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

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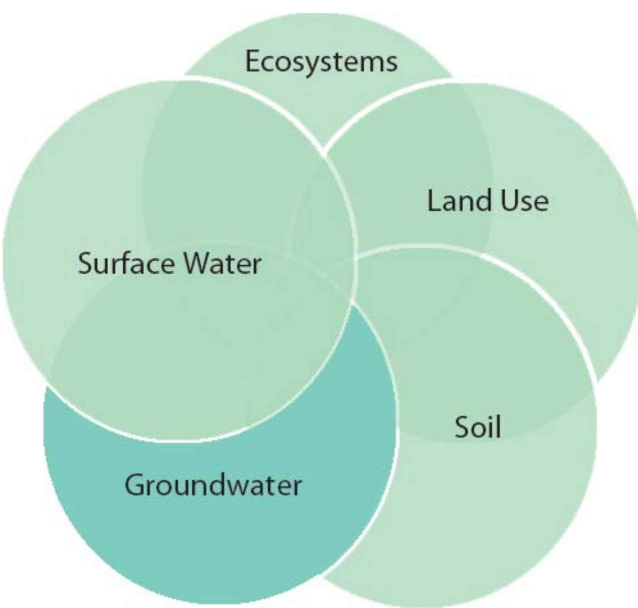

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Contents

Attachments Section

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Abstract

The deepest bedrock aquifer of south central/southeastern Minnesota, including the Minneapolis/St. Paul metro area, is the thick (50 to 200 feet) Cambrian sandstone Mt. Simon aquifer. It supplies all or some of the water used by over one million Minnesotans. The few water level measurements available from this aquifer in the Mankato and Minneapolis/St. Paul metro area indicate declining water levels in areas where water is being withdrawn for municipal and industrial use.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 aquifer the western and northern edge of the Mt. Simon aquifer was investigated and characterized through observation well installations, water level monitoring, groundwater chemical analysis, and aquifer capacity testing. Most data collected for this study are derived from the wells installed at 14 locations by contracted drilling companies.

The combination of chemical residence time indictors, continuous water level data from nested well locations, and a general knowledge of the regional hydrostratigraphy, show an aquifer with a very slow recharge rate from a large source area located south of the Minnesota River and a smaller source area located in the northern portion of the study area. The younger ^{14}C residence time values of Mt. Simon groundwater (7,000-8,000 years) from this project roughly correspond to a time after the last ice sheet had receded from southern Minnesota suggesting groundwater in the Mt. Simon aquifer in this region began as precipitation that inf ltrated during the post-glacial period. The stable isotope data of oxygen and hydrogen support this conclusion. A recharge estimate of the Mt. Simon aquifer south of the Minnesota River based on these minimum residence time data suggest an inf ltration rate of approximately 2 cm/year. The resulting 5 billion gallons/year of recharge from the southern source area is less than the amount of groundwater used from the most recent year for which data are available (2009) but approximately equal to permitted volumes (i.e., the volume of water that the users are allowed to pump) for appropriators in this area. At current groundwater extraction rates, the region's groundwater supply appears to be in a steady state. The effect of future increases in groundwater appropriation from the Mt. Simon due to population growth, industrial development, or drought might push this resource beyond this steady state.

A major accomplishment of this project is the creation of a network of observation well nests along the western margin of this aquifer system. Long term water level data and geochemistry from these wells will enable future hydrologists to evaluate the local and regional effects of any future expansion of Mt. Simon groundwater pumping in the region beyond current volumes.

Introduction and Purpose

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 provide $4,295,000 for a 4-year project. The allocation is being shared by the DNR ($2,769,000) and the Minnesota Geological Survey (MGS, $1,526,000) to evaluate the Mt. Simon aquifer and produce geologic atlases. The purpose of this report is to compile, summarize, and interpret data collected from the f rst phase of the DNR portion of this project as required by the statute (ML 2008, Chap. 367, Sec. 2, Subd. 4 (h)). A report summarizing the second phase of the project west and northwest of the Twin Cities Metropolitan area is scheduled for completion June 30, 2012.

The deepest bedrock aquifer of south central/southeastern Minnesota, including the Minneapolis/St. Paul metro area, is the thick (50 to 200 feet) Cambrian sandstone Mt. Simon aquifer. and it supplies all or some of the water used by over one million Minnesotans. The few water level measurements available from this aquifer in the Mankato and Minneapolis/St. Paul metro area indicate declining water levels in some parts of these areas where water is being withdrawn for municipal and commercial use. While efforts currently are underway through other agency and additional Minnesota Department of Natural Resources projects to locally map and understand these depressed Mt. Simon water level areas, we believed a project to regionally understand the recharge dynamics of the Mt. Simon aquifer was needed. The western and northern edge of the Mt. Simon aquifer (Figure 1), where it is not overlain by relatively impermeable Paleozoic shale formations, was considered the most likely area for aquifer recharge. This edge of the Mt. Simon aquifer also was investigated and characterized through observation well installations, water level monitoring, groundwater chemical analysis, and aquifer capacity testing to help determine recharge pathways and sustainable limits for this aquifer. These data will help determine aquifer recharge characteristics and potential limitations for future use.

Most data collected for this study are derived from the wells installed at 14 locations by contracted drilling companies. Staff from the DNR Ecological and Water Resource Division coordinated the installation of these wells, which are known among groundwater professionals also as observation wells. Drilling in the northern portion of the investigation area (Phase 2) began in the fall of 2009 to complete well nests (two or more observation wells completed at the same location but at different depths) at an additional 10 locations. The wells are completed in the Mt. Simon aquifer and shallower aquifers on public property in the project area to depths of 70 feet to 680 feet (Table 1). The wells were sampled for chemical constituents such as tritium and carbon-14 that will help 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.

Geology of South-Central Minnesota

The focus of this investigation was the Cambrian Mt. Simon Sandstone (Figure 2) which is located at the base of a thick sequence of marine Paleozoic 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 formation cuttings observed from drill holes for this project generally indicated the unit is dominated by thick beds of gray, white silty, very f ne to medium-grained quartzose to feldspathic sandstones with thin white-grey and light green shale beds. The basal portion of the Mt. Simon Sandstone has somewhat thicker shale beds and coarse yellowish quartz grains ranging from very coarse sand to medium pebble size.

Various Precambrian rocks 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, Early Proterozoic igneous and metamorphic rocks, and in some southern areas, the Lower Proterozoic Sioux Quartzite. None of these underlying rocks have desirable aquifer properties for most purposes. Therefore, the Mt. Simon Sandstone is the deepest bedrock aquifer in the region. Furthermore, along the western edge of the Hollandale embayment (Figure 3), the Mt. Simon is commonly the only aquifer available for large capacity (i.e., municipal and industrial) use.

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. During the Late Cretaceous period 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 this period a shallow epicontinental (inland) sea covered the western interior of North America. Relatively thick sections of these types are rocks are common in the southern portion of the 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 has left a legacy of both bedrock and glacial aquifer systems.

Investigation methods

Site selection

The wells for this investigation were drilled on public land to help ensure the longevity of these monitoring locations. With the exception of one location, all the wells are on state land managed by the Department of Natural Resources, on either wildlife management areas (WMAs) or at water access (WA) locations. One well site in Sibley County is owned by the county. At that location Special access permission for that location was obtained from the County Board of Commissioners.

Site locations were chosen in suspected recharge areas for the Mt. Simon aquifer near the western edge of the Hollandale embayment at location where the Mt. Simon Sandstone was likely to be the uppermost bedrock to be found beneath the surf cial glacial deposits or Cretaceous shale and sandstone. A shallow and deep well were drilled at most locations to provide data on the vertical hydraulic head gradients, changes in groundwater chemistry, and residence time with depth. These sites were evenly spaced as evenly as much as possible 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 interior of the hollow rod and bit assembly which pushes the ground rock and sediment upward through the annular space between the drilling rods and the larger diameter borehole to the surface. The drilling mud f ows into an open tank at the surface and is subsequently recirculated back down the inside of the drill bit/rod assembly to the bottom of the borehole. The advantage of this method is that it is relatively fast and inexpensive. The disadvantage of this method is that the ground-up bits of rock and sediment (also known as "cuttings") that the driller and geologist use to identify drilling progress become diff cult or impossible to identify below a depth of a couple hundred feet because of mixing and mechanical degradation of the cuttings on their way to the surface.

Another type of drilling method was used in selected areas called dual rotary/ reverse circulation (DR/RC). During DR/RC drilling, the drill cuttings are returned to surface inside the rods. Reverse circulation is achieved by pumping air down the outer tube of the rods with a large compressor. The differential 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. RC drilling produces discrete and easily identif able 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. 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, an 8- inch or 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. A geophysical log of the hole was then made by the Minnesota Geological Survey at which time the depth of the permanent 4-inch diameter casing was decided based on the gamma log characteristics of the Mt. Simon Sandstone. 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.

Drilling with the mud rotary method followed a different sequence. A seven-inch diameter borehole was drilled into the top of the Mt. Simon Sandstone and a four-inch steel casing was grouted in place. Once the grout had set, the drilling crew would drill inside the four-inch casing with a smaller drill bit and rod assembly until they had drilled through the Mt. Simon Sandstone into the underlying Pre-cambrian bedrock. The depth at which the Mt. Simon is encountered is estimated by reference to logs of nearby wells and carful observation of changes in the cuttings that come to the surface with the drilling mud. The main disadvantage of this method is that if the top of the Mt. Simon Sandstone is misidentif ed, the base of the permanent casing might not be placed at an ideal depth.

Once the deep Mt. Simon 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. These shallow wells were completed in the discontinuous sand and sandstone layers of the Quaternary and Cretaceous units at a relatively wide range of depths. In general, we were seeking the shallowest aquifer that might be used for domestic or larger capacity purposes.

Geophysical well logging

Well logging, also known as borehole logging, is the practice of making a detailed record (a well log) of the geologic formations penetrated by a borehole. The log may be based either on visual inspection of samples brought to the surface (geological logs) or on physical measurements made by instruments lowered into the hole (geophysical logs). The geophysical well log is a record of formation properties with an electrically powered instrument. Both types of logs are used to infer properties and make decisions about drilling and production operations. The geophysical log types collected for this project include passive nuclear measurements (natural gamma rays), resistivity, and spontaneous potential. 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 multiple conductor, armored wireline. Once lowered to the bottom of the interval of interest, the measurements are taken on the way out of the wellbore. Measurements are recorded continuously while the probe is moving.

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 and different spectra of natural gamma radiation. In particular, shales and clay usually emit more gamma rays than other sedimentary rocks, such as sandstone, or sand and gravel because radioactive potassium is a common component in their clay content, and because the cation exchange capacity of clay causes them to adsorb uranium and thorium. This difference in radioactivity between shales and sandstones/carbonate rocks (or clay-rich, non-clay rich sediments) allows the gamma tool to distinguish between shales (or clay-rich and non-clay-rich sediments).

Resistivity is a fundamental material property which represents how strongly a material opposes the f ow of electric current. This log is run in holes containing electrically conductive mud or water. Sand and sandstone tend to be insulators (high resistivity), and 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 resistivity tool to distinguish between the two general categories of sediments or sedimentary rocks.

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

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 is designed to ensure that all or most of the open hole portion of the well 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 many 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 and because well performance testing information can be collected during the same f eld event. Therefore, the collection of water samples was organized to complete 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 and operated by a State-certif ed water well contractor. An electric generator was used to provide power to the pump and a combination of piping and f exible hose were installed to deliver the groundwater to the surface. During the course of the f eld sampling events two different pumps were used. The f rst pump had a capacity of eight gallons per minute which proved too low to pump out the required volumes of water at an acceptable rate. To speed up the f eld pace, a pump capable of producing pumping rates of 25 gallons per minute was used. Table 2 presents the basic information collected during these 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 pre-pumped until constant values of pH, temperature and specific conductance were observed. The 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 Laboratory (Waterloo).

Specific capacity procedures and results

Specific capacity provides an estimate of the potential yield from a water well. It 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 (Selected Aquifer Parameters for Ground Water Provinces, 2004 DNR) range from less than 1.0 gpm/ft. to values greater than 100 gpm/ft. Specific capacities for the Mt. Simon- Hinckley 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 13 gpm/ft at Exceder WMA to less than 1 gpm/ft at Helget-Braulick WMA.

The depths to groundwater were measured from dedicated measuring points located at the top of the well casings. For this project the measuring points elevations were measured using engineering grade global positioning systems (GPS) that use the Minnesota Department of Transportation Continuously Operating Reference Station (CORS) 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 or TOC). Groundwater depth measurements were collected before, during and after pumping using electronic 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. DNR observation well 83012 and Flandrau State Park campground well was not accessible for instrumentation and is not represented in Appendix B with a hydrograph.

Continuous water level measurements

Unattended continuous water level measurements can be made with pressure transducers – 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/pressure transducer units that are about the size of a small flashlight.

Sealed data logger/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 sort out changes in pressure reading that are related to barometric pressure from real water level changes, a record of barometric pressure must also be made. Three data logger/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 the quarterly site visit occurs. Communication cables connected to the instruments are accessible from the top of each well. The data are downloaded from the instruments, a water level measurement is taken with a measuring tape, and computer software calibrates the data stream to the actual measurements and adjusts for changes in barometric pressure.

Thickness of the Mt. Simon aquifer near the western subcrop

One of the objectives of the project was to better define the physical boundaries of the Mt. Simon aquifer in the study area to help with future water resource evaluations. With the exception of the well at the Nicollet Bay unit, all the Mt. Simon wells drilled for this project penetrated to the base of the formation. Most existing wells in this area (Figure 4) provide a minimum thickness value since most of the wells are domestic and are only drilled into the top of the aquifer to provide relatively small quantities of water.

Across the study area thicknesses of the Mt. Simon aquifer increase toward the east over a short distance with the exception of an apparently broad and thin (0-50 feet) area in eastern Brown county. East of the western aquifer edge the Mt. Simon aquifer is commonly 200 feet thick or greater (Mossler, 1992).

Groundwater movement and potentiometric surface – Mt. Simon 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 unchangeable. 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 and measurements by personnel from the Department of Natural Resources were plotted and contoured to create the potentiometric contour map (Figure 5). Additional wells in fractured Precambrian crystalline aquifers beyond the extent of the Mt. Simon 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 generally not the physical top of the water table, but is a representation of the potential energy that is available to move the ground- water 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 shown as arrows).

Groundwater flow pathways from recharge areas through the aquifer to discharge locations operate on 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 5 shows northeasterly groundwater flow directions toward the Minnesota River in the southern portion of the study area. In the northern portion of the study area flow is southeasterly in Sibley County and then diverges toward the Minnesota River in Nicollet County at a very low gradient. This map and Figure 6 (cross section Z-Z’) the potentiometric contours bend toward the Minnesota River indicating that it is a discharge feature for the Mt. Simon aquifer. Even though the potentiometric contours indicate discharge to the Minnesota River, the previously mentioned low gradient in the northern portion of the study area could indicate low flow to the river.

Geochemistry

All the wells constructed for this project and two additional wells 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 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 these investigations. In general, short residence time suggests high recharge rates, whereas long residence time suggests low recharge rates.

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 12.43 years. Groundwater samples with concentrations of tritium equal to or greater than 10 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).

With one exception, none of the groundwater samples contained detectable tritium concentrations (Table 4) and therefore, the residence time for these samples is greater than approximately 60 years. This is consistent with the generally high depths of the sampled aquifers and general lack of thick surf cial sand and gravel in the study area. The one mixed tritium sample was from the shallow well at the Long Lake WA that was screened in a sand and gravel aquifer at a depth of 128 feet.

Figure 7 shows the distribution of ^{14}C residence time values from the shallow wells constructed for this project. These values represent data from aquifers with a wide depth range (70 to 444 feet). This map, therefore, is not intended to show any regional trends or tendencies but is shown to illustrate the wide range of values in these settings. These values are more interesting in comparison to the values discussed below and shown in Figure 8 from the underlying Mt. Simon aquifer.

Figure 8 shows the distribution of ^{14}C residence time values from the Mt. Simon wells constructed for this project, two additional Mt. Simon wells sampled for this project, and Mt. Simon data from other studies (Lively and others, 1992; Alexander, personal communication). Values in the southern portion of the study area range from 7,000 – 8,000 years in central Watonwan County to 30,000 years near the Minnesota River following a pattern of increasing age away from central Watonwan County. The youngest values (8,000-10,000 years) in the northern portion of the study area occur in northeastern Sibley County and also increase in age toward the Minnesota River to the south and east.

The younger ^{14}C residence time values (7,000-8,000 years) roughly correspond to a time not only after the last ice sheet had receded from southern Minnesota, but also after the time when the modern day Minnesota River Valley (Glacial River Warren) ceased to be the main discharge route for the glacial melt water (9,500 years) that was stored in Glacial Lake Agassiz (Wright, 1987). These ^{14}C values and the unique glacial history of the region suggest groundwater in the Mt. Simon aquifer in this region began as precipitation that inf ltrated during the post-glacial period. The stable isotope data described in the following section provided important corroborating evidence for this conclusion.

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 atoms 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, 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 $^{16}O/^{18}O$ and $^{1}H/^{2}H$ ratios in rain, snow, rivers, and lakes. The values are expressed as del^{2}H and del^{18}O. The abbreviation “del” denotes the relative difference from standard mean ocean water and express the relative abundance or the rarer heavy isotopes, del^{2}H and del^{18}O. These values from precipitation water generally plot close to a straight line known as the meteoric water line (Figure 9). 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 9 shows a plot of del^{18}O and del^{2}H values from groundwater samples collected in the study area compared to the meteoric water line. Three 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, relative mixing of water from cold and warm sources, and evaporation of source water.

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 et al (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 del^{18}O groundwater values from cold ice or snow melt sources ranges from del -25 to -9. Most values of groundwater samples from south central Minnesota ranged from approximately del -8 to del -10 suggesting a mixture of glacial meltwater and a larger component of post-glacial precipitation. The data are consistent with the younger ^{14}C ages dates (7,000 to 8,000 years) from the post-glacial and post River Warren era as discussed previously.

It is also signif cant to note that many of the older ^{14}C values in this area are in the range of the last glacial advance in the upper Midwest (12,000 to 24,000 years BP) but the del^{18}O values are just slightly within the range of water from ice melt sources (del-25 to del-9). This apparent discrepancy suggests that these waters are from mixed sources and time periods, indicating a combination of much younger and much older water. Recognizing that all groundwater is a mixture, Mt. Simon ^{14}C residence time values greater than 9,000 or 10,000 years may represent a minimum age in these areas.

Evaporation of Source Water

Deuterium (^{2}H) is an isotope of hydrogen consisting of a proton and a neutron, whereas hydrogen (^{1}H) consists of a proton. Deuterium, therefore, has approximately twice the mass of common hydrogen. Similarly, oxygen-18 (^{18}O) has more mass than the more common oxygen-16 (^{16}O). Fractionation occurs because of these mass differences. Molecules of water with the more common hydrogen and oxygen are lighter and more readily evaporated, leaving the remaining water more concentrated in the heavier isotopes. As a result, lake water typically shows an evaporative signature (a higher concentration of the heavier isotopes than precipitation). Water that directly inf ltrates the ground is not fractionated in this manner, so it has a *meteoric signature* (higher concentration of the lighter, more prevalent isotopes). The effect of this type of fractionation is that isotopic values from samples with an evaporative signature will plot along a line with a slope less than the slope of the meteoric water line.

On Figure 9 the evaporated types of samples are shown on the right upper portion of the graph (Peterson unit, Helget Braulick WMA, and the Nicollet Bay unit). These three samples, from buried sand and gravel aquifers, show evidence of water that inf ltrated from lakes or wetlands.

The majority of samples plotted in the center portion of the graph along the meteoric water line (Figure 9) suggest sources from post ice-age precipitation (normal rain and snow meltwater) that inf ltrated directly into the subsurface and did not reside for long periods in lakes or similar water bodies.

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 10 shows the relative abundances of these common ions plotted on a ternary plot. 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. There is a fairly even distribution between waters containing bicarbonate as the primary anion and waters containing sulfate as the predominant 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 inf ltrating precipitation. Higher sulfate concentrations in the Mt. Simon aquifer tend to occur in the southern and western portions of the study area (Figure 11) where inf ltrating water has passed through Cretaceous sandstone and shale layers that contain sulfate minerals such as gypsum and anhydrite.

The data from a few samples plotted on the lower right corner of the cation ternary plot show that some Na/K waters are also present in the area. These Na/K type waters (Mt. Simon aquifer: Norwegian Grove and Flandreau; Sioux Quartzite: Courtland West) may have a partial deep bedrock origin. Other evidence of deep isolated groundwater or upwelling from deep crystalline bedrock sources is suggested by some elevated chloride values of samples collected near the Minnesota River Valley (Figure 12). Elevated chloride values at the Helget Braulick and Peterson unit sites should be dismissed since samples from these wells probably contain some chloride from the chloride disinfectant that was added to these wells during the well construction process.

Trace Elements
Analysis of groundwater samples for a suite of trace element constituents reveal exceedences of drinking water standards for boron (one sample) and arsenic (f ve samples). A boron concentration of 1,910 ug/l (ppb) was measured in water from the Lake Hanska well that was completed in a Cretaceous sandstone aquifer. The Minnesota Department of Health (MDH) health risk limit (HRL) for this element is 600 ug/l. This elevated value is not typical of concentrations measured in the rest of the samples which otherwise ranged from 74 to 464 ug/l (Table 4). The reason for the elevated concentration of boron is unknown; however, the most negative ^{18}O value (del -10.27) of all the samples collected in the study area was also detected in the sample from this well which suggests that this aquifer is relatively stagnant and isolated.

Arsenic concentrations that exceeded the federal drinking water standard of 10 ug/l were detected in samples collected from f ve wells, three from buried sand and gravel aquifers and two from the Mt. Simon aquifer (Table 4 and Figure 13). Two of the exceedences (Nicollet Bay unit and Helget-Braulick WMA) from buried sand and gravel aquifers also contained water from evaporated surface water sources (discussed in evaporation of source water section). Arsenic in groundwater tends to come from disseminated mineral sources in glacial till (MDH, 2001; Erickson, M.L. 2005). Arsenic can be released from these minerals into solution by oxygenated water. Inf ltrated lake water could be a possible source of oxygenated water resulting in the elevated arsenic concentrations found in these samples.

Two of the elevated arsenic samples were collected from the Mt. Simon wells at the Peterson unit and the Nicollet Bay unit. Both of these wells are near Swan Lake in Nicollet County, the apparent source of the evaporated water from the shallow Nicollet Bay unit well. Elevated arsenic values in the Mt.

Simon aquifer may be also due to mobilization of arsenic by oxygenated lake water that has inf ltrated through multiple interconnected layers of glacial sand and till.

Hydrogeology illustrated by cross sections and hydrographs from observation well nests

A set of 12 geologic cross sections were created for this report to provide location-specif c 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 line of each cross section (Figure 3) from within a one kilometer zone on either side of the cross section.

Water level data 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 well. The water elevation hydrographs are included in the Figures section. Each displays the water levels recorded in two wells nested at the same site, the Mt. Simon well (blue) and the shallower depth well (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.

Seasonal high and low water level cycles are apparent on most hydrographs. These are yearly cycles where groundwater levels decline during the summer months and increase during the winter and spring. In many cases both nested wells follow similar trends. Average cumulative precipitation increased throughout the period of record for the water level data (Figure 14). A corresponding rise of water levels throughout 2010 is apparent from the hydrographs at several sites. Considering the relatively old residence times typical of most aquifers that were sampled for this study most of these water level f uctuations are not caused by rapid inf ltration 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 et al, 2011).

The hydrograph data of the nested observation wells, shown on Figures 15b through 26b, show two general patterns of vertical gradients: downward and upward. Most of the hydrograph comparisons show a downward gradient. A downward gradient exists where the shallower groundwater elevation is higher than a deeper groundwater elevation. This condition indicates that groundwater will move downward, if a f ow pathway is available. Within this group of downward gradient hydrograph pairs most of the hydrographs follow identical although offset patterns (Sibley County Landf ll, Peterson Unit, Bergdahl WMA, Case WMA, Madelia WMA, Exceder WMA, and Rooney Run WMA). These identical patterns strongly suggest that f uctuations within both the shallow and Mt. Simon aquifers are due to pressures affects of changes in the overlying water weight of the water table aquifer. A smaller group of downward gradient nests (Severance Lake WMA, Nicollet Bay Unit, and Helget Braulick WMA) show shallow aquifer patterns that a different from the Mt. Simon hydrograph pattern suggesting local pumping or surf cial inf uences in the shallow aquifer.

The Courtland West Unit, Long Lake WA, and possibly Norwegian Grove WMA sites demonstrate locations where upward groundwater movement is apparently occurring. At these locations the groundwater elevation from the shallower well is lower than the deeper bedrock groundwater elevations indicating an upward gradient condition. An upward gradient suggests that groundwater from the deeper bedrock will move upward if a f ow pathway is available due to local pumping inf uences or proximity to major discharge zones such as the Minnesota River.

Cross section A-A' and Severence Lake WMA hydrograph (Figures 15a and b)

The Severence Lake WMA is located in northern Sibley County near the subcrop (eastern edge) of the Mt. Simon. The shallow well was completed in a buried sand and gravel aquifer that appears to be part of a stack of intermingled and hydraulically connected sand bodies. The hydrograph from this well shows several feet of variation throughout 2010 with low water levels occurring during summer and early fall (high water use period) and higher recovery values occurring through late fall through early spring. A similar but more muted pattern is apparent for the Mt. Simon aquifer, suggesting no connection or a very minor connection to the summer pumping that is occurring in the area.

Cross section B-B' and Sibley County landfill property (Figures 16a and b)

The well nest on the Sibley County landf ll property in central Sibley County is located near the City of Gaylord. The Gaylord city wells and some domestic wells completed in the same buried sand aquifer as the shallow well are shown northwest of the well nest. The stratigraphy and geochemistry shown on Cross section B-B' (Figure 16a) suggest a direct hydraulic connection between the buried sand and gravel aquifer that the shallow well is completed in and the Mt. Simon aquifer. The well nest hydrographs (Figure 16b) show a downward gradient from the buried sand and gravel aquifer. The area stratigraphy, old residence times, and identical water level f uctuation trends suggest that the water level f uctuations are a pressure response to the changes in weight of overlying water table aquifer.

Cross section C-C' and Norwegian Grove WMA hydrograph (Figures 17a and b)

The Norwegian Grove WMA well nest in northern Nicollet County is located at the eastern edge of the Mt. Simon subcrop. The cross section (Figure 17a) shows the shallow well is completed in a stack of intermingled, and hydraulically connected sand bodies and an almost direct connection of these buried sand aquifers to the underlying Mt. Simon aquifer. The hydrographs (Figure 17b) shows a very slight upward gradient from the Mt. Simon to the buried sand and gravel aquifer. The hydraulic connection between the two aquifers, however, may not be very extensive since there is a large difference in groundwater residence time (4,000 years versus 20,000 years) and chloride/sodium concentrations.

Cross Section D-D' and Peterson Unit Hydrograph (Figures 18a and b)

The Peterson unit well nest in central Nicollet County is located near the eastern edge of the Mt. Simon subcrop. The hydrograph (Figure 18a) shows very little f uctuation in water levels (approximately one foot) and the buried sand aquifer levels are about eight feet higher than those of the Mt. Simon. These water level data and the 22,000 year ^{14}C residence time of the Mt. Simon aquifer suggest that these aquifers are not directly connected and are both relatively isolated.

Cross section E-E' and Courtland West/Nicollet Bay unit hydrographs (Figures 19a, b and c)
The geologic setting of two well nests (Courtland West unit and Nicollet Bay unit) in south central Nicollet County and an existing well that was sampled (Flandreau State Park) in eastern Brown County, is shown on this cross section. An upward gradient exists at the Courtland West site, east of the Minnesota River, which may result in upward groundwater f ow direction due to the proximity of the river. Upward gradients are commonly found near major rivers where groundwater discharges to the alluvial aquifer from underlying aquifers locally. West of the Minnesota River a similar upward gradient is suggested by the 30,000 year ^{14}C residence time and high sodium - chloride concentrations (Table 5 and Figure 12). These chemical characteristics suggest old, isolated groundwater from the underlying crystalline bedrock is moving upward through the thin Mt. Simon aquifer to the base of the Minnesota River alluvium.

At the Nicollet Bay unit location at the east side of the cross section the shallow well is shown completed in a stacked complex of buried sand and gravel aquifers. The graph of stable isotope values (Figure 9) shows that the sample from this well contains some water from an evaporated surface water source. The detectable tritium concentration from this sample is also good evidence of focused recharge at this location. The relatively constant water level elevation measurements from this well (Figure 19c) and these chemical characteristics suggest a strong hydraulic connection to a stable surface water source such as Swan Lake. The hydrograph of the Mt. Simon well at this location appears to show some inf uence from local pumping possibly from the wells shown on the cross section west of the Nicollet Bay well nest.

Cross section F-F' and Helget-Braulick WMA hydrograph (Figures 20a and b)
The Helget-Braulick WMA well nest is located in central Brown County near the western edge of the Mt. Simon subcrop. The shallow well, completed in a buried sand and gravel aquifer, contained some groundwater from an evaporated surface water source (Figure 9). A very short ^{14}C residence value (500 years) is consistent with this stable isotope data. In addition, the hydrograph trend follows the precipitation trend of higher than average rainfall during the summer of 2010, also suggesting a hydraulic connection and pressure response to the additional water at or near the surface. The muted but similar hydrograph pattern of the Mt. Simon well hydrograph is probably a pressure response.

Cross section G-G' and Bergdahl WMA hydrograph (Figure 21a and b)
The Bergdahl WMA well nest of northeastern Watonwan County and a shallower well completed in Cretaceous sandstone at the SE Lake Hanska WA are shown on this cross section. The deeper well that was planned for the Lake Hanska site was not built since no Mt. Simon sandstone was found at this site during drilling. Both hydrographs in the Bergdahl WMA well nest show a rising pressure response corresponding to a cumulative increase in precipitation in the area.

Cross section H-H' and Case WMA hydrograph (Figures 22a and b)
The Case WMA well nest located in eastern Watonwan County and an irrigation well that was sampled for this project are shown on this cross section. Some of the youngest Mt. Simon groundwater in the area was collected from the irrigation well which is located at the eastern edge of the Mt. Simon subcrop. The 7,000 year ^{14}C residence time from this well is actually younger than groundwater that was sampled from the shallower buried sand and gravel aquifer at the Case WMA well nest. This irrigation well sample also contained elevated concentrations of sulfate indicating migration through the overlying sulfate mineral rich Cretaceous sandstone and shale. Both hydrographs at the Case WMA well

nest show an approximate 4.5 foot pressure response rise in water levels throughout 2010 which corresponds to a cumulative increase in precipitation in the area.

Cross section I-I' and Madelia WMA hydrograph (Figures 23a and b)
The Madelia WMA well nest located in eastern Watonwan County is shown on the eastern side of this cross section. The Mt. Simon sample from this location was also one of the youngest ^{14}C residence values suggesting a closer proximity to the eastern edge of the Mt. Simon subcrop than is suggested by this cross section or Figure 4. Both hydrographs at the Madelia WMA well nest show an approximate 4.5 foot pressure response rise in water levels throughout 2010 corresponding to a cumulative increase in precipitation in the area.

Cross section J-J 'and Long Lake WA hydrograph (Figures 24a and b)
The Long Lake WA well nest located in south central Watonwan County is shown on the western side of this cross section possibly near the center of the Mt. Simon subcrop. Similar to the sites described on cross sections H-H' and I-I', the Mt. Simon ^{14}C residence time value at this location is among the youngest (8,000 years). Elevated sulfate concentrations indicate groundwater migration through the overlying Cretaceous sandstone and shale.

The shallow well was completed in a buried sand and gravel aquifer just above the Cretaceous sandstone and shale. The gradient between the shallow well and the Mt. Simon well is upward (lower hydraulic head in the shallow aquifer compared to the deeper aquifer) possibly due to intensive pumping of the shallow buried aquifers from domestic wells surrounding Long Lake. The approximate 1.5 to 2.5 foot rise of water levels in both wells throughout 2010 corresponds to a cumulative increase in precipitation in the area.

Cross section K-K' and Exceder WMA hydrograph (Figures 25a and b)
The Exceder WMA well nest, located in north central Martin County, is shown near the center of this cross section. The approximate two-foot pressure response rise of water levels in both wells throughout 2010 corresponds to a cumulative increase in precipitation in the area.

Cross section L-L' and Rooney Run WMA hydrograph (Figures 26a and b)
The bedrock geology of the Rooney Run area is relatively unknown. The top of the Mt. Simon Sandstone at the DNR observation well site was deeper than the Mt. Simon tops from wells drilled in the Welcome area (Figure 26b). Therefore, a fault is shown on cross section L-L' northwest of Welcome to account for this elevation difference. Southwick (2002) also shows a fault in this area shown as an "Inferred fault, mapped beneath the Sioux Quartzite or Paleozoic strata." The hydrographs of the buried sand and gravel and Mt. Simon wells show very little f uctuation during 2010 and are diff cult to interpret without a longer period of record.

Paleohydrology and Recharge Estimates

Data and interpretations generated by this project provide some basis for a rough estimate of groundwater recharge through overlying glacial sediments and Cretaceous formations to the Mt. Simon aquifer subcrop in south central Minnesota. In addition to improving the general understanding of the aquifer boundaries, thickness, permeability, and extent of overlying conf ning units, basic data have been generated regarding the residence time of groundwater in the Mt. Simon aquifer and its source water characteristics.

The 7,000-8,000 year residence time of Mt. Simon groundwater in the region (Figure 27- Watonwan County and adjoining areas and northern Sibley County near the City of Arlington) and development of post-glacial drainage conditions in the Minnesota River Valley at approximately 9,000 years BP (before present) suggests the current f ow conditions toward the valley and slow recharge of the aquifer began at approximately that time. Prior to that time the much larger volume of water f owing through the valley as glacial River Warren would have created higher head conditions in that area and a lower gradient that would have inhibited f ow toward the valley in the Mt. Simon and overlying aquifers. Siegel (1989) suggests that f ow in the Mt. Simon aquifer during the glacial maximum (16,000-14,000 years BP) was easterly toward the ancestral Mississippi River.

A conceptual model of recharge to the Mt. Simon subcrop is based on geochemical data shown on the generalized cross section Z-Z' (Figure 28) which extends from the Long Lake WA site in southwestern Watonwan County to the North Star WMA observation well in the Minnesota River Valley. This cross section is drawn perpendicular to the potentiometric contours of the Mt. Simon aquifer and is meant to represent a f ow path from the recharge areas southwest of the Minnesota River to the discharge area (Minnesota River).

On cross section Z-Z' ^{14}C residence times are younger in areas to the southwest in the Mt. Simon aquifer and overlying aquifers. Higher sulfate concentrations in the Mt. Simon aquifer in the southwest indicate downward groundwater f ow through the overlying Cretaceous formations. Slightly higher chloride concentrations have been detected in wells closer to the discharge area suggesting some upward migration of older water from Precambrian crystalline bedrock. Finally, the least negative (warmer) del ^{18}O values are found in Mt. Simon wells on the left portion (upgradient) of the cross section and in the shallower wells, whereas the more negative del ^{18}O values (colder) were found in wells on the right (downgradient) portion of the cross section.

Southern area recharge

A recharge model based on this information is shown in Figure 29. The groundwater residence time values from most of the Mt. Simon wells are assumed to be an average value of age-stratif ed water in the well. Actual values from discrete intervals within the wells might vary from top to bottom. Therefore, an assumed 5,000 year value contour was placed near the top of the Mt. Simon aquifer for the wells in the “post-glacial recharge” area. The depth to the top of this contour in this area ranges from approximately 350 to 450 feet. Assuming an average inf ltration depth of 400 feet, groundwater inf ltrating to the top of the Mt. Simon aquifer moved at approximately 0.08 feet/year or approximately 2 cm/year. The area labeled “post- glacial recharge” (Figure 27) is approximately 1,000 square km (386 square miles). The volume of recharge across this area would be approximately 20 million cubic meters or about 5 billion gallons/year.

Northern area recharge

A similar recharge estimate of the Mt. Simon aquifer for the eastern portions of Nicollet and Sibley Counties (area north and west of the Minnesota River) is more diff cult since only a small portion of the area west of the City of Arlington and the Severence Lake WMA is shown as post-glacial recharge (Figure 27). In most of this area ^{14}C residence time values are approximately three times older than the youngest values southwest of the Minnesota River. In general, groundwater recharge of the Mt. Simon in the northern portion of this region (north and west of the Minnesota River) is probably lower than in the southern part of this region (south of the Minnesota River).

2009 Groundwater Appropriation

Southern area appropriation

For this appropriation discussion the southern area is def ned as a triangular area that extends from the southernmost well nest (Rooney Run WMA) to Mankato and along the Minnesota River to New Ulm (Figure 30). Mt. Simon groundwater in the southern area is currently used by permitted (large capacity) municipal wells, agricultural processing wells, and irrigation wells (DNR web page). The DNR 2009 reported use data indicate approximately 2.2 billion gallons were pumped out of the Mt. Simon aquifer in this area. However, the actual volume pumped from just the Mt. Simon aquifer is smaller since some of the older municipal wells in the area are also open to overlying aquifers. This volume, therefore, may be approximately one third of the post-glacial recharge described in the previous section. Permitted volumes (volume of water that the users are allowed to pump) for appropriators in this area are approximately 4.7 billion gallons/year, or roughly equal to the estimated Mt. Simon post-glacial recharge in the southern area.

Northern Area Appropriation

The northern area is def ned as the eastern parts of Nicollet and Sibley Counties. Mt. Simon groundwater in the northern area is currently used by permitted (large capacity) municipal wells, agricultural processing wells, and crop irrigation wells, and golf course irrigation wells (DNR web page). The DNR 2009 reported use data indicate approximately 1.1 billion gallons were pumped out of the Mt. Simon aquifer in this area. As in the southern area, the actual number from just the Mt. Simon aquifer is smaller since some of the older municipal wells in the area are also open to overlying aquifers. Permitted volumes for appropriators in this area are approximately 1.9 billion gallons/year.

Conclusions

The results of this project suggest that Mt. Simon groundwater use in the study area, for the most recent period, may be below the replacement rate along the Mt. Simon subcrop. However, the sum of the permitted volumes may be equal to those replacement rates. The region is currently not an area of rapid municipal or industrial growth. Locally intensive groundwater pumping can create groundwater interference issues (lowered water levels in nearby wells or surface water features) but at current extraction the region appears to be in a steady state. The effect of future increases in groundwater appropriation from the Mt. Simon due to population growth, industrial development, or drought might push this resource beyond this steady state. However, a major accomplishment of this project is the creation of a network of observation well nests along the western margin of this aquifer system. Long term water level data and geochemistry from these wells will enable future hydrologists to evaluate the local and regional affects of any future expansion of Mt. Simon groundwater pumping in the region beyond current volumes. In addition, this project demonstrated the value of continuous, nested water level measurements, and groundwater chemistry/residence time data in constructing conceptual models of groundwater f ow and recharge.

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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)
52001	768263	Nicollet	Nicollet Bay	CMTS	DR/RC	519	400938.203	4902807.503	990.669	988.370	410-519	157.07
52002	768264	Nicollet	Nicollet Bay	QBAA	MR	198	400936.287	4902804.578	990.761	988.448	188-198	145.60
52003	768261	Nicollet	Courtland West	PMSX	DR/RC	463	392095.616	4905565.047	996.321	992.730	356-463	108.87
52004	768262	Nicollet	Courtland West	QBAA	MR	202	392095.445	4905567.941	994.935	992.493	195-205	108.21
52005	770449	Nicollet	Peterson	CMTS	DR/RC	545	397939.24	4911110.024	993.467	991.333	390-545	163.92
52006	770450	Nicollet	Peterson	QBAA	MR	223	397937.852	4911106.35	993.752	991.497	215-223	156.12
52007	770444	Nicollet	Norwegian Grove	CMTS	DR/RC	537	405653.717	4923018.885	981.188	978.378	390-537	152.71
52008	770445	Nicollet	Norwegian Grove	QBAA	MR	260	405655.564	4923015.735	980.876	978.349	245-253	152.37
08012	768259	Brown	Heget Braulick	CMTS	DR/RC	282	369435.816	4896564.649	1021.947	1019.757	267-282	40.10
08013	768260	Brown	Heget Braulick	QBAA	RS	70.5	369438.015	4896564.977	1021.900	1019.371	65.5-70.5	26.23
sealed	760651	Brown	Lake Hanska	CMTS	MR	316	374745.213	4885215.946	1004.311	1004.161	sealed	sealed
08014	760692	Brown	Lake Hanska	KRET	MR	164	374743.738	4885218.599	1009.414	1003.582	155-164	3.52
83017	760687	Watonwan	Case	CMTS	MR	672	389450.77	4871991.533	1041.922	1038.803	495-672	55.30
83018	760686	Watonwan	Case	QBAA	MR	206	389453.682	4871989.969	1041.967	1039.160	197-206	38.62
83019	760689	Watonwan	Madelia	CMTS	MR	648	382101.048	4870093.555	1067.011	1063.842	495-648	48.65
83020	760688	Watonwan	Madelia	KRET	MR	120	382101.235	4870090.087	1067.303	1064.408	109-119	28.10
83021	760691	Watonwan	Bergdahl	CMTS	MR	479	388508.699	4883267.002	999.802	996.857	415-479	40.31
83022	760690	Watonwan	Bergdahl	QBAA	MR	129	388504.074	4883267.280	1002.757	1000.712	119-129	36.67
83023	770427	Watonwan	Long Lake	CMTS	DR/RC	547	365169.986	4862854.602	1131.407	1129.111	373-547	32.69
83024	770439	Watonwan	Long Lake	QBAA	MR	128	365174.415	4862852.802	1131.731	1129.249	118-128	32.59
46006	768125	Martin	Exceder	CMTS	MR	680	372699.859	4851318.450	1176.856	1174.015	497-680	75.24
46007	768139	Martin	Exceder	KRET	MR	232	372700.159	4851322.787	1176.966	1174.086	222-232	81.95
46008	771163	Martin	Rooney Run	CMTS	MR	718	366704.522	4843431.030	1203.873	1201.236	640-718	69.06
46009	771161	Martin	Rooney Run	QBAA	MR	444	366705.458	4843427.544	1204.317	1201.381	434-444	68.12
72000	770440	Sibley	Sibley Co. LF	CMTS	MR*	575	405883.249	4932926.374	995.742	993.624	460-575	126.90
72001	770441	Sibley	Sibley Co. LF	QBAA	MR	430	405888.095	4932926.352	996.049	993.974	420-430	126.73
72002	770442	Sibley	Severance Lake	CMTS	DR/RC	630	410698.789	4947369.756	1010.648	1008.529	458-630	144.23
72003	770443	Sibley	Severance Lake	QBAA	DR/RC	280	410696.317	4947369.955	1009.977	1008.182	272-280	88.32

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

QBAA = Quaternary buried aquifer; KRET = Cretaceous sandstone

CMTS = Cambrian Mt. Simon sandstone; PMSX = Precambrian Sioux quartzite

Table 2 - Specific Capacity and Water Level Data Summary

Date sampled	MN unique	County	Site name	Formation	Depth to static water from top casing (ft)	Static water elevation (ft above msl)	Pumping (minutes)	Pumped volume (gallons)	Average pumping rate (gpm)	Water level drawdown (feet)	Specific capacity (gpm/drawdown)
10/7/2009	770442	Sibley	Severance Lake	CMTS	144.18	866.468	156	1240	8.0	1.22	6.5
10/7/2009	770443	Sibley	Severance Lake	QBAA	88.78	921.197	78	620	7.9	0.86	9.2
10/8/2009	770440	Sibley	Sibley Co. LF	CMTS	126.95	868.792	114	970	8.5	1.69	5.0
10/8/2009	770441	Sibley	Sibley Co. LF	QBAA	126.74	869.309	70	590	8.4	0.30	28.0
10/8/2009	770444	Nicollet	Norwegian Grove	CMTS	152.38	828.808	107	880	8.2	1.18	7.0
10/9/2009	770445	Nicollet	Norwegian Grove	QBAA	152.25	828.626	44	310	7.1	0.88	8.0
10/9/2009	770449	Nicollet	Peterson	CMTS	163.69	829.777	120	834	7.0	1.22	5.7
10/9/2009	770450	Nicollet	Peterson	QBAA	155.94	837.812	40	326	8.2	2.66	3.1
10/13/2009	768261	Nicollet	Courtland West	PMSX	109.65	886.670	90	126	1.4	186.25	0.0075
10/9/2009	768262	Nicollet	Courtland West	QBAA	108.57	886.365	39	320	8.1	0.69	11.8
10/14/2009	768263	Nicollet	Nicollet Bay	CMTS	157.73	832.940	57	1200	21.2	8.27	2.6
10/14/2009	768264	Nicollet	Nicollet Bay	QBAA	146.52	844.240	13	250	20	4.8	4.2
10/14/2009	768259	Brown	Heget Braulick	CMTS	40.71	981.237	103	230	2	63	0.036
10/14/2009	768260	Brown	Heget Braulick	QBAA	25.95	995.950	29	337	11.7	32.0	0.367
10/15/2009	760691	Watonwan	Bergdahl	CMTS	42.03	957.770	36	944	26	22.8	1.1
10/14/2009	760690	Watonwan	Bergdahl	QBAA	38.45	964.307	20	536	26	90.2	0.3
10/15/2009	760687	Watonwan	Case	CMTS	57.20	984.722	40	1040	26	4.7	5.5
10/15/2009	760686	Watonwan	Case	QBAA	40.10	1001.867	38	930	25	8.7	2.8
10/15/2009	760689	Watonwan	Madelia	CMTS	50.43	1016.581	62	1610	26	7.2	3.6
10/15/2009	760688	Watonwan	Madelia	KRET	29.40	1037.903	23	627	27	5.3	5.1
10/15/2009	770427	Watonwan	Long Lake	CMTS	32.49	1098.917	74	1887	26	3.8	6.7
10/15/2009	770439	Watonwan	Long Lake	QBAA	32.70	1099.031	23	586	25	11.3	2.2
10/16/2009	768125	Martin	Exceder	CMTS	76.38	1100.476	64	1503	23	1.8	13.1
10/16/2009	768139	Martin	Exceder	KRET	63.20	1113.766	48	967	20	16.7	1.2
10/26/2009	771163	Martin	Rooney Run	CMTS	69.06	1134.813	65	1070	17	12.5	1.3
10/26/2009	771161	Martin	Rooney Run	QBAA	68.12	1136.197	53	1270	24	12.6	1.9
10/28/2009	760692	Brown	Lake Hanska	KRET	4.33	1005.084	57	171	3	0.6	4.8
11/24/2009	132275	Watonwan	83012	CMTS	8.89	1025.87	16	14400	900	na	na
10/26/2009	405338	Brown	Flandrau SP	CMTS	na	na	150	450	3	na	na

QBAA = Quaternary buried aquifer
CMTS = Cambrian Mt. Simon sandstone
KRET = Cretaceous sandstone
PMSX = Precambrian Sioux quartzite

Table 3 Field Sample Collection and Handling Details

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	Mn
00405338	Flandrau State Park	Brown	CMTS	200	10/26/2009	0.19	89	30,000	<0.8	-68.61	-9.95	0.074
00760692	Lake Hanska WMA	Brown	Kret	164	10/28/2009	0.13	1910	11,000	<0.8	-68.69	-10.27	0.215
00768259	Helget-Braulick WMA	Brown	CMTS	284	10/14/2009	0.29	361	13,000	<0.8	-63.42	-8.56	0.304
00768260	Helget-Braulick WMA	Brown	QBAA	70.5	10/14/2009	41.2	376	500	<0.8	-50.23	-6.39	0.143
00768125	Exceder WMA	Martin	CMTS	680	10/16/2009	0.37	173	13,000	<0.8	-69.97	-9.85	0.192
00768139	Exceder WMA	Martin	KRET	231	10/16/2009	0.44	272	11,000	<0.8	-65.92	-9.11	0.256
00771161	Rooney Run WMA	Martin	QBAA	444	10/26/2009	3.78	335	8,000	<0.8	-66.69	-9.88	0.274
00771163	Rooney Run WMA	Martin	CMTS	718	10/26/2009	0.61	193	10,000	<0.8	-69.42	-9.70	0.210
00768261	Courtland West Unit*	Nicollet	PMSX	463	10/9/2009	0.23	571	NA	<0.8	-72.7	-9.81	0.0185
00768262	Courtland West Unit*	Nicollet	QBAA	202	10/9/2009	1.45	74	2,300	<0.8	-54.04	-7.72	0.429
00768263	Nicollet Bay Unit*	Nicollet	CMTS	474	10/14/2009	44.2	152	18,000	<0.8	-65.90	-9.66	0.126
00768264	Nicollet Bay Unit*	Nicollet	QBAA	198	10/14/2009	14.3	114	Recent	<0.8	-40.89	-4.84	0.311
00770444	Norwegian Grove WMA	Nicollet	CMTS	540	10/8/2009	1.93	497	20,000	<0.8	-66.42	-9.59	0.141
00770445	Norwegian Grove WMA	Nicollet	QBAA	260	10/9/2009	1.75	452	4,000	<0.8	-64.82	-8.65	0.838
00770449	Peterson Unit*	Nicollet	CMTS	545	10/9/2009	22.8	89	22,000	<0.8	-60.05	-8.23	0.165
00770450	Peterson Unit*	Nicollet	QBAA	223	10/9/2009	1.37	322	8,000	<0.8	-56.77	-7.45	0.191
00770440	Sibley Co Landfill	Sibley	CMTS	575	10/8/2009	2.41	336	17,000	<0.8	-67.46	-9.75	0.0925
00770441	Sibley Co Landfill	Sibley	QBAA	430	10/8/2009	0.36	344	18,000	<0.8	-67.27	-10.09	0.203
00770442	Severance Lake WMA	Sibley	CMTS	630	10/7/2009	1.88	241	10,000	<0.8	-66.70	-9.28	0.114
00770443	Severance Lake WMA	Sibley	QBAA	280	10/7/2009	0.42	192	5,000	<0.8	-61.30	-8.88	0.271
00132275	Darrin Bocock	Watonwan	CMTS	484	11/24/2009	0.21	357	7,000	<0.8	-58.41	-9.15	0.197
00760686	Case WMA	Watonwan	QBAA	209	10/15/2009	0.26	317	9,000	<0.8	-65.65	-9.07	0.1126
00760687	Case WMA	Watonwan	CMTS	672	10/15/2009	0.1	213	10,000	<0.8	-66.38	-9.36	0.203
00760688	Madelia WMA	Watonwan	QBAA	120	10/15/2009	5.11	183	4,000	<0.8	-63.67	-9.04	0.313
00760689	Madelia WMA	Watonwan	CMTS	648	10/15/2009	0.37	244	7,000	<0.8	-65.18	-9.18	0.1134
00760690	Bergdahl WMA	Watonwan	QBAA	129	10/14/2009	10.3	260	8,000	<0.8	-65.96	-9.19	0.891
00760691	Bergdahl WMA	Watonwan	CMTS	479	10/15/2009	0.13	225	20,000	<0.8	-67.30	-9.39	0.218
00770427	Long Lake WA	Watonwan	CMTS	547	10/15/2009	1.67	464	8,000	<0.8	-61.71	-8.64	1.037
00770439	Long Lake WA	Watonwan	QBAA	128	10/15/2009	5.27	295	2,600	2.9	-58.81	-8.31	0.388

*part of Swan Lake WMA
** 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
KRET = Cretaceous sandstone

CMTS = Cambrian Mt. Simon Sandstone
PMSX = Precambrian Sioux Quartzite

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
00405338	Flandrau State Park	Brown	CMTS	200	10/26/2009	130.9	239	0.450	291	47.2	22.0	203	10.02	1.30	0.074
00760692	Lake Hanska WA	Brown	KRET	164	10/28/2009	4.21	544	0.052	81	219	71.2	57.4	5.21	3.72	0.215
00768259	Helget-Braulick WMA	Brown	CMTS	284	10/14/2009	34.6	191	0.038	911	96.0	42.7	45.3	12.4	1.28	0.304
00768260	Helget-Braulick WMA	Brown	QBAA	70.5	10/14/2009	0.60	481	0.013	46	168	106.5	48.7	10.38	4.26	0.143
00768125	Exceder WMA	Martin	CMTS	680	10/16/2009	2.67	493	0.049	54	190	58.4	65.6	5.49	2.12	0.192
00768139	Exceder WMA	Martin	KRET	231	10/16/2009	2.25	435	0.043	52	186	57.5	54.4	5.49	1.91	0.256
00771161	Rooney Run WMA	Martin	QBAA	444	10/26/2009	2.10	615	0.043	49	208	60.9	82.2	5.71	2.90	0.274
00771163	Rooney Run WMA	Martin	CMTS	718	10/26/2009	7.04	475	0.057	124	172	51.9	70.1	7.64	2.55	0.210
00768261	Courtland West Unit*	Nicollet	PMSX	463	10/9/2009	10.1	433	0.059	171	8.62	60.9	131	27.1	0.012	0.0185
00768262	Courtland West Unit*	Nicollet	QBAA	202	10/9/2009	1.10	63.6	0.016	69	123	36.6	8.27	4.24	3.90	0.429
00768263	Nicollet Bay Unit*	Nicollet	CMTS	474	10/14/2009	18.0	175	0.062	290	109	35.8	39.9	6.71	0.246	0.126
00768264	Nicollet Bay Unit*	Nicollet	QBAA	198	10/14/2009	2.93	31.4	0.041	71	150	65.8	22.3	8.71	3.52	0.311
00770444	Norwegian Grove WMA	Nicollet	CMTS	540	10/8/2009	60.9	162	0.249	245	86.9	36.7	150	8.70	0.920	0.141
00770445	Norwegian Grove WMA	Nicollet	QBAA	260	10/9/2009	2.5	206	0.060	42	108.7	45.5	95.1	5.85	2.02	0.838
00770449	Peterson Unit*	Nicollet	CMTS	545	10/9/2009	48.7	181	0.016	3044	126	44.4	53.4	5.25	0.780	0.165
00770450	Peterson Unit*	Nicollet	QBAA	223	10/9/2009	3.36	705	0.078	43	198	63.3	170	4.67	2.30	0.191
00770440	Sibley Co Landfill	Sibley	CMTS	575	10/8/2009	3.59	45.1	0.053	68	90.5	38.7	75.0	5.62	1.68	0.0925
00770441	Sibley Co Landfill	Sibley	QBAA	430	10/8/2009	3.43	29.8	0.054	64	93.5	39.5	73.3	5.64	2.21	0.203
00770442	Severance Lake WMA	Sibley	CMTS	630	10/7/2009	21.4	131.7	0.073	293	104.6	40.1	64.4	9.50	2.06	0.114
00770443	Severance Lake WMA	Sibley	QBAA	280	10/7/2009	0.65	51.7	0.043	15	111	43.6	31.4	4.93	1.18	0.271
00132275	Darrin Bocock	Watonwan	CMTS	484	11/24/2009	1.21	751	0.037	33	269.4	95.8	52.3	7.79	5.91	0.197
00760686	Case WMA	Watonwan	QBAA	209	10/15/2009	1.83	320	0.033	55	150	55.8	49.0	5.77	3.81	0.1126
00760687	Case WMA	Watonwan	CMTS	672	10/15/2009	1.75	523	0.042	42	227	66.3	45.1	4.96	2.92	0.203
00760688	Madelia WMA	Watonwan	QBAA	120	10/15/2009	0.56	99.1	0.015	37	112	35.3	22.1	4.88	3.18	0.313
00760689	Madelia WMA	Watonwan	CMTS	648	10/15/2009	0.99	388	0.028	35	192	58.1	33.0	6.25	3.44	0.1134
00760690	Bergdahl WMA	Watonwan	QBAA	129	10/14/2009	1.98	544	0.042	47	210	66.4	68.7	5.49	2.92	0.891
00760691	Bergdahl WMA	Watonwan	CMTS	479	10/15/2009	11.2	586	0.067	167	212	77.6	77.3	6.62	3.25	0.218
00770427	Long Lake WA	Watonwan	CMTS	547	10/15/2009	1.49	1114	0.048	31	363	117	77.6	6.92	1.05	1.037
00770439	Long Lake WA	Watonwan	QBAA	128	10/15/2009	7.77	665	0.056	139	255	84.9	53.2	6.77	3.62	0.388

*part of Swan Lake WMA

QBAA = Quaternary buried aquifer
KRET = Cretaceous sandstone
CMTS = Cambrian Mt. Simon sandstone
PMSX = Precambrian Sioux quartzite

Figures

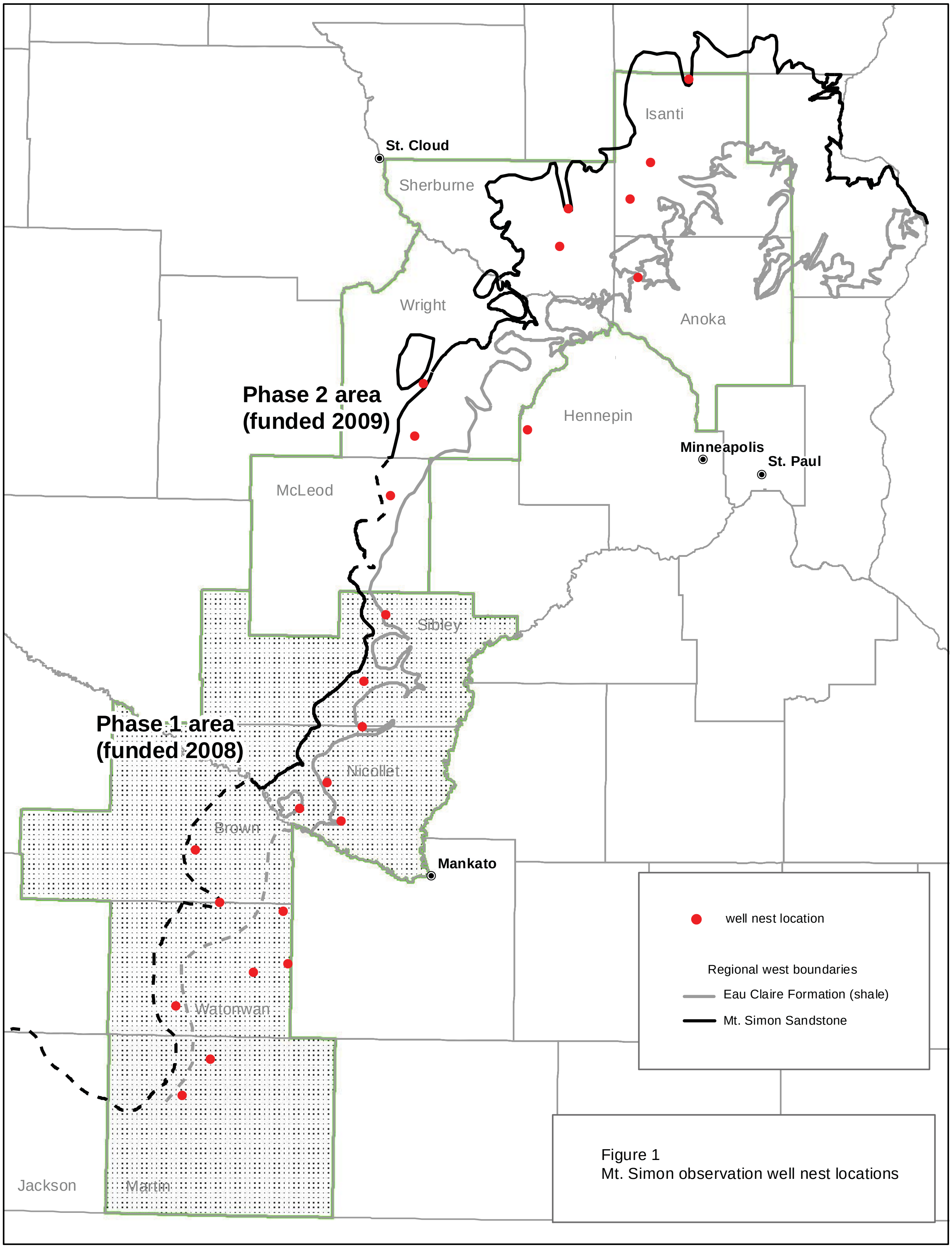


Figure 1
Mt. Simon observation well nest locations

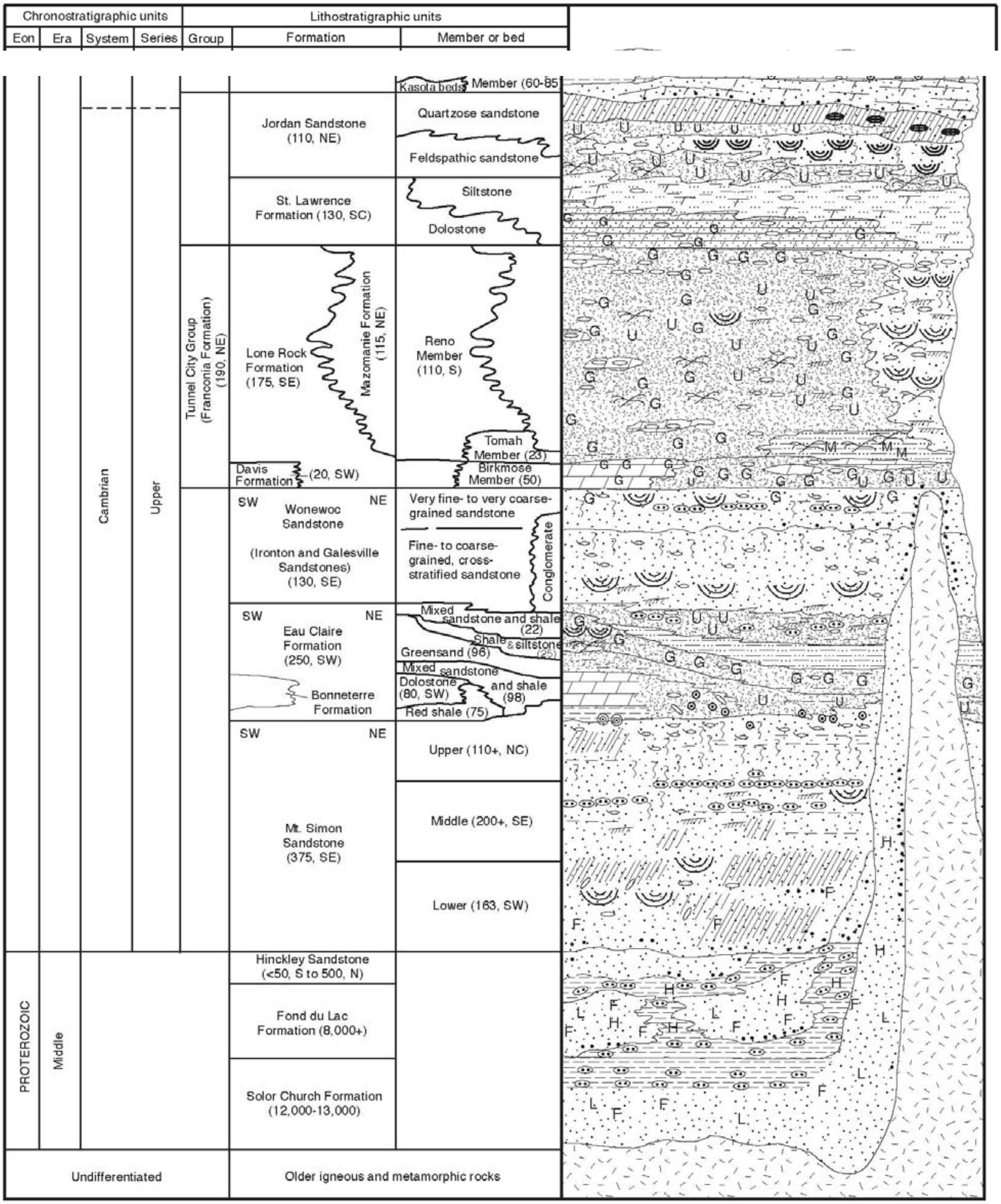
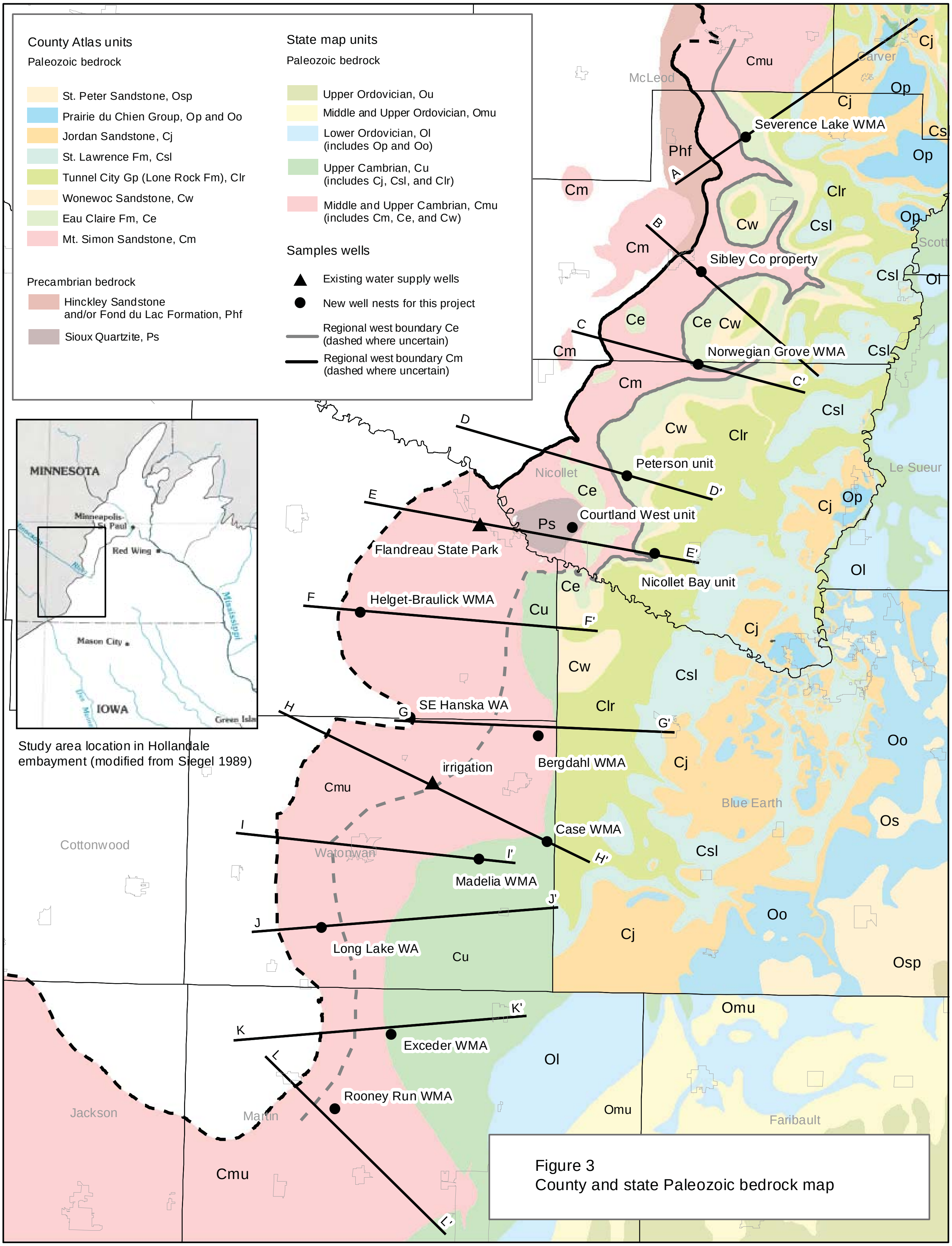


Figure 2 Cambrian and older stratigraphy in study area (Modified from Mossler 2008)


County Atlas units
Paleozoic bedrock
St. Peter Sandstone, Osp
Prairie du Chien Group, Op and Oo
Jordan Sandstone, Cj
St. Lawrence Fm, Csl
Tunnel City Gp (Lone Rock Fm), Clr
Wonewoc Sandstone, Cw
Eau Claire Fm, Ce
Mt. Simon Sandstone, Cm
Precambrian bedrock
Hinckley Sandstone and/or Fond du Lac Formation, Phf
Sioux Quartzite, Ps
State map units
Paleozoic bedrock
Upper Ordovician, Ou
Middle and Upper Ordovician, Omu
Lower Ordovician, Ol (includes Op and Oo)
Upper Cambrian, Cu (includes Cj, Csl, and Clr)
Middle and Upper Cambrian, Cmu (includes Cm, Ce, and Cw)
Samples wells
Existing water supply wells
New well nests for this project
Regional west boundary Ce (dashed where uncertain)
Regional west boundary Cm (dashed where uncertain)
MINNESOTA
Minneapolis-St. Paul
Red Wing
Mississippi
Mason City
IOWA
Study area location in Hollandale embayment (modified from Siegel 1989)
Severence Lake WMA
Sibley Co property
Norwegian Grove WMA
Peterson unit
Courtland West unit
Flandreau State Park
Nicollet Bay unit
Helget-Braulick WMA
SE Hanska WA
Bergdahl WMA
irrigation
Case WMA
Madelia WMA
Long Lake WA
Exceder WMA
Rooney Run WMA
McLeod
Carver
Scott
Nicollet
Le Sueur
Blue Earth
Cottonwood
Watonwan
Jackson
Martin
Faribault
Figure 3
County and state Paleozoic bedrock map

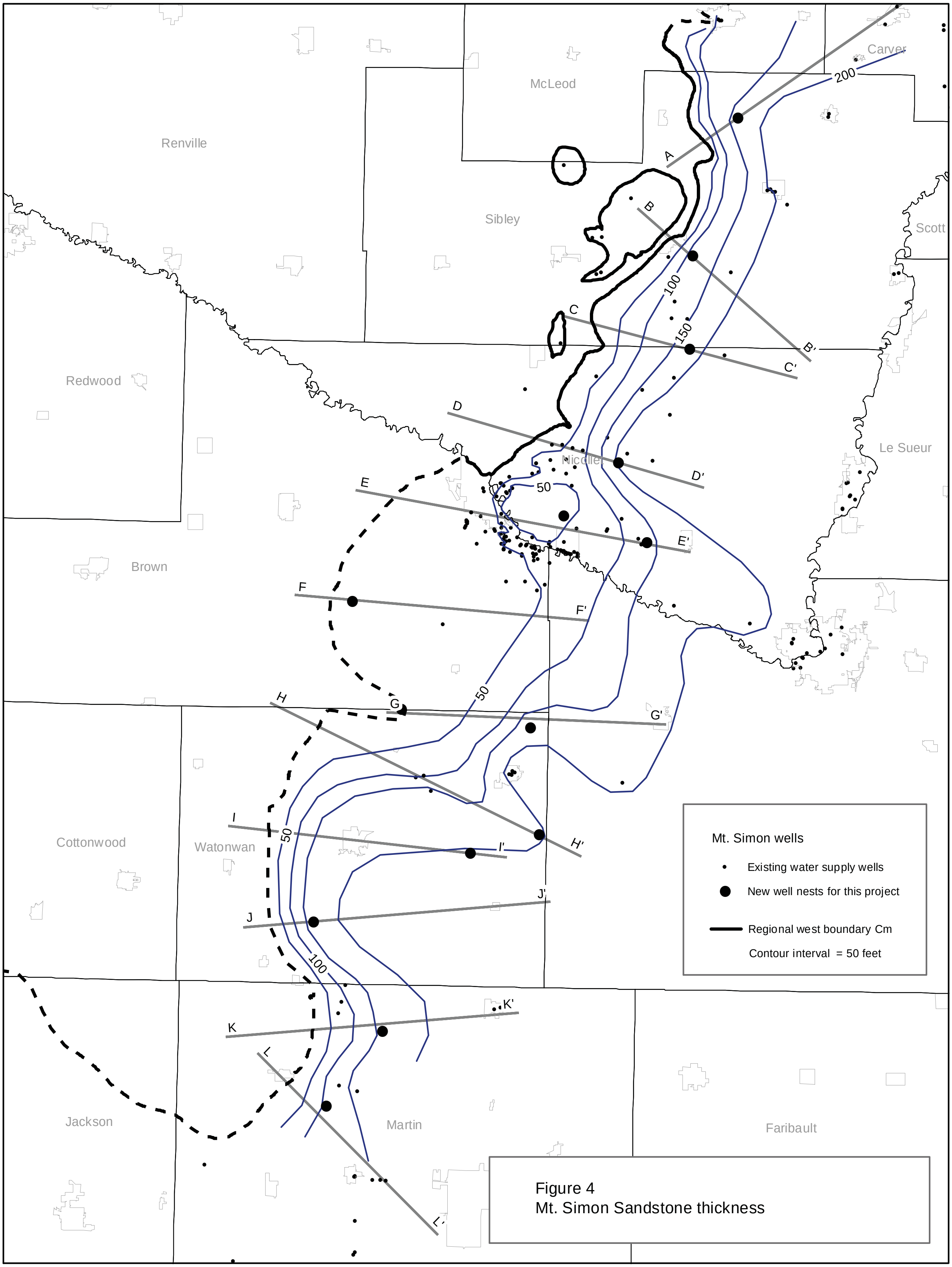


Figure 4
Mt. Simon Sandstone thickness

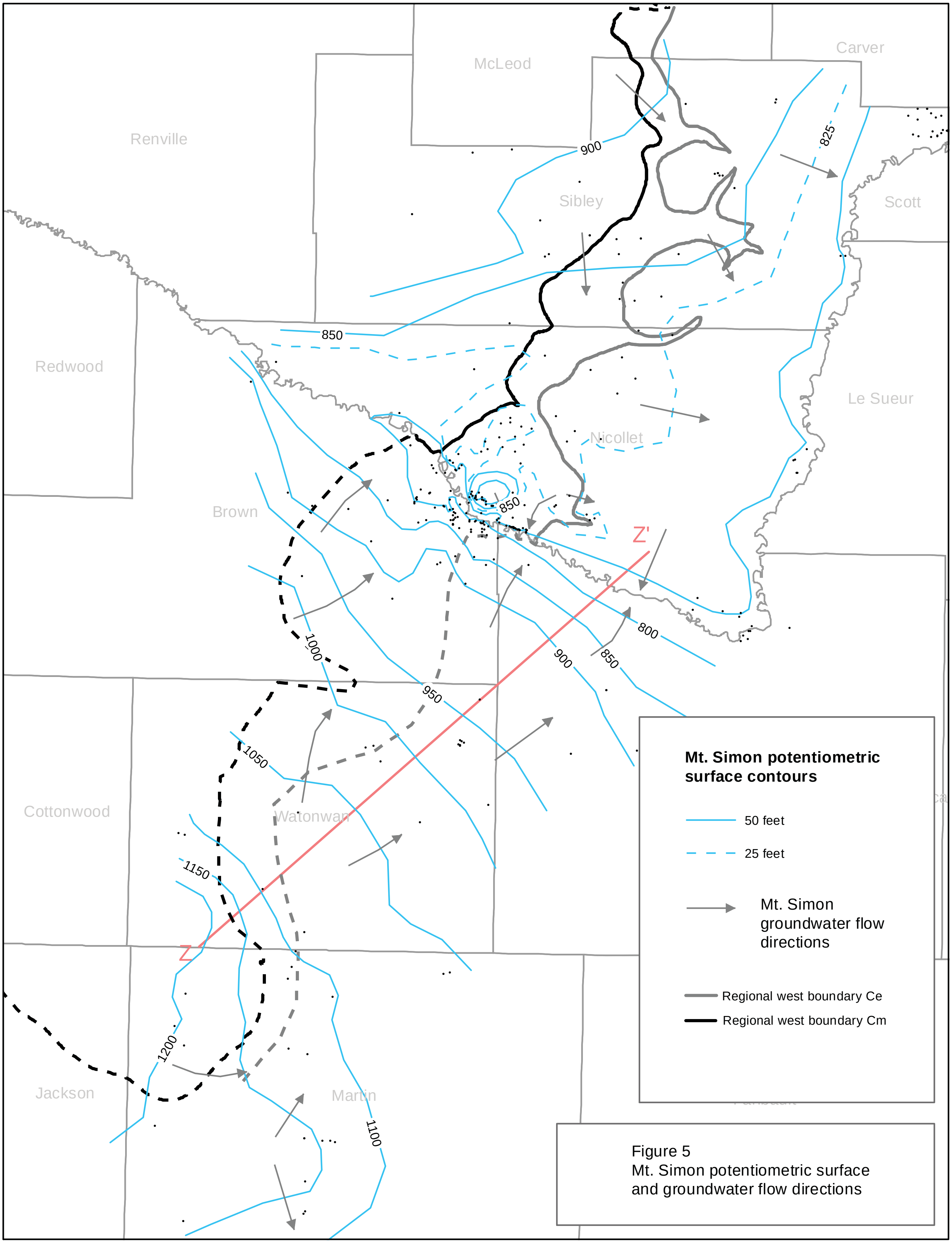


Figure 5
Mt. Simon potentiometric surface and groundwater flow directions

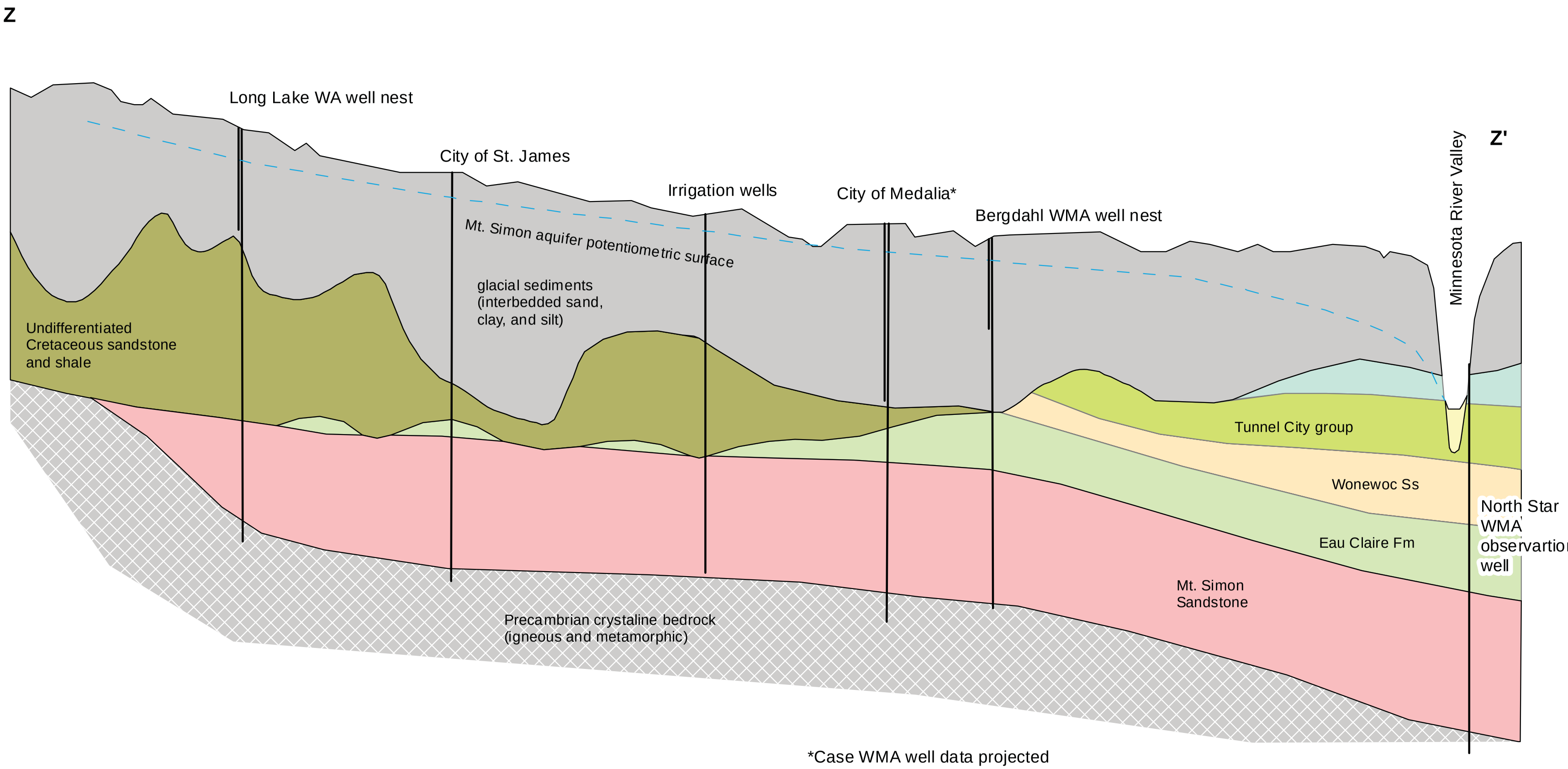


Figure 6 Cross section Z-Z'
Mt. Simon potentiometric surface

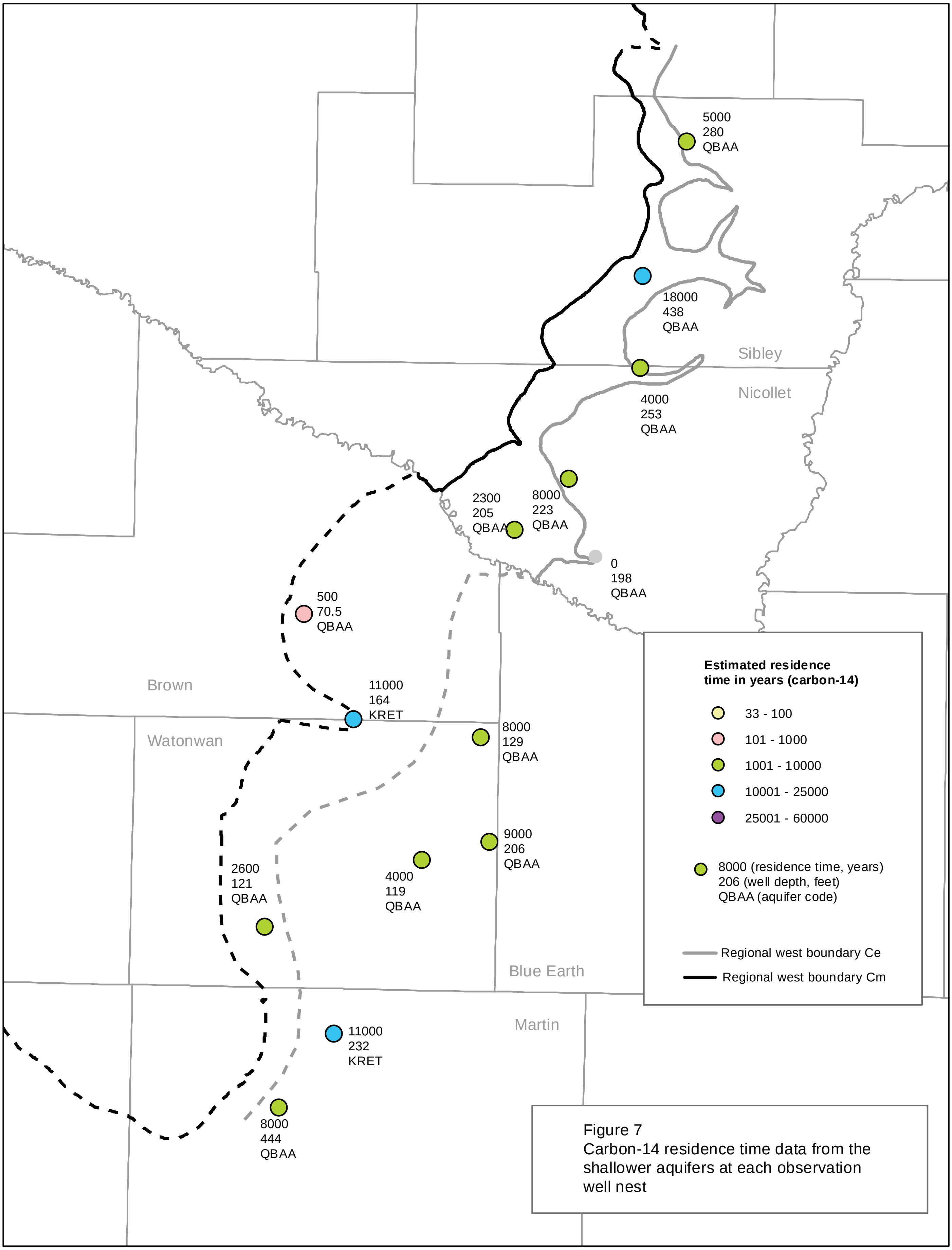


Figure 7
Carbon-14 residence time data from the shallower aquifers at each observation well nest

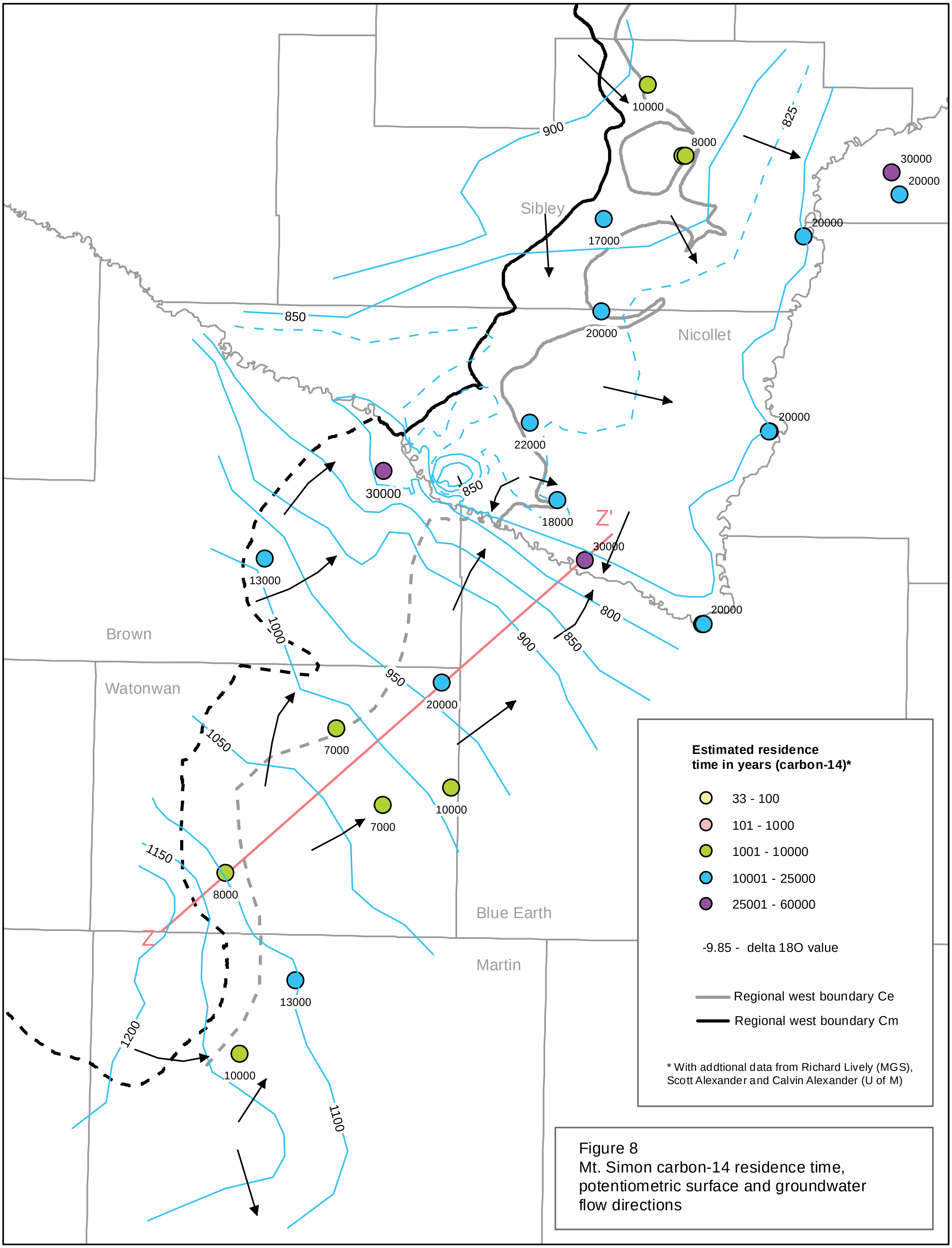
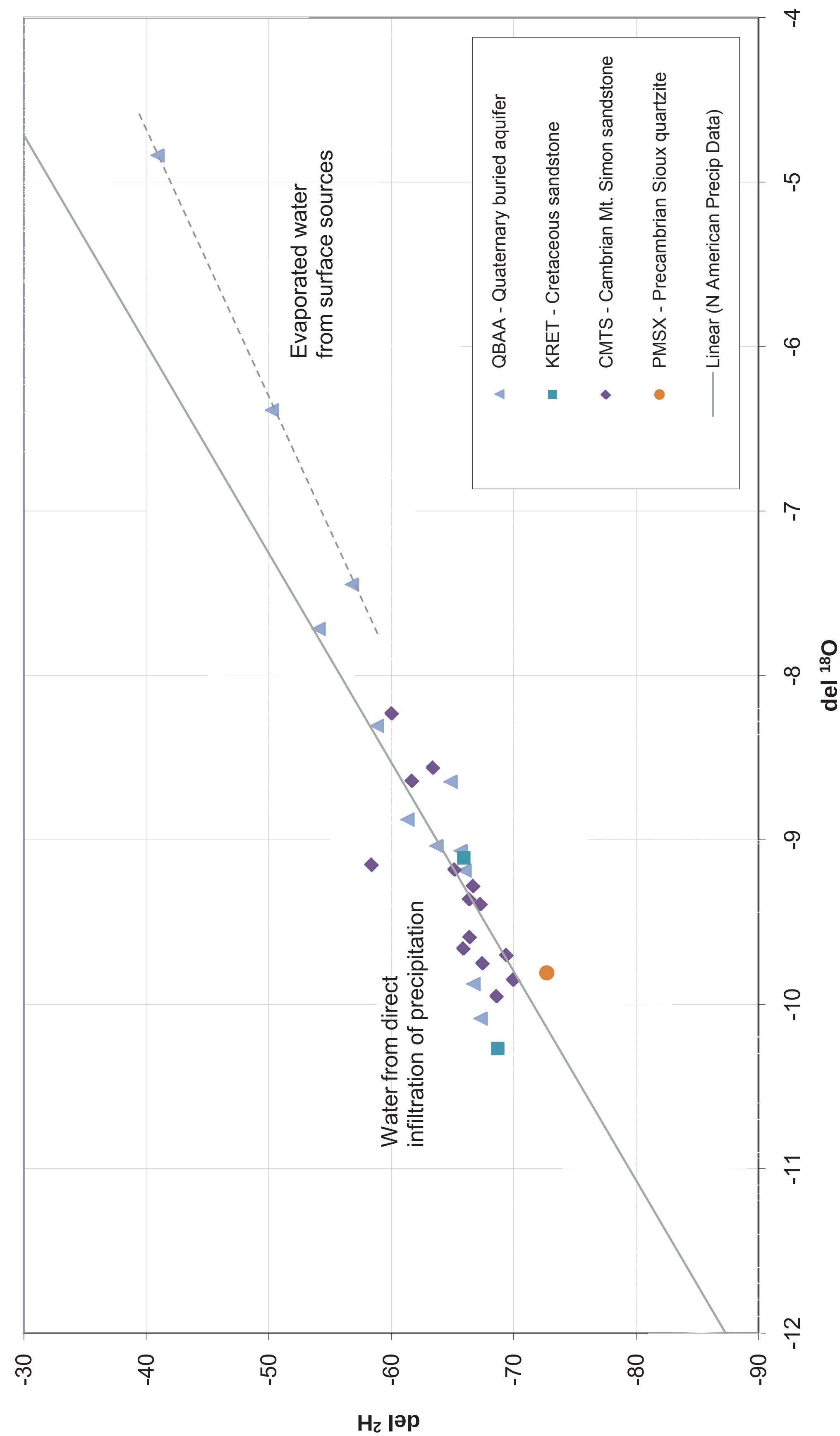


Figure 8
Mt. Simon carbon-14 residence time, potentiometric surface and groundwater flow directions

Figure 9 Stable isotope data compared with North American meteoric line



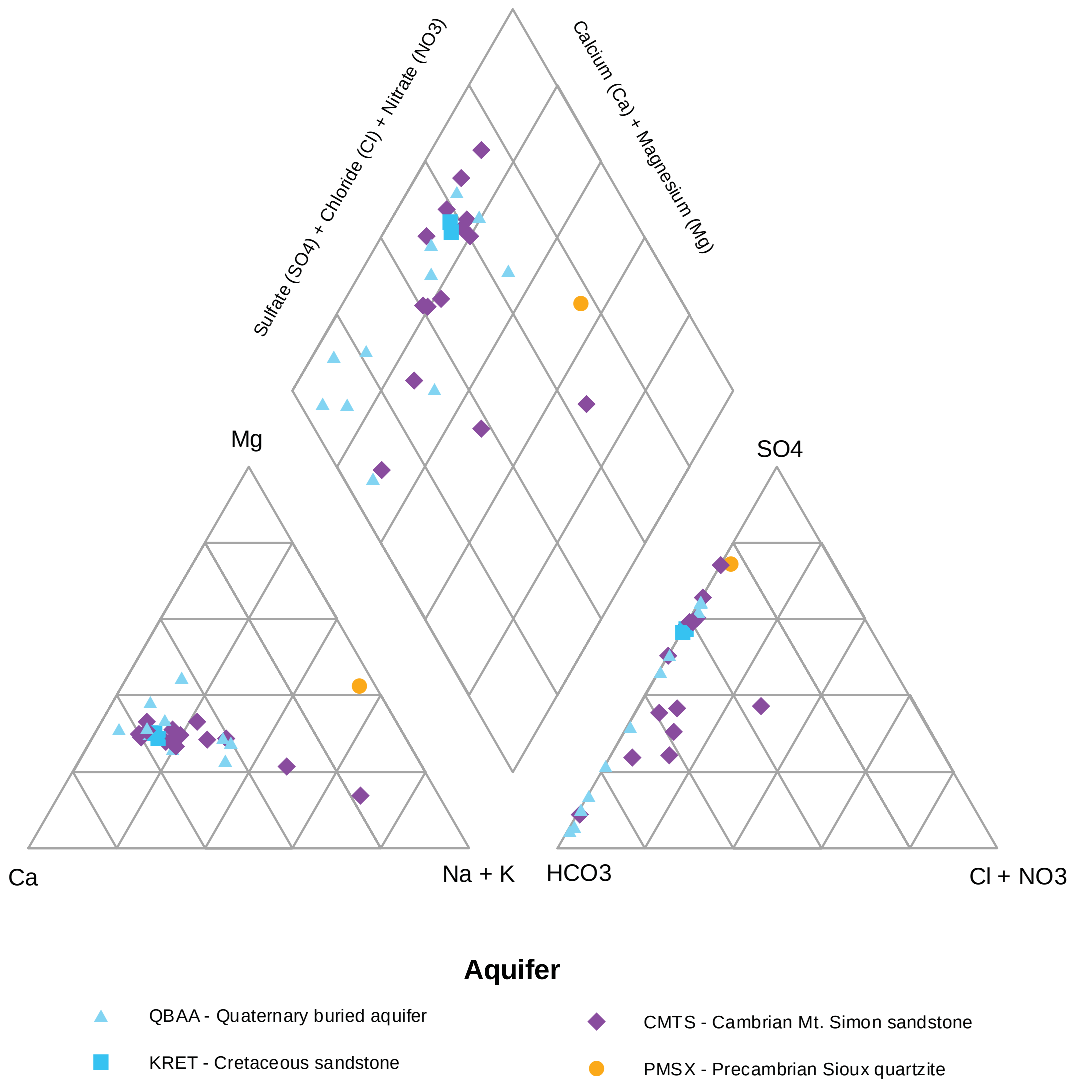


Figure 10
Ternary diagram - relative abundances of major cations and anions

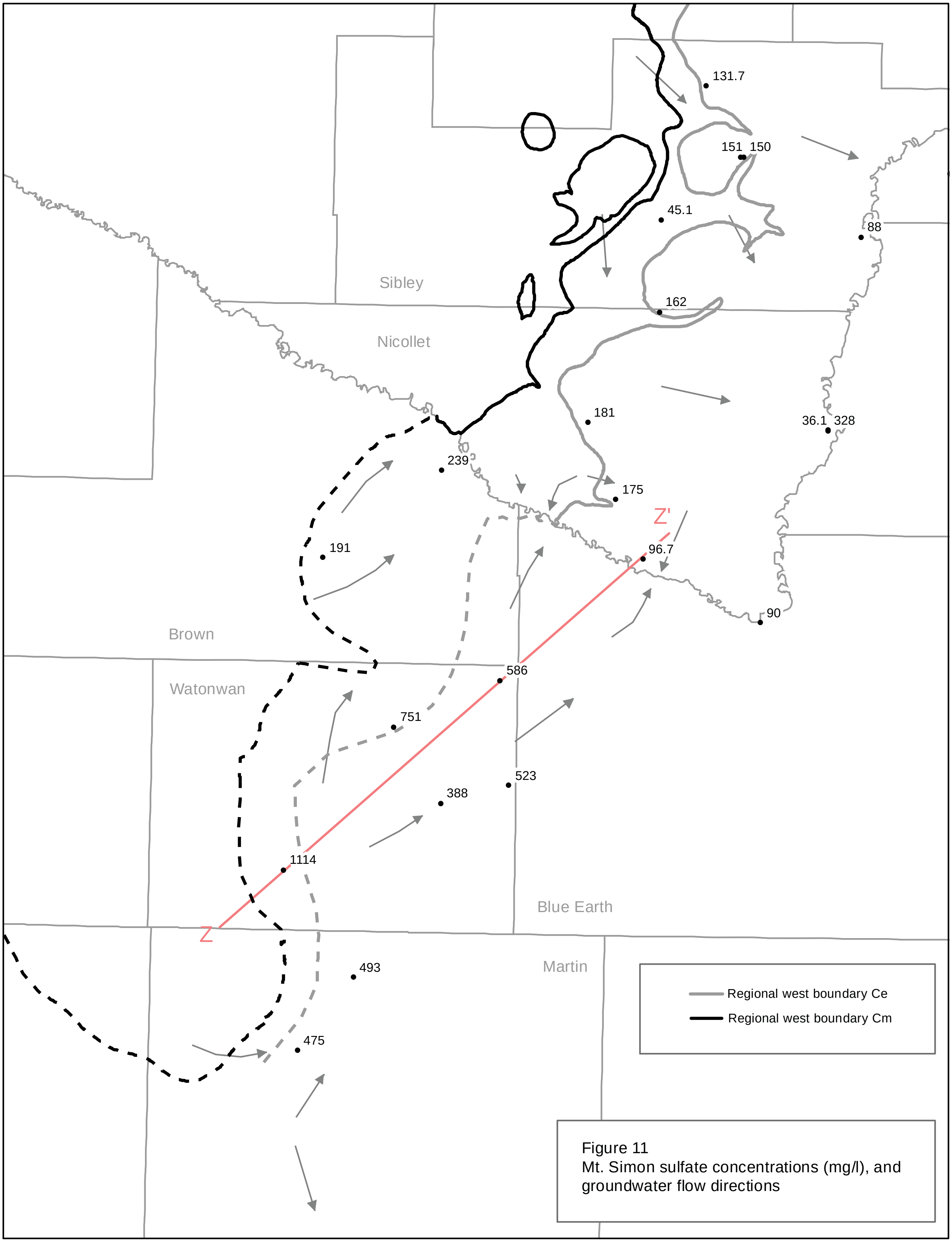


Figure 11
Mt. Simon sulfate concentrations (mg/l), and groundwater flow directions

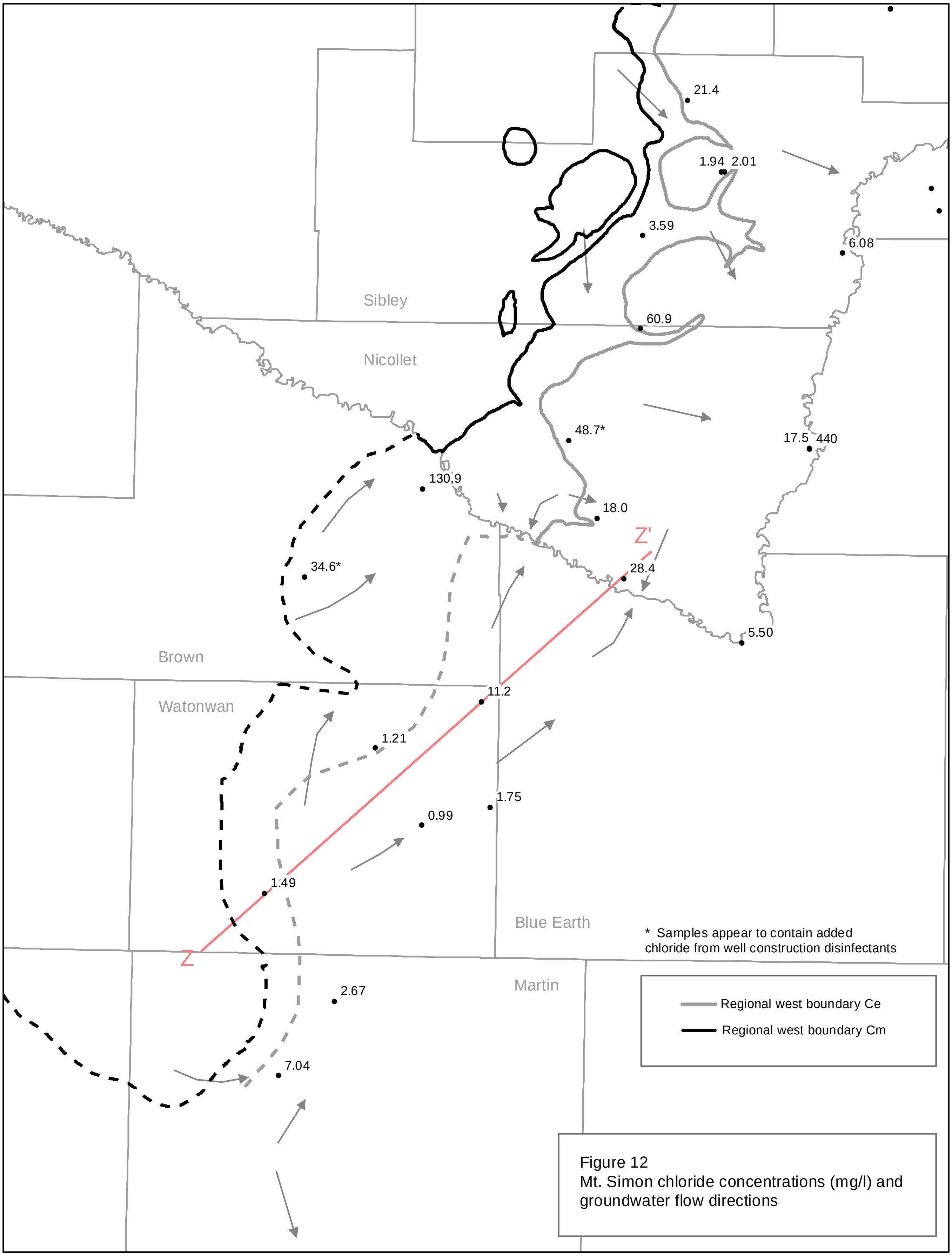


Figure 12
Mt. Simon chloride concentrations (mg/l) and groundwater flow directions

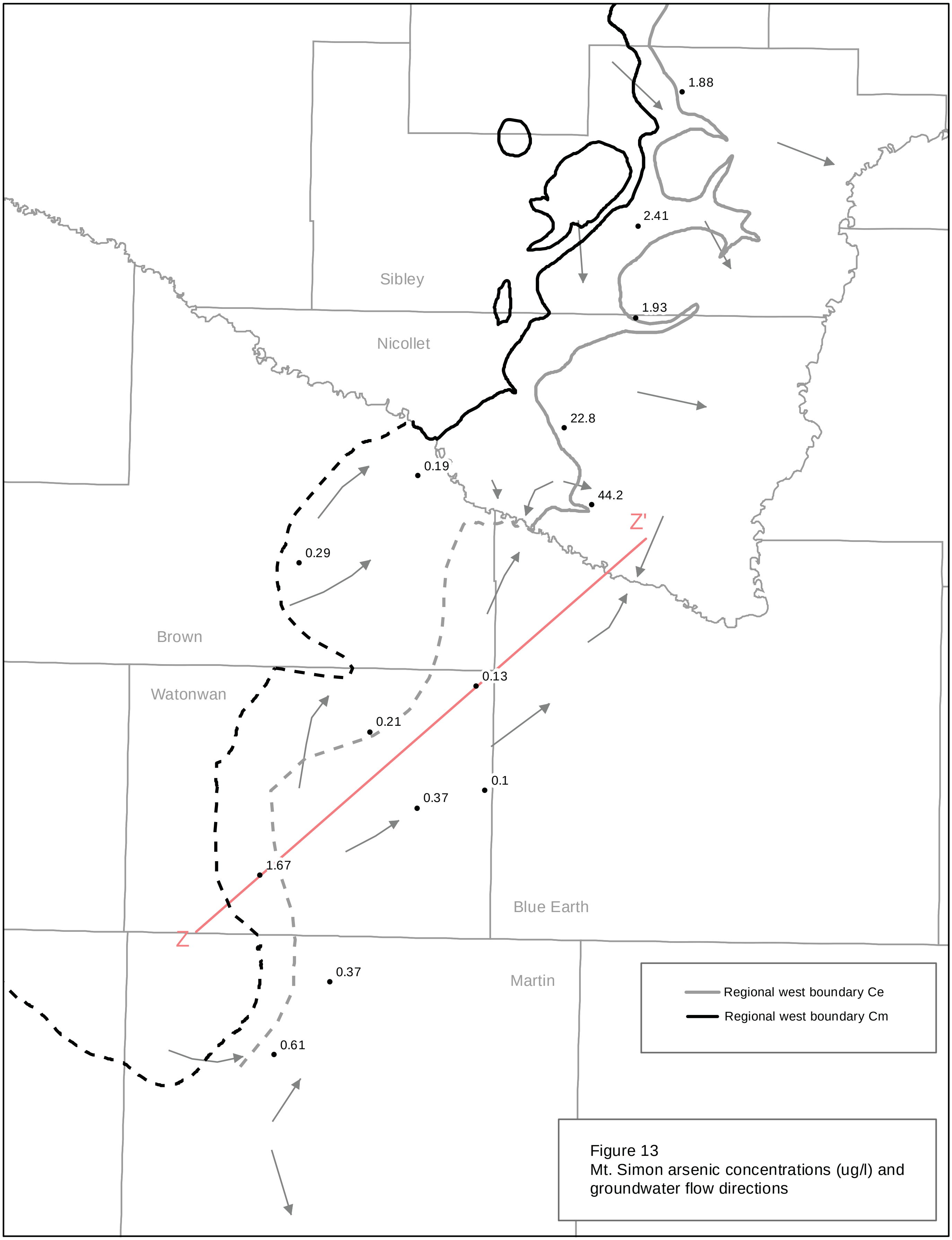


Figure 13
Mt. Simon arsenic concentrations (ug/l) and groundwater flow directions

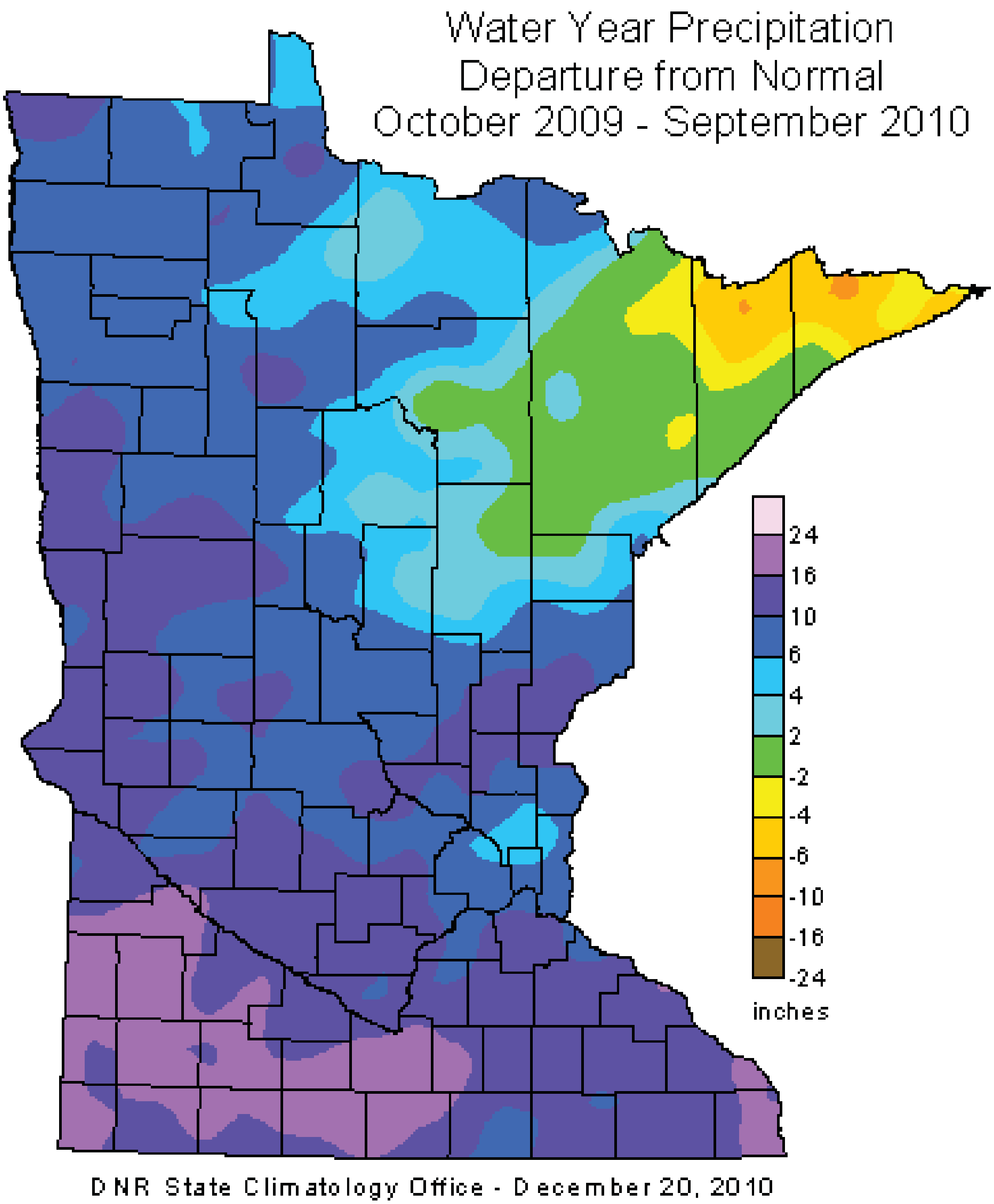


Figure 14
Precipitation departure from normal
October 2009 – September 2010

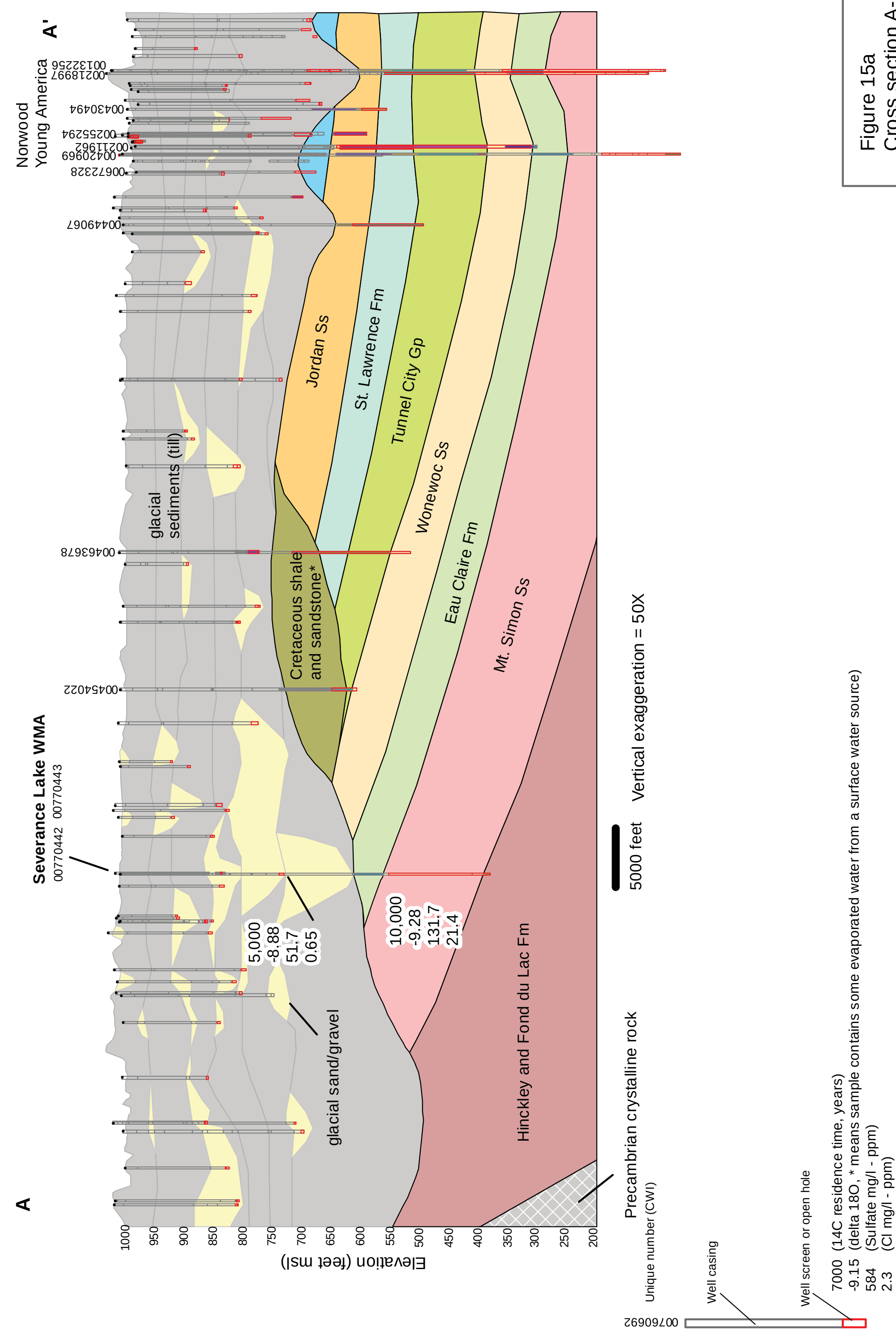


Figure 15a
Cross section A-A'

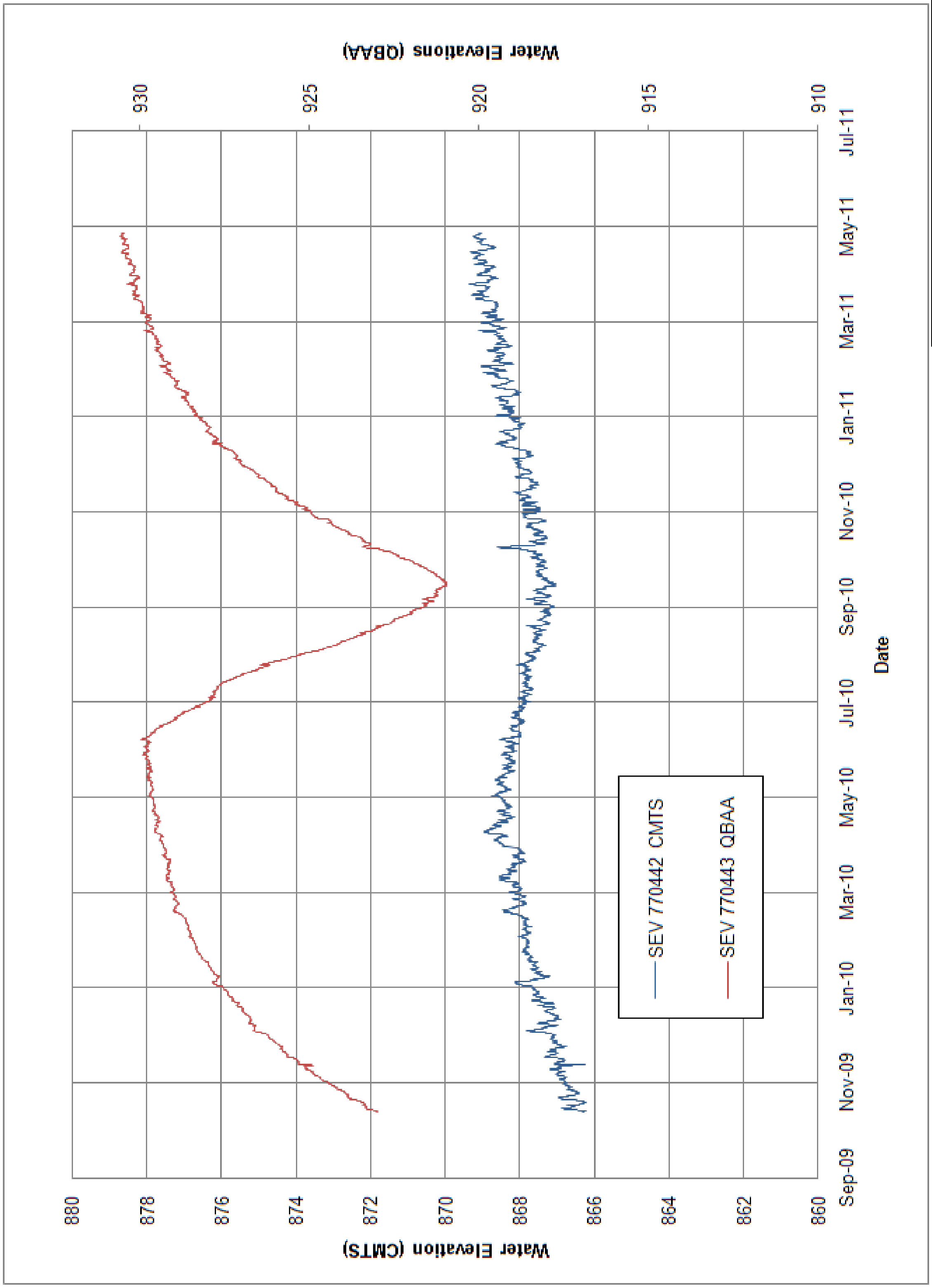
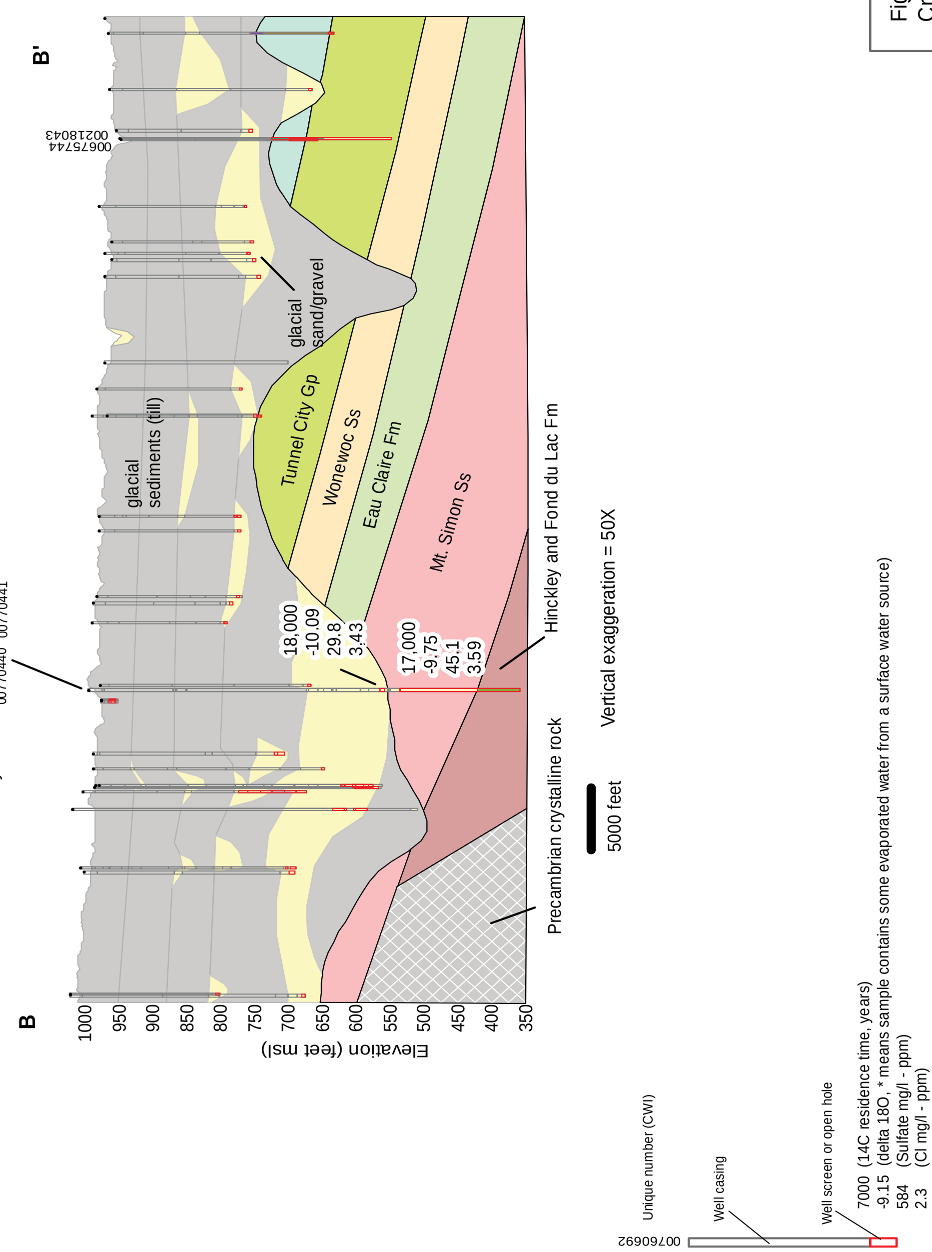


Figure 15b
Severance Lake WMA
Hydrograph

Figure 16a
Cross section B-B'



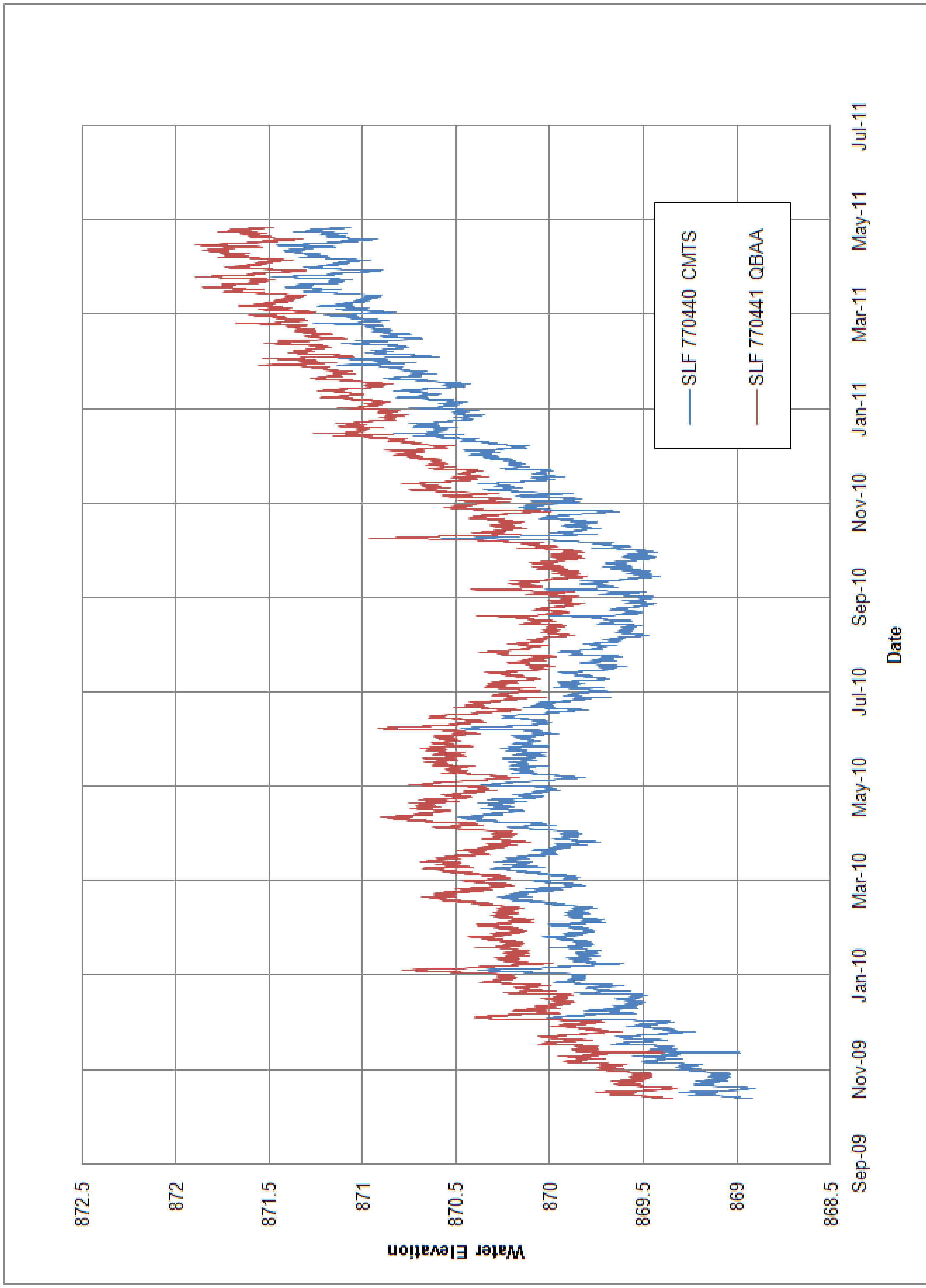


Figure 16b
Sibley County Landfill
Hydrograph

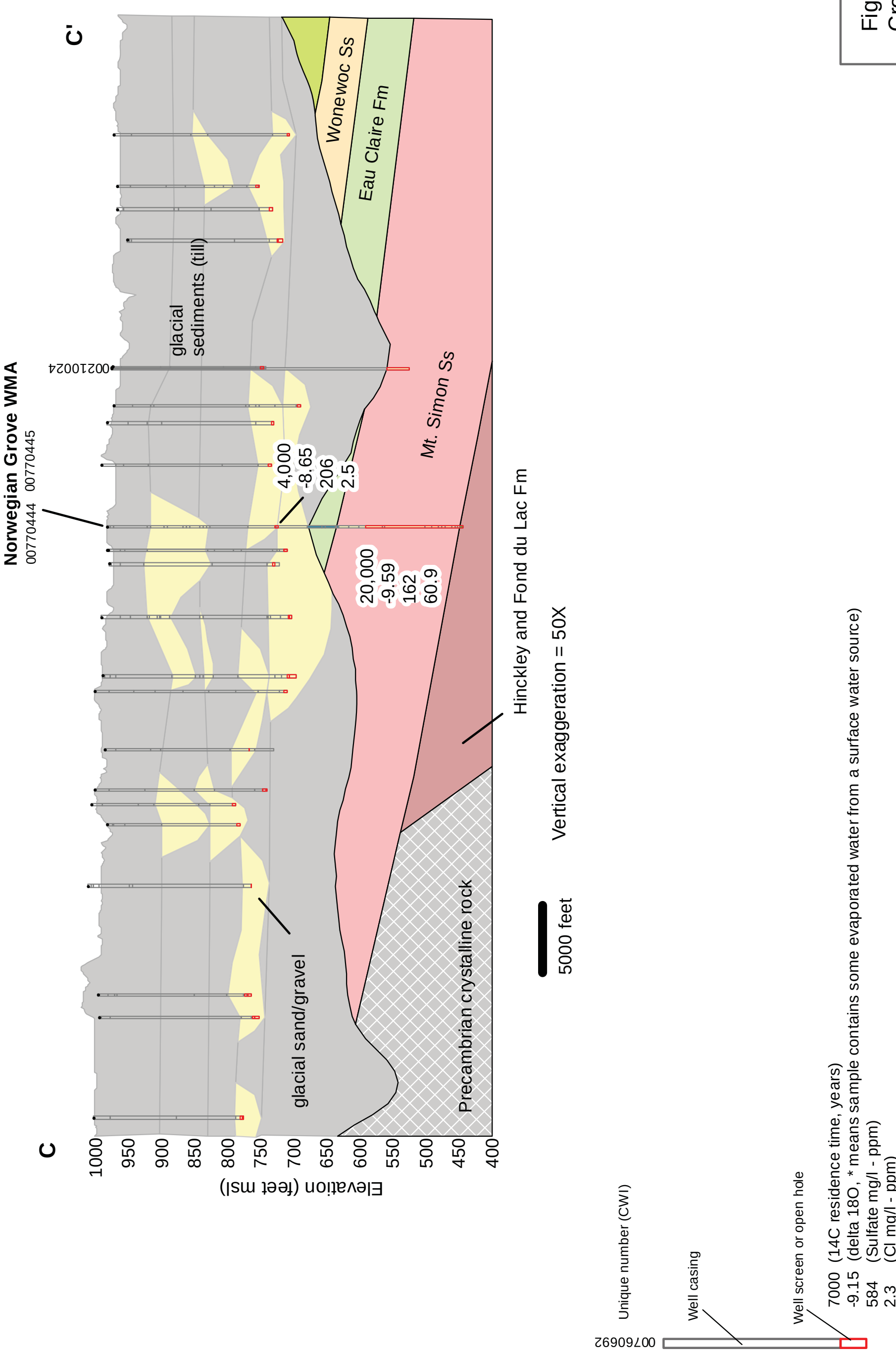


Figure 17a
Cross section C-C'

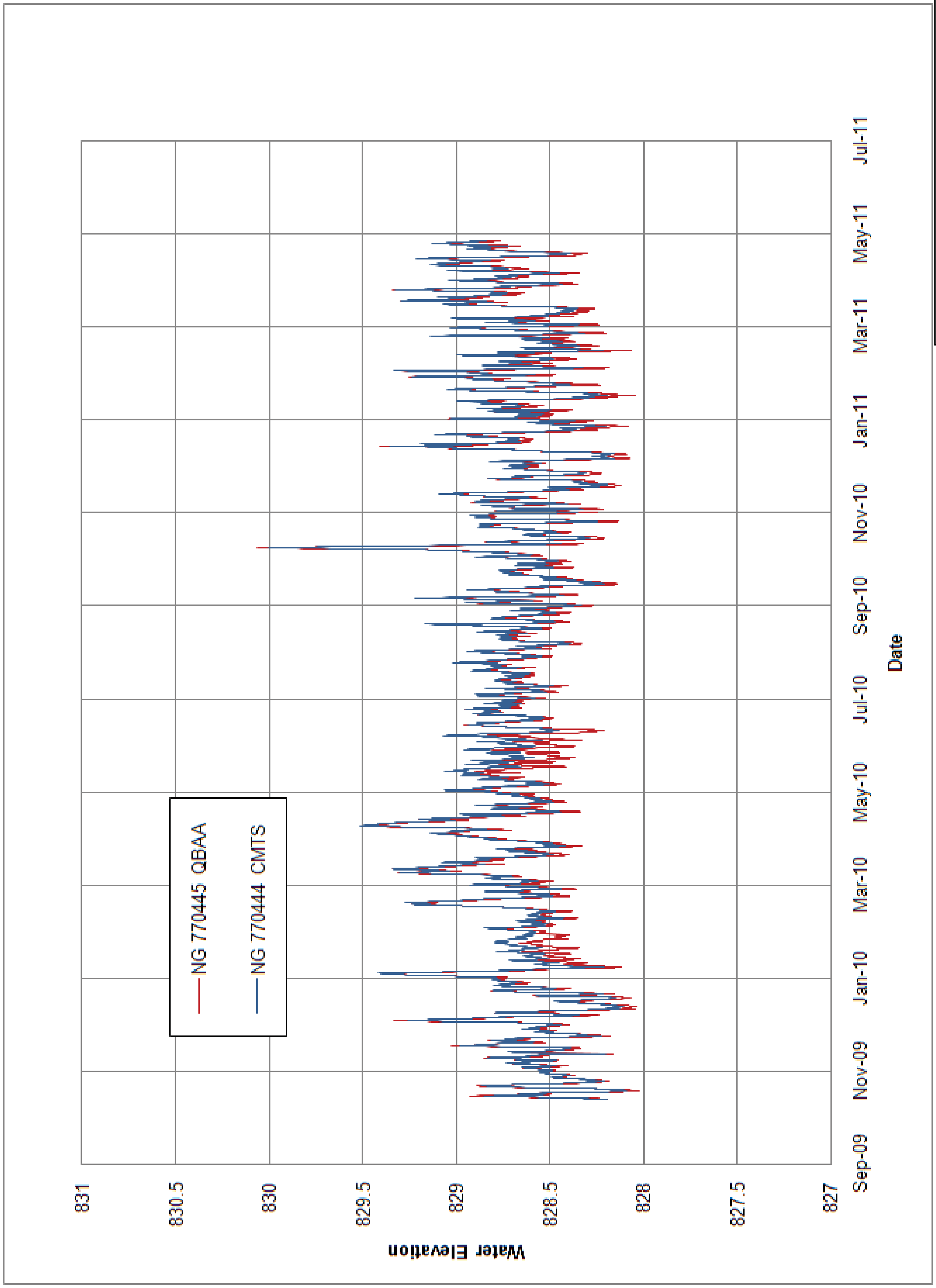


Figure 17b
Norwegian Grove WMA
Hydrograph

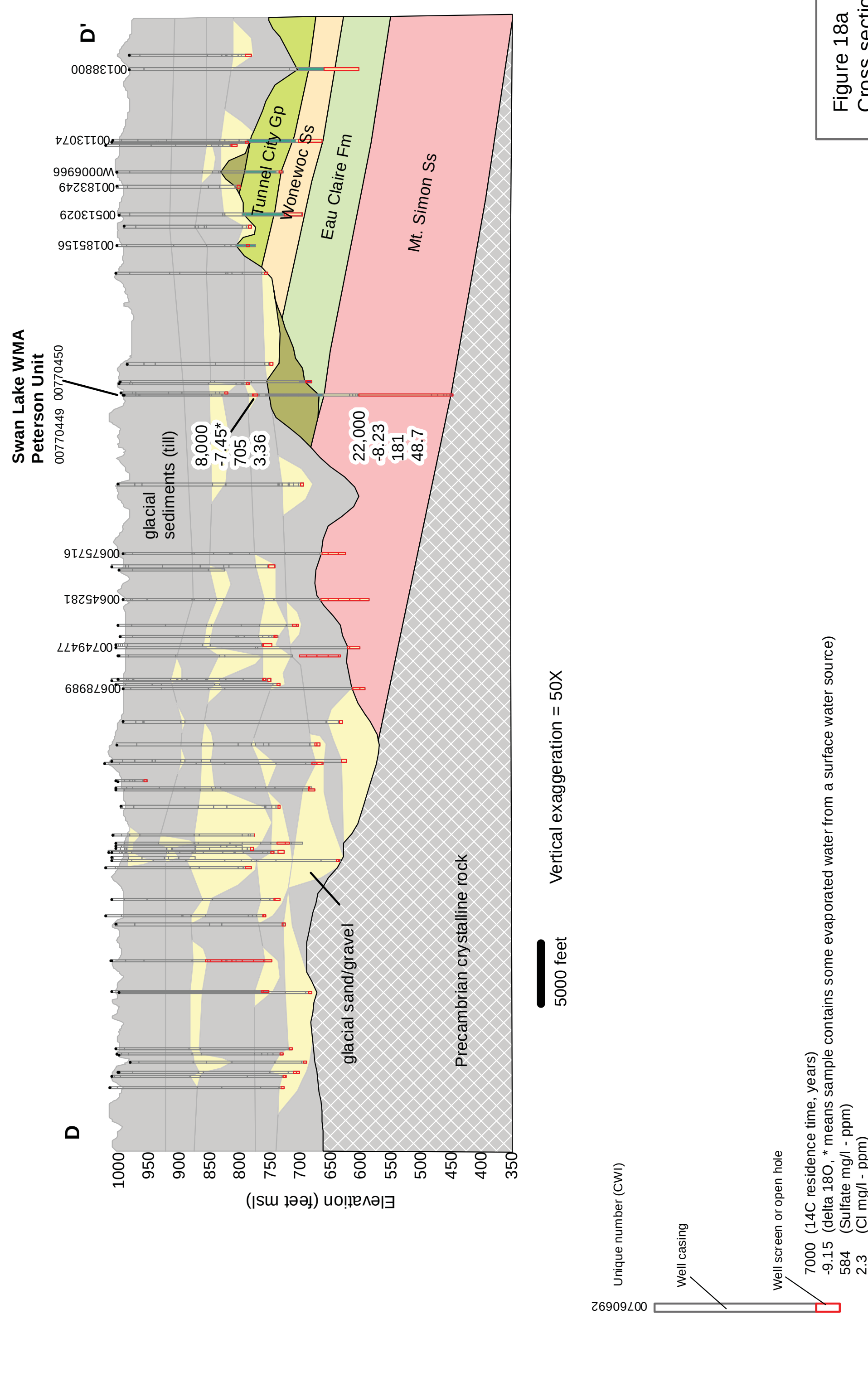


Figure 18a
Cross section D-D'

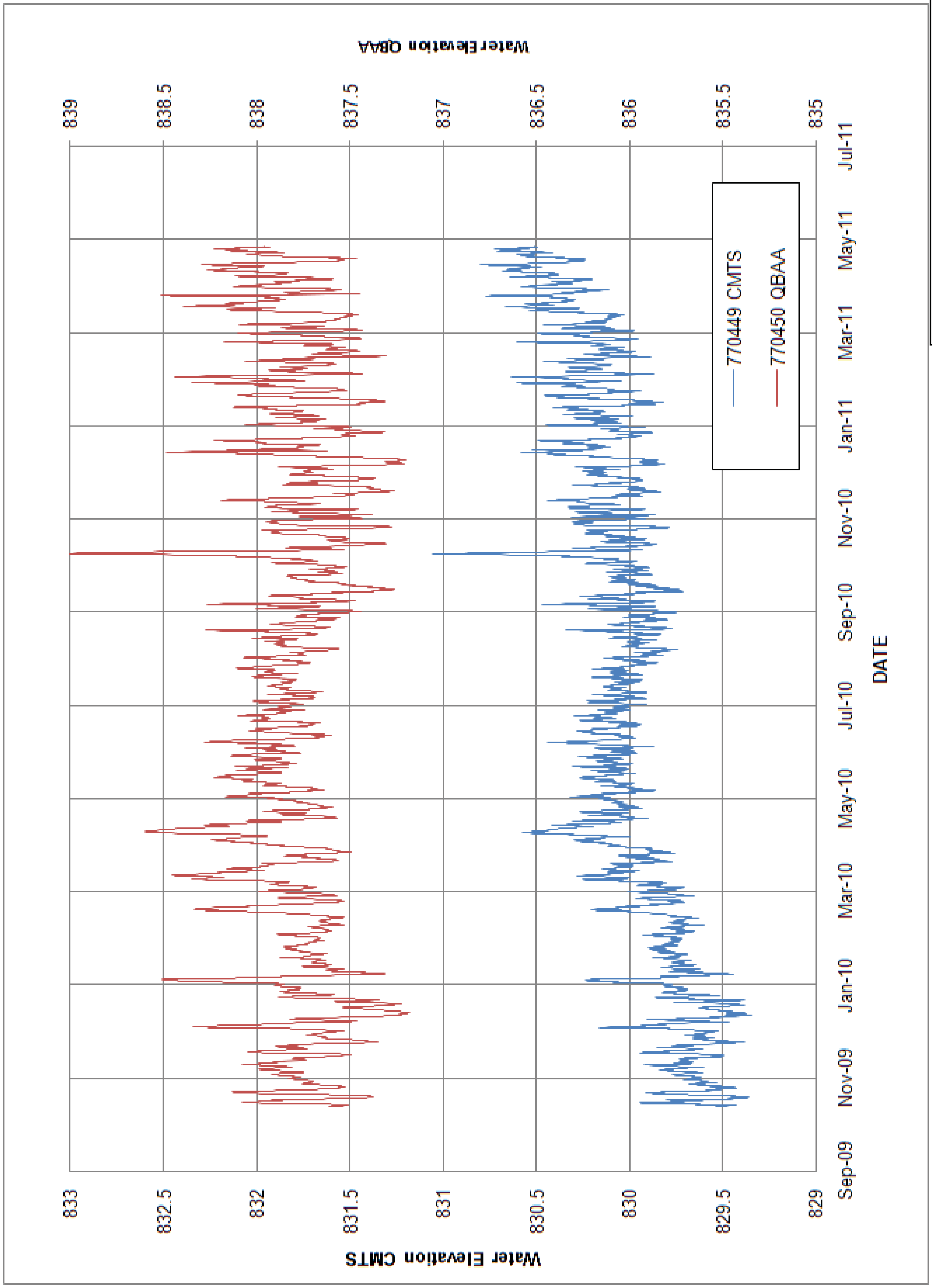


Figure 18b
Peterson Unit
Hydrograph

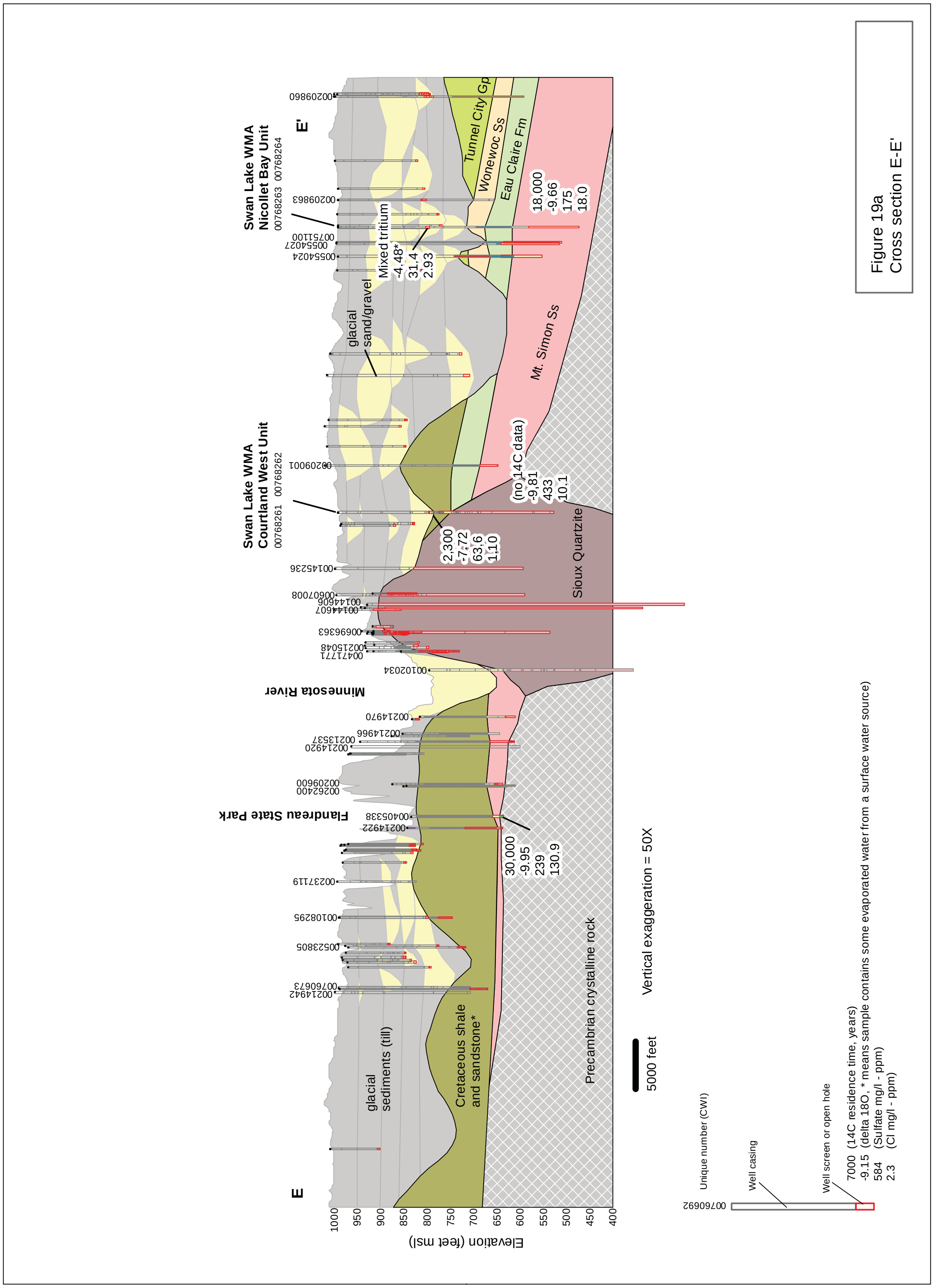


Figure 19a
Cross section E-E'

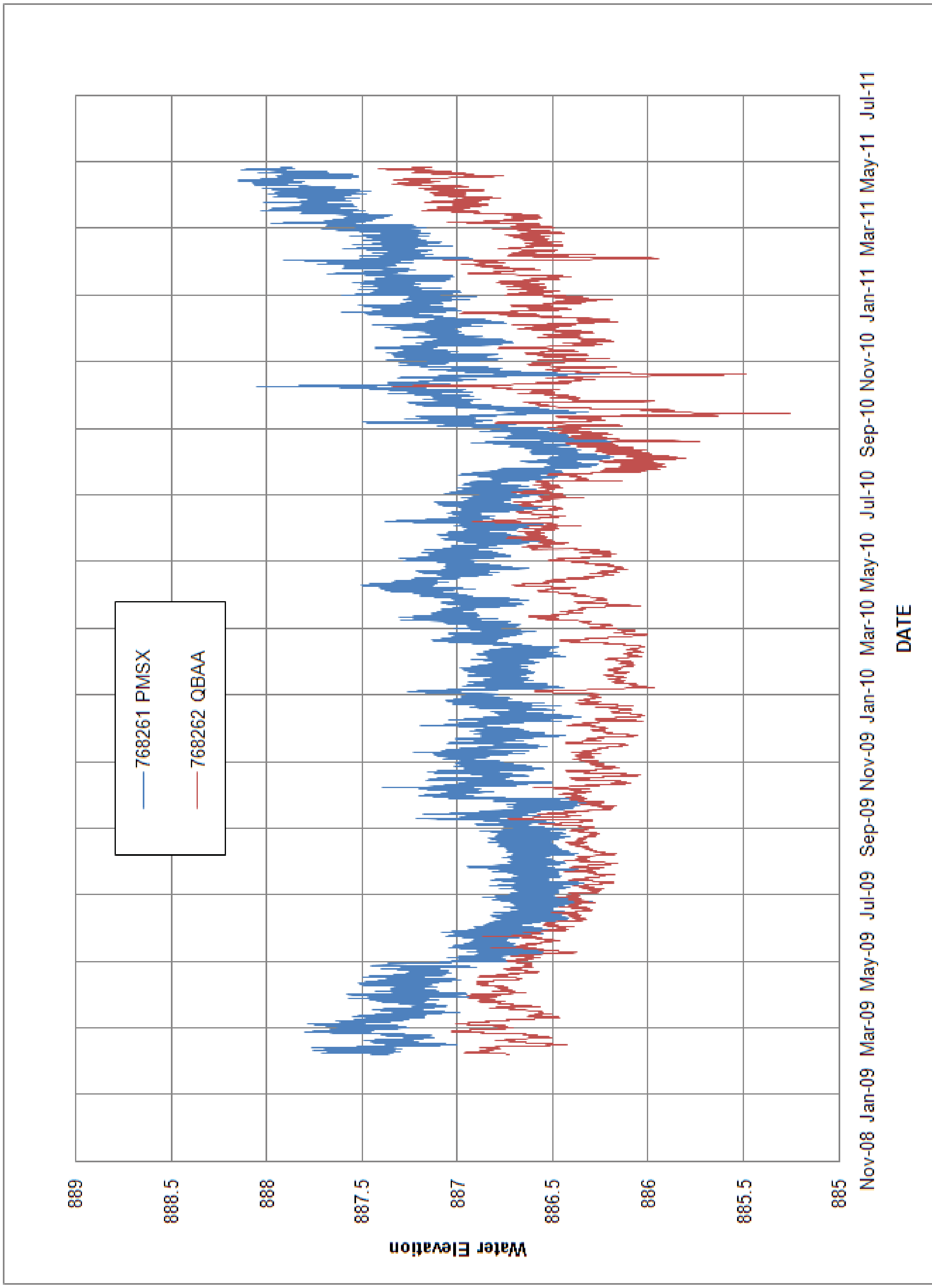


Figure 19b
Courtland West Unit
Hydrograph

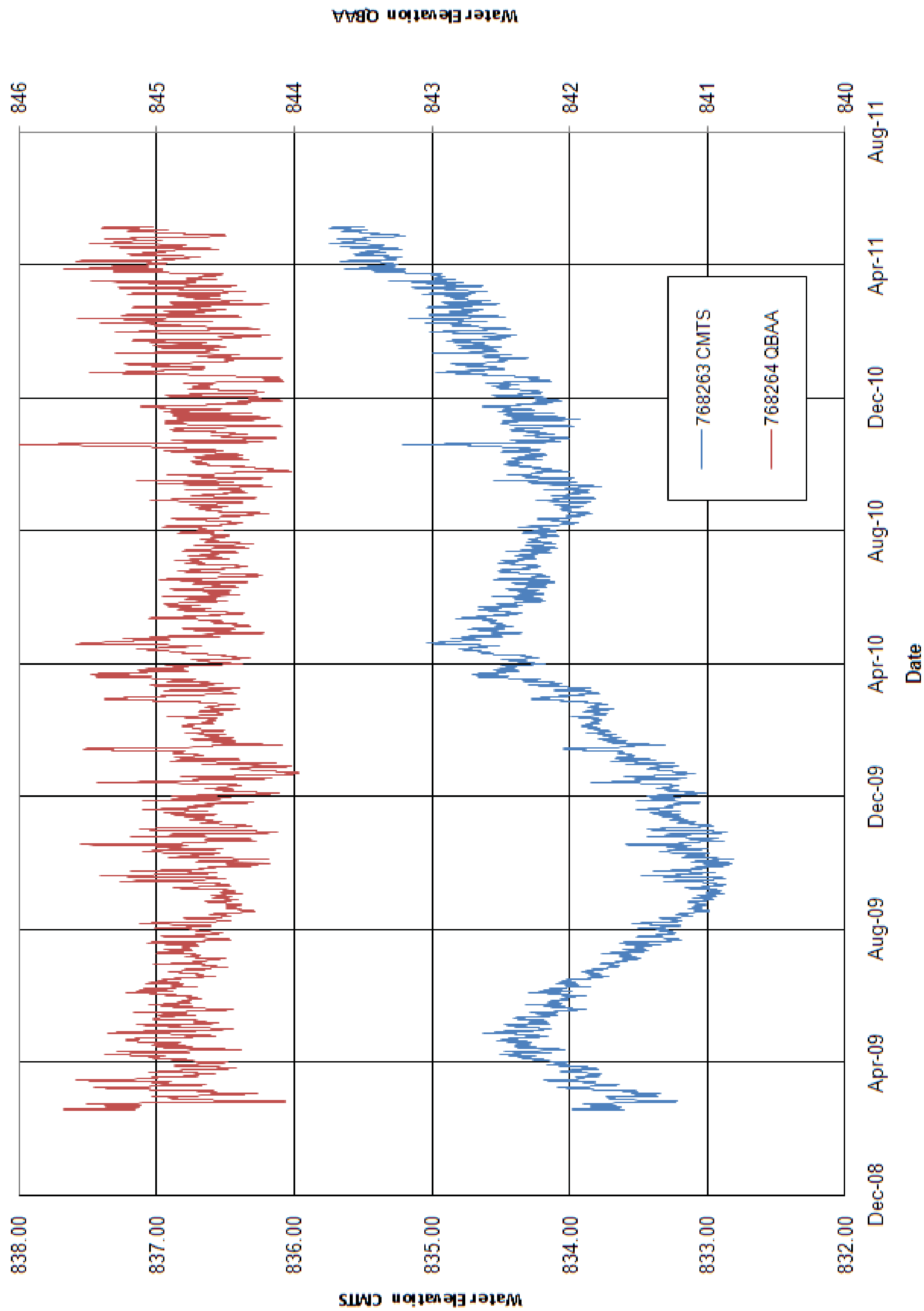


Figure 19c
Nicollet Bay Unit
Hydrograph

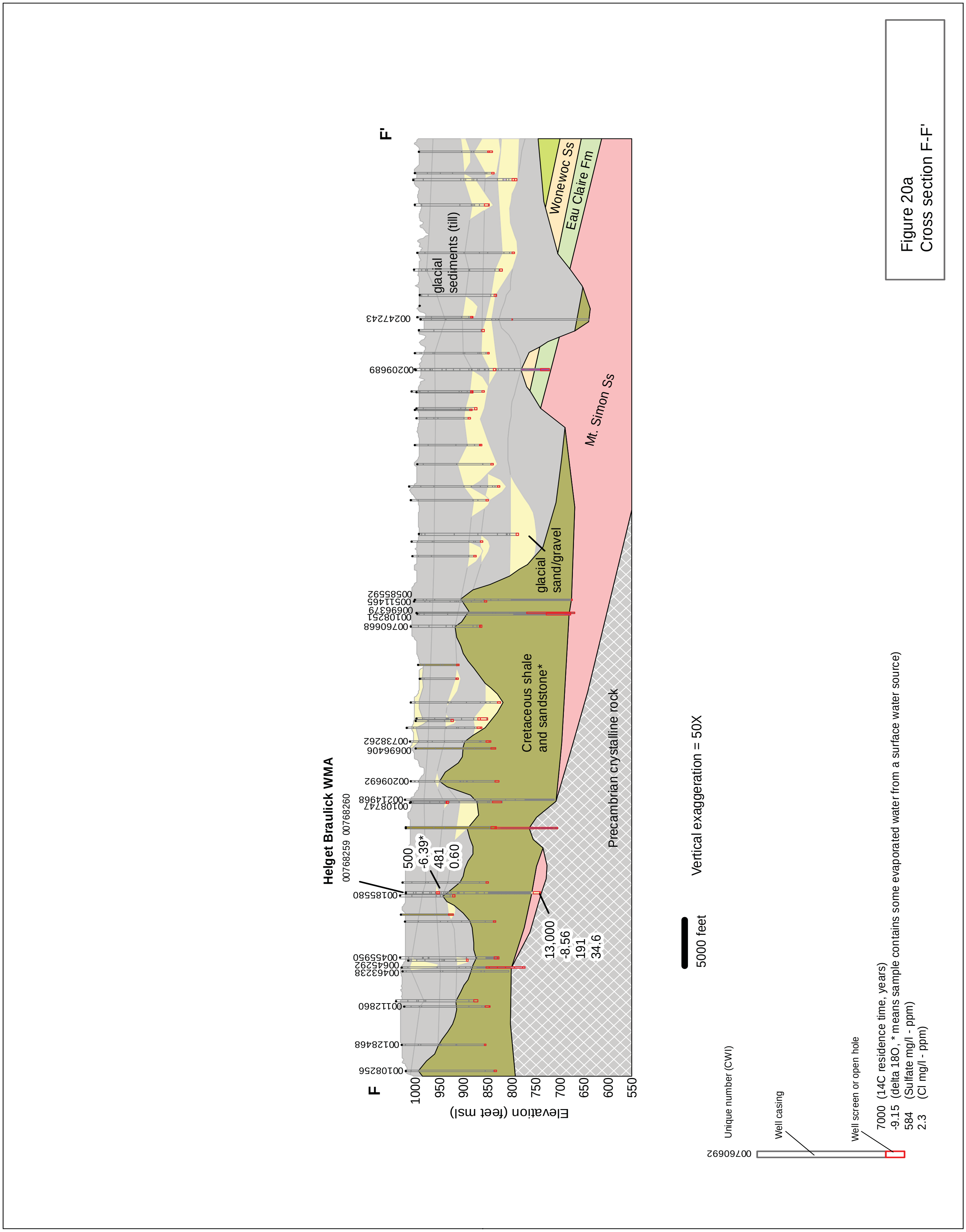


Figure 20a
Cross section F-F'

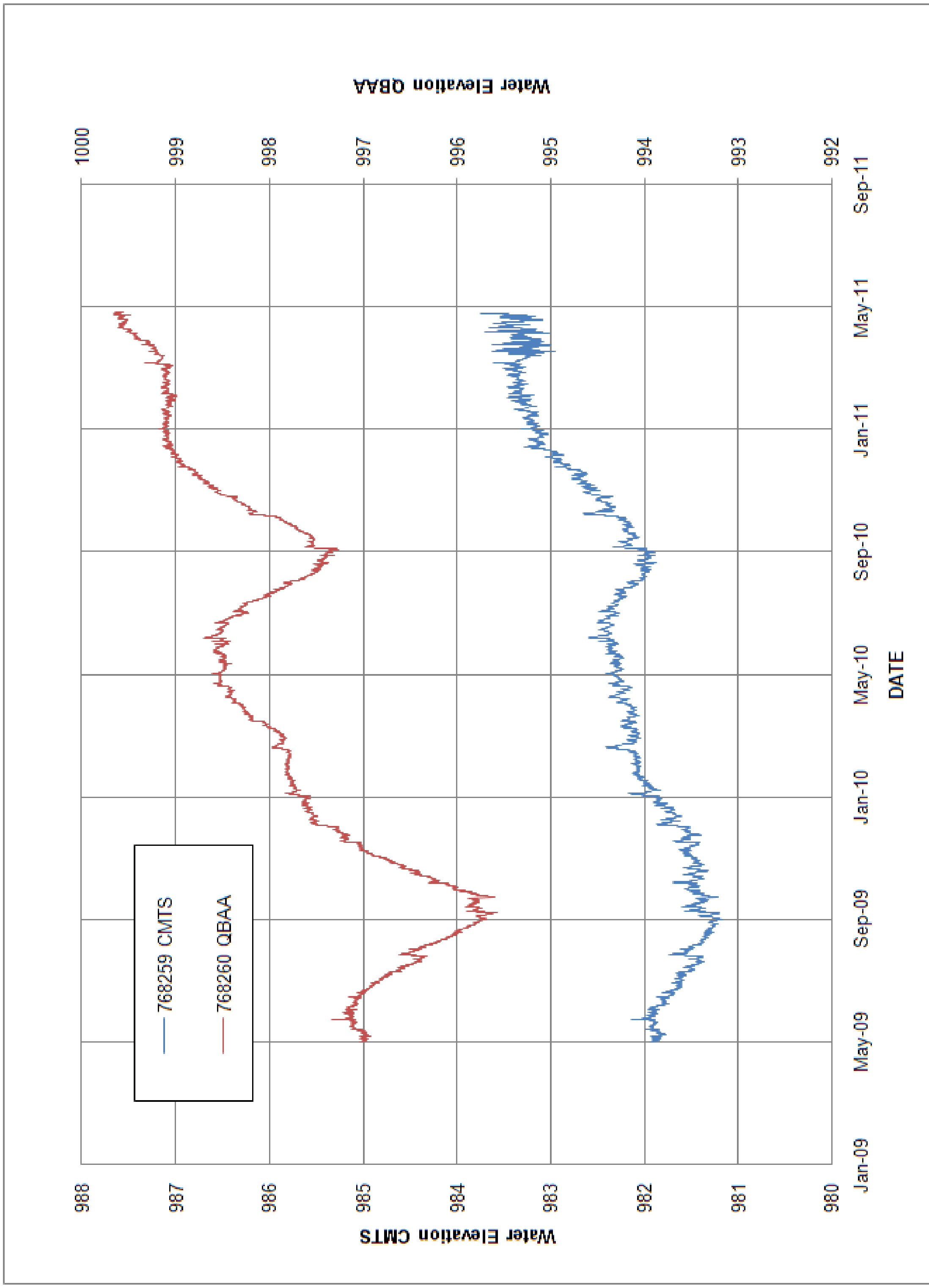


Figure 20b
Helget Braulick WMA
Hydrograph

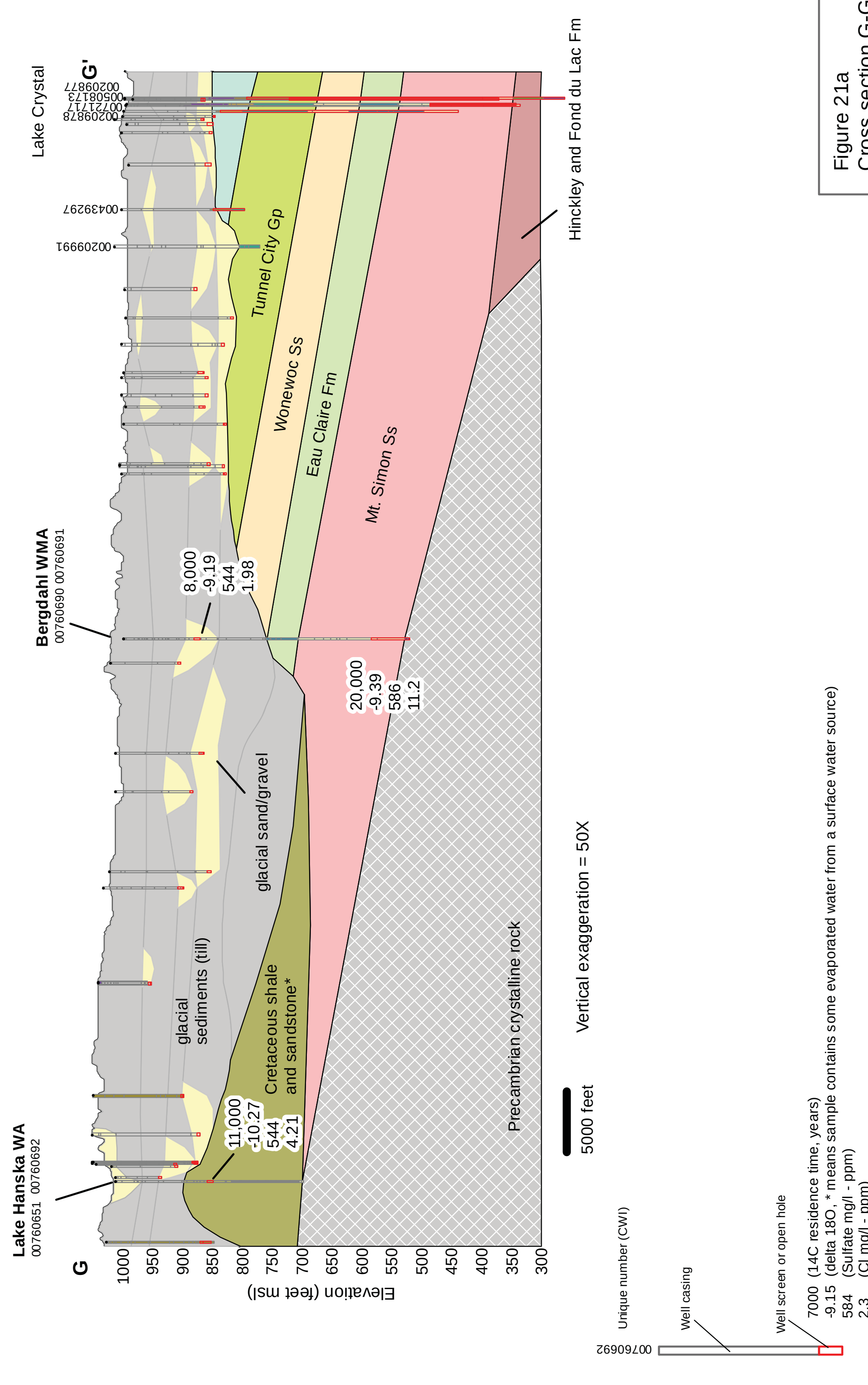


Figure 21a
Cross section G-G'

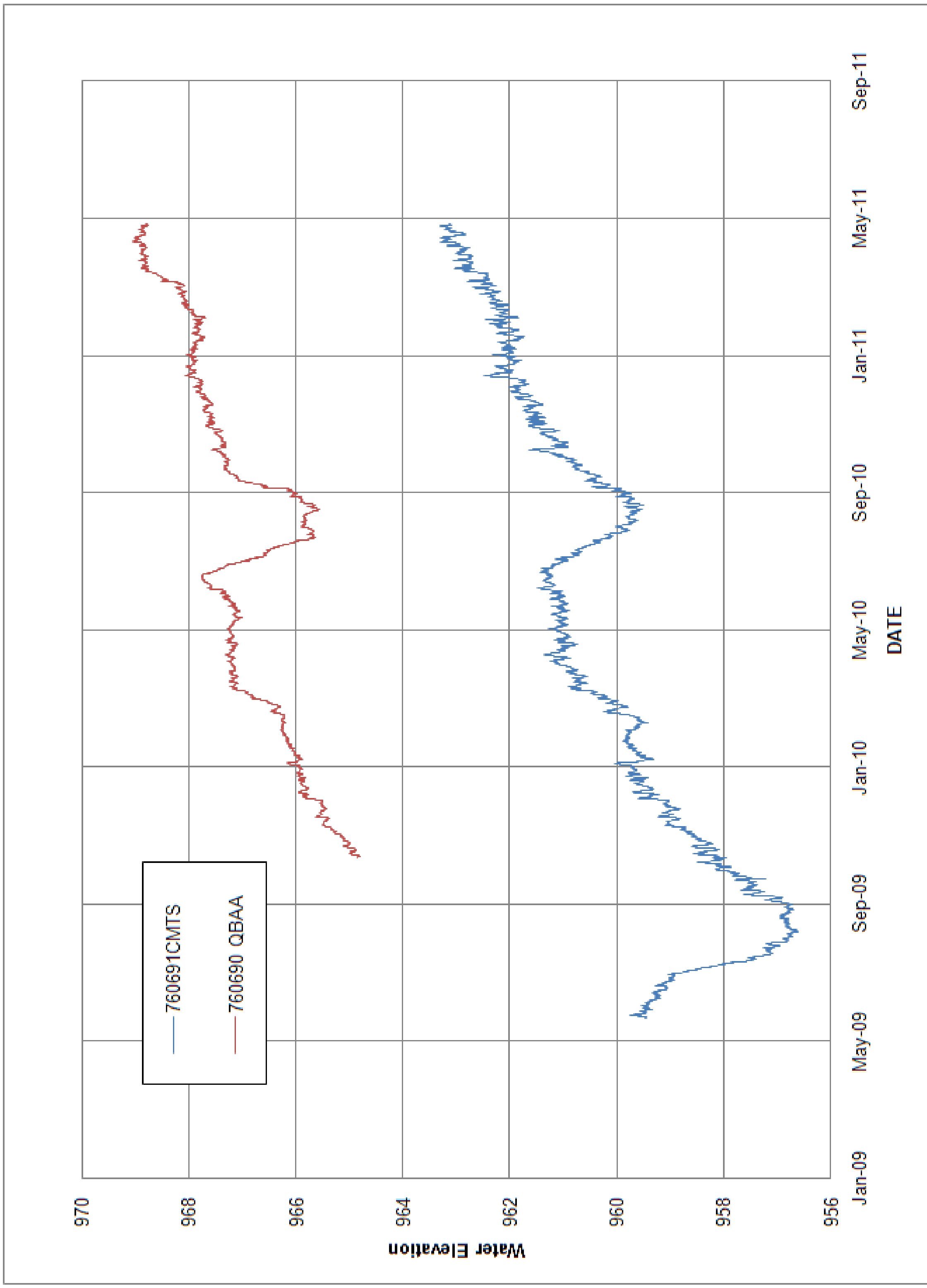


Figure 21b
Bergdahl WMA
Hydrograph

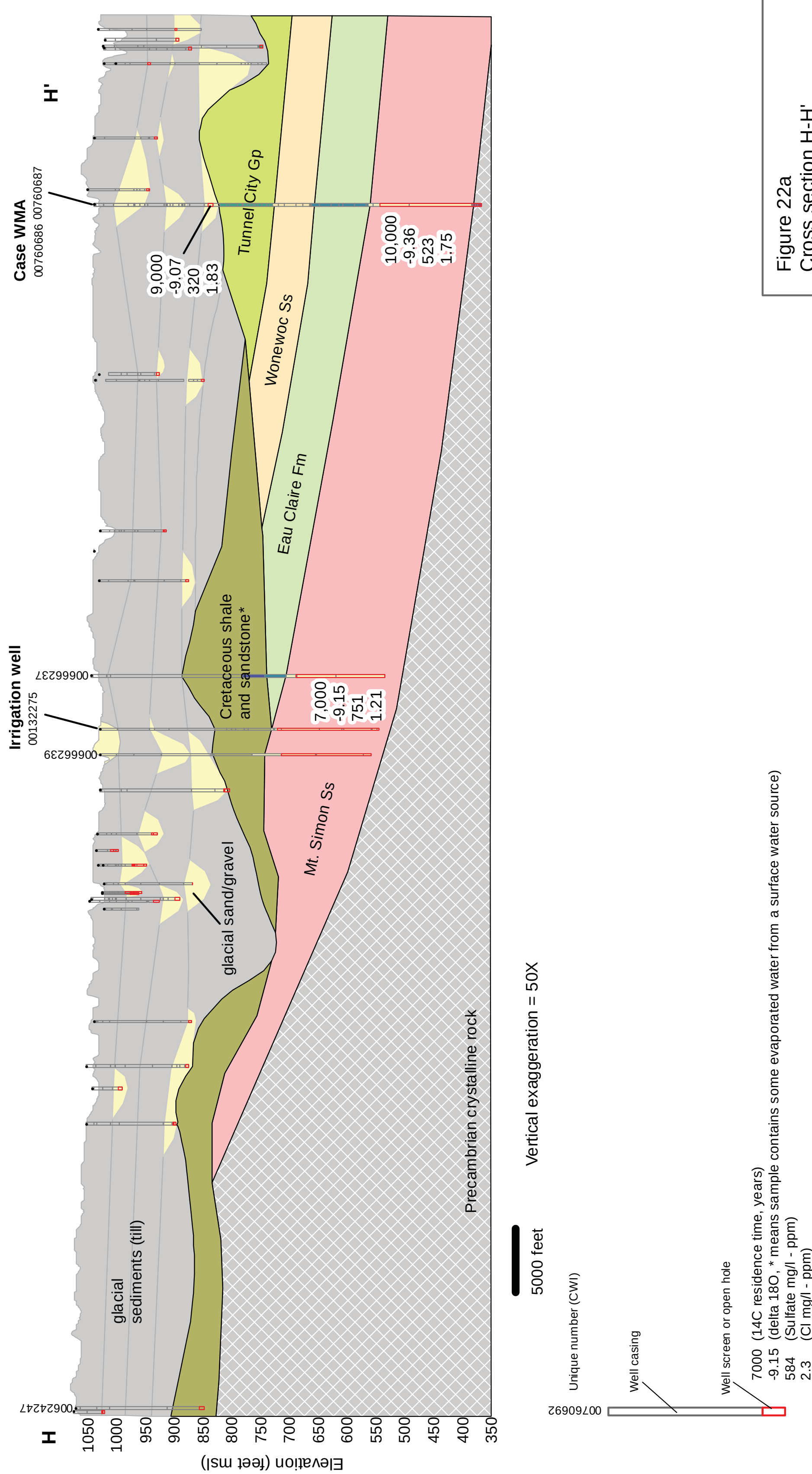


Figure 22a
Cross section H-H'

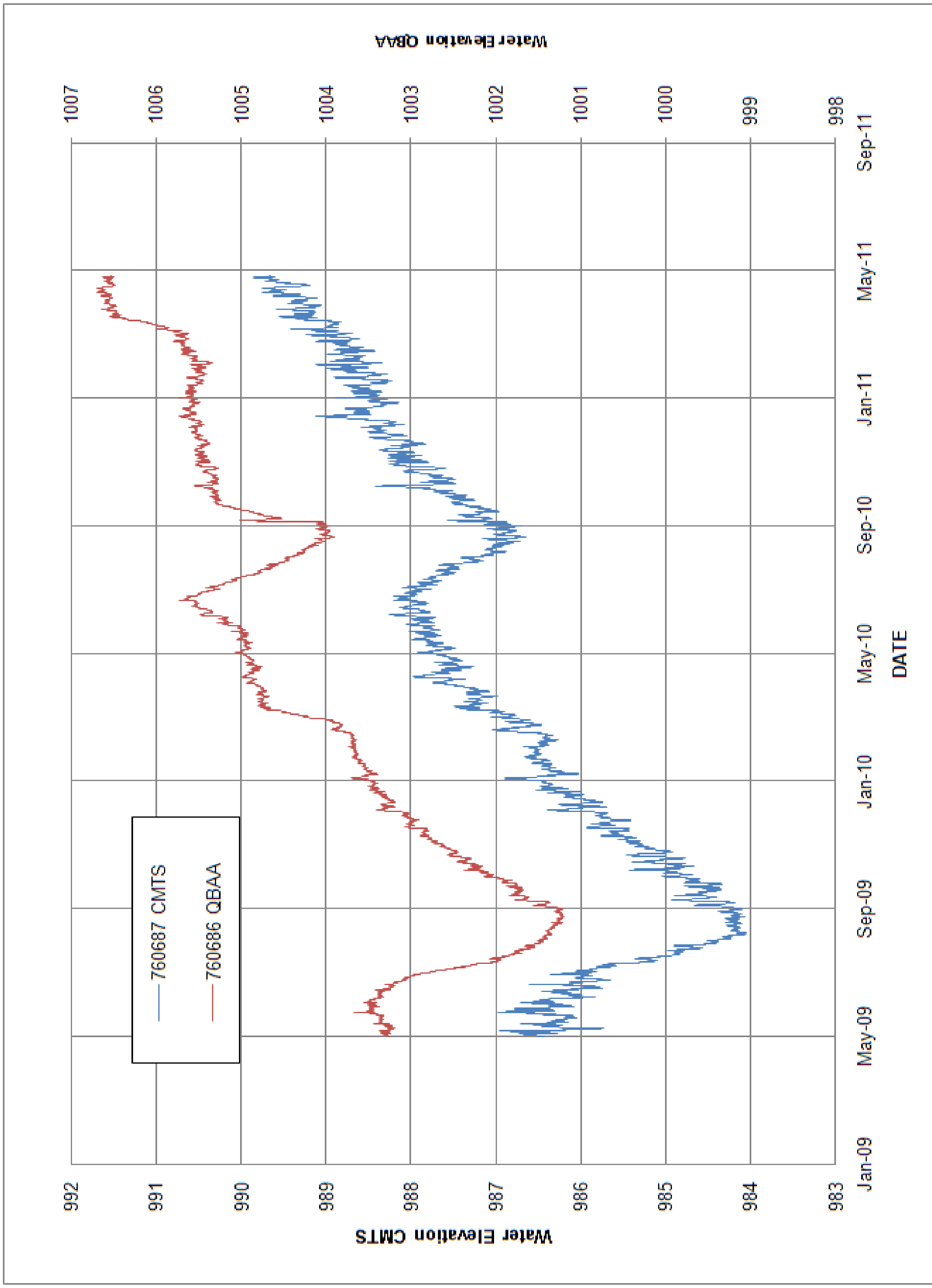


Figure 22b
Case WMA
Hydrograph

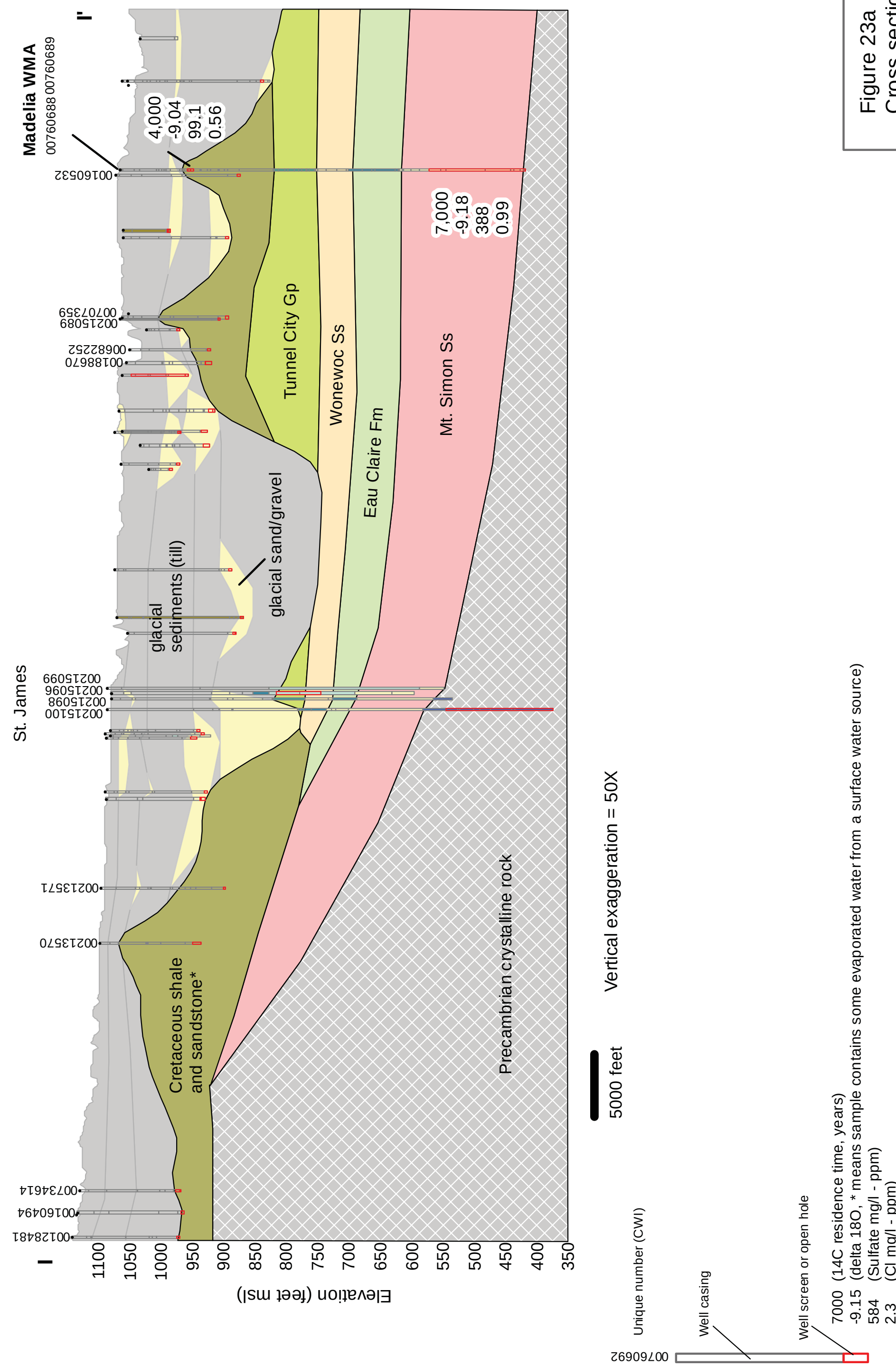


Figure 23a
Cross section I-I'

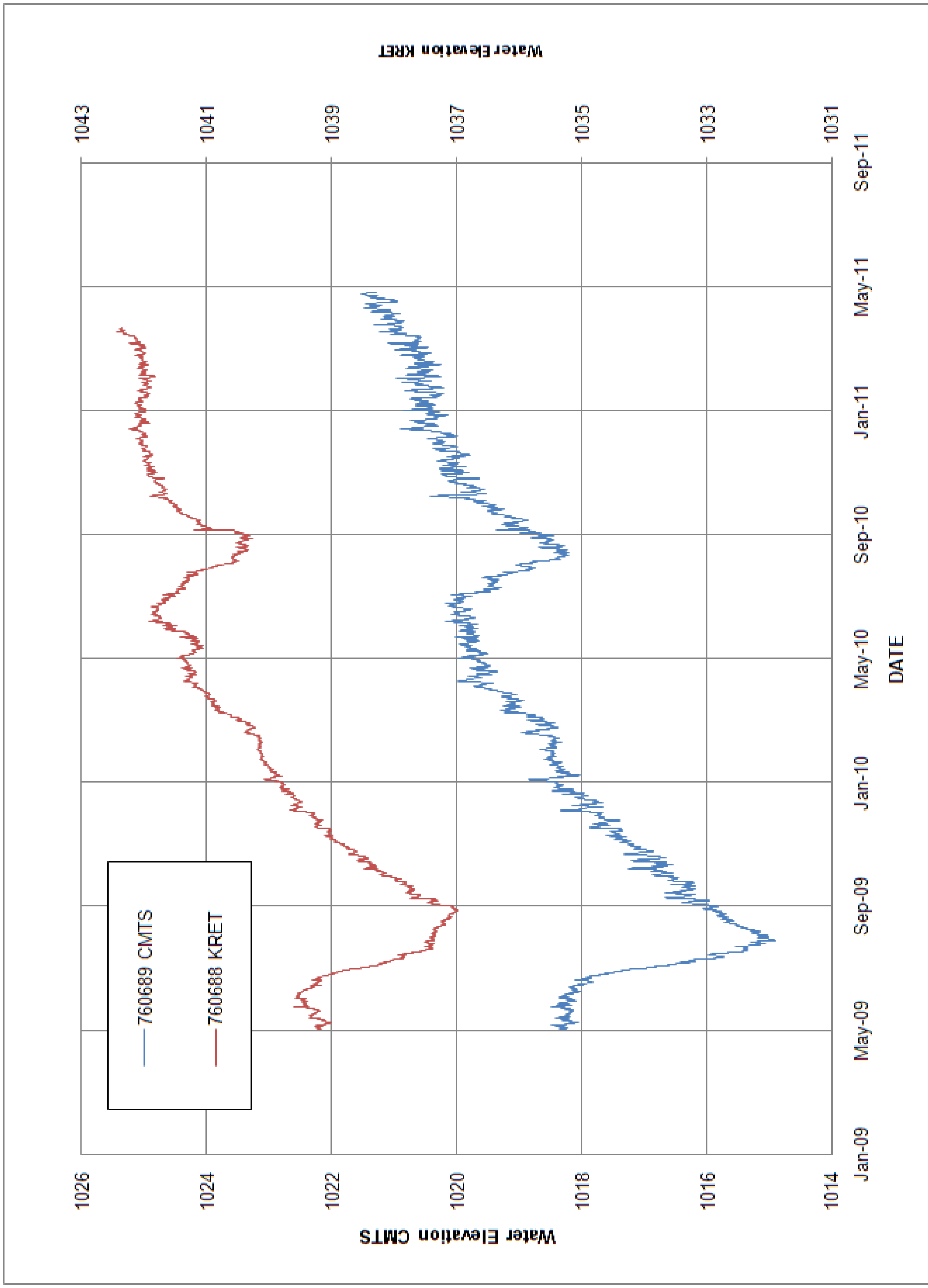


Figure 23b
Madelia WMA
Hydrograph

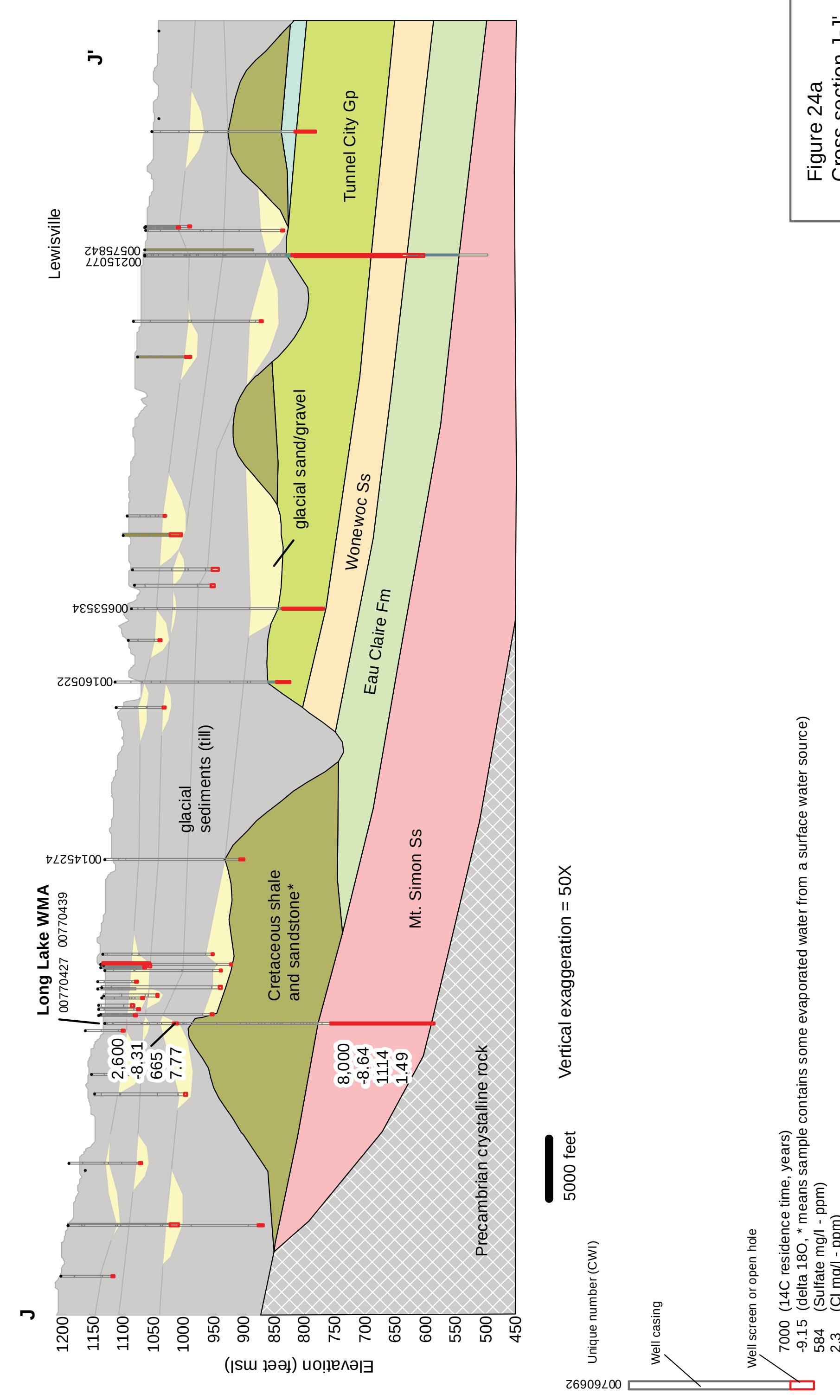


Figure 24a
Cross section J-J'

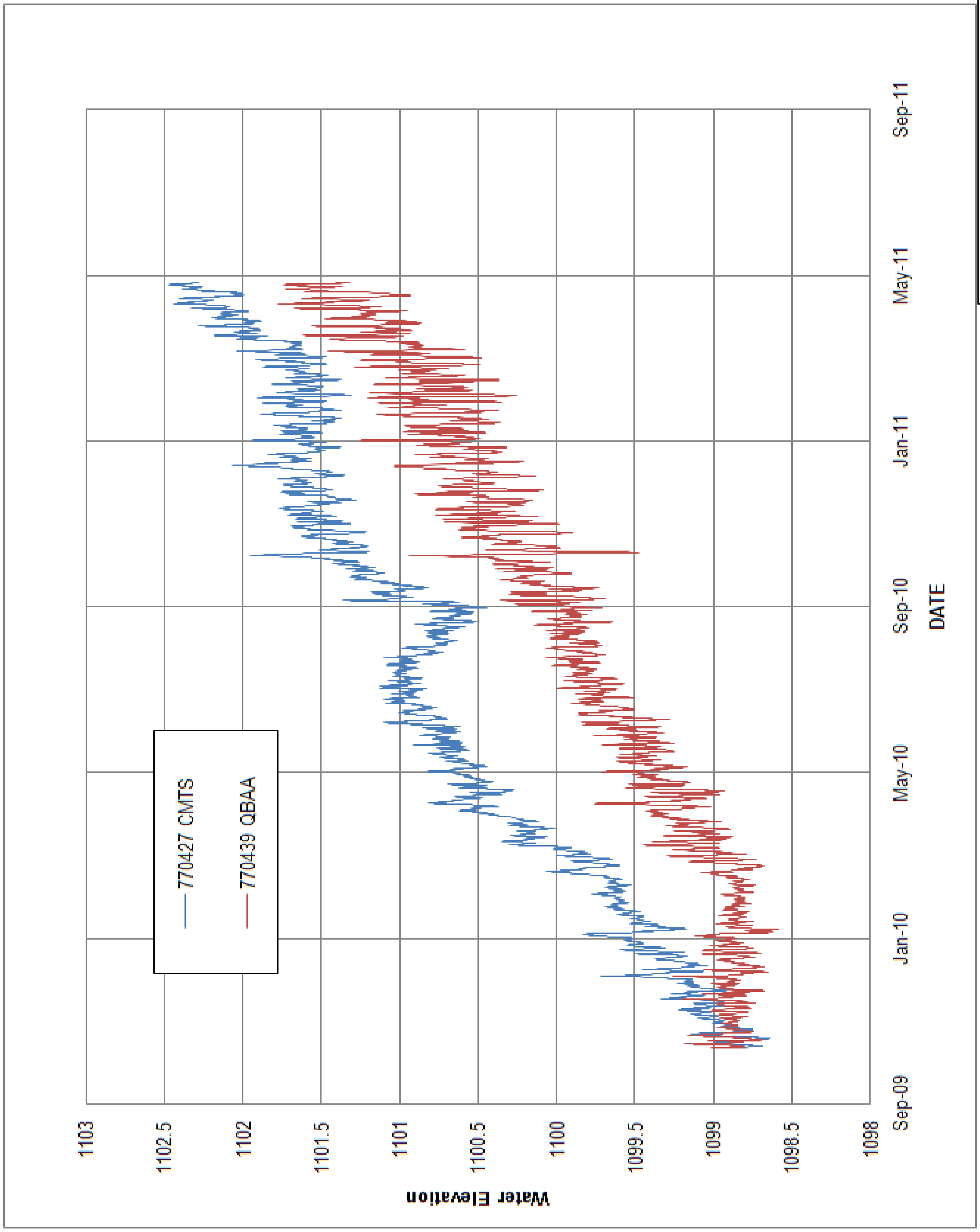


Figure 24b
Long Lake WA
Hydrograph

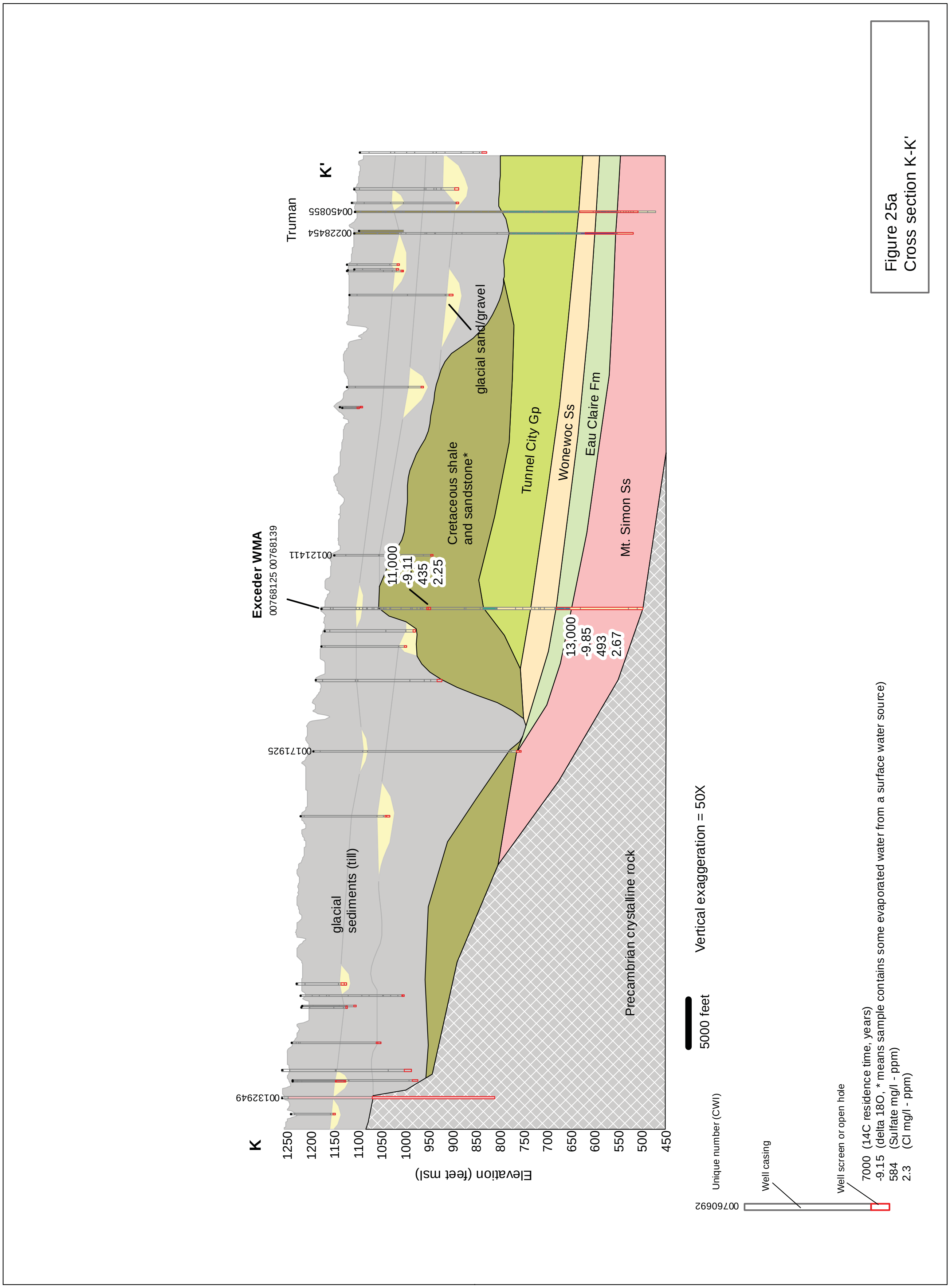


Figure 25a
Cross section K-K'

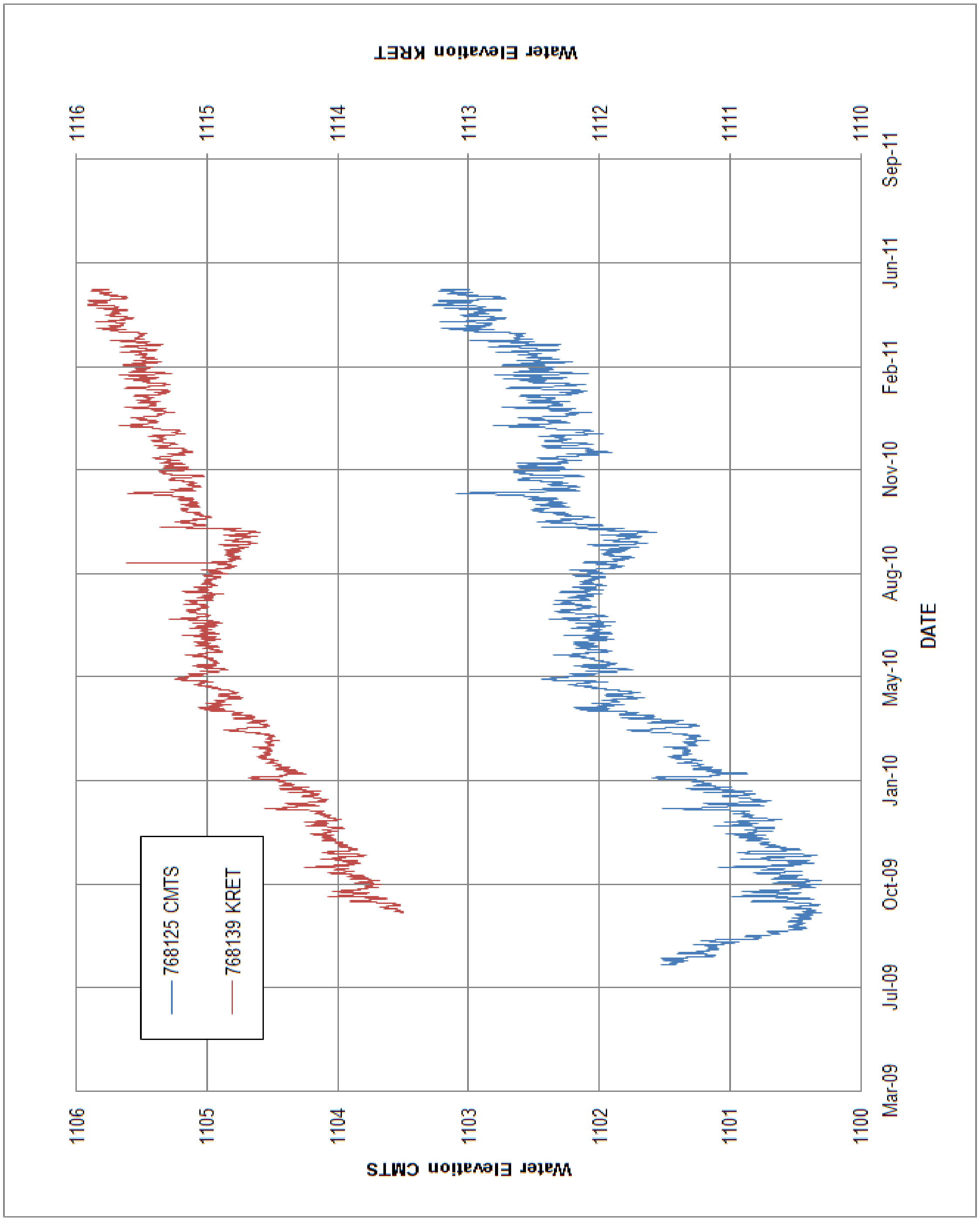


Figure 25b
Exceder WMA
Hydrograph

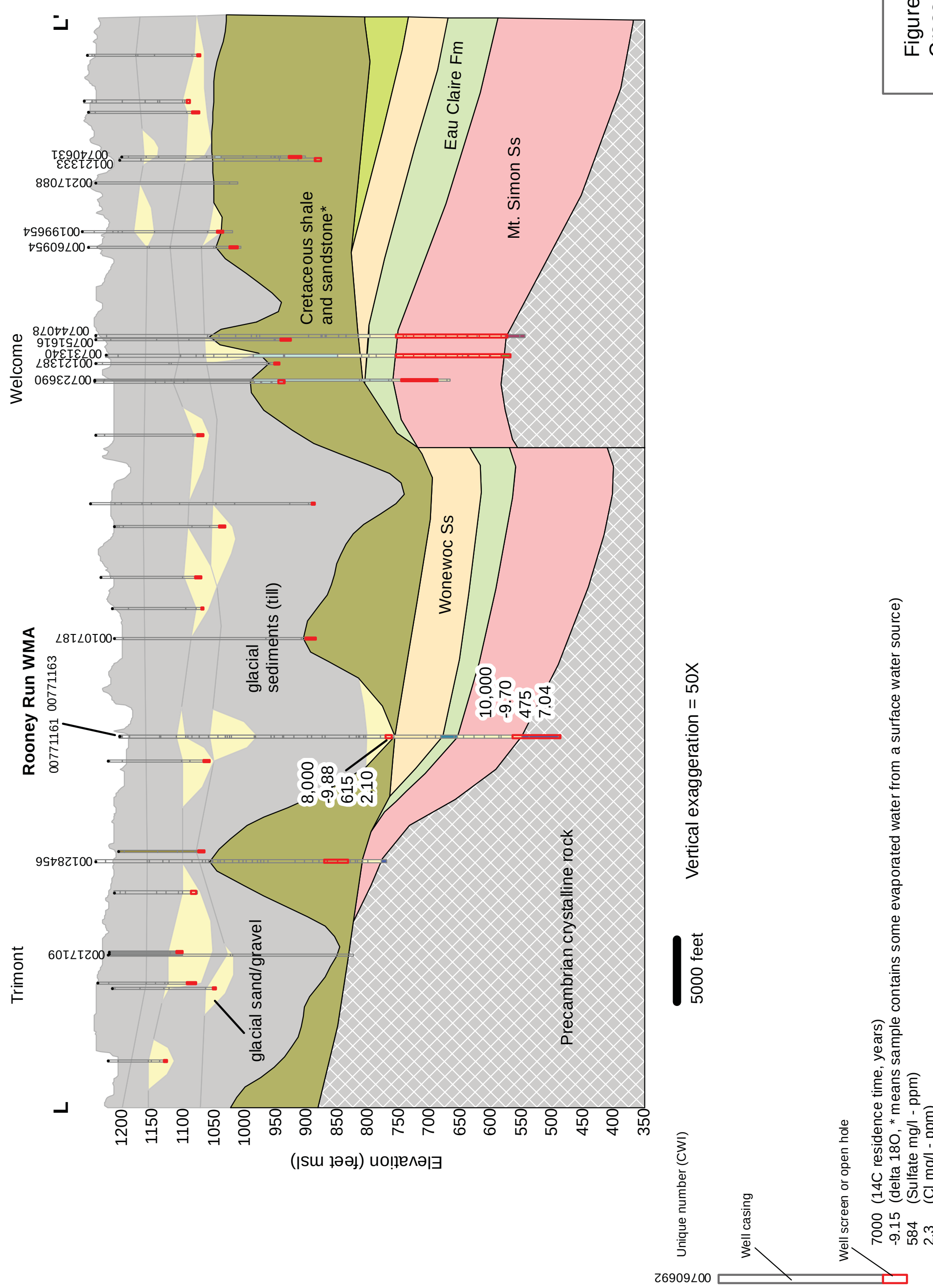


Figure 26a
Cross section L-L'

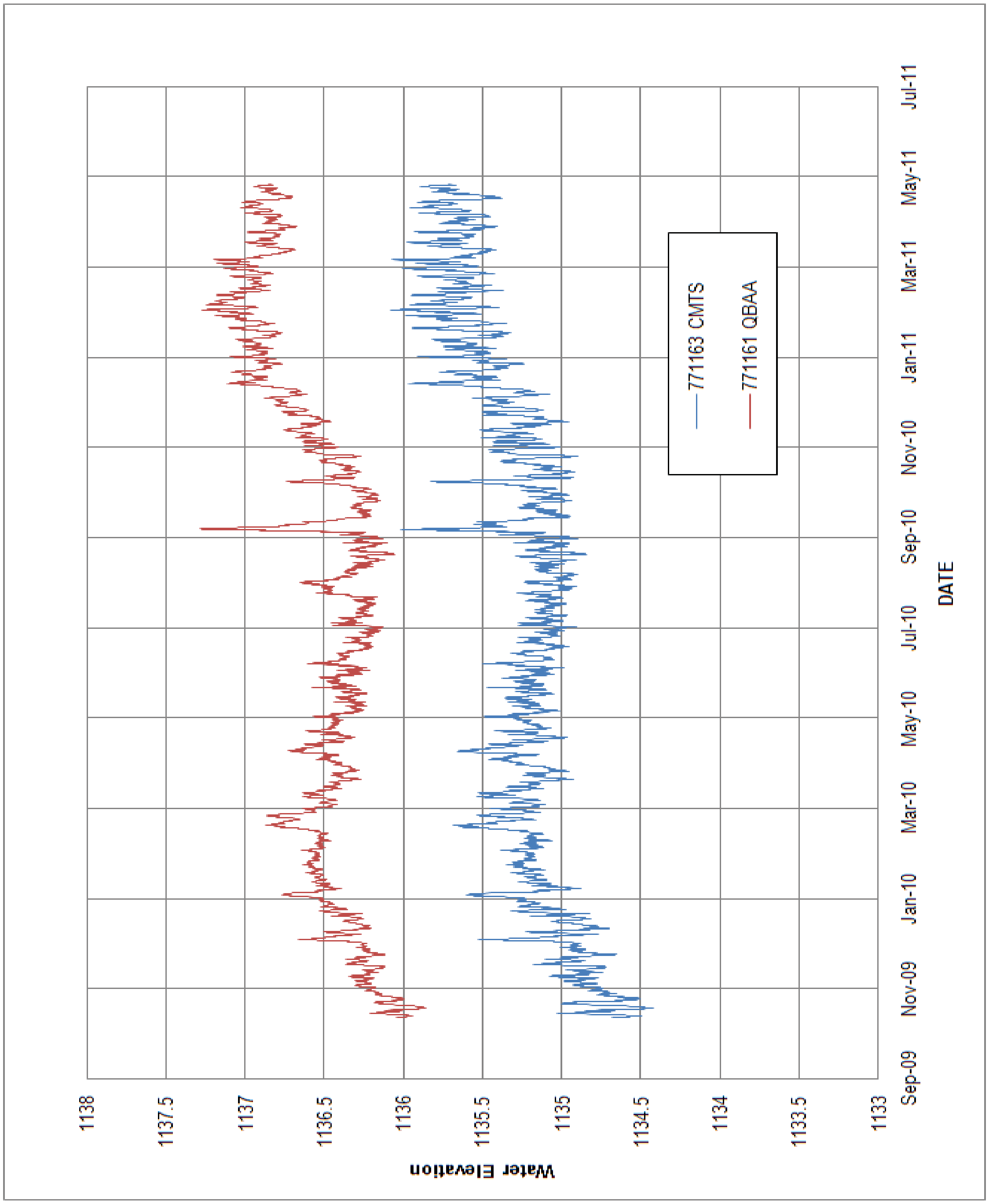


Figure 26b
Rooney Run WMA
Hydrograph

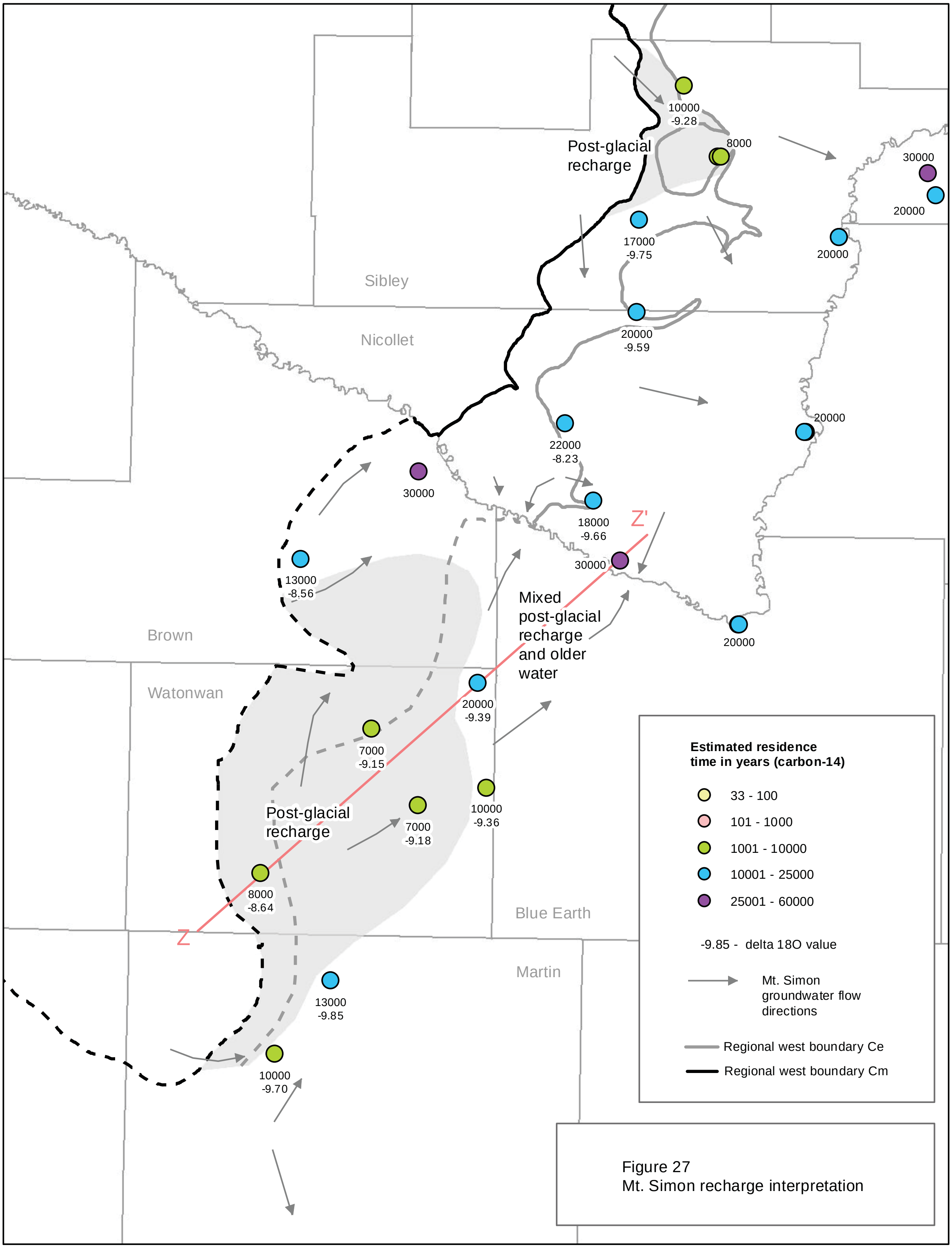


Figure 27
Mt. Simon recharge interpretation

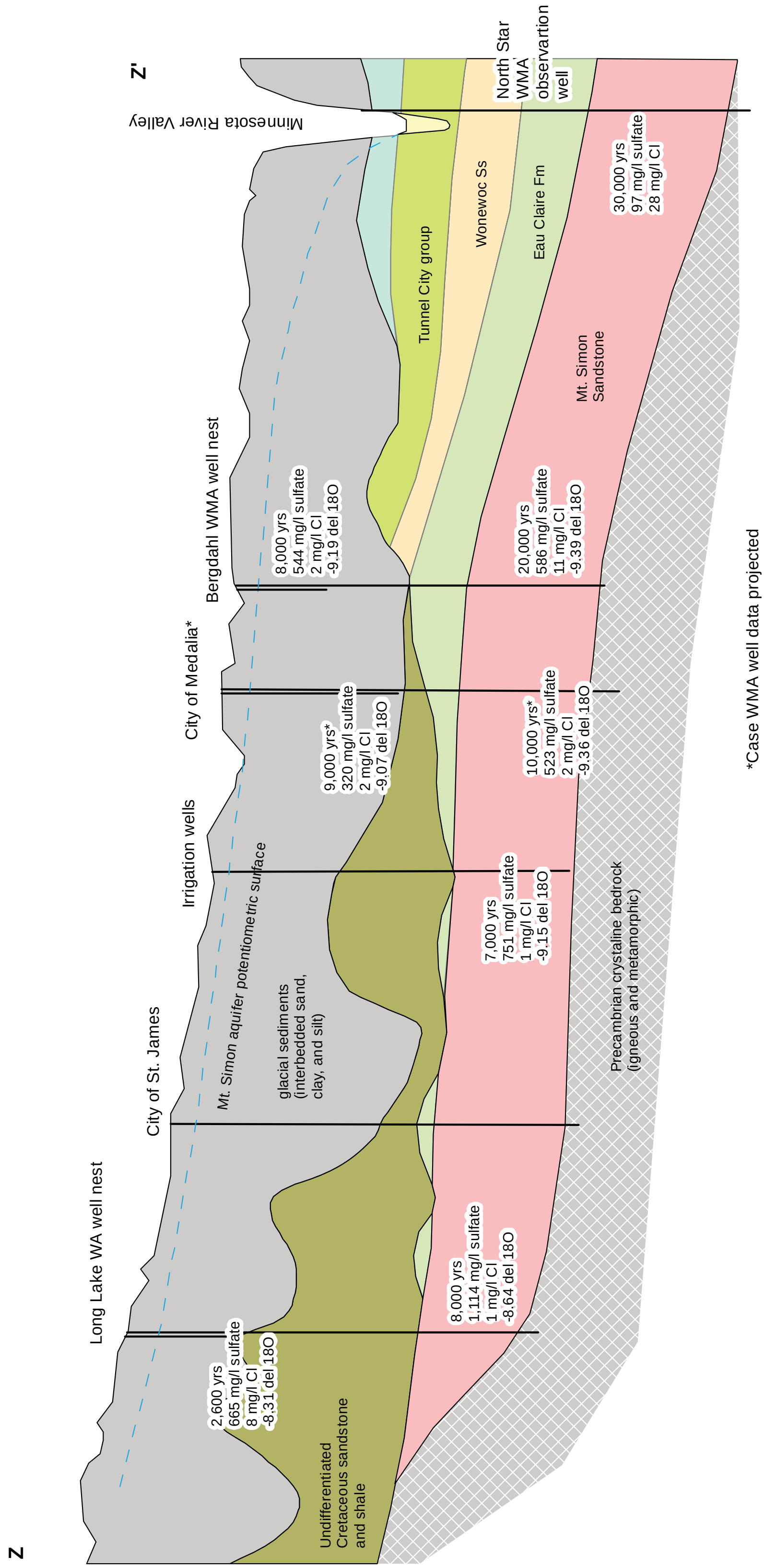


Figure 28
Generalized cross section Z-Z' and selected geochemical data

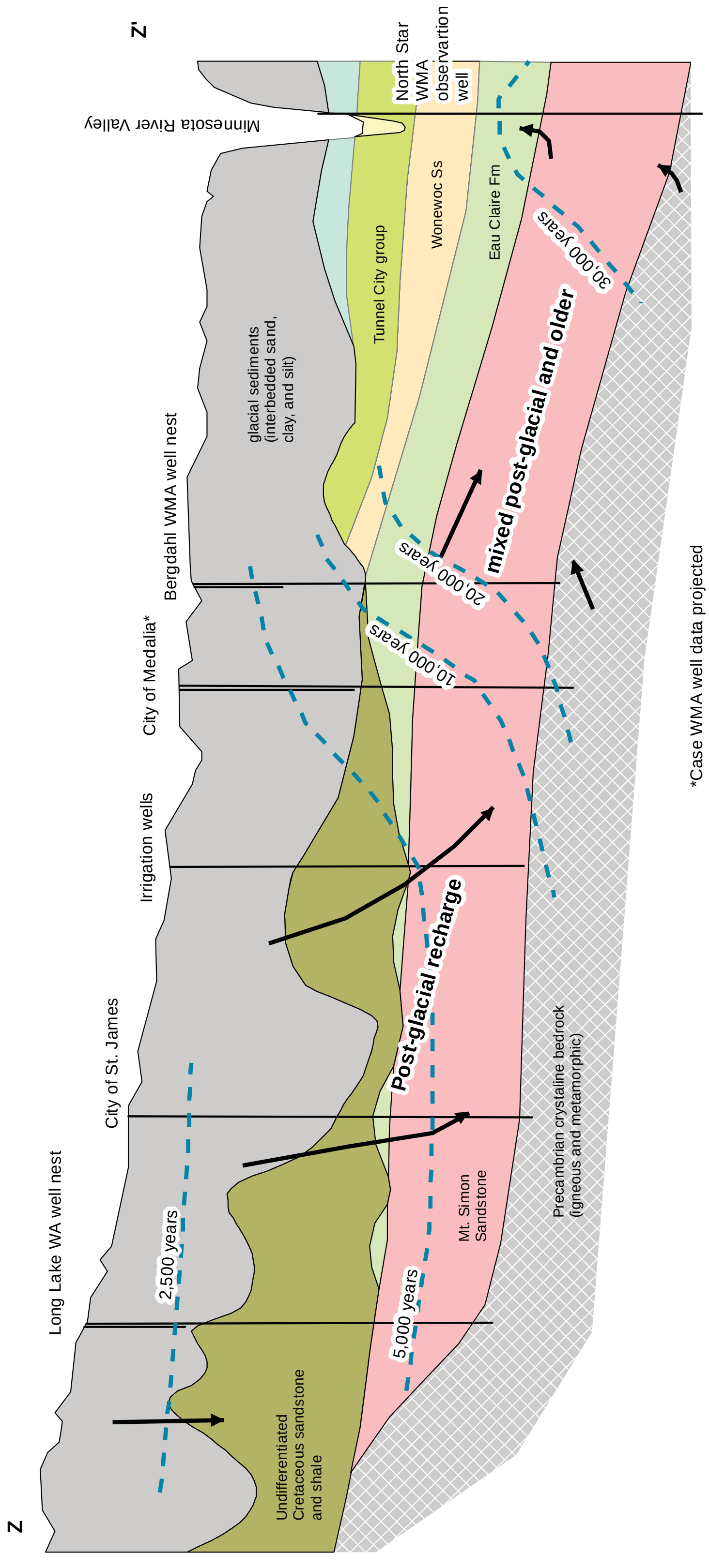


Figure 29 Cross section Z-Z'
Mt. Simon recharge and discharge

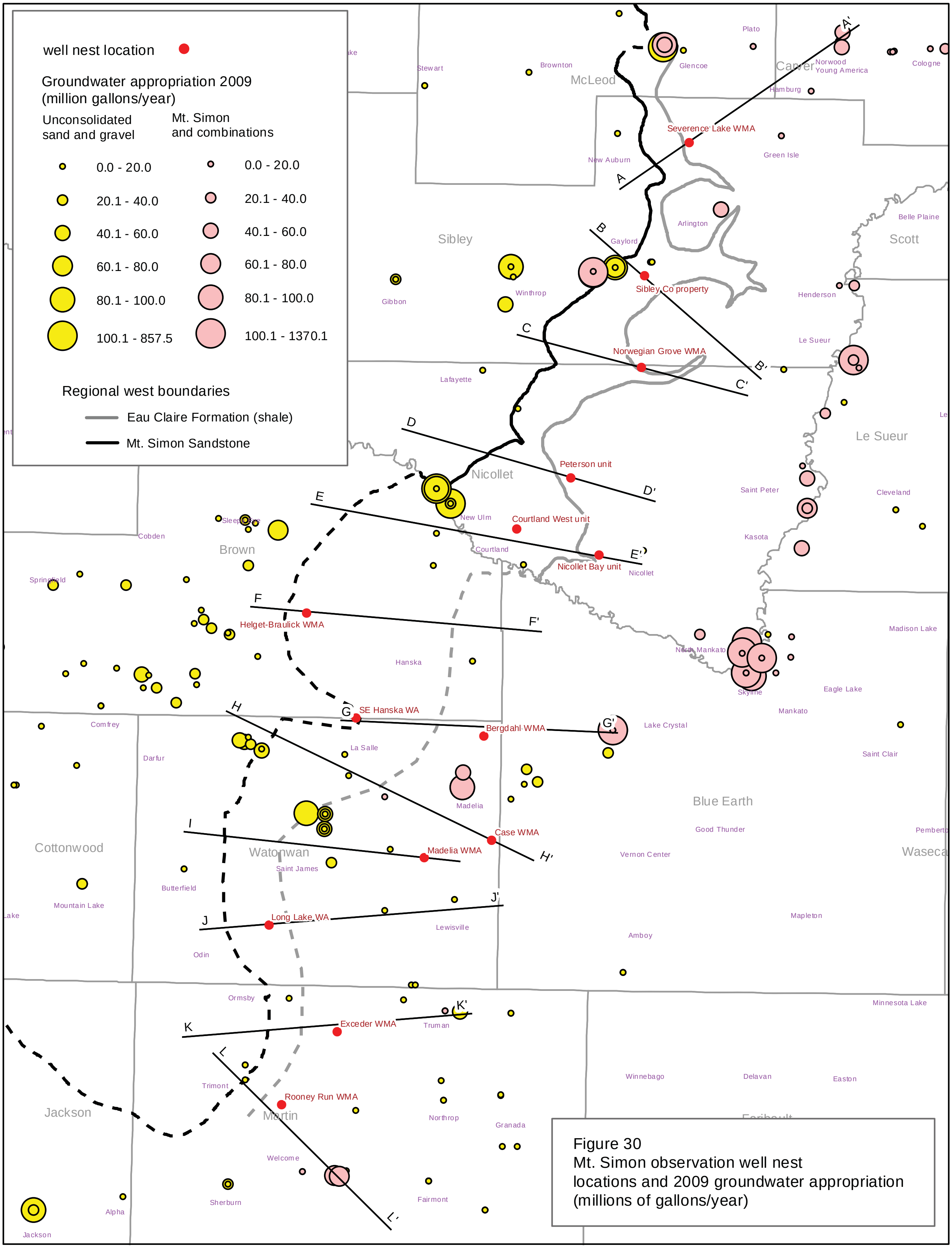
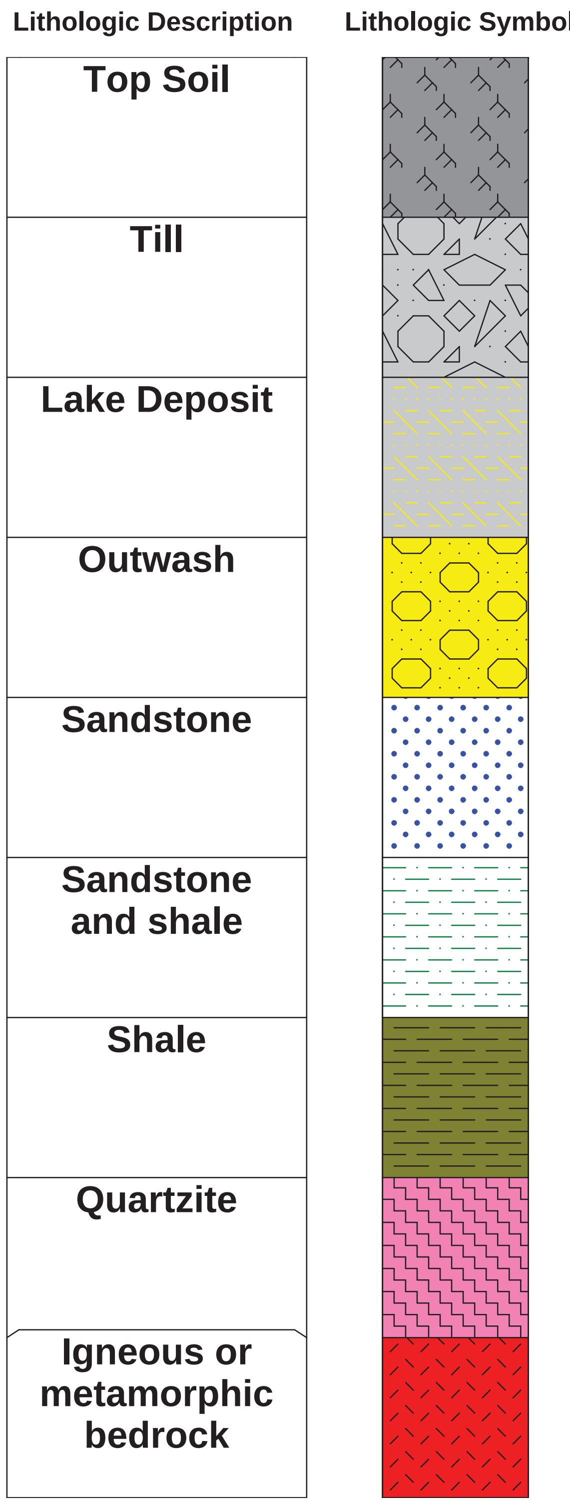


Figure 30
Mt. Simon observation well nest locations and 2009 groundwater appropriation (millions of gallons/year)

Appendix A

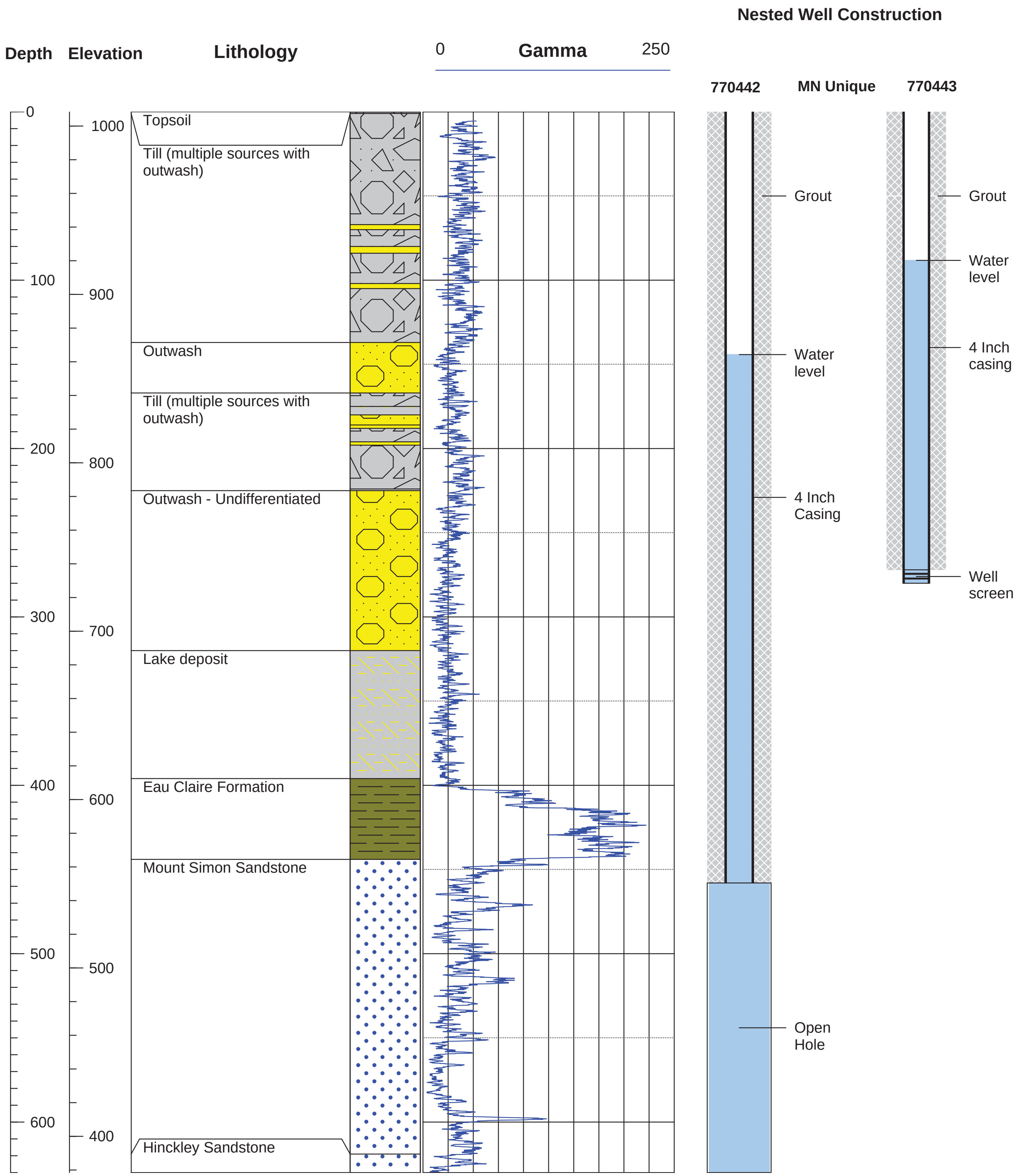
Geological Log Legend



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Severance Lake WMA

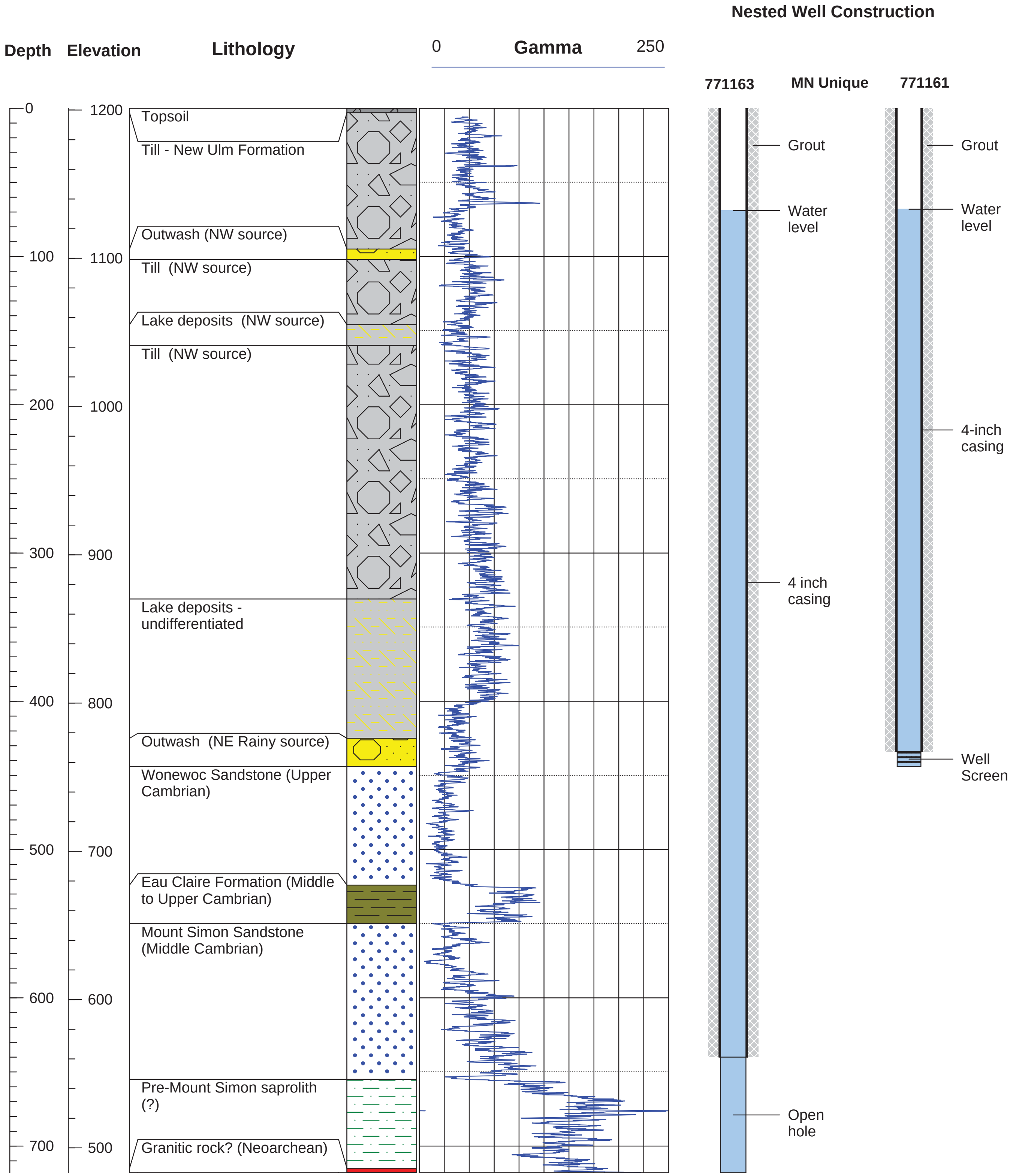
County Sibley



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Rooney Run WMA

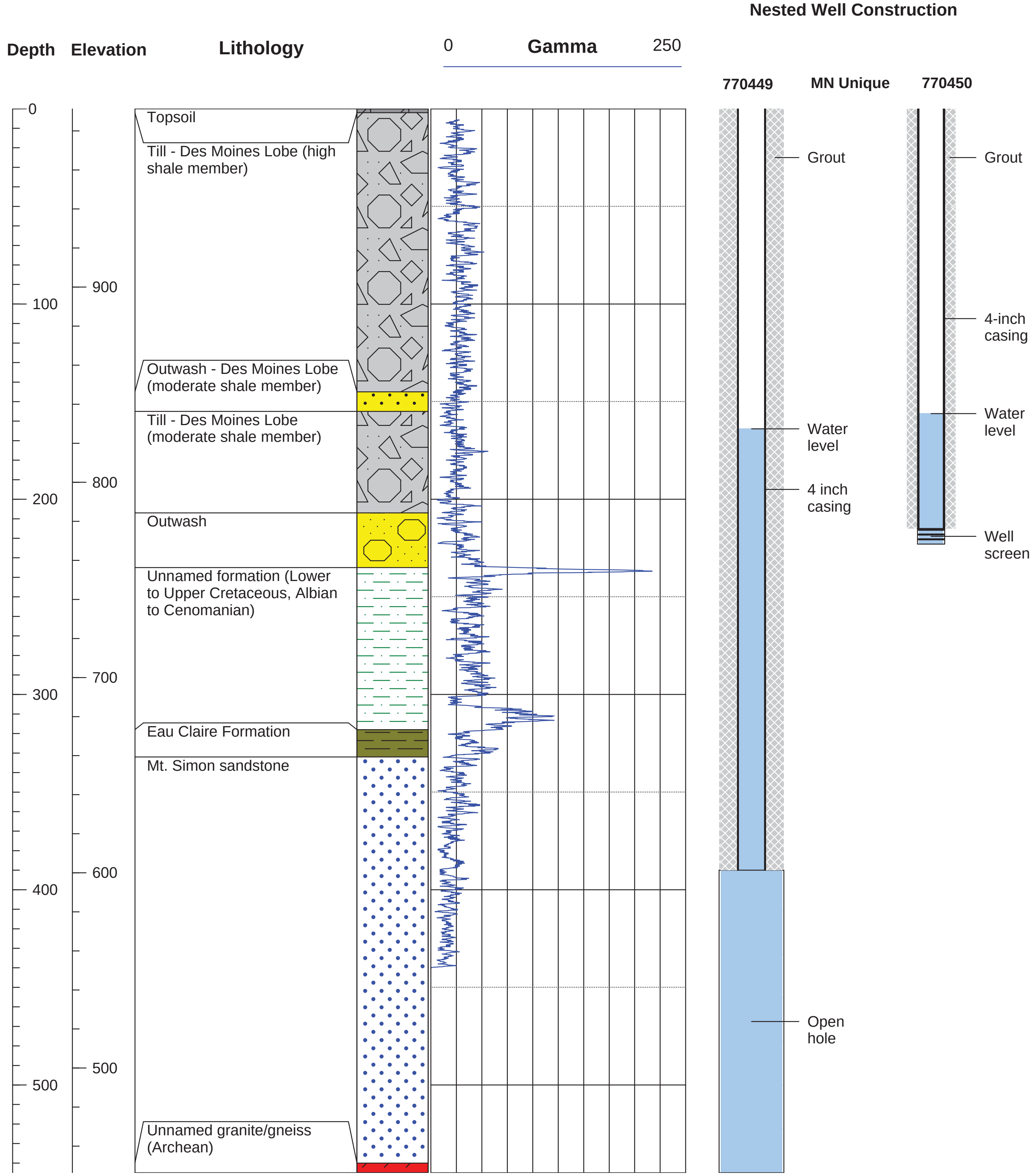
County Martin



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Swan Lake WMA Peterson Unit

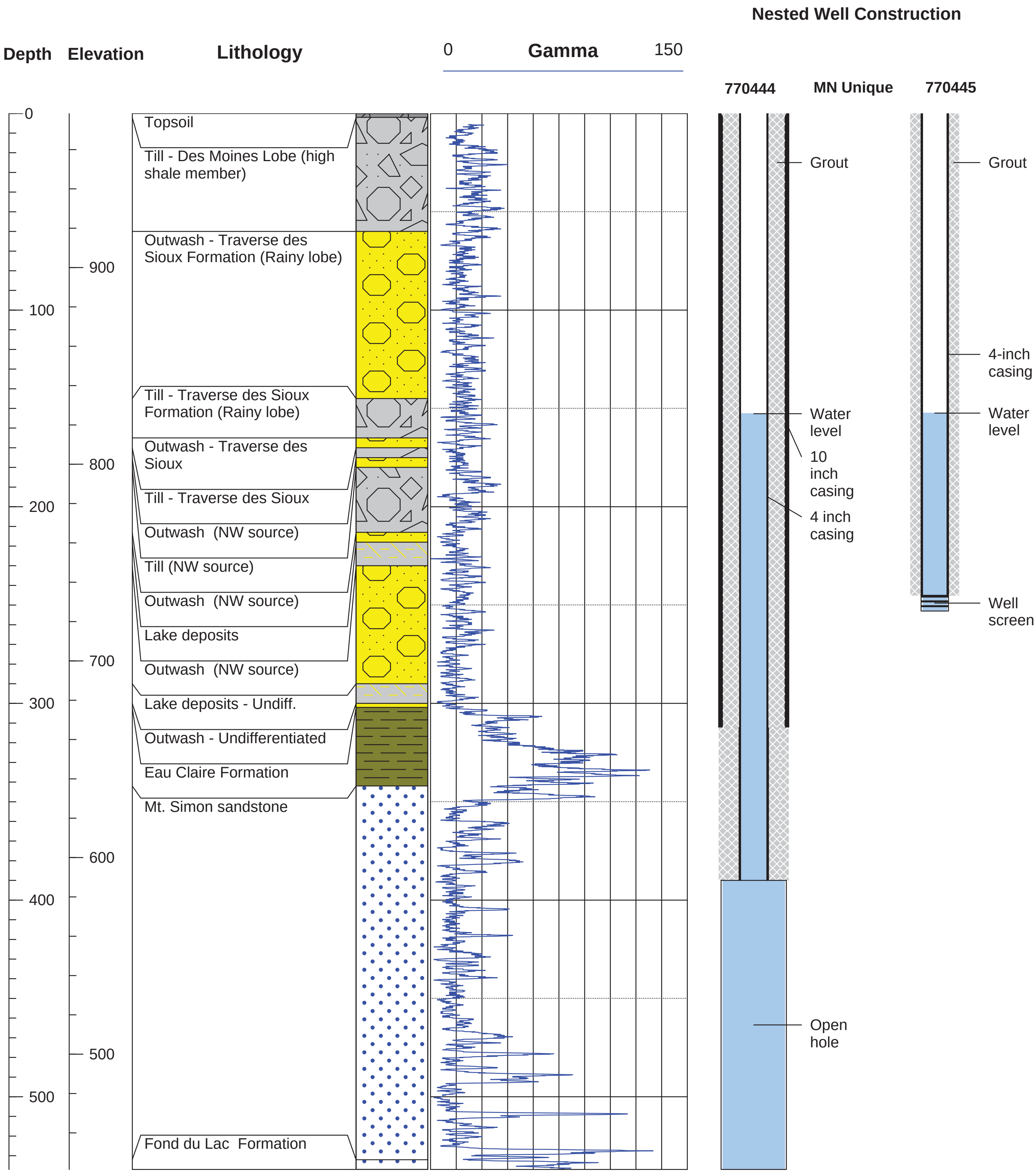
County Nicollet



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Norwegian Grove WMA

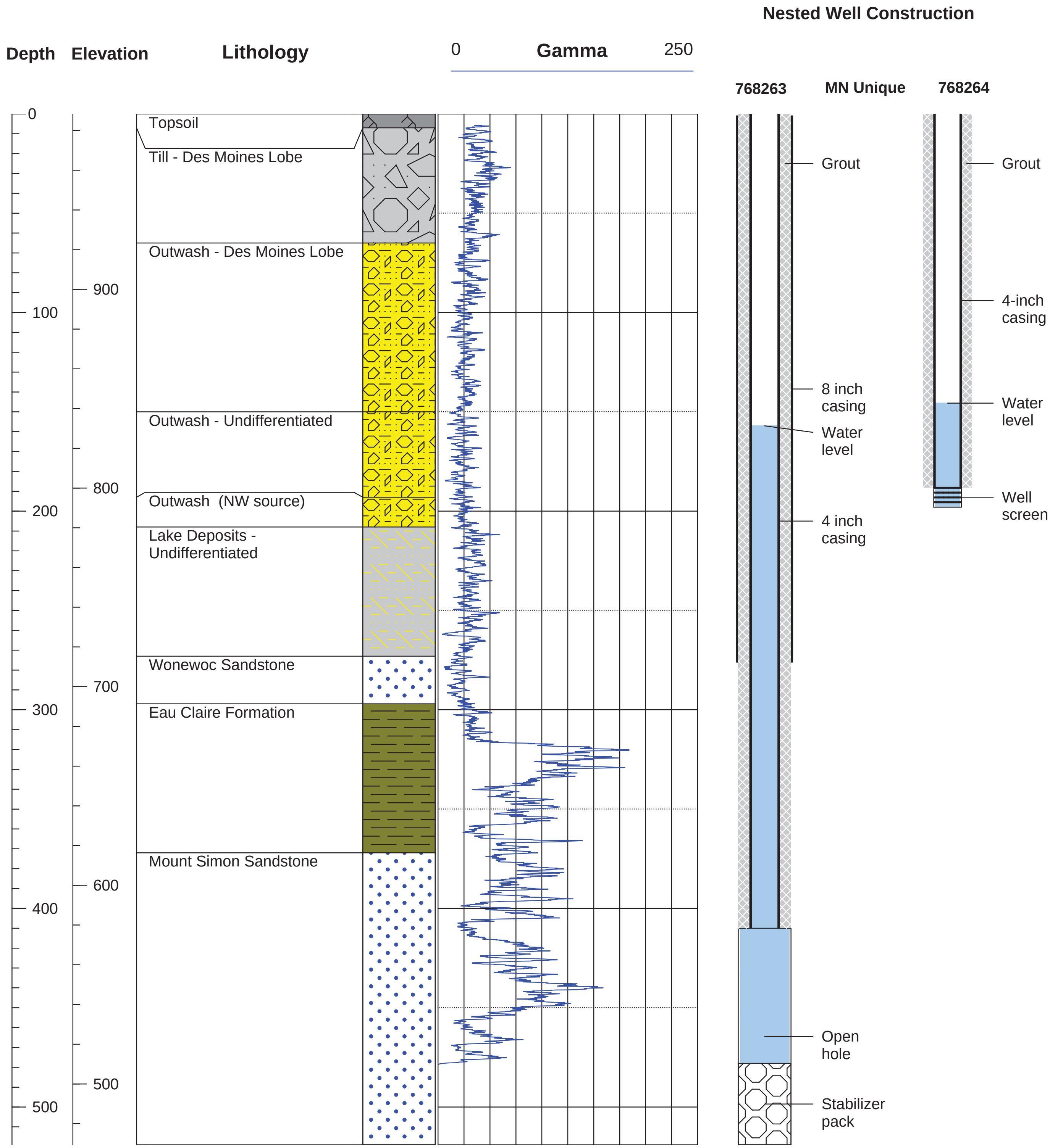
County Nicollet



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Swan Lake WMA - Nicollet Bay Unit

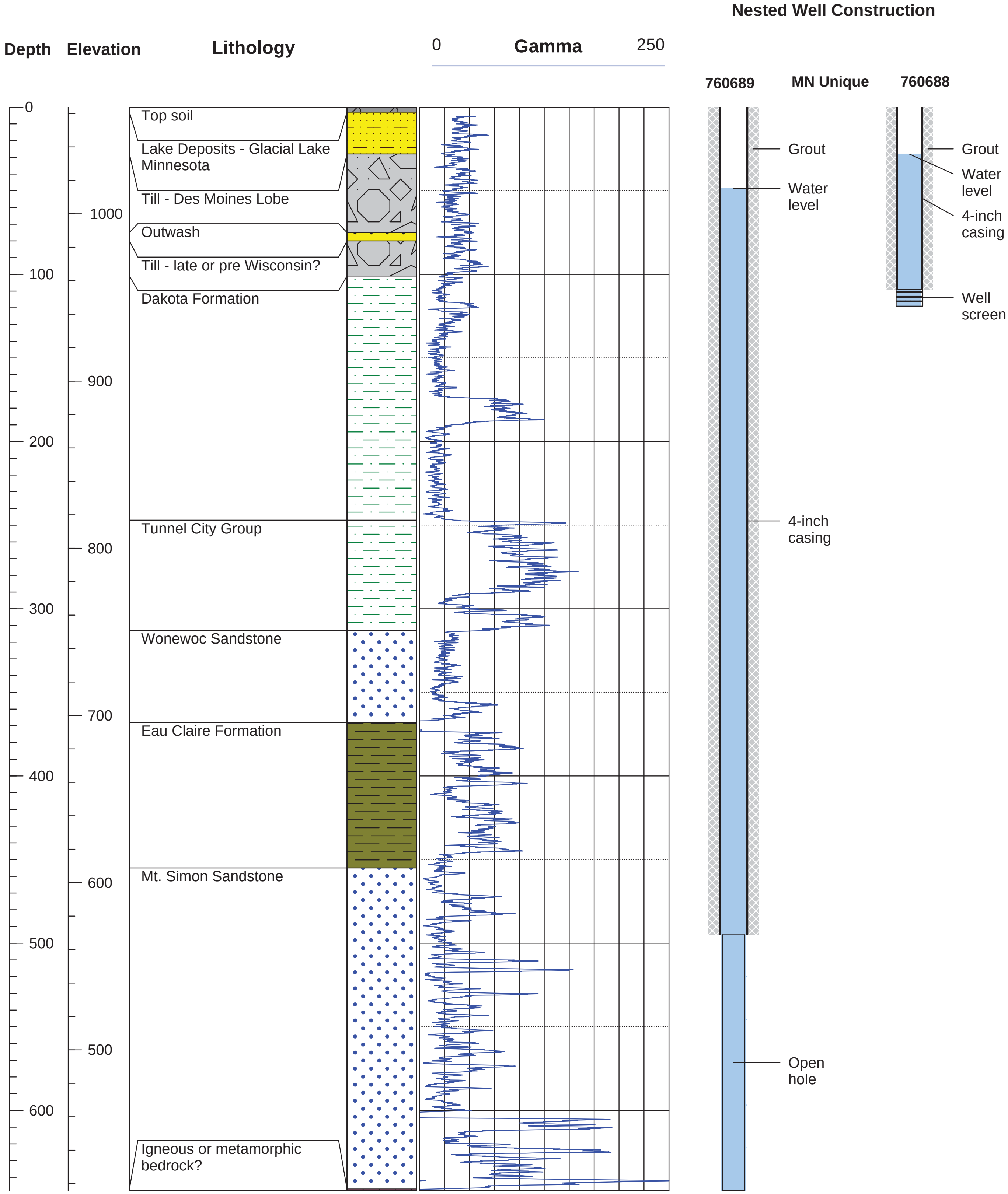
County Nicollet



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Madelia WMA

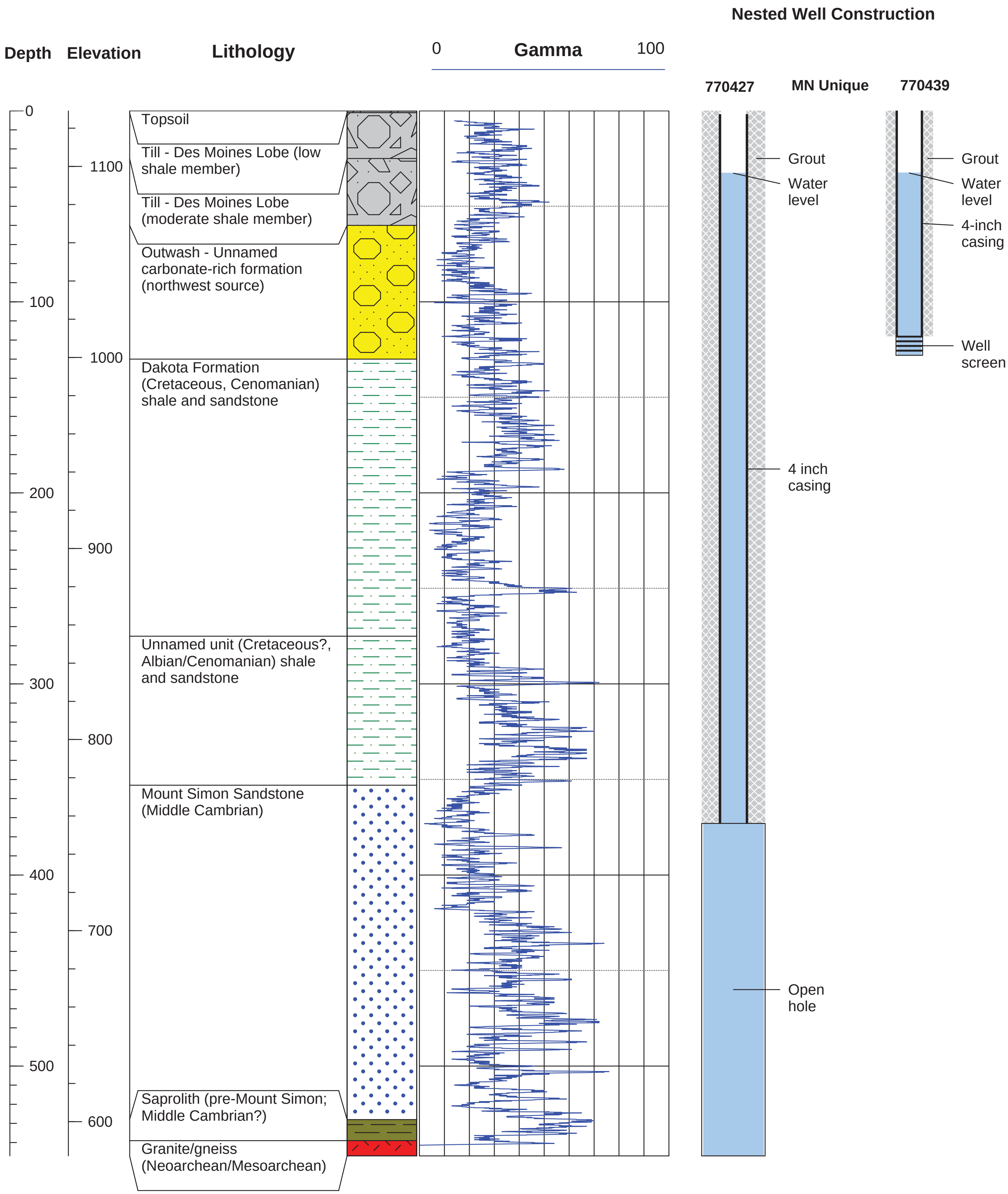
County Watonwan



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Long Lake WA

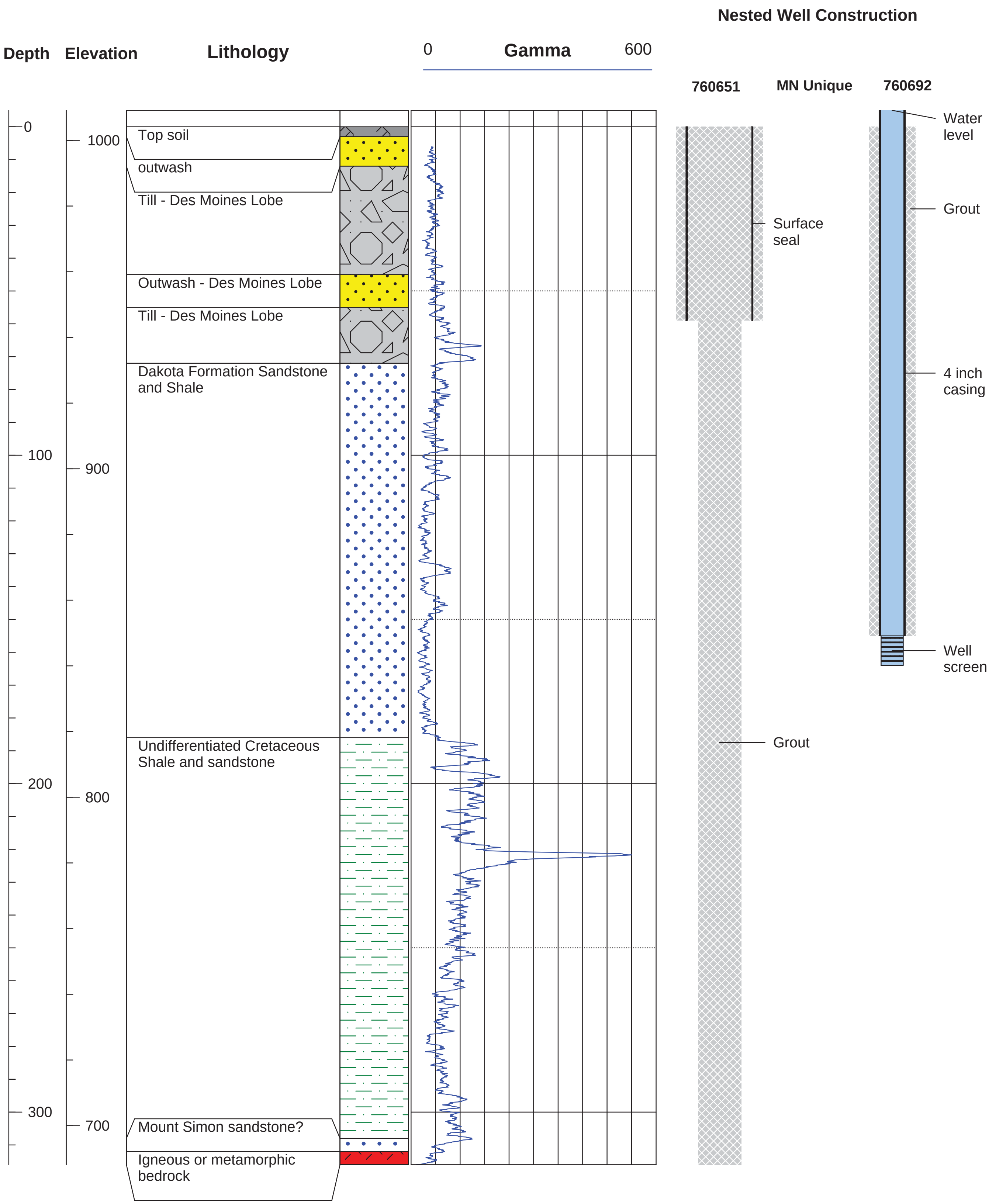
County Watowan



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Lake Hanska WA

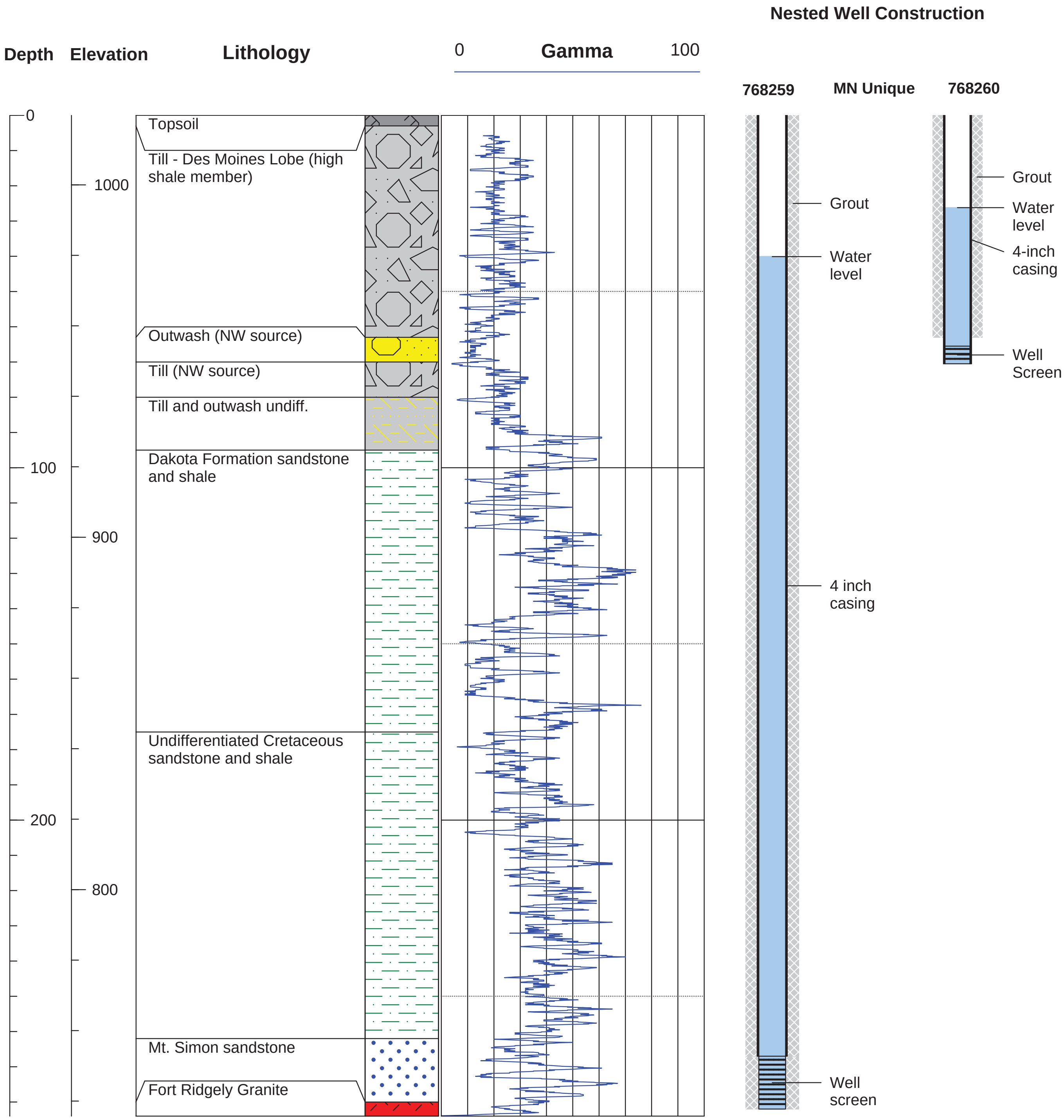
County Brown



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Helget Braulick WMA

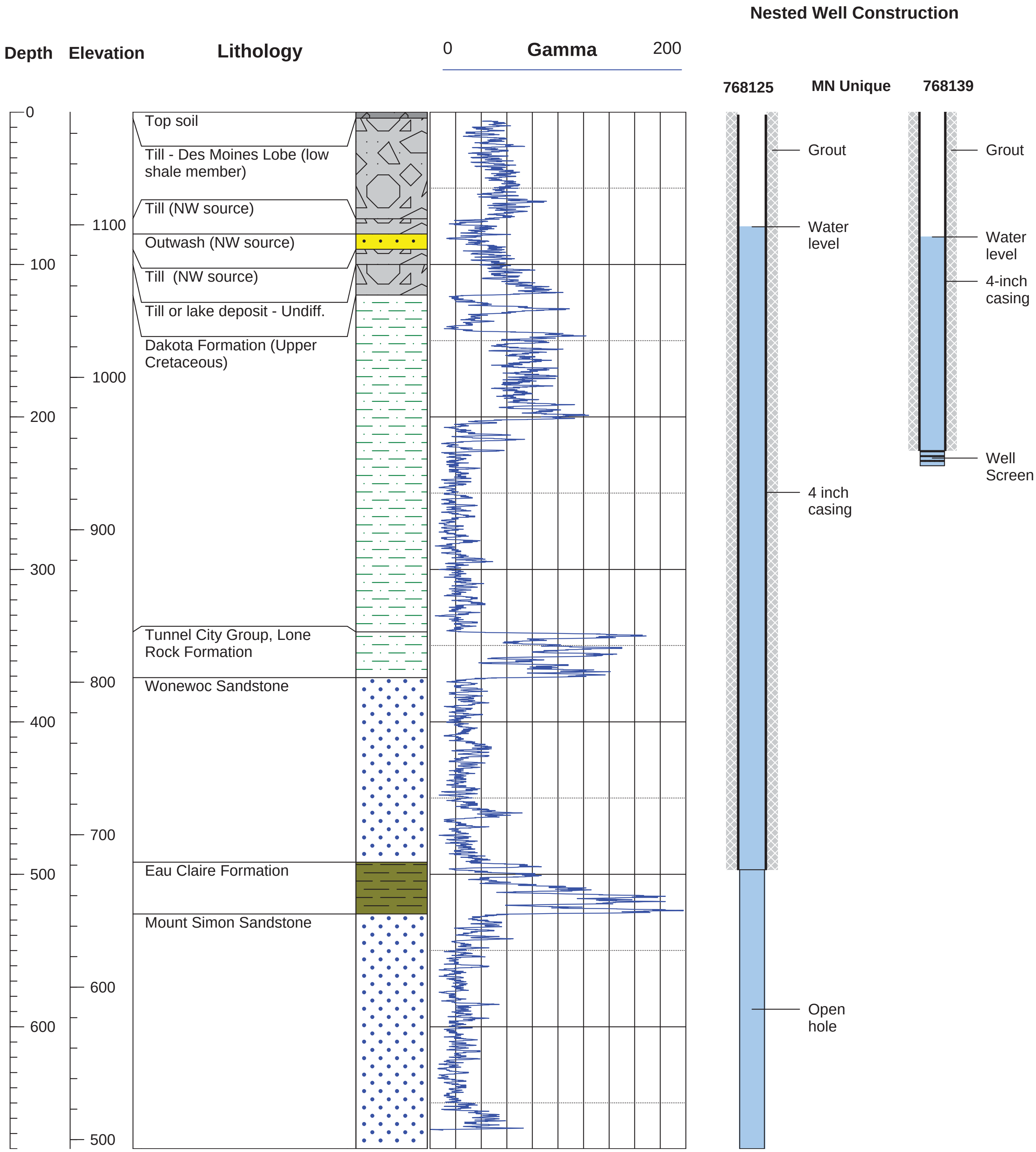
County Brown



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Exceder WMA

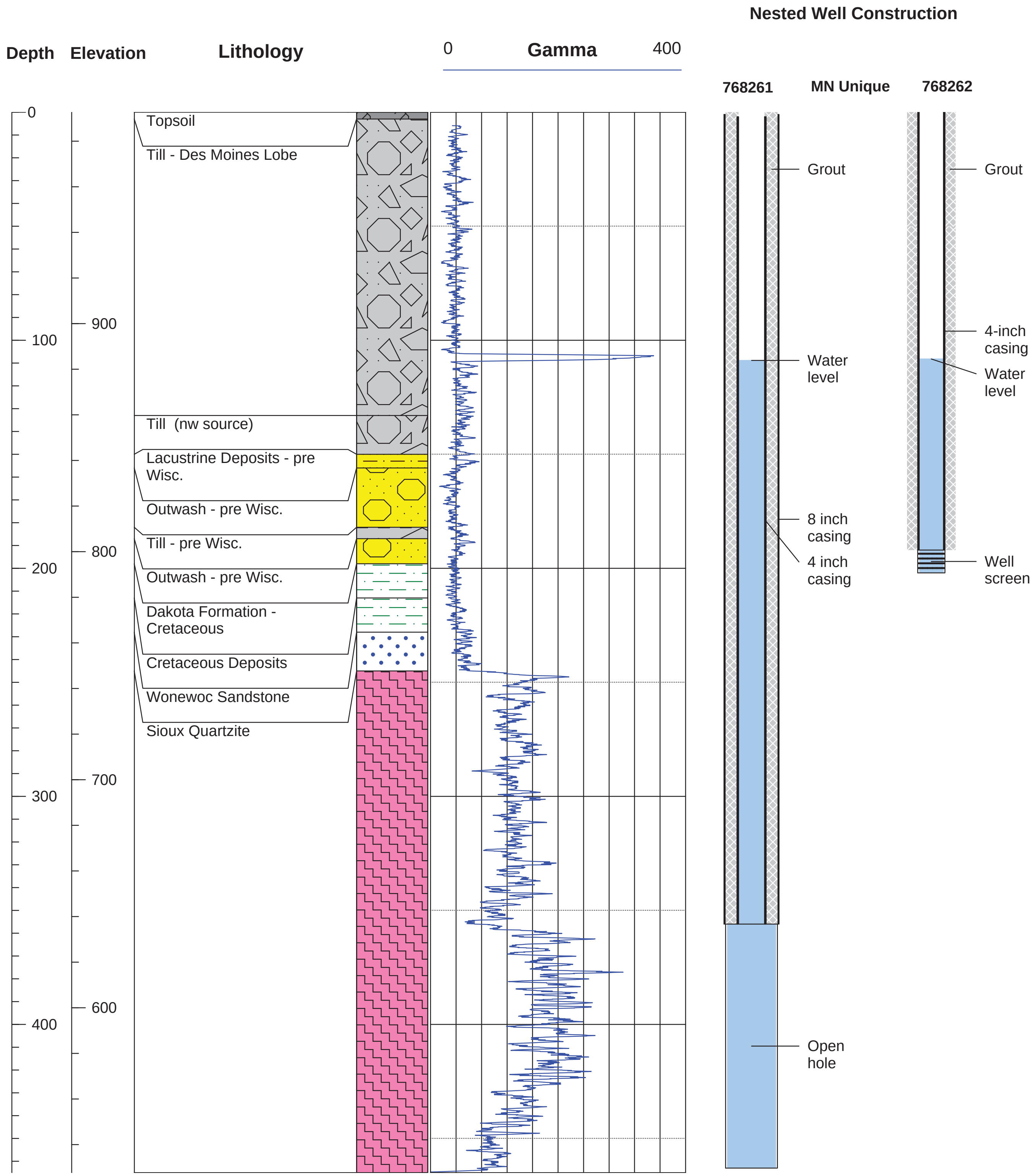
County Martin



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Swan Lake WMA - Courtland West Unit

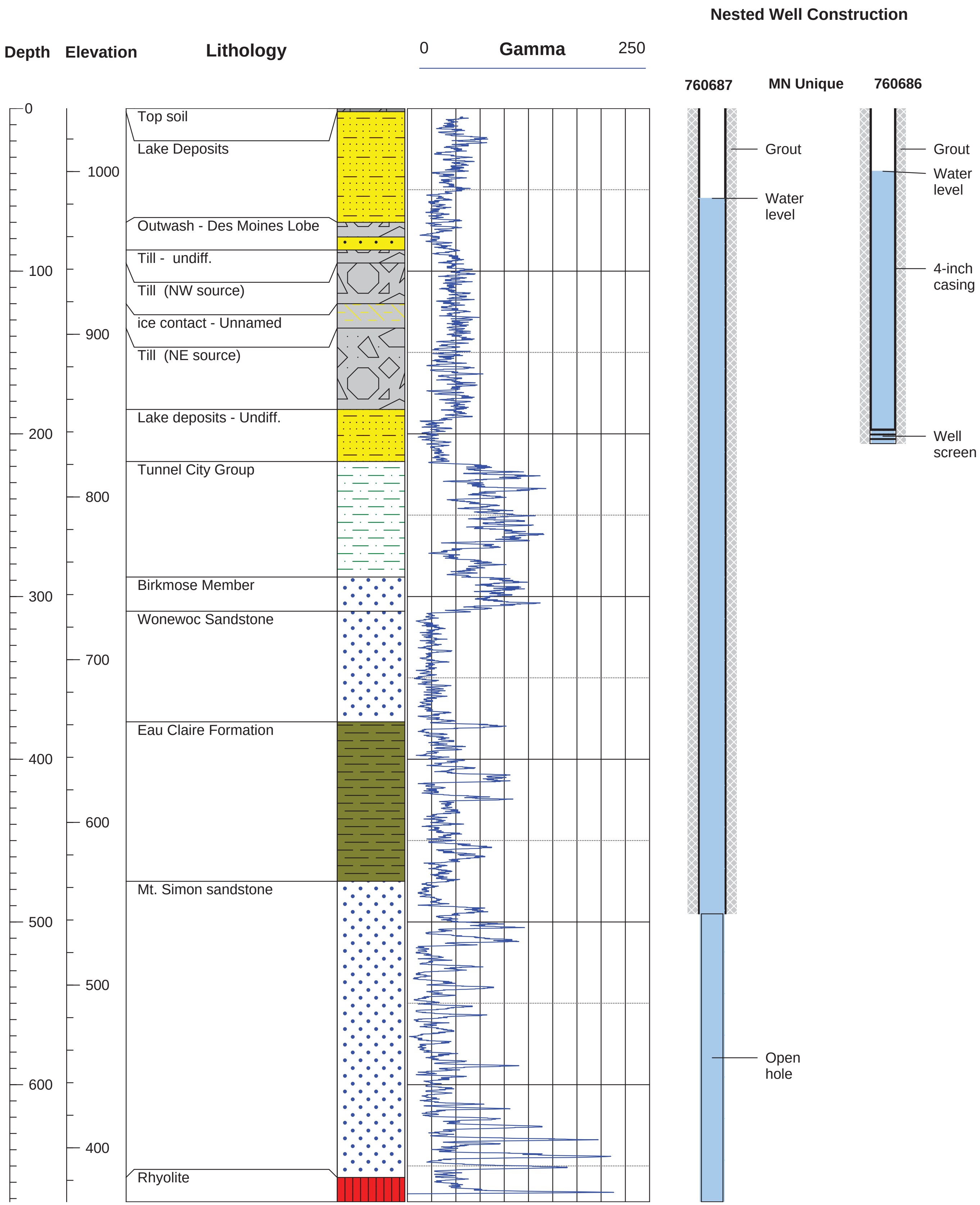
County Nicollet



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Case WMA

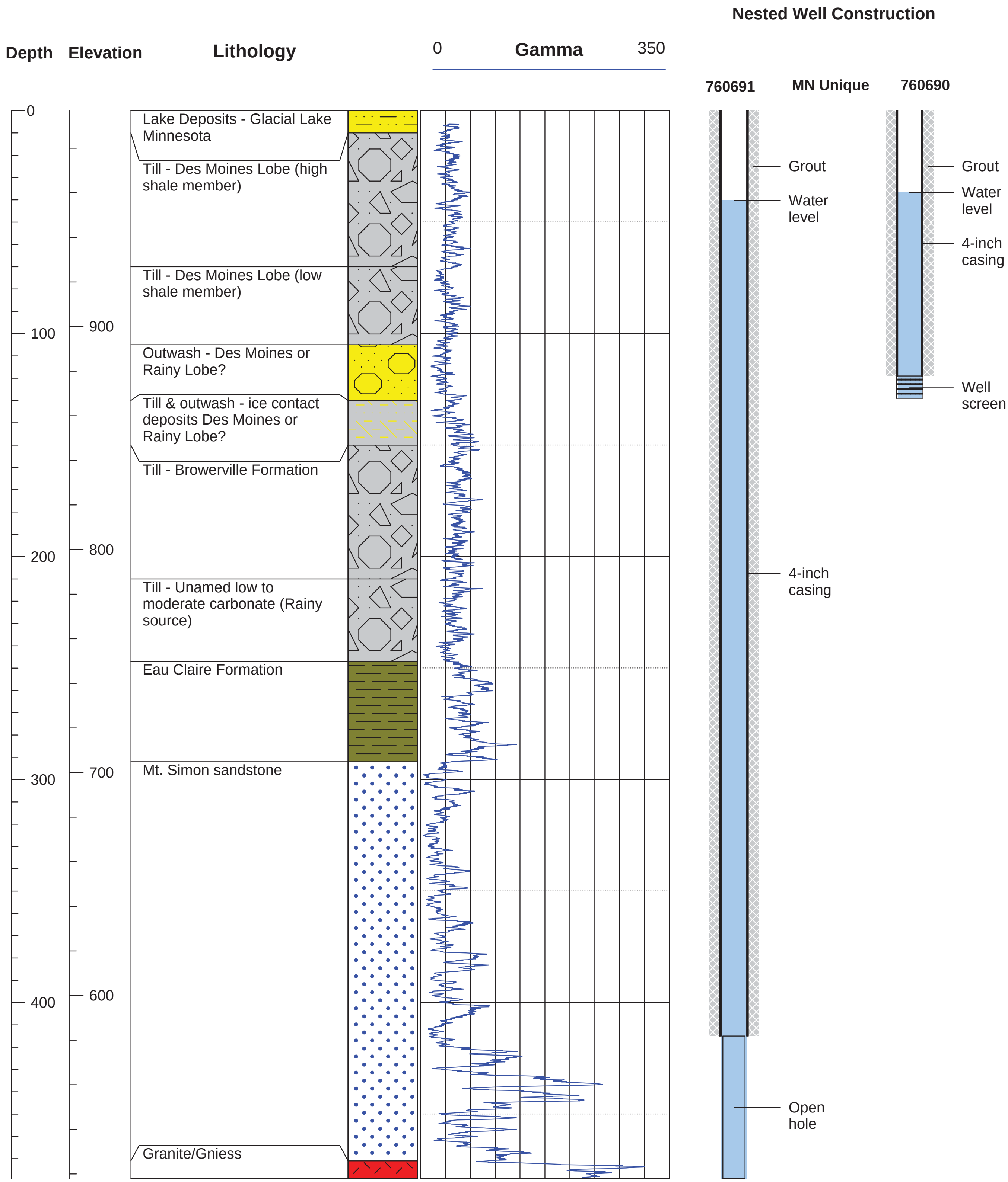
County Watonwan



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Bergdahl WMA

County Watonwan



Geological / Geophysical Logs and Well Construction Diagrams

Site Name Sibley County Landfill

County Sibley