South-Central Minnesota Groundwater Monitoring of the Mt. Simon Aquifer – Phase 2

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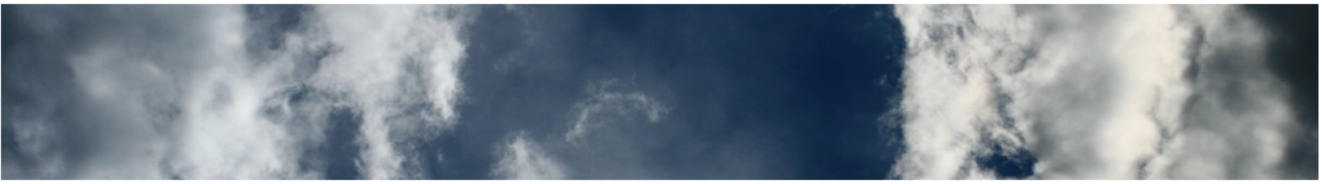

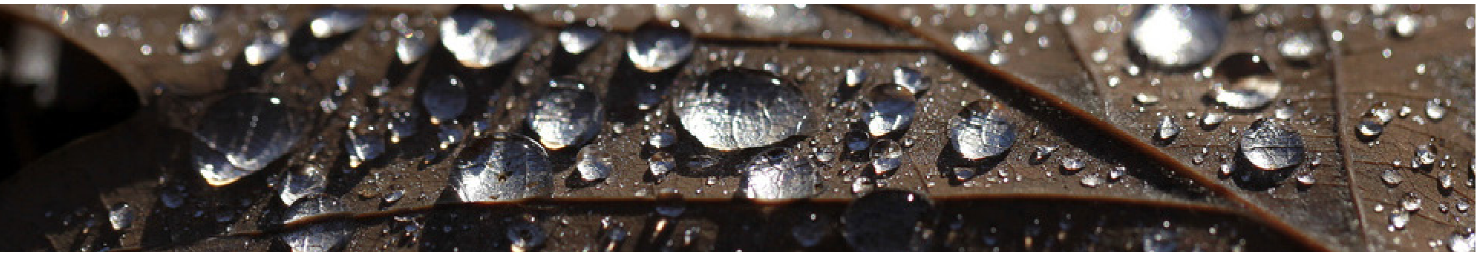

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This report is available in additional formats upon request, and online at www.dnr.state.mn.us

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Abstract

This Phase 2 report is the final of two reports covering groundwater investigations for the Mt Simon and Mt. Simon-Hinckley aquifers in southern and central Minnesota. The Phase 1 report published in June 2011 reported on work accomplished in Martin, Watonwan, Brown, Nicollet, and Sibley counties. Both investigation phases included observation well installations, water level monitoring, groundwater chemical analysis, and aquifer capacity testing to determine recharge pathways and sustainable limits for this aquifer. Most data collected for this Phase 2 study are derived from 16 wells installed at 10 locations to depths of 100 to 695 feet in McLeod, Wright, Hennepin, Sherburne, Anoka, and Isanti counties.

In the southern part of the study area (Phase 1 area) hydrograph and geochemical residence time data (^{14}C and tritium) show relatively isolated conditions with groundwater ages ranging from 6,000 to 30,000 years for the Mt. Simon aquifer. In the northern portion of the study area (Phase 2 area) chemical residence time indicators from the Mt. Simon aquifer indicate groundwater ages less than approximately 1,000 years in eastern Wright and Sherburne counties and northern Isanti County. These relatively young groundwater ages are consistent with water level and stratigraphic information that indicate both direct and indirect connection of surface water to the Mt. Simon-Hinckley aquifer through localized focused recharge.

This project has shown that the most critical recharge area for the Mt. Simon-Hinckley aquifer and Minneapolis-St. Paul metropolitan area water supply includes portions of Wright, Sherburne, and Isanti counties. Protection of this region from water pollution should be a high priority for all levels of government. Continued monitoring of wells installed for this investigation will create a long term record that can be used to interpret changes in local and regional water supply due to water use or climate changes.

Acknowledgements

The 2008 and 2009 legislatures allocated funding from the Environment and Natural Resources Trust Fund for an aquifer investigation, mapping, and monitoring project in south-central and east-central Minnesota (Figure 1). The 2008/2009 allocations provided $4,295,000 for a 4-year project. The allocation is being shared by the Minnesota DNR ($2,769,000) and the Minnesota Geological Survey (MGS, $1,526,000) to evaluate the Mt. Simon-Hinckley aquifer and produce geologic atlases. The purpose of this report is to compile, summarize, and interpret data collected from the second phase of the Minnesota DNR portion of this project as required by the statute (ML 2009, Chap.143, Sec. 2, Subd. 3 (b)). The Phase 1 report (Berg and Pearson, 2011) was submitted to the Legislative-Citizen Commission on Minnesota Resources in July 2011 and is available online at the DNR website on the water publications web page.

Introduction and Purpose

The deepest bedrock aquifer of east central Minnesota, including the Minneapolis-St. Paul metropolitan area, is the thick (50 to 200 feet) Mt. Simon Sandstone of Cambrian age. In areas where the Mt. Simon Sandstone is underlain by the Hinckley Sandstone, the two formations together are called the Mt. Simon-Hinckley aquifer. This aquifer supplies all or some of the water used by over one million Minnesotans. Measurements of water levels in this aquifer are taken from groundwater level monitoring wells, which are also known as observation wells. The water level measurements that are available from this aquifer in the Minneapolis-St. Paul metropolitan area indicate declining water levels in areas where water is being withdrawn for municipal and industrial use.

To better understand the recharge dynamics of the Mt. Simon-Hinckley aquifer, the western and northern edges were investigated where it was not likely to be overlain by thick, relatively impermeable Paleozoic shale formations. A total of seven Mt. Simon Sandstone observation wells and nine wells in other geologic units were drilled. Staff from the Minnesota DNR Ecological and Water Resource Division coordinated the installation of these wells. Drilling in the northern portion of the investigation area (Phase 2) began in the fall of 2009. The wells are completed in the Mt. Simon and Hinckley sandstones, the Fond du Lac Formation, and shallower units on public property in the project area to depths of 100 feet to 695 feet (Table 1). The wells were sampled for chemical constituents such as tritium and carbon-14 that helped determine the residence time or age of the groundwater in this aquifer and overlying aquifers. The wells were also instrumented with equipment to continuously record groundwater levels.

Bedrock Geology of Investigation Area

The focus of this investigation was the Cambrian Mt. Simon Sandstone (Figure 2) which was deposited at the base of a thick sequence of Paleozoic marine carbonate, shale, and sandstone formations that underlie central and southeastern Minnesota in a broad structural basin known as the Hollandale embayment (Figure 3). The Mt. Simon Sandstone is generally a medium to coarse grained quartzose sandstone (Mossler, 2008). The Mt. Simon Sandstone cuttings observed from drill holes for this project generally indicated the unit is dominated by thick beds of gray and white, silty, very fine to medium-grained quartzose to feldspathic sandstones with thin white-grey, light green, and reddish shale layers. The basal portion of the Mt. Simon Sandstone has coarse yellowish quartz grains ranging from very coarse sand to medium pebble size.

Various Precambrian bedrock units underlie the Mt. Simon Sandstone due to a complicated geologic history prior to the deposition of the Paleozoic rocks. These older underlying rocks include Middle Proterozoic sedimentary rocks, such as the Hinckley Sandstone and the Fond du Lac Formation, Early Proterozoic igneous and metamorphic rocks, and in some southern areas the Lower Proterozoic Sioux Quartzite. Few of these underlying rocks, with the exception of the Hinckley Sandstone, have desirable aquifer properties for most purposes. Therefore, the Mt. Simon Sandstone and combined portions of the underlying Hinckley Sandstone is the deepest bedrock aquifer in the region. The only aquifer available for large capacity (i.e., municipal and industrial) use along the western edge of the Hollandale embayment (Figure 3) is the Mt. Simon aquifer in the Phase 1 area and the Mt. Simon-Hinckley aquifer in the Phase 2 area.

Following the deposition of sand and other sediments that would become the Mt. Simon Sandstone and overlying formations, there was a long period of exposure and non-deposition of rock materials. Marine and non-marine sedimentary rocks (mostly shale and sandstone) were deposited along the western edge of the Hollandale embayment in south-central Minnesota during the Late Cretaceous period. During this period, a shallow epicontinental (inland) sea covered the western interior of North America. Relatively thick sections (50-200 feet) of these types are rocks are common in the southern portion of the investigation area.

Surficial Geology of Investigation Area

Following another long period of exposure and non-deposition of rock materials after the Cretaceous period, the region was affected by repeated continental glaciations during the Quaternary period. These glaciations deposited thick alternating layers of glacial outwash (sand and gravel), glacial till (dense mixture of silt, sand, and clay), and other types of deposits. Thus, the depositional history for most of southeastern and south-central Minnesota left a legacy of both bedrock and glacial aquifer systems.

Recharge of the Mt. Simon-Hinckley aquifer depends not only on the absence of overlying impermeable bedrock layers, but also on the existence of a downward gradient and interconnected surficial and buried sand layers that create pathways for focused recharge (Figure 4). The portion of the investigation area south of the City of Buffalo in Wright County is generally characterized by fine grained glacial sediments at the surface that inhibit rapid groundwater recharge. Northeast of the City of Buffalo, sand or sand and gravel at the surface is very common which creates the potential for focused recharge to the Mt. Simon aquifer (Figure 5). Two recent MGS publications (Tipping and Meyer, 2007; and Tipping, 2011) have focused on the characteristics of glacial sediments in the Twin Cities area and evidence of bedrock aquifer recharge. Writing about this sandy area northwest of the Minneapolis-St. Paul metropolitan area, Tipping and Meyer (2007) observe: “Commonly perceived as sand over bedrock, the Quaternary stratigraphy of this area is actually a complex sequence of coarse and fine grained sediments, including multiple till layers, sand bodies and lacustrine deposits.” Furthermore, due to these conditions they conclude that “recharge to bedrock aquifers in the northwest and west-central parts of the metropolitan area appears to be largely localized due to a combination of high permeability zones in unconsolidated sediments…” One of the major goals of this investigation is to help regionally define and characterize Mt. Simon-Hinckley aquifer recharge areas; however, due to the stratigraphic complexity of the glacial sediments overlying the aquifer, a more detailed and local definition will have to wait for the completion of county geologic atlases.

Investigation Methods

Site Selection

The wells for this investigation were drilled on publically owned land to help ensure the longevity of these monitoring locations. With the exception of two locations, all the wells are on state land managed by the Department of Natural Resources, either wildlife management areas (WMA) or water access (WA) locations. One well site in Wright County is owned by the county (Anderson County Park) and another at a National Wildlife Refuge (Sherburne NWR) is owned by the federal government. At these locations special access permission was obtained from the Wright County Board of Commissioners and the U.S. Fish and Wildlife Service, respectively.

Site locations were chosen in suspected recharge areas for the Mt. Simon-Hinckley aquifer near the western edge of the Hollandale embayment at locations where the Mt. Simon Sandstone was likely to be the uppermost bedrock found underlying the surficial glacial deposits or Cretaceous shale and sandstone. A shallow and a deep well were constructed at most locations to provide data on the vertical hydraulic head gradients, changes in groundwater chemistry, and residence time at depth. At the three locations in Isanti County only a Mt. Simon or Hinckley aquifer well was installed and not a shallower well in a nested situation. The Mt. Simon-Hinckley aquifer at these locations was generally overlain by sand and gravel to the surface. Wells and well nest sites were spaced as evenly as possible across the recharge area given the existing distribution of public land in the region. The well nest locations are typically near existing roads and parking lots for easy access and to minimize disturbance of undeveloped parts of these properties.

Drilling Methods and Well Construction

Two different kinds of drilling methods were used to install wells for this project (Table 1). Mud rotary (MR) is a commonly used and widely available method for drilling and completing water wells. Typically a hollow tricone drilling bit is attached to hollow drilling rods that are turned by the drilling rig. During the drilling process, a drilling mud mixture is pumped through the inside of the hollow rod and bit assembly which pushes the ground rock and sediment upward through the space between the drilling rods and the borehole to the surface. The drilling mud flows into an open tank at the surface and is recirculated back down the inside of the drill bit and rod assembly to the bottom of the borehole. The advantage of the MR method is that it is relatively fast and inexpensive. The disadvantage of this method is that the cuttings (ground-up bits of rock and sediment) that the driller and geologist need to find in the drilling mud so they can track drilling progress become difficult or impossible to identify below a certain depth because the cuttings are mixed and degraded as they are pushed to the surface.

Another type of drilling method called dual rotary/reverse circulation (DR/RC) was used in selected areas. During DR/RC drilling, the drill cuttings are returned to surface inside the rods. Air pressure at the drill bit creates suction that pulls the water and cuttings up the “inner tube” which is inside the rod. Once the water and cuttings reach the surface, the cuttings move through a sample hose and are collected in a sample pail. DR/RC drilling produces easily identifiable rock chips from all depths and is therefore ideal for drilling in unknown areas where the geologist does not know exactly what to expect at depth. However, DR/RC drilling is slower and more expensive than mud rotary.

Aquifer Interval Selection for Monitoring

Methods for well construction were somewhat different for boreholes drilled with the two methods. For the dual rotary holes, a 10-inch diameter temporary steel surface casing was driven simultaneously during drilling to the base of the unconsolidated or poorly consolidated Quaternary and Cretaceous layers. Once solid bedrock was reached, the remainder of the hole was drilled without casing because the hole was unlikely to collapse. Drilling continued until Precambrian bedrock was encountered beneath the Mt. Simon Sandstone. At three locations (Anderson County Park, Sherburne NWR, and Stanchfield WMA), the Mt. Simon Sandstone was not present so the deep well was constructed in the Precambrian Hinckley Sandstone or Fond du Lac Formation. After the borehole drilling was completed, a geophysical log of the hole was made by geologists from the Minnesota Geological Survey; at this time, the depth of the permanent 4-inch diameter casing was determined based on the gamma log characteristics of the target formation. For the Mt. Simon wells the relatively shale-free portions of the formation were typically left as open hole. The casing was then constructed by the drilling crew and grouted in place and the temporary casing was removed. The advantage of this procedure was that the depth of the permanent casing could be chosen based on the cuttings and the geophysical log ensuring that the open-hole portion of the well was in the correct depth range, such as the most transmissive portion of the Mt. Simon Sandstone.

Once the deep Mt. Simon Sandstone, Hinckley Sandstone, or Fond du Lac Formation well was completed and logged with geophysical tools, the aquifer for the shallower well in the nest was chosen based on gamma log and cuttings characteristics. In general, we were seeking the shallowest aquifer that might be used for domestic or larger capacity purposes. These shallow wells were generally completed in the discontinuous sand layers of the Quaternary units at a relatively wide range of depths; the shallower well at the Pickerel Lake location was completed in the Cambrian Wonewoc Sandstone.

At three locations wells were completed in buried sand and gravel aquifers using the mud rotary method. A seven-inch diameter borehole was drilled into the top of the buried sand and gravel aquifer and a four-inch steel casing and well screen were placed in the borehole. The casing was then grouted in place.

Geophysical Well Logging

Well logging is the practice of making a detailed record (a well log) of the geologic formations penetrated by a borehole. The geologic log is the geologists's interpretation of the samples brought to the surface. The geophysical well log is a record of formation physical properties measured with electrically powered instruments. The main geophysical log types collected for this project include passive measurements of natural gamma rays and resistivity. After the borehole has been completed, but before the permanent casing has been grouted in the borehole, the logging tool (or probe) is lowered into the open wellbore on a wire connected a reel at the surface. Once lowered to the bottom of the hole, measurements are taken as the probe is reeled up through the wellbore. Measurements are recorded continuously while the probe is ascending from the bottom of the hole.

Gamma ray logging is a method of measuring naturally occurring gamma radiation to characterize the rock or sediment in a borehole. Different types of rock emit different amounts of natural gamma radiation (Driscoll, 1986). Shale and clay usually emit more gamma rays than other sedimentary rocks, such as sandstone, or sand and gravel because radioactive potassium, uranium and thorium are common components in their clay content. This difference in radioactivity between shale and sandstone/carbonate rocks (or clay-rich and non-clay rich sediments) allows the geologist to distinguish between shale and non-clay-rich rock with the natural gamma log.

Resistivity is a property of all materials which represents how strongly a material opposes the flow of electric current. This log is recorded in boreholes containing electrically conductive fluid (drilling mud or water). Sand and sandstone tend to be insulators (high resistivity); clay and shale tend to be conductors (low resistivity). Similar to the gamma log, this difference in resistivity between shale (or clay-rich sediments) and sandstones/carbonate rocks (or non-clay rich sediments) allows the geologist to distinguish between the two general categories of sediments or sedimentary rocks using the resistivity log.

Generalized versions of the gamma logs completed by the staff of the Minnesota Geological Survey (MGS) are shown with the lithologic logs for each of the project well nests in the Appendix. The lithologic descriptions on each of these logs are summarized from MGS interpretations of cuttings. Detailed copies of these logs can be obtained from the MGS.

Well Development

After the borehole is drilled and the permanent well casing is grouted in the well, the well is purged for one to two hours to remove sediment that may have accumulated at the base of the well. This well development procedure is designed to ensure that all or most of the open hole portion of the well is unclogged and water level measurements from the well are representative of water levels in the aquifer at that location.

Groundwater Sample Collection

Protocols commonly employed for the collection of groundwater samples generally require the removal of much of the standing water in the borehole prior to the collection of groundwater samples. This is done so that the sample represents fresh groundwater and is representative of the resource. Removing groundwater from a well can be completed through the use of any of a number of mechanical methods including bailers, air injection and pumping. An electric submersible well pump was selected for this project because it is capable of removing hundreds of gallons of water from depths greater than 150 feet in a relatively short period of time in preparation for groundwater sampling. In addition, well performance testing can be conducted during the same pumping process. Therefore, the collection of water samples was organized to complete the following two tasks: the collection of groundwater samples and a short duration well performance test.

To accomplish these two tasks, a submersible water well pump was temporarily installed in each well to be sampled. An electric generator was used to provide power to the pump and a combination of piping and flexible hose were installed to deliver the groundwater to the surface. The pump used was capable of producing pumping rates of 15 to 31 gallons per minute. Table 2 presents the basic information collected during the performance test procedures.

Groundwater was pumped through a hose from the flow meter to a clean, white five-gallon bucket that allowed field observations of color and odor. The bucket was also used as a flow through chamber into which the probes of several instruments were suspended. Sequential measurements of temperature, pH and specific conductance were made. The wells were pumped until constant values of pH, temperature and specific conductance were observed. The groundwater sample was collected after the values of these parameters remained stable and at least one well volume of water had been removed from the well.

The sampling consisted of filling prepared and labeled containers with groundwater from the hose discharge at the stabilization bucket. The carbon-14 (^{14}C) sample size was approximately 30 gallons and required special handling and containers. Analytes and sampling protocol are summarized in Table 3. Samples were sent to the University of Minnesota Hydrochemistry Laboratory (U of M) and the University of Waterloo Isotope Laboratory (Waterloo) for analysis. Alkalinity was measured with field titration equipment onsite or within 24 hours.

Specific Capacity Procedures and Results

A specific capacity test provides an estimate of the potential yield from a water well. Specific capacity can be calculated from the results of a short duration pumping test. Specific capacity is the pumping rate (gallons per minute) divided by the measured drawdown (feet) and is reported in units of gallons per minute per foot of drawdown (gpm/ft). In Minnesota's principal aquifers, the observed specific capacities range from less than 1.0 gpm/ft to values greater than 100 gpm/ft (Minnesota DNR, 2004). Specific capacities for the Mt. Simon-Hinckley aquifer wells typically range from 1 to 33 gpm/ft; specific capacities for glacial drift wells show greater variability from less than 1 to greater than 50 gpm/ft. As shown in Table 2, the observed specific capacities for the Mt. Simon wells ranged from approximately 1 gpm/ft at Crooked Road WMA to 9 gpm/ft at Robina WMA.

The depths to groundwater were measured from dedicated measuring points located at the top of the well casings. For this project the measuring point elevations were measured using engineering grade global positioning systems that use the Minnesota Department of Transportation Continuously Operating Reference Station network. The measuring point at each well is on the north side of the top of the four-inch diameter steel well casing (top of casing). Groundwater depth measurements were collected before, during, and after pumping using electronic water level measuring tapes and electronic pressure transducer instruments.

A flow meter was used to measure rate and a flow totalizer was used to measure total water discharge in gallons. The flow rate from the well was controlled with the well head check valve. At the start of each pumping test the valve was opened to allow the full pumping rate. Some of the wells were pumped at rates lower than the capacity of the pump to maintain water levels above the pump intake.

Continuous Water Level Measurements

Unattended continuous water level measurements can be made with pressure transducers which are instruments that respond to changes in pressure created by the water column above the instrument. A data logger can record the measurements taken by a pressure transducer at specific intervals set by the user. Improvements in technology over the last decade have resulted in combined data logger and pressure transducer units that are about the size of a small flashlight.

Sealed data logger and pressure transducer units were submerged in each well to a depth of 20 to 25 feet below the water surface. Sealed units record changes in total pressure including barometric pressure. To discriminate changes in pressure reading that are related to barometric pressure change from real water level changes, a record of barometric pressure must also be made. Three data logger and barometer units were deployed across the study area for this purpose. All of the instruments were programmed to collect and store hourly readings.

Data are stored in the data logger until downloaded during site visits that were scheduled quarterly. Communication cables connected to the instruments are accessible from the top of each well. At each location the data are downloaded from the instruments and a water level measurement is taken with a measuring tape. After the data are downloaded, computer software is used to calibrate the data series to the actual measurements and adjust for changes in barometric pressure.

Thickness of the Mt. Simon Sandstone Near the Western Subcrop

One of the objectives of the project was to better define the physical characteristics, including extent and thickness, of the Mt. Simon Sandstone in the study area to help with future water resource evaluations. All the Mt. Simon aquifer wells drilled for the Phase 2 project were drilled to the base of the formation. Most existing wells in this area (Figure 6) provide a minimum thickness value since most of the wells are only drilled into the top of the aquifer to provide water for domestic and irrigation users. Across the study area the thicknesses of the Mt. Simon Sandstone gradually increase toward the southeast to thicknesses of 200 feet and greater in the Minneapolis-St. Paul metropolitan area. Most Mt. Simon aquifer users in the northwestern metropolitan area are pumping water from the portion of the aquifer that ranges from 50 to 125 feet thick.

Groundwater Movement and Potentiometric Surface of the Mt. Simon-Hinckley Aquifer

A key aspect of understanding the hydrogeology of any area is to develop a basic understanding of the groundwater flow pathways. Aquifers and systems of aquifers are rarely static or unchanging. Water is usually moving into the aquifers (recharge), through the aquifers, and out of the aquifers (discharge) in complicated but definable patterns. Three primary types of data are used by investigators to understand these relationships: chemical data from collected samples, aquifer test data gathered by pumping wells under controlled conditions, and static (non-pumping) data measured from wells and surface water bodies. Static water-level data and potentiometric surfaces are the primary focus of this section.

A potentiometric surface is defined as “a surface that represents the level to which water will rise in a tightly cased well” (Fetter, 1988). The potentiometric surface of a confined aquifer (aquifer under pressure) occurs above the top of an aquifer where an overlying confining (low-permeability) layer exists. Static (non-pumping) water-level data from the County Well Index, measurements from the project wells, and data from a U.S. Geological Survey synoptic water level measurement project (Sanocki and others, 2009) were combined and contoured to create the potentiometric contour map (Figure 7). Additional wells in fractured Precambrian crystalline aquifers beyond the extent of the Mt. Simon-Hinckley aquifer are included to show the hydraulic head conditions near the boundary of the aquifer. The contour lines illustrate the potentiometric surface much like the contour lines of a topographic map represent a visual model of the ground surface. The potentiometric surface is not the same as the water table, which is the physical surface of the saturated zone. The potentiometric surface is an imagined representation of the potential energy that is available to move the groundwater in a confined aquifer. Low-elevation areas on the potentiometric surface that could be above the coincident surface-water bodies may indicate discharge areas; when combined with other information sources, high-elevation areas on the potentiometric surface can be identified as important recharge areas. Groundwater moves from higher to lower potentiometric elevations perpendicular to the potentiometric elevation contours (flow directions are shown as arrows). Groundwater flow pathways from recharge areas through the aquifer to discharge locations occur over a wide continuum of depth, distance, and time. Flow into, through, and out of shallow aquifers can occur relatively quickly in days or weeks over short distances of less than a mile, whereas flow through deeper aquifers across dozens of miles may take centuries or millennia.

Figure 7 shows generally, southeasterly groundwater flow directions toward the Minneapolis-St. Paul metropolitan area, and with some local flow toward the Mississippi and Rum Rivers. On cross section Y-Y' (Figure 8) the Mt. Simon-Hinckley aquifer potentiometric surface is relatively shallow across much of the cross section. Near the right (southeastern) portion of the cross section, however, the potentiometric surface becomes much deeper due to the long term effects of high capacity pumping from the aquifer in the Minneapolis-St. Paul metropolitan area. This roughly circular area of depressed water levels is often referred to as a "cone of depression" because the amount of depression gradually lessens as the distance from the centers of pumping increases, resulting in a cone-shaped depression.

Geochemistry

All the wells constructed for this project and one existing well in the area were sampled for analysis of common ions, trace constituents, residence time indicators (tritium and ^{14}C), and stable isotopes (^{18}O and deuterium). The results of all these analyses (Tables 4 and 5) assist in the interpretation of the recharge characteristics of the Mt. Simon-Hinckley aquifer.

Groundwater Residence Time

Two residence time indicators were used in this project: tritium and carbon-14 (^{14}C). Residence time is the approximate time that has elapsed from when the water infiltrated the land surface to when it was pumped from the aquifer for this investigation. In general, short residence time suggests high recharge rates or short travel paths; whereas long residence time suggests low recharge rates or long travel paths.

Tritium (^{3}H) is a naturally occurring isotope of hydrogen. Concentrations of this isotope in the atmosphere were greatly increased from 1953 through 1963 by above ground detonation of hydrogen bombs (Alexander and Alexander, 1989). This isotope decays at a known rate, with a half-life of 12.32 years. Groundwater samples with concentrations of tritium equal to or greater than 8 tritium units (TU) are considered recent water (mostly recharged in the past 60 years). Concentrations equal to or less than 1 TU are considered vintage water (recharged prior to 1953). Concentrations between these two limits are considered a mixture of recent and vintage water and are referred to as mixed water.

The carbon-14 (^{14}C) isotope, which also occurs naturally, has a much longer half-life than tritium (5730 years). Carbon-14 is used to estimate groundwater residence in a time span from about 100 years to 40,000 years (Alexander and Alexander, 1989).

Two shallow groundwater samples in Sherburne County contained detectable tritium concentrations (Table 4 and Figure 9). The sample to the north in this county was collected from a well in the Sherburne National Wildlife Refuge (NWR) from a buried sand and gravel aquifer at a depth of 161 feet. The mixed tritium value and ^{14}C age of 1,300 years could be considered typical of groundwater at this general depth beneath a thick extensive surficial sand layer (Figure 5). The other detectable tritium occurrence from a shallow well, located at the Sand Dunes State Forest, is unusual as the sample contained a high tritium concentration (19.6) indicting recharge within the past 60 years. Both tritium detections from shallow wells were from the sandy area of the Mt. Simon Sandstone subcrop shown on Figure 5. This limited data set supports the idea that this sandy area is a potential Mt. Simon-Hinckley aquifer recharge area.

Tritium data from the Mt. Simon-Hinckley aquifer are shown in Figure 10 including data produced by this project (labeled symbols) and data acquired from the Minnesota Department of Health (James Walsh, unpublished data). Sixteen occurences of recent and mixed tritium have been found within or near the Mt. Simon Sandstone subcrop and within the area of laterally extensive surficial sand. These data represent an important starting point for beginning to understand the distribution of rapid recharge areas within Wright, Sherburne, and Isanti counties.

Figure 11 shows the distribution of ^{14}C residence time values from the Mt. Simon Sandstone, Hinckley Sandstone, and Fond du Lac Formation wells for this project. One additional Mt. Simon-Hinckley aquifer well was sampled for this project from an existing well near Glencoe in McLeod County. Other Mt. Simon-Hinckley aquifer data (Scott Alexander, unpublished data; Lively and others, 1992; Todd Petersen, unpublished data) are also shown on Figure 11 for comparison.

Samples collected from Mt. Simon wells in southern Wright and eastern McLeod counties along the Mt. Simon subcrop mostly did not contain detectable tritium and had old ^{14}C residence time values (6,000 to 20,000 years) indicating hydraulically isolated conditions and very slow recharge similar to values and conditions found in the Phase 1 project area (Berg and Pearson, 2011). The sample collected from the existing well near Glencoe did contain detectable tritium (2.7 TU). This relatively old well, constructed in 1971, may have a corroded casing that allows leakage of recent surficial water into the aquifer. This value may not represent tritium conditions in the aquifer. The 2,000 year old water located in north-central Carver County is along a north–northwest fault trend that may have created a fracture-enhanced flow zone within the Mt. Simon aquifer. Groundwater flow directions suggest the relatively young water at this location was recharged from northeastern Wright County.

In the northern portion of the Phase 2 study area along the Mt. Simon Sandstone subcrop, tritium was detected only at the Sand Dunes State Forest location (4.6 TU). At the other locations, tritium was not detected, but ^{14}C residence time values within or near the Mt. Simon Sandstone subcrop were generally young and ranged from recent to 2,000 years. A somewhat older ^{14}C value of 3,000 years from the Mt. Simon aquifer well at Spectacle WMA in western Isanti County seems anomalous and may be due to local isolated conditions or an upward gradient in the Rum River valley that may be bringing deeper and older water upward.

Stable Isotopes, ^{18}O and Deuterium

All groundwater samples collected from the study area were analyzed for stable isotopes of oxygen and hydrogen, the two elements found in water. Analysis of the results provides an additional tool for characterizing the area groundwater. Isotopes of a particular element have the same number of protons but different numbers of neutrons. Stable isotopes are not involved in any natural radioactive decay; they are used to understand water sources or the processes affecting them (Kendall and Doctor, 2003). Commonly used isotopes for these purposes include oxygen isotopes ^{16}O and ^{18}O and hydrogen isotopes ^{1}H and ^{2}H. The heavy hydrogen (^{2}H) is called deuterium. The mass differences between ^{16}O and ^{18}O or ^{1}H and ^{2}H result in water molecules that evaporate or condense at different rates. Thus, the concentrations of these isotopes in water changes (fractionates) during evaporation and precipitation, resulting in different $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios in rain, snow, rivers, and lakes. The values are expressed as $\delta^{2}H$ and ^{18}O. The symbol "δ" (i.e., delta) denotes the relative difference from standard mean ocean water (Vienna standard mean ocean water - VSMOW) and expresses the relative abundance of the rarer heavy isotopes, $\delta^{2}H$ and $\delta^{18}O$. These values from precipitation water generally plot close to a straight line known as the meteoric water line (Figure 12). The departure of ^{18}O and ^{2}H values from the meteoric water line can indicate evaporation or mixing of water from different sources.

Figure 12 shows a plot of $\delta^{18}O$ and $\delta^{2}H$ values from groundwater samples collected in the study area compared to the meteoric water line. Two types of information regarding the origin and history of these water samples can be interpreted from this graph: relative atmospheric temperature during source water precipitation and relative mixing of water from cold and warm sources.

Source Water Temperature and Mixing

For the samples that plot along the same slope as the meteoric water line, the samples more depleted in heavy isotopes (samples that plot closer to the bottom left of the graph) suggest water that precipitated from a colder atmosphere (Siegel, 1989). Person and others (2007) provided a compilation of paleohydrological studies of groundwater systems in North America that were affected by the advance and retreat of the Laurentide ice sheet. He concluded that the range of $\delta^{18}O$ groundwater values from cold ice or snow melt sources ranges from -25‰ to -9‰. Studies of glacial waters, as evidenced by ostracodes in Lake Agassiz sediments, however, shows ranges of $\delta^{18}O$ from -25‰ to -20‰ (Birks and others, 2007; Breckenridge and Johnson, 2009). Most $\delta^{18}O$ values of groundwater samples from the south central Minnesota Phase 1 and Phase 2 projects (Berg and Pearson, 2011) ranged from approximately -10‰ to -8‰; these values suggest this water is derived from post-glacial precipitation.

In the Phase 1 area in every well nest, the sample from the shallower well had less negative (warmer) $\delta^{18}O$ values than the sample from the associated Mt. Simon aquifer sample. An example of this typical situation is shown in the lower left corner of Figure 13 from the Phase 1 area in northern Sibley County (Severance Lake). This typical pattern may be due to more seepage of meteoric water with warmer isotope values into the shallower aquifer replacing more of the relict older and colder water. Less of this seepage and relict cold water replacement has occurred in the Mt. Simon aquifer of the Phase 1 area and therefore the stable isotope values are slightly colder.

Another possibility (Scott Alexander, personal communication) relates to the timing of the main recharge events for prairie versus woodland areas. Climate changes over geologic time scales are well documented in the geologic literature (Dean, 1999). As climates change, ecosystems shift as well. Regions of Minnesota that were once woodland would now be a prairie type and vice versa. The prairies would develop a larger water demand earlier in the season than the woodlands, and create a slight difference in the stable isotopes of the recharge waters.

At two locations in the Phase 2 area, and possibly a third, this pattern has been reversed. These locations include Anderson County Park in central Wright County, Pickerel Lake WA in western Anoka County and possibly the Robina WMA location in western Hennepin County. This reversal of the typical stratification pattern found in south central Minnesota may be due to the much greater volume of groundwater usage in the Minneapolis-St. Paul metropolitan area. The huge volume of groundwater pumped from the Mt. Simon-Hinckley aquifer over many years that created the cone of depression shown in Figure 7 has increased the hydraulic gradient in the aquifer; this has accelerated the influx of meteoric water from the Mt. Simon Sandstone and Hinckley Sandstone subcrop areas or nearby fracture zones, thereby flushing relict cold water at a faster rate compared to the overlying less-used aquifer. At the Robina WMA location only the Mt. Simon aquifer wells had been completed when all the project wells were sampled in the fall of 2010 so there is no shallow aquifer data for comparison. However, the Robina WMA sample has the warmest stable isotope values of the data set and may represent the same kind of flushed conditions found at the other two locations.

Major Ions

Some evidence of distinct source water types and mixing of these waters can be understood by considering the relative abundances of some common cations and anions as ion concentrations plotted as percentages from area groundwater samples. Figure 14 shows the relative abundances of these common ions plotted on a ternary graph (Piper diagram). Table 5 also shows the concentrations of these constituents in mg/l. The most common type of water in this area has Ca and Mg (Ca+Mg) as the predominant cation and bicarbonate as the most common anion. The bicarbonate type of water is common in glacial aquifers of the upper Midwest (Freeze and Cherry, 1979, p. 284) and is derived from dissolution of calcite and dolomite minerals in soil and glacial sediments by infiltrating precipitation. Higher sulfate concentrations (greater than 100mg/l) in the Mt. Simon aquifer tend to occur in the Phase 1 study area (Berg and Pearson, 2011) where infiltrating water passed through Cretaceous sandstone and shale layers that contain sulfide minerals that are oxidized to sulfate.

The data from five Phase 2 samples plotted on the center of the cation ternary plot show that some slightly elevated Na+K waters are also present in the area (Figure 14). These slightly Na+K type waters (McLeod County Highway building, Mt. Simon Sandstone well; Clouster Lake WMA Mt. Simon Sandstone and buried sand and gravel wells; and Anderson County Park, Hinckley Sandstone well) are more characteristic of water in the Phase 1 area where the Mt. Simon sandstone subcrop is not overlain by a thick extensive surficial sand layer that is present in northeastern Wright, eastern Sherburne, and southwestern Isanti counties (Figure 5). None of the samples from that sandy area contained elevated concentrations of sulfate or Na+K due to a general lack of Cretaceous bedrock and greater flushing of the aquifers with recharging meteoric water.

Trace Elements

Analysis of groundwater samples for a suite of trace element constituents reveals exceedences of the drinking water standard for arsenic (10 ug/l) in two samples. These samples were collected from the buried sand and gravel aquifer at the Lake Ann WA site and the Wonewoc aquifer at the Pickeral Lake WA site (Table 4). Naturally occurring elevated arsenic values are common in aquifers in western and central Minnesota that are hydraulically connected to Des Moines lobe glacial till (Erickson and Barnes, 2005).

Hydrogeology Illustrated by Cross Sections and Hydrographs from Observation Well Nests

A set of seven geologic cross sections were created for this report to provide location-specific representations of the stratigraphy and geologic structure for each well nest and to provide a hydrogeologic context for the hydrograph and geochemical data. The cross sections were constructed by projecting lithologic, stratigraphic, and well construction information onto the trace of each cross section (Figure 3) from within a one kilometer zone on either side of the cross section.

Water level data from each well constructed for this project were plotted to create hydrographs illustrating water elevation changes over time. Hydrographs provide a method of representing large amounts of data from one or more wells. The water elevation hydrographs are provided for each corresponding cross section. Each hydrograph displays the water levels recorded in one or two wells nested at the same site with the Mt. Simon Sandstone, Hinckley Sandstone, or Fond du Lac Formation wells shown in blue and the shallower depth well shown in red. Nested wells are located at the same site within a few feet of each other. On several hydrographs the difference in water elevation is large enough to require the use of a secondary axis. The shallower well information is set on the secondary axis and the corresponding units are indicated on the right side of the hydrograph.

Most of the water level data cover the time period between early 2011 through the spring of 2012. In general, the precipitation pattern for that time period consisted of a relatively wet summer and fall for 2011 (Figure 15) followed by a dry 2012 winter (Figure 16) and early 2012 spring. The following hydrographs follow this pattern and suggest at least some direct hydraulic connection to the surface:

Observation wells completed in aquifers with direct hydraulic connections to the surface

Site	Aquifer(s)	Figures
Stanchfield WMA	PMHN	17
Spectacle Lake WMA	CMTS	18 and 19
Crooked Road WMA	CMTS	20 and 21
Sherburne NWR	QBAA and PMFL	22 and 23
Pickerel Lake WA	CWOC	22 and 24
Sand Dunes SF	QBAA and CMTS	25 and 26
Anderson County Park	QBAA	27 and 28
Lake Ann WA	QBAA	30 and 31
Clouster Lake WMA	QBAA	32 and 33

The relatively old ^{14}C residence time values from the Mt Simon-Hinckley aquifer in the southern portion of the Phase 2 area indicate very slow recharge and hydraulically isolated conditions. The limited range of water level fluctuations shown on the hydrographs reflects this relative hydraulic isolation. Water level fluctuations shown on these hydrographs are not caused by rapid downward flow of precipitation (recharge), but a pressure response to the increased volume and weight of additional groundwater in the overlying water table aquifer and shallow buried aquifers (Maliva and others, 2011). The following wells appear to be in the category:

Observation wells completed in aquifers with very limited hydraulic connections to the surface

Site	Aquifer(s)	Figures
Pickerel Lake WA	CMTS	22 and 24
Anderson County Park	PMHN	27 and 28
Robina WMA	CMTS	27 and 29
Lake Ann WA	CMTS	30 and 31
Clouster Lake WMA	CMTS	32 and 33
McLeod County Hwy Dept	CMTS	34

Comparisons of hydrographs of deep wells with nearby shallow wells can reveal vertical gradients. A downward gradient exists where the groundwater elevation in the shallower well is higher than the groundwater elevation in the deeper well. This condition indicates that groundwater will move downward if a flow pathway is available. All hydrograph pairs show generally downward gradients (Figures 23, 24, 26, 28, 31, and 33). Hydrograph pairs at four locations (Sherburne NWR, Sand Dunes SF, Anderson County Park, and Pickerel Lake WA) follow similar although offset patterns. At the Sherburne NWR (Figure 23) and Sand Dunes (Figure 26) sites these similar patterns are probably because both the shallow and deeper aquifers at each site are separated only by very leaky confining layers; therefore, they are connected partially to the same overlying recharging aquifers (Figures 22 and 25). At the Pickerel Lake WA (Figure 22) and Anderson County Park (Figure 27) sites the hydrograph patterns are less similar (Figures 24 and 28, respectively), with the deeper aquifer having a smaller fluctuation range and a subdued pattern compared to the shallower aquifer. This type of relationship suggests fluctuations within Mt. Simon aquifer wells are due to pressure effects of changes in the overlying water weight of the water table aquifer.

Finally, the hydrograph patterns between the well pairs at Lake Ann WA (Figure 31) and Clouster Lake WMA (Figure 33) do not suggest similarity. Also, the hydrographs of the Mt. Simon aquifers wells at the Robina WMA (Figure 29) or the McLeod County Highway Department (Figure 34) sites do not appear to follow the precipitation pattern for the area during 2011 and early 2012. These hydrograph data along with the old ^{14}C age data and stratigraphic relationships shown on the corresponding cross sections indicate the Mt. Simon-Hinckley aquifer at these locations is the most isolated within the Phase 2 study area. These data have been collected over a relatively short time, and these analyses should be considered preliminary. Longer periods of record will reveal additional insights.

Mt. Simon and Mt. Simon-Hinckley and Aquifer Carbon-14 Residence Time Distribution and Conceptual Recharge Models

Figure 35 shows a simplified distribution of ^{14}C ages of samples collected from the Mt. Simon and Mt. Simon-Hinckley aquifers along the western and northern boundaries of the aquifers. The areas colored in dark blue (^{14}C age < 1,000 years), light blue (1,000 to 2,000), and gray (2,000 to 10,000 years) represent a significant portion of post-glacial recharge in this aquifer in Minnesota.

The two main factors influencing the distribution of this post-glacial recharge are the three major river valleys (Minnesota, Mississippi, and St. Croix) that are Mt. Simon-Hinckley groundwater discharge features and a relatively thin and sandy Quaternary layer in the northern portion of the Phase 2 study area (eastern Wright, Sherburne, and Isanti counties) that enhanced recharge in that area (Figure 5). Another factor may be the Mt. Simon aquifer cone of depression that has been acting over such a short time, but has significantly changed the magnitude of the vertical gradient.

The influence of the Minnesota River valley is apparent by the elongated shapes of three zones of younger (less than 10,000 year) groundwater in Watonwan and Brown counties, Sibley County, and eastern Wright and Carver counties. All of these zones are elongated toward the Minnesota River valley. The two southerly zones were created by slow dispersed downward migration of recharge water through fine-grained glacial sediment and Cretaceous sand and shale (Figure 36, Z-Z’) that is described in more detail in the Phase 1 report (Berg and Pearson, 2011).
The lobe of relatively young groundwater in Wright and Carver counties is also migrating toward the Minnesota River valley, but the core of this zone may be comprised of much younger water (<2000 years) that originated in a stratigraphic setting similar to eastern Sherburne County shown on cross section Y-Y’ (Figure 36). Instead of the slow dispersed recharge characteristic of the Mt. Simon subcrop south of northeastern Wright County, recharge in eastern Wright County

that created this lobe is characterized by areas of local and focused recharge through interconnected sand and gravel layers. Detailed mapping of these focused recharge areas was beyond the scope of this project, but some progress identifying these areas has been made by GIS modeling of vertical travel time from the water table to the top of bedrock (Tipping 2011) and will continue with geologic atlases that are currently in progress for Wright and Sherburne counties.

Figure 37 shows a comparison of Mt. Simon-Hinckley aquifer ^{14}C age values and modeled vertical travel time to the top of the Mt. Simon aquifer. Vertical travel time values should be similar but not the same as ^{14}C ages. The residence time data always represent mixtures of younger and older water and vertical travel time models do not account for the effects of mixing and horizontal groundwater flow.

The remainder of the large area of younger groundwater northeast and east of Wright County also likely originated in the type of setting shown on cross section Y-Y' (Figure 36) because the sandy and thin overlying Quaternary sediments extend into southern Isanti County. Most of the migration of this relatively young body of groundwater would have been controlled by the natural gradients created by the Mississippi and St. Croix rivers prior to human settlement of the Twin Cities metropolitan area.

Summary and Conclusions

- Beginning in the fall of 2009, a total of seven Mt. Simon Sandstone wells and nine wells in other geologic units were drilled in the northern portion of the investigation area (Phase 2). The wells are completed in the Mt. Simon Sandstone, the Hinckley Sandstone, the Fond du Lac Formation, and shallower units on public property in the project area to depths of 100 feet to 695 feet.

- The wells were sampled for chemical constituents, tritium, and carbon-14 that helped determine the residence time or age of the groundwater in this aquifer and overlying aquifers. The wells were also instrumented with equipment to record groundwater levels hourly.

- As the wells were purged prior to sampling, the pumping rate and water level drawdown data showed specific capacities for the Mt. Simon wells ranged from approximately 1 gpm/ft at Crooked Road WMA to 9 gpm/ft at Robina WMA.

- Most Mt. Simon aquifer users in the northwestern metropolitan area are pumping water from the portion of the aquifer that ranges from 50 to 125 feet thick.

- Tritium detections from the project well groundwater samples were somewhat rare with four detections: two from buried sand and gravel aquifers in Sherburne County and two from Mt. Simon aquifer wells in McLeod and Sherburne counties.

- In the southern part of the Phase 2 area (southern Wright and eastern McLeod counties) samples collected from the Mt. Simon aquifer wells had old ^{14}C residence time values of 6,000 to 20,000 years indicating hydraulically isolated conditions and very slow recharge similar to values and conditions found in the Phase 1 project area.

- In the northern portion of the Phase 2 study area ^{14}C residence time values from the Mt. Simon aquifer wells were generally young, typically less than 1,000 years. These values indicate this is an important recharge area.

- Most $\delta^{18}O$ values of groundwater samples from both project phases ranged from approximately -10‰ to -8‰ suggesting small variations of post-glacial climate and/or regional vegetation types.

- Four Mt. Simon-Hinckley or Hinckley groundwater samples in the southern portion of the Phase 2 area contained slightly elevated Na+K water similar to some groundwater in the Phase 1 area where the Mt. Simon Sandstone subcrop is not overlain by a thick extensive surficial sand layers typical of the northern portion of the Phase 2 area.

- Two groundwater samples exceeded the drinking water standard for arsenic (10 ug/l). These samples were collected from the buried sand and gravel aquifer at the Lake Ann WA site (Wright County) and the Wonewoc aquifer at the Pickerel Lake WA site (Anoka County).

- Hydrographs of Mt. Simon-Hinckley, Hinckley, and Fond du Lac aquifer wells in the northern portion of the Phase 2 area from early 2011 through the spring of 2012 correlate well with the precipitation pattern during that period. These data along with local stratigraphic information and residence time data indicate at least some direct hydraulic connection to the surface.

- Four zones of younger (less than 10,000 years) Mt. Simon aquifer groundwater were defined by this project. Three of these zones are elongated toward the Minnesota River valley. The two southerly zones were created by slow dispersed downward migra tion of recharge water through fine-grained glacial sediment and Cretaceous sand and shale. The northern two zones comprised of younger water were created by recharge from areas of local and focused recharge through interconnected sand and gravel layers.

A major accomplishment of this project is the creation of a network of observation well nests along the western margin of the Mt. Simon Sandstone that is considered an important recharge area for the aquifer. Long term water level and geochemistry data from these wells will enable future hydrologists to evaluate the local and regional effects of continuing future Mt. Simon aquifer groundwater pumping in the region. In addition, this project demonstrated the value of high frequency, nested water level measurements, groundwater chemistry, and residence time data in constructing conceptual models of groundwater flow and recharge.

Recommendations

The observation wells installed for this project have become part of the DNR observation well network. Continued monitoring of these wells will create a long term record that can be used to interpret changes in local and regional water supply due to water use or climate changes. In general, observation well record data become increasingly valuable as the length of record increases over time.

This project and Tipping (2011) have shown that the most critical recharge area for the Mt. Simon-Hinckley aquifer and Minneapolis-St. Paul metropolitan area water supply includes northeastern Wright County, eastern Sherburne County, and southern Isanti County. Protection of this region from water pollution should be a high priority for all levels of government. One of the primary purposes of the DNR and MGS County Geologic Atlas program is to create maps of pollution sensitivity for important aquifers. Atlases for Wright and Sherburne counties are currently in progress and will provide information for the next step in defining sensitive areas of the Mt. Simon-Hinckley aquifer. Unfortunately, there are no current plans for an Isanti County geologic atlas. This study has shown that protection of water resources in the Buffalo to Cambridge area has not only local implications but also is of significant importance for one of the major aquifers in the Minneapolis-St. Paul metropolitan area.

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Tables

Table 1 - Well summary

DNR OB#	MN Unique	County	Site Name	Formation	Drilling Method	Depth	UTM Easting	UTM Northing	Top casing elevation (ft above msl)	Ground elevation (ft above msl)	Depths of open hole or screened interval (ft)	Depth to Water (ft)
43000	210308	McLeod	McLeod Co Hwy Dept*	CMTS	unknown	500	408846	4959611	1020.9	1018.1	446-500	143
43005	773241	McLeod	Clouster Lake WMA	CMTS	DR/RC	580	411577	4973105	1033.1	1031.0	491-580	137.67
43006	773242	McLeod	Clouster Lake WMA	QBAA	DR/RC	120	411575	4973104	1033.2	1030.8	112-120	17.01
86011	773244	Wright	Lake Ann WA	CMTS	DR/RC	530	416903	4986009	1000.0	997.9	456-476	87.76
86012	773243	Wright	Lake Ann WA	QBAA	DR/RC	118	416904	4986010	1000.3	998.4	110-118	12.08
86013	777348	Wright	Anderson County Park	PMHN	DR/RC	450	418750	4997277	1004.4	1002.2	393-450	77.38
86014	777349	Wright	Anderson County Park	QBAA	MR	138	418750	4997276	1004.2	1002.2	130-138	65.54
27058	779945	Henn	Robina WMA	CMTS	DR/RC	695	441275	4987241	991.3	989.1	595-695	79.33
71027	777350	Sherburne	Sand Dunes State Forest	CMTS	DR/RC	208	448200	5026886	973.7	971.7	140-208	28.02
71028	777351	Sherburne	Sand Dunes State Forest	QBAA	MR	100	448202	5026888	973.8	971.9	90-98	27.66
71029	777352	Sherburne	Sherburne Nat WLR	PMFL	DR/RC	355	450173	5035011	981.9	979.8	215-355	31.04
71030	777353	Sherburne	Sherburne Nat WLR	QBAA	MR	161	450174	5035014	981.9	979.9	145-155	30.86
30015	779949	Isanti	Crooked Road WMA	CMTS	DR/RC	311.5	463566	5037109	973.6	971.4	270-310	26.81
30016	779947	Isanti	Spectacle Lake WMA	CMTS	DR/RC	262	467925	5045052	963.5	961.3	221-261	35.38
30017	779944	Isanti	Stanchfield WMA	PMHN	DR/RC	185	476144	5062969	962.5	960.5	164-184	12.06
2031	779942	Anoka	Pickerel Lake WMA	CMTS	DR/RC	410	465172	5020025	930.9	928.9	310-410	19.94
2032	779941	Anoka	Pickerel Lake WMA	CWOC	DR/RC	195	465172	5020027	931.0	929.0	170-195	14.14

Drilling methods:
MR = mud rotary
DR/RC = dual rotary/reverse circulation

QBAA = Quaternary buried aquifer
CWOC= Cambrian Wonowoc
CMTS = Cambrian Mt. Simon Sandstone

PMHN = Precambrian Hinckley Sandstone
PMFL = Precambrian Fond du Lac Formation

* Existing well, completed 1971

Table 2   Well pumping data summary

Date Sampled	MN Unique	County	Site Name	Formation	Depth to static water from top Casing (ft.)	Static water water elevation (ft. above msl)	Pumping Minutes	Volume (gallons)	Pumping Rate (gpm)	Drawdown (feet)	Specific Capacity (gpm/drawdown)
10/11/2010	210308	McLeod	McLeod Co Hwy Dept	CMTS	146.02	874.88	56	890	16	11.17	1.4
10/12/2010	773241	McLeod	Clouster Lake WMA	CMTS	137.62	895.43	74	1145	15	1.83	8.5
10/11/2010	773242	McLeod	Clouster Lake WMA	QBAA	16.69	1016.47	26	560	22	3.57	6.1
10/12/2010	773244	Wright	Lake Ann WA	CMTS	87.83	912.13	40	865	22	28.98	0.7
10/12/2010	773243	Wright	Lake Ann WA	QBAA	11.76	988.54	24	600	25	2.25	11.2
10/12/2010	777348	Wright	Anderson County Park	PMHN	77.31	927.04	46	715	16	43.36	0.4
10/12/2010	777349	Wright	Anderson County Park	QBAA	64.54	939.68	20	295	15	39.20	0.4
10/13/2010	777350	Sherburne	Sand Dunes State Forest	CMTS	27.61	946.04	41	1260	31	5.53	5.6
10/13/2010	777351	Sherburne	Sand Dunes State Forest	QBAA	27.34	946.48	40	1192	30	22.17	1.4
10/13/2010	777352	Sherburne	Sherburne National Wildlife Refuge	PMFL	30.73	951.21	45	1180	26	14.86	1.8
10/13/2010	777353	Sherburne	Sherburne National Wildlife Refuge	QBAA	30.44	951.46	37	670	18	64.91	0.3
10/13/2010	779949	Isanti	Crooked Road WMA	CMTS	26.99	946.57	40	1190	30	24.5	1.2
10/14/2010	779947	Isanti	Spectacle Lake WMA	CMTS	35.83	927.62	52	1590	31	9.06	3.4
10/14/2010	779944	Isanti	Stanchfield WMA	PMHN	12.39	950.14	40	1040	26	47.38	0.55
12/2/2010	779942	Anoka	Pickerel WA	CMTS	20.54	910.34	63	1040	17	3.88	4.3
12/2/2010	779941	Anoka	Pickerel WA	CWOC	14.6	916.28	39	1020	26	6.7	3.9
10/12/2010	779945	Hennepin	Robina WMA	CMTS	79.33	911.97	57	1745	31	3.33	9.3

QBAA = Quaternary buried aquifer
CWOC= Cambrian Wonowoc
CMTS = Cambrian Mt. Simon Sandstone
PMHN = Precambrian Hinckley Sandstone
PMFL = Precambrian Fond du Lac Formation

Table 3 Field sample collection and handling

Parameter	Lab	Sample container	Head space	Rinse	Filter	Preservative	Refrigeration	Shelf life	Field duplicate	Field blank	Storage duplicate
Tritium	Waterloo	500 ml, HDPE	yes	**NO**	no	no	no	long	1 for every 20	none	yes
18O, Deuterium	Waterloo	60 ml, HDPE	yes	**NO**	no	no	no	long	1 for every 20	none	yes
Cations	U of M	15 ml, Fisherbrand BLUE cap	yes	yes *	yes	1 drop 6N HCl	yes	2-3 weeks	1 for every 20	1 for every 20 ****	no
Anions	U of M	50 ml, Argos BLACK ***	yes	yes *	yes	no	yes	2-3 weeks	1 for every 20	1 for every 20 ****	no
Trace constituents	U of M	15 ml, Sarstedt RED cap	yes	yes *	yes	5 drops 15N HNO_3	yes	2-3 weeks	1 for every 20	1 for every 20 ****	no
Alkalinity	onsite	500 ml, plastic	**NO**	yes **	no	no	Yes, if not analyzed onsite	24-48 hours	none	none	no
14C	U of M	30 gallon barrel	yes	no	yes	NH_4OH to pH 8.5	no	years	none	none	no

* Rinse the bottle once with FILTERED sample water prior to collecting the sample. Rinsing means fill the bottle with sample water (FILTERED if sample is filtered) and then pour the contents out over the cap.

** Rinse the bottle three times with sample water prior to collecting the sample. Fill bottle submerged with cap in hand. Seal bottle submerged ensuring no remnant bubbles.

*** Fill 50 ml anion bottle unless filtering is very difficult. Bottle must be at least 1/3 full.

**** Use DI water from small bottle for field blanks (NOT THE CARBOY). Pour DI water into the back of the syringe when the plunger is removed. Fill bottles through filter.

Table 4 Residence time indicators, stable isotopes, and selected trace elements

						Trace elements**		Residence time indicators		Stable isotopes****	
MN unique	Site name	County	Formation	Depth (ft)	Date sampled	As	B	^{14}C (years)	Tritium***	Deuterium	^{18}O
210308	McLeod Co Hwy Dept	McLeod	CMTS	500	10/11/2010	<0.66	500	11,000	2.7	-63.58	-9.5
773241	Clouster Lake WMA	McLeod	CMTS	580	10/12/2010	<2.3	150	14,000	<0.8	-68.45	-10.24
773242	Clouster Lake WMA	McLeod	QBAA	120	10/11/2010	9.66	200	6,000	<0.8	-64.86	-9.97
773243	Lake Ann WA	Wright	QBAA	118	10/12/2010	11.63	100	60	<0.8	-58.96	-9.38
773244	Lake Ann WA	Wright	CMTS	530	10/12/2010	<0.66	300	20,000	<0.8	-64.49	-9.59
777348	Anderson County Park	Wright	PMHN	450	10/12/2010	<2.3	500	6,000	<0.8	-62.97	-8.26
777349	Anderson County Park	Wright	QBAA	138	10/12/2010	<2.3	270	2,000	<0.8	-60.07	-8.82
777350	Sand Dunes State Forest	Sherburne	CMTS	208	10/13/2010	<0.66	<45	1,400	4.6	-72.42	-10.44
777351	Sand Dunes State Forest	Sherburne	QBAA	100	10/13/2010	<2.3	<45	60	19.6	-72.15	-10.37
777352	Sherburne Nat NWR	Sherburne	PMFL	355	10/13/2010	<0.66	<45	8,000	<0.8	-65.99	-8.83
777353	Sherburne Nat NWR	Sherburne	QBAA	161	10/13/2010	3.29	<45	1,300	4.1	-61.91	-8.44
779941	Pickerel Lake WMA	Anoka	CWOC	195	12/2/2010	14.4	46	2,000	<0.8	-67.18	-9.79
779942	Pickerel Lake WMA	Anoka	CMTS	410	12/2/2010	6.4	<45	2,000	<0.8	-60.01	-8.08
779944	Stanchfield WMA	Isanti	PMHN	185	10/14/2010	<0.66	60	300	<0.8	-57.09	-8.13
779945	Robina WMA	Hennepin	CMTS	695	10/12/2010	<2.3	100	15,000	<0.8	-53.97	-7.67
779947	Spectacle Lake WMA	Isanti	CMTS	262	10/14/2010	<0.66	<45	3,000	<0.8	-67.05	-9.85
779949	Crooked Road WMA	Isanti	CMTS	311.5	10/13/2010	4.62	<45	600	<0.8	-62.87	-9.02

** ug/l (parts per billion)
*** tritium units (TU), < means not detected

**** delta values reported in units per thousand relative to standard
NA = not analyzed

QBAA = Quaternary buried aquifer
CWOC = Cambrian Wonewoc Sandstone

CMTS = Cambrian Mt. Simon Sandstone
PMHN = Precambrian Hinckley Sandstone
PMFL = Fond du Lac Formation

Table 5 Selected anion and cation data

						Anions mg/l				Cations mg/l					
MN unique	**Site name**	**County**	**Formation**	**Depth (ft)**	**Date sampled**	Cl	SO4	Br	Cl/Br	Ca	Mg	Na	K	Fe	Mn
210308	McLeod Co Hwy Dept	McLeod	CMTS	500	10/11/2010	11.3	8.03	0.050	226	39.9	15.3	76.9	2.69	1.15	0.066
773241	Clouster Lake WMA	McLeod	CMTS	580	10/12/2010	2.08	95.2	0.034	61	83.1	38.7	57.5	4.92	1.80	0.026
773242	Clouster Lake WMA	McLeod	QBAA	120	10/11/2010	0.88	62.1	0.022	40	86.4	38.9	47.3	4.84	1.06	0.094
773243	Lake Ann WA	Wright	QBAA	118	10/12/2010	0.79	16.1	0.024	33	100.5	38.5	22.1	6.32	0.952	0.232
773244	Lake Ann WA	Wright	CMTS	530	10/12/2010	3.45	75.8	0.027	128	42.1	19.1	75.5	5.13	0.585	0.075
777348	Anderson County Park	Wright	PMHN	450	10/12/2010	1.97	122	0.025	79	73.6	37.7	90.6	7.05	2.82	0.051
777349	Anderson County Park	Wright	QBAA	138	10/12/2010	1.68	64.9	0.025	67	83.1	39.8	47.7	5.71	0.527	0.376
777350	Sand Dunes State Forest	Sherburne	CMTS	208	10/13/2010	0.65	13.4	0.005	130	47.1	11.3	2.68	1.35	0.581	0.182
777351	Sand D unes State Forest	Sherburne	QBAA	100	10/13/2010	0.70	16.1	0.006	117	49.7	11.9	3.42	1.11	0.185	0.134
777352	Sherburne Nat NWR	Sherburne	PMFL	355	10/13/2010	1.80	2.61	0.011	164	45.4	12.8	9.73	2.91	0.685	0.034
777353	Sherburne Nat NWR	Sherburne	QBAA	161	10/13/2010	0.93	2.30	0.008	116	43.8	13.4	9.29	1.79	1.082	0.263
779941	Pickerel Lake WMA	Anoka	CWOC	195	12/2/2010	2.13	12.6	0.008	266	49.4	20.0	7.93	6.46	0.006	0.083
779942	Pickerel Lake WMA	Anoka	CMTS	410	12/2/2010	1.04	1.17	0.005	208	57.6	21.0	6.24	2.27	1.364	0.113
779944	Stanchfield WMA	Isanti	PMHN	185	10/14/2010	1.31	0.63	0.008	164	69.2	30.3	5.47	1.98	1.990	0.421
779945	Robina WMA	Hennepin	CMTS	695	10/12/2010	0.98	61.1	0.016	61	97.9	29.1	10.5	7.73	1.660	0.072
779947	Spectacle Lake WMA	Isanti	CMTS	262	10/14/2010	0.52	3.09	0.005	104	36.9	13.4	6.44	2.96	0.029	0.125
779949	Cr ooked Road WMA	Isanti	CMTS	311.5	10/13/2010	0.48	1.67	0.006	80	48.2	14.2	4.08	1.48	0.029	0.102

QBAA = Quaternary buried aquifer
CWOC = Cambrian Wonewoc Sandstone
CMTS = Cambrian Mt. Simon Sandstone
PMHN = Precambrian Hinckley Sandstone
PMFL = Fond du Lac Formation

Figures

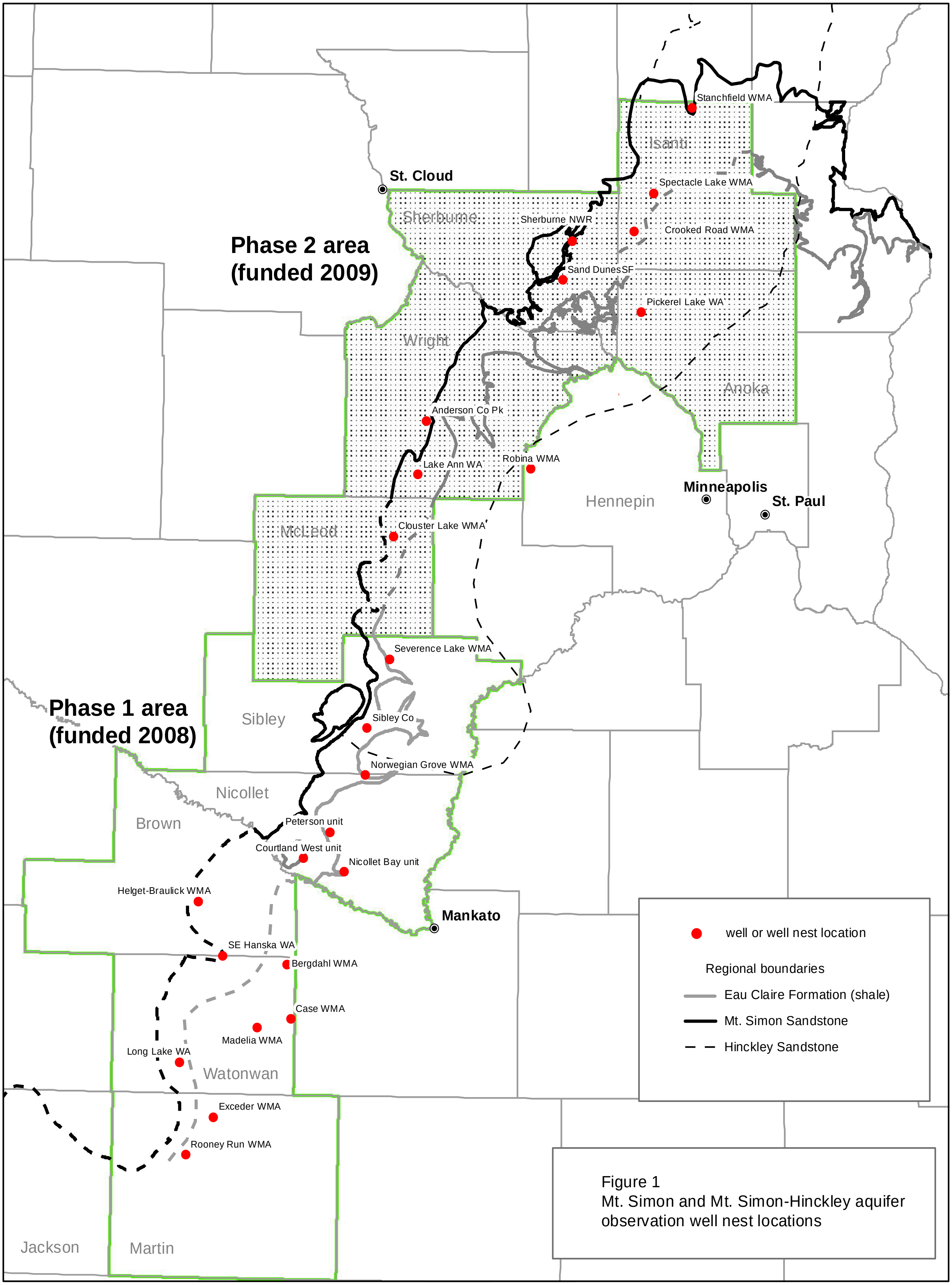


Figure 1
Mt. Simon and Mt. Simon-Hinckley aquifer observation well nest locations

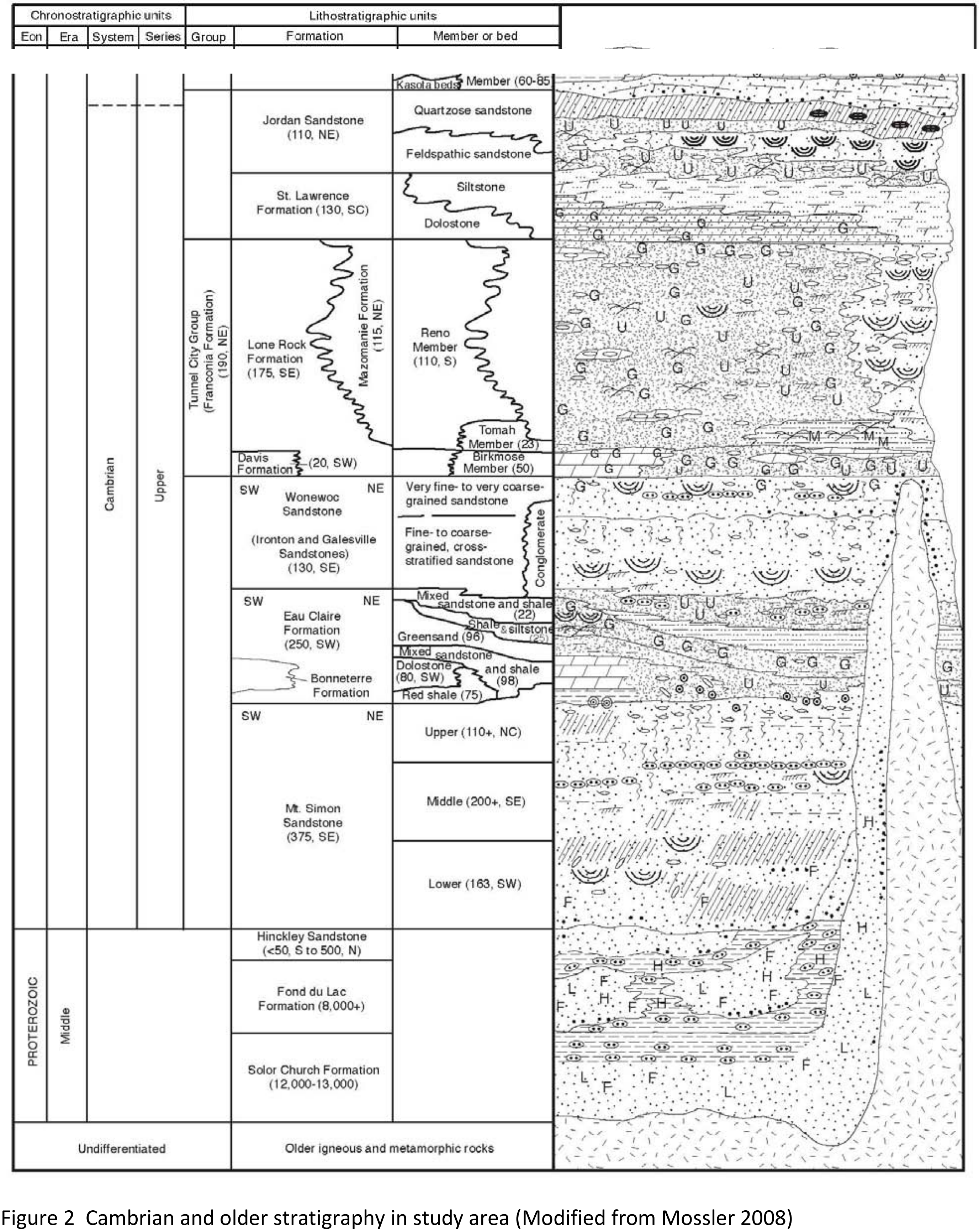


Figure 2 Cambrian and older stratigraphy in study area (Modified from Mossler 2008)

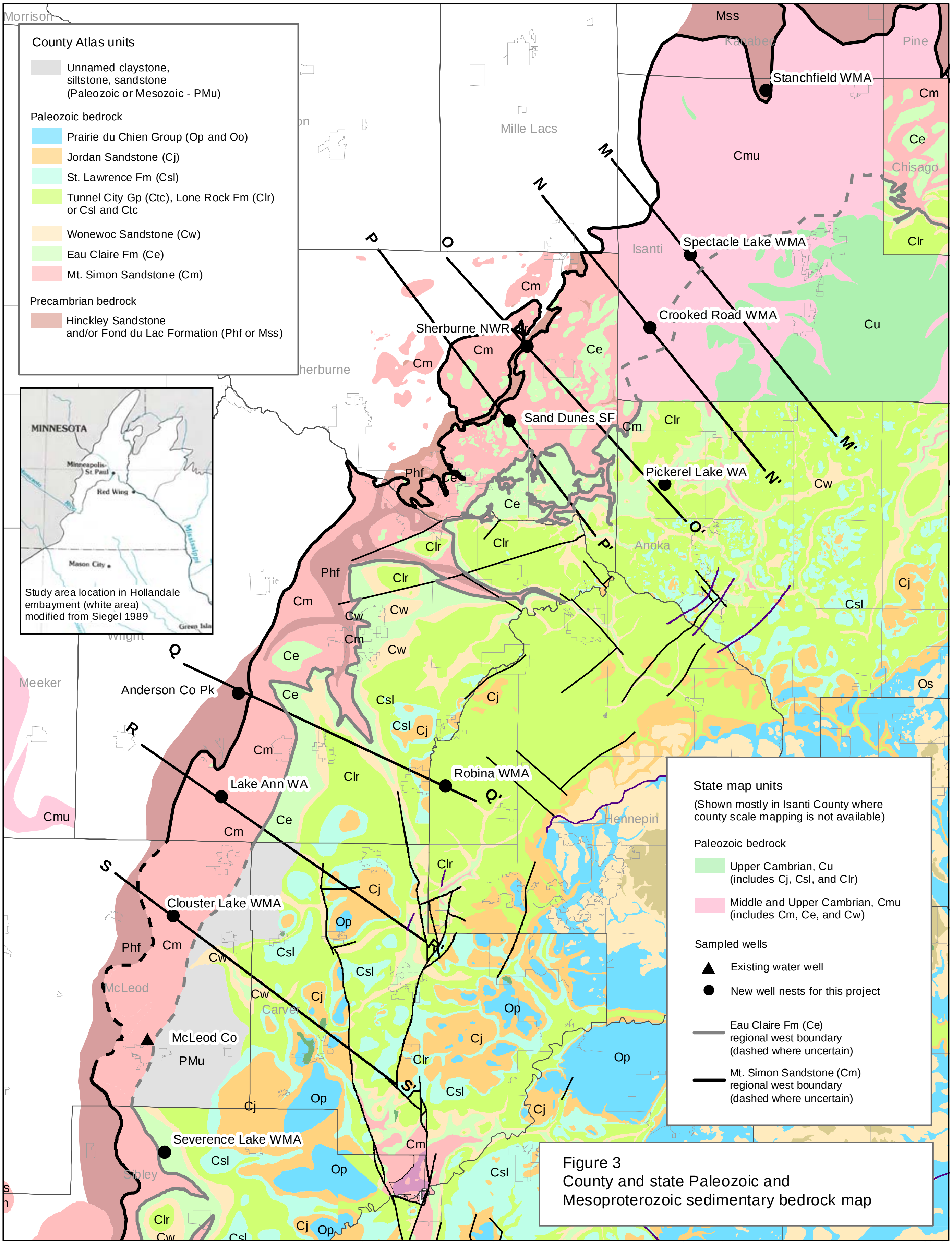


Figure 3
County and state Paleozoic and Mesoproterozoic sedimentary bedrock map

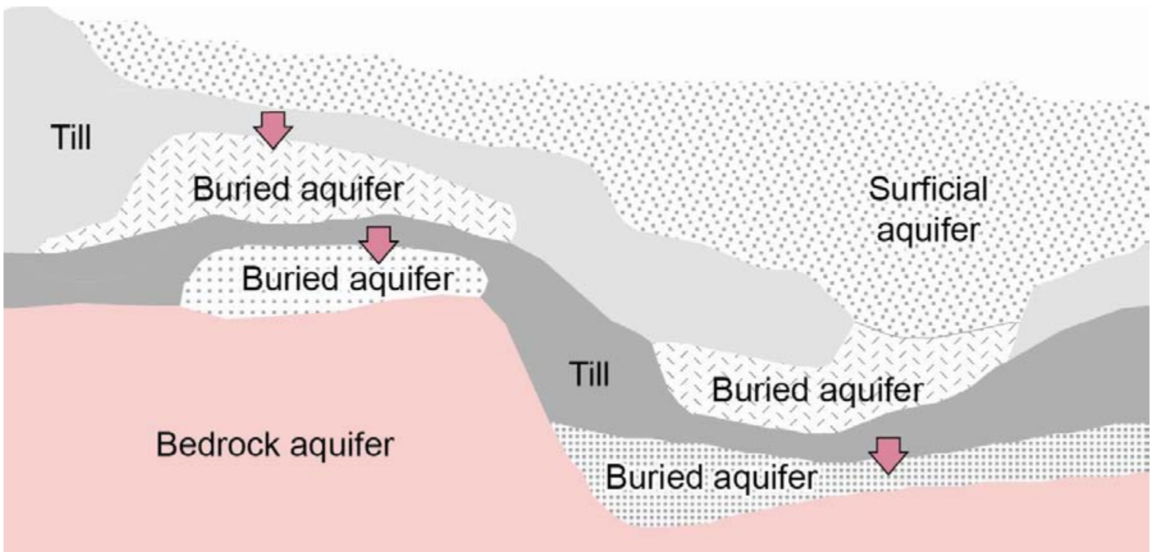


Figure 4

Schematic cross section of focused recharge to a bedrock aquifer through connected buried sand and gravel aquifers

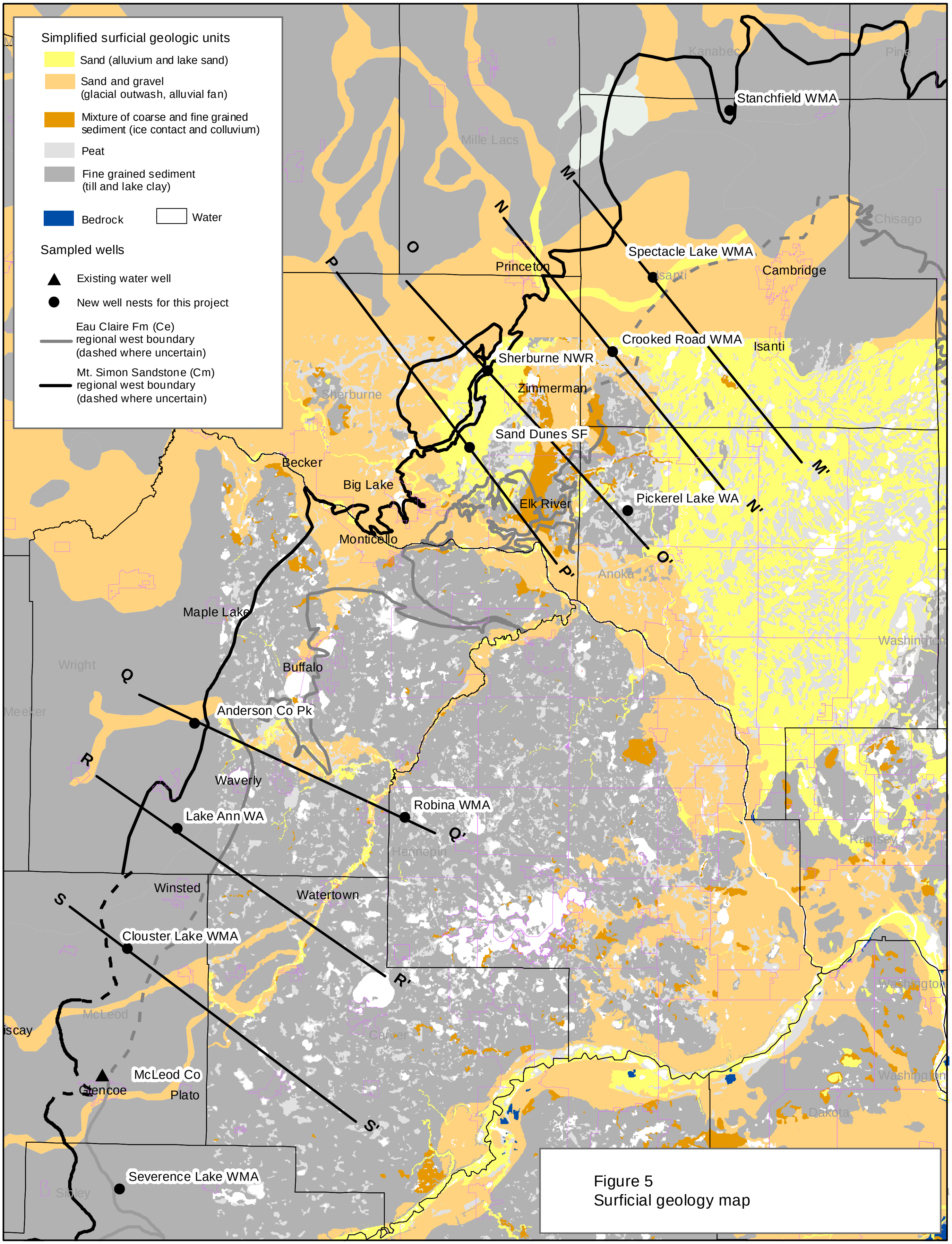


Figure 5
Surficial geology map

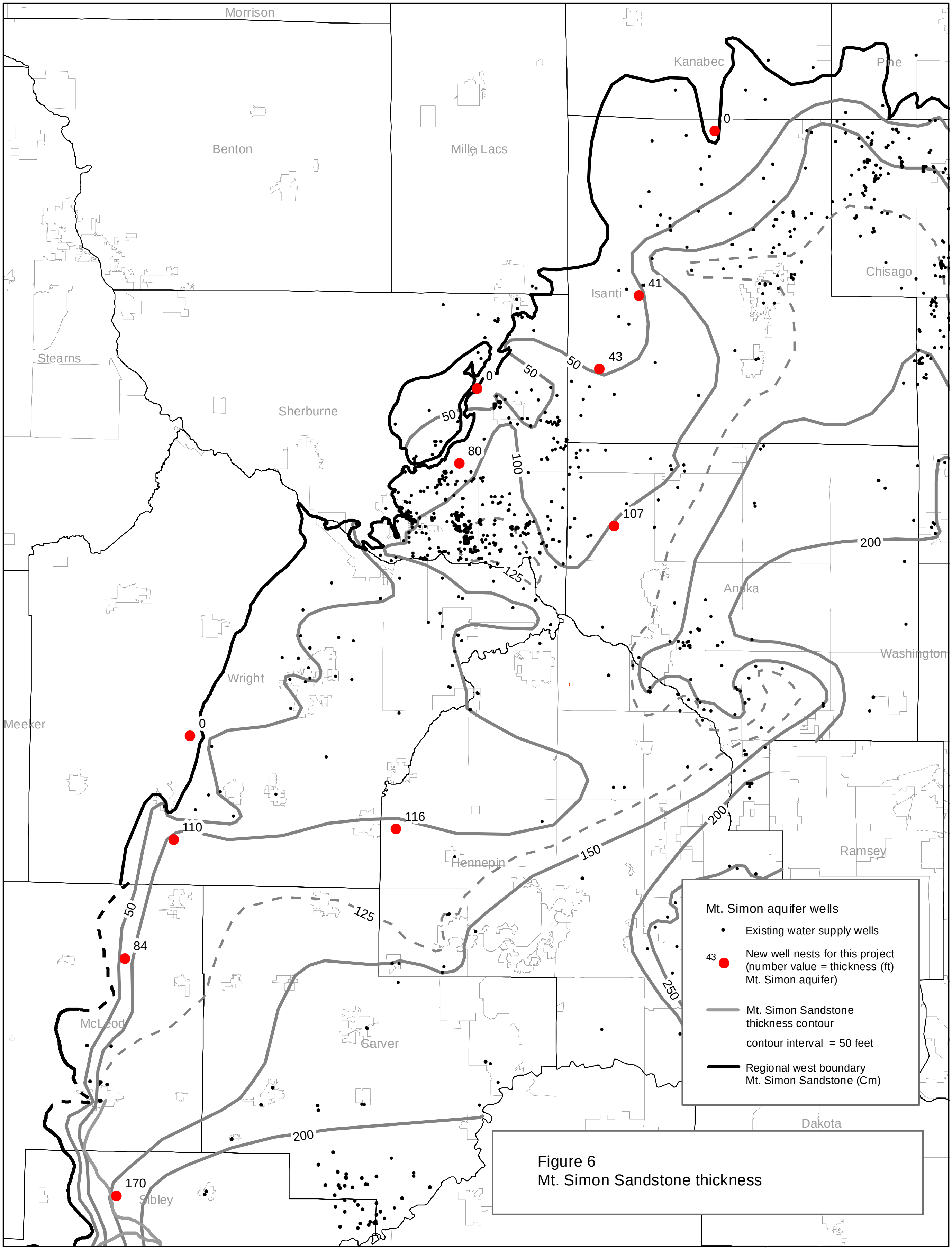


Figure 6
Mt. Simon Sandstone thickness

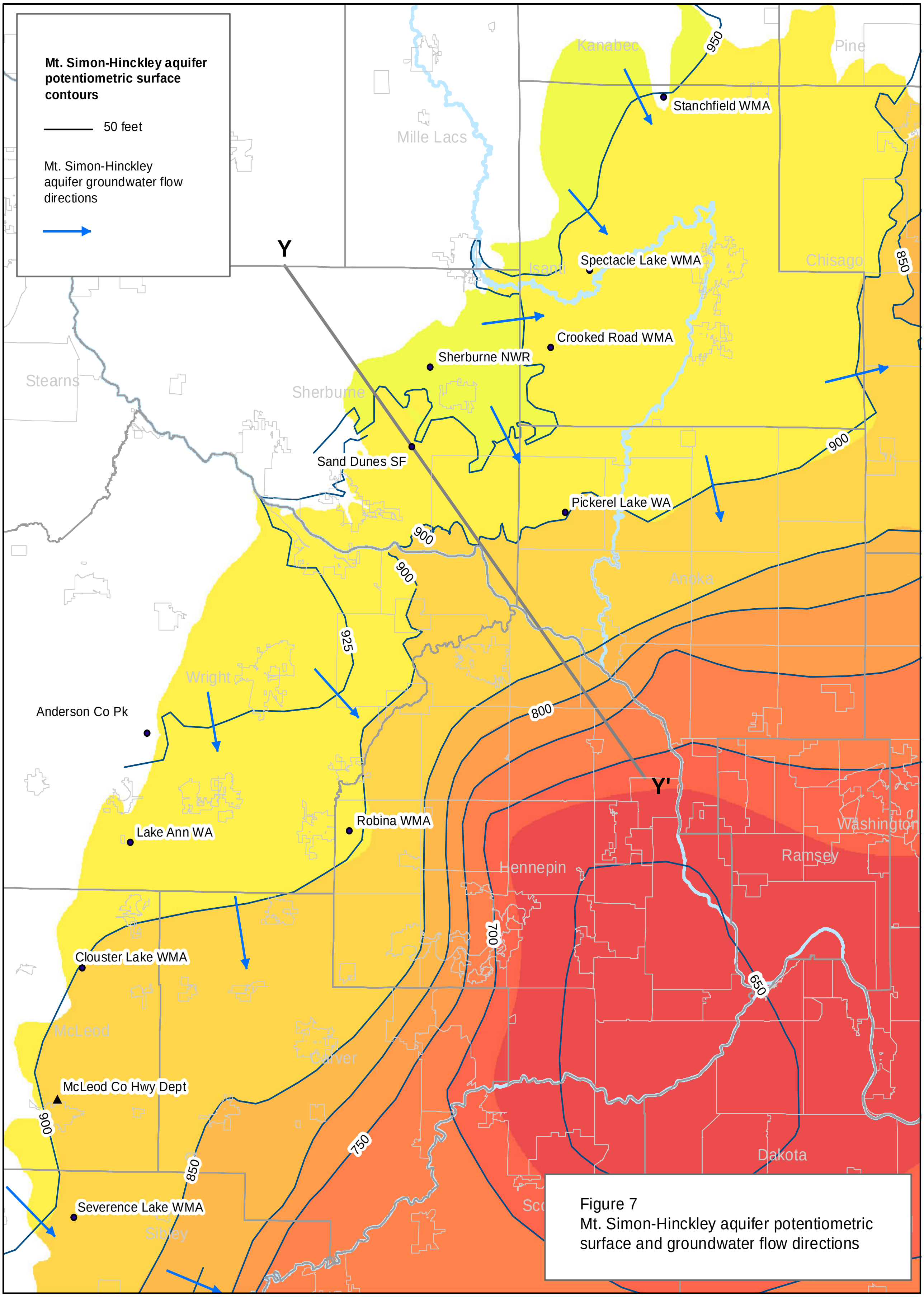


Figure 7
Mt. Simon-Hinckley aquifer potentiometric surface and groundwater flow directions

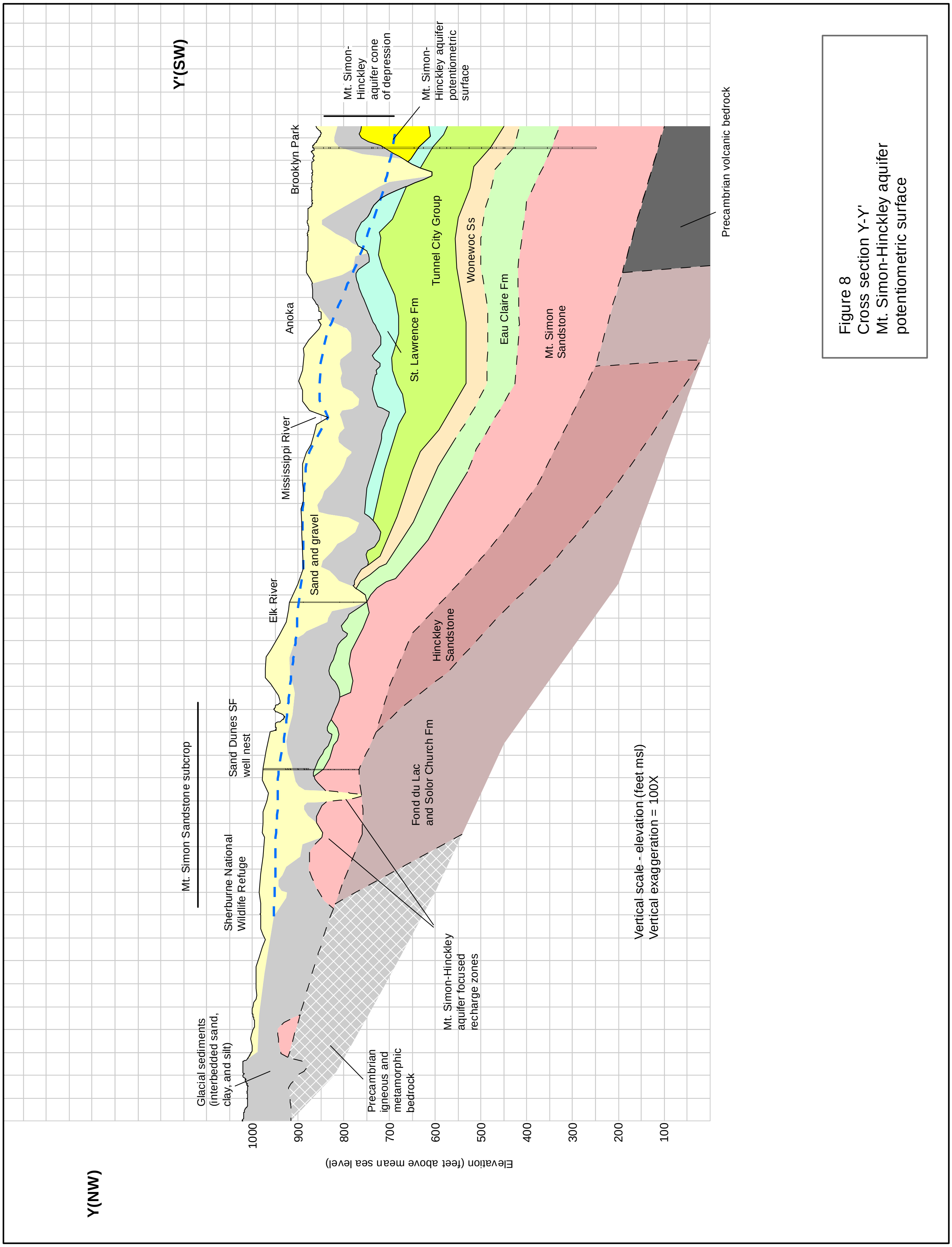


Figure 8
Cross section Y-Y'
Mt. Simon-Hinckley aquifer potentiometric surface

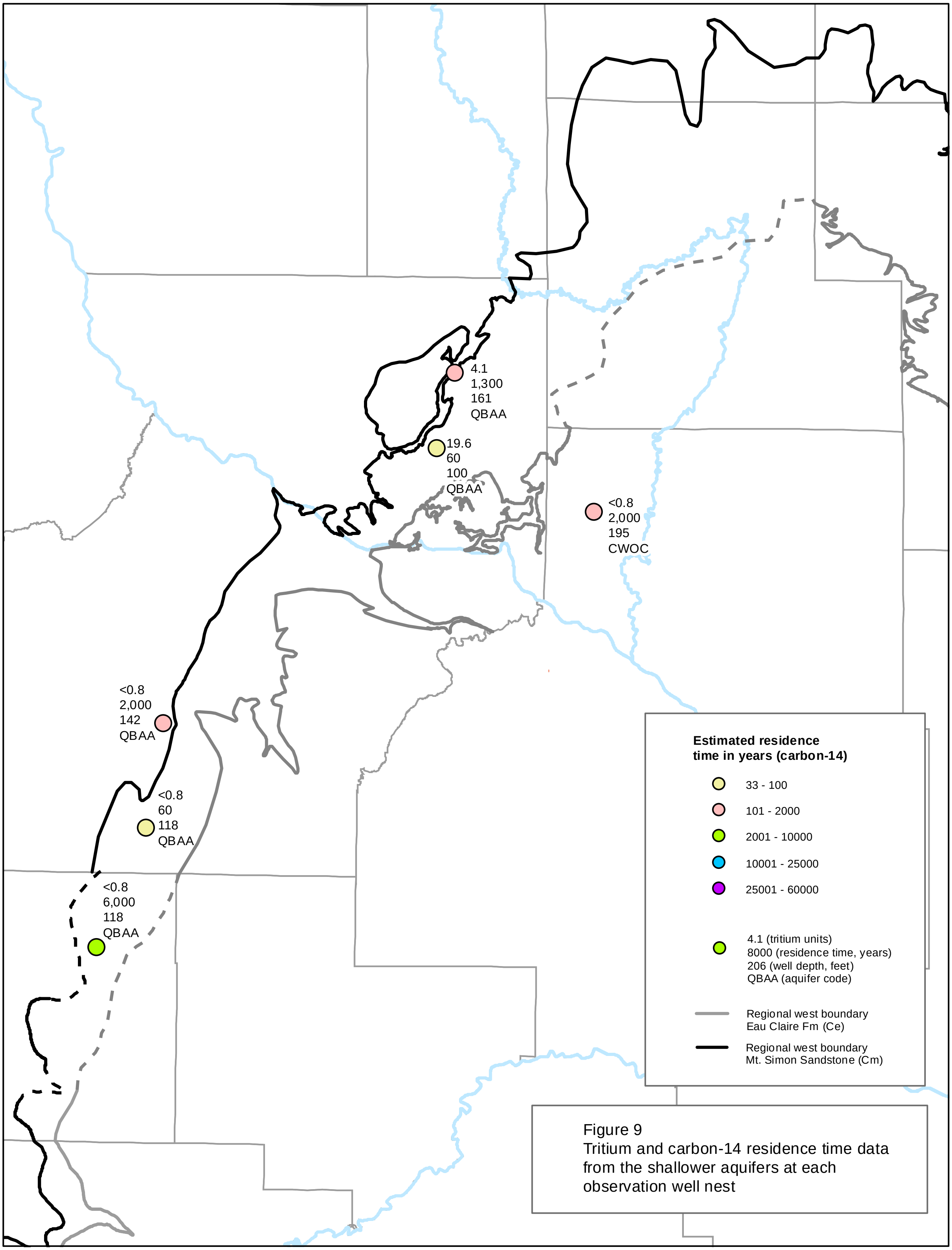


Figure 9
Tritium and carbon-14 residence time data from the shallower aquifers at each observation well nest

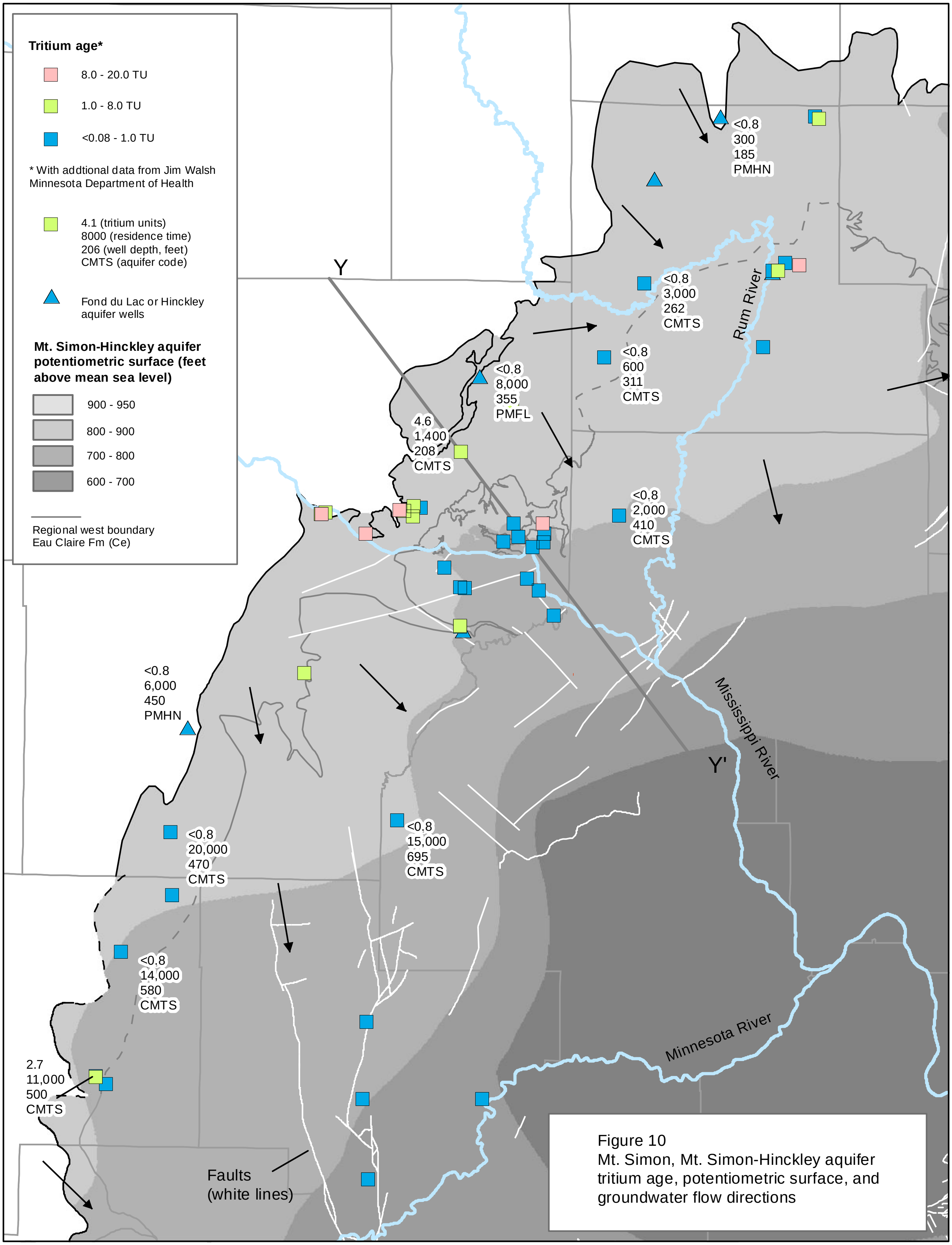


Figure 10
Mt. Simon, Mt. Simon-Hinckley aquifer tritium age, potentiometric surface, and groundwater flow directions

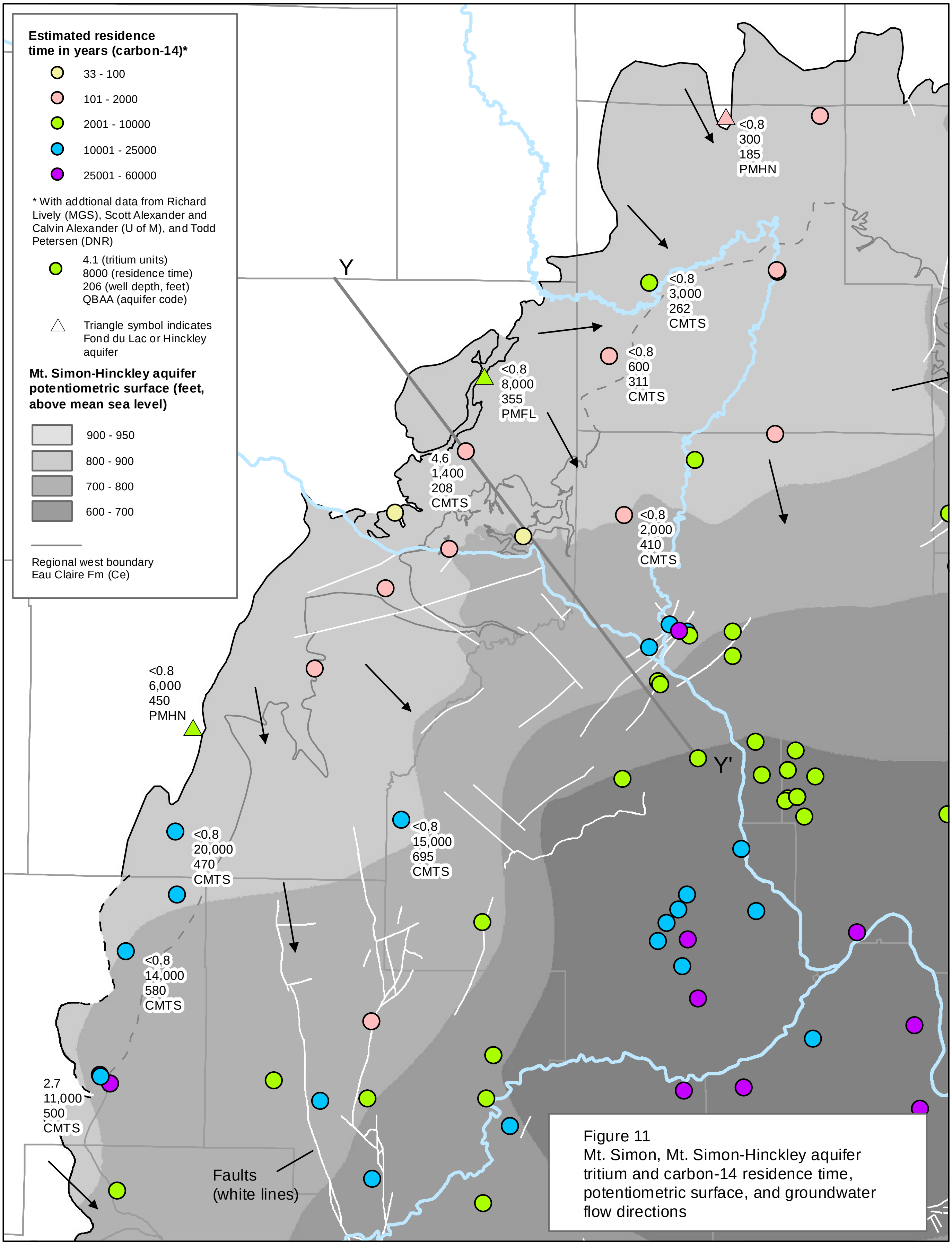
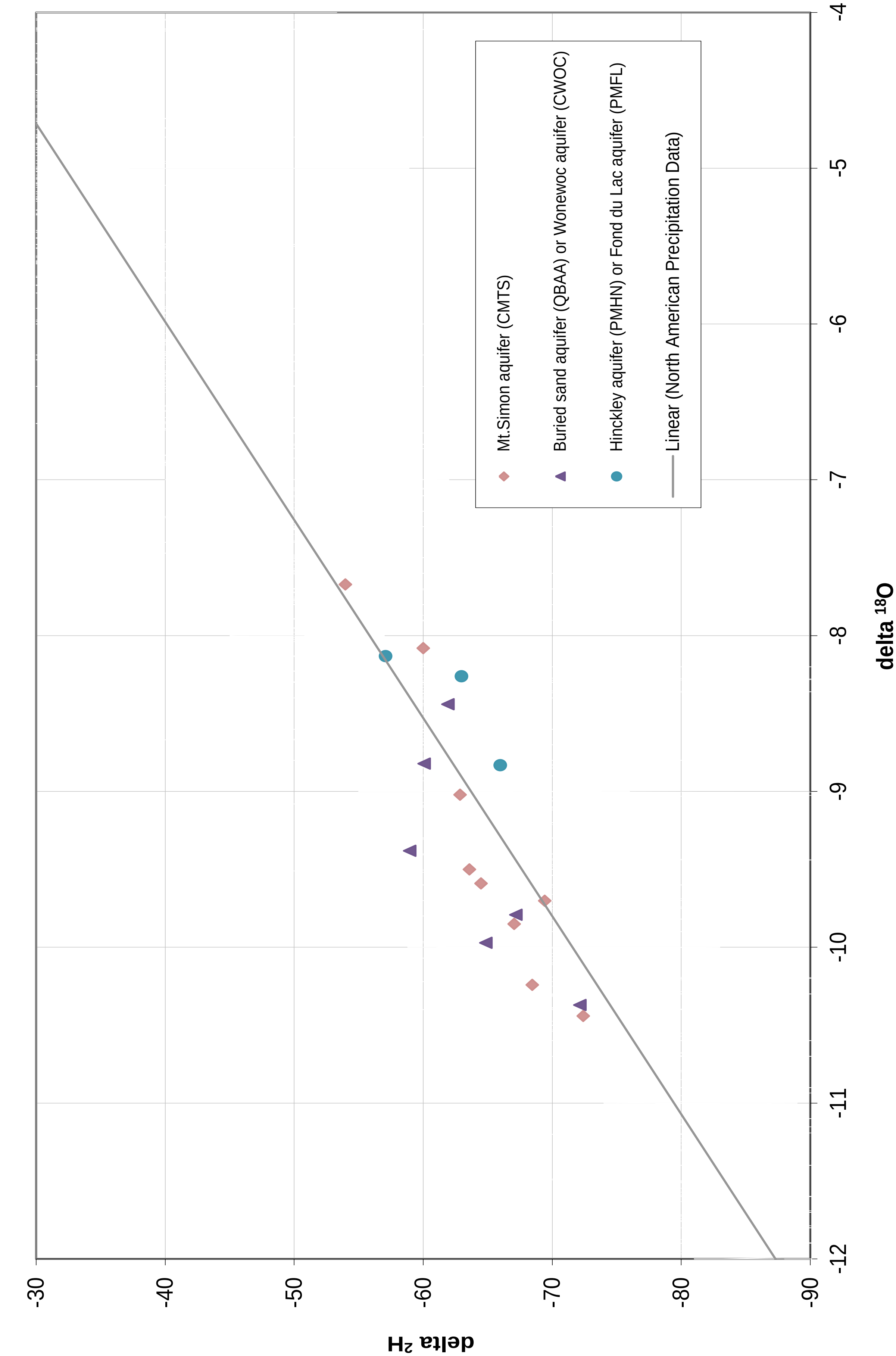


Figure 11
Mt. Simon, Mt. Simon-Hinckley aquifer tritium and carbon-14 residence time, potentiometric surface, and groundwater flow directions

Figure 12 Stable isotope data compared with North American meteoric line



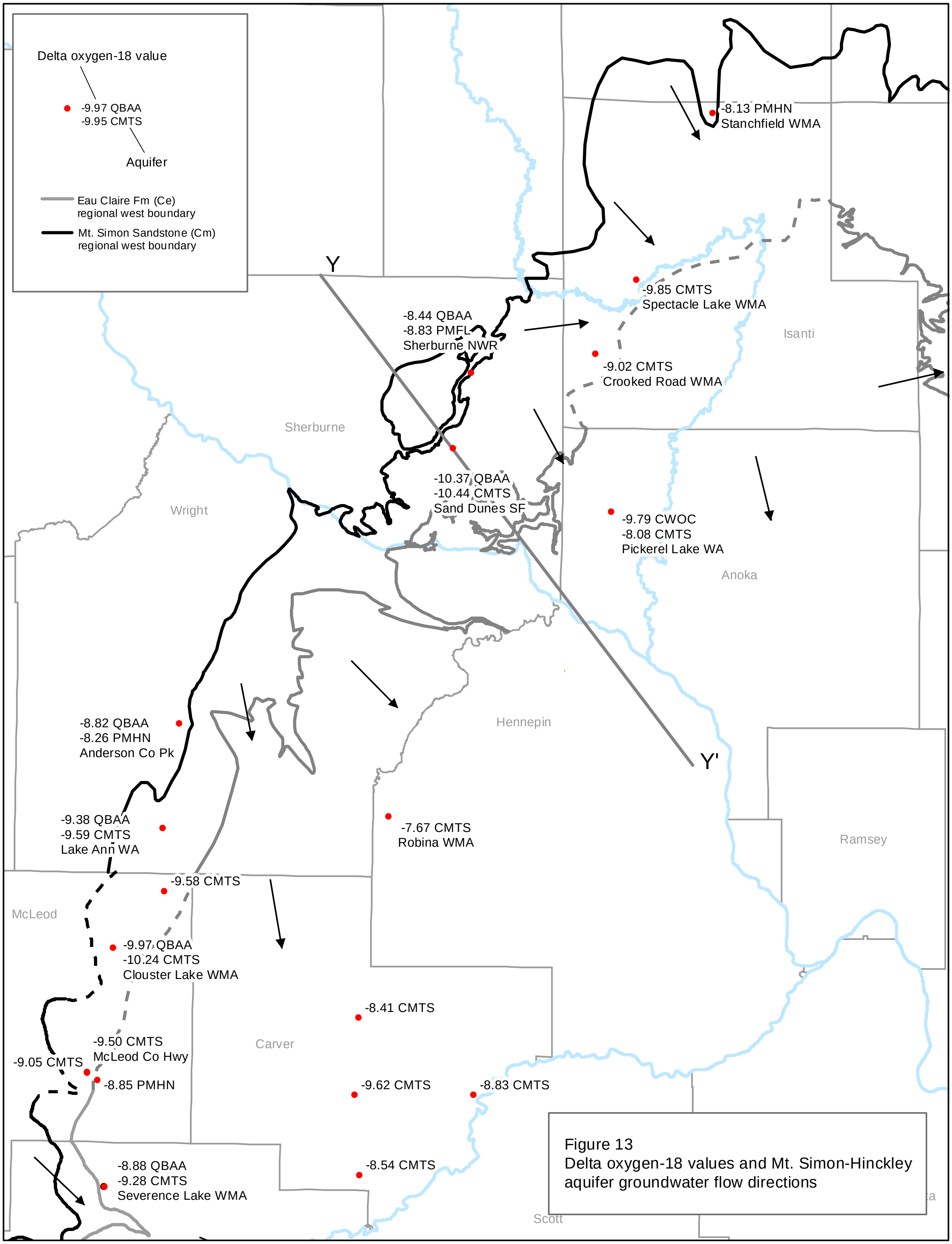
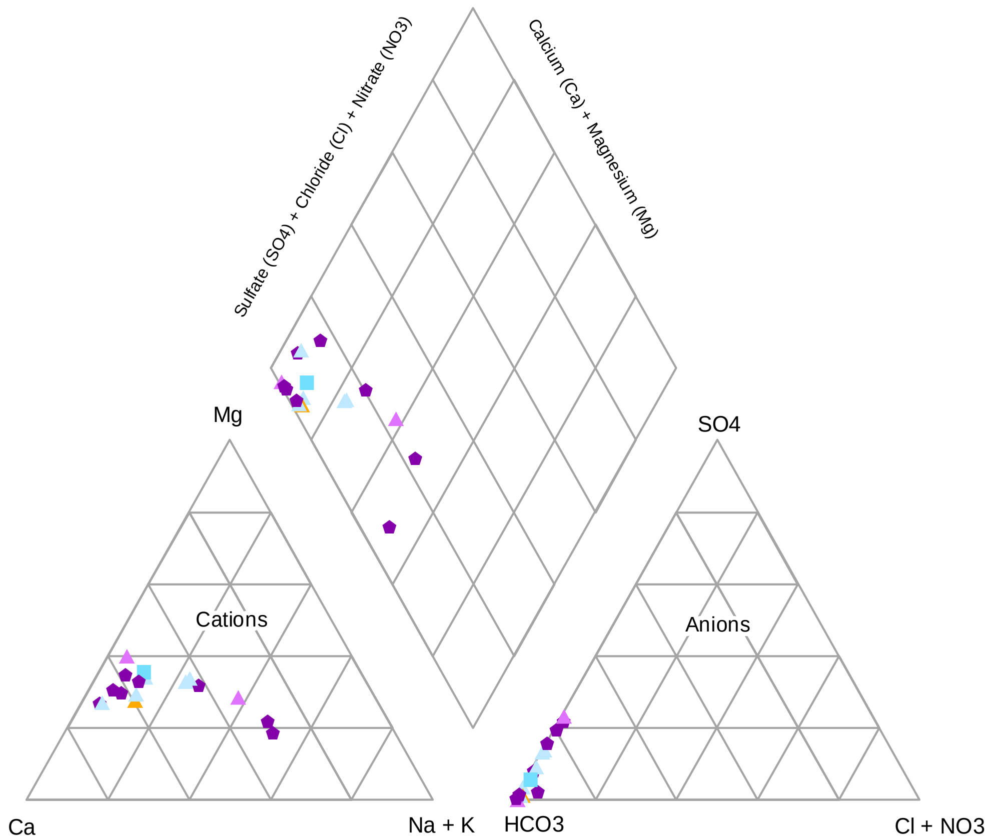


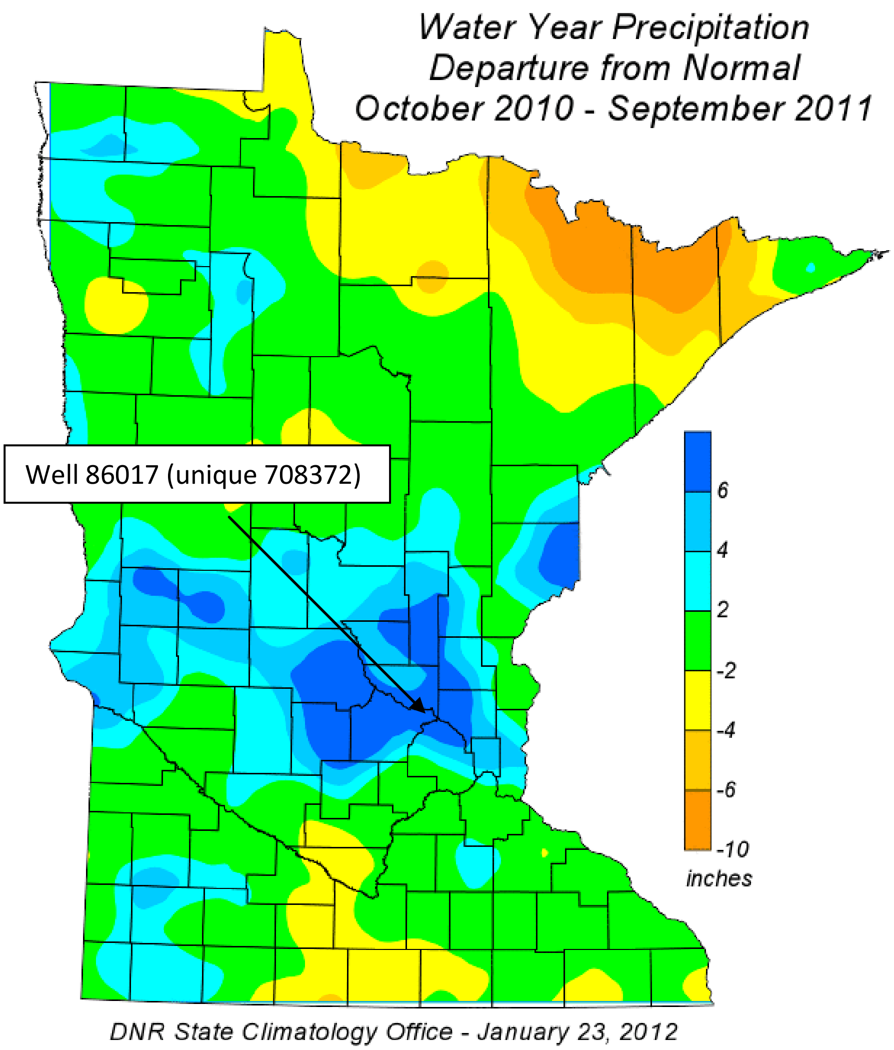
Figure 13
Delta oxygen-18 values and Mt. Simon-Hinckley aquifer groundwater flow directions



Aquifer

- QBAA - Quaternary buried aquifer
- CWOC - Cambrian Wonewoc Sandstone
- CMTS - Cambrian Mt. Simon Sandstone
- PMHN - Precambrian Hinckley Sandstone
- PMFL - Precambrian Fond du Lac Formation

Figure 14
Ternary diagram showing relative abundances of major cations and anions



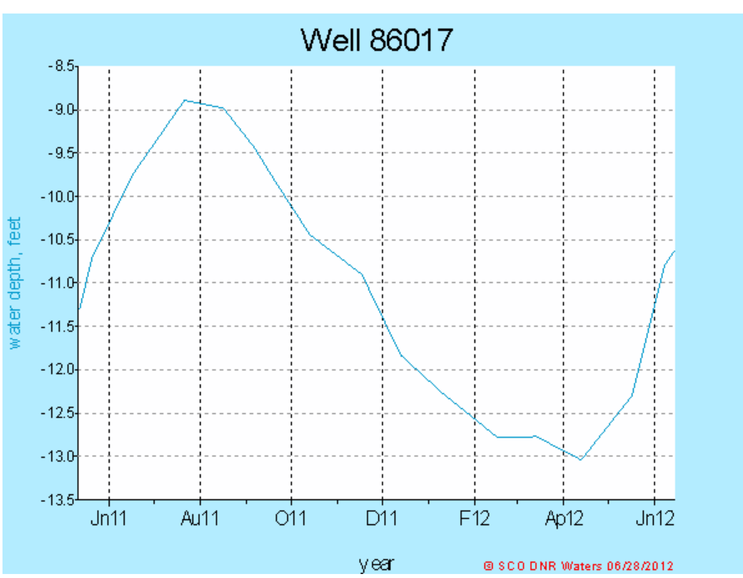


Figure 15

Precipitation departure from normal October 2010 - September 2011 and hydrograph of typical water table observation well in the Phase 2 study area

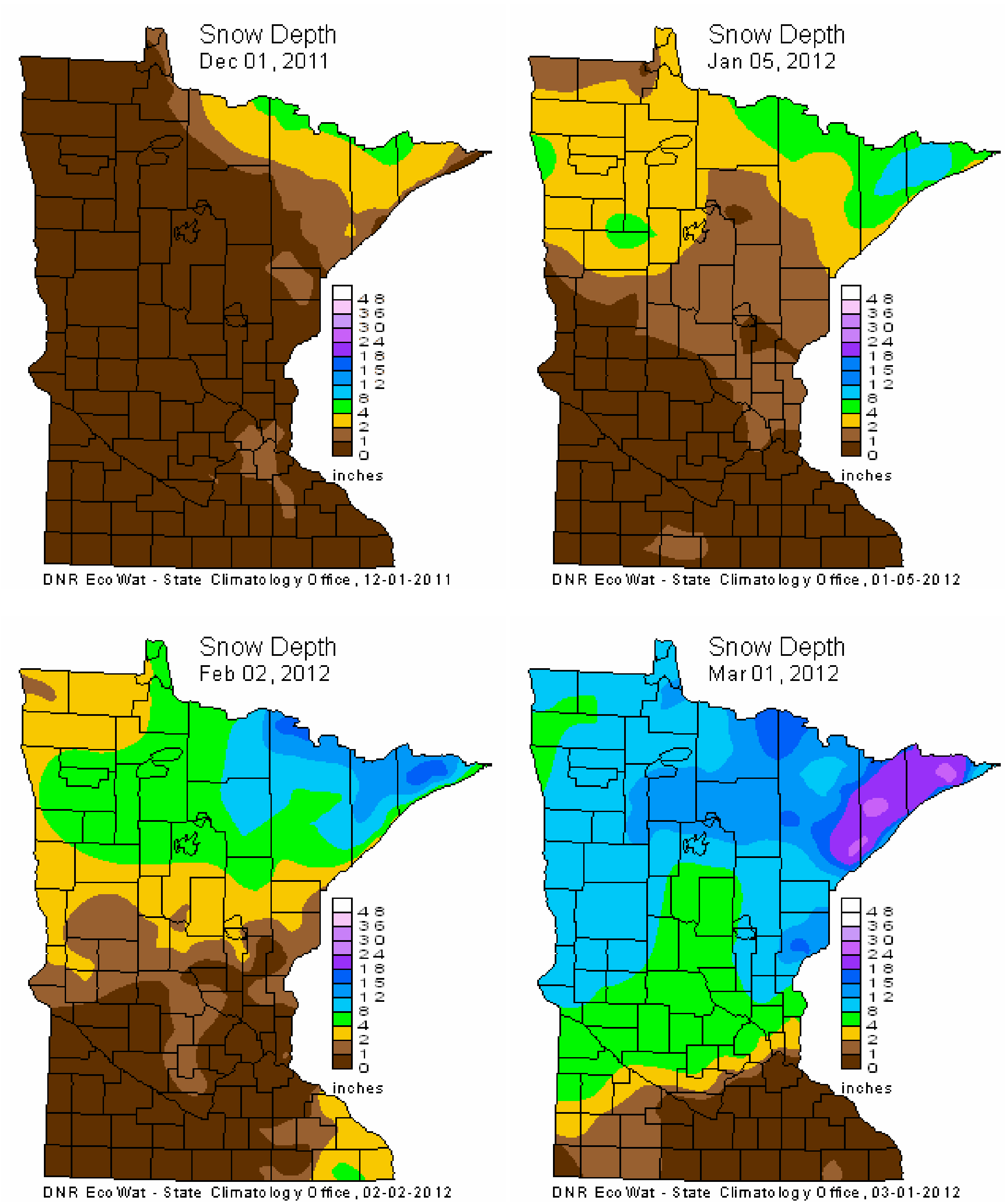


Figure 16

Snow depth December 2011 - March 2012

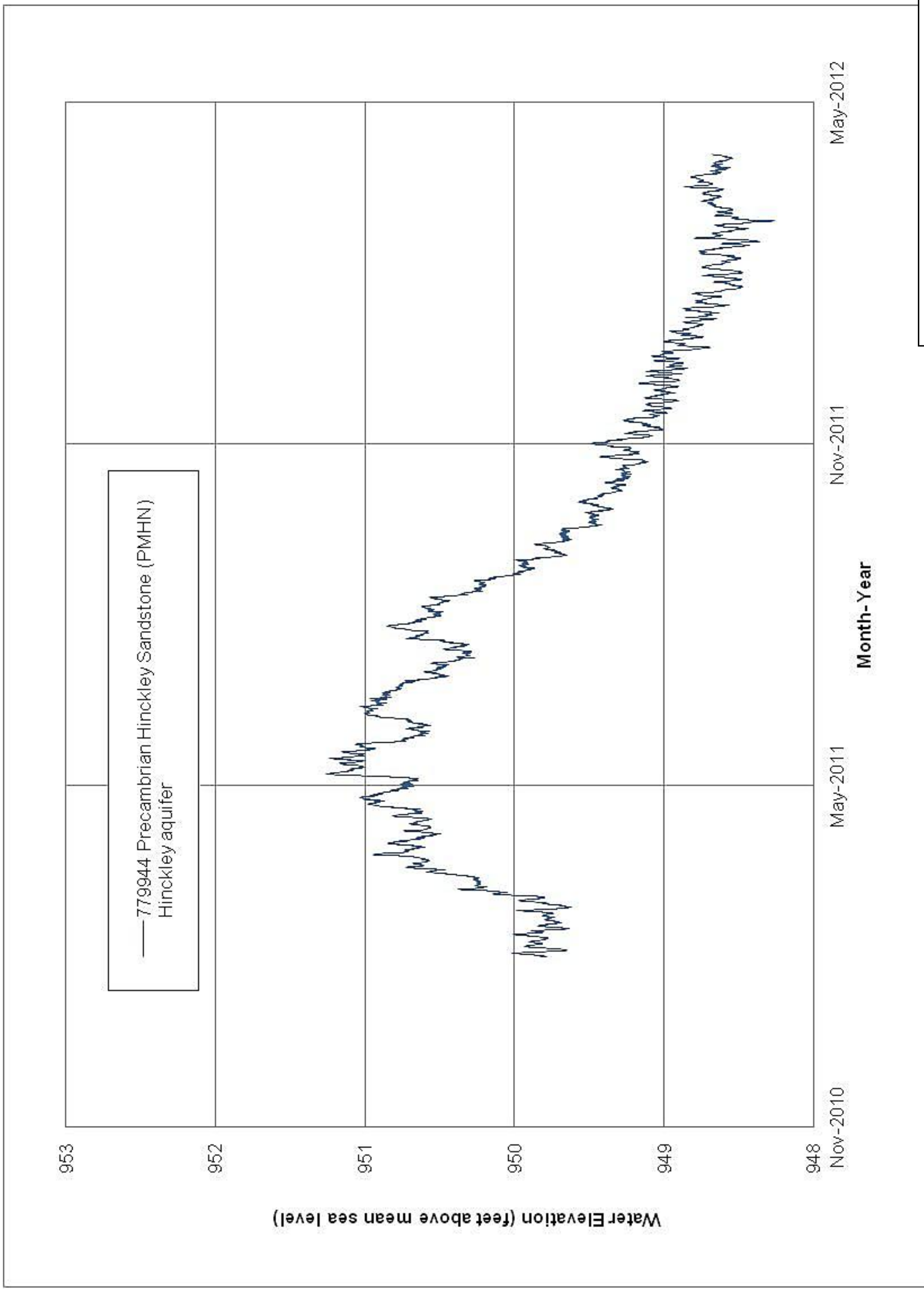


Figure 17
Stanchfield WMA
hydrograph

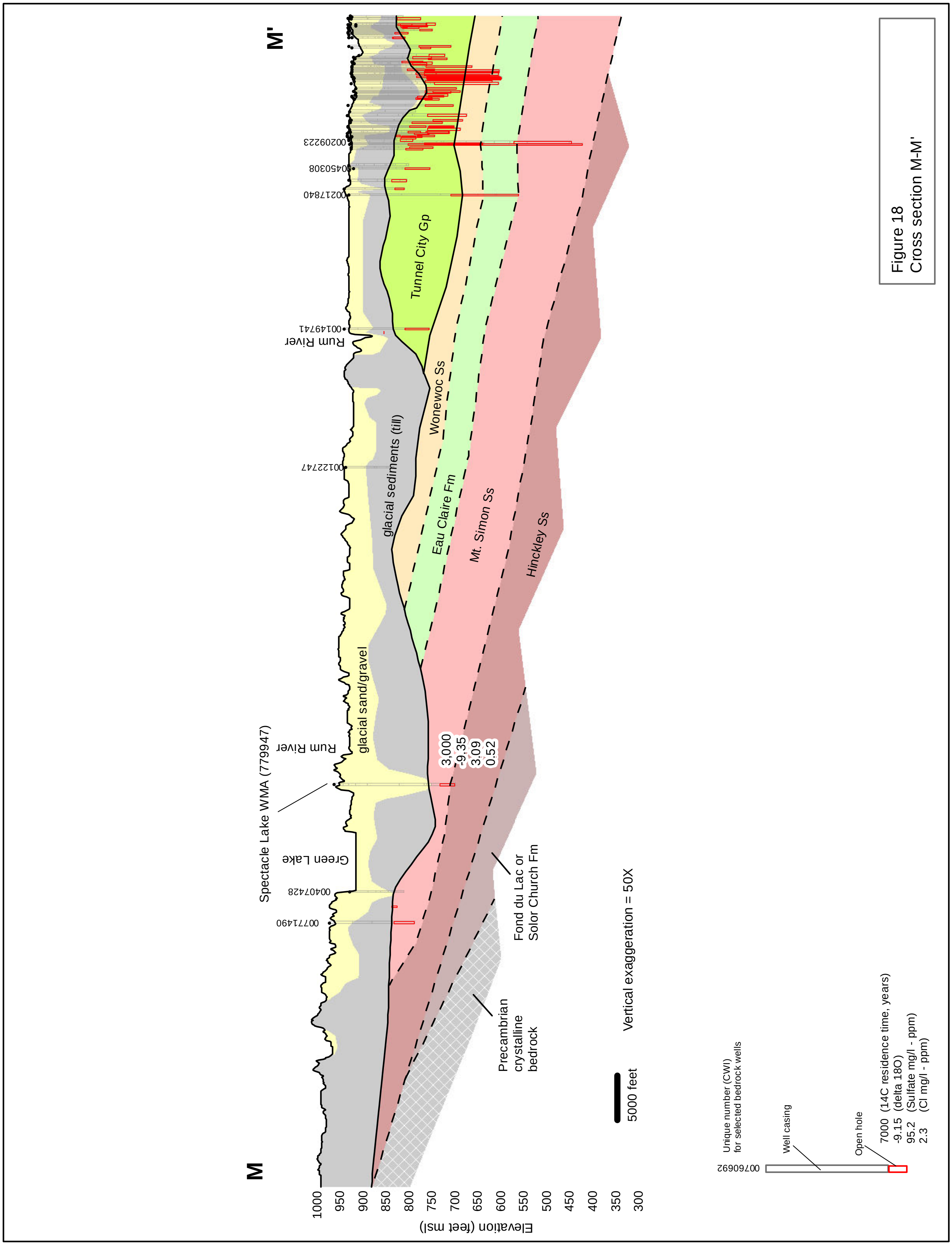


Figure 18
Cross section M-M'

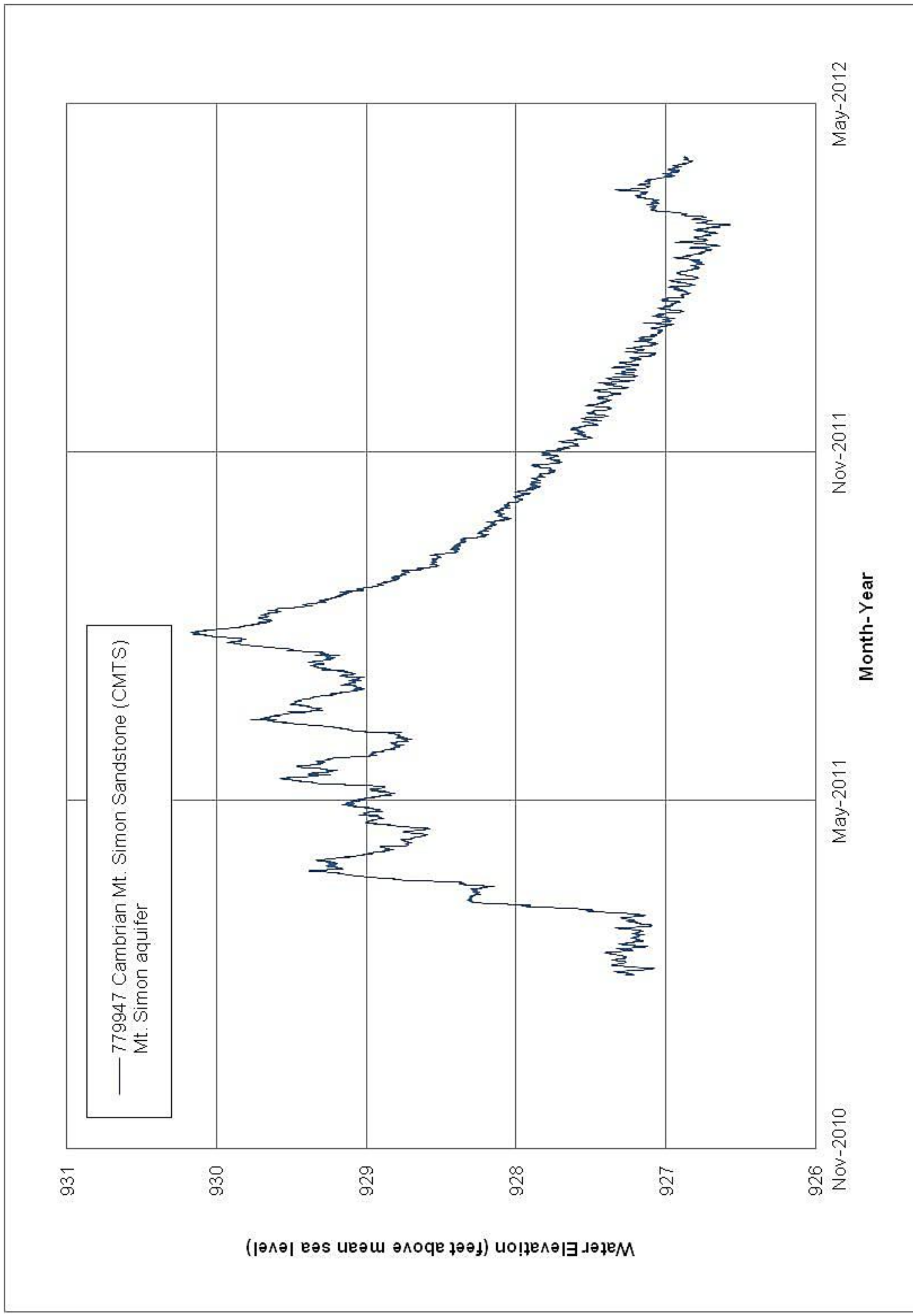


Figure 19
Spectacle Lake WMA
hydrograph

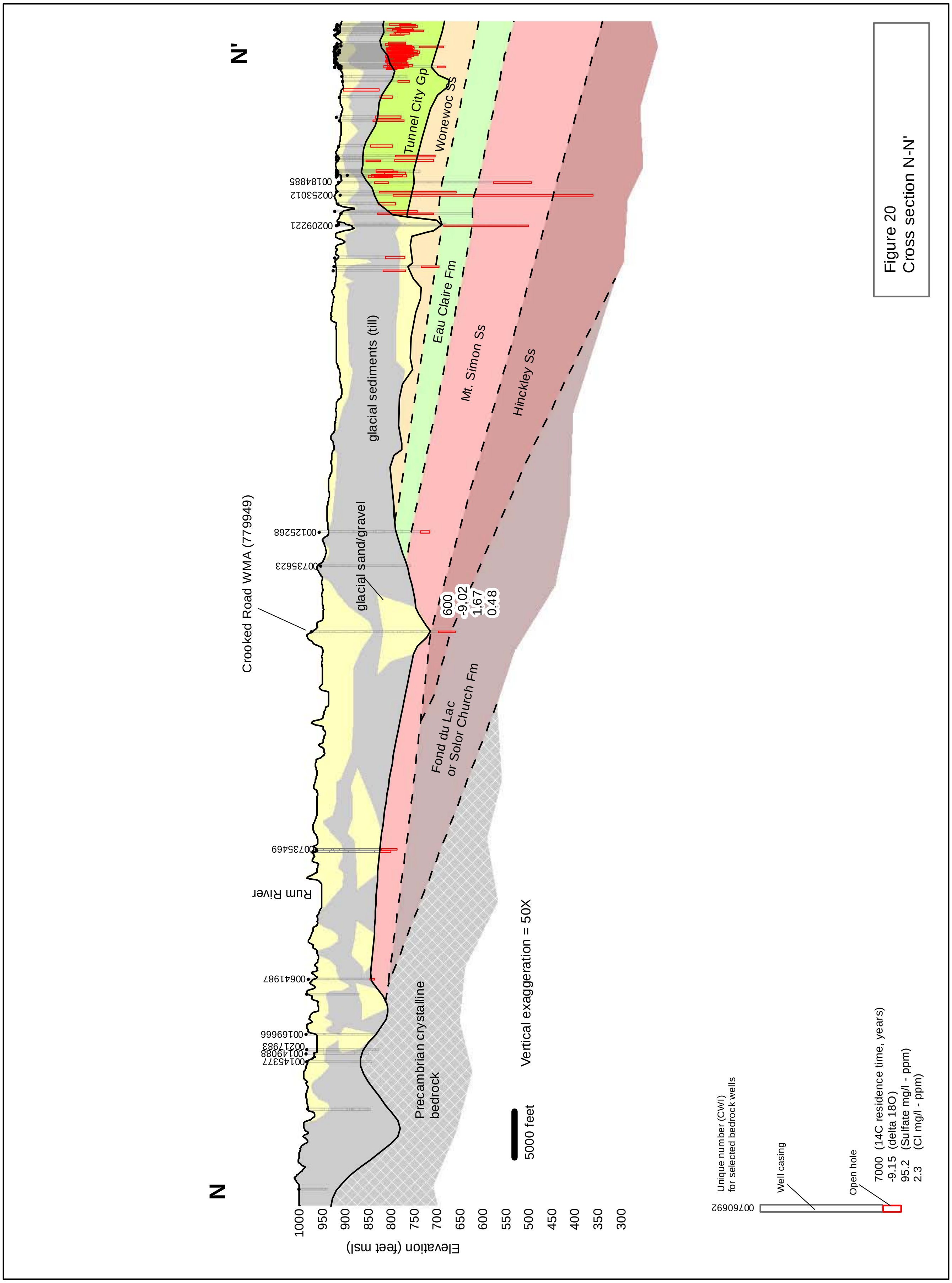


Figure 20
Cross section N-N'

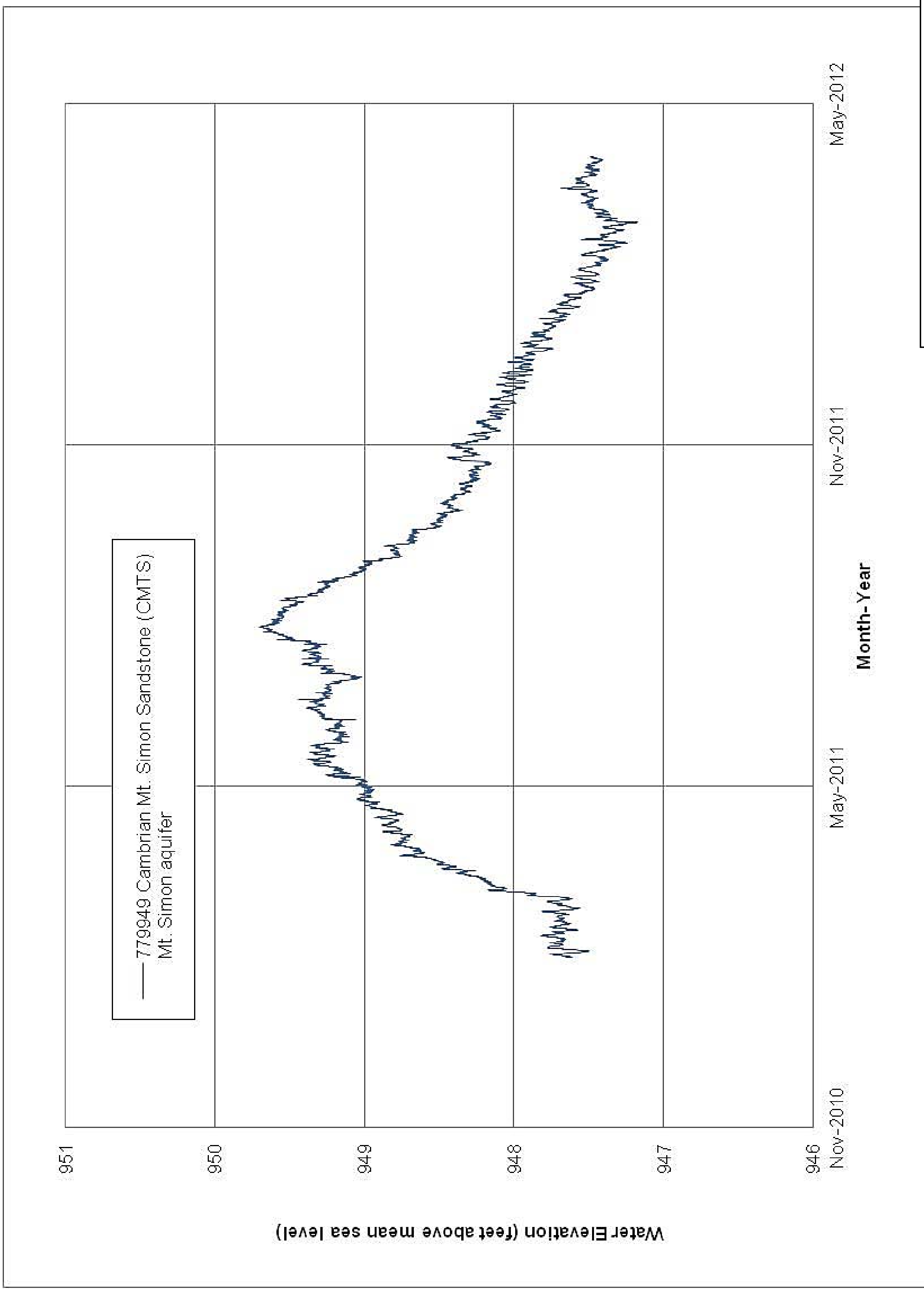


Figure 21
Crooked Road WMA
hydrograph

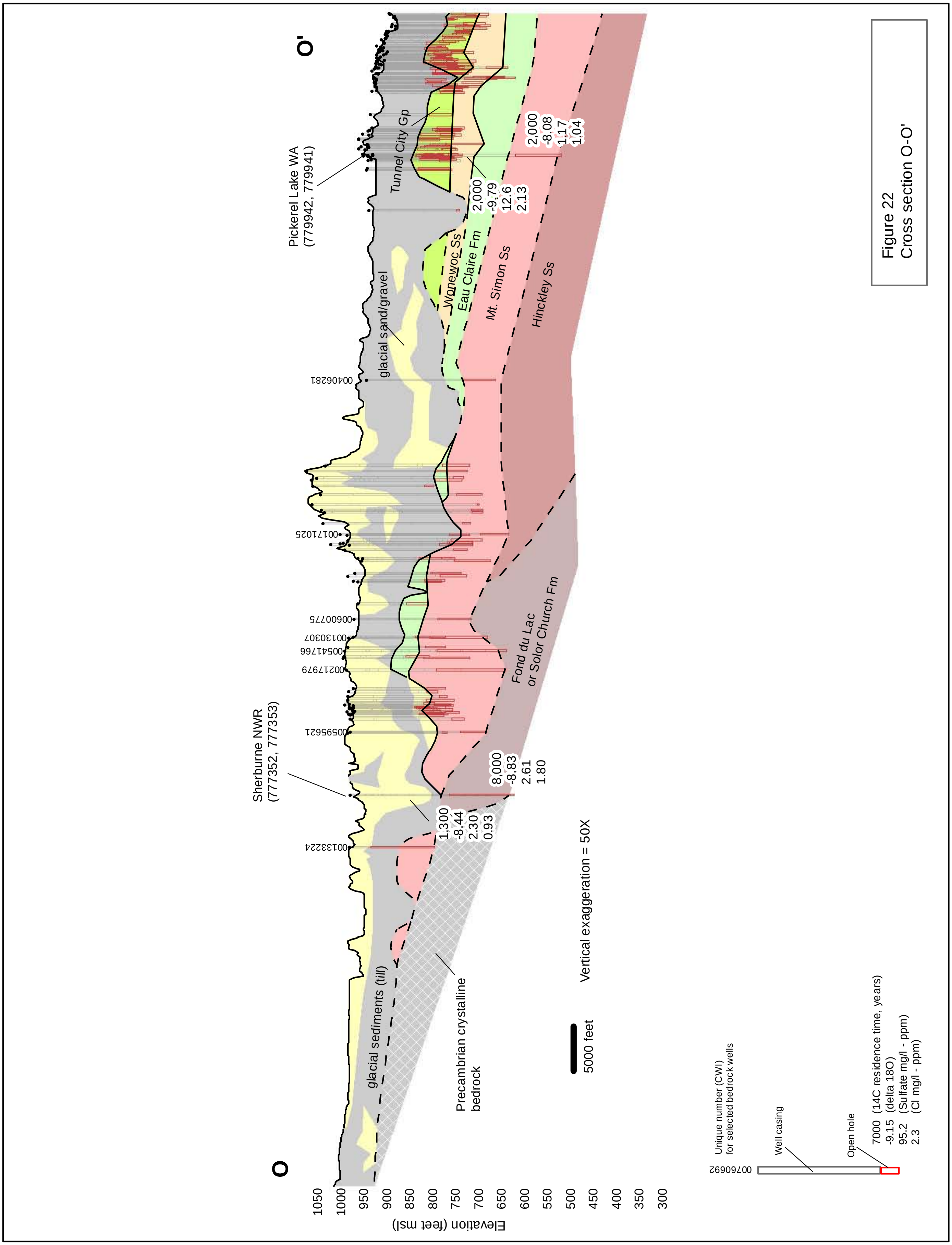


Figure 22
Cross section O-O'

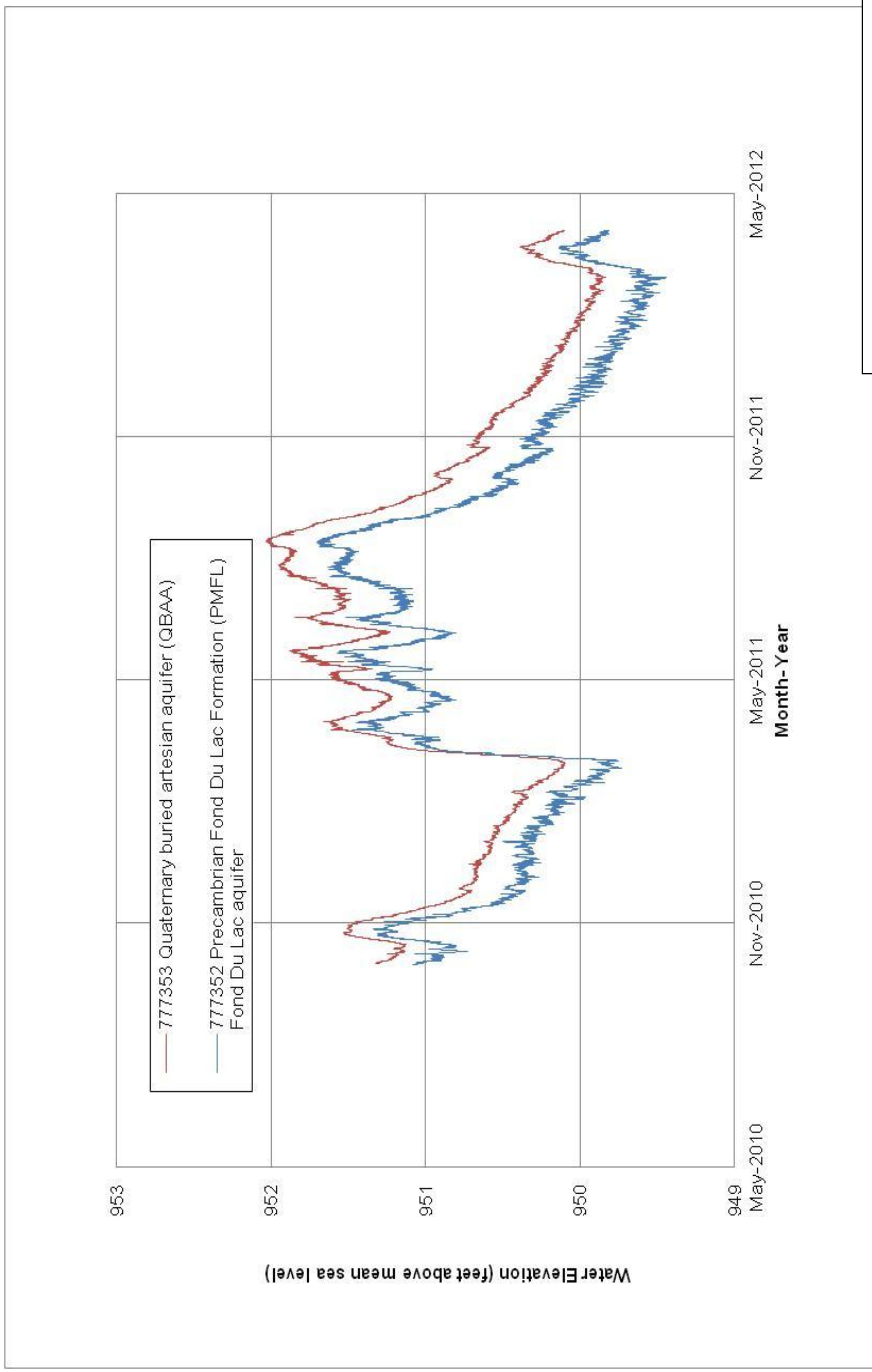


Figure 23
Sherburne National Wildlife Refuge hydrograph

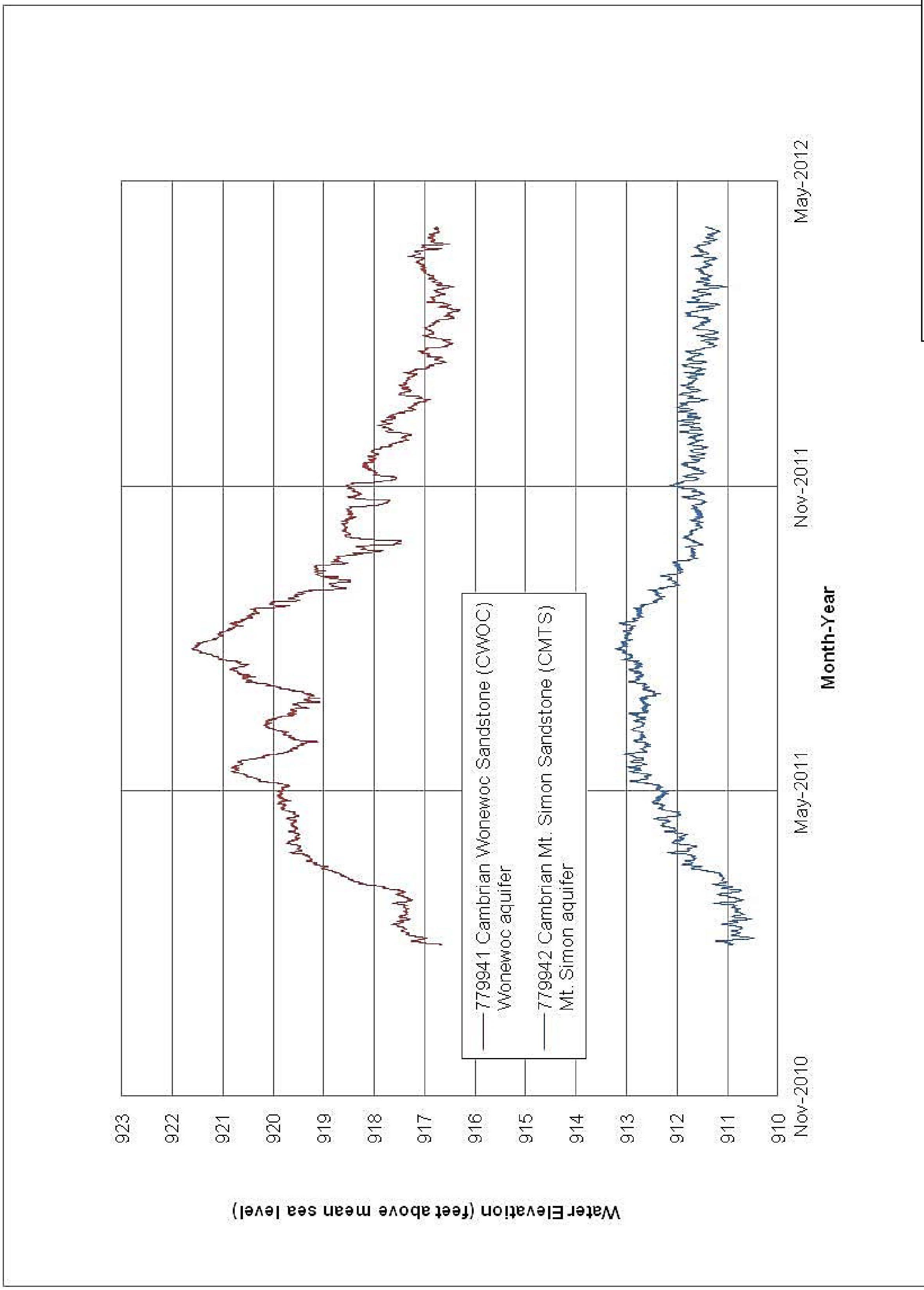


Figure 24
Pickerel Lake WA
hydrograph

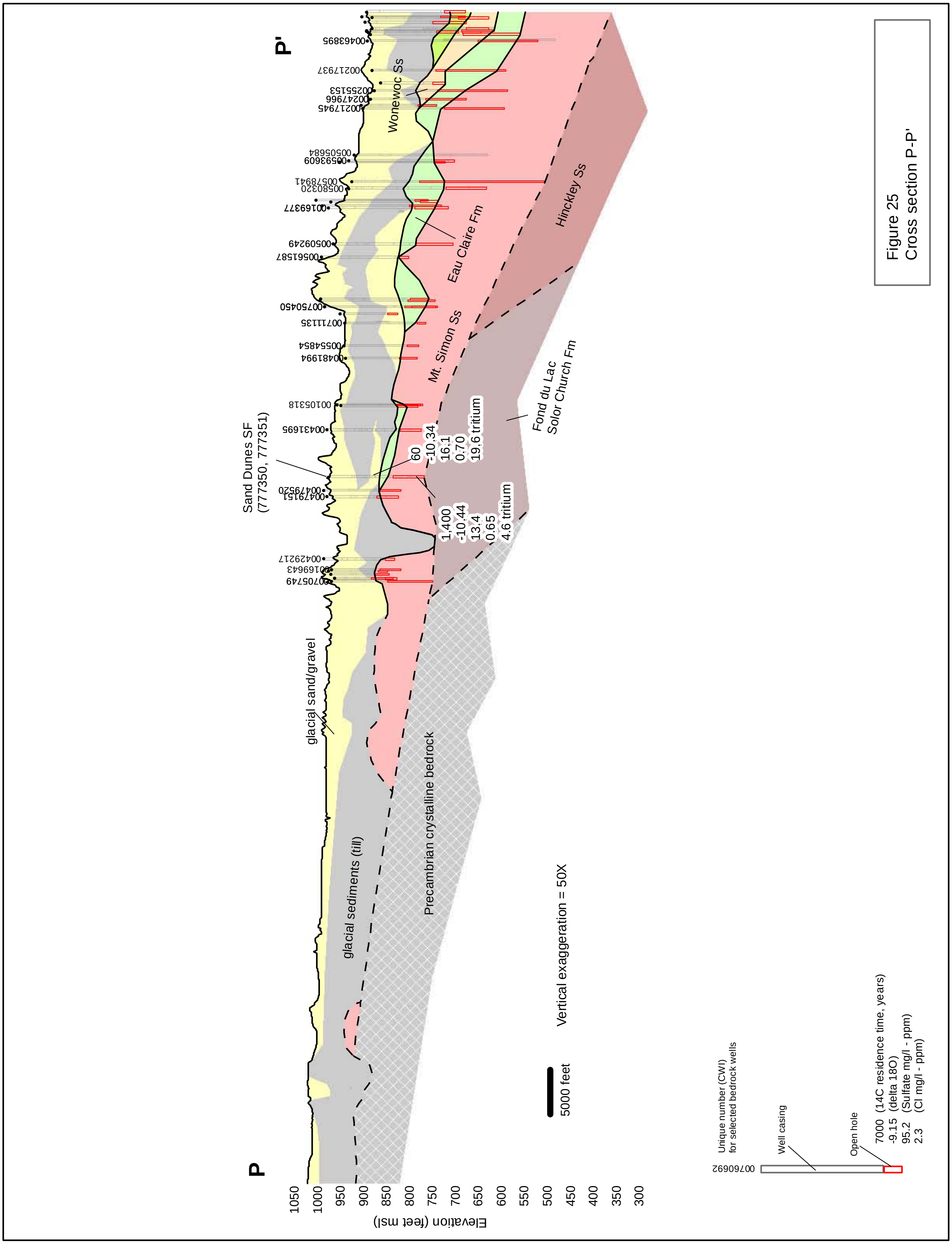


Figure 25
Cross section P-P'

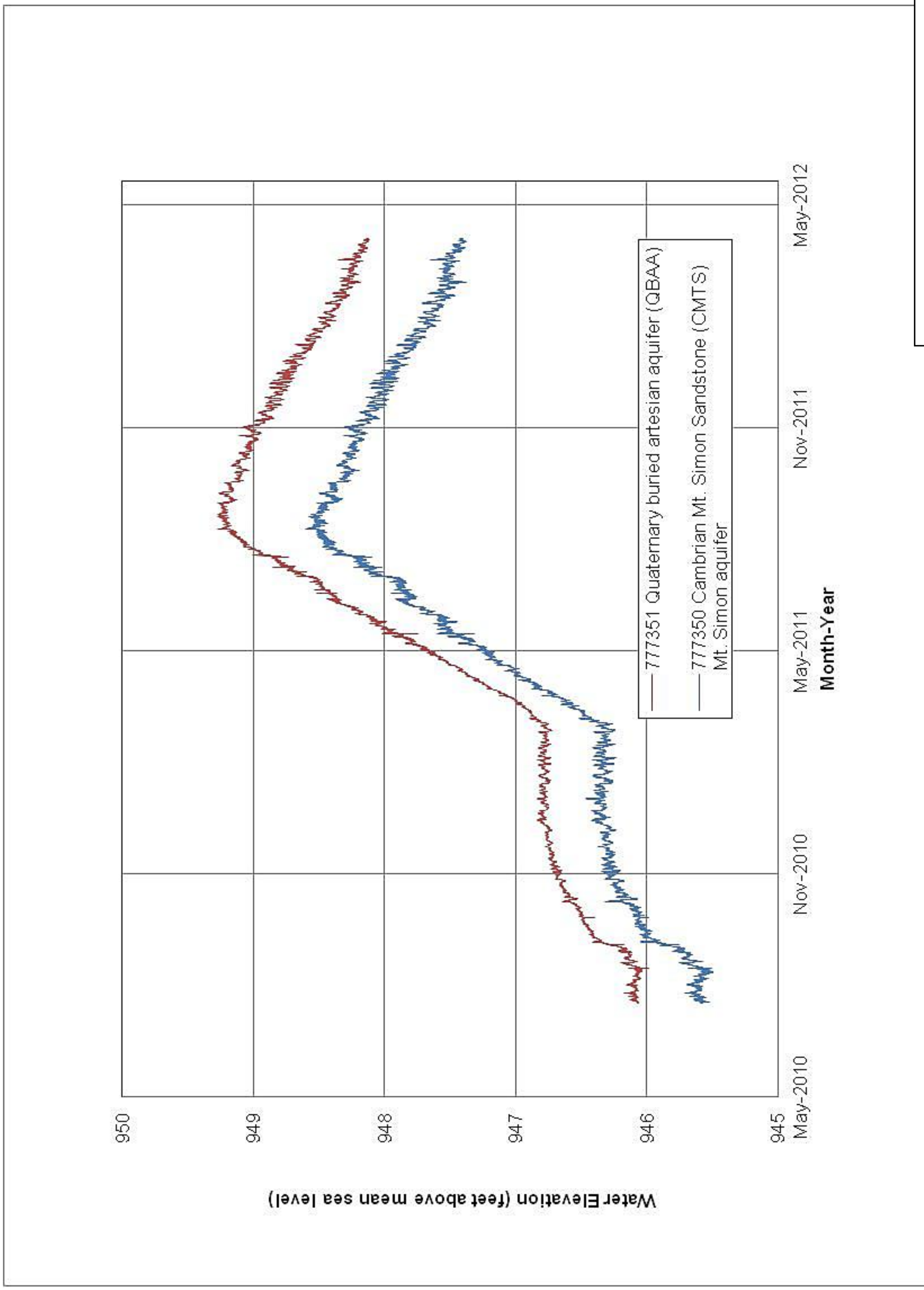


Figure 26
Sand Dunes State Forest
hydrograph

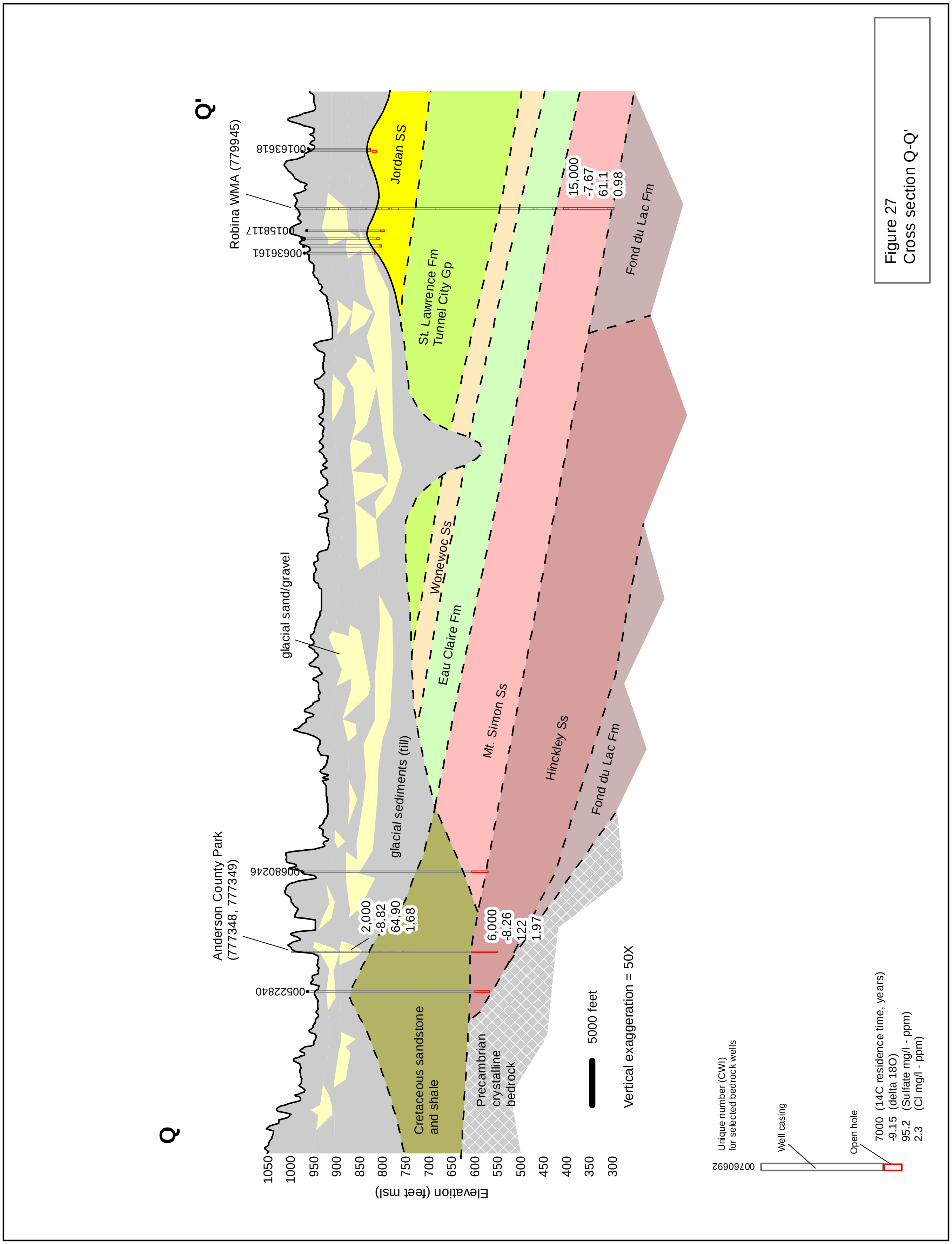


Figure 27
Cross section Q-Q'

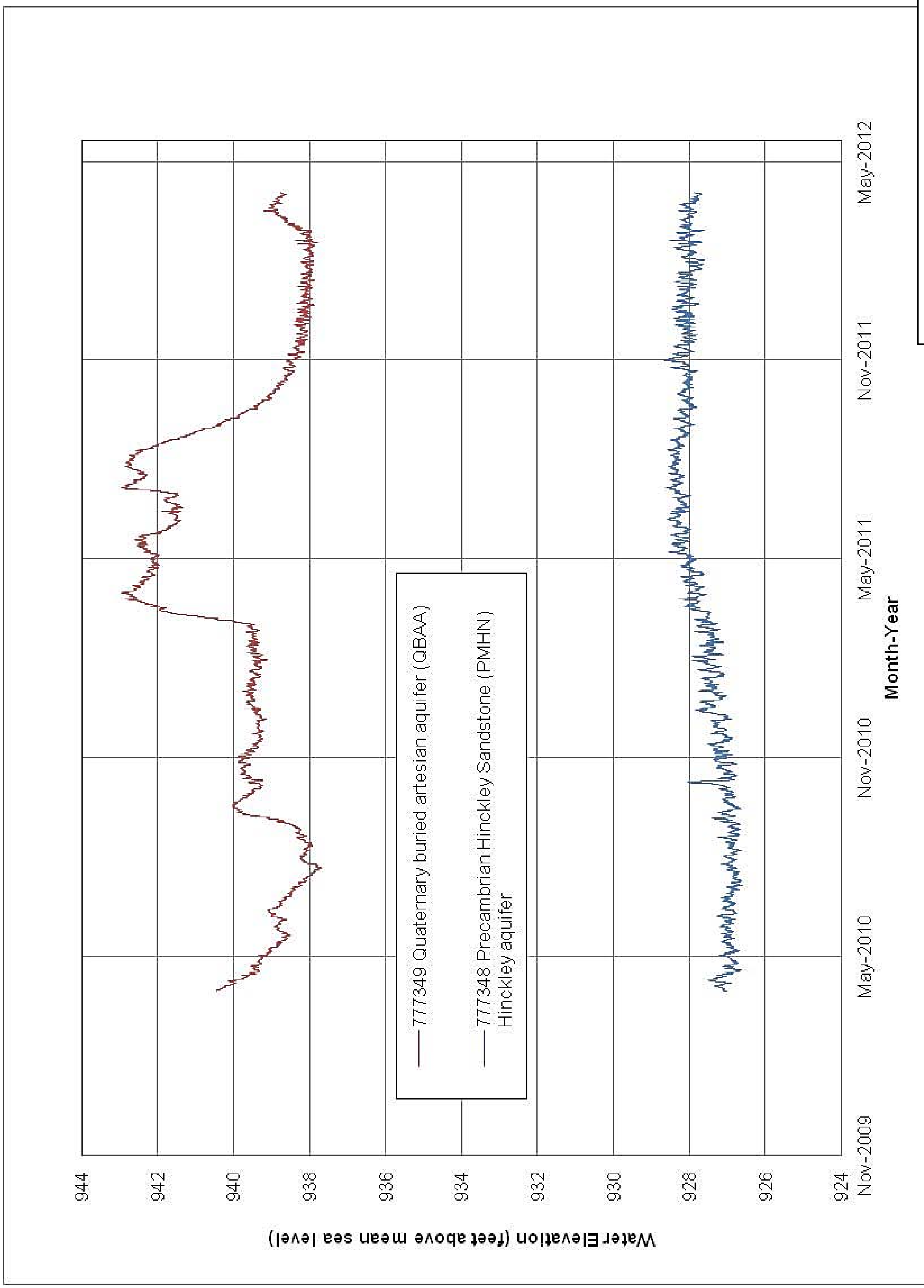


Figure 28
Anderson County Park
hydrograph

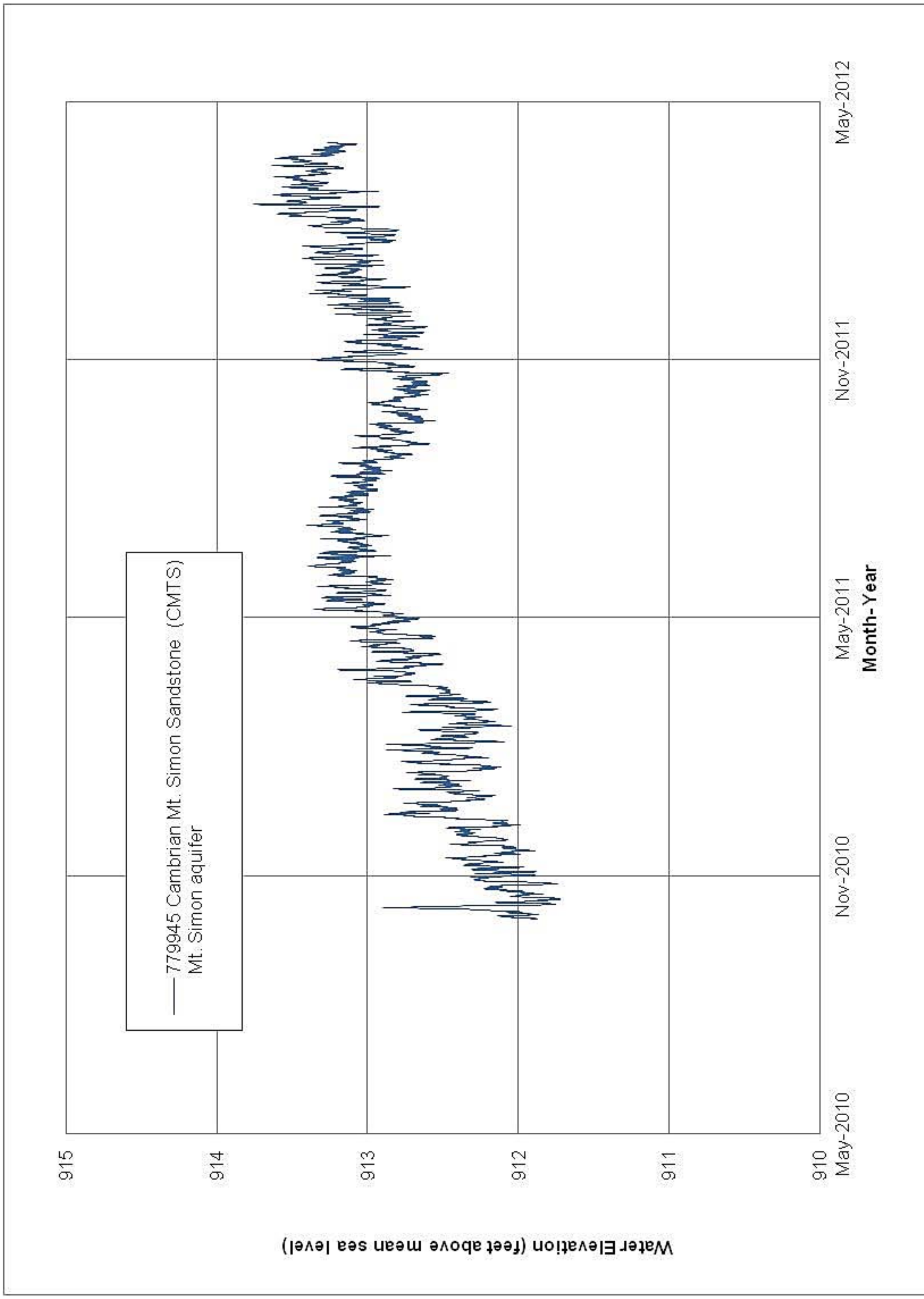


Figure 29
Robina WMA
hydrograph

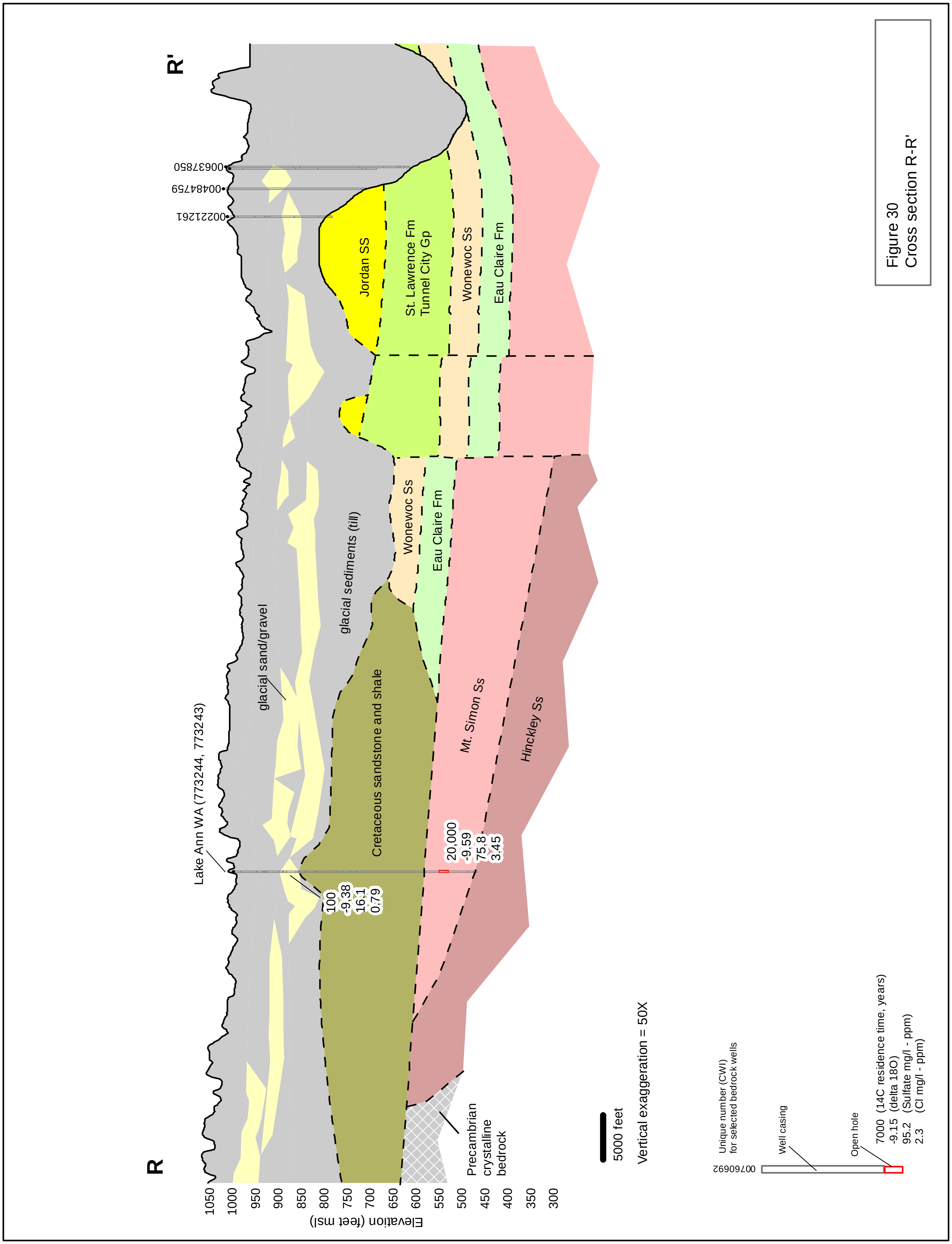


Figure 30
Cross section R-R'

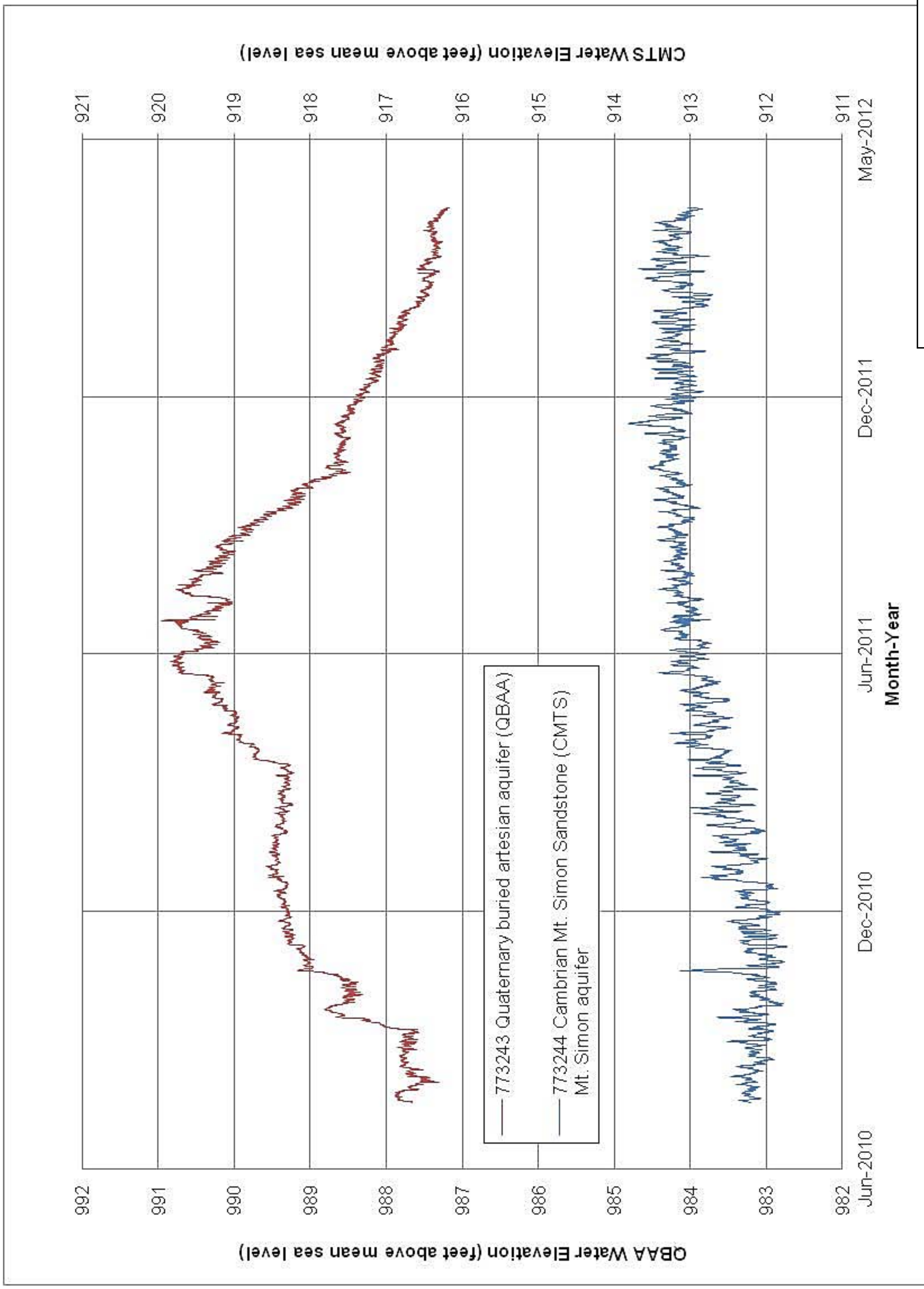


Figure 31
Lake Ann WA
hydrograph

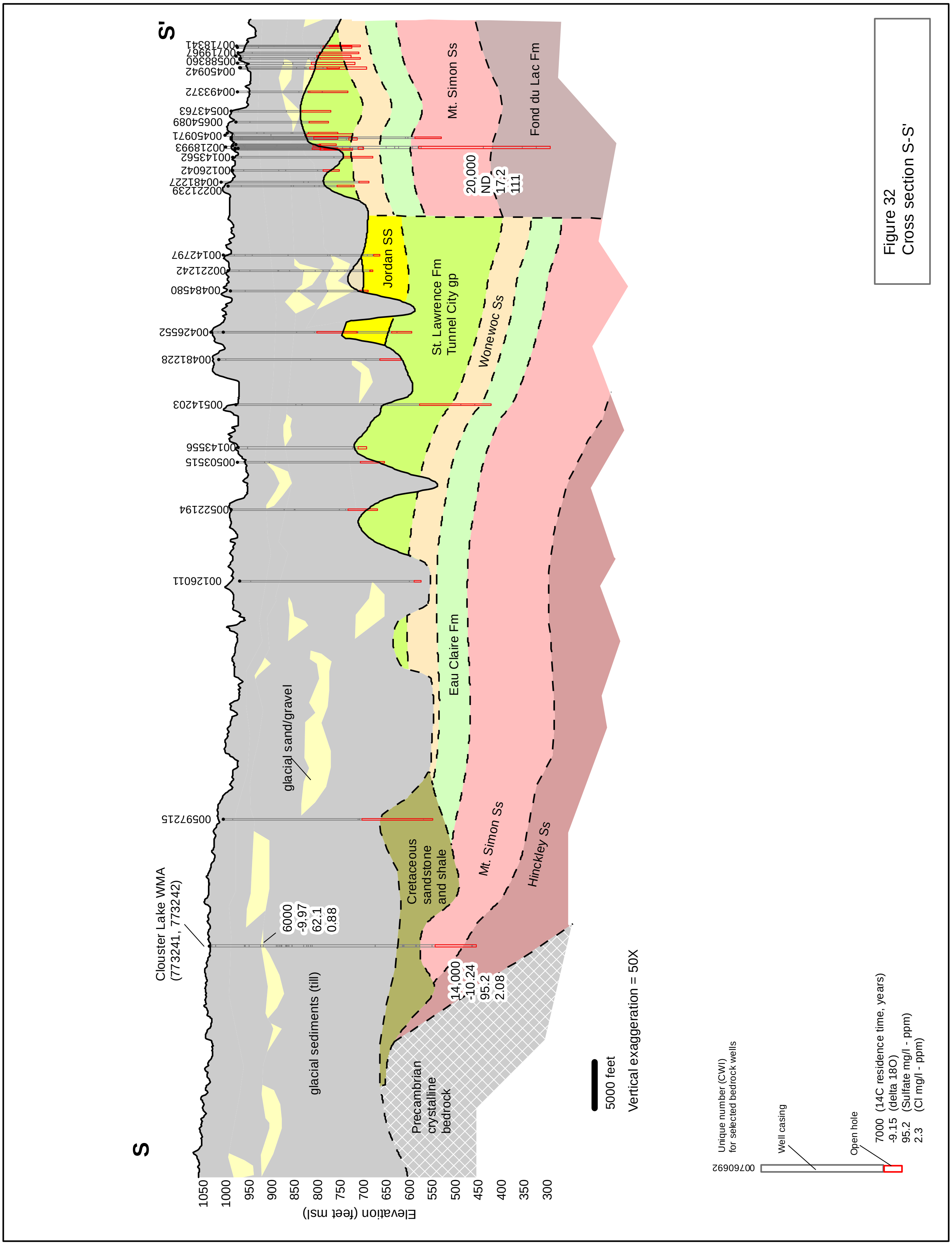


Figure 32
Cross section S-S'

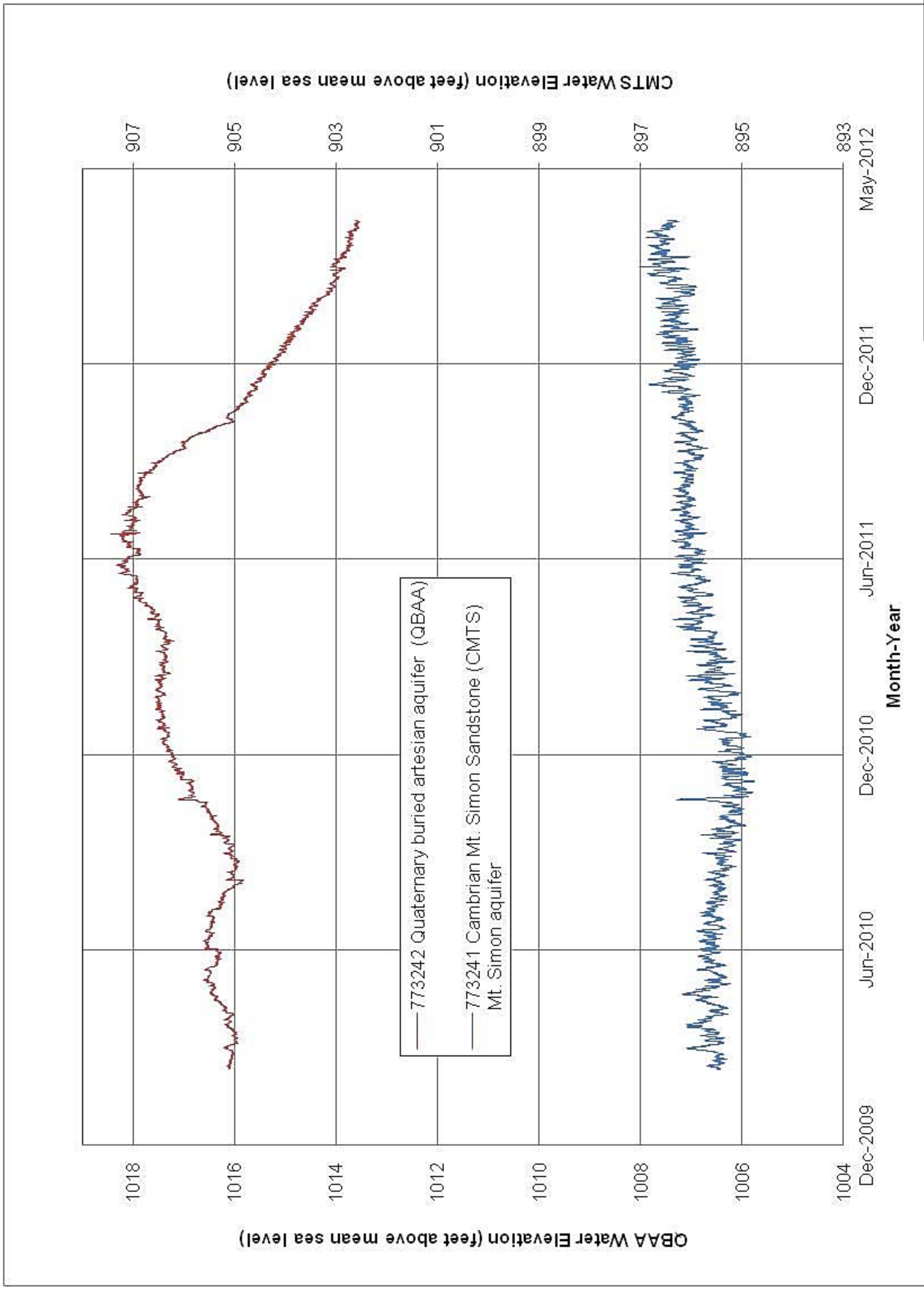


Figure 33
Clouster Lake WMA
hydrograph

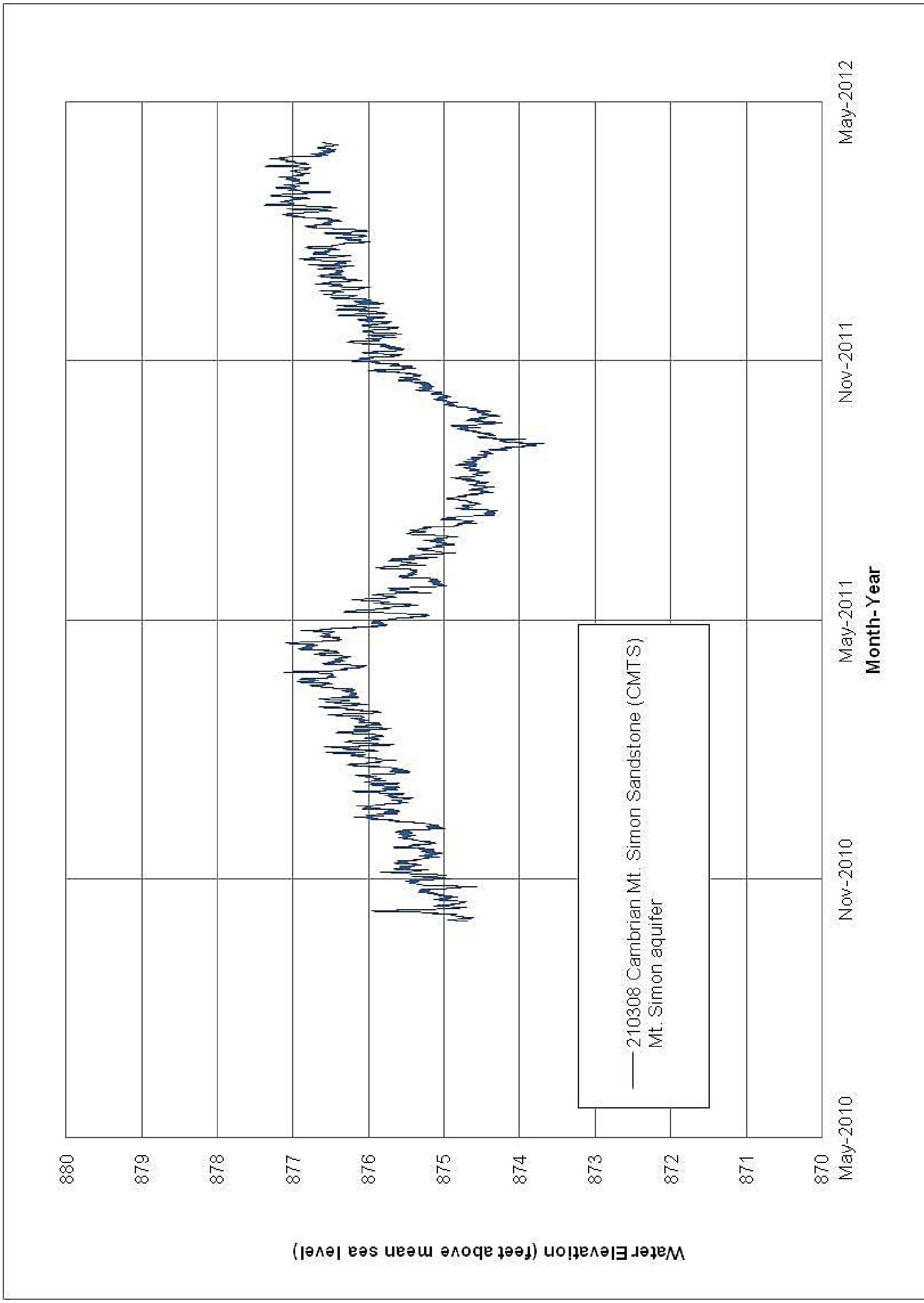


Figure 34
McLeod County Highway Department
hydrograph

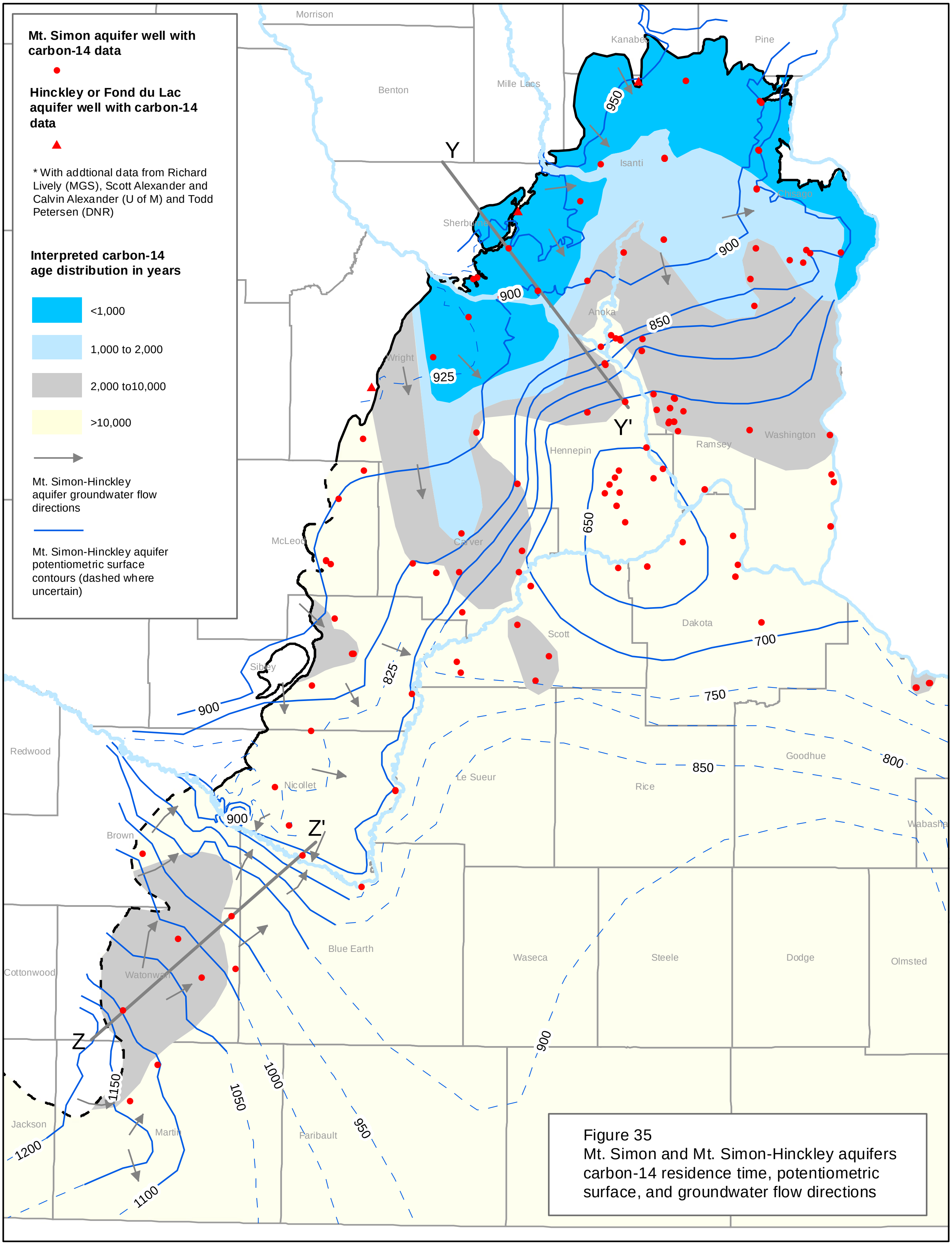


Figure 35
Mt. Simon and Mt. Simon-Hinckley aquifers carbon-14 residence time, potentiometric surface, and groundwater flow directions

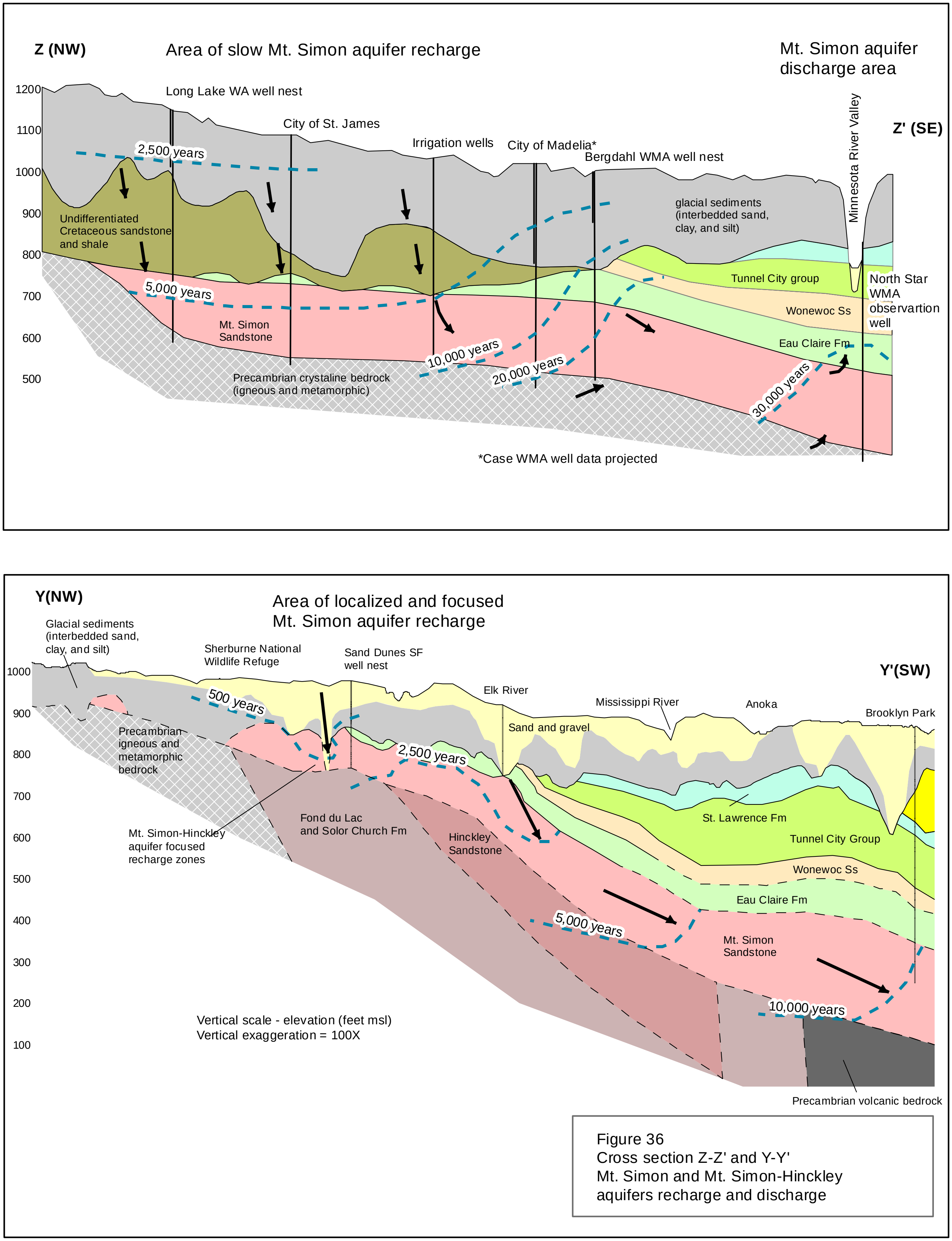


Figure 36
Cross section Z-Z' and Y-Y'
Mt. Simon and Mt. Simon-Hinckley aquifers recharge and discharge

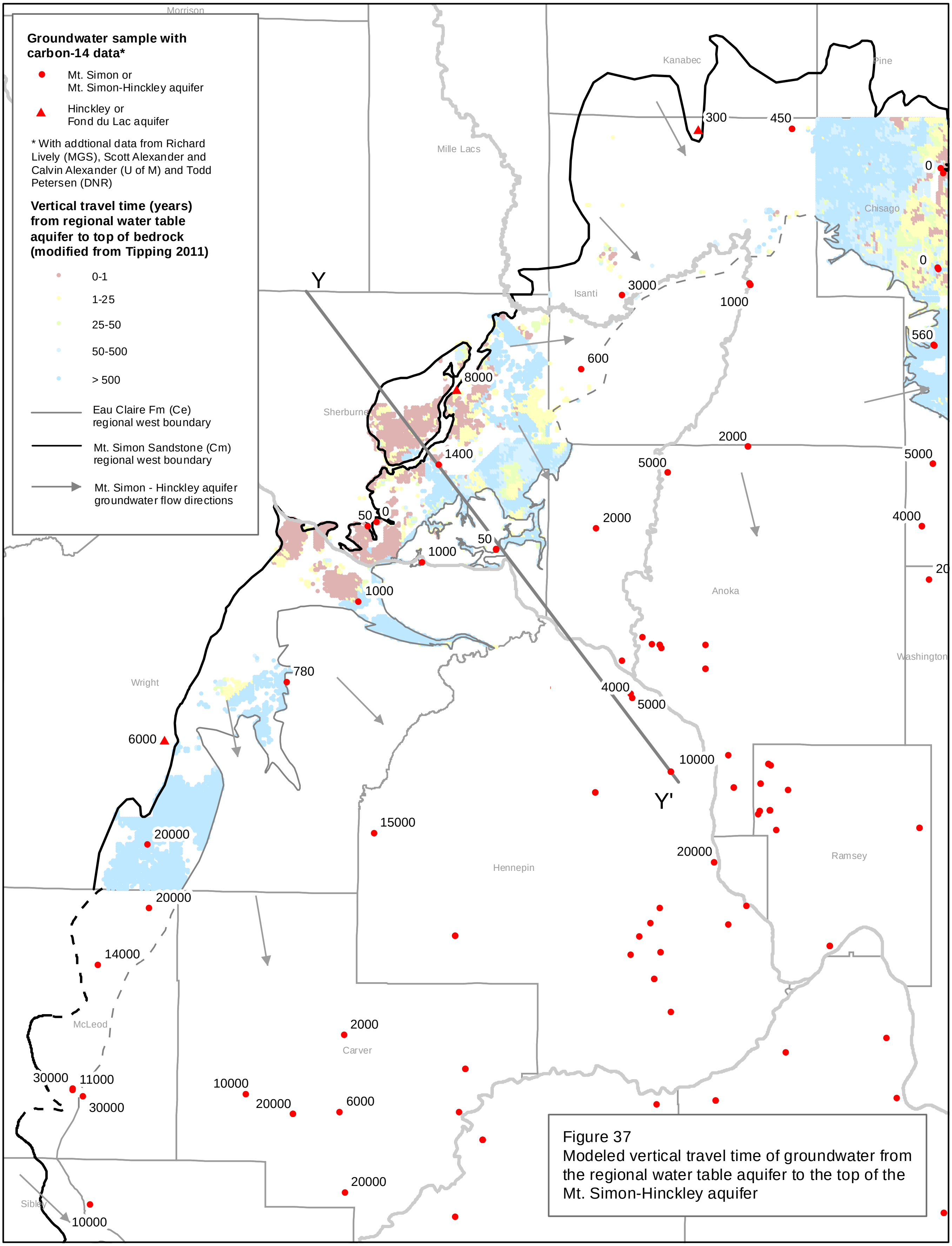
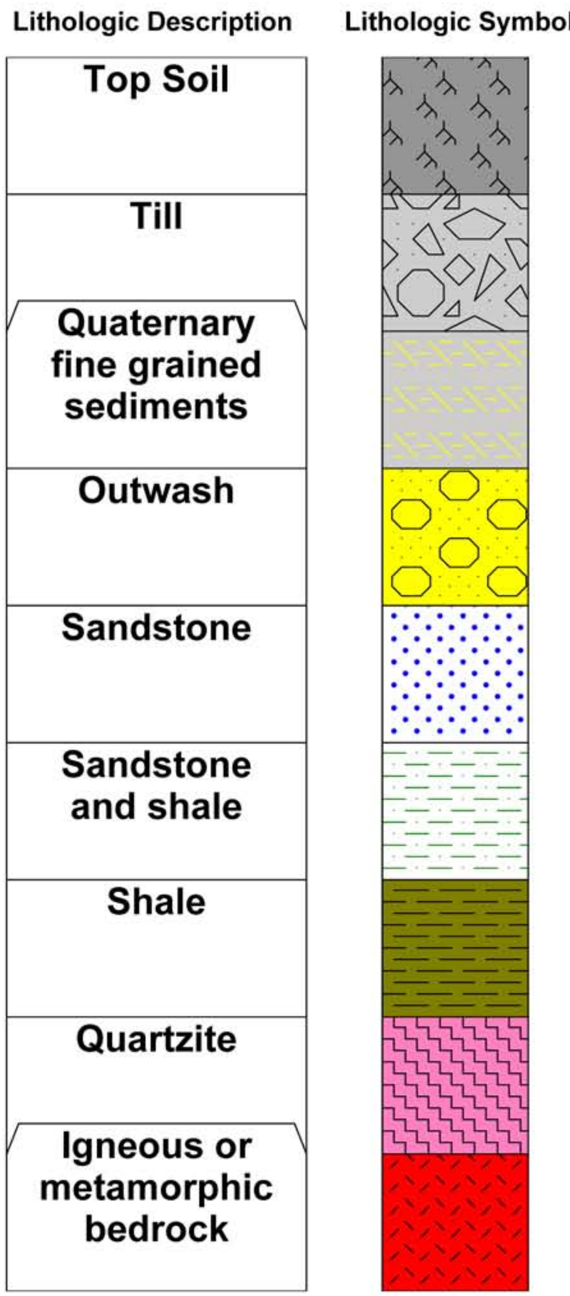


Figure 37
Modeled vertical travel time of groundwater from the regional water table aquifer to the top of the Mt. Simon-Hinckley aquifer

Appendix

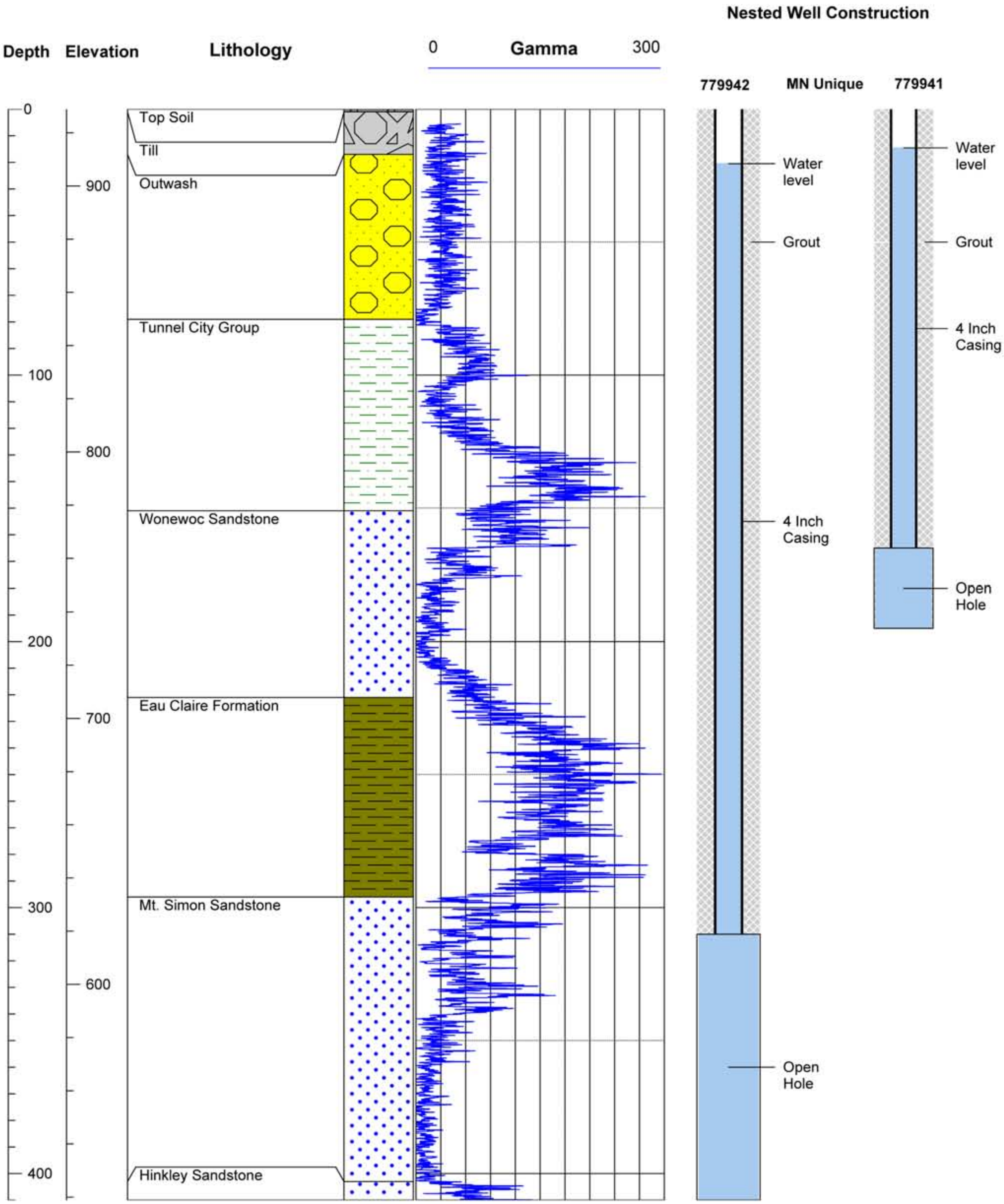
Geologic Log Legend



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Pickerel Lake WA

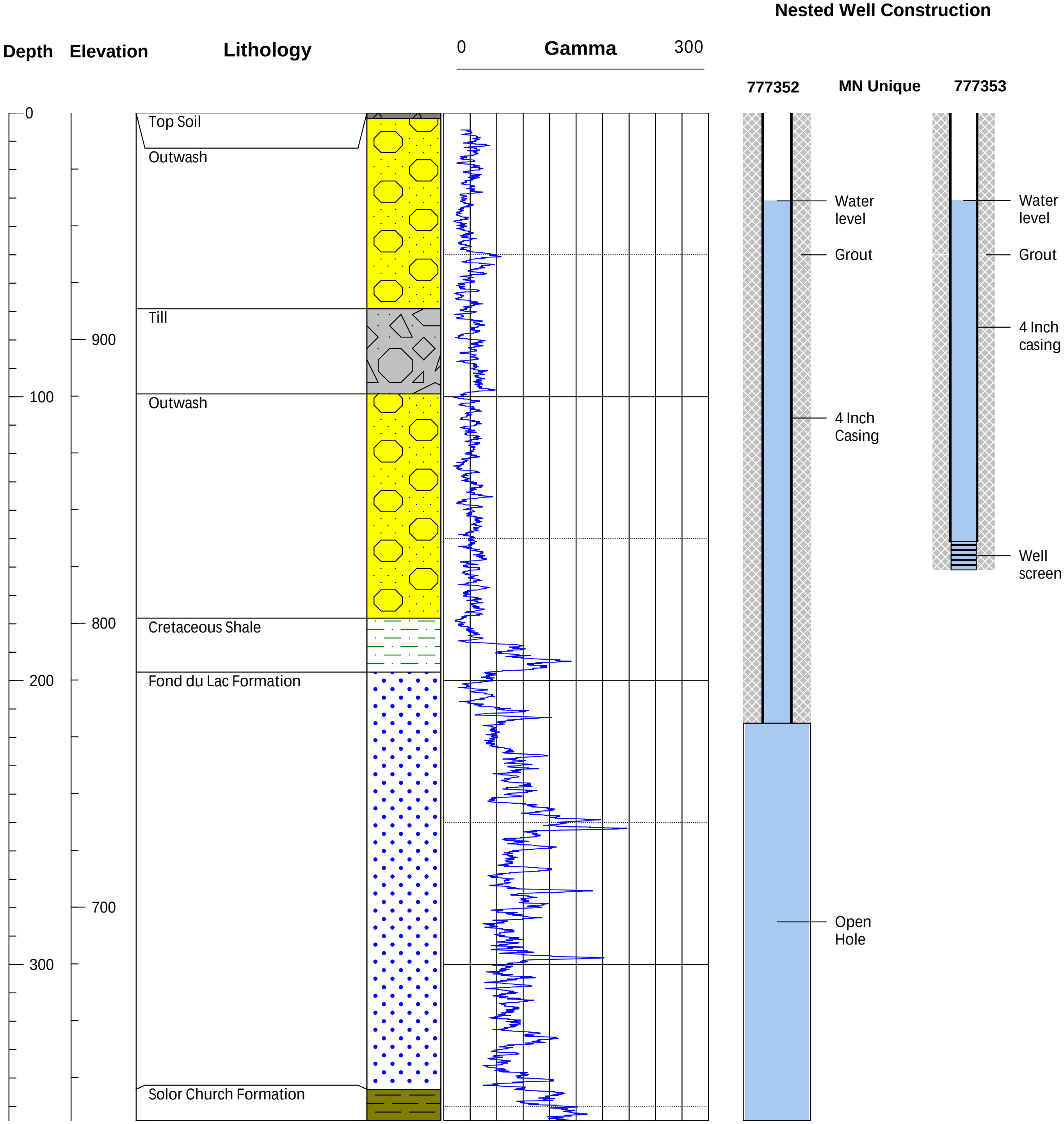
County Anoka



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Sherburne National Wildlife Refuge

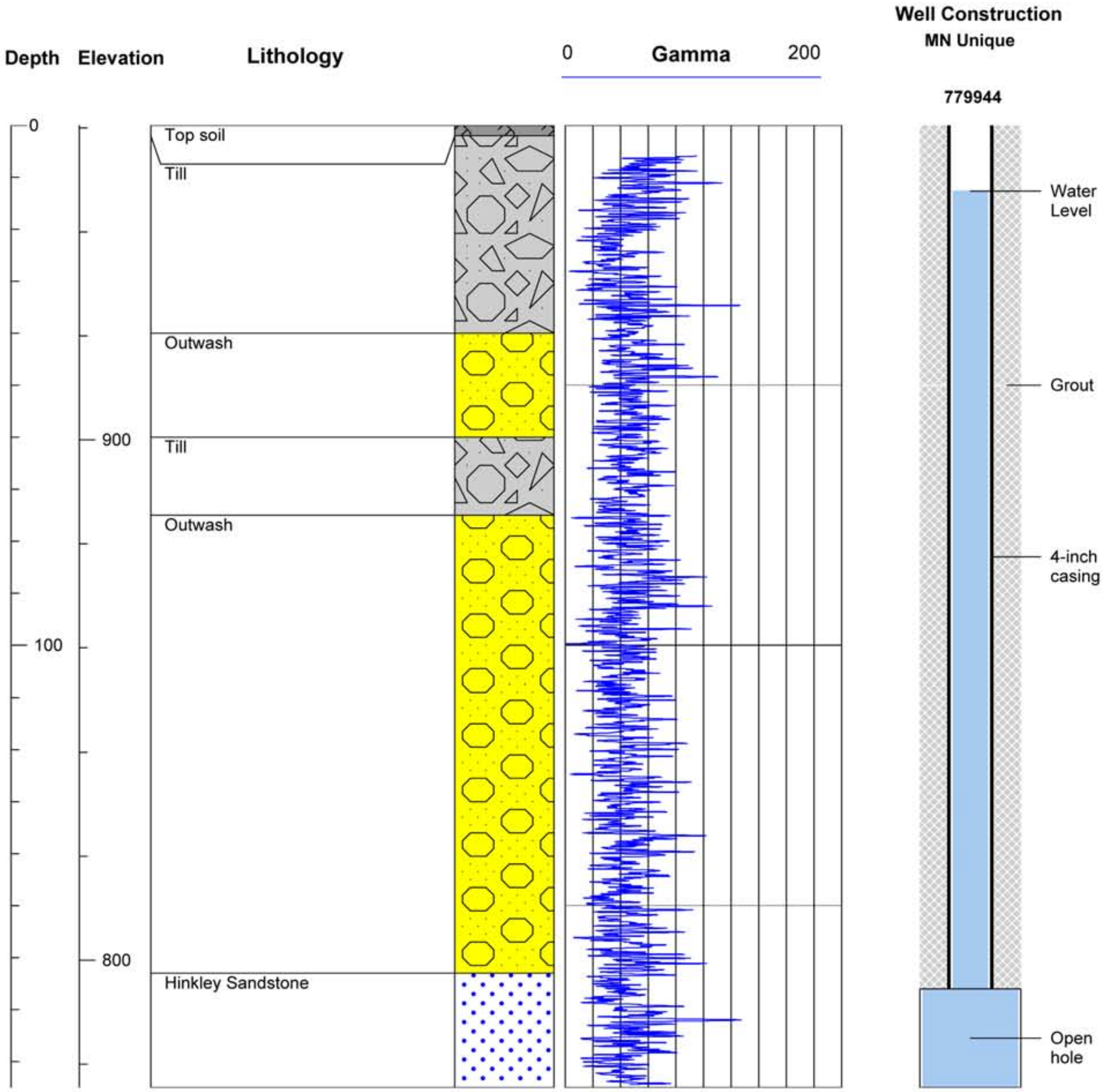
County Sherburne



Geological / Geophysical Logs and Well Construction Diagram

Site Name Stanchfield WMA

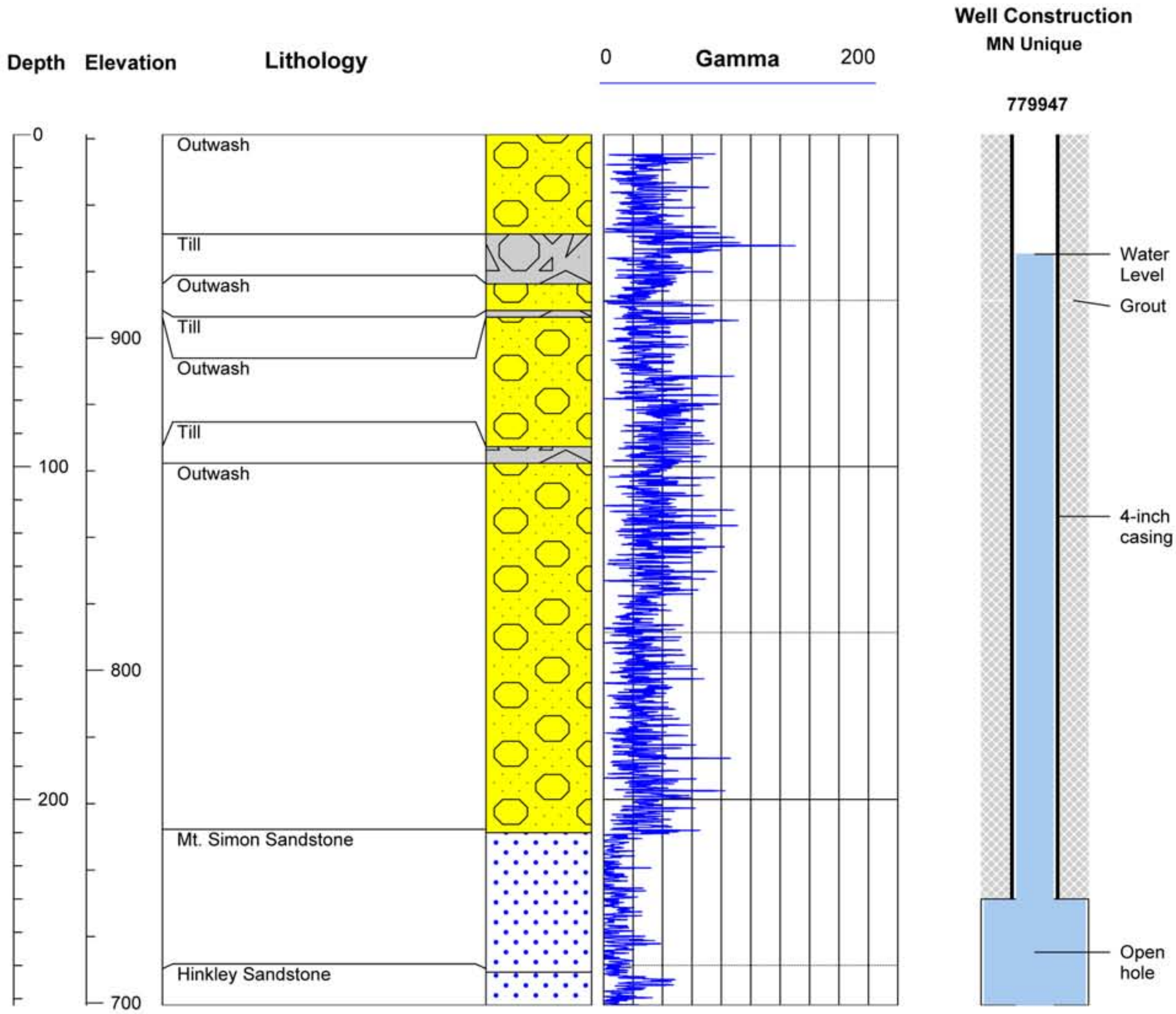
County Isanti



Geological / Geophysical Logs and Well Construction Diagram

Site Name: Spectacle Lake WMA

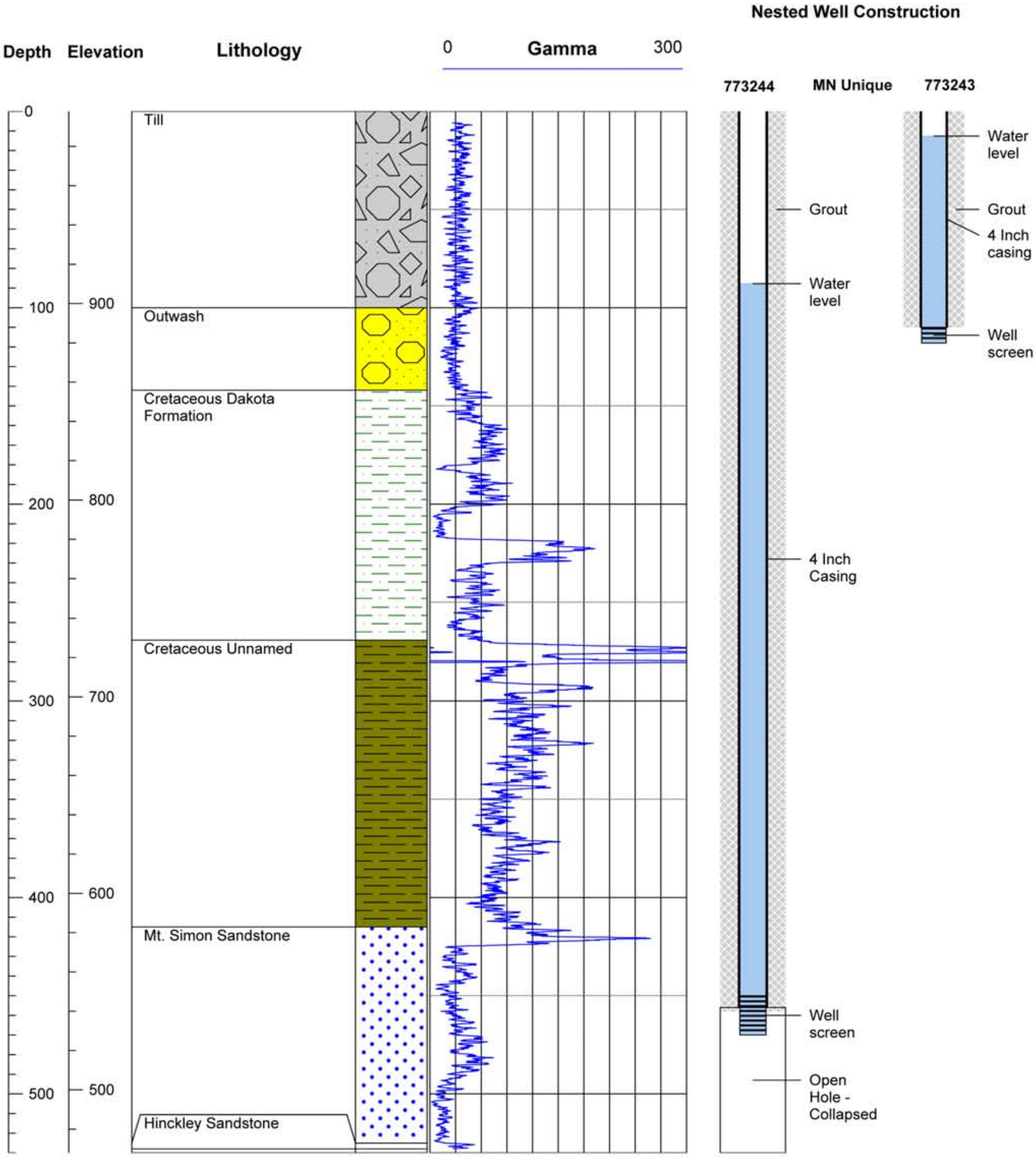
County: Isanti



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Lake Ann WA

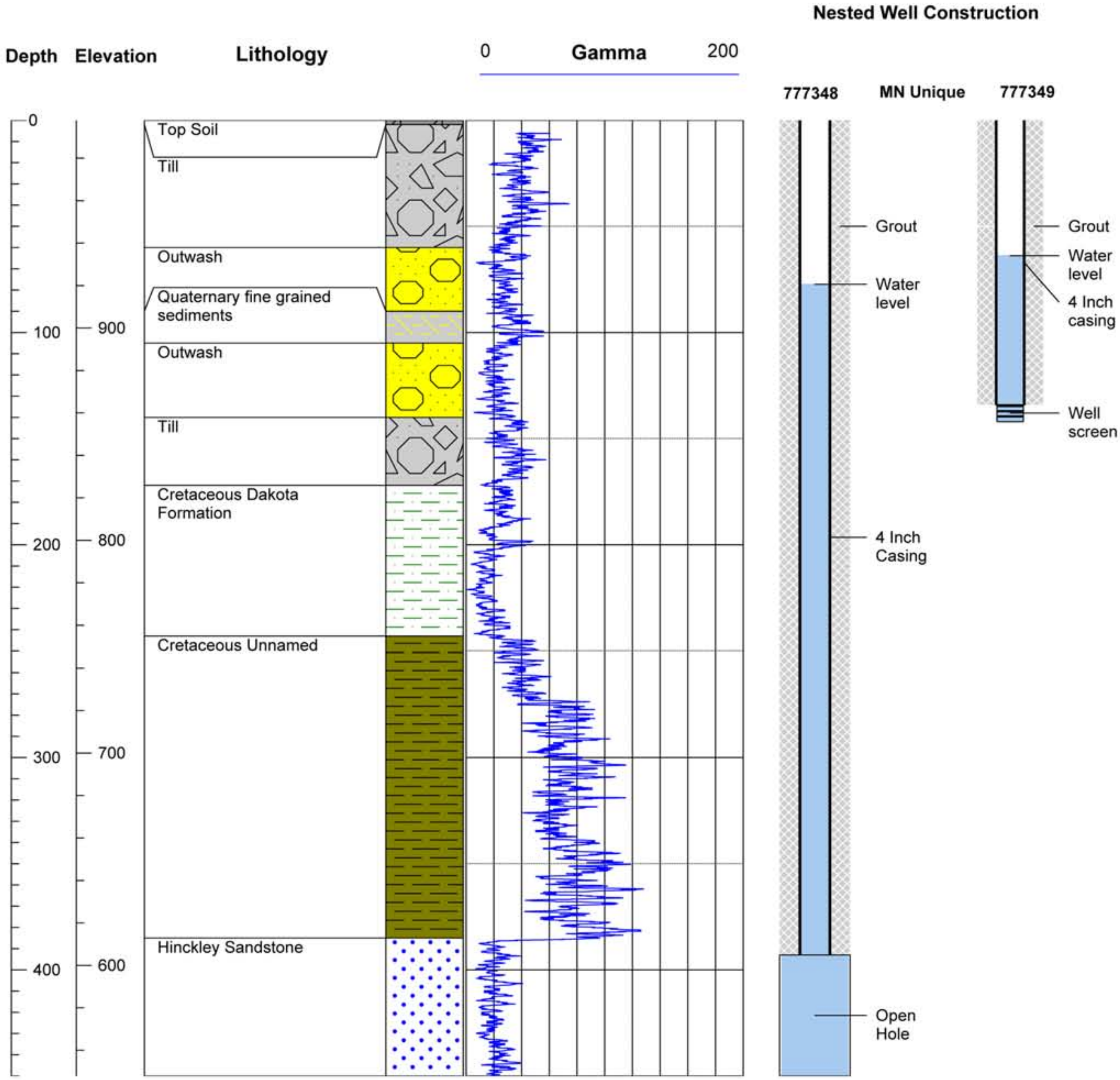
County Wright



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Anderson County Park

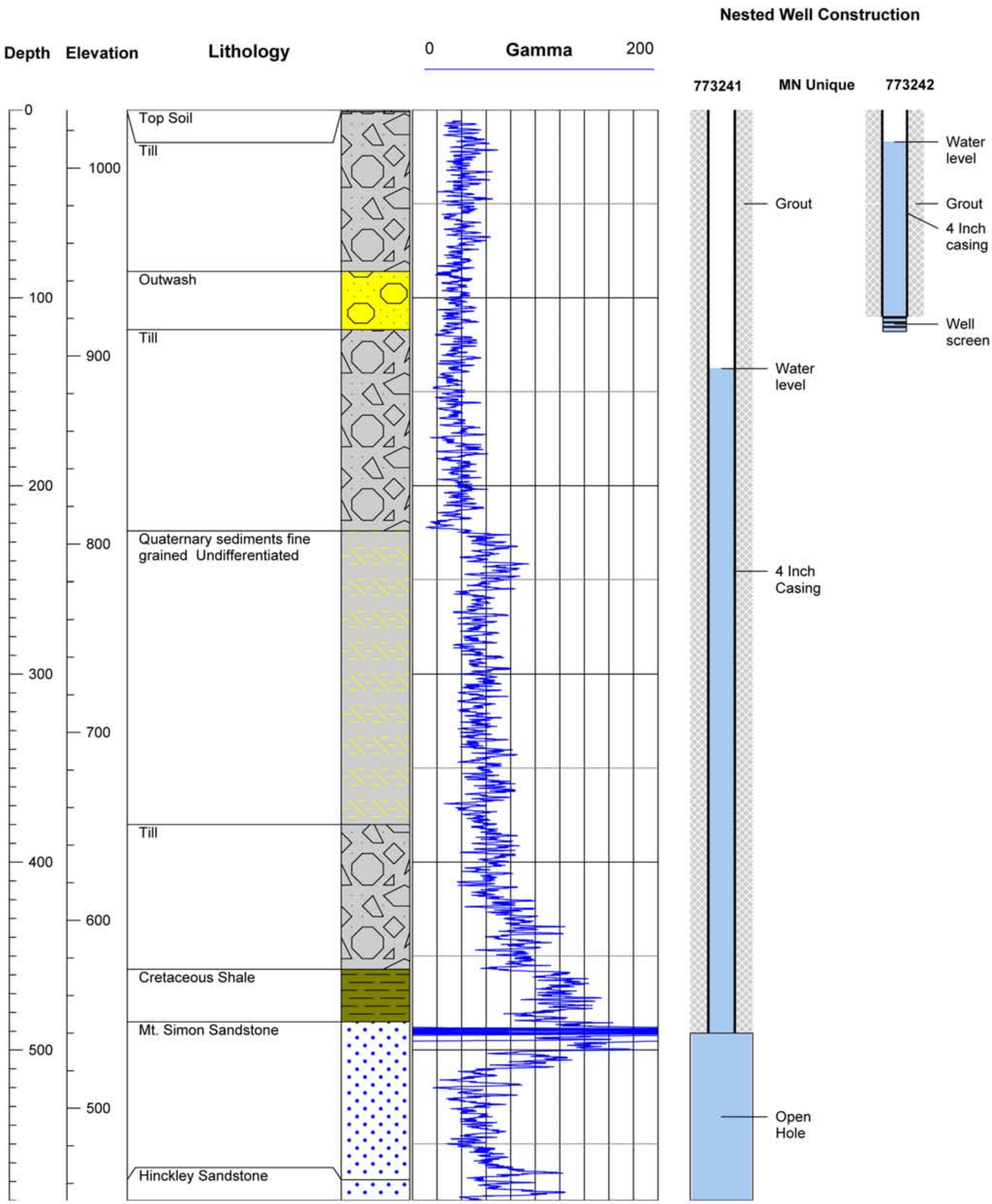
County Wright



Geological / Geophysical Logs and Well Construction Diagrams

Site Name: Clouster Lake WMA

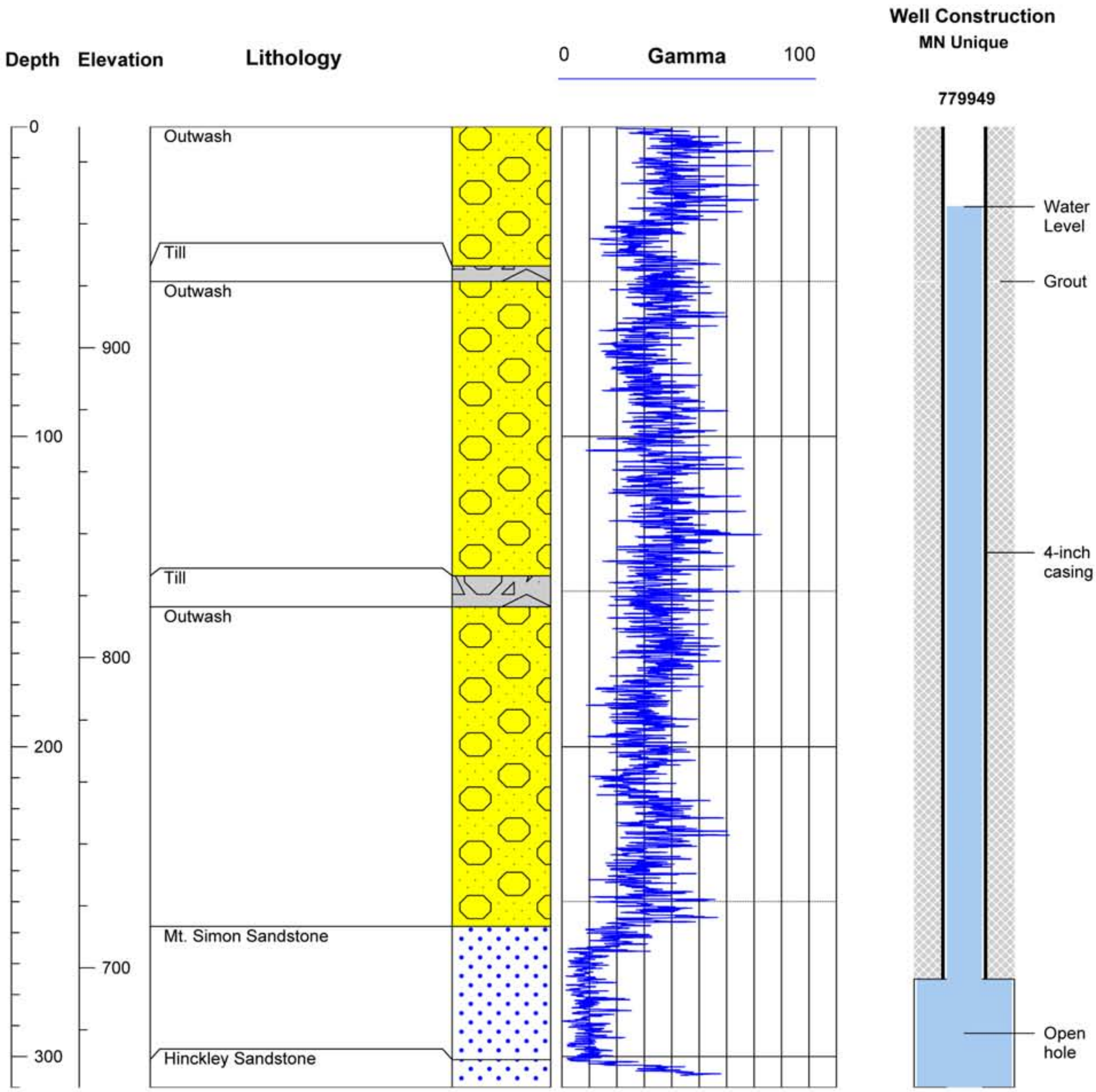
County: McLeod



Geological / Geophysical Logs and Well Construction Diagram

Site Name Crooked Road WMA

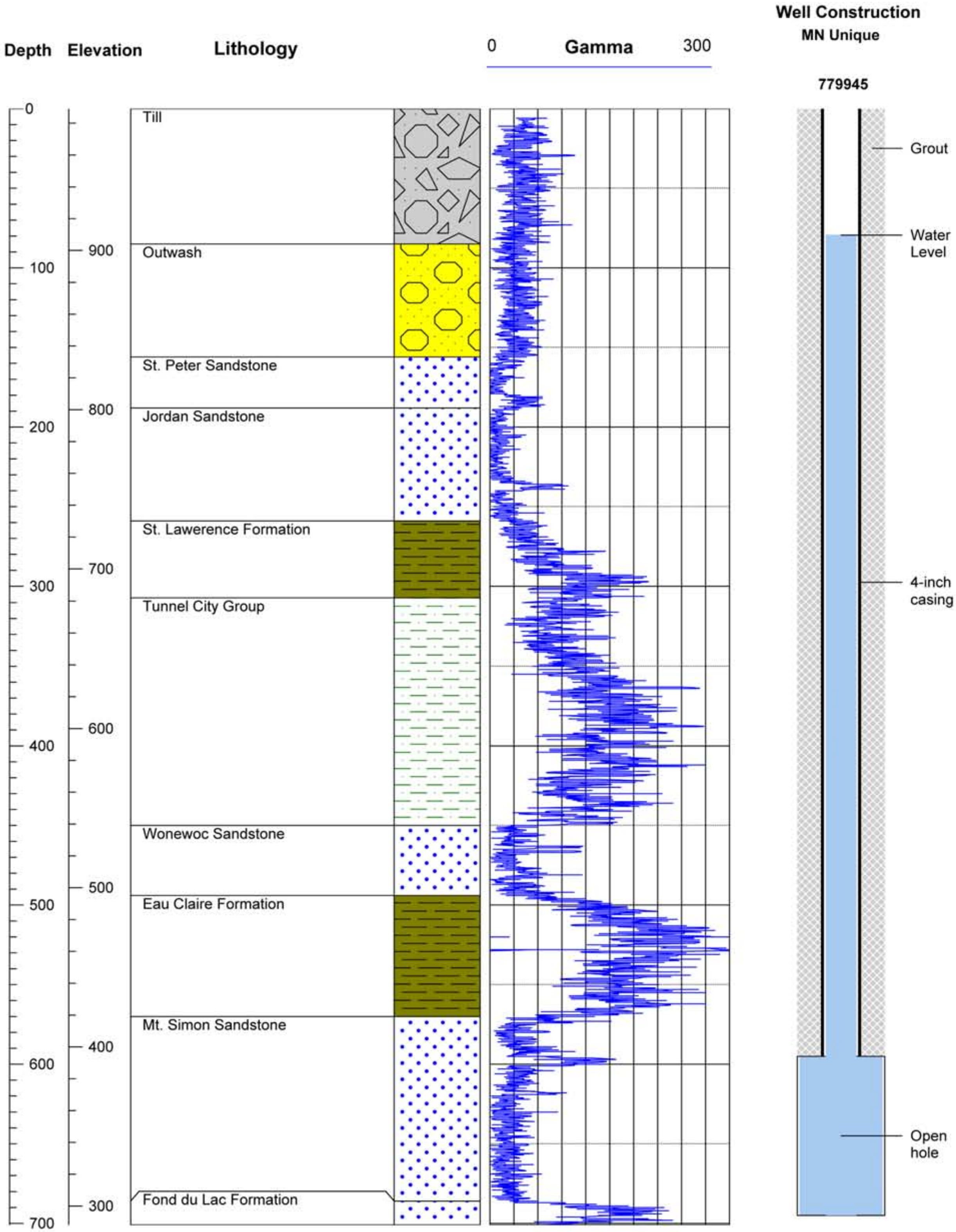
County Isanti



Geological / Geophysical Logs and Well Construction Diagram

Site Name Robina WMA

County Hennepin



Geological / Geophysical Logs and Well Construction Diagrams

Site Name: Sand Dunes State Forest

County: Sherburne