.4.8 Wells

High capacity pumping wells are included in the model if they are listed in the Minnesota Department of Natural Resources SWUDS data base for 2004. These are wells that have groundwater appropriations permits. There are 84 pumping wells in the model. Pumping rates assigned to the wells are the average annual rates for 2004, converted to cubic meters per day. Depending on the length of the well screen or open-hole interval, wells may penetrate multiple layers. Wells in the model are shown on Figure 9.

2.5 Model Calibration

2.5.1 Overview of Calibration Process

Model calibration is the process of varying aquifer parameters (e.g., hydraulic conductivity, recharge) within expected ranges of values until an acceptable match is obtained between observed groundwater levels in wells and simulated groundwater levels. The observed water levels are called calibration “targets”. The difference between the observed data and the simulated data is called a “residual”. The objective of calibration is to minimize the residual.

It is impossible to perfectly match every observation. The objective of calibration is to obtain a minimum residual for all of the calibration targets. The “objective function”, as it is called, is to minimize the sum of the squares of all residuals. Residuals are squared to normalize values that would otherwise be either negative residuals or positive residuals.

An automated calibration method was used in this study. This process is called “automated inverse optimization” and involves the use of another program, called PEST (Watermark Computing, 1994). PEST numerically solves for the derivative of the objective function, thereby obtaining the minimum. The types of parameters, the parameter zones, and the permissible upper and lower limits of the parameter values are set prior to the optimization process. PEST then runs the groundwater model several hundred times until the objective function is minimized.

2.5.2 Calibration Targets

In this study, 5,258 calibration targets, representing groundwater elevation data from wells in all layers were used, with the exception of Layer 3 (Eau Claire aquitard), which does not have wells completed in it. The calibration targets themselves have associated measurement errors. The calibration targets used in this study were obtained from the static water elevations listed in the County Well Index. The sources of error in these data include the following:

- Error in measurement by the driller at time that the well was drilled;
- Seasonal variations, depending on when the well was drilled;

- Year-to-year variations, depending on when the well was drilled;
- Error in estimating the ground surface elevation of the well;
- Error in assigning the well to the correct hydrostratigraphic unit;
- Errors caused by local pumping conditions not included in the model.

Despite these errors, CWI calibration data has proven to be very useful. The shear size of the data set (over 5,000 targets) negates many of the errors.

A weighting process was used to assign more emphasis on certain target values than others. Most of the targets in the model domain are shallow wells in the glacial drift aquifer. This aquifer is of less importance to the objectives of this study than bedrock aquifers. Therefore, during the calibration/optimization process, twice the weight was assigned to bedrock targets than glacial dirft aquifer targets.

2.5.3 Calibration Results

A plot of the observed and simulated observations is shown on Figure 10. The residual mean is -3.22 meters. The residual standard deviation divided by the range in head over the model domain is 0.063. Values less than 0.1 are indicative of a good calibration. An example of the calibrated model's simulated potentiometric head is shown on Figure 11 for Layer 4 (Mt. Simon-Hinckley aquifer). As seen in Figure 11, the area of the horst is a location where aquifer transmissivities decrease and hydraulic head gradient increases. This trend in groundwater levels is similar in all five layers.

2.5.4 Sensitivity and Uncertainty

The model's results are most sensitive to values of recharge, as shown on Figure 12. This is typical, because recharge is the primary source of water to the groundwater flow system. Recharge Zone 1, which is recharge to areas where the Mt. Simon-Hinckley aquifer subcrops beneath glacial drift, is the most sensitive parameter.

It is important to recognize that the calibrated model represents one possible representation of the conceptual flow system – there may be others that are equally plausible. As such, there is inherent uncertainty in the model's conceptualization, parameter values, and predictive results.

3 Predictive Simulations of Future Well Locations

3.1 Design Considerations

For the purpose of evaluating future well locations with the groundwater flow model, it was assumed that the City of North Branch will need a total of approximately 4,500 gallons per minute (gpm) firm capacity 18 years from present (2024). This 900 gpm higher than the estimated 3,600 gpm needed but provides for some additional capacity, beyond the estimated future needs. The predictive simulations assume that this demand will be met by 5 wells, each pumping at 900 gpm. These five wells would be located in an area west of the City limits and west of the area where faulting is believed to be prevalent. It was also assumed that the five wells would be serviced by a single raw water main connecting the wells to treatment within the City limits.

The length of raw water main could be a limiting factor (e.g., cost, accessibility, etc.). The alternative well locations that are evaluated in this section attempt to balance the length of raw water main with the need to keep separation of wells in order to minimize well interference effects.

Alternative results are presented in the form of maps of drawdown (lowering of pressure head in the aquifer) within the Mt. Simon-Hinckley aquifer, the Franconia-Ironton-Galesville aquifer, and the water table (glacial drift or surficial aquifer). It is important to recognize that some drawdown does take place in adjoining aquifers that are not being directly pumped, due to induced leakage through separating aquitards. The drawdown maps provide a relative comparison between alternatives, based on how much drawdown is induced – particularly near the wells. Greater amounts of drawdown increase the likelihood of greater well interference effects and less individual well capacity.

It is also important to recognize that well efficiency is not considered in the modeling results – wells are assumed to be 100% efficient. Wells that are not 100% efficient will have addition drawdowns within the well (but not within the aquifer adjacent to the well) that can further reduce the total available well yield. In general, a well is at least 90% efficient if the drawdown in the well is no greater than 1/3 of the total available drawdown in a well (provided the well is properly designed, constructed, developed, and maintained).

3.2 Well Location Alternative Evaluation

3.2.1 Well Alternative 1

Well Alternative 1 includes five wells completed in the Mt. Simon-Hinckley aquifer, each pumping at an average rate of 900 gpm. Spacing between wells is approximately 2,300 to 2,800 feet. The wells are located along existing roads and the spacing of the wells is staggered. The distance from the City limits to the farthest well (via roads) is about 2 miles.

Well locations and the predicted drawdown (feet) in the Mt. Simon-Hinckley aquifer, the Franconia-Ironton-Galesville aquifer, and the water-table (surficial) aquifer caused by continuous, steady-state pumping of the wells are shown on Figures 13, 14, and 15.

Drawdown in the wells (assuming 100% efficiency) is about 70 feet. The resulting cone of depression in the Mt. Simon-Hinckley aquifer extends radially for about 10 miles. The cones of depression in the overlying Franconia-Ironton-Galesville and water-table aquifers are much less extensive, with maximum drawdown near the wells of about 10 feet.

3.2.2 Well Alternative 2

Well Alternative 2 includes five wells completed in the Mt. Simon-Hinckley aquifer, each pumping at an average rate of 900 gpm. Spacing between wells is approximately 1,200 feet. The wells are located along an existing north-south township road. The distance from the City limits to the line of wells is slightly farther than 1 mile.

Well locations and the predicted drawdown (feet) in the Mt. Simon-Hinckley aquifer, the Franconia-Ironton-Galesville aquifer, and the water-table (surficial) aquifer caused by continuous, steady-state pumping of the wells are shown on Figures 16, 17, and 18.

Drawdown in the wells (assuming 100% efficiency) is about 80 to 90 feet. The resulting cone of depression in the Mt. Simon-Hinckley aquifer extends radially for about 10 miles. The cones of depression in the overlying Franconia-Ironton-Galesville and water-table aquifers are much less extensive, with maximum drawdown near the wells of about 10 feet.

3.2.3 Well Alternative 3

Well Alternative 3 includes three wells completed in the Mt. Simon-Hinckley aquifer and two wells completed in the Franconia-Ironton-Galesville aquifer, each pumping at an average rate of 900 gpm.

Spacing between wells is approximately 1,200 feet and the locations are identical to Well Alternative 2.. The wells are located along an existing north-south township road. The distance from the City limits to the line of wells is slightly farther than 1 mile.

Well locations and the predicted drawdown (feet) in the Mt. Simon-Hinckley aquifer, the Franconia-Ironton-Galesville aquifer, and the water-table (surficial) aquifer caused by continuous, steady-state pumping of the wells are shown on Figures 19, 20, and 21.

Drawdown in the three Mt. Simon-Hinckley wells (assuming 100% efficiency) is about 45 to 50 feet. Drawdown in the two Franconia-Ironton-Galesville wells (assuming 100% efficiency) is about 20 feet. The resulting cone of depression in the Mt. Simon-Hinckley aquifer extends radially for about 10 miles. The cone of depression in the overlying Franconia-Ironton-Galesville aquifer extends about 6 miles and the cone of depression in water-table aquifer extends about 2 to 3 miles from the wells.

3.3 Discussion of Well Alternatives

3.3.1 Well Capacity and Drawdown at the Wells

All three well alternatives appear to be viable – i.e., all three alternatives can supply 4,500 gpm without excessive drawdown at the wells that would substantially affect well capacity. The predicted drawdowns at the wells are not below the top of the pumped aquifer(s). From a well capacity point of view, any of the three alternatives appear to be viable.

Other configurations of wells would likely work equally well. However, an important consideration must always be well spacing. <u>Wells should be spaced at least 1,200 feet apart to prevent excessive drawdown at the wells.</u>

3.3.2 Regional Drawdown Effects

The model predicts that there will be widespread drawdown in the Mt. Simon-Hinckley aquifer. However, the pre-pumping potentiometric head in the Mt. Simon-Hinckley aquifer is about 300 feet above the top of the aquifer. Thus, there should not be any issues of interference with other wells in the area that are completed in the Mt. Simon-Hinckley aquifer, unless the pump setting of a particular well is too high (in which case, the pump can be lowered by adding more drop pipe).

For Alternatives 1 and 2, the model predicts that drawdowns in the Franconia-Ironton-Galesville aquifer and the surficial aquifer will be no more than 5 to 10 feet. Again, unless a pump is set in an existing well at a very shallow depth, this drawdown should not result in any noticeable loss in a well's capacity. It may be necessary, as part of the Appropriations Permit approval process, to tabulate wells in the area and identify any wells that might be susceptible to drawdown effects.

For Alternative 3, drawdown in the Franconia-Ironton-Galesville aquifer is predicted to be about 10 to 20 feet. Again, this will likely not cause capacity issues unless a well's pump is set very shallow in an existing well.

3.2.3 Effect of Nearby Fault System

The fault system, which is located approximately parallel to Interstate 35, was modeled in such a manner that its effects would be conservative – i.e., it would error on the side of causing more drawdown, rather than less. The modeling indicated that for the three alternatives, the fault has little impact on drawdown and capacity.

As new wells are located, it will be important to identify locations that are a distance sufficiently west of the fault system that wells are not installed in the fault (which can cause failing of open holes and reduced yields). The three alternatives likely are located in an area where the Franconia-Ironton-Galesville aquifer and the Eau Claire Formation are present above the full thickness of Mt. Simon-Hinckley aquifer. Caving or other hole failures should not be a problem at these locations, but test drilling will be required to verify that the Franconia-Ironton-Galesville aquifer is present. If, during drilling of a well, the Franconia-Ironton-Galesville units are not encountered, that location should be abandoned and another location (likely farther to the west) should be selected.

4 Considerations for Future Well Siting

4.1 Test Drilling and Test Wells

The groundwater modeling presented in this report suggests that groundwater supplies are plentiful in areas to the west of North Branch but the model relies on imperfect information in that area. As new wells are contemplated, test drilling and test wells should be installed. The test well should verify:

1. The presence (and thickness) of the Franconia-Ironton-Galesville aquifer. If this unit is thin (or absent) in a test hole, there is a high likelihood that the location is not west of the fracture zone.

2. Aquifer parameters and predictions of drawdown. The groundwater model relies on information from regional information and the calibration process and as such, has uncertainty associated with predictions of yield and drawdown. A pumping test should be performed on a new test well and drawdowns should be monitored in piezometers (monitoring wells) installed in both the Mt. Simon-Hinckley aquifer and the Franconia-Ironton-Galesville aquifer. A pumping test would likely involve continuous pumping of a test well for 96 hours and monitoring of changes in water levels in the piezometers. Transmissivity values can be calculated from the pumping test results and if necessary, the model can be updated to evaluate the well yields.

Test wells can be installed in a such a manner that they can be converted to production wells at a later date. It is likely that the information from one test well can be applicable to the entire well field.

4.2 Appropriations Permits

An application for an appropriations permit from the Department of Natural Resources will likely require some provision for aquifer testing. The DNR will also be interested in the effects of drawdown on nearby wells. This model (perhaps with adjustments after a pumping test) would be a good tool for addressing those types of issues. DNR staff have looked for and accepted this type of modeling result in other permit applications.

4.3 Wellhead Protection Area Delineation

Preliminary wellhead protection areas (WHPAs) will need to be delineated well when a new well is installed. Final WHPAs will need to be delineated using time-of-travel criteria. Typically, a groundwater flow model is used. The model constructed for this study could be used for delineating WHPAs for future wells and for the City's existing wells.

References

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Morey, G.B., 1972. Petrology of Keweenawan sandstones in the subsurface of southeastern Minnesota in Geology of Minnesota: A Centennial Volume, Sims and Morey, eds., p. 436-449.

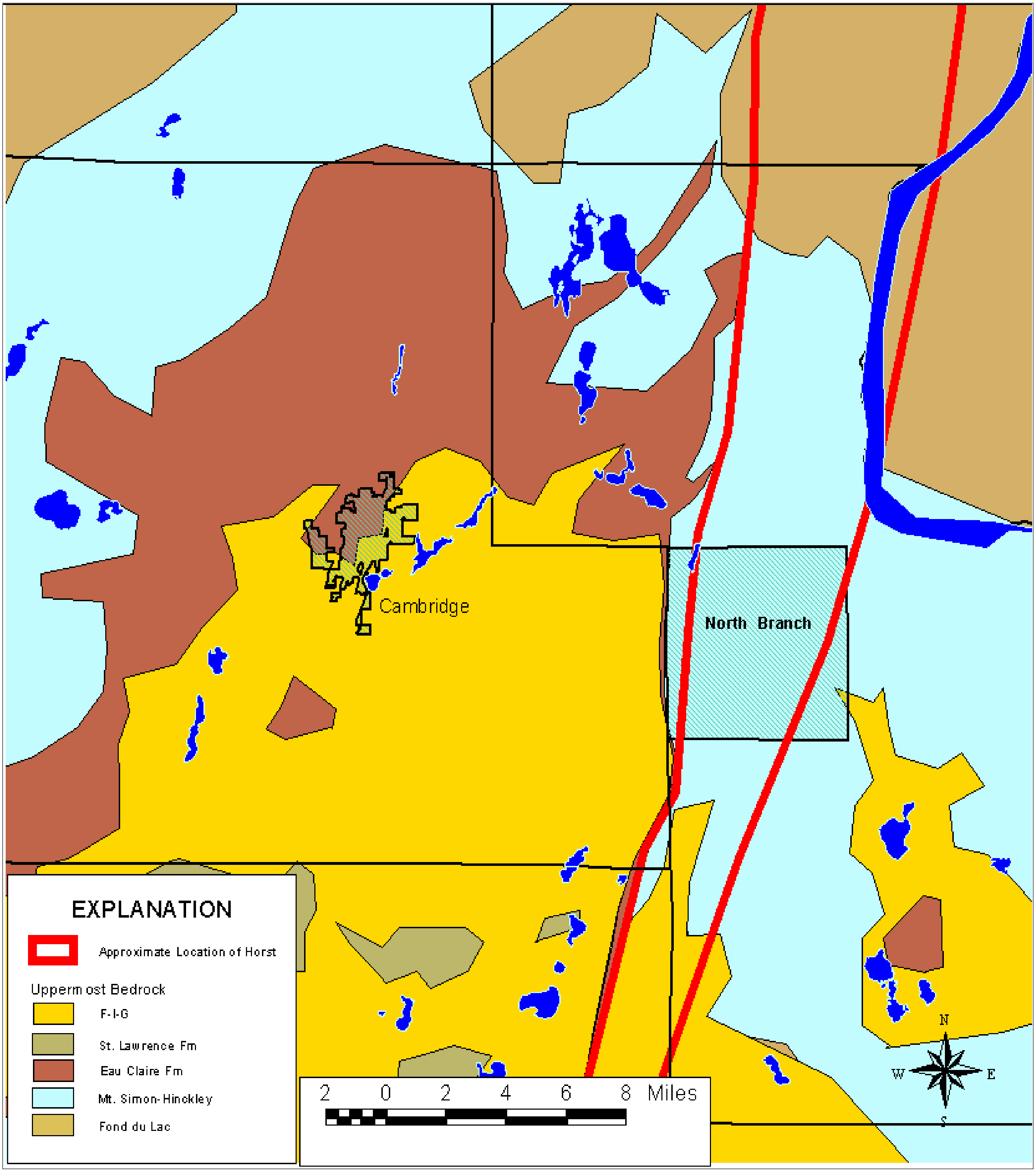


Figure 1

Uppermost Bedrock Interpreted from County Well Index Data

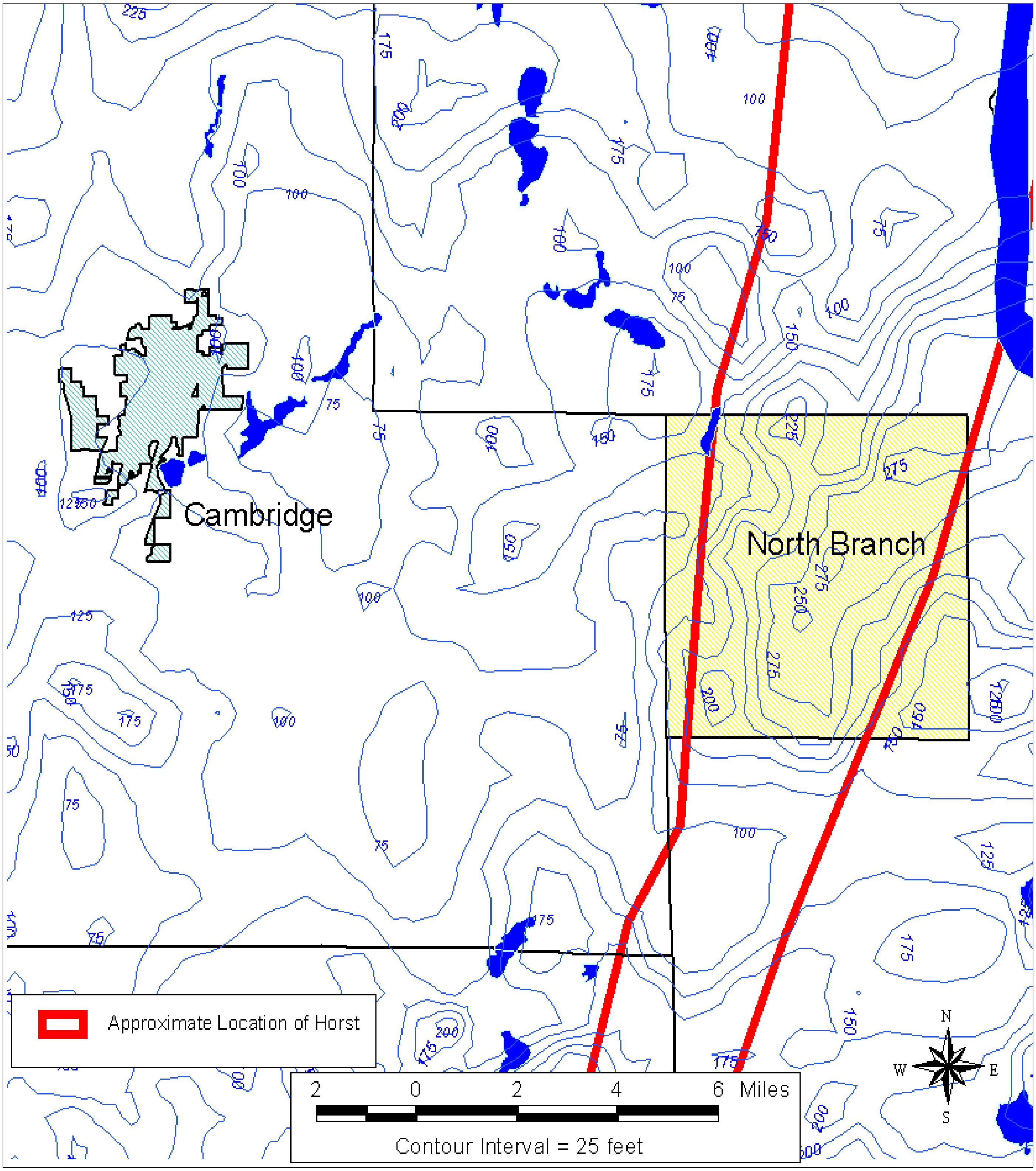


Figure 2

Approximate Depth to Bedrock (feet)

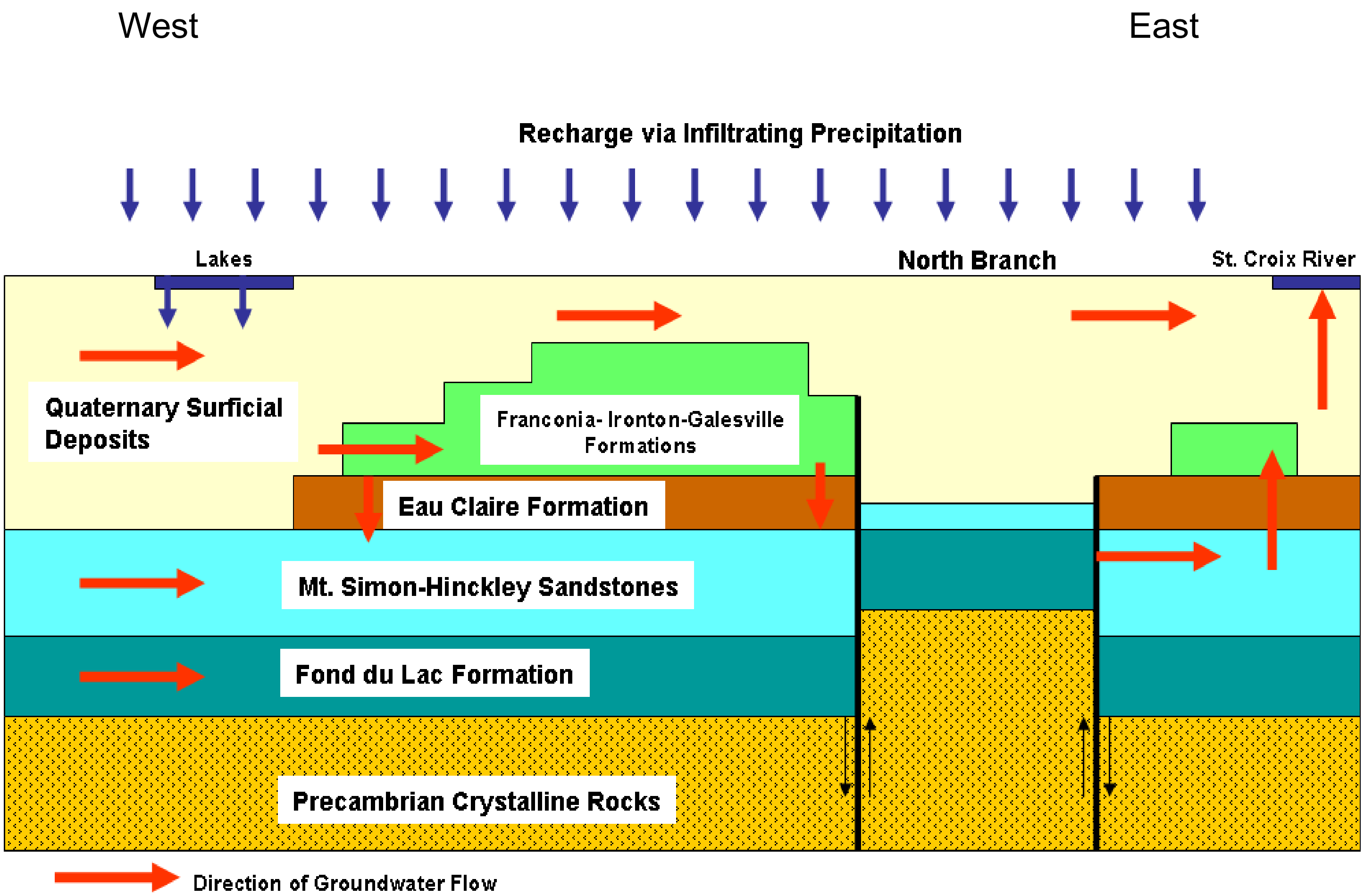


Figure 3

Conceptual Model of Groundwater Flow

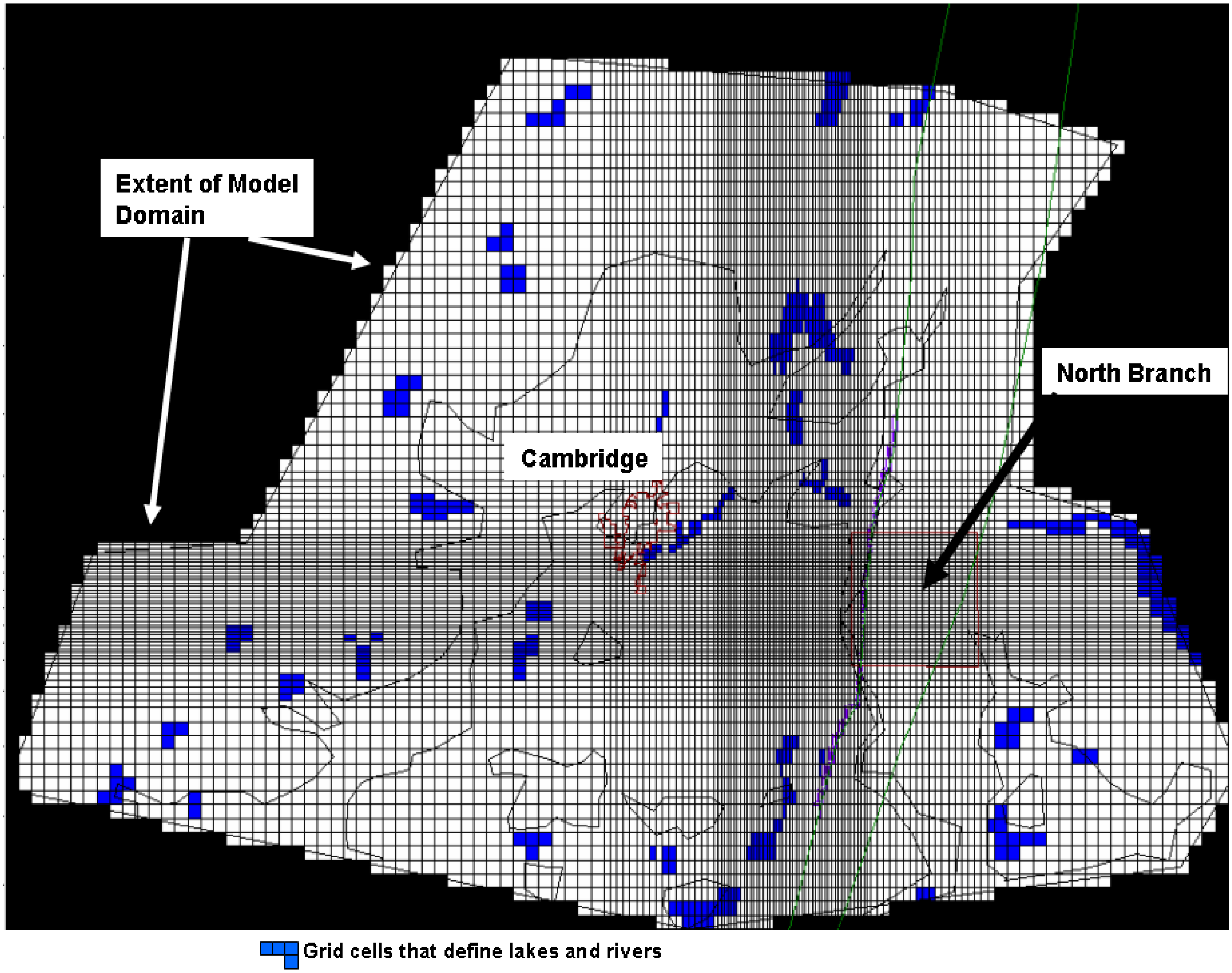


Figure 4

Model Domain and Horizontal Grid Discretization

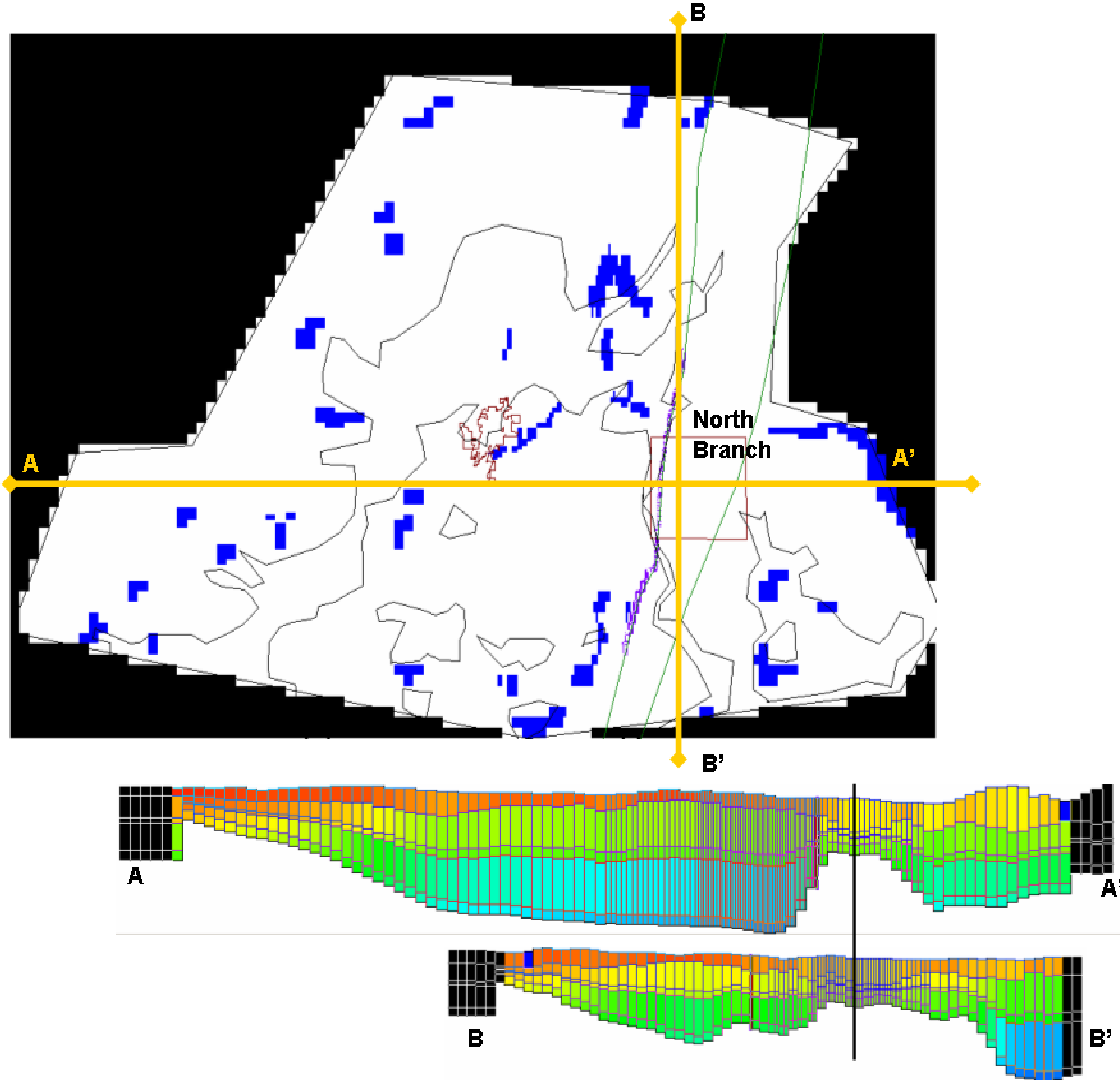
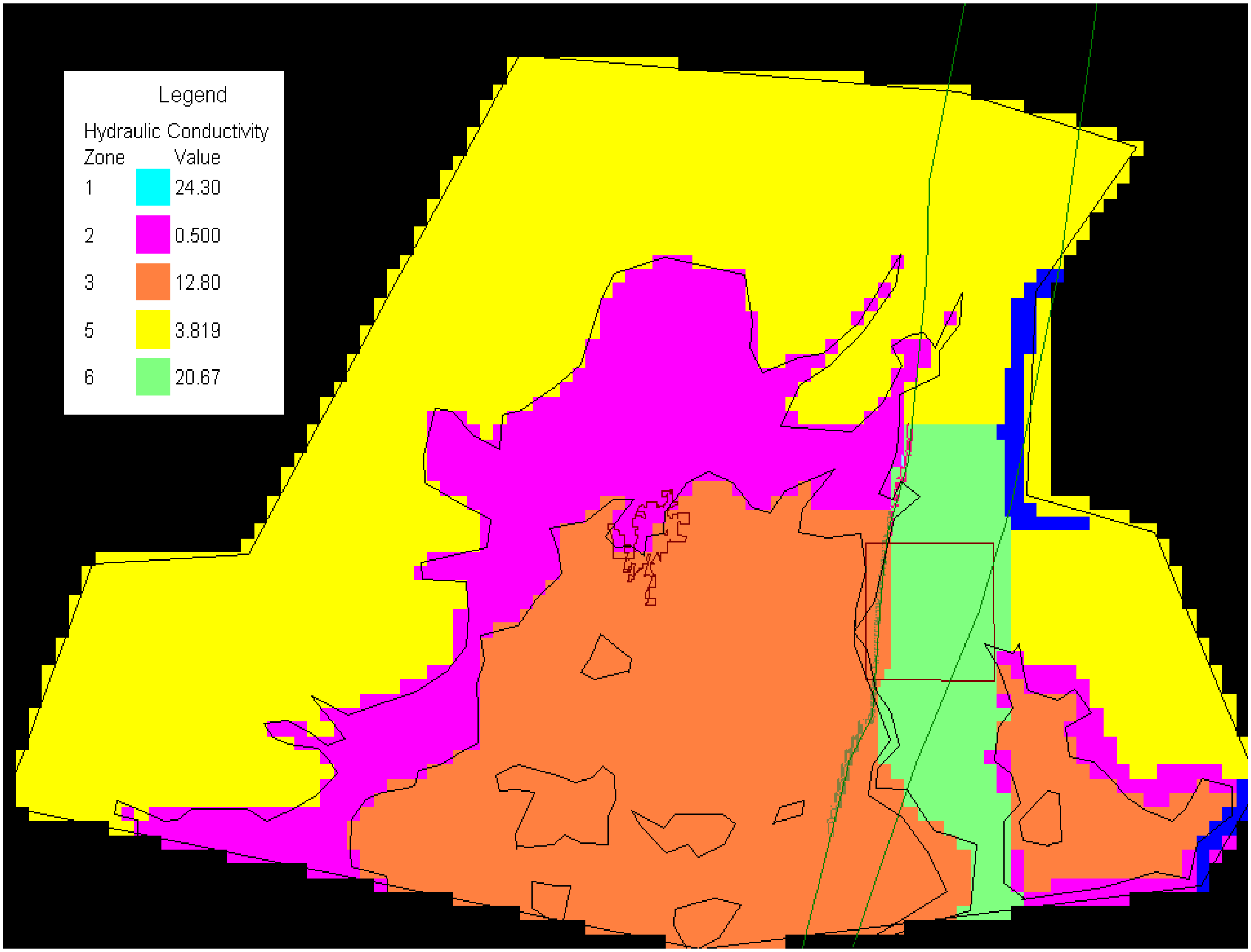


Figure 5

Cross Sections Through Model Depicting Vertical Discretization



Layer 2

Figure 6

Example of Zonation for Hydraulic Conductivity

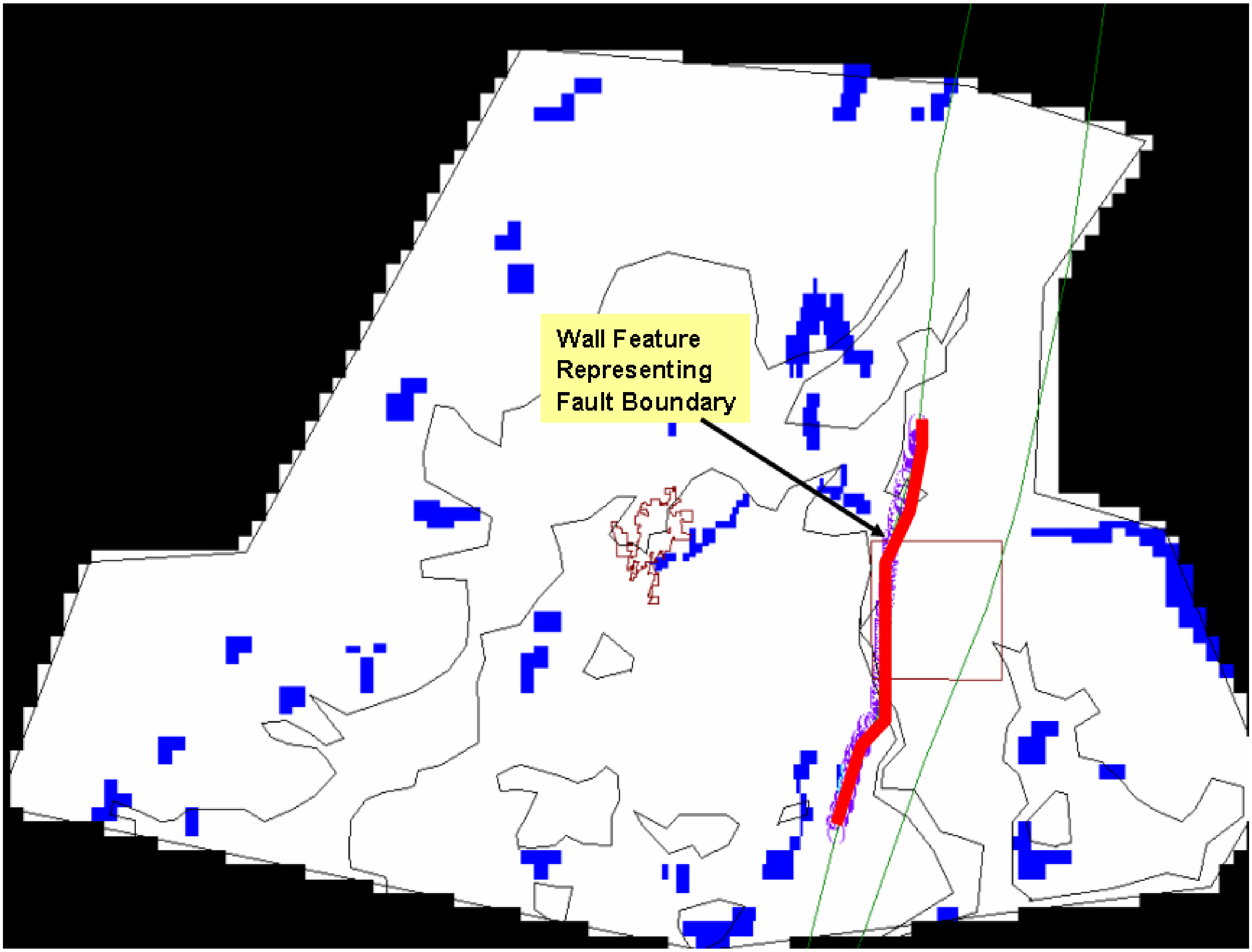


Figure 7

Wall Feature, Representing Fault Boundary

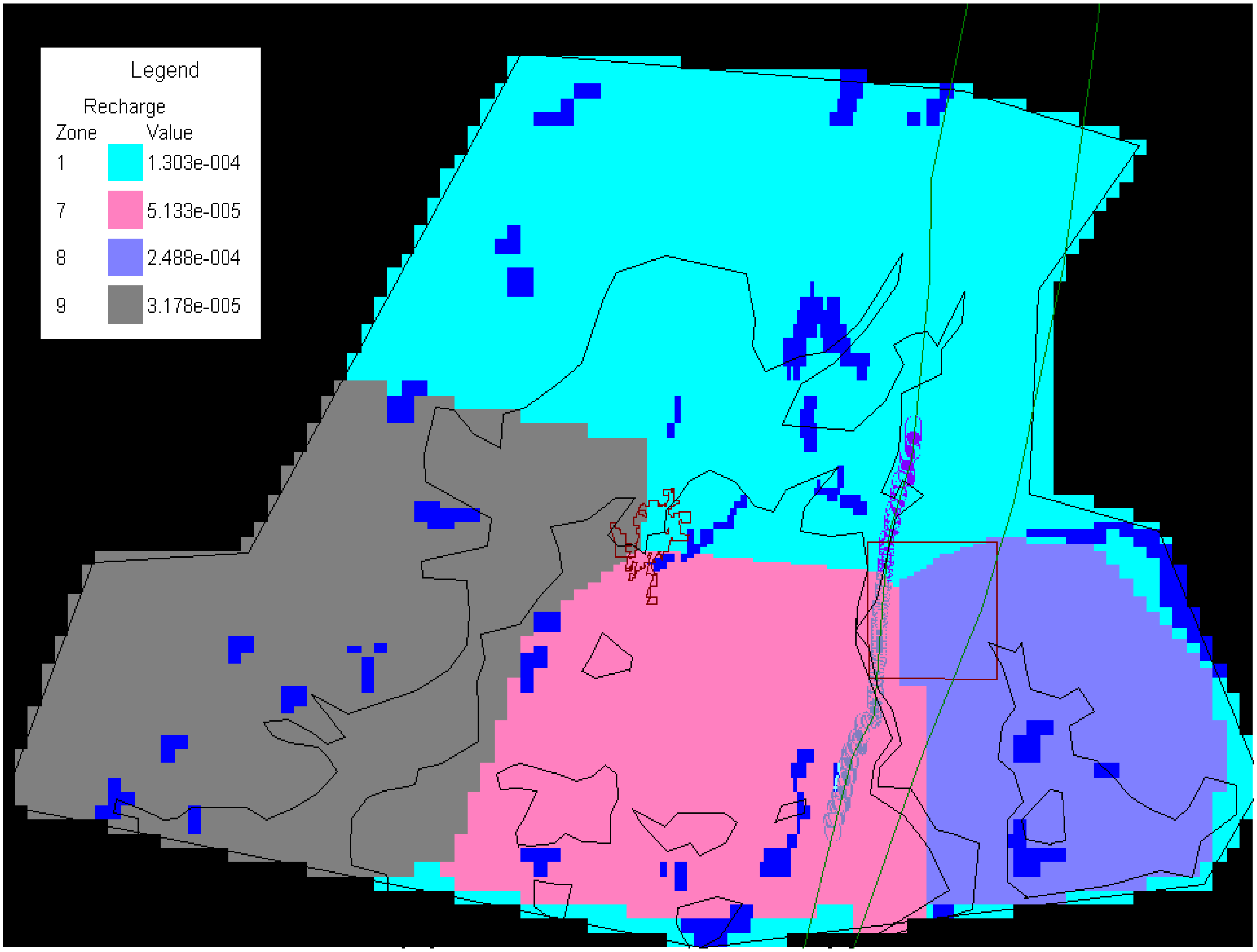
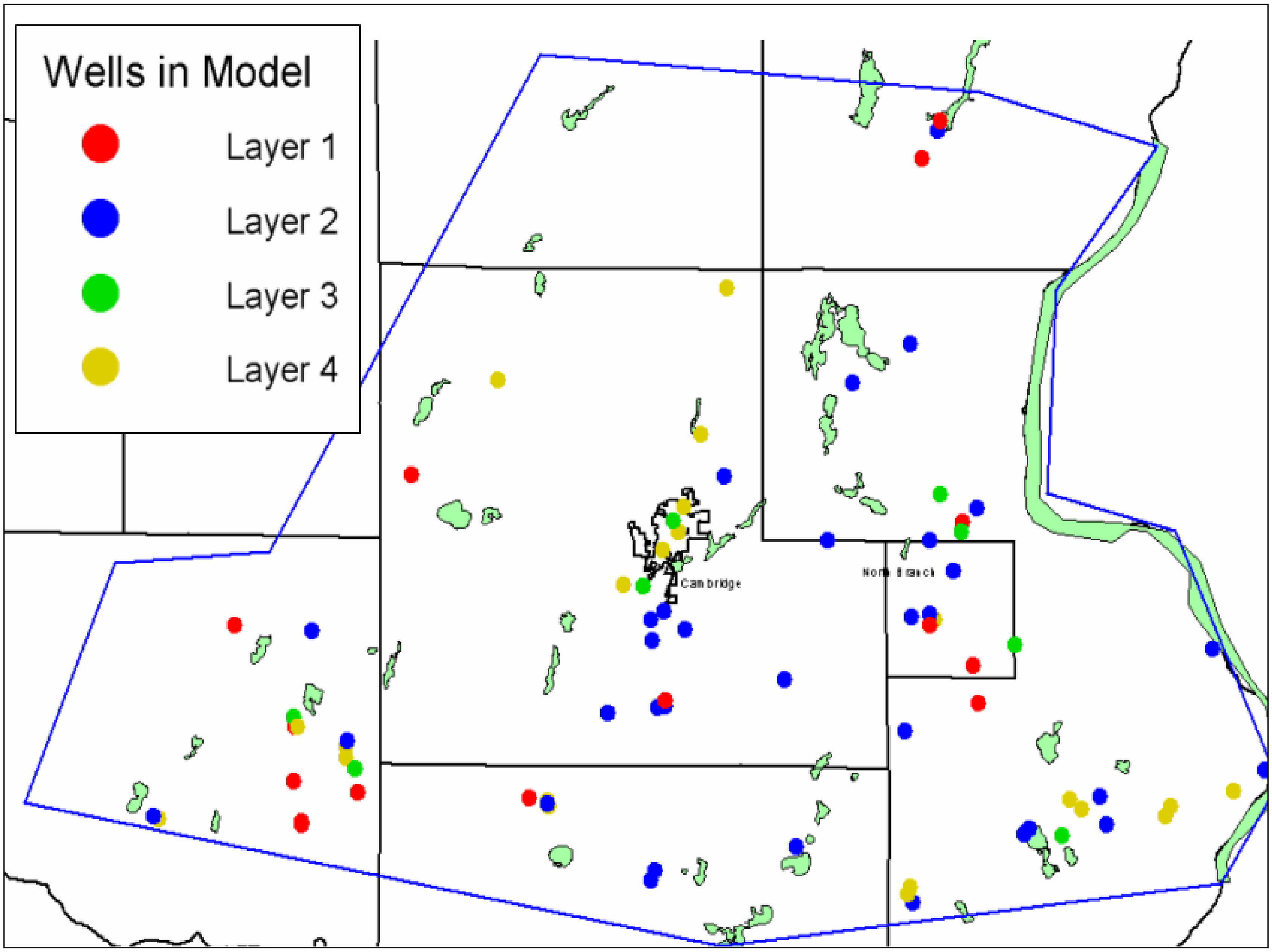


Figure 8

Recharge Zones in the Model



Note: Many wells penetrate multiple layers

Figure 9

Wells in Model

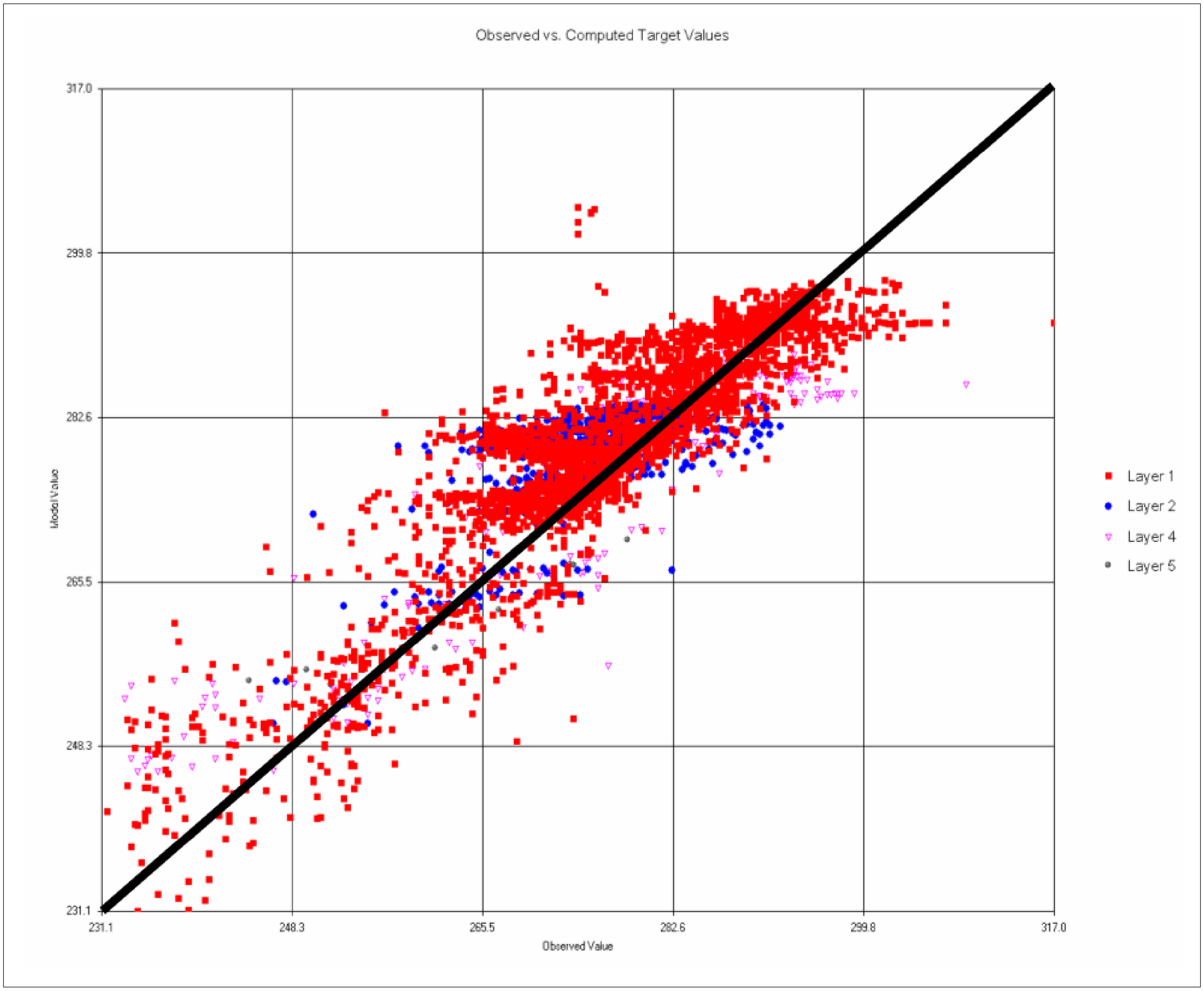
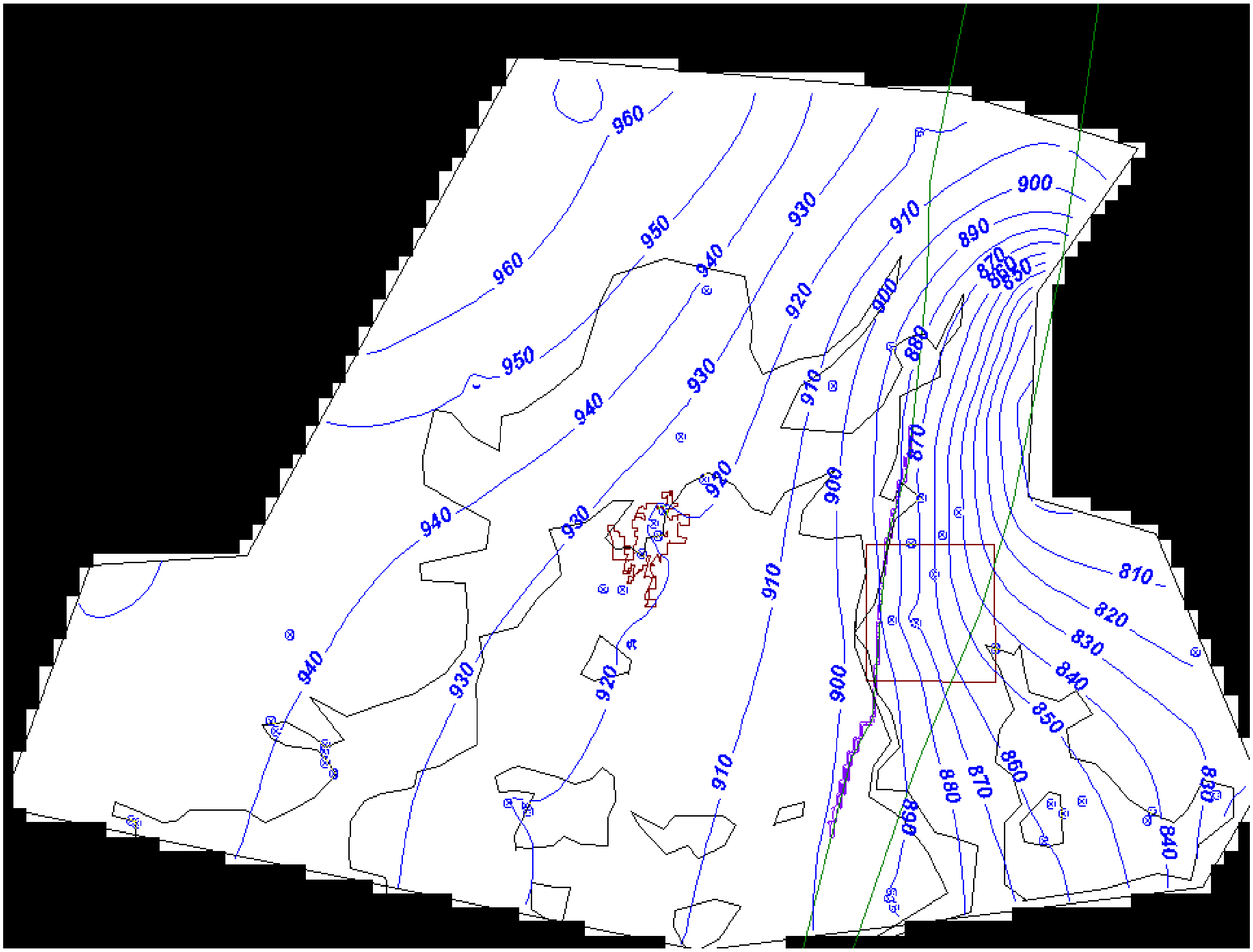


Figure 10

Plot of Observed and Simulated Observations



Contour Interval = 10 feet

Figure 11

Contours of Simulated Potentiometric Head (feet, above mean sea level)for Layer 4 (Mt. Simon-Hinckley Aquifer)

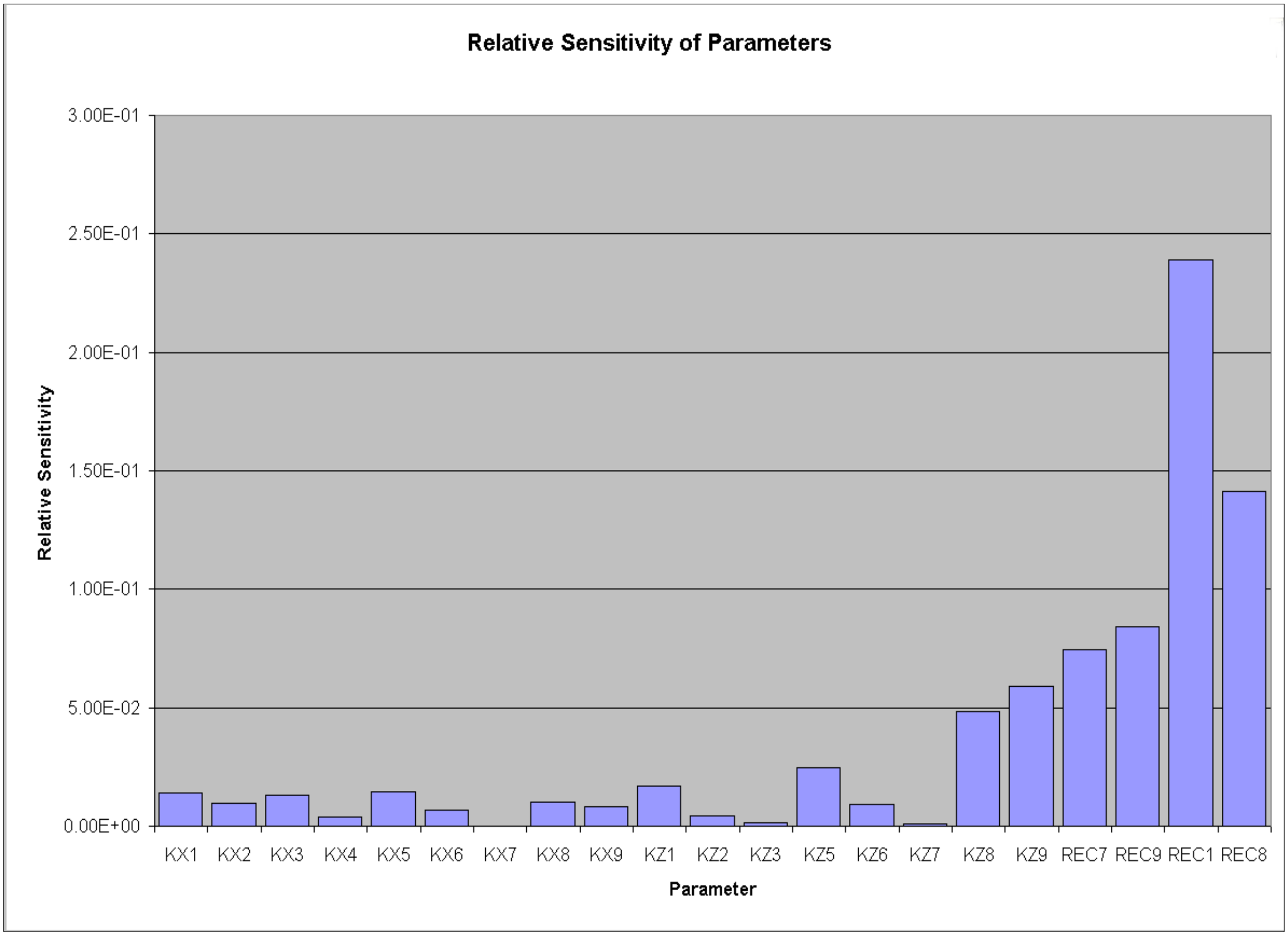


Figure 12

Relative Sensitivity of Model Calibration to Parameters

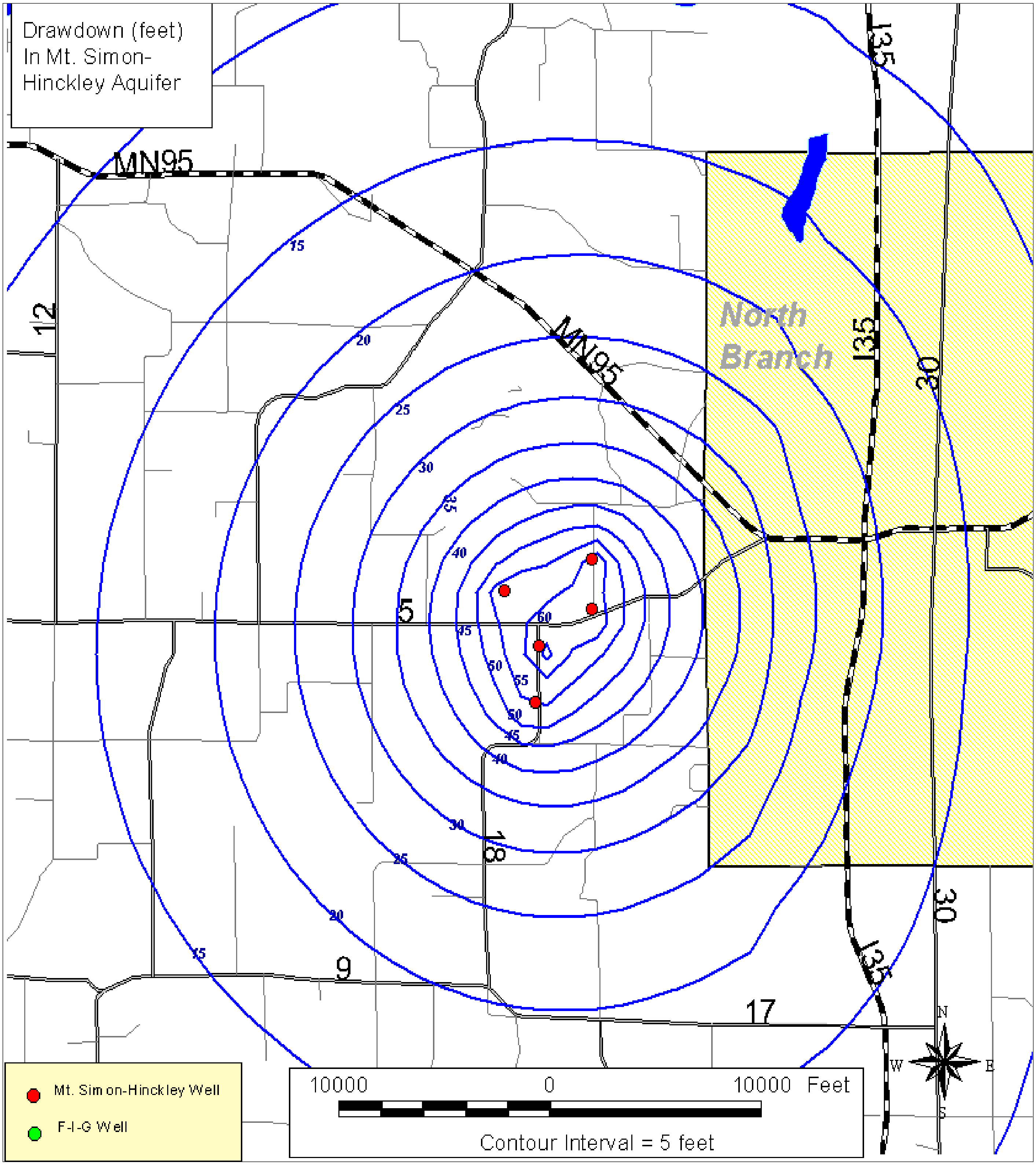


Figure 13

Well Alternative 1: Predicted Drawdown (feet) in Mt. Simon-Hinckley Aquifer

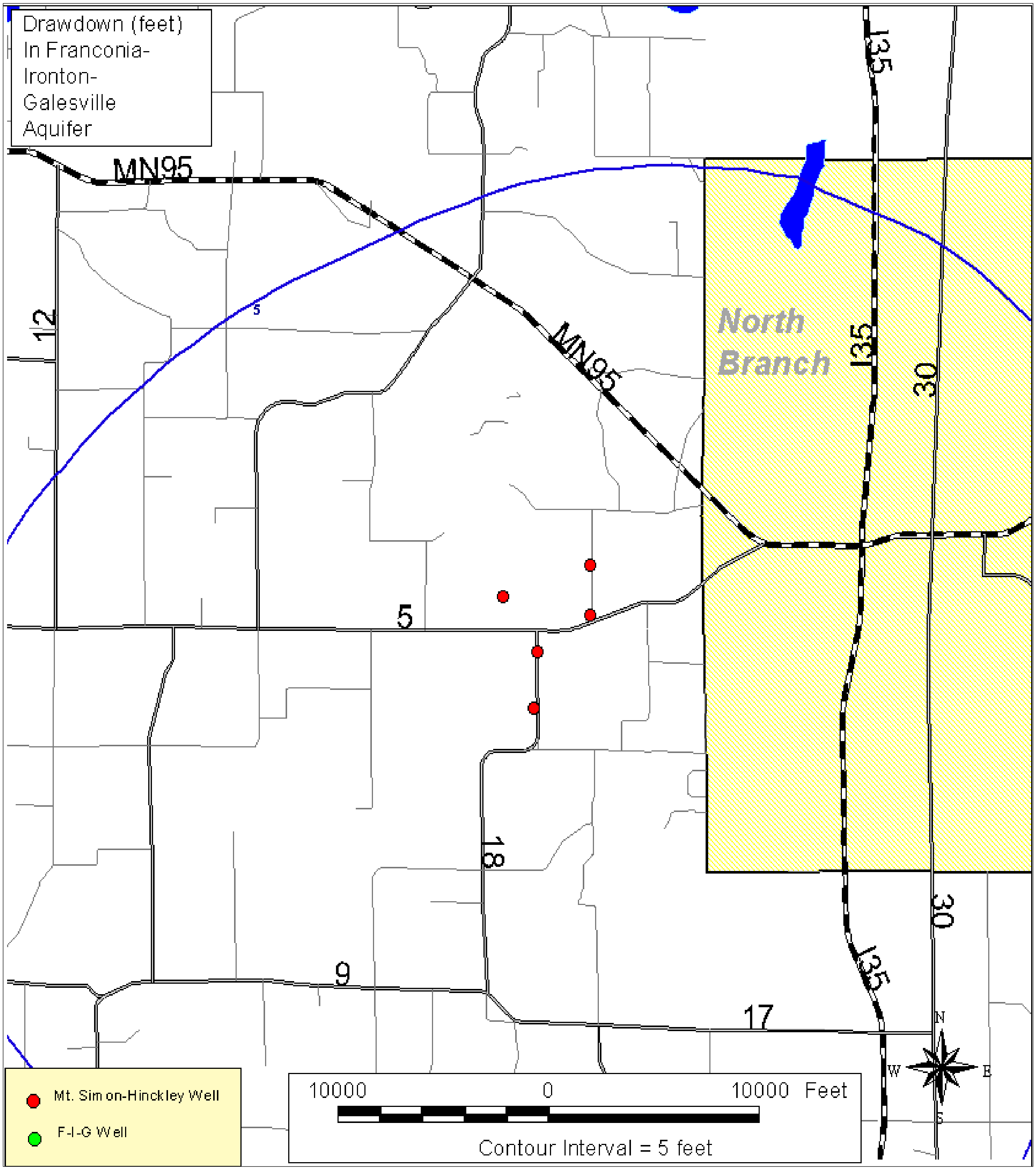


Figure 14

Well Alternative 1: Predicted Drawdown (feet) in Franconia-Ironton-Galesville Aquifer

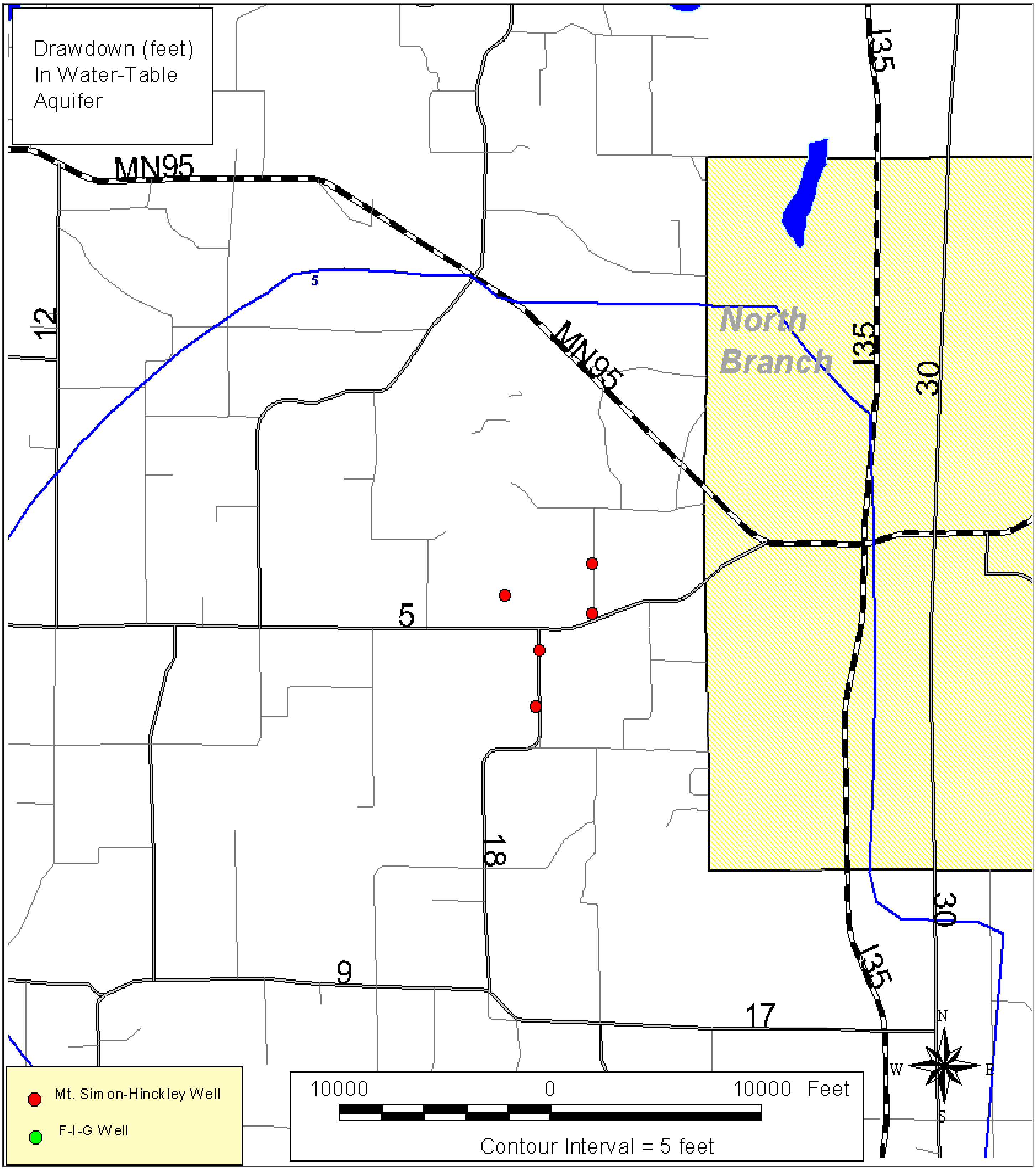


Figure 15

Well Alternative 1: Predicted Drawdown (feet) in Water-Table Aquifer

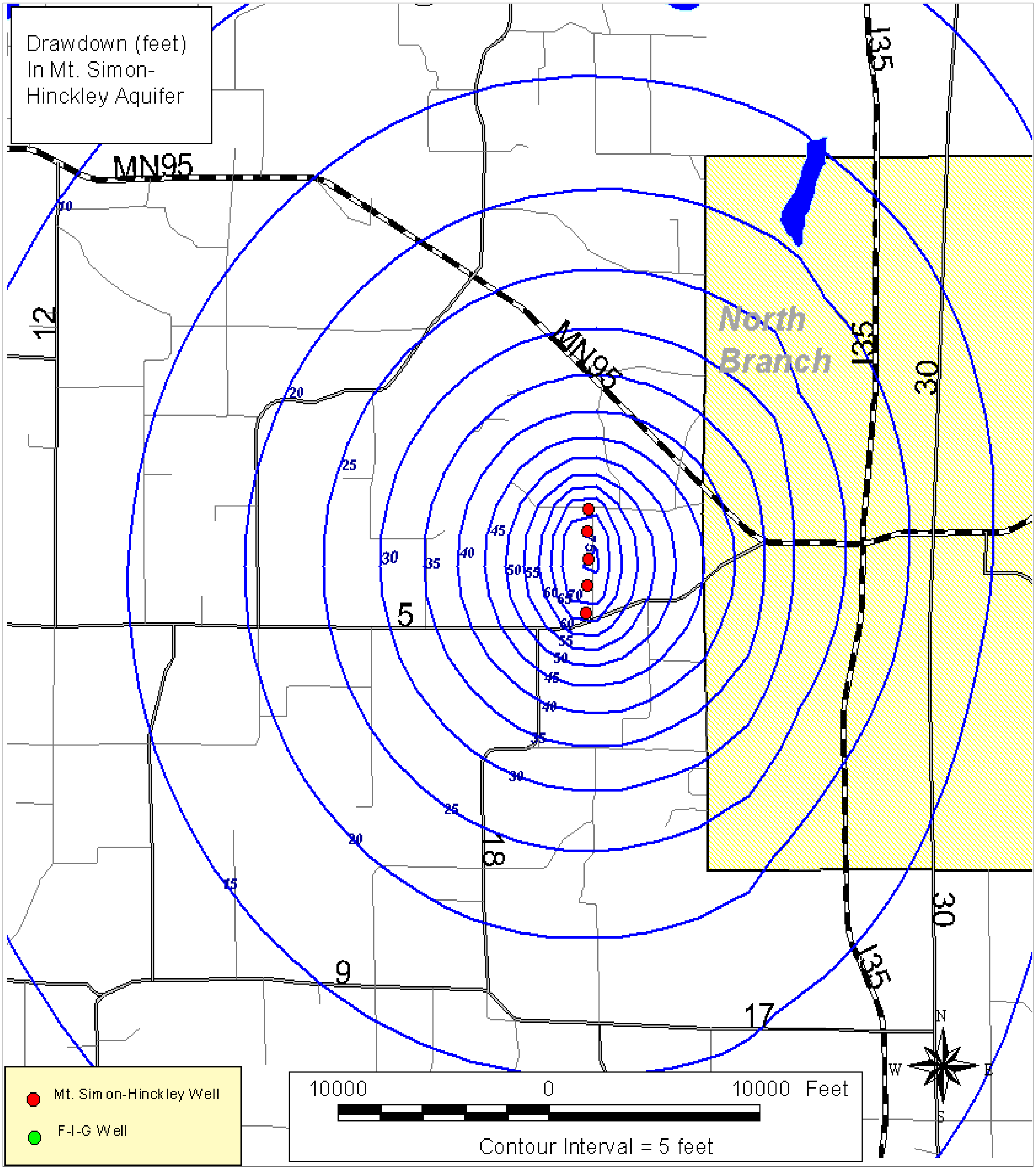


Figure 16

Well Alternative 2: Predicted Drawdown (feet) in Mt. Simon-Hinckley Aquifer

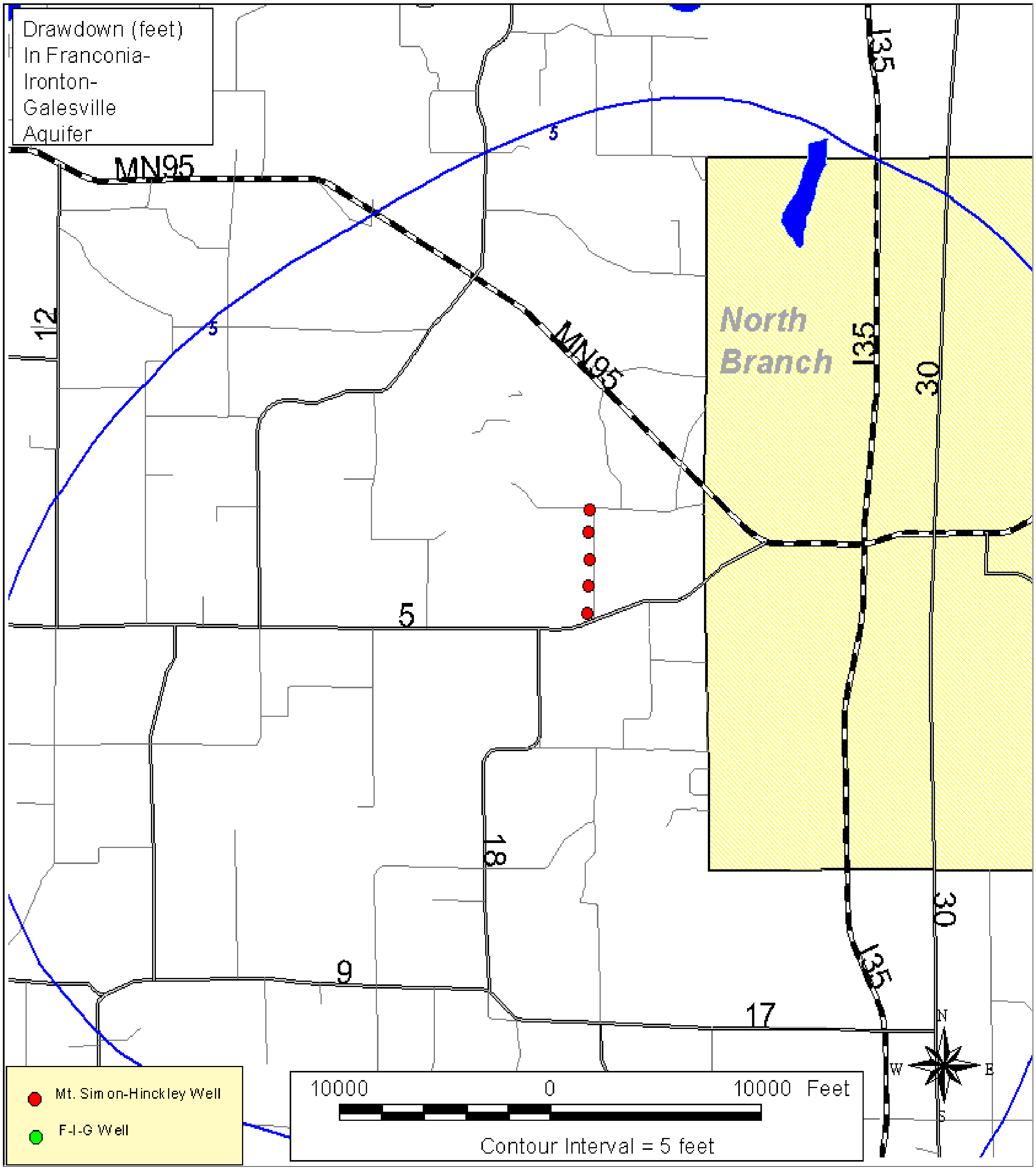


Figure 17

Well Alternative 2: Predicted Drawdown (feet) in Franconia-Ironton-Galesville Aquifer

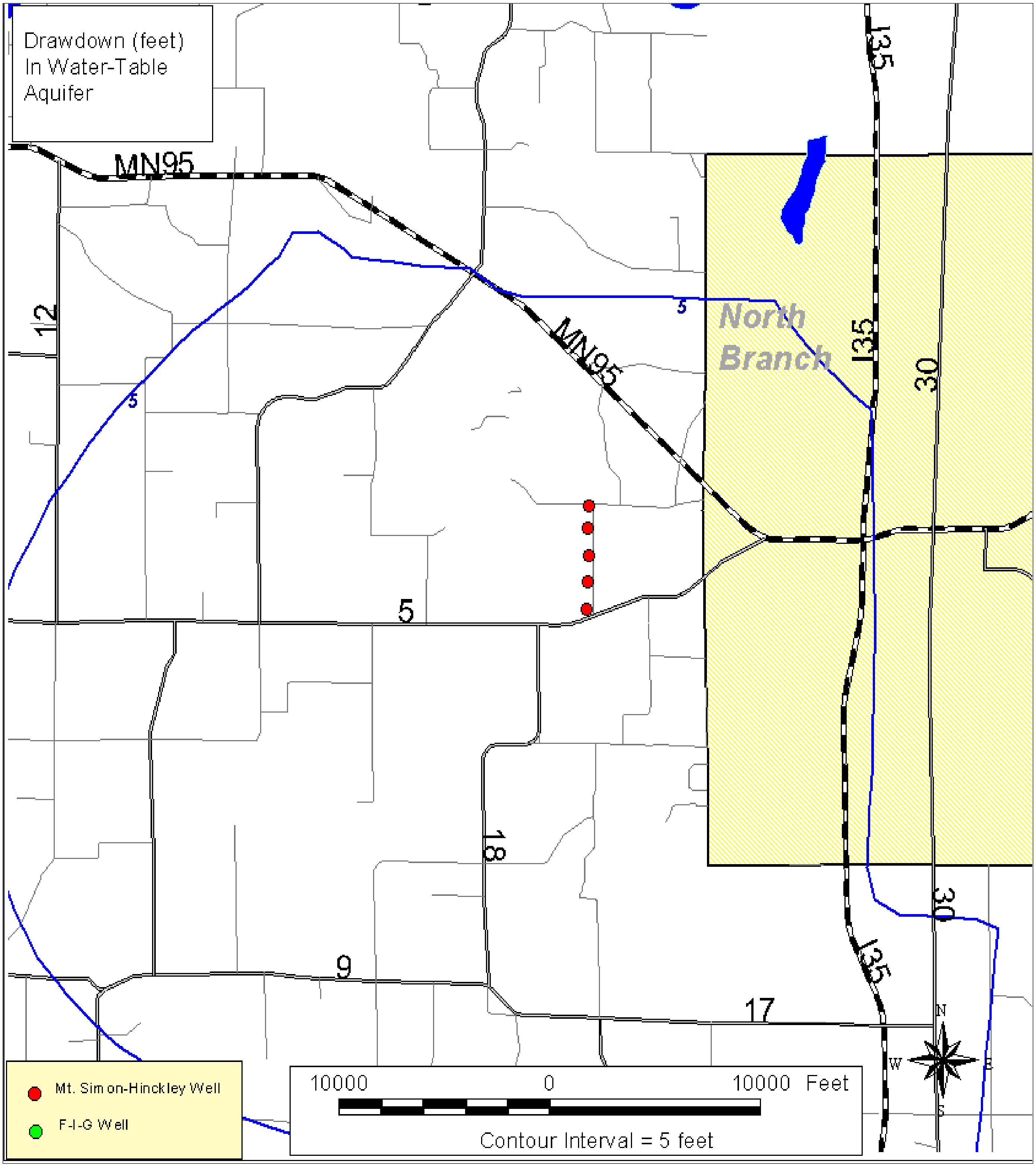


Figure 18

Well Alternative 2: Predicted Drawdown (feet) in Water-Table Aquifer

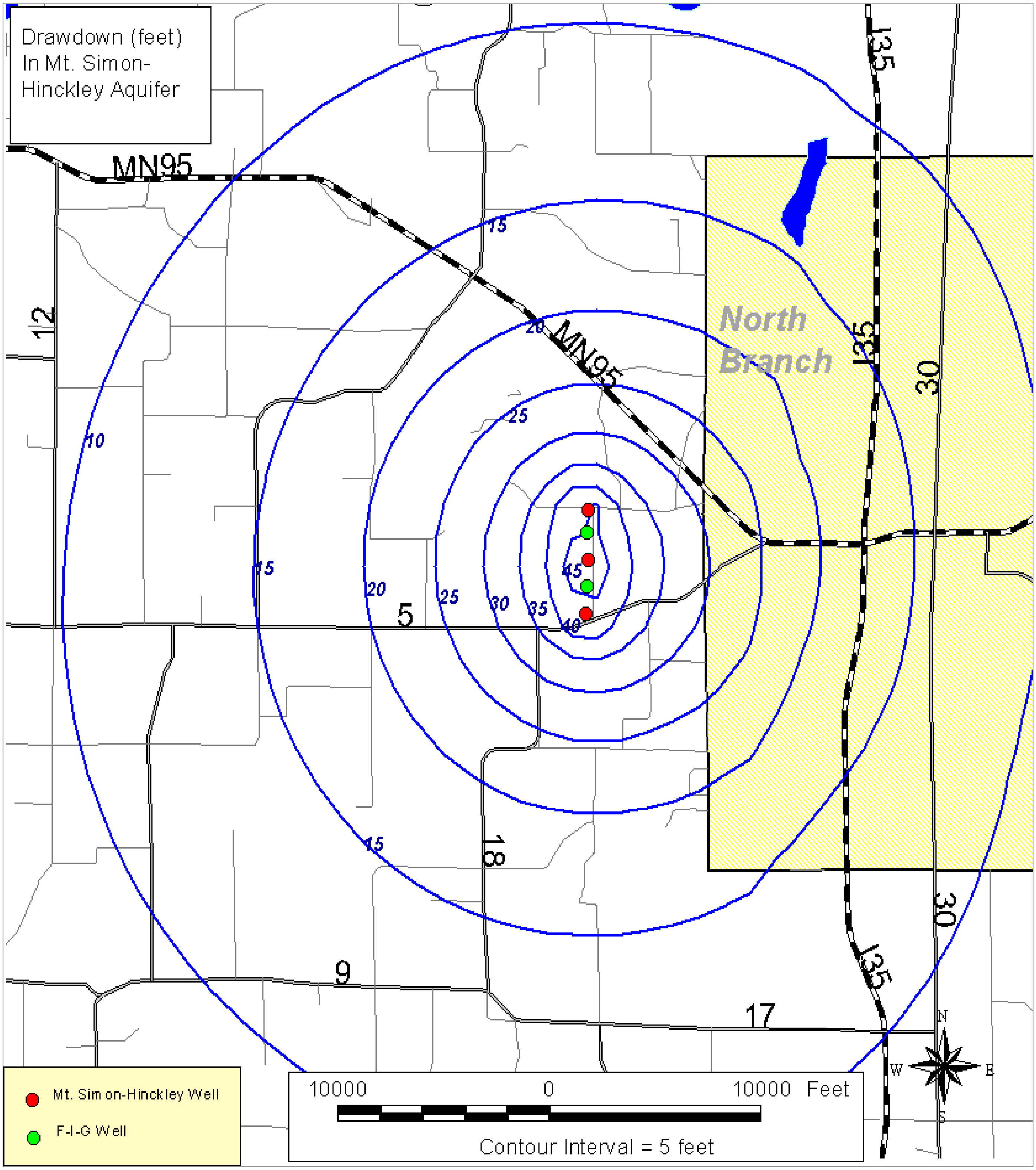


Figure 19

Well Alternative 3: Predicted Drawdown (feet) in Mt. Simon-Hinckley Aquifer

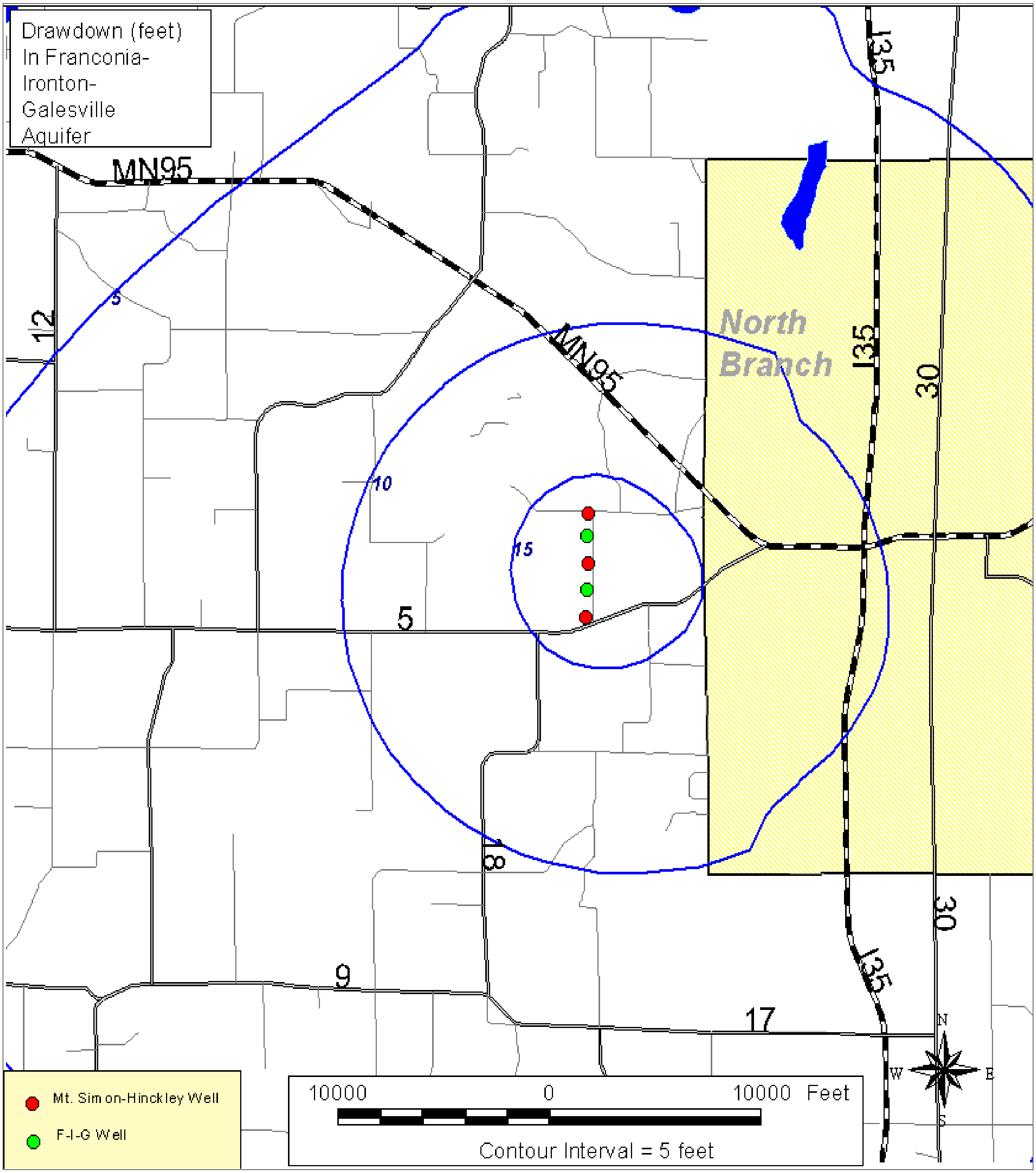


Figure 20

Well Alternative 3: Predicted Drawdown (feet) in Franconia-Ironton-Galesville Aquifer

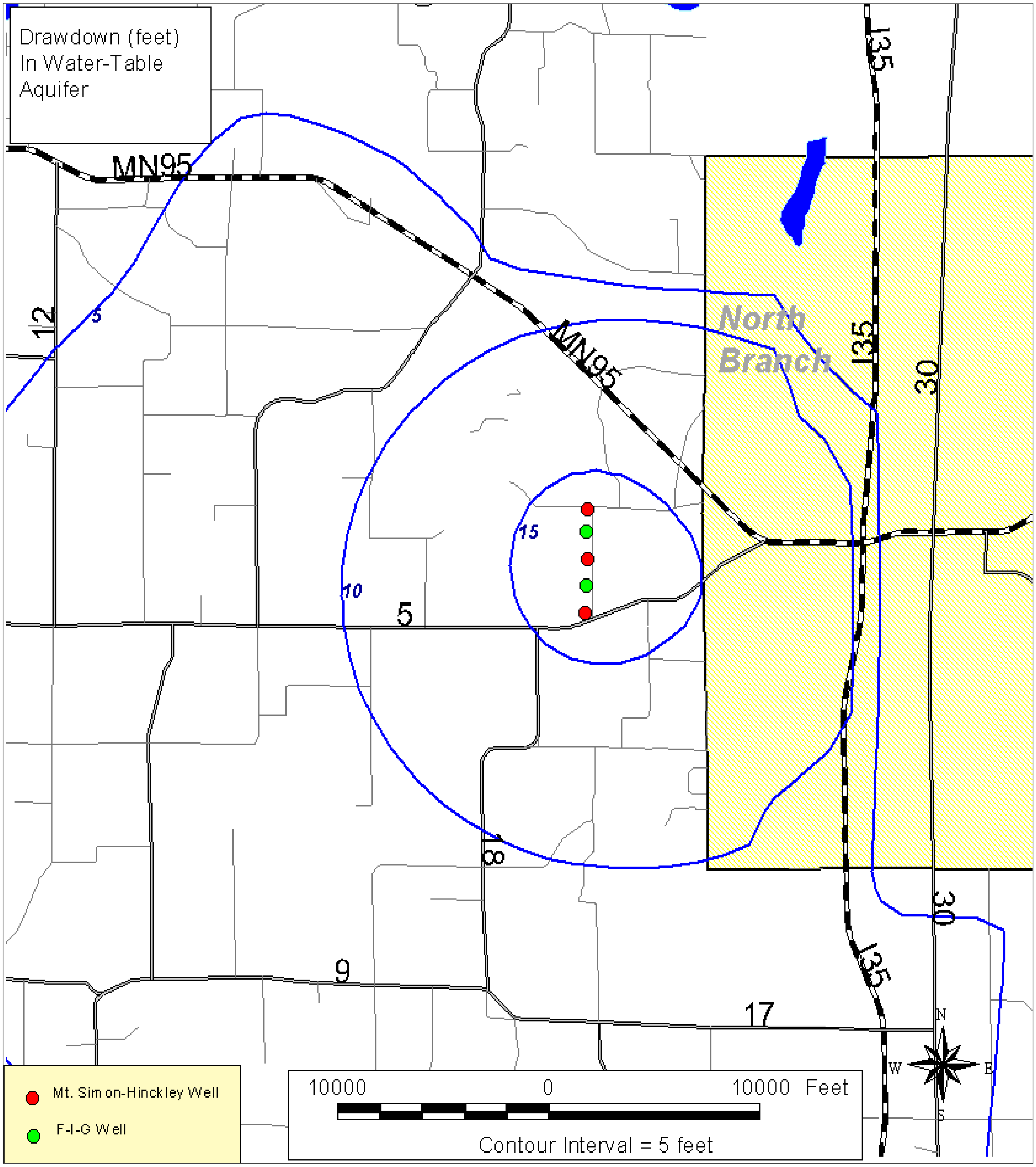
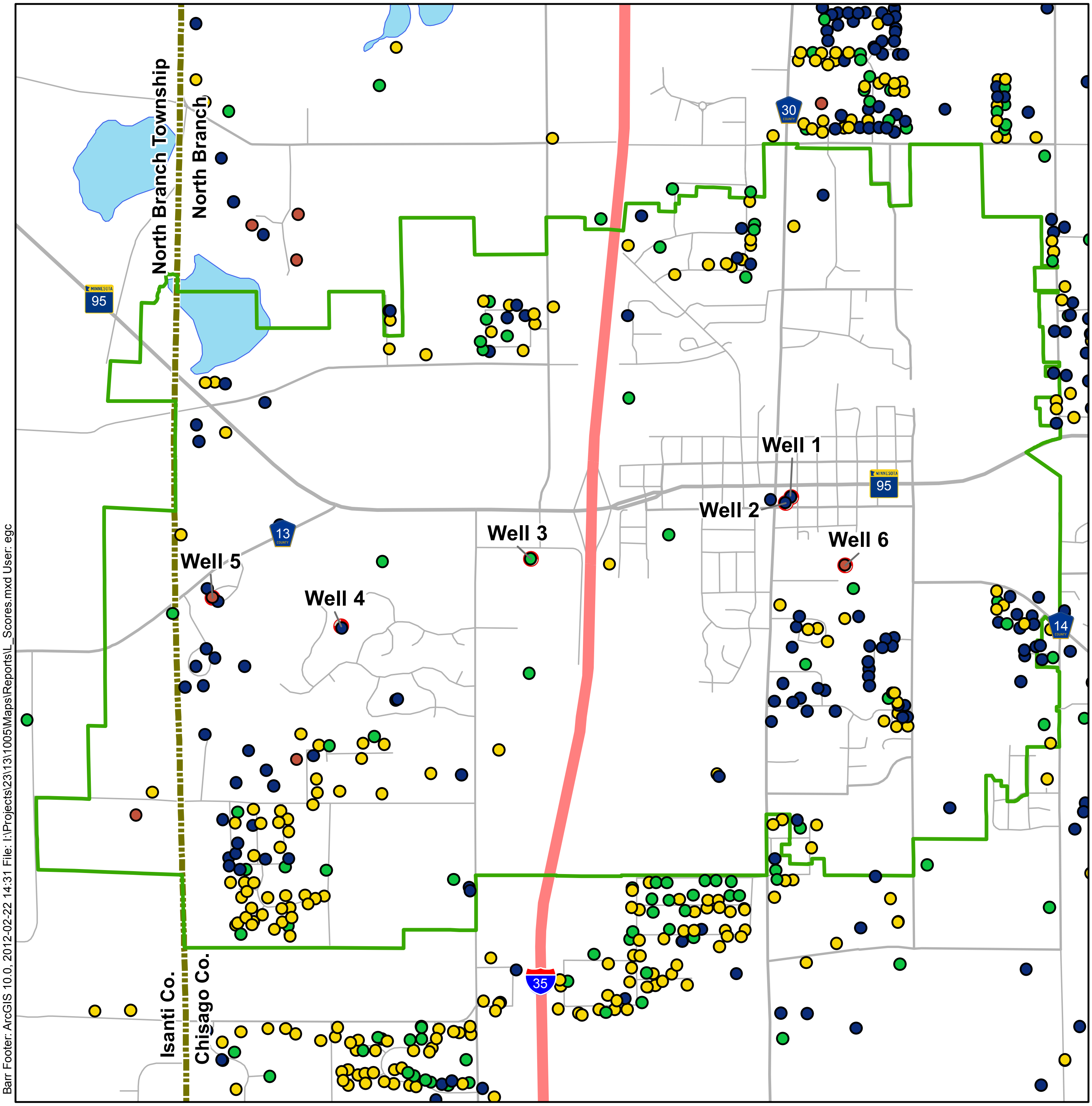


Figure 21

Well Alternative 3: Predicted Drawdown (feet) in Water-Table Aquifer

Appendix F

L-Score Map



L Score

- 0
- 1
- 2
- >2

North Branch Water & Light Well

DWSMA

Muncipal Boundary

Water Body

N

Miles

0 1

BARR

Figure F-1

L SCORES
WHPP Part 1
North Branch Municipal
Water and Light
Chisago County, MN

Appendix G

Groundwater Model Files and GIS Shapefiles (Electronic Format)