Hydrogeologic Assessment of the Drinking Water Source and Wells for the City of Sandstone

DELINEATIONS – WELLHEAD PROTECTION AREA AND DRINKING WATER SUPPLY MANAGEMENT AREA

VULNERABILITY ASSESSMENTS – WELLS AND DRINKING WATER SUPPLY MANAGEMENT AREA

June 11, 2019

Hydrogeologic Assessment of the Drinking Water Source and Wells for the City of Sandstone

Public Water Supply ID: 1580010

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

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Glossary of Terms

Data Element. A specific type of information required by the Minnesota Department of Health to prepare a wellhead protection plan.

Drinking Water Supply Management Area (DWSMA). The area delineated using identifiable land marks that reflects the scientifically calculated wellhead protection area boundaries as closely as possible (Minnesota Rules, part 4720.5100, subpart 13).

Drinking Water Supply Management Area Vulnerability. An assessment of the likelihood that the aquifer within the DWSMA is subject to impact from land and water uses within the wellhead protection area. It is based upon criteria that are specified under Minnesota Rules, part 4720.5210, subpart 3.

Emergency Response Area (ERA). The part of the wellhead protection area that is defined by a one-year time of travel within the aquifer that is used by the public water supply well (Minnesota Rules, part 4720.5250, subpart 3). It is used to set priorities for managing potential contamination sources within the DWSMA.

Inner Wellhead Management Zone (IWMZ). The land that is within 200 feet of a public water supply well (Minnesota Rules, part 4720.5100, subpart 19). The public water supplier must manage the IWMZ to help protect it from sources of pathogen or chemical contamination that may cause an acute health effect.

Wellhead Protection (WHP). A method of preventing well contamination by effectively managing potential contamination sources in all or a portion of the well's recharge area.

Wellhead Protection Area (WHPA). The surface and subsurface area surrounding a well or well field that supplies a public water system, through which contaminants are likely to move toward and reach the well or well field (Minnesota Statutes, section 103I.005, subdivision 24).

Well Vulnerability. An assessment of the likelihood that a well is at risk to human-caused contamination, either due to its construction or indicated by criteria that are specified under Minnesota Rules, part 4720.5550, subpart 2.

Acronyms

CWI - County Well Index

DNR - Minnesota Department of Natural Resources

EPA - United States Environmental Protection Agency

FSA - Farm Security Administration

MDA - Minnesota Department of Agriculture

MDH - Minnesota Department of Health

MGS - Minnesota Geological Survey

MLAEM - Multi Layer Analytic Element Model

MnDOT - Minnesota Department of Transportation

MnGEO - Minnesota Geospatial Information Office

MPCA - Minnesota Pollution Control Agency

NRCS - Natural Resource Conservation Service

SWCD - Soil and Water Conservation District

UMN - University of Minnesota

USDA - United States Department of Agriculture

USGS - United States Geological Survey

Summary

Protection Areas - The recharge area for the wells is known as the wellhead protection area, or WHPA, and represents the area that contributes water to the city's wells within a 10-year time period. The area that contributes water within a one-year time period is known as the emergency response area, or ERA. Practical reasons require the designation of a management area that fully envelops the wellhead protection area, called the drinking water supply management area, or DWSMA. Each of these areas is shown in Figure 1.

Geology and Groundwater Flow – The city of Sandstone has two primary wells that draw groundwater from the Hinckley Sandstone - Fond du Lac Aquifer (PMHF). Well #1 (242053) is considerably deeper compared to Well #2 (219291) and is open to both sandstone formations that comprise the PMHF Aquifer, whereas Well #2 is only open to the Hinckley Sandstone (PMHN). In the vicinity of the city's wells, the sandstone bedrock is encountered at a depth of less than 10 feet below the ground surface (Table 1). Regionally, groundwater flow is to the east, toward the Kettle River.

Table 1 - Water Supply Well Information

Local Well ID	Unique Number	Use/ Status	Casing Diameter (inches)	Casing Depth (feet)	Well Depth (feet)	Date Constructed/ Reconstructed	Aquifer	Well Vulnerability
Well #1	242053	Primary	12	unknown	725	1904	PMHF	Not Vulnerable
Well #2	219291	Primary	10	66	392	1969	PMHN	Not Vulnerable

Well Vulnerability - The vulnerability of each well has been assessed based on 1) well construction details, especially conformance with standards required by the state well code, 2) the geologic sensitivity of the aquifer, and 3) past monitoring results. It is unknown whether Well #1 (242053) meets current State Well Code specifications (Minnesota Rules, part 4725) due to the lack of complete well construction information. The construction of Well #2 (219291) appears to be consistent with current well code specification. However, at this time, both of the wells are considered not vulnerable to contamination due to lack of tritium

detected in the well water (Table 2). Tritium testing allow us to age-date water and determine whether the water is older or younger than the 1950's. The lack of tritium indicates that most of the water from the city wells is relatively "old" (pre-1950's). The not vulnerable rating is also supported by the low chloride and chloride/bromide results presented below.

Table 2 - Isotope and Water Quality Results (July 30, 2013)

Well Name (Unique Number)	Tritium	Nitrate (mg/L)	Chloride (mg/L)	Bromide (mg/L)	Chloride/ Bromide Ratio
Well #1 (242053)	< 0.8	0.11	0.736	0.0114	65
Well #2 (219291)	< 0.8	0.16	0.723	0.0066	110

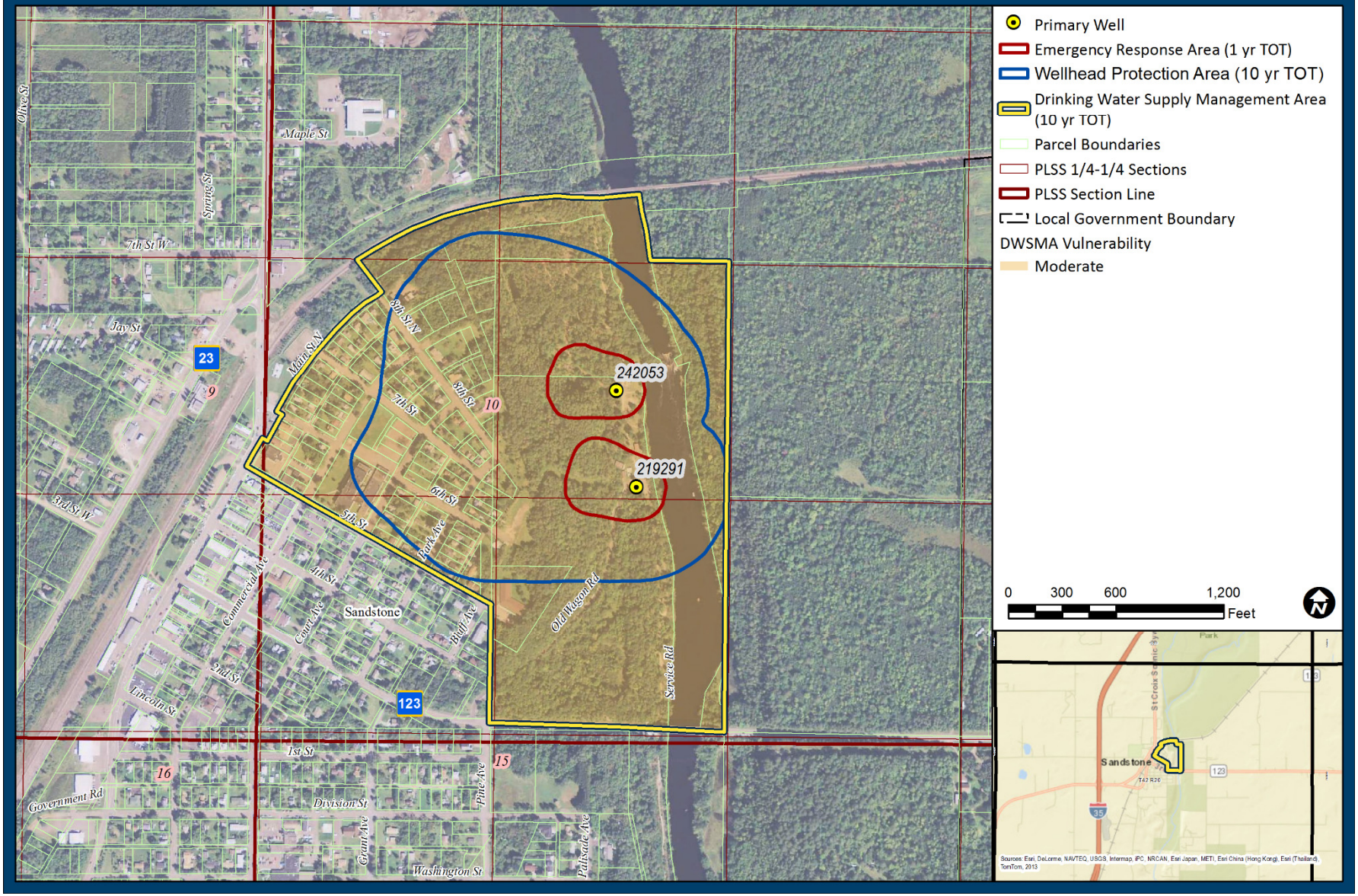
DWSMA Vulnerability - The vulnerability of the city's aquifer throughout the DWSMA is based on the geologic sensitivity ratings of wells and their monitoring data (Table 2). Based on this information MDH has assigned a moderate vulnerability to the DWSMA. This suggests that water and contaminants may travel from the land surface to the city's aquifer within a time span of years to decades. This rating balances the tritium results, suggesting the predominance of old water in the city wells, with available geologic data suggesting the city's aquifer is geologically sensitive to contamination due to an absence of overlying low-permeability geologic materials. The absence of tritium in the city's drinking water suggests that the wells are primarily being recharged by water from a longer travel path rather than from more recent precipitation events, as would typically be expected with geologically sensitive aquifers. In addition, the city wells are naturally flowing wells, which also adds a degree of natural protection from contaminants infiltrating downward into the aquifer. The low but detectable nitrate values seen at the city wells may reflect this mixed vulnerability picture, as does an older tritium result from 2000 that showed a low but detectable value (3.1 TU). Moderately vulnerable aquifers are prone to a variety of contaminant threats, including chemical storage tanks and abandoned wells which can provide conduits for contaminants to quickly reach the city's aquifer.

Water Quality Concerns - At present, none of the contaminants for which the Safe Drinking Water Act has established health-based standards is found above maximum allowable levels in the city's water supply, nor are any present at one-half of those levels.

Recommendations - Recommendations have been generated to improve future delineations and vulnerability assessments and should be considered for inclusion as management strategies in the city's wellhead protection plan. These activities include well locating and water quality monitoring. Further details can be found in the Recommendations section of this report.

Pine County
Minnesota

Figure 1
Drinking Water Supply Management Area and Vulnerability
City of Sandstone



Technical Report

Discussion

The Minnesota Department of Health (MDH) developed Part I of the wellhead protection (WHP) plan at the request of the city of Sandstone (PWSID 1580010). The work was performed in accordance with the Minnesota Wellhead Protection Rule, parts 4720.5100 to 4720.5590.

This report presents delineations of the wellhead protection area (WHPA) and drinking water supply management area (DWSMA), and the vulnerability assessments for the public water supply wells and DWSMA. Figure 1 shows the boundaries for the WHPA and the DWSMA. The WHPA is defined by a 10-year time of travel. Figure 1 also shows the emergency response area (ERA), which is defined by a one-year time of travel. Definitions of rule-specific terms used are provided in the "Glossary of Terms."

In addition, this report documents the technical information required to prepare this portion of the WHP plan in accordance with the Minnesota Wellhead Protection Rule. Additional technical information is available from MDH.

Table 1 lists all the wells in the public water supply system. Only wells listed as primary are required to be included in the WHP plan.

Assessment of the Data Elements

MDH staff met with representatives of the city of Sandstone on February 15, 2018, for a scoping meeting that identified the data elements required to prepare Part I of the WHP plan. Appendix A presents the assessment of these data elements relative to the present and future implications of planning items specified in Minnesota Rules, part 4720.5210.

General Descriptions

Description of the Water Supply System

The city of Sandstone obtains its drinking water supply from two primary wells. Table 1 summarizes information regarding them.

Description of the Hydrogeologic Setting

The city of Sandstone draws groundwater from the Hinckley Sandstone - Fond du Lac (PMHF) Aquifer. Well #1 (242053) is considerably deeper compared to Well #2 (219291) and is open to both the Hinckley Sandstone and Fond du Lac formations, whereas Well #2 is open only to the Hinckley Sandstone. With respect to Well #1, the contact location between the two formations

is not known due to the lack of a construction record for the well. The Fond du Lac formation is generally assumed to be hydraulically connected to the overlying Hinckley Sandstone due to the absence of a geologic confining unit separating the sandstone formations.

The combined thickness of the PMHF Aquifer is not well established. It is thought that the Hinckley Sandstone formation may be as thick as 500 feet (Boerboom, 2002). The majority of the potable wells in the Sandstone area are less than 200 feet deep and are completed in the Hinckley Sandstone Aquifer. In the vicinity of the city's municipal wells, the depth to bedrock is generally less than 10 feet. Further to the west and beyond the river bluffs, the geologic materials overlying bedrock are considerably thicker (up to 150 feet) and consist of varied sequences of glacial till and outwash sands.

Karst features at the land surface have been mapped along the Kettle River by researchers from the University of Minnesota and the Pine County Soil and Water Conservation District (Shade et al., 2001). The karst features identified in the Sandstone area are predominately sinkholes and springs, with several potential sinkholes mapped in and around the ERA for Well #1 (242053). The Hinckley Fault, located east of Sandstone and trending northeast-southwest, is a geologic boundary affecting the occurrence of sinkholes. In bedrock exposures along the Kettle River, parallel fractures have been so deeply weathered that caves have developed (T. Boerboom, personal communication, 2006).

Regional groundwater flow is easterly towards the Kettle River. Locally, Skunk and Wolf Creeks also have an influence on groundwater flow.

Both of the city's wells are classed as flowing artesian wells. This means that the groundwater is under enough pressure at the locations of the wells to rise naturally above the ground surface without the need to pump it. Meters on the wells indicate that Well #1 (242053) flows at a rate of 84 gallons per minute (gpm), while Well #2 (219291) flows at a rate of 88 gpm. This is a unique hydrologic condition and provides a degree of natural protection to the city's source water.

A description of the hydrogeologic setting for the aquifers used to supply drinking water is presented in Table 3.

Table 3 - Description of the Local Hydrogeologic Setting

Attribute	Descriptor	Data Source
Aquifer Material	Sandstone, with interbedded shale and siltstone	Well records; Boerboom, 2001; Boerboom, 2002.
Porosity Type and Value	0.21	Norvitch et. al., 1973

Attribute	Descriptor	Data Source
Aquifer Thickness	720 feet	Well records
Stratigraphic Top Elevation	965 feet	Well records
Stratigraphic Bottom Elevation	245 feet	Well records
Hydraulic Confinement	Confined	Hydrologic condition at the well field (artesian flowing wells)
Transmissivity	Representative Value: 1800 ft2/d Range of Values: 320 - 3600 ft^2/day	A range of transmissivity values was used to reflect changes in aquifer composition and thickness as well as uncertainties related to the quality of existing aquifer test data. See Table 4 for the reference value.
Hydraulic Conductivity	Representative value: 5 ft/day Range of Values: 1 – 10 ft/day	The range of values was derived using specific capacity data obtained from well records and/or from additional aquifer test results listed in the "Selected References" section of this report.
Groundwater Flow Field	Groundwater flow is toward the east, with an approximate compass direction of 288° and gradient of 0.0178 (Figure 2)	Defined by using static water level elevations from well records in the CWI database and documents listed in the "Selected References" section of this report.

The distribution of the aquifer and its stratigraphic relationships with adjacent geologic materials are shown in Figures 3, 4, and 5. They were prepared using well record data contained in the CWI database. The geological maps and studies used to further define local hydrogeologic conditions are provided in the "Selected References" section of this report.

Delineation of the Wellhead Protection Area

Delineation Criteria

The boundaries of the WHPA for the city of Sandstone are shown in Figure 1. Table 4 describes how the delineation criteria specified under Minnesota Rules, part 4720.5510, were addressed.

Table 4 - Description of WHPA Delineation Criteria

Criterion	Descriptor	How the Criterion was Addressed
Flow Boundary	Surface Water Features	The regional flow system is driven by a number of surface water features, including: the Kettle River and Skunk and Wolf Creeks. These are simulated in the flow model used to delineate the city's WHPA.
Flow Boundary	Other High Capacity Wells	No known active high-capacity wells exist within 1.5 miles of the city of Sandstone's wells.
Daily Volume of Water Pumped	See Table 5	The natural artesian flow rates of the wells were used instead of the annual volumes reported to the DNR (Appropriations Permit Number 1980-3006).
Groundwater Flow Field	Groundwater flow is toward the east, with an approximate compass direction of 288° and gradient of 0.0178 (Figure 2).	The groundwater flow field was determined from local well data and input explicitly into the fracture flow calculations. Oneka was also used to evaluate the uncertainty of the wells' capture areas based on regional flow, recharge and local well data.

Criterion	Descriptor	How the Criterion was Addressed
Aquifer Transmissivity	Representative Value: 1800 ft2/d Range of Values: 320 - 3600 ft^2/day	The aquifer test plan was approved on January 15, 2019, and T was determined using specific capacity data obtained from well records and/or from additional aquifer test results from neighboring communities. Uncertainty regarding aquifer transmissivity was addressed as described in the "Addressing Model Uncertainty" section.
Time of Travel	10 years	The public water supplier selected a 10-year time of travel.

Pumping data was obtained from the DNR Permit and Reporting System (MPARS) for the public water supply's Appropriations Permit Number 1980-3006. These values, confirmed by the public water supplier, were used to identify the maximum volume of water reported annually over the previous five-year period, as shown in Table 5. An estimate of the water use for the next five years is also shown. City staff indicate that the water use reported to the DNR represents the water volume that flows from their treatment plant into the city's water distribution system. Both of the city's wells flow continuously (due to artesian pressure) at a rate that exceeds the water demand needs of the city. For this reason, the artesian flow volumes were used in the groundwater flow models for the delineation of the WHPA. The maximum daily volume was calculated by dividing the annual artesian flow volumes by 365 days.

Table 5 - Annual Volume of Water Discharged from Water Supply Wells

Well Name/ Unique Number	2013	2014	2015	2016	2017	5-Year Projection	Annual Artesian Flow Volume	Daily Volume (cubic meters)
Well #1 (242053)	0	0	0	0	0	--	**44.15**	458

Well Name/ Unique Number	2013	2014	2015	2016	2017	5-Year Projection	Annual Artesian Flow Volume	Daily Volume (cubic meters)
Well #2 (219291)	31.65	34.15	30.26	30.14	30.4	35.86	**46.25**	480

(Expressed as millions of gallons. Bolding indicates greatest annual pumping volume.)

Method Used to Delineate the Wellhead Protection Area

The WHPA for the city of Sandstone's wells was determined using the porous media modeling software code MLAEM (Strack, 1989). The WHPA was also calculated using the calculated fixed radius procedure, which is described in the *MDH Guidance for Delineating Wellhead Protection Areas in Fractured and Solution-Weathered Bedrock* (MDH, 2011). Additional capture zone calculations were conducted using the stochastic analytical groundwater flow method Oneka (Barnes and Soule, 2002). The resulting WHPA boundaries are a composite of the capture zones calculated from several different model scenarios (Figure 1).

Porous Media Delineation

The MLAEM Code was selected because it is capable of simulating the influence of 1) surface water features, 2) vertical infiltration, and 3) the pumping influence of multiple high-capacity wells. All of these conditions were considered for this delineation. In general, the input parameters for the model were determined from information 1) provided by the public water supplier, 2) interpreted from local well logs and pumping test data, and 3) obtained from existing published reports and maps (see References).

The PMHF Aquifer was simulated as a single layer system. A previous groundwater flow model used for the delineation of WHPAs for the city of Hinckley was geographically extended to the Sandstone area and then refined for this specific hydrogeologic setting. The Kettle River was refined in the vicinity of the wellfield using resistance varel elements. Skunk and Wolf Creeks, and a few smaller lakes, were also added to the model using resistance varel elements. The surface water features were primarily included in order to adequately simulate the configuration of the ambient groundwater flow field. Global infiltration was simulated using given varel elements.

Oneka was used to assess the probability of impacts that local variations in hydrogeologic conditions may have on a well capture zone. This model treats the aquifer properties and the available water level measurements as variable input parameters. The locations of wells, water levels, and the aquifer geometry were evaluated using information from the CWI database. For the solution, Oneka finds the flow field that best fits the network of water level elevations by varying the values of the aquifer thickness and transmissivity. Oneka then evaluates the

probability of the capture of a given point based on the number of times it is included in the capture areas generated by the total number of solutions. The output from the model is a capture zone probability map for the specified time of travel (10 years).

Representative aquifer parameters were used in the base case model scenario. Additional modeling scenarios using MLAEM and Oneka were then simulated using reasonable estimations of parameters to demonstrate model sensitivity and to reflect uncertainty conditions, which are addressed in the next section. The model parameters for all porous media model runs are listed in Table 6.

Fractured and Solution-Weathered Rock Delineation

The fracture-flow delineation procedure was developed to address the increased variability in flow velocities and directions in geologic settings with secondary porosity (MDH, 2011). This guidance describes a modified volumetric analysis and does not use a model based on flow equations. The area that is calculated by this procedure is called a calculated-fixed-radius (CFR) capture zone with an upgradient extension. Appendix B of this report documents the steps and results of the fracture-flow analysis.

The combined output of all model results and the fractured rock procedure were composited to create the final WHPA (Figure 1).

Results of Model Calibration and Sensitivity Analysis

Model calibration is a procedure that compares the results of a model based on estimated input values to measured or known values. This procedure can be used to define model validity over a range of input values, or it helps determine the level of confidence with which model results may be used. As a matter of practice, groundwater flow models are usually calibrated using water elevation and/or flux. The sensitivity analysis quantifies the differences in model results produced by the natural variability of a particular parameter. Uncertainty analysis addresses the effects of poor data quality (lack of local detailed information or deficiencies in the data) on the model results. Together, sensitivity and uncertainty analyses are commonly used to evaluate the effects that natural variability and uncertainties in the hydrogeologic data have on the size and shape of the capture zones. In regards to the WHPA delineation, these analyses are used to document that the delineation is optimal, conservative, and protective of public health based on existing information.

Model Calibration

A qualitative evaluation of the calibration can be made by comparing the simulated potentiometric surface (Figure 2) with observed water level targets obtained from the CWI database. Upon review, the calibrated flow model generally captures the major features of the groundwater flow system along with the elevation, shape, magnitude, and gradient of the CWI database observed flow field.

A quantitative measure by which to evaluate the success obtained during calibration is to compare the root mean square of the residuals (RMSE) and the maximum observed head difference of the calibration dataset. The calibration dataset included water level information from 62 wells located within the city and surrounding township. The residual root mean square (RMS) error of the calibration well set was approximately 4.7 meters with a normalized RMSE of 11 percent. It is noted that this error is less than the calibration target of 15 percent (Anderson et al., 2015). The calibration targets (wells) with the greatest residual difference between measured and simulated heads were generally at locations beyond the contribution area to the city's wells.

There is nothing to calibrate for the fracture flow delineation because it is a calculation of the volume of aquifer that contributes water to the public water supply wells over a 10-year period.

Sensitivity Analysis

Model sensitivity is the amount of change in model results caused by the variation of a particular input parameter. Because of the relative simplicity of the MLAEM and Oneka models, the direction and extent of the modeled capture zone may be sensitive to input parameters. In this particular setting, a rigorous sensitivity exercise isn't necessarily required because of the large-sized capture zones created from the fracture flow delineation compared to the porous media modeling approaches. However, the following briefly addresses model parameters:

- The **pumping rate** directly affects the volume of the aquifer that contributes water to the well. An increase in pumping rate leads to an equivalent increase in the volume of aquifer and an expanded capture zone, proportional to the porosity of the aquifer materials.

  How Addressed and Results – The pumping rate is based on the results presented in Table 5 and, therefore, is not considered a variable factor that will influence the delineation of the WHPA. The modeled pumping rates are based on the measured artesian flow rates of the two wells, as shown in Table 5. The sensitivity of the delineation to this parameter is proportional to the amount of change in pumping volume.

- The **direction of groundwater flow** determines the orientation of the capture zone. Variations in the direction of groundwater flow will not affect the size of the capture zone but are important for defining the areas that are contributing water to the well.

  How Addressed and Results – General flow direction was determined based upon static water levels of similarly screened wells in the area of the model. Overall, the sensitivity of the WHPA to the direction of groundwater flow should not be significant, given the current knowledge of the hydraulic head distribution in the aquifer. However, the direction of groundwater flow computed by the

delineation model can be influenced by changes to other input parameters, such as thickness. For the fracture flow delineation, the groundwater flow direction is input directly into the capture zone calculations.

- The **hydraulic gradient** (along with aquifer hydraulic conductivity) determines the rate at which water moves through the aquifer materials.

  How Addressed and Results – The flow field shown in Figure 2 provides the basis for determining the extent to which each model run reflects the conceptual understanding of the orientation of the capture area for each well. The regional model has been calibrated to hydraulic heads. The sensitivity of the WHPA to the hydraulic gradient should not be significant given the current knowledge of the hydraulic head distribution in the aquifer.

  For the fracture flow delineation, the groundwater flow gradient is input directly into the capture zone calculations and is used to determine whether upgradient extensions are necessary for the capture zones.

- The **hydraulic conductivity** influences the size and shape of the capture zone. A decrease in hydraulic conductivity decreases the length of the capture zone and increases the distance to the stagnation point, making the capture zone more circular in shape and centered on the well.

  How Addressed and Results – For the porous media calculation, initial hydraulic conductivity was calculated from specific capacity and aquifer tests conducted throughout the region. The representative hydraulic conductivity value is relatively low, which is typical of conductivity values estimated from public wells completed in the PMHF Aquifer in neighboring communities. There were no additional MLAEM runs performed with respect to hydraulic conductivity.

  The Oneka modeling approach addresses uncertainty in this parameter by solving for a lognormal distribution of hydraulic conductivity values. In addition to the basecase scenario, the Oneka Model was also run using an initial hydraulic conductivity value that is 100 percent of the representative value. This resulted in capture zones that were of similar size, but slightly elongated compared to the basecase model scenario.

  Hydraulic conductivity is not an input parameter for the fracture flow procedure.

- The **aquifer porosity** influences the size and shape of the capture zone.

  How Addressed and Results – Decreasing the porosity causes a linear, proportional increase in the areal extent of the capture zone. A literature value of 21 percent was used for the porous media delineation and this value was not varied (Norvitch et. al., 1973). For the fracture flow procedure a value of 21 percent was also used as recommended by the MDH Guidance (2011).

- The **aquifer thickness** influences the size and shape of the capture zone.

  How Addressed and Results – Final aquifer thicknesses used in the porous media model were weighted to the aquifer thicknesses estimated from the two city wells. The city wells are relatively deep compared to existing wells in the area, with the exception of the former Land O' Lakes Creamery wells. For the base case MLAEM scenario, an aquifer thickness of 720 feet was used, as estimated from Well #1 (242053). As part of the sensitivity analysis, a second aquifer thickness of 377 feet was used. Well #1 (242053) is considerably deeper compared to Well #2 (219291); for this reason, an alternate thickness similar to the depth of Well #2 was used. The change in aquifer thickness influenced the orientation and size of the resulting Well #2 capture zone compared to the base case scenario. There was an approximate 8 degree shift (so the south) in the capture zone orientation. The resulting capture zone was approximately 80 percent larger than the base case scenario.

  For the fracture flow procedure, MDH guidance requires a maximum aquifer thickness value of 200 feet (61 meters) for the volumetric calculation (MDH, 2011).

Addressing Model Uncertainty

Using computer models to simulate groundwater flow involves representing a complicated natural system in a simplified manner. Local geologic conditions may vary within the capture areas of the public water supply wells, but the amount of existing information needed to accurately define this degree of variability is often not available for portions of the WHPA. In addition, the current capabilities of groundwater flow models may not be sufficient to represent the natural flow system exactly. However, the results are valid within a range defined by the reasonable variation of input parameters for this delineation setting.

The steps employed for this delineation to address model uncertainty were:

1. Pumping Rate – For each well, the natural artesian flow rate was used. The natural flow rates exceed the maximum historical (five-year) pumping rate or an engineering estimate of future pumping (Minnesota Rules, part 4720.5510, subpart 4), and are conservative estimates.
2. Aquifer Thickness – Capture zones for Well #2 (219291) were simulated using an aquifer thickness that was approximately 52 percent of the base case scenario.
3. Probability Analysis – The Oneka Model was used to estimate capture zone probability, including varying hydraulic conductivity from the base case scenario.

Capture areas were developed using the representative hydraulic conductivity and aquifer thickness, as well as an aquifer thickness that resembled the depth of Well #2 (219291), and times of travel of one and of 10 years (Figure 6). Typically, additional uncertainty scenarios are often simulated using a range of input values, however, this was deemed unnecessary for this delineation due to the comparatively large zones resulting from the fracture flow delineation approach. Table 6 documents the variables used to address MLAEM uncertainty.

Table 6 - Model Parameters Used in MLAEM Base Case and Uncertainty Runs

File Name	Well Discharge (cubic meters per day)	Hydraulic Conductivity (meters per day)	Aquifer Thickness (meters)	Local Varel Resistances	Infiltration (meters per day)	Porosity (%)	Other High Capacity Wells
Basecase.dat	W1= 458 W2 = 480	1.53	220	Kettle River = 10 days Local creeks & lakes= 50 days	0.000278 – 0.000417 (= 4 to 6 inches/year)	21	none
SA1.dat	W1= 458 W2 = 480	1.53	115	Kettle River = 10 days Local creeks & lakes= 50 days	0.000278 – 0.000417 (= 4 to 6 inches/year)	21	none

The Oneka Model helps to address uncertainties related to aquifer parameters as variations of the flow field. A 10-year capture zone probability map (Figure 6) was generated for the public water supply wells; the values used for the Oneka Model are shown in Table 7. Two model runs were simulated, where both the representative hydraulic conductivity value and a value that was twice (100%) of the representative value were used for the analysis. The probability map for the public water supply wells shows that uncertainty of the capture zone increases as the distances from the public water supply wells increase.

Table 7 - Ranges of Values Used for the Oneka Model

File Name	Hydraulic Conductivity (meters/day)	Thickness (meters)	Porosity (%)	Remark
Sandstone.one	ln(K)= 0.42 Std Dev = 0.5	b=115 Std Dev = 18	21	base case
Sandstone_uncert.one	ln(K)=1.1 Std Dev = 0.5	b=115 Std Dev =18	21	probability zones are slightly narrower and elongated

Conjunctive Delineation

The area where the city wells are located presents a unique hydrogeologic setting. Even though the Hinckley Sandstone Aquifer has a high geologic sensitivity classification at the location of the wellfield, the city's wells are not considered vulnerable. There are locations in the Sandstone area, especially near the Kettle River, where the bedrock aquifer is relatively shallow. At these locations, there is little to no natural geologic protection afforded the aquifer and it has been assigned a high geologic sensitivity. However, the city wells are artesian flowing wells, meaning that they have a natural upward flow dynamic and are discharging to the land surface. Given the flow dynamic, the likelihood of surface water mixing with the source aquifer is minimal. In addition, tritium testing of the wells indicates that they are being recharged predominantly by older water (Table 2), which suggests little or no contribution of recent surface water to the wells. An assessment of the stable isotope results for a water sample collected from Well #2 (219291), also confirms the lack of surface water contribution to the well water. For these reasons, it was determined that a conjunctive delineation approach is not necessary at this time.

Delineation of the Drinking Water Supply Management Area

The boundaries of the Drinking Water Supply Management Area (DWSMA) were defined by the city of Sandstone using the following features (Figure 1):

- Center-lines of highways, streets, roads, or railroad rights-of-ways.
- Public Land Survey coordinates.
- Property lines.

Vulnerability Assessments

The Part I wellhead protection plan includes the vulnerability assessments for the city of Sandstone's wells and DWSMA. These vulnerability assessments are used to help define potential contamination sources within the DWSMA and select appropriate measures for reducing the risk that they present to the public water supply.

Assessment of Well Vulnerability

The vulnerability assessments for each well used by the city of Sandstone are listed in Table 1 and are based upon the following conditions:

1. It is unknown whether Well #1 (242053) meets current State Well Code specifications (Minnesota Rules, part 4725) due to the lack of complete well construction information. The construction of Well #2 (219291) appears to be consistent with current well code specification.
2. The geologic conditions at the wellfield lack natural protective materials over the aquifer, such as clay-rich till. However, the unique hydrogeologic setting affords a degree of natural protection because the city wells are flowing artesian wells.
3. None of the human-caused contaminants regulated under the federal Safe Drinking Water Act have been detected at levels indicating that the well itself serves to draw contaminants into the aquifer as a result of pumping.
4. Water samples were collected from the wells on July 30, 2013, and were analyzed for tritium, nitrate, chloride and bromide (Table 2). Tritium was not detected in the well samples, confirming the non-vulnerable nature of the wells (Alexander and Alexander, 1989). In addition, the low nitrate, chloride, and chloride/bromide results also confirm the non-vulnerable nature of the city's wells (Mullaney et al., 2009).

Assessment of Drinking Water Supply Management Area Vulnerability

The vulnerability of the DWSMA is shown in Figure 7A and is based upon the following information:

1. Isotopic and water chemistry data from wells located within the DWSMA indicate that the aquifer contains water that has no detectable levels of tritium or human-caused contamination, with the possible exception of the very low levels of nitrate detected at the city wells.
2. Review of the geologic logs contained in the CWI database, geological maps, and reports indicate that the aquifer exhibits a high geologic sensitivity at the location of the wellfield, with some potential sinkholes mapped in and around the ERA for Well #1 (242053) [Figure 7B]. However, the unique hydrogeologic setting affords a degree of natural protection because the city wells are naturally flowing.

Therefore, given the information currently available, it is prudent to assign a moderate vulnerability rating to the DWSMA, in accordance with the Minnesota Wellhead Protection Rule (parts 4720.5100 to 4720.5590).

Recommendations

The following recommendations have been generated to inform the next amendment of the city of Sandstone's Wellhead Protection Plan.

1. Well Locating: This delineation is based on very little well data. If wells are constructed within one mile of the DWSMA, their locations should be verified. This information may allow a better understanding of the extent and thickness of the city's aquifer, and could result in a more refined WHPA in the future.

2. The city wells were constructed prior to the promulgation of the state's Well Code; as a result, the wells are not currently in conformance with requirements regarding well construction near water bodies. Current rules specify that grading around a community water supply well should be established to ensure that floodwaters do not reach within 50 feet of the well. In addition, current rules specify that casings should be extended to at least two feet above the ground surface.

    a. It is noted that the MDH district engineer has recommended improved grading in the sanitary survey reports, citing an event in 2012 when flood waters came within 20 to 30 feet of each well. As part of wellhead planning, the team should include a measure in their plan to explore whether there are practical steps, such as grading, that the city can take to protect the wells from potential flooding in the future. Pending available funding and resources, the measure(s) identified could be implemented during the course of the current wellhead plan, or perhaps included in the plan amendment in ten years.

    b. With respect to extending the casing of Well #1 (242053) above grade, it is recommended that the wellhead team meet or confer with a field representative from MDH's Well Management Section regarding this issue. It is recognized that extending the casing above grade may be problematic given the age of the well and existing artesian flow conditions. It is important that an assessment of the integrity of the existing casing and well materials is made before attempts to re-construct the well. It is also recognized that sanitary impacts to the well from flooding may be less likely if grading is improved (item 2a), and because the well is under artesian flow conditions. For these reasons, it may be determined that it is impractical to bring existing well construction into conformance with current well rules.

c. Well #1 (242053) is more than 100 years old, and Well #2 (219291) is 50 years old. Given the age of the wells, the city should consider including a measure in their plan regarding new well planning in the event that a well fails. Pending available funding and resources, the city may want to work with an engineering consultant, drill test holes, perform aquifer testing and/or conduct monitoring in order to find a suitable location for a replacement well.

3. Water Quality Monitoring: The standard assessment monitoring package should be analyzed during year six, including the primary wells and river, contingent on funding assistance from MDH for sampling and analysis. The city may need to collect the samples and ship them to MDH. Information generated by this sampling will be used to refine vulnerability assessments for the next amendment.

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Minnesota Department of Health (2011), *Guidance for delineating wellhead protection areas in fractured and solution-weathered bedrock in Minnesota*, St. Paul, Minn., 81 p.

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Norvitch, R.F., Ross, T.G., and Briekrietz, A. (1973), *Water resources outlook for the Minneapolis-Saint Paul Metropolitan Area, Minnesota*, U.S. Geological Survey, Open-File Report, 73-203, St. Paul, Minn., 219 p.

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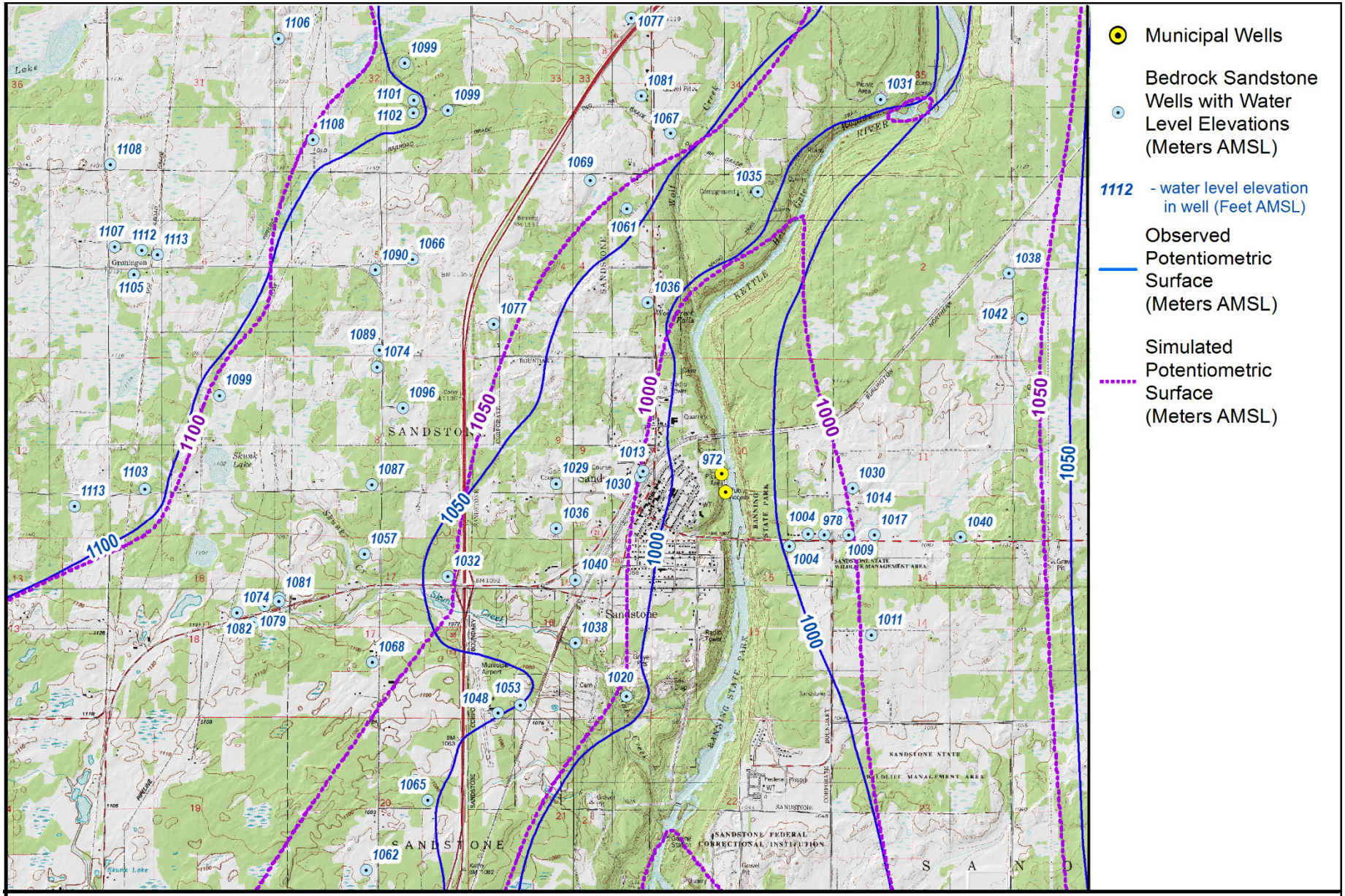
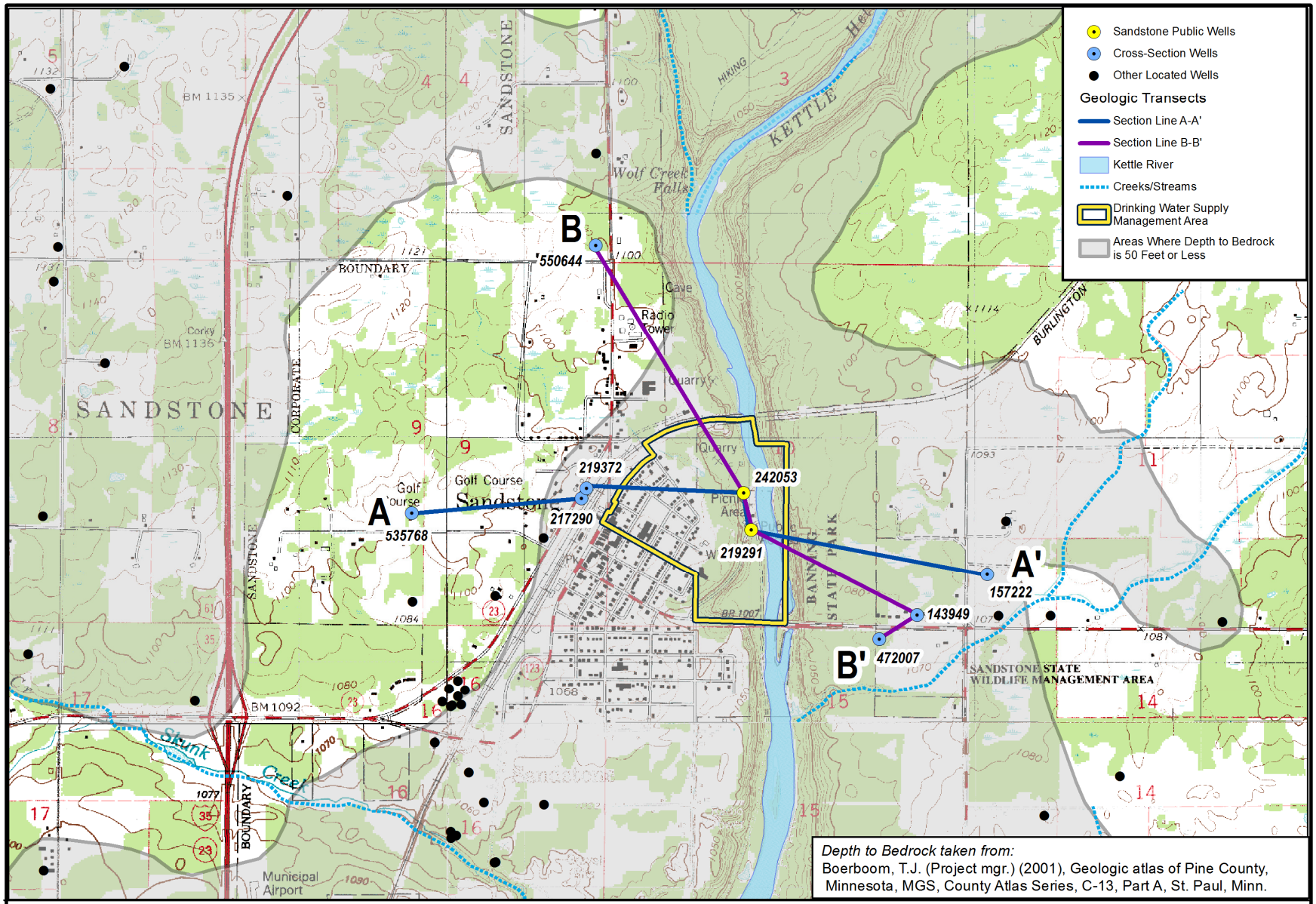
Figures


Municipal Wells
Bedrock Sandstone Wells with Water Level Elevations (Meters AMSL)
1112 - water level elevation in well (Feet AMSL)
Observed Potentiometric Surface (Meters AMSL)
Simulated Potentiometric Surface (Meters AMSL)
1100
1050
1000
1050
SANDSTONE
Sandstone
Groningen
Skunk Lake
KETTLE RIVER
BANNING STATE PARK
SANDSTONE FEDERAL CORRECTIONAL INSTITUTION
SANDSTONE STATE WILDLIFE MANAGEMENT AREA
Municipal Airport
Picnic Area
Campground
Quarry
Gravel Pit
Cemetery
Radio Tower
Golf Course
Lake
Stunk Creek
Wolf Creek
Kettle River
Sand
Sandstone
Groningen
Skunk Lake
Sandstone State Wildlife Management Area
Sandstone Federal Correctional Institution
Banning State Park



Depth to Bedrock taken from:
Boerboom, T.J. (Project mgr.) (2001), Geologic atlas of Pine County, Minnesota, MGS, County Atlas Series, C-13, Part A, St. Paul, Minn.

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N

0 2,000 4,000 Feet

Figure 3
Database Map and Cross-Section Transects
City of Sandstone

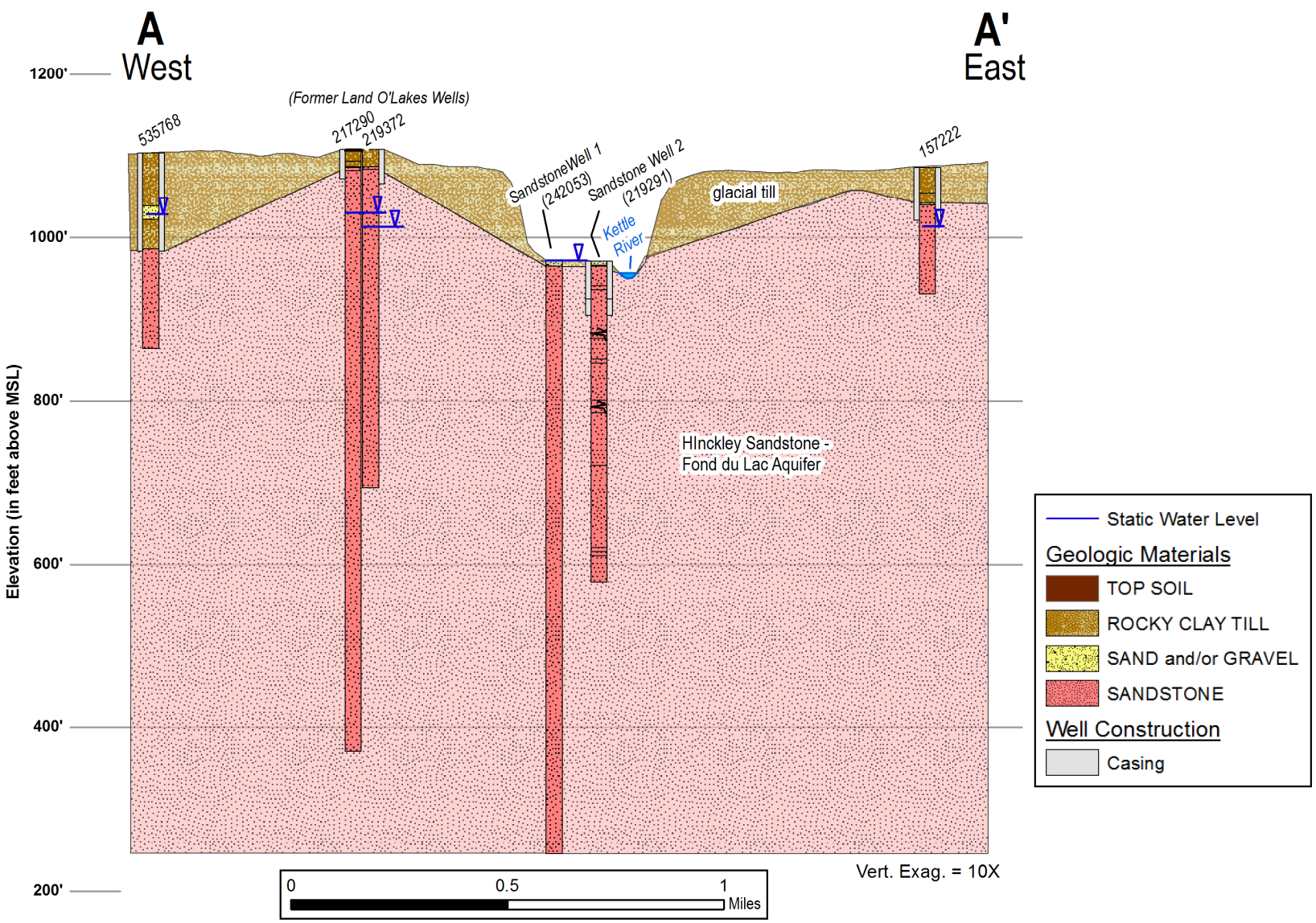

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Figure 4
Geologic Cross-Section A-A'
City of Sandstone

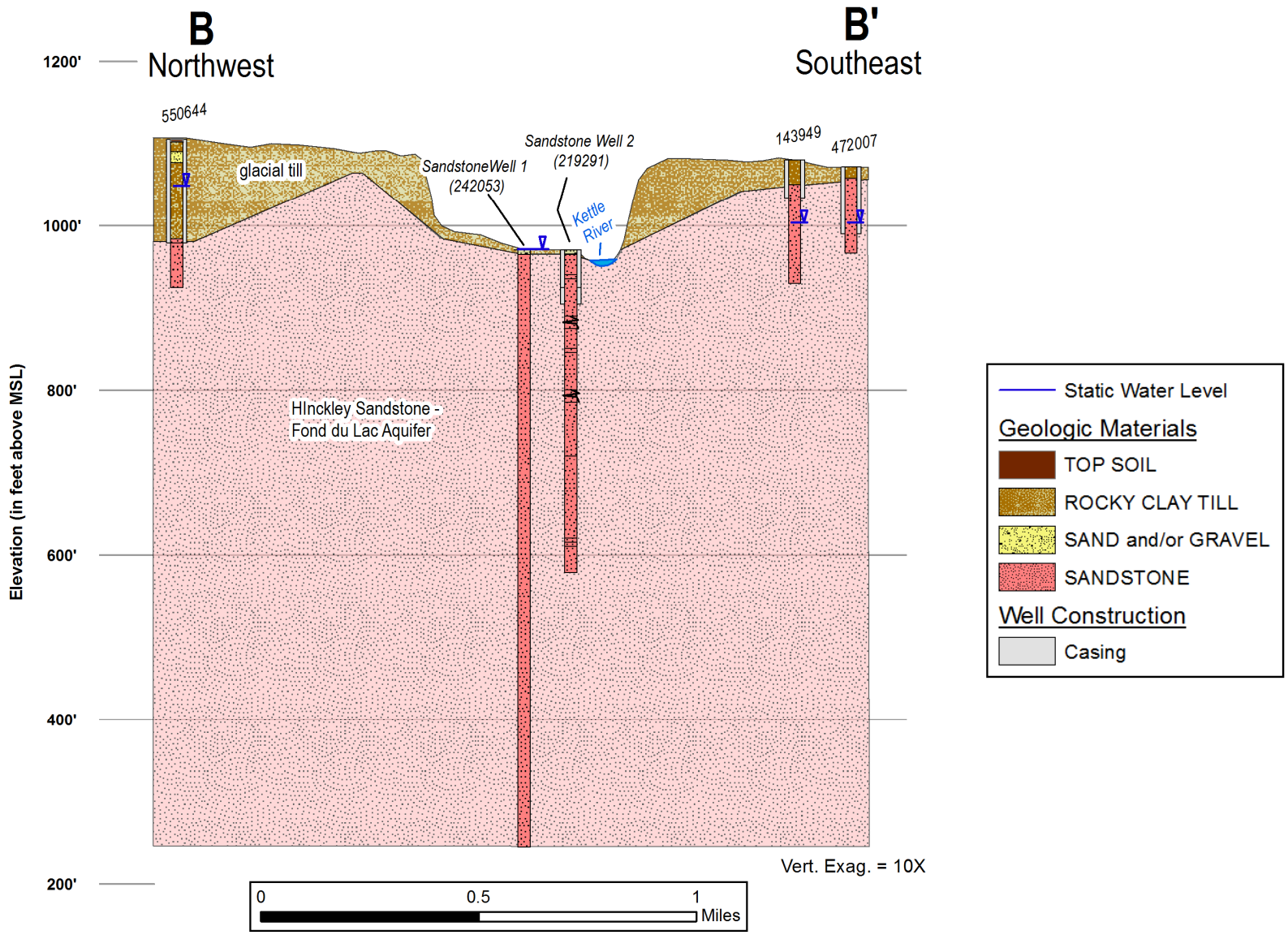

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Figure 5
Geologic Cross-Section B-B'
City of Sandstone

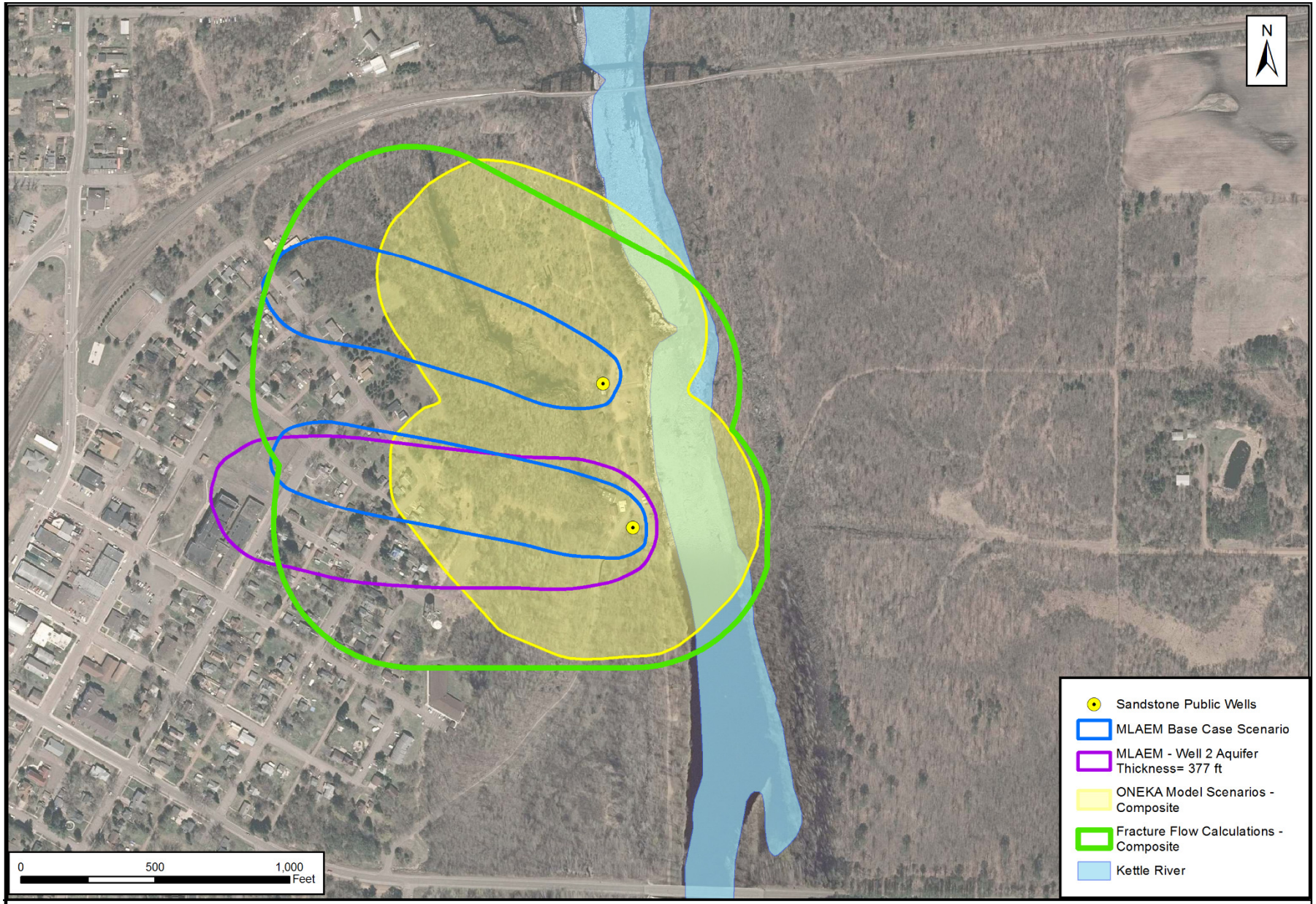

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Figure 6
Uncertainty Analysis: 10-Year Capture Zones
City of Sandstone

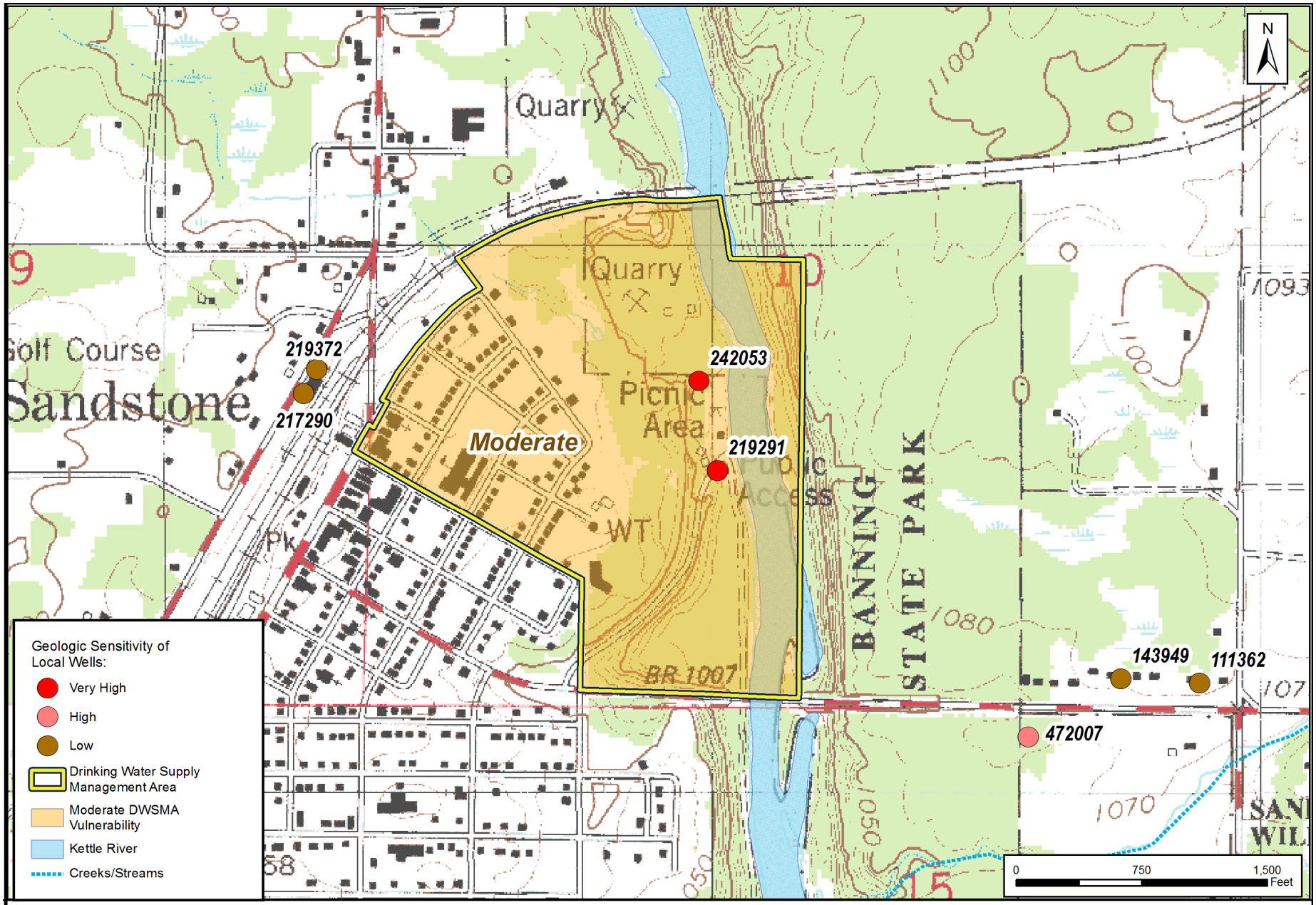

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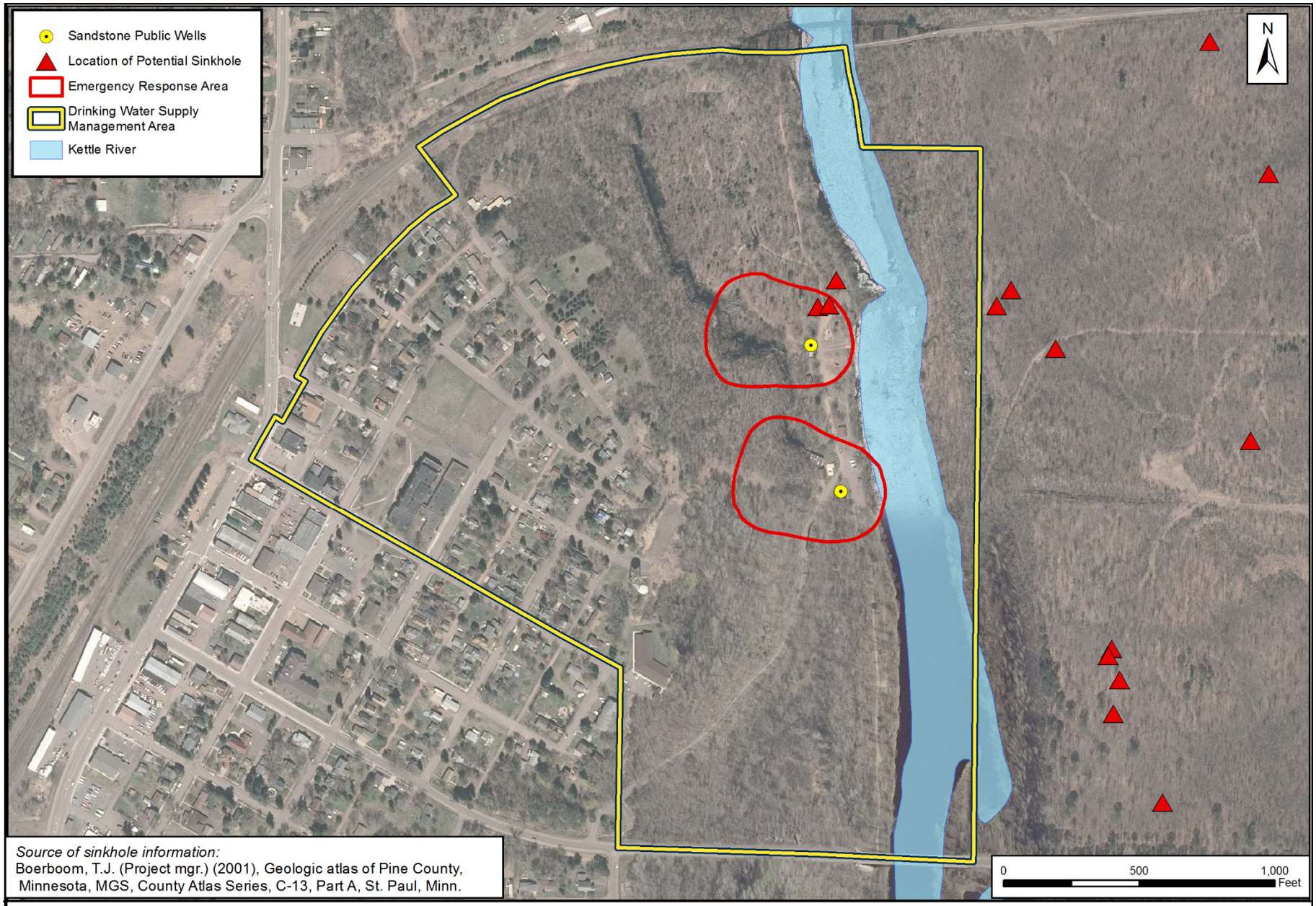
Figure 7A
Drinking Water Supply Management Area Vulnerability
City of Sandstone



Source of sinkhole information:
Boerboom, T.J. (Project mgr.) (2001), Geologic atlas of Pine County, Minnesota, MGS, County Atlas Series, C-13, Part A, St. Paul, Minn.

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Figure 7B
Locations of Mapped Sinkholes
City of Sandstone

Appendix A: Data Elements Assessment

Data Type	Data Element	Use of the Well(s)	Delineation Criteria	Quality and Quantity of Well Water	Land and Groundwater Use in DWSMA	Data Source
Climate	Precipitation	M	M	M	M	USGS
Geology	Maps and geologic descriptions	M	H	H	H	Boerboom (2001), Berg (2004), USGS
Geology	Subsurface data	M	H	H	H	Boerboom (2001), Berg (2004), USGS
Geology	Borehole geophysics	M	H	H	H	MGS
Geology	Surface geophysics	L	L	L	L	No relevant data found.
Soils	Maps and soil descriptions					
Soils	Eroding lands					
Water Resources	Watershed units	L	H	L	L	DNR, National Hydrography Dataset (USGS)
Water Resources	List of public waters					
Water Resources	Shoreland classifications					
Water Resources	Wetlands map					
Water Resources	Floodplain map					
Land Use	Parcel boundaries map	L	H	L	L	Pine County
Land Use	Political boundaries map	L	H	L	L	MnGEO, City
Land Use	Public Land Survey map	L	H	L	L	MnGEO
Land Use	Land use map and inventory					
Land Use	Comprehensive land use map					
Land Use	Zoning map					
Public Utility Services	Transportation routes and corridors	L	L	L	L	MnDOT, MnGEO
Public Utility Services	Storm/sanitary sewers and PWS system map					
Public Utility Services	Oil and gas pipelines map					
Public Utility Services	Public drainage systems map or list					
Public Utility Services	Records of well construction, maintenance, and use	H	H	H	H	City, CWI, MDH
Surface Water Quantity	Stream flow data					
Surface Water Quantity	Ordinary high water mark data					

Data Type	Data Element	Use of the Well(s)	Delineation Criteria	Quality and Quantity of Well Water	Land and Groundwater Use in DWSMA	Data Source
Surface Water Quantity	Permitted withdrawals					
Surface Water Quantity	Protected levels/flows					
Surface Water Quantity	Water use conflicts					
Groundwater Quantity	Permitted withdrawals	H	H	H	H	DNR
Groundwater Quantity	Groundwater use conflicts	H	H	H	H	DNR
Groundwater Quantity	Water Levels	H	H	H	H	DNR
Surface Water Quality	Stream and lake water quality management classifications					
Surface Water Quality	Monitoring data summary					
Groundwater Quality	Monitoring data	H	H	H	H	MPCA, MDH, MDA,
Groundwater Quality	Isotopic data	H	H	H	H	MDH, DNR
Groundwater Quality	Tracer studies	H	H	H	H	No relevant data found.
Groundwater Quality	Contamination site data	M	M	M	M	MPCA, MDA (no relevant data found in DWSMA).
Groundwater Quality	Property audit data from contamination sites					
Groundwater Quality	MPCA and MDA spills/release reports	M	M	M	M	MPCA, MDA (no relevant data found in DWSMA).

Definitions Used for Assessing Data Elements

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

Acronyms used in this report are listed after the Glossary of Terms.

Appendix B: Fracture Flow Delineation

Upgradient Extension Needs Assessment

The procedure for fracture flow analysis is outlined in the MDH Fracture Flow Guidance (2011).

The need for upgradient extensions to the capture zones was assessed by calculating the discharge to discharge vector ratio for the aquifer using the following equation:

$$Ratio = \frac{Q}{T * i}$$

Table B1 – Well discharge to discharge vector calculation

Equation Symbol	Parameter	Value
T	Transmissivity (m^2/day)	176
i	Gradient (i)	0.0178
Q	Well Discharge (m^3/day)	480
Ratio	Ratio of the discharge to the discharge vector	153

The ratio is less than 3000, therefore additions of upgradient extensions to the capture zones are necessary. The calculated fixed radius capture zones were calculated with a five year time of travel.

Calculated Fixed Radius Capture Zone Calculations

The calculated fixed radius (CFR) capture zones were calculated using the following equation:

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

The radii calculations are shown in the tables below.

Table B2 -- Well #1 (242053) CFR Calculation Values

Equation Symbol	Parameter	Value
Q	Well Discharge (cubic meters per day)	457.89
t	Time (in years, as calculated above)	5
L	Aquifer Thickness (meters)	60.96
n	Aquifer Effective Porosity (proportion or percentage)	0.21
π	Pi	3.14159
R	Well 1 CFR Radius (meters)	144

Rule requires the use of a maximum of 200 feet (60.96 meters) of aquifer thickness for this calculation.

Table B3 -- Well #2 (219291) CFR Calculation Values

Equation Symbol	Parameter	Value
Q	Well Discharge (cubic meters per day)	479.69
t	Time (in years, as calculated above)	5
L	Aquifer Thickness (meters)	60.96
n	Aquifer Effective Porosity (proportion or percentage)	0.21

Equation Symbol	Parameter	Value
π	Pi	3.14159
R	Well 2 CFR Radius (meters)	148

Rule requires the use of a maximum of 200 feet (60.96 meters) of aquifer thickness for this calculation.

Overlapping Capture Zone Analysis

It was determined that the five-year CFR capture zones for Wells 1 and 2 (242053 and 219291) overlapped due to the close proximity of the wells and the estimated discharge volumes. For each scenario, +/- 10 degrees were added to both sides of the flow angle. The overlap was accounted for in the final fracture flow calculations:

<u>Scenario 1</u> – fracture flow base case (ambient flow angle estimated = 288 degrees).

Unique Well# = 242053
Sandstone #1
X = 510,960.732, Y = 5,108,958.171

5 Year Pumping Volume (1825 days)

Pumping Volume (Q):	457.883	m3/day	16,170.000		cu.ft./day	84.000	gal./min.	120,960.000	gal./day
Water Producing Zone Thickness (L):	60.960	m		200.000	ft.				
Effective Porosity (n):	0.21								
Original (CFR) Radius:	144.146	m	472.919	ft.					
New Radius:	154.989	m	508.495	ft.					
New Pumping Volume (Q): *	529.363	m3/day	18,694.282		cu.ft./day	97.113	gal./min.	139,842.946	gal./day

Unique Well# = 219291
Sandstone #2
X = 510,994.301, Y = 5,108,794.357

5 Year Pumping Volume (1825 days)

Pumping Volume (Q):	479.687	m3/day	16,940.000		cu.ft./day	88.000	gal./min.	126,720.000	gal./day
Water Producing Zone Thickness (L):	60.960	m		200.000	ft.				
Effective Porosity (n):	0.21								
Original (CFR) Radius:	147.538	m	484.048	ft.					
New Radius:	158.636	m	520.461	ft.					
New Pumping Volume (Q): *	554.571	m3/day	19,584.486		cu.ft./day	101.738	gal./min.	146,502.133	gal./day

OVERLAP SUMMARY INFORMATION

Original (CFR) Area for Well# 242053:	65,276.001	m2	702,624.347	sq.ft.
New (CFR) Area for Well# 242053:	75,466.173	m2	812,310.335	sq.ft.
Original (CFR) Area for Well# 219291:	68,384.382	m2	736,082.649	sq.ft.
New (CFR) Area for Well# 219291:	79,059.800	m2	850,991.779	sq.ft.

Overlap Area to Well# 242053:	10,190.172	m2	109,685.988	sq.ft.
Overlap Area to Well# 219291:	10,675.418	m2	114,909.131	sq.ft.
Total Overlap Area:	20,865.590	m2	224,595.119	sq.ft.

* = New Pumping Volumes (Q) if needed for additional overlap computations with another well.

UP-GRADIENT EXTENSION (UGE)
(area beyond the New Areas of both Wells)
(area beyond the New Areas of both Wells)
Bearing from Well# 242053 = 288° from North +/- 10°.
Bearing from Well# 219291 = 288° from North +/- 10°.

Up-Gradient Extension Area:	111,923.297	m2	1,204,731.174	sq.ft.
Up-Gradient Intersection Area:	23,414.704	m2	252,033.535	sq.ft.

<u>Scenario 2</u> – Ambient flow angle = 280 degrees, estimated from MLAEM results when aquifer thickness = 377 ft (similar to Well 2 depth).

Unique Well# = 242053
SANDSTONE 1
X = 510,960.732, Y = 5,108,958.171

5 Year Pumping Volume (1825 days)

Pumping Volume (Q):	457.883	m3/day	16,170.000	cu.ft./day	84.000	gal./min.	120,960.000	gal./day
Water Producing Zone Thickness (L):	60.960	m	200.000	ft.				
Effective Porosity (n):	0.21							
Original (CFR) Radius:	144.146	m	472.919	ft.				
New Radius:	154.989	m	508.495	ft.				
New Pumping Volume (Q): *	529.363	m3/day	18,694.282	cu.ft./day	97.113	gal./min.	139,842.946	gal./day

Unique Well# = 219291
SANDSTONE 2
X = 510,994.301, Y = 5,108,794.357

5 Year Pumping Volume (1825 days)

Pumping Volume (Q):	479.687	m3/day	16,940.000	cu.ft./day	88.000	gal./min.	126,720.000	gal./day
Water Producing Zone Thickness (L):	60.960	m	200.000	ft.				
Effective Porosity (n):	0.21							
Original (CFR) Radius:	147.538	m	484.048	ft.				
New Radius:	158.636	m	520.461	ft.				
New Pumping Volume (Q): *	554.571	m3/day	19,584.486	cu.ft./day	101.738	gal./min.	146,502.133	gal./day

OVERLAP SUMMARY INFORMATION

Original (CFR) Area for Well# 242053:	65,276.001	m2	702,624.347	sq.ft.
New (CFR) Area for Well# 242053:	75,466.173	m2	812,310.335	sq.ft.
Original (CFR) Area for Well# 219291:	68,384.382	m2	736,082.649	sq.ft.
New (CFR) Area for Well# 219291:	79,059.800	m2	850,991.779	sq.ft.
Overlap Area to Well# 242053:	10,190.172	m2	109,685.988	sq.ft.
Overlap Area to Well# 219291:	10,675.418	m2	114,909.131	sq.ft.
Total Overlap Area:	20,865.590	m2	224,595.119	sq.ft.

* = New Pumping Volumes (Q) if needed for additional overlap computations with another well.

UP-GRADIENT EXTENSION (UGE)
(area beyond the New Areas of both Wells)
(area beyond the New Areas of both Wells)
Bearing from Well# 242053 = 280° from North +/- 10°.

Bearing from Well# 219291 = 280° from North +/- 10°.

Up-Gradient Extension Area:	113,718.269	m2	1,224,052.075	sq.ft.
Up-Gradient Intersection Area:	24,398.172	m2	262,619.484	sq.ft.

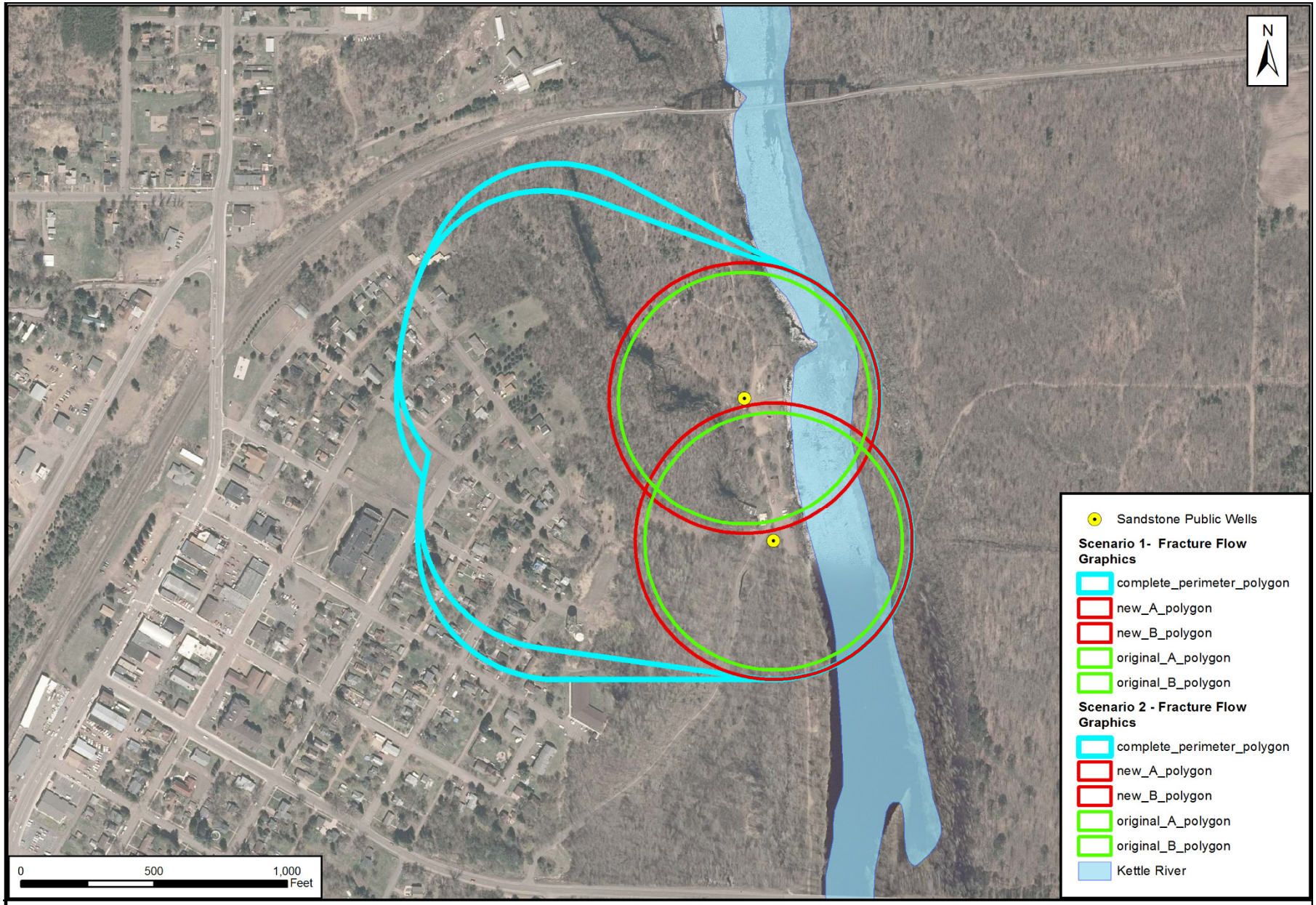

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Figure B-1
Fracture Flow Calculations Accounting for Overlap
City of Sandstone

Lineament Analysis Needs Assessment and Results

It was determined that a lineament analysis was not needed for this fracture flow delineation. The city wells are artesian flowing wells, meaning that they have an upward flow dynamic and are discharging to the land surface. Tritium testing of the wells indicates they are being recharged by older water (Table 2). With respect to the need for a lineament analysis, the lack of tritium means that there is little or no contribution of recent surface water to the wells. In addition, an assessment of the stable isotope results for a water sample collected from Well #2 (219291) also confirms the lack of an evaporative signature or surface water contribution. Accordingly, other vulnerability chemistry results, such as total chloride and the chloride/bromide ratio, confirm the non-vulnerable nature of the wells. For these reasons, it was determined that a lineament analysis approach is not necessary at this time.

Appendix C: Vulnerability Suite Chemistry Results

The city of Sandstone's primary wells are considered non-vulnerable to contamination primarily because tritium testing of the wells indicates that they are being primarily recharged by older water (Table C-10). Tritium tests allow us to age-date water and determine if the water is older or younger than the 1950's. The lack of tritium in the well water suggests that the source water is relatively old, and subsequently less vulnerable to more recent activities occurring at the land surface that can potentially impact the aquifer. In addition, an assessment of the stable isotope results for a water sample collected from Well #2 (219291) also confirms the lack of an evaporative signature. The low chloride levels and chloride/bromide ratios also confirm the non-vulnerable nature of the city's wells.

Table C-1 – Vulnerability Suite Chemistry Results

Sample Results from 7/30/2013 *(unless otherwise noted)*

Sampling Point	Tritium (TU)	Delta 180 (per mil)	Delta 2H (per mil)	Nitrate (mg/L)	Ammonia Nitrogen (mg/L)	Chloride (mg/L)	Bromide (mg/L)	Cl/Br	Sulfate (mg/L)	TOC (mg/L)	Arsenic (ug/l)
Well #1 (242053)	< 0.8	*not sampled*	*not sampled*	0.110 ---------- 0.08 *8/18/2014*	0.06 ---------- < 0.05 *4/17/2013*	0.736 ---------- 1.04 *4/17/13*	0.0114 ---------- 0.0106 *4/17/13*	65 ---------- 98 *4/17/13*	< 1.00 ---------- 1.02 *4/17/13*	< 1.0 ---------- < 1.0 *4/17/13*	< 1.0 *4/17/2013*
Well #2 (219291)	< 0.8	-9.6	-67.9	0.16 ---------- 0.16 *8/18/2014*	< 0.05 ---------- < 0.05 *4/17/2013*	0.723 ---------- 0.84 *4/17/13*	0.0066 ---------- 0.0118 *4/17/13*	110 ---------- 71 *4/17/13*	1.31 ---------- 1.33 *4/17/13*	1.9 ---------- < 1.0 *4/17/13*	< 1.0 *4/17/2013*