DEPARTMENT OF NATURAL RESOURCES

Cold Spring Groundwater Study

Model Report

2/4/2021

Ecological and Water Resources Division

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Executive summary

Multiple field investigations and groundwater models have shown that Cold Spring Creek is impacted by groundwater use in the area of Cold Spring, Minnesota. In 2016, the Minnesota State Legislature directed the Minnesota Department of Natural Resources (DNR) to "*conduct necessary monitoring of stream flow and water levels and develop a groundwater model to determine the amount of water that can be sustainably pumped in the area of Cold Spring Creek for area businesses, agriculture, and city needs*." This report describes the groundwater model that DNR constructed and the results of predictive simulations conducted with the model.

Minnesota Statute 103G.287 Subd. 5 defines sustainability as: protecting the ability of future generations to meet their needs, not harming ecosystems, not degrading water, and not reducing water levels beyond the reach of public and domestic supply. In the 2016 DNR Report to the Legislature, it was found that a 20 percent change in hydrologic regime (relative to the August median base flow) will negatively affect the ecosystem, while a change less than 10 percent is not likely to be detectable (Minnesota Department of Natural Resources, 2016).

Starting in the 1980s, multiple agencies including the DNR and United States Geological Survey (USGS) collected streamflow and water level data and built groundwater models of the Cold Spring area. During 2016 the DNR compiled available data, and during 2017 the DNR initiated more intensive field monitoring in the Cold Spring area and began to construct a groundwater flow model. The groundwater model was completed in 2018 and refined in 2019.

The model is a tool designed to inform permitting decisions. The purpose of the model is to characterize groundwater flow and calculate how pumping affects base flow in Cold Spring Creek. Two types of numerical models could be used for this calculation: a steady-state model or a transient model. Steady-state models predict how the groundwater system affects the stream on average over the long term, that is, over many years. Transient models are capable of predicting the effects of short-term changes, that is, over weeks or months. However, transient models require more streamflow and water-level data than steady-state models. The available data was sufficient to build a steady-state model. In addition, the field data that the DNR started collecting in 2017 (that we will continue to collect at least through 2020) would eventually allow us to build a transient model, if needed.

The DNR developed the steady-state groundwater model using all available data: streamflow, lake levels, groundwater levels, geologic information, and aquifer test results. The model includes key information about the hydrologic system so that it can calculate how changing one component affects the other components. The model was built for the purpose of calculating how pumping affects base flow in Cold Spring Creek. Therefore the goal of model calibration was to reasonably match historic groundwater levels, groundwater flow patterns near Cold Spring Creek, and base flow in Cold Spring Creek. Once calibration was complete, the model was used to calculate the average rate of base flow depletion for different groundwater use scenarios. The model does not calculate median base flow or base flow values on a monthly basis.

The DNR used the calibrated steady-state model to conduct 18 groundwater-use simulations. The scenarios were chosen to illustrate how current pumping affects base flow in Cold Spring Creek and how pumping from different distances affects base flow in Cold Spring Creek. The scenarios were not chosen to be prescriptive;

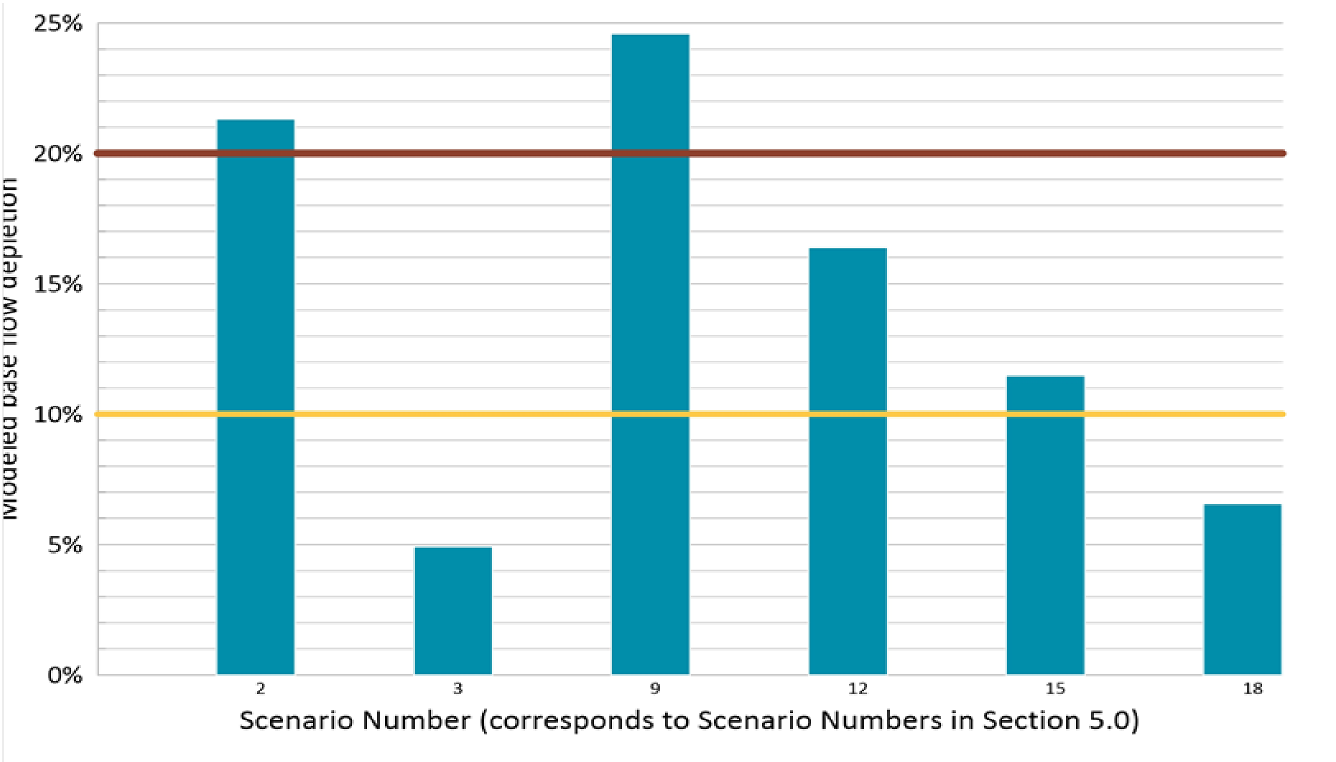
rather they were chosen to provide useful information to inform permitting decisions. The results of six simulations are especially illustrative, as shown on Figure ES-1.

These six scenarios illustrate the effect of pumping different volume and locations and show that:

- Groundwater pumping at 2018 use rates depletes base flow by approximately 20 percent (Scenario 2);
- Pumping from within ¼ mile of the creek is responsible for much of the current base flow depletion (Scenario 3);
- If all wells pumped their maximum permitted volumes, it would cause approximately 25 percent base flow depletion (Scenario 9); and
- Pumping some water from the Lot 1/Block 1 site causes less base flow depletion than pumping only from the City's existing well field (Scenarios 12, 15, and 18).

The steady-state model simulates average conditions over many years and does not calculate base flow depletion specifically in August. In Minnesota base flow tends to be lowest in August, which is when groundwater use tends to be high. It is likely that a transient model would calculate a higher rate of base flow depletion than the steady-state model described in this report. The DNR, with input from the Technical Advisory Group, will evaluate whether a transient model would add sufficient value to justify the time and expense. However, field data collection will continue at least through 2020, in case a transient model is needed in the future.

Figure ES-1 Calculated base flow depletion in Cold Spring Creek at the upstream reach



Summary description of scenarios:

Scenario 2 (2018): All wells were pumped at 2018 pumping rates, averaged over the year.

Scenario 3 (1/4 mile): All wells within ¼ mile of Cold Spring Creek were turned off and the rest of the wells in the model domain were pumped at 2018 rates.

Scenario 9 (Permitted): All wells within the model domain pump maximum permitted volume, averaged over the year.

Scenario 12 (Permitted, ¼ mile, 20 millions of gallons per year (mgy), the City's well field, +103 mgy): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek and supply an additional 103 mg (505 mgy minus 20 mgy plus 103 mgy).

Scenario 15 (Permitted, ¼ mile, 20 mgy, +103mgy, 300 mgy Lot 1/Block 1): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek minus 197 mgy. The Lot 1/Block 1 site supplies the 197 mgy from the City's wells and an additional 103 mgy from test well (unique number 00812233).

Scenario 18 (Permitted, ¼ mile, 20 mgy, +103mgy, all Lot 1/Block 1): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and the Lot 1/Block 1 site supplies the remaining demand and an additional 103 mgy from test well (unique number 00812233).

1.0 Introduction

The glacial aquifer system in the vicinity of Cold Spring, Minnesota is the main source of water in the area. The glacial aquifer supplies the city of Cold Spring (the City), Cold Spring Brewing Company (CSBC), and numerous private and irrigation supply wells and is strongly connected to Cold Spring Creek. Groundwater use in the area of Cold Spring impacts flow in Cold Spring Creek. The many field investigations and modeling conducted by the Minnesota DNR and USGS documenting the impact are described in Appendix A (Minnesota Department of Natural Resources, 2017). The purpose of the groundwater model described in this report is to characterize groundwater flow and calculate how groundwater pumping affects base flow in Cold Spring Creek.

1.1 Policy background

The DNR was directed by the Minnesota State Legislature (Minnesota State Legislature, 2016) to "conduct necessary monitoring of stream flow and water levels and develop a groundwater model to determine the amount of water that can be sustainably pumped in the area of Cold Spring Creek for area businesses, agriculture, and city needs." Minnesota state statute 103G.287 defines sustainable groundwater use as follows:

- Able to supply the needs of future generations
- Does not harm ecosystems
- Does not degrade water
- Does not reduce water levels beyond the reach of public or domestic supply

Cold Spring Creek is a designated trout stream protected by Minnesota Statute 103G.285. Negative impacts to surface waters, including trout streams, are defined in the *Report to the Minnesota State Legislature: definitions and thresholds for negative impacts to surface waters* (Minnesota Department of Natural Resources, 2016).

In the 2016 DNR Report to the Legislature, it was found that a 20 percent change in hydrologic regime (relative to the August median base flow) will negatively affect the ecosystem, while a change less than 10 percent is not likely to be detectable. In general, diversions of greater than 20 percent will negatively affect biological systems, while change less than 10 percent in base flow is not likely to be detectable in biological systems (Minnesota Department of Natural Resources, 2016).

1.2 Technical background

In 2001, the USGS created a groundwater model as part of the wellhead protection planning process, primarily to determine the contribution area to the City's high-capacity wells and to understand the interaction between the Sauk River valley aquifer, the Sauk River, and Cold Spring Creek. The USGS model was built for a different purpose than the DNR's model needs, therefore DNR chose to build a new groundwater model rather than attempting to modify the USGS model.

The DNR first compiled and used existing data to determine how groundwater flows through the aquifer system and is connected to the surface-water system. The DNR then used the data to develop the steady-state numerical groundwater model. The model simulates groundwater flow and calculates, on average, how much base flow depletion in Cold Spring Creek is caused by groundwater pumping. The model does not calculate median base flow or base flow values on a monthly basis, because it is a steady-state model.

As the DNR compiled data, data gaps were identified that would need to be filled to build a transient numerical model, if needed. A transient model could calculate the depletion in Cold Spring Creek on a smaller time step for example, monthly).

1.2.1 Site description

The study area covers about 134 square miles in central Minnesota in southeastern Stearns County (Figure 1). The City is located in the center of the study area; the area of interest is a smaller area within the study area, with Cold Spring Creek near its center. The area of interest is where the model is designed to calculate the cumulative impacts on Cold Spring Creek. There are many water needs in and around Cold Spring Creek including municipal supply, commercial, industrial, agricultural, and ecological.

The topography in the study area is rolling in the upland area, steep around streams, and generally flat along the Sauk River valley. Steep bluffs dip down to the Sauk River valley about 1 mile northeast of the downtown area of Cold Spring and along the southeast side of the Sauk River.

The Sauk and the South Fork of the Watab rivers drain the study area (Figure 2). The Sauk River drains the majority and flows generally east-northeast to the confluence with the Mississippi River about 8 miles northeast (Figure 2 inset). The Watab River drains a small portion of the northern part of the study area to its confluence with the Mississippi River about 12 miles northeast.

The annual average precipitation in the study area is 27.7 inches (Sauk River Watershed District, 2014).Previous studies suggest an average range of 4.4 to 9.0 inches of precipitation recharges the surficial aquifers (Smith, 2015) and 4.5 inches leaves the basin as runoff (Baker & Kuehnast, 1978). In addition, 15 to 20 percent of crop irrigated water returns to the surficial aquifer as recharge, and the rest leaves the basin as evapotranspiration (Lindholm, 1980).

1.2.2 History of groundwater appropriation around Cold Spring Creek

Cold Spring Creek is a trout stream that runs through the city of Cold Spring adjacent to municipal and brewery water supply wells. Groundwater appropriation in the Cold Spring area started in 1952. The City of Cold Spring has been using groundwater since at least 1966; the City applied for a groundwater appropriation permit in 1975. The connection between groundwater and the creek was demonstrated in 1980 when Cold Spring Creek temporarily dried up during temporary construction dewatering by the City. The DNR recommended monitoring to characterize the groundwater-creek interaction. In 1984 and 1988, Cold Spring Brewery installed three production wells near Cold Spring Creek. Since their original wells were drilled, the City of Cold Spring and Cold Spring Brewery's water needs have now grown to a projected combined water use of 605 mgy.

In 2016 the DNR granted increased temporary appropriation permits through the end of 2021 for CSBC and the City. The intention of the temporary permits was to ensure CSBC and the City had the water they needed while giving them time to identify and develop new, sustainable water sources for the expansion of the city and businesses. The presence of nitrate in some of the City's wells has made the search for new water sources more complex. A full timeline of the study area history relevant to water appropriation is found in Appendix A.

1.2.3 Contributors

The DNR would like to thank the City and Cold Spring Brewing Company for their commitment to working with the DNR to help protect valuable water features and helping to ensure an adequate water supply for future generations. The DNR would also like to thank the following members of the Technical Advisory Committee for their assistance:

- Dr. Bob Tipping, previously Minnesota Geological Survey - University of Minnesota, now Minnesota Department of Health
- Mr. Jeppe Kjaersgaard - Minnesota Department of Agriculture
- Mr. John Woodside - Minnesota Department of Health
- Mr. Larry Kramka - Foth Engineering (representing Cold Spring Brewing Company)
- Mr. Mark Janovec - Stantec (representing City of Cold Spring)
- Mr. Mike MacDonald - Minnesota Department of Agriculture
- Mr. Richard Soule - Minnesota Department of Health

2.0 Hydrogeologic setting

2.1 Geologic deposits

The geology in the study area is largely glacial till and outwash overlying bedrock. Surficial deposits (Figure 3) consist mostly of glacial till and outwash sands and gravels deposited by the Des Moines and Superior lobes (Meyer, 1995). The Sauk River and other hydrologic processes eroded and thinned the glacial sediment in the Sauk River bedrock valley. Highly-permeable sand and gravel were deposited over this, resulting in layers that are highly hydraulically connected (Gold'n Plump®, 1995).

2.1.1 Quaternary

Most of the Sauk River valley is filled with surficial outwash sands and gravels from the Des Moines lobe (New Ulm Formation). The glacial deposits within the valley were eroded by the Sauk River and overlain by deposits of alluvium (Lingren, 2001). The upland glacial deposits (Figure 4) are mainly till, containing buried outwash from the Cromwell, Hewitt, Sauk Centre, and two unnamed formations (Figure 5). The locations of the buried outwash lenses are complex and not well understood, but are commonly the main source of water where surficial outwash is absent.

2.1.2 Bedrock

Quaternary deposits are underlain by Cretaceous and Precambrian bedrock throughout the study area (Figure 6). Precambrian igneous and metamorphic rocks directly underlie the glacial sediment in portions of the study area. The Precambrian bedrock surface is topographically irregular and exists in both weathered and unweathered states. These dense rocks generally have low porosity and permeability but low yields can be obtained from discontinuous fractures (Lindholm, 1980). Discontinuous Cretaceous shale deposits separate glacial sediment from the underlying igneous and metamorphic rocks throughout the study area.

2.2 Hydrogeologic units

There are seven main aquifer units in the study area (Figure 5):

- Surficial sand aquifer (that includes the New Ulm Formation Sand, where present)
- Cromwell Formation buried sand aquifer
- Hewitt Formation buried sand aquifer
- Sauk Centre buried sand aquifer
- Unnamed buried sand 2
- Unnamed buried sand 3
- Fractured Cretaceous bedrock aquifer

This discussion focuses on the dominant water-bearing formations: the Surficial Sand aquifer and the Hewitt Formation sand aquifer. The northeastern part of the study area includes areas of the Hewitt Formation sand aquifer. The aquifer thickness ranges from 5 to 69 feet. Underlying the Hewitt Formation till deposits is a thin sand lens (Sauk Centre sand aquifer, typically about 10 feet thick). This sand lens is likely connected to the overlying Hewitt Formation sand aquifer through the thin layers of leaky till (less than 5 feet thick in some locations). Moving to the south, the surficial sands of the Sauk River valley aquifer become more aerially widespread.

The Surficial Sand aquifer consists of river deposits of sand and gravel units and is highly hydraulically connected to portions of the New Ulm sand aquifer. Other sand and gravel units are buried under till. There are both buried unconfined and confined units. Maximum saturated thickness of the Surficial Sand aquifer is about 50 feet. Where sufficient saturated thickness is penetrated, well yields are greater than 1,000 gallons per minute (Lindholm, 1980).

Where it is sufficiently fractured, the Cretaceous bedrock acts as an aquifer. This underlies most of the study area, although this aquifer is not very productive or often used because of its depth and the existence of overlying sand and gravel aquifers.

2.3 Hydraulic properties

Hydraulic properties of glacially-deposited aquifer systems are highly variable. The glacial deposit units can act as either aquifers or aquitards. The regional aquitards in the study area can be used as low-yield aquifers sufficient for domestic use. Table 1 summarizes hydraulic conductivities of the materials in the study area, as compiled from the sources listed. Aquifer tests specific to the study area are discussed in the Cold Spring Existing Data Summary Report (Minnesota Department of Natural Resources, 2017).

Table 1. Hydraulic conductivities of key materials in the study area

Material	Hydraulic Conductivity (ft/day)	Source
Confined glacial sand and gravel aquifer	10 to 750	(Delin, 1988)
Glacially deposited gravel	700	(Lindholm, 1980)
Glacially deposited clay	10	(Lingren, 2001)
Till in west central Minnesota	1.4×10^{-1}	(Delin, 1988)
Till	10^{-6} to 1	(Cherry, 1979)
Till in west central Minnesota*	8.6×10^{-6} to 1.8	(Delin, 1988)
Till*	1.8×10^{-2}	(Delin, 1988)
Weathered bedrock	9.35×10^{-1} to 14.7	(Health, 1983)

*Vertical hydraulic conductivity

2.4 Groundwater flow, sources, and discharge

Regional groundwater flow is toward the Sauk and Mississippi rivers, whereas locally groundwater discharges to smaller streams and lakes (Minnesota Department of Natural Resources, Division of Waters, 1998). Within the study area, groundwater flow is to the Sauk River valley from the upland formations. The Sauk River valley is composed of outwash deposits of sand, gravelly sand, and gravel interbedded with till and clay. The Sauk River valley generally narrows as it moves west to east through the study area. In general, the depth to groundwater increases with increasing elevation and distance from the Sauk River due to topographic changes.

There appears to be a groundwater divide north of the study area boundary, which coincides with the topographic high north of Big Fish Lake (Figure 7). The western boundary of the study area is part of the Sauk River valley. The groundwater likely flows west to east through the western boundary through the valley.

Sources of water into the area's aquifers include the following:

- Recharge from precipitation
- Flow through study area boundaries
- Leakage through till and clay layers to buried aquifer units

Groundwater leaves aquifers through the following processes:

- Withdrawals from wells
- Discharges to springs, streams, and lakes
- Flow through study area boundaries

2.4.1 Pumping

Groundwater provides the main source of water for residents and businesses within the study area (Figure 8). Table 2 and Figure 9 shows the total pumping within the study area from 2006 to 2018.

Table 2. Pumping in study area by use 2006 through 2018

Use	Number of Wells[1]	Average Water Use (MGY)	Percent of Water Use in Study Area
Industrial Processing	28	437.7[2]	27.5
Domestic[3]	743	81.4[4]	5.1
Agricultural Irrigation	130	727.1[2]	45.6
Water Supply	34	293.3[2]	18.4
Other	51	54.1[2]	3.4

[1]Number of wells as described in the Minnesota Well Index (MWI) with use taken from the Minnesota Permitting and Reporting System (MPARS). Where no permit could be found domestic use was assumed.

[2]As reported to the DNR through MPARS

[3]Domestic wells were selected from the Minnesota well index where the status was active and the use was domestic. Domestic wells from Minnesota well index are not included in the groundwater model, as domestic users are assumed to have a septic system to recharge much of the water use. Not all domestic wells are included in the Minnesota well index.

[4]Assume 300 gallons per day per family of four (Sciences, 2017)

2.4.2 Stream-aquifer seepage

Stream-aquifer seepage describes the movement of water between the stream and the underlying aquifer system. Seepage can occur from the aquifer to the stream (gaining stream/reach), resulting in increased flows and cooler summer water temperatures. It can also occur from the stream to the aquifer (losing stream/reach), resulting in decreased or potentially disappearing flows. Streams can switch from gaining to losing depending on the location and the elevation of the water-table aquifer, which changes over time. The rate of stream seepage depends on the following:

- Type and thickness of streambed material
- Vertical hydraulic conductivity of streambed material
- Hydraulic conductivity of the aquifer near the stream
- The difference in head between the stream and the aquifer

Measuring stream-aquifer seepage on the Sauk River can be problematic due to the water storage behind the dam located slightly upstream at the mouth of Cold Spring Creek. The calculated streamflow gains and losses on the Sauk River during low flow periods is less than the measurement error (Lingren, 2001). However, it can be determined whether the river is gaining or losing flow. The USGS monitored flow on the Sauk River in preparation for the 2001 USGS report and determined that the Sauk River gained flow slightly downstream of the City, lost flow near the Gold‘n Plump poultry processing plant, and switched back to gaining flow as it moved east (Figure 10).

The DNR studies showed that during low-flow periods groundwater represented most of the flow in Cold Spring Creek (Appendix A). The DNR Fish and Wildlife Division studied the stream 13 times since 1977 (Pelham, 2012). Fisheries divided the stream into the seven reaches shown in Figure 11. Fishery reach 1 is a wetland with low flow that was ditched for drainage and is unlikely to be significantly gaining or losing. Fishery reach 2 is a channelized stream with low flow. Fishery reach 3 and Tributary Wetland are wetland areas that do not appear to be significantly gaining or losing. Cold Spring Creek was a gaining stream for fishery reaches 4 through 7. The lower portion of reach 4 and reaches 5 through 7 comprise the length of Cold Spring Creek for which base flow depletion was calculated using the groundwater flow model.

3.0 Representation of the groundwater flow system

The system representation is based on geologic and hydrogeologic data available within the study area. This representation, illustrated in Figure 12, is the basis for the development of the numerical flow model. Figure 13 depicts groundwater pumping near a stream.

The data collection area for the Cold Spring Groundwater Study was set as a rectangular shape with boundaries on groundwater divides where possible (Figure 7). The previously developed USGS model covered a smaller area that resulted in the model's boundaries artificially influencing predictions at wells within the Cold Spring area. The study area was increased for this project to ensure the model boundaries have limited impact on the wells near Cold Spring.

Figure 12 illustrates the system representation as follows. Water falls on the landscape as precipitation and either runs across the landscape as overland flow or enters the aquifer system as recharge. Groundwater moves downward and laterally through the aquifer and naturally discharges at low points in the landscape such as streams and wetlands. Groundwater moves through the leaky till to the sand and gravel lenses within the till where it can either continue to flow slowly through to the next unit or be removed by pumping. When a well is pumped a cone of depression is created where the water level is lowered in an area surrounding the well. This can reduce the flow of water to the natural discharge points. Groundwater near the land surface can be removed from the system through vegetation uptake for growth, evaporation, or transpiration.

The approximate locations of groundwater divides were determined using the *Stearns County Groundwater Atlas Part B* (Minnesota Department of Natural Resources, Division of Waters, 1998). The locations of the groundwater divides can be affected by pumping. There is some through-flow from areas across the northern boundary into the study area. The western boundary of the study area is largely defined by Kolling Creek, Sauk River, and the Sauk River chain of lakes, which are surface representations of the water table aquifer system. In general, the southern and eastern boundaries of the study area are defined by a combination of groundwater divides and surface subwatershed boundaries. There is some through-flow from areas across the southern and eastern boundary into the study area.

4.0 Steady-state numerical model

The system representation was the basis for developing the numerical model, described in section 3.0. The model was calibrated for steady-state conditions using pumping rates and head elevations from 2006 to 2018. A steady-state model represents average conditions that do not change over time. That is, in the model, the volume of water in storage within the aquifer system does not change, wells in the model pump constantly at their average rate, and hydraulic heads are constant.

4.1 Purpose

The purpose of the steady-state numerical model is to characterize groundwater flow and calculate how pumping affects base flow in Cold Spring Creek. The model was constructed to meet the following requirements:

- Represent the hydrogeologic system in a simplified but robust manner that includes the essential elements
- Simulate observed hydraulic heads that are overall consistent with available groundwater level data
- Match base flow in Cold Spring Creek to the degree possible without creating an over-parameterized or over-calibrated model

4.2 Hydrologic model selection

Model codes were selected to suit the purpose of the model and availability of data.

4.2.1 Groundwater model

For groundwater flow, this study used the industry-standard base code developed by the USGS: MODFLOW-NWT (Niswonger, Panday, & Ibaraki, 2011). MODFLOW-NWT solves groundwater problems involving drying and rewetting nonlinearities of the unconfined groundwater-flow equation. The NWT linearization approach generates an asymmetric matrix, which is different from the standard MODFLOW formulation that generates a symmetric matrix. *MODFLOW-NWT, A Newton formulation for MODFLOW-2005* fully describes the difference between standard MODFLOW and MODFLOW-NWT (Niswonger, Panday, & Ibaraki, 2011). MODFLOW-NWT is advantageous in the Cold Spring area because of the commonness of unconfined groundwater flow.

4.2.2 Recharge model

To estimate recharge rate and distribution, the study used the USGS Soil-Water Balance (SWB) model (Westenbroek, Kelson, Dripps, & Hunt, 2010). Groundwater recharge varies over time and space. Site-specific data are not available or applicable to large-scale models such as the Cold Spring area model. The SWB model calculates components of the soil water balance on a daily time step using a modified version of the Thornthwaite-Mather soil-moisture approach. SWB provides physically-based, spatially-variable results, yet is much less time- and computationally-intensive than a fully-coupled groundwater-surface-water model. Appendix B describes the development of the SWB model for the Cold Spring area.

4.3 Numerical model construction

The study area was divided into irregularly-spaced rectangular finite-difference grid cells (Figure 14). Within the grid cells the properties of the hydrogeologic unit represented are assumed to be uniform. The node is the center of a grid cell and represents the location for the hydraulic head computed by the model. The grid cells are irregularly spaced to allow for finer spatial discretization of the model in areas where more information was available or in the areas of interest. The model has 260 rows and 279 columns with cells ranging from 15 meters by 15 meters to 120 meters by 120 meters. The smallest cells are near the City's wellfield and Cold Spring Creek. These smaller cells allow for the simulation of the interaction between Cold Spring Creek and nearby wells.

The active model domain is smaller than the study area and is defined using the boundary conditions as discussed in section 4.3.2. The study area is larger than the active model domain because we needed to gather information to define the model's boundary conditions. In turn, the active model domain is larger than the area of interest so that the area of interest is far enough from the model's boundaries that features in the area of interest (like wells and the creek) aren't artificially influenced by the boundaries.

4.3.1 Vertical discretization

The groundwater system in the model area was subdivided vertically into fourteen layers, based on the fourteen hydrogeologic units defined in the area. Where hydrogeologic units are absent, the properties of the overlying unit are used. To allow for layer continuity, the layer is assigned a thickness of 1.0. Each hydrogeologic unit corresponds to a property zone that can span multiple model layers. This methodology was used in a variety of other groundwater models in settings with glacial sediments (Parsen, Bradbury, Hunt, & Feinstein, 2016; Eggleston, Zarriello, & Carlson, 2015). The elevation of the tops and bottoms of each layer were specified for each model cell. The number of hydrogeologic units in the numerical model differs from the number of hydrogeologic units in the data summary report because an additional unnamed sand and till unit was identified on further evaluation by professional geoscientists at the DNR.

East-west cross-sections were drawn across the study area at one-kilometer spacing. The geology was interpreted using well logs by a professional geoscientist at the DNR (Appendix C). These cross-sections were then interpolated across the study area using the methodology used by the Minnesota Geological Survey. Where "till" is noted on the cross sections, "till 1" was assigned in the numerical model. Another professional geoscientist at the Minnesota Geological Survey completed a sand probability analysis to evaluate the interpolated cross-sections (Appendix D). This analysis confirmed that some domestic wells are screened in the Cromwell Till. This indicates the till acts as a low-yield aquifer in this region. Simulation of leakage of water between model layers is dependent on the thickness and vertical hydraulic conductivities between adjacent layers. Figures 15 through 17 show cross-sections through Cold Spring Creek.

The hydrogeologic units in Table 3 represent aquifers in the model in descending order. For a description of these and other hydrogeologic units in the model, see Appendix Figure C-2.

Table 3. Aquifer units

Hydrogeologic units	Zone
Surficial Sand Aquifer	1
Cromwell Sand	3
Cromwell Till	4
Hewitt Sand	5
Sauk Center Sand	7
Buried Sand 2	9
Buried Sand 3	11
Fractured Bedrock	13

4.3.2 Boundary conditions

Ideally, boundaries around the perimeter of a model should be located at physical limits of the aquifer system or at other hydrogeologic boundaries such as major rivers. Practical considerations can necessitate the use of perimeter model boundaries that do not coincide with hydrogeologic boundaries, such as limitations concerning the size of the area modeled. Types of boundary conditions used in this model include no flow boundaries, general head boundaries, river cells, wells, and recharge.

The DNR Cold Spring model area was enlarged from the USGS Cold Spring model area to include natural groundwater divides. The study area contains the active domain of the model. The boundary for the active model domain was developed using the USGS model, the Stearns County Atlas Part B (to delineate groundwatersheds) and subwatershed boundaries (Vaughn, MNDNR Watershed Suite, 2018). The study area was larger than the active model domain because the data collected help define the boundaries of the model within (Figure 18). Groundwatersheds are areas where groundwater flows from a high point (groundwater divides) to a low point (discharge area). These high points can shift slightly with intensive pumping and variations in recharge. Sometimes these divides coincide with surface watershed boundaries. The watershed boundary was used as the edge of the active model domain where the edges of the groundwatershed and the watershed generally overlap. The northeastern model boundaries follow the watershed boundary because the groundwatershed extends further east to the Mississippi River.

A “no flow” boundary is used along boundaries of a groundwater divide. A “no flow” boundary does not allow any water to cross either into or out of the model. A “general head” boundary is used where expanding the model to the groundwater divides created an area too large to model effectively.

The area of interest is where the model will be used to answer questions: the area around Cold Spring Creek and around the Cold Spring municipal well field (Figure 14). It is completely within the model and sufficiently far from the boundaries. The increased distance from the model’s outer boundaries to the area of interest minimizes the effect of boundaries on the creek and City’s well field. The area of interest is discretized into a smaller grid size than the rest of the model area because of the larger amounts of information, such as closely neighboring wells, or areas where generalizing over a large grid cell would make the model less useful. The general head, river, and no flow boundary types are shown in Figure 18.

No-flow boundary

The southern and parts of the eastern and western boundaries of the model are no flow boundaries. This was used because the Stearns County Atlas, Part B indicated that there was a groundwater flow divide at these locations or the groundwater flow was parallel to the boundary (Figure 7). Any cell that is not actively modeled is considered a no flow cell.

General head boundary

The northern, western, and parts of the eastern boundary are represented using general head boundaries (GHB). The flow across the northern boundary is generally northwest to southeast into the active model domain. The flow on eastern and western the boundaries is generally toward the Sauk River. The GHB were determined using surface waters around the boundary. The GHB were vertically placed in the layers with corresponding groundwater elevation.

Surface-water features

Stream-aquifer leakage between the surface-water bodies including lakes, creeks, and rivers was simulated using head-dependent flux nodes, known as river cells. Stream-aquifer leakage through each streambed cell is approximated (Harbaugh, 2005) by Darcy's Law as:

$$Q_{RIV} = CRIV \times (H_{RIV} - H_{AQ}) \text{ when } H_{AQ} \geq R_{Bot}$$

$$Q_{RIV} = CRIV \times (H_{RIV} - R_{Bot}) \text{ when } H_{AQ} < R_{Bot}$$

Where:

Q_{RIV} = Stream aquifer leakage through the reach of the streambed (L^3/T)

H_{RIV} = Head (elevation) in the waterbody in the cell (L)

H_{AQ} = Head (elevation) in the aquifer (L)

R_{Bot} = River bottom (elevation) (L)

For lakes with lake gage records, the head elevation was assigned to be equal to the average water elevation at the gage. For lakes and streams without gages, the head elevation was assigned to be equal to that from the Light Detection and Ranging (LiDAR)-based digital elevation model. The bottom elevation in lakes with bathymetry data used the bathymetric-calculated values for the lakebed. For all other lakes the assumed lakebed elevation was 1 meter below LiDAR.

River cells were grouped by hydrologic soil type (Natural Resources Conservation Service, 2007). Hydrologic soil type was assigned based on the soil type underlying and immediately adjacent to the river cells (Figure 19). These river cell groups are not the same as the reaches defined in the DNR Fisheries stream survey (Pelham, 2012), because the stream survey evaluated stream segments based on fish habitat, whereas the river cell groups for the groundwater model were determined based on soil type.

The conductance of a river cell depends on the dimensions of the cell and so it is different for each cell. Conductance is computed using the formula (Harbaugh, 2005) below:

$$CRIV = (K \times L \times W)/M$$

Where:

CRIV = Riverbed conductance (L^2/T)

K = Vertical hydraulic conductivity of the streambed (L/T)

L = Length of the waterbody in the cell (L)

W = Width of the waterbody in the cell (L)

M = Thickness of the streambed (L)

The length and width of the waterbody in each cell was calculated using Geographic Information System (GIS) tools. The thickness of the riverbed is assumed to be constant at 0.3048 meters. Stream depth was assumed to be 1.33 meters for the Sauk River. For small streams a depth of 0.333 meters was used. Hydraulic conductivity was assumed to be constant for each river cell in a group. The vertical hydraulic conductivity of the streambed was initially set equal to 1 for each river cell in the model and then modified during calibration as described in Section 4.5.1.

Recharge

Recharge was included using the MODFLOW Recharge Package. Recharge was set as a model parameter during model calibration. The initial recharge values were equal to the mean recharge for 2006 to 2018, as calculated by the SWB recharge model. Recharge in the SWB model was calculated on a regular grid with 30 meter by 30 meter cells. For groundwater model cells larger than 30 meters by 30 meters, the spatial average of the SWB values within the groundwater cell was used for recharge. For groundwater model cells smaller than 30 meters by 30 meters, the model calculated value was used for recharge. The 13-year mean annual potential recharge rate from 2006 through 2018 was 10.2 inches per year, excluding open water cells. This value is the average parameter produced in the SWB array, and a multiplier was used in MODFLOW calibration to maintain relative recharge rates. Generally, the higher potential recharge rates occurred near the existing and buried river channels and directly north of the City. For more information, see Appendix B.

Evapotranspiration

Evapotranspiration from the soil was accounted using the SWB model (Appendix B). The SWB model has been used in Minnesota and Wisconsin to develop estimates of recharge (Smith, 2015) (Bradbury, et al., 2017) (Metropolitan Council, 2014). Using SWB to calculate potential recharge instead of the groundwater evapotranspiration package in the groundwater model was used in previous studies (Bradbury, et al., 2017) (Metropolitan Council, 2014), and the DNR followed this convention. Major surface-water boundaries and net groundwater exchange along these features such as lakes, large wetlands, and rivers are represented with the MODFLOW River Package as described above.

4.3.3 MPARS permitted wells

Wells with water use permit records maintained by the DNR through the Minnesota Permitting and Reporting System (MPARS) were included in this study. The DNR requires users to obtain a water use permit and submit monthly water use records, if they withdraw more than 10,000 gallons of water per day or 1 million gallons per year. The use for these wells was averaged over 2006–2018. Table 4 shows the average water use in the active model domain.

Table 4. Groundwater use in the model, averaged 2006 to 2018

Use	Number of Wells[1]	Average Water Use[2] (MGY)	Percent of Water Use in model
Industrial Processing	16	412.2	33.8
Agricultural Irrigation	53	430.9	35.3
Water Supply	9	211.5	17.3
Other[3]	12	77.0	6.3
Feedlots (MPARS permit not required)[4]	66	88.2	7.2

[1]Number of wells as described in the Minnesota Well Index (MWI) with use taken from the Minnesota Permitting and Reporting System (MPARS). Where no permit could be found domestic use was assumed.

[2]As reported to the DNR through MPARS.

[3]Other categories include: golf course irrigation, landscaping/athletic field irrigation, livestock watering (with MPARS permit), and sand/gravel washing.

[4]Feedlot water use estimated. The feedlots wells were domestic or "other" category in table 2. For a discussion on feedlots where MPARS permits were not required see section 4.3.3 (below).

Feedlot permits from the Pollution Control Agency were used to determine the location of feedlots in the study area. For feedlot wells that were permitted in MPARS, the average water use was determined as it was for the other wells. For feedlots without a permitted well, water use was estimated by the number and type of animals on the feedlot permit and average water use for that type and number of animals per University of Minnesota publications (Baidoo, 2015). That estimated water use was assigned to wells on or near the feedlot based on GIS analysis.

It is assumed that the water use reported in MPARS is accurate. The reported values and wells are what is used in the model. The exception is Permit 1976-3296. This is a groundwater use permit, but no unique well ID was assigned in MPARS. The permit file included well depth and width, but not screen length or aquifer. The well was placed using the location provided in MPARS and a 30' screen at the bottom of the well was assumed.

4.3.4 Hydraulic conductivity

Hydrogeologic units were each assigned to a zone, where the horizontal hydraulic conductivity and vertical anisotropy is consistent across each zone (Figures 20 through 33). Initial hydraulic conductivities were based on either existing aquifer tests or literature values for that hydrogeologic unit. The horizontal hydraulic conductivity of each zone was allowed to range between the upper and lower values in Table 5. In general, the ranges in Table 5 represent the likely range of hydraulic conductivity for each material type according to aquifer tests and literature values. Where the tested range was narrow, an order of magnitude was added to account for uncertainty.

The vertical anisotropy was allowed to range between the upper and lower values found in Table 6, which are based on observed values of vertical anisotropy. As for hydraulic conductivity, an order of magnitude was added to account for uncertainty and to allow the calibration algorithm more room to explore the solution space.

Table 5. Horizontal hydraulic conductivity ranges by zones

Zone	Material	Initial value (m/day)	Lower value (m/day)	Upper value (m/day)
1	Surficial Sand	200.0	6.90E-04[1]	450[2]
2	New Ulm Till	0.5039	8.64E-08[1]	8.64E-02[1]
3	Cromwell Sand	200.0	6.90E-04[1]	240[3]
4	Cromwell Till	6.6991	8.64E-08[1]	8.64E-02[1]
5	Hewitt Sand	167.4884	6.90E-04[1]	240[3]
6	Hewitt Till	0.6935	8.64E-08[1]	8.64E-02[1]
7	Sauk Centre Sand	80.5246	6.90E-04[1]	240[3]
8	Sauk Centre Till	3.97E-02	8.64E-08[1]	8.64E-02[1]
9	Buried Sand 2	4.3054	6.90E-04[1]	240[3]
10	Buried Till 2	0.417	8.64E-08[1]	8.64E-02[1]
11	Buried Sand 3	200.0	6.90E-04[1]	240[3]
12	Buried Till 3	3.84E-02	8.64E-08[1]	8.64E-02[1]
13	Fractured Bedrock	1.5206	8.60E-04[1]	8.64[1]
14	Bedrock	3.05E-03	8.64E-09[1]	8.64E-02
15	Surficial New Ulm Till	84.7	8.64E-08[1]	150
16	Surficial Cromwell Till	84.7	8.64E-08[1]	150

[1] (Cherry, 1979)

[2] Saint Joseph Aquifer Test

[3] (Lindholm, 1980)

Table 6. Vertical anisotropy ranges by zones

Zone	Material	Initial value (m/day)	Lower value (m/day)	Upper value (m/day)
1	Surficial Sand	0.1	1.00E-09	1
2	New Ulm Till	0.1	1.00E-09	1
3	Cromwell Sand	0.1	1.00E-09	1
4	Cromwell Till	0.1	1.00E-09	1
5	Hewitt Sand	0.1	1.00E-09	1
6	Hewitt Till	0.1	1.00E-09	1
7	Sauk Centre Sand	0.1	1.00E-09	1
8	Sauk Centre Till	0.1	1.00E-09	1
9	Buried Sand 2	0.1	1.00E-09	1
10	Buried Till 2	0.1	1.00E-09	1
11	Buried Sand 3	0.1	1.00E-09	1
12	Buried Till 3	0.1	1.00E-09	1
13	Fractured Bedrock	0.1	1.00E-09	1
14	Bedrock	0.1	1.00E-09	1
15	Surficial New Ulm Till	0.1	1.00E-09	1
16	Surficial Cromwell Till	0.1	1.00E-09	1

4.4 Steady-state optimization

The steady-state numerical model was calibrated through a series of automated inverse optimization procedures using the model-independent parameter estimating software PEST (Version 14.2) (Watermark Numerical Computing, 2016). Automated inverse optimization is a method for minimizing the differences between simulated results and observations. The overall process of the calibration procedure employed for this study was as follows:

1. The model was constructed.
2. Calibration targets for optimizing were established. The calibration targets included:
    a. Hydraulic head
    b. Base flow
3. The model was manually calibrated.
4. PEST was used to optimize the model. Parameters that were allowed to vary within a set upper and lower bound during the optimization process included:
    a. Horizontal hydraulic conductivity
    b. Vertical anisotropy

    c. Riverbed conductance
    d. Recharge scaling factor

5. The results of the PEST optimization were evaluated and changes were made to the model:
    a. The weights of parameters were adjusted. In general, higher weights were given to base flow estimates for Cold Spring Creek, and water elevations in the DNR and USGS observation wells. These measurements are taken using consistent data collection procedures and likely to be more accurate in comparison to other hydraulic head targets available from the CWI database.

6. Steps 3–5 were repeated several times to improve the optimization.

4.5 Numerical model calibration and results

Model calibration is a process in which the initial estimates of aquifer properties and boundary conditions are adjusted until the simulated hydraulic heads and flows reach an acceptable match to historical conditions. For this study, aquifer properties and recharge were adjusted within the limits shown on Tables 5 through 7, and described in Section 4.5.1 to produce an acceptable match between groundwater levels and the estimated base flow in Cold Spring Creek. The model runs conducted during calibration assumed steady-state conditions, 2006 through 2018.

4.5.1 Parameters for optimization

Using PEST involved deciding which parameters would be allowed to vary, the maximum and minimum values that a parameter could vary, and initial estimates for each parameter value. PEST was not used until the traditional manual calibration had achieved a reasonable result.

Riverbed hydraulic conductivity

During calibration riverbed hydraulic conductivity for each river cell group (rv1, rv2, rv3, and rv4; described in Section 4.3.2) was allowed to vary within the multiplier range shown on Table 7 for that group. This method, which allows a multiplier to represent the hydraulic conductivity for each group, is similar to the method followed by the USGS (Haserodt, Hunt, Cowdery, Leaf, & Baker, 2019).

Certain river cells representing reaches of Cold Spring Creek and the Sauk River where base flow is known were assigned to their own river cell groups (rv5, rv6, rv10, rv12, and rv13; Figure 34). This allows the base flow in each of these reaches to be a calibration point. In total nine adjustable riverbed hydraulic conductivity parameters were used during model calibration.

Table 7. Hydrologic soil groups (Natural Resources Conservation Service, 2007)

Hydrologic Soil Type	Material Type	Multiplier Range	Parameter group
A	Sand and/or gravel	0.3048 to 3.05	rv1, rv5
B	Loamy sand or sandy loam	0.02348 to 3.3048	rv2
C	Loam, silty loam, sandy clay loam, clay loam and silty clay loam	0.01348 to 3.3048	rv3
D	Clayey textures	0.01348 to 3.3048	rv4, rv6, rv10, rv 12, rv13

Riverbed hydraulic conductivity for parameters rv5 and rv1 were forced to be equal (tied) because they have the same underlying hydrologic soil type. Similarly, riverbed hydraulic conductivity for rv4 and rv6, rv10, rv12, and rv13 were tied. Tied parameters must scale together during calibration and in this case rv5 was equal to rv1 and rv4 was equal to rv6, rv10, rv12, and rv13.

Recharge scaling factor

A scaling factor for recharge was used as an adjustable parameter during model calibration (Marini, Hoogestraat, Aurand, & Putnam, 2012). Recharge varies due to changing climatic conditions, but it was assumed that the geospatial distribution of recharge stays about the same, because the geospatial distribution of recharge was based on soil type and land use conditions. The recharge scaling factor was allowed to range from 0.5 to 1.1. An optimized value of 1.0 was determined during calibration.

Hydraulic conductivity

Initial values of hydraulic conductivity for the zones were based on existing aquifer tests and literature values where available. During the model calibration, the hydraulic conductivity values were allowed to vary within a range to better fit the calibration targets. The final calibrated values of the hydraulic conductivities can be found in Tables 9 and 10. Figures 20 through 33 show the hydraulic conductivity zones for all layers in the model.

4.5.2 Calibrated parameters

Tables 8, 9 and 10 below show the calibrated parameters for the model.

Table 8. Calibrated river and recharge model parameters

Parameter	Final Value	Units
rv1	8.39E-01	m^2/day
rv2	2.24E-01	m^2/day
rv3	8.97E-02	m^2/day
rv4	3.89E-01	m^2/day
rv5	8.39E-01	m^2/day
rv6	3.89E-01	m^2/day
rv10	3.89E-01	m^2/day
rv12	3.89E-01	m^2/day
rv13	3.89E-01	m^2/day
rm1	1.0	--

Table 9. Calibrated horizontal hydraulic conductivity model parameters

Parameter	Final Value (m/day)	Represents
kx1	172.8	Surficial Sand horizontal hydraulic conductivity
kx2	1.31-05	New Ulm Till horizontal hydraulic conductivity
kx3	25.1	Cromwell Sand horizontal hydraulic conductivity
kx4	1.29E-04	Cromwell Till horizontal hydraulic conductivity
kx5	9.40E-02	Hewitt Sand horizontal hydraulic conductivity
kx6	1.66E-03	Hewit Till horizontal hydraulic conductivity
kx7	240	Sauk Centre Sand horizontal hydraulic conductivity
kx8	2.17E-02	Sauk Centre Till horizontal hydraulic conductivity
kx9	2.31	Buried Sand 2 horizontal hydraulic conductivity
kx10	3.97E-02	Buried Till 2 horizontal hydraulic conductivity
kx11	3.39	Buried Sand 3 horizontal hydraulic conductivity
kx12	29.3	Buried Till 3 horizontal hydraulic conductivity
kx13	3.62	Fractured Bedrock horizontal hydraulic conductivity
kx14	2.98E-04	Bedrock horizontal hydraulic conductivity
kx15	100	Surficial New Ulm Till horizontal hydraulic conductivity
Kx16	100	Surficial Cromwell Till horizontal hydraulic conductivity

Table 10. Calibrated vertical hydraulic conductivity model parameters

Parameter	Final Value (m/day)	Represents
kz1	5.53E-02	Surficial Sand vertical anisotropy
kz2	7.18-03	New Ulm Till vertical anisotropy
kz3	1.0	Cromwell Sand vertical anisotropy
kz4	5.93E-03	Cromwell Till vertical anisotropy
kz5	5.43E-02	Hewitt Sand vertical anisotropy
kz6	5.32E-01	Hewitt Till vertical anisotropy
kz7	1.03E-01	Sauk Centre Sand vertical anisotropy
kz8	9.4E-02	Sauk Centre Till vertical anisotropy
kz9	1.0	Buried Sand 2 vertical anisotropy
kz10	1.0	Buried Till 2 vertical anisotropy
kz11	1.30E-02	Buried Sand 3 vertical anisotropy
kz12	1.10E-01	Buried Till 3 vertical anisotropy
kz13	2.70E-01	Fractured Bedrock vertical anisotropy
kz14	1.00E-01	Bedrock vertical anisotropy
kz15	7.26E-01	Surficial New Ulm Till vertical anisotropy
Kz16	3.06E-02	Surficial Cromwell Till vertical anisotropy

4.5.3 Calibration targets

Calibration targets include both hydraulic head and base flow. Using both types of targets limits the correlation between hydraulic heads and recharge. The targets were comprised of water levels measured in wells and base flow values classified into one of four groups. These groups are discussed in the following sections.

Hydraulic head targets

A total of 312 hydraulic head calibration targets were used for model calibration (Figure 35). Due to consistent data collection practices, the highest quality data were assumed to be hydraulic head values from the existing DNR monitoring wells with at least one water level measured between 2006 and 2018. Where observation wells have more than one measurement, the average of the measurements was used. There were a total of ten wells in this group. Wells in the secondary group involve any wells with any water level between 2006 and 2018. This includes any wells in CWI drilled between 2006 and 2018. There were a total of 61 wells in this group. All other CWI wells with water levels outside of the 2006 through 2018 range were considered the third group of data. The water levels in group 3 were not given as much weight as the water levels in the first two groups, but helped to fill in data gaps.

Target head values from CWI data generally represent water levels measured by drilling contractors during well installation. Some sources of errors in these targets could include the following:

- Inaccuracy of well location: Many wells are identified to the nearest quarter-quarter-quarter section.
- Inaccuracy of well elevation: This is typically estimated using 7.5 minute topographic maps.

- Water levels did not stabilized following well development at the time of measurement.
- Water levels affected by seasonal pumping.
- Actual water elevation at the time of measurement differs from the 2006 through 2018 average.

After the completion of calibration, the simulated hydraulic heads correlated with measured values, particularly within the area of interest around Cold Spring Creek. The final calibrated steady-state model had the following characteristics:

- Mean residual for all head targets: -1.16 meters
- Mean residual for head targets in the area of interest: -0.36 meters
- Residual standard deviation for all head targets: 4.28 meters
- Residual standard deviation for head targets in area of interest: 3.98 meters

A plot that compares all model-simulated heads to measured heads is shown on Figure 36. Maps of head residuals for all head targets are shown on Figure 37. Simulated groundwater contours and head targets by layer are shown on Figures 38 through 51.

Cold Spring base flow targets

Base flow targets were established for two reaches on Cold Spring Creek (Figure 52). The base flow target reaches on Cold Spring Creek were chosen to coincide with the two continuous monitoring locations on Cold Spring Creek:

- The upstream reach is located from where flow originated in the winter 2018 field season downstream to gaging location H16011008. All the cells in rv6 contributed to the base flow target at H16011008.
- The downstream reach includes river cells located between gaging location H16011008 and gaging location H16011007. All of the cells in rv5 contributed to the base flow target at the DNR monitoring station H16011007.

Average monthly base flow was estimated for each of the two continuous gage stations (H16011008 and H16011007) on Cold Spring Creek for the period of record 2014 through 2018. All monthly average base flows (October 2014 through December 2018) were then averaged to estimate the annual average base flow. A detailed description of how the base flow in Cold Spring Creek was calculated can be found in Appendix E.

Overall simulated base flow values along Cold Spring Creek correspond with observed values (Table 11).

Table 11. Comparison of observed base flow and calculated base flow

Simulation	Observed m^3/day	Model Calculated m^3/day
H16011008 (Cold Spring upstream)	-1198.9	-1031.7
H16011007 (Cold Spring downstream)[1]	-4746.4	-4281.9

[1]Model calculated base flow at H16011007 is the sum of modeled base flow in reaches rv5 and rv6 (Figure 52). Rv5 and rv6 were separate calibration targets.

[2]Negative values indicate the aquifer is losing water to the stream.

Sauk River base flow targets

Base flow targets were established for three reaches along the Sauk River: rv10, rv12, and rv13. These reaches coincide with the reaches developed by the USGS (Lingren, 2001). The Sauk River base flow targets were weighted less than the base flow targets on Cold Spring Creek during calibration.

The observed values for the Sauk River are -29,000, 16,000, and -23,000 m^3/day for the west, central, and east reaches respectively. The model calculated values for the Sauk River were -8,400, -26,000, and -34,000 m^3/day respectively. Simulated base flow values along the Sauk River generally are not a good match to the target values. This discrepancy is attributed to the challenges in calculating base flow along the Sauk River described in Section 2.4.2.

4.5.4 Wells with reduced pumping after calibration

MODFLOW will automatically reduce pumping from a well, if the program cannot get enough water out of the well. MODFLOW will reduce pumping down to zero, if it is necessary. In the calibrated model, MODFLOW reduced pumping at eight wells (Figure 54 and Table 12).

Table 12. Reduced pumping wells and rates

Unique well ID	Use	Model layer/ Zone pumped	Distance from Cold Spring Creek (miles)	Input pumping rate (m^3/day)	Modeled pumping rate (m^3/day)
124212	Irrigation	L1/kx1	3.1	88.021	0
157334	Feedlot	L1/kx1	5.6	1.131	0
160085	Feedlot	L1/kx1	1.7	31.531	0
175902	Irrigation	L1-3/kx1 and kx4	1.7	176.032	0
433902	Feedlot	L3/kx5	3.6	6.559	0
485493	Feedlot	L2-3/kx5	2.4	3.852	0
582913	Feedlot	L5-6/kx16	4.0	1.131	0
711406	Feedlot	L2-6/kx6	3.8	2.290	0

All of the wells with reduced rates are outside the area of interest. In total MODFLOW reduced pumping at these eight wells by 310.547 m^3/day, which represents 2.5 percent of the total volume pumped in the model. This reduction in flowrates is not expected to significantly affect model results.

4.6 Mass balance

The mass balance achieved in the calibrated model is shown on Table 13. The overall mass discrepancy was low, at 0.003 percent (20.0625 m^3/day).

Table 13. Mass balance for the calibrated model

Budget component	Flowrate (m^3/day)
Inflow: River leakage	241654.5625
Inflow: Head-dependent boundaries	218974.7500
Inflow: Recharge	122880.7656
Total inflow:	583510.0625
Outlow: Wells	12433.6523
Outflow: River leakage	473778.5312
Outflow: Head-dependent boundaries	97277.7891
Total outflow:	58490.0000

4.7 Parameter sensitivities

Composite model parameter sensitivities calculated using PEST are shown on Figure 55. Model calibration was most sensitive to both the horizontal hydraulic conductivity in zone 9 and the vertical anisotropy in zone 6. Zone 9 represents a buried sand layer that underlies the area of interest and stretches from east to west. Zone 6 outcrops in layer one in the model and is fairly widespread throughout the model domain. Its vertical anisotropy controls how quickly water moves to the lower layers.

4.8 Model validation

In June of 2018 the DNR measured water levels in thirty wells in the Cold Spring Study area to validate the model. These synoptic water levels were not included in calibration and instead were used to check the model's accuracy. Overall, the model matched the validation head targets fairly well, but didn't do quite as well on the western edge of the model (Figure 56). Simulated groundwater levels along the western boundary were lower than observed heads. This is not expected to affect the model results at Cold Spring Creek.

4.9 Numerical model limitations and accuracy of results

A numerical groundwater model is a practical tool for simulating the response of the groundwater system to changes in groundwater withdrawals. It is a simplification of a complex flow system, and the accuracy of the simulation is limited by the accuracy of the data that is used to describe the system. This model is a sub-regional model, and therefore caution should be used to assess localized effects such as the effect of a single pumping well on a stream reach.

The model is steady-state and does not account for seasonal changes. Rather, the estimated base flow diversion from the steady-state model is an average over the time period modeled. Calculating base flow diversion during August would require a transient groundwater model. In Minnesota, groundwater use tends to be relatively high in summer, whereas stream base flow tends to be low during late summer and fall. A transient model for Cold

Spring would be expected to predict higher rates of base flow depletion in August than the average depletion rates calculated by this steady-state model.

Use of the model as a predictive tool is based on the premise that if historical simulations can be simulated then future conditions can be simulated. However, the model is calibrated to a specific timeframe. The further the conditions vary from the calibrated conditions, the less likely future simulations will be accurate. These conditions can include climate and groundwater withdrawal changes.

5.0 Applying the groundwater model

Three sets of predictive scenarios were run using the groundwater model. The first set of modeling scenarios (Section 5.2) was developed to help understand how pumping groundwater at different volumes and distances cumulatively affects the creek. The second set of scenarios (Section 5.3) was developed to show how hypothetical groundwater use scenarios at the City's existing wellfield would affect Cold Spring Creek. The third set of scenarios (Section 5.4) shows how hypothetical groundwater use scenarios at the Lot 1/Block 1 site would affect Cold Spring Creek. The Lot 1/Block 1 site was evaluated because the City has drilled a test well there; other sites can be evaluated in future. None of the scenarios are meant to be prescriptive. Rather, they are intended to be informative. We can use the groundwater model to test other scenarios in future.

5.1 Calculating percent reduction in base flow

To calculate base flow depletion it is first necessary to determine how much base flow would be present in the stream, absent pumping (i.e., the reference base flow). The reference base flow is calculated using both model results and field-based data, as follows:

$$reference\ depletion = base\ flow_{no\ pumping} - base\ flow_{2014-2018}$$

In the equation above, "reference depletion" is a modeled value which represents the average base flow depletion during the period from 2014 through 2018. The reference depletion is then added to the base flow measured in the creek over the same time period (2014 through 2018) to calculate the "reference base flow", as follows.

$$reference\ base\ flow = base\ flow_{measured} + reference\ depletion$$

The "reference base flow" represents how much base flow, on average, would have been in the creek over the period from 2014 through 2018 without pumping. Using field data to calculate the reference base flow (instead of simply using the results of the base flow from the no-pumping model scenario) minimizes the impact of model error on the calculation of depletion.

Base flow depletion for each of the model scenarios was calculated as follows:

$$depletion_{scenario\ x} = base\ flow_{no\ pumping} - base\ flow_{scenario\ x}$$

It is common practice for a prediction to be presented not in absolute terms but as a difference relative to the base case (Barnett, et al., 2012). For the Cold Spring model, the base case is the reference base flow defined above. The percent difference in base flow was calculated using the equation below:

$$Percent\ difference_{scenario\ x} = \frac{depletion_{scenario\ x}}{reference\ base\ flow}$$

5.2 Cumulative impact scenarios

To determine the current cumulative impact of groundwater withdrawal on Cold Spring Creek and to calculate the effect of pumping distance and volume on the creek, five scenarios were simulated (results in Table 14):

Scenario 1 (Calibrated): All wells were pumped at the average 2006-2018 pumping rates, i.e., this is what the calibrated model calculates.

Scenario 2 (2018): All wells were pumped at 2018 pumping rates, averaged over the year.

Scenario 3 (1/4 mile): All wells within ¼ mile of Cold Spring Creek were turned off and the rest of the wells in the model domain were pumped at 2018 rates.

Scenario 4 (half mile): All wells within ½ mile of Cold Spring Creek were turned off and the rest of the wells in the model domain were pumped at 2018 rates.

Scenario 5 (one mile): All wells within 1 mile of Cold Spring Creek were turned off and the rest of the wells in the model domain were pumped at 2018 rates.

Scenario 6 (two miles): All wells within 2 miles of Cold Spring Creek were turned off and the rest of the wells in the model domain were pumped at 2018 rates.

Table 14. Simulated base flow in Cold Spring Creek for Scenarios 1 through 6

Scenario	Simulation	Pumping volume (mgy)	Upstream reach H16011008 (cfs)	Depletion over upstream reach (cfs)	Upstream reach % difference	Downstream reach H16011007 (cfs)	Depletion over downstream reach (cfs)	Downstream reach % difference
	Measured (from field data)	--	***0.49***	--	--	***1.94***	--	--
	No pumping	0	0.52	--	--	2.13	--	--
	2014-2018	1150	0.4	0.12	--	1.65	0.48	--
1	Calibrated	1199	0.42	0.1	16.4	1.75	0.38	15.7
2	2018	1313	0.39	0.13	21.3	1.66	0.47	19.4
3	Quarter mile (Figure 57)	1125	0.49	0.03	4.9	2.02	0.11	4.5
4	Half mile (Figure 58)	1121	0.49	0.03	4.9	2.02	0.11	4.5
5	One mile (Figure 59)	811	0.49	0.03	4.9	2.03	0.1	4.1
6	Two miles (Figure 60)	377	0.52	0	0.0	2.12	0.01	0.4

For Scenarios 2 through 5, MODFLOW reduced the specified pumping by 17.3 mgy (179.21 m^3/day). For Scenario 6, MODFLOW reduced the specified pumping by 0.9 mgy (9.16 m^3/day). The pumping volume shown in Table 14 is what was modeled after the automatic reduction.

5.3 Hypothetical water supply scenarios at the City's wellfield

Six model scenarios were simulated to demonstrate the effect of different pumping regimes at the City's existing wellfield. These scenarios are not intended to be prescriptive, but rather to help understand how different pumping configurations affect Cold Spring Creek. Results are shown in Table 15 and Figure 63.

Scenario 7 (2018, ¼ mile, the City's well field): All wells within ¼ mile of Cold Spring Creek are turned off. City wells 4, 5, and 6 supply the 2018 demand from the wells within ¼ mile of Cold Spring Creek split evenly among the three wells.

Scenario 8 (2018, ¼ mile, 20 mgy, the City's well field): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (440639 and 718237, because these are the two wells with reported pumping in 2018) and City well 3. City wells 4, 5, and 6 supply the remaining 2018 demand from the wells within ¼ mile of Cold Spring Creek (188 mgy minus 20 mgy).

Scenario 9 (Permitted): All wells within the model domain pump maximum permitted volume, averaged over the year.

Scenario 10 (Permitted, ¼ mile, 20 mgy, the City's well field): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek (505 mgy minus 20 mgy).

Scenario 11 (Permitted, +103 mgy): All wells within the model domain pump maximum permitted volume, averaged over the year. City wells 4, 5, and 6 supply an additional 103 mgy.

Scenario 12 (Permitted, ¼ mile, 20 mgy, the City's well field, +103 mgy): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek and supply an additional 103 mg (505 mgy minus 20 mgy plus 103 mgy).

Table 15. Simulated base flow in Cold Spring Creek for Scenarios 7 through 12

Scenario	Simulation	Pumping volume (mgy)	Upstream reach H16011008 (cfs)	Depletion over upstream reach (cfs)	Upstream reach % difference	Downstream reach H16011007 (cfs)	Depletion over downstream reach (cfs)	Downstream reach % difference
	Measured	--	*0.49*	--	--	*1.94*	--	--
	No pumping	0	0.52	--	--	2.13	--	--
	2014-2018	1150	0.4	0.12	--	1.65	0.48	--
7	2018, ¼ mile, the City's well field (Figure 57)	1313	0.47	0.05	8.2	1.94	0.19	7.9
8	2018, ¼ mile, 20 mgy, the City's well field (Figure 57)	1313	0.46	0.06	9.8	1.92	0.21	8.7
9	Permitted	2377	0.37	0.15	24.6	1.52	0.61	25.2
10	Permitted, ¼ mile, 20 mgy, the City's well field (Figure 57)	2377	0.43	0.09	14.8	1.81	0.32	13.2
11	Permitted, +103 mgy	2480	0.35	0.17	27.9	1.48	0.65	26.9
12	Permitted, ¼ mile, 20 mgy, the City's well field, +103 mgy (Figure 57)	2480	0.42	0.1	16.4	1.77	0.36	14.9

For Scenarios 9 through 12, MODFLOW reduced the specified pumping by 129 mgy (1338 m^3/day). The pumping volume shown in Table 15 is what was modeled after the automatic reduction.

5.4 Hypothetical water supply scenarios at Lot 1/Block 1

Six model scenarios were simulated to demonstrate the effect of shifting water supply demand to a potential new well field. These scenarios are not intended to be prescriptive, but rather to help understand how different pumping configurations affect Cold Spring Creek. Results are shown in Table 16 and Figure 63.

Scenario 13 (Permitted, ¼ mile, 20 mgy, +103 mgy Lot 1/Block 1): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek. The Lot 1/Block 1 site supplies an additional 103 mgy from test well (unique number 00812233).

Scenario 14 (Permitted, ¼ mile, 20 mgy, +103mgy, 200 mgy Lot 1/Block 1): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek minus 97 mgy. The Lot 1/Block 1 site supplies the 97 mgy from the City's wells and an additional 103 mgy from test well (unique number 00812233).

Scenario 15 (Permitted, ¼ mile, 20 mgy, +103mgy, 300 mgy Lot 1/Block 1): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek minus 197 mgy. The Lot 1/Block 1 site supplies the 197 mgy from the City's wells and an additional 103 mgy from test well (unique number 00812233).

Scenario 16 (Permitted, ¼ mile, 20 mgy, +103mgy, 400 mgy Lot 1/Block 1): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek minus 297 mgy. The Lot 1/Block 1 site supplies the 297 mgy from the City's wells and an additional 103 mgy from test well (unique number 00812233).

Scenario 17 (Permitted, ¼ mile, 20 mgy, +103mgy, 500 mgy Lot 1/Block 1): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek minus 397 mgy. The Lot 1/Block 1 site supplies the 397 mgy from the City's wells and an additional 103 mgy from test well (unique number 00812233).

Scenario 18 (Permitted, ¼ mile, 20 mgy, +103mgy, all Lot 1/Block 1): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and the Lot 1/Block 1 site supplies the remaining demand and an additional 103 mgy from test well (unique number 00812233).

Table 16. Simulated base flow in Cold Spring Creek for Scenarios 13 through 18

Scenario	Simulation	Pumping volume (mgy)	Upstream reach H16011008 (cfs)	Depletion over upstream reach (cfs)	Upstream reach % difference	Downstream reach H16011007 (cfs)	Depletion over downstream reach (cfs)	Downstream reach % difference
	Measured	--	*0.49*	--	--	*1.94*	--	--
	No pumping	0	0.52	--	--	2.13	--	--
	2014-2018	1150	0.4	0.12	--	1.65	0.48	--
13	Permitted, ¼ mile, 20 mgy, +103 mgy Lot 1/Block 1 (Figure 62)	2480	0.43	0.09	14.8	1.8	0.33	13.6
14	Permitted, ¼ mile, 20 mgy, +103 mgy, 200 mgy Lot 1/Block 1 (Figure 62)	2480	0.44	0.08	13.1	1.84	0.29	12.0
15	Permitted, ¼ mile, 20 mgy, +103 mgy, 300 mgy Lot 1/Block 1 (Figure 62)	2480	0.45	0.07	11.5	1.88	0.25	10.3
16	Permitted, ¼ mile, 20 mgy, +103 mgy, 400 mgy Lot 1/Block 1 (Figure 62)	2480	0.46	0.06	9.8	1.92	0.21	8.7
17	Permitted, ¼ mile, 20 mgy, +103 mgy, 500 mgy Lot 1/Block 1 (Figure 62)	2480	0.47	0.05	8.2	1.95	0.18	7.4
18	Permitted, ¼ mile, 20 mgy, +103 mgy, all Lot 1/Block 1 (Figure 62)	2480	0.48	0.04	6.6	1.99	0.14	5.8

For Scenarios 13 through 18, MODFLOW reduced the specified pumping by 128.9 to 129.2 mgy (1,337 m^3/day to 1340 m^3/day). The pumping volume shown in Table 16 is what was modeled after the automatic reduction.

6.0 Summary

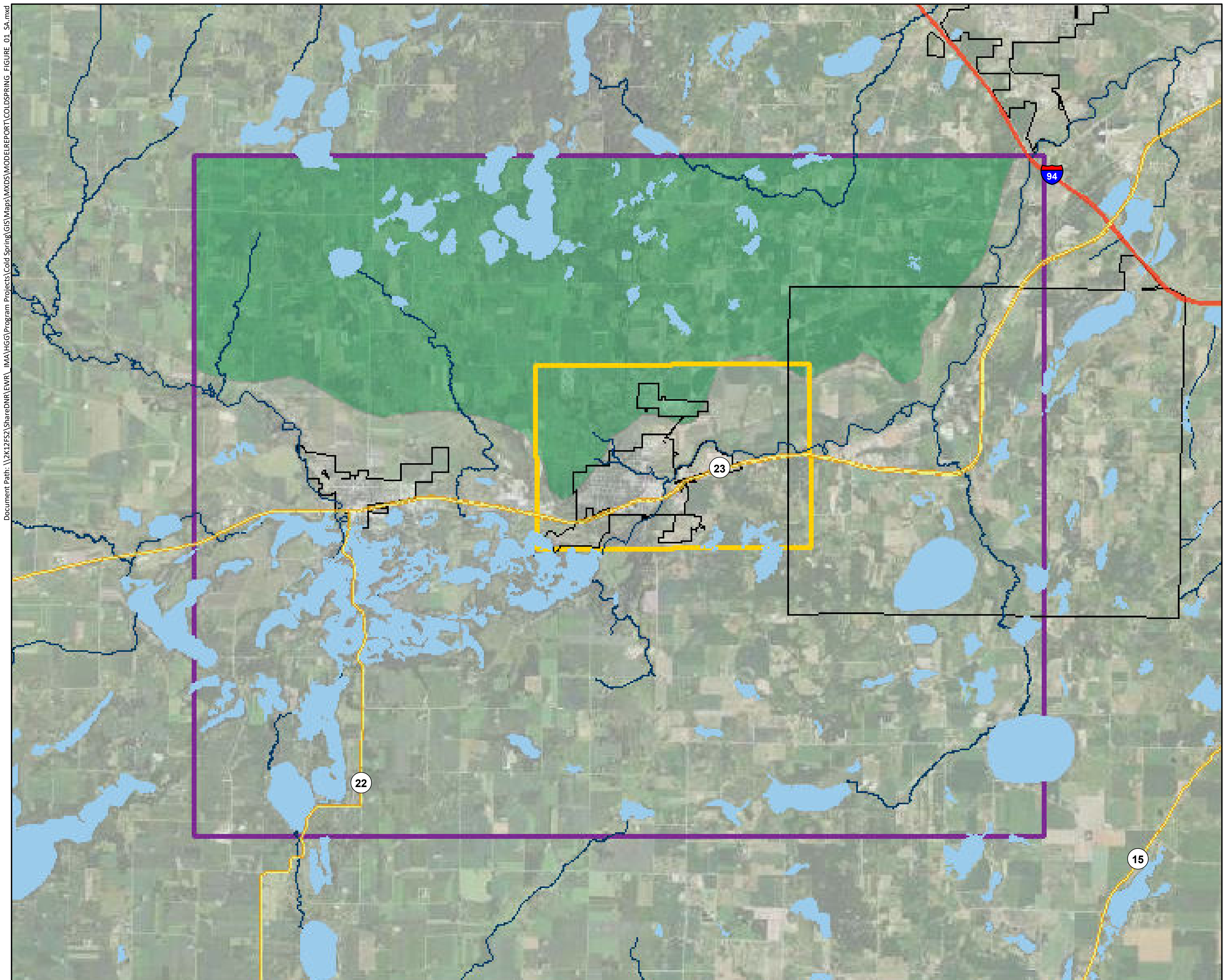
Groundwater use in and around Cold Spring, Minnesota impacts Cold Spring Creek, as shown through multiple field investigations and models (the DNR and USGS). The glacial aquifer system is strongly connected to Cold Spring Creek and supplies the City, CSBC, and numerous private and irrigation wells. The steady-state groundwater model was developed as a tool to evaluate existing and potential impacts to base flow in Cold Spring Creek.

The model simulations conducted using the steady-state numerical model show that:

- Average pumping during 2018 diverted about 21 percent (0.13 cfs) of base flow from the upstream reach of the creek on average and about 19 percent (0.47 cfs) from the downstream reach of the creek on average.
- Wells within ¼ mile of Cold Spring Creek contribute most substantially to base flow diversion in the creek.
- If all wells in the model domain pumped their maximum permitted volumes, base flow depletion would be about 25 percent (0.15 cfs) of base flow from the upstream reach and about 25 percent (0.61 cfs) of base flow from the downstream reach.
- Pumping approximately half of the City and Brewery’s water supply (300 mgy) from the Lot 1/Block 1 site instead of pumping only from the City’s current well field reduces base flow depletion to about 12 percent (0.07 cfs) at the upstream reach and 10 percent (0.25 cfs) at the downstream reach.

The DNR is evaluating seasonality of pumping and base flow. If the DNR determines that a transient model is necessary to more precisely evaluate base flow depletion, then the steady-state model described in this report could be further developed into a transient model.

7.0 Figures 1–62



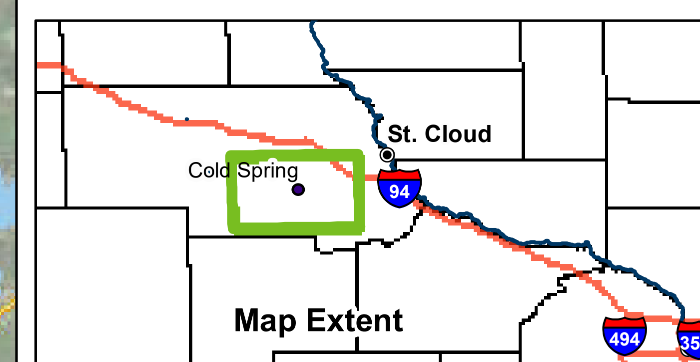


Figure 1. Study Area

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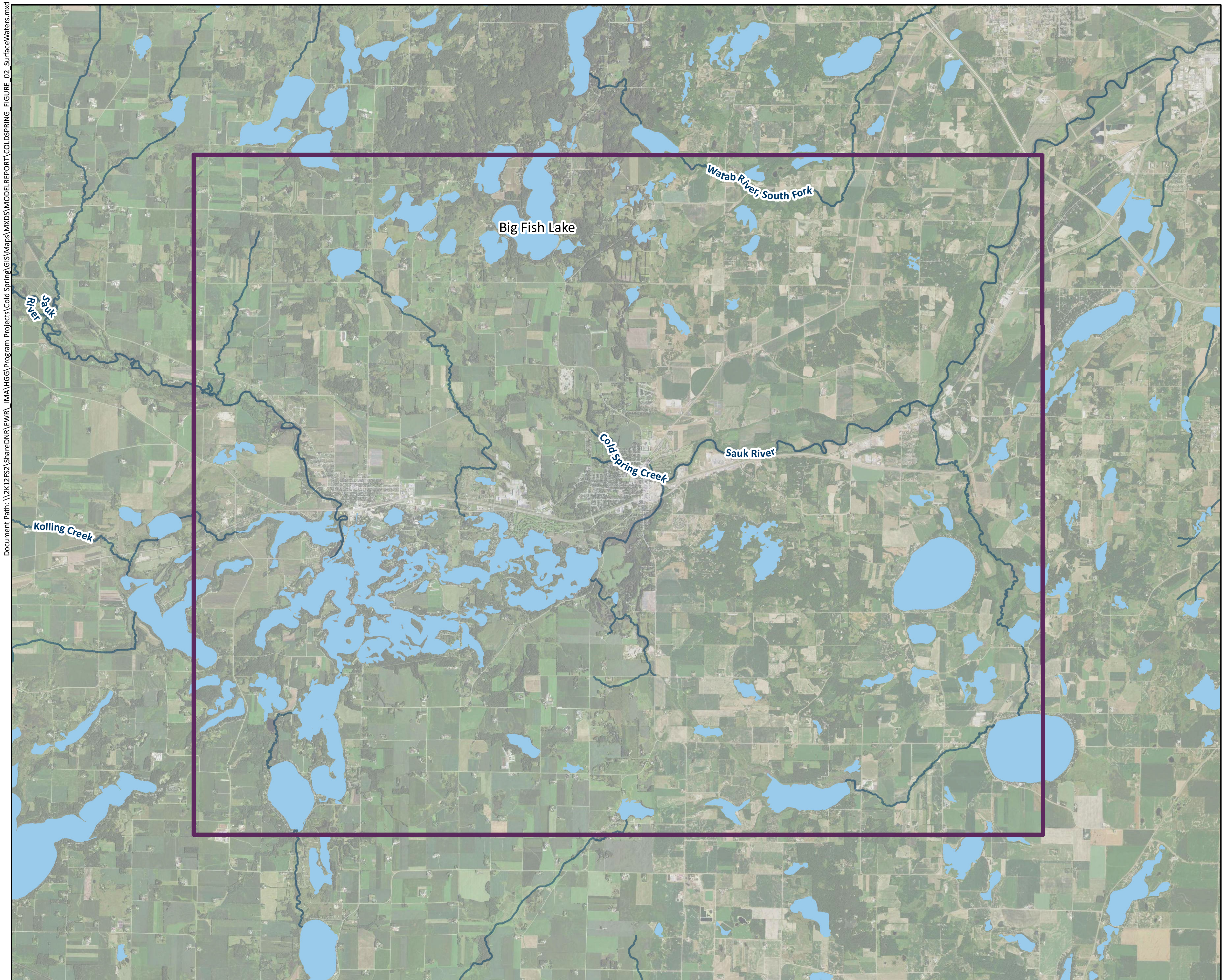

Legend

Lakes and Wetlands
Rivers and Streams
Study Area

0 0.75 1.5 3 Miles

N

Figure 2. Surface Waters

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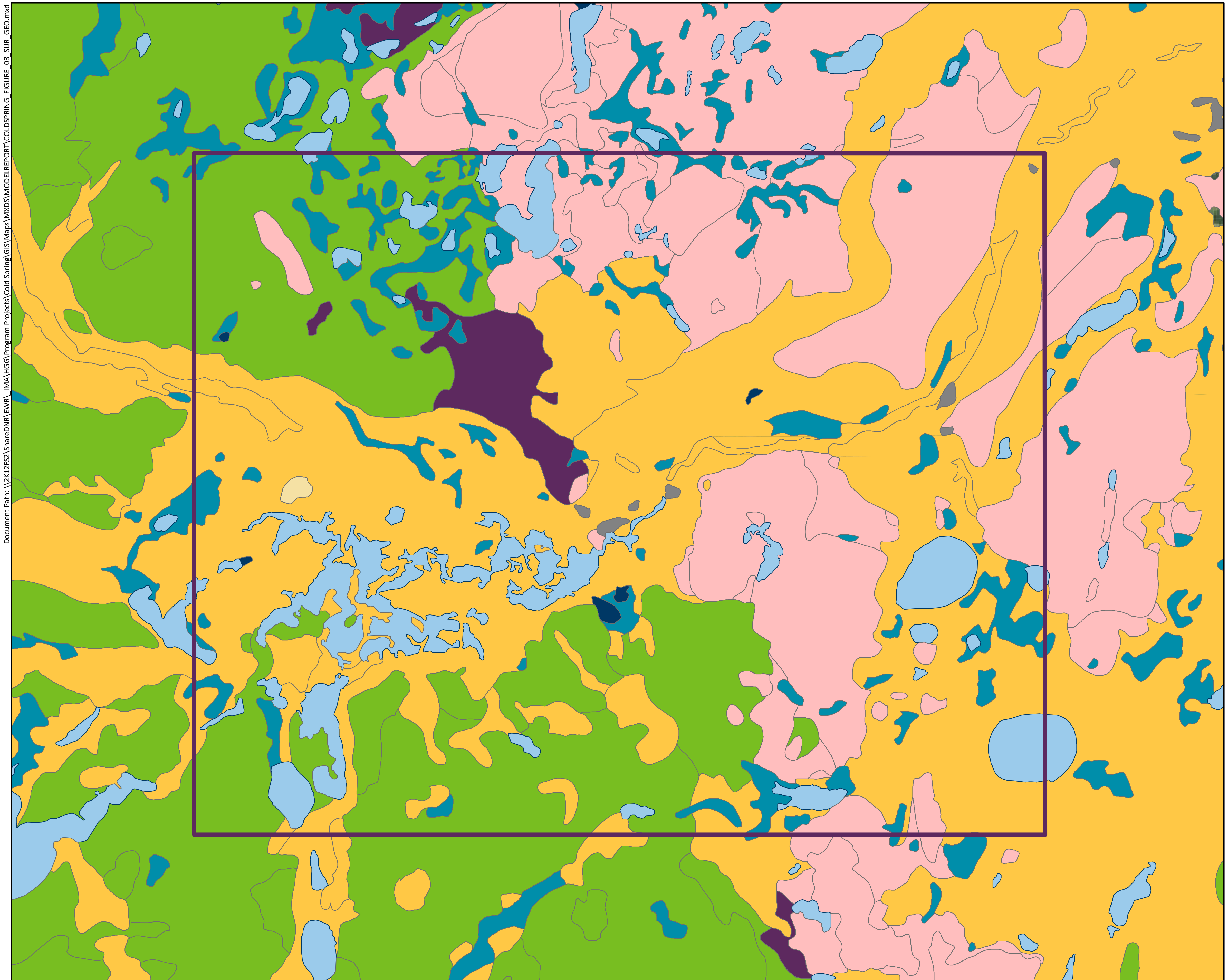

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Surficial Geology

DESCRIPTION

- Precambrian
- Sand and Gravel
- Des Moines Till
- Des Moines till/Superior cmplx
- Superior Till
- Marl
- Peat
- Winnipeg Till
- Water
- Study Area

0 0.75 1.5 3 Miles

N

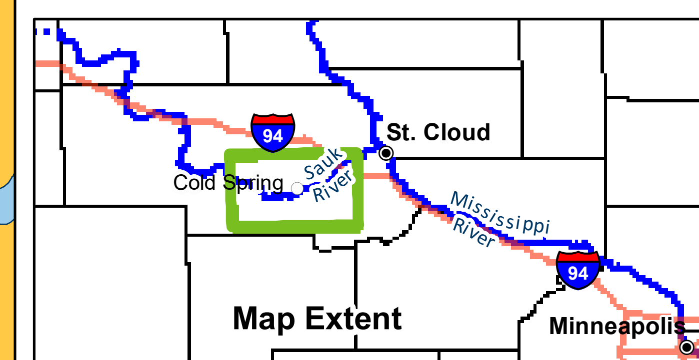

Figure 3. Surficial Geology

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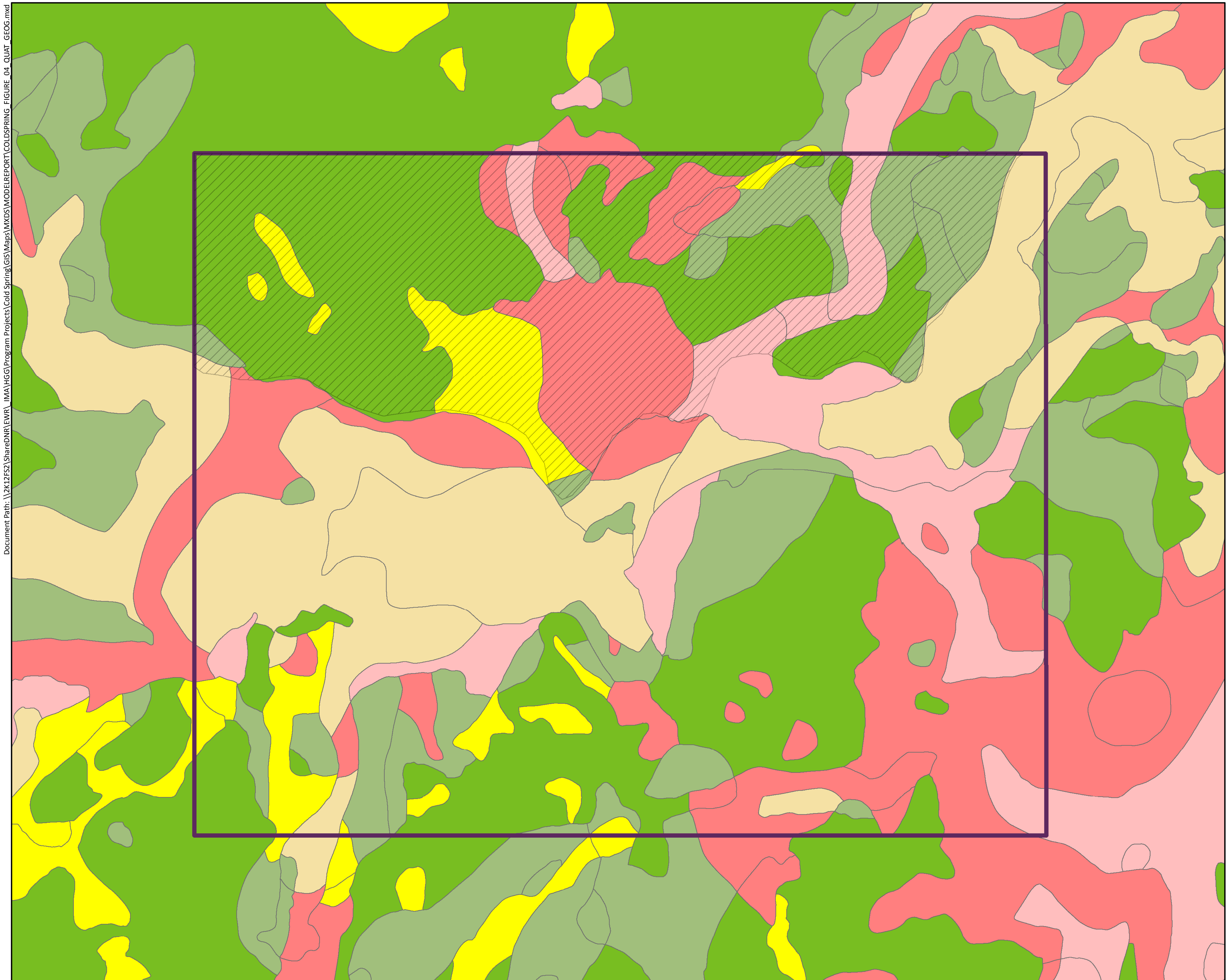

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Quaternary Deposits

- Clayey to sandy till with thick sand layers
- Clayey to sandy till with thin sand layers
- Till, sand and gravel
- Sand and Gravel outwash
- > 50 feet of sand to gravel over till
- < 50 feet of sand to gravel over till
- Upland area
- Study Area

0 0.75 1.5 3 Miles

N

Figure 4. Quaternary Geology

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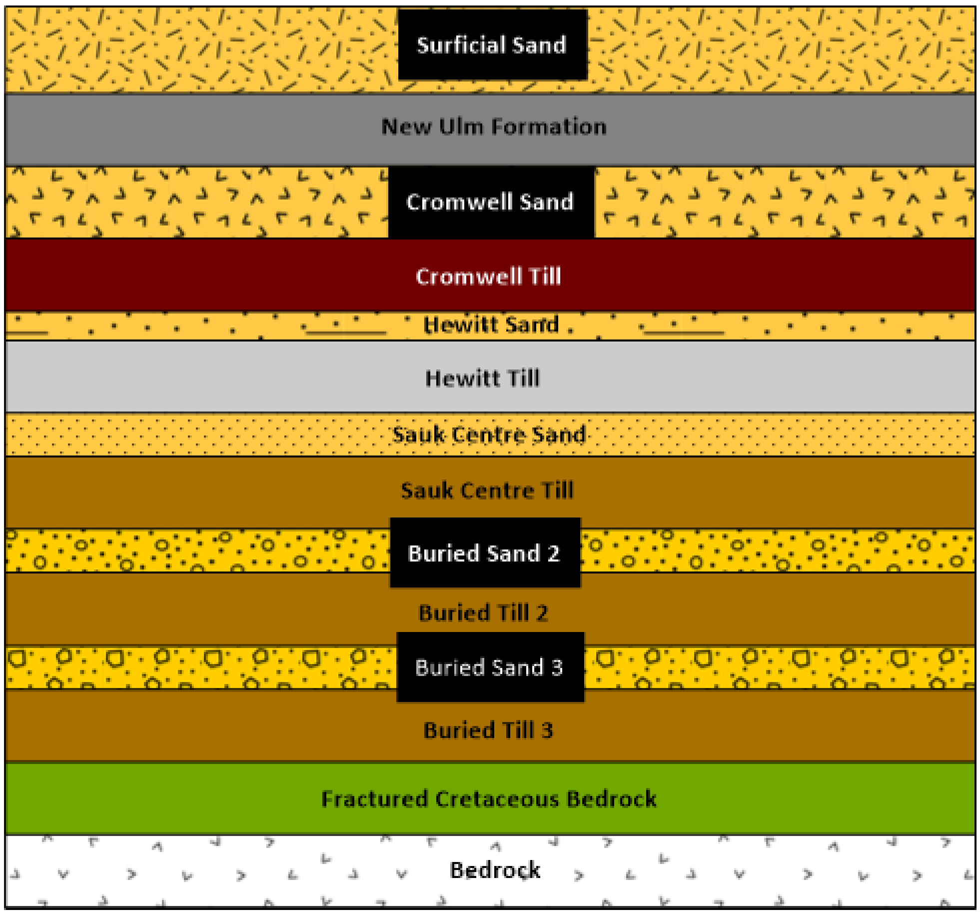

Figure 5. Stratigraphic Column

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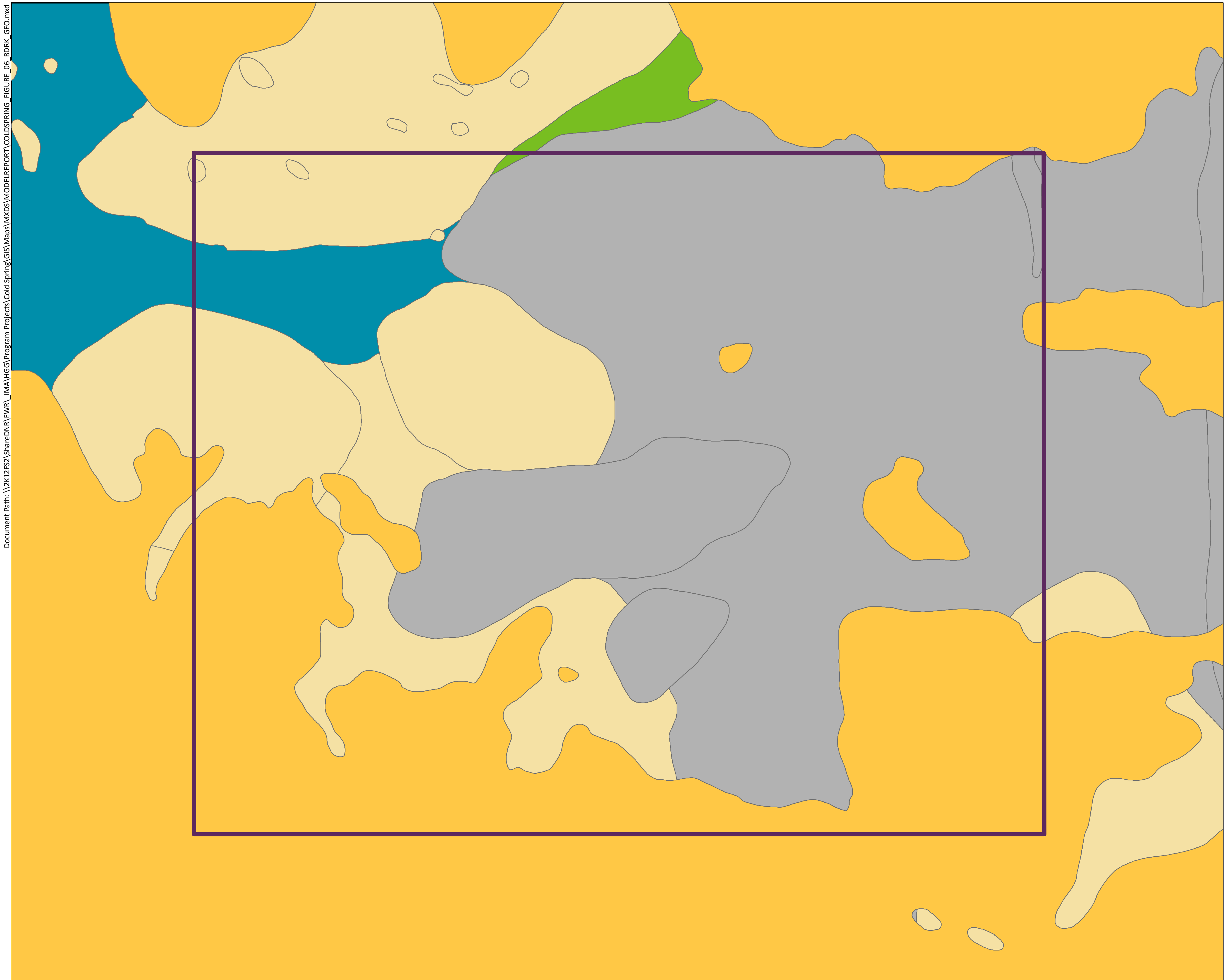

Figure 6. Bedrock Geology

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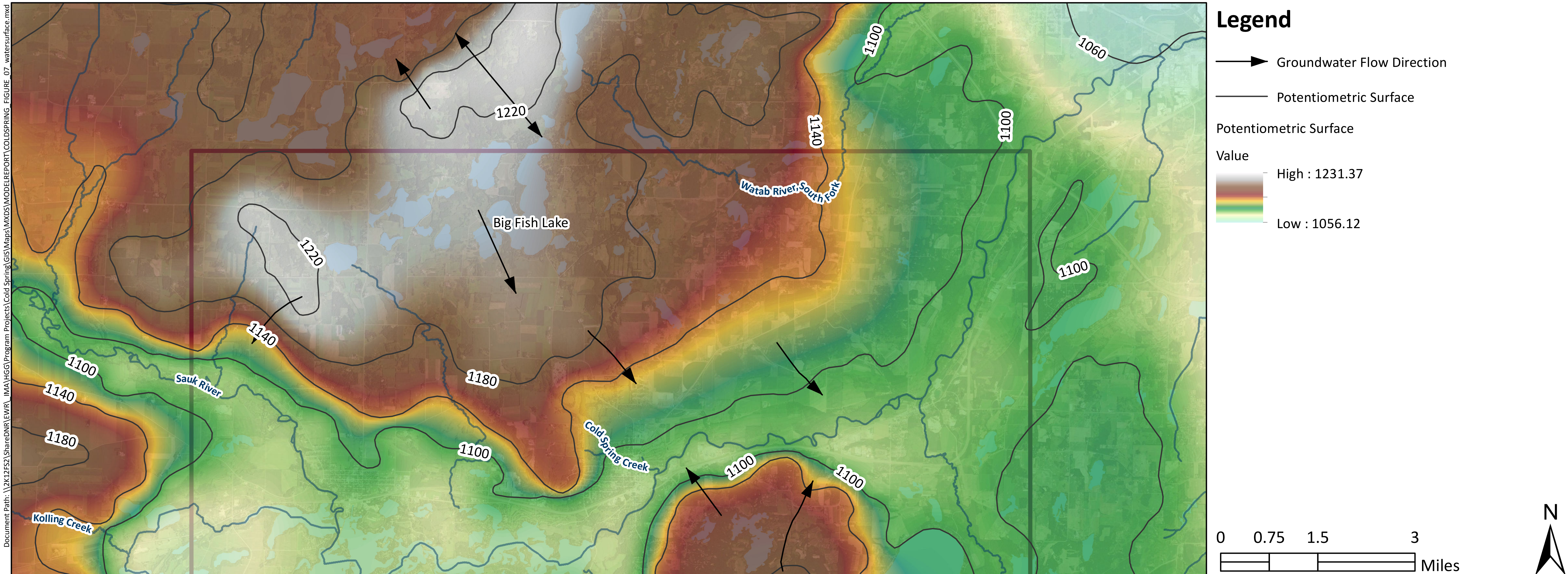

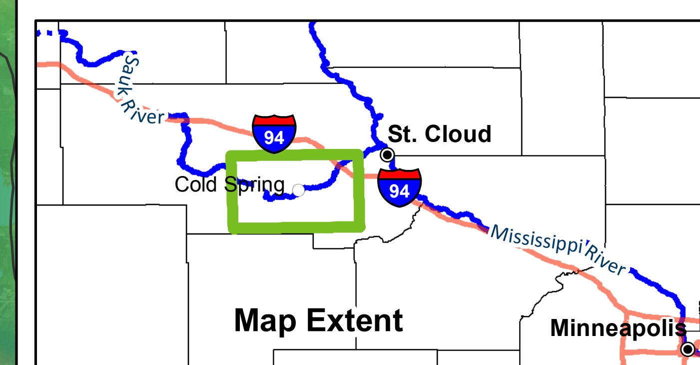

Figure 7. Potentiometric Surface

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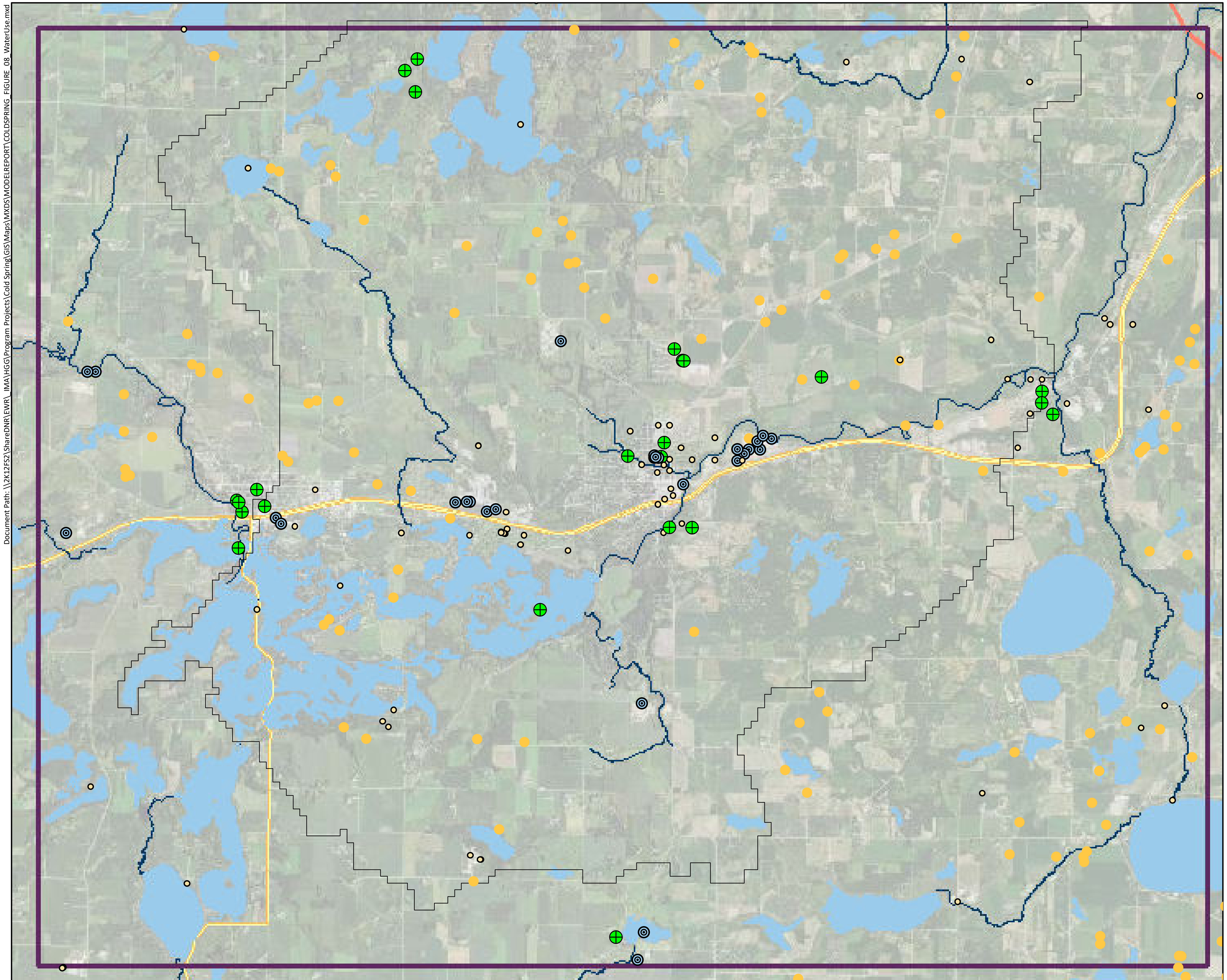

Legend

MPARS use type

- Other Uses
- Agricultural Irrigation
- Industrial Processing
- Water Supply
- Study Area
- Groundwater model boundary

Estimated water use from feedlot and domestic wells not included in this map.

0 0.5 1 2 Miles

N

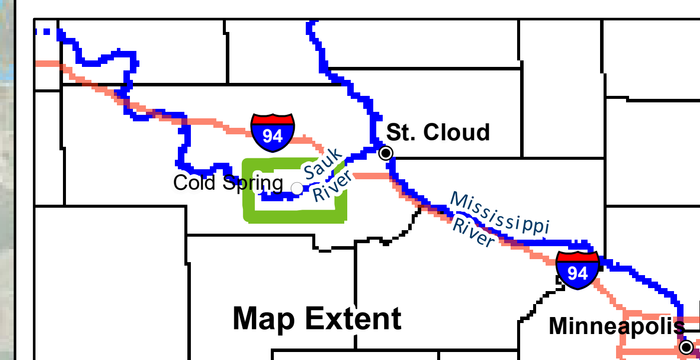

Figure 8. Permitted Water Use Map

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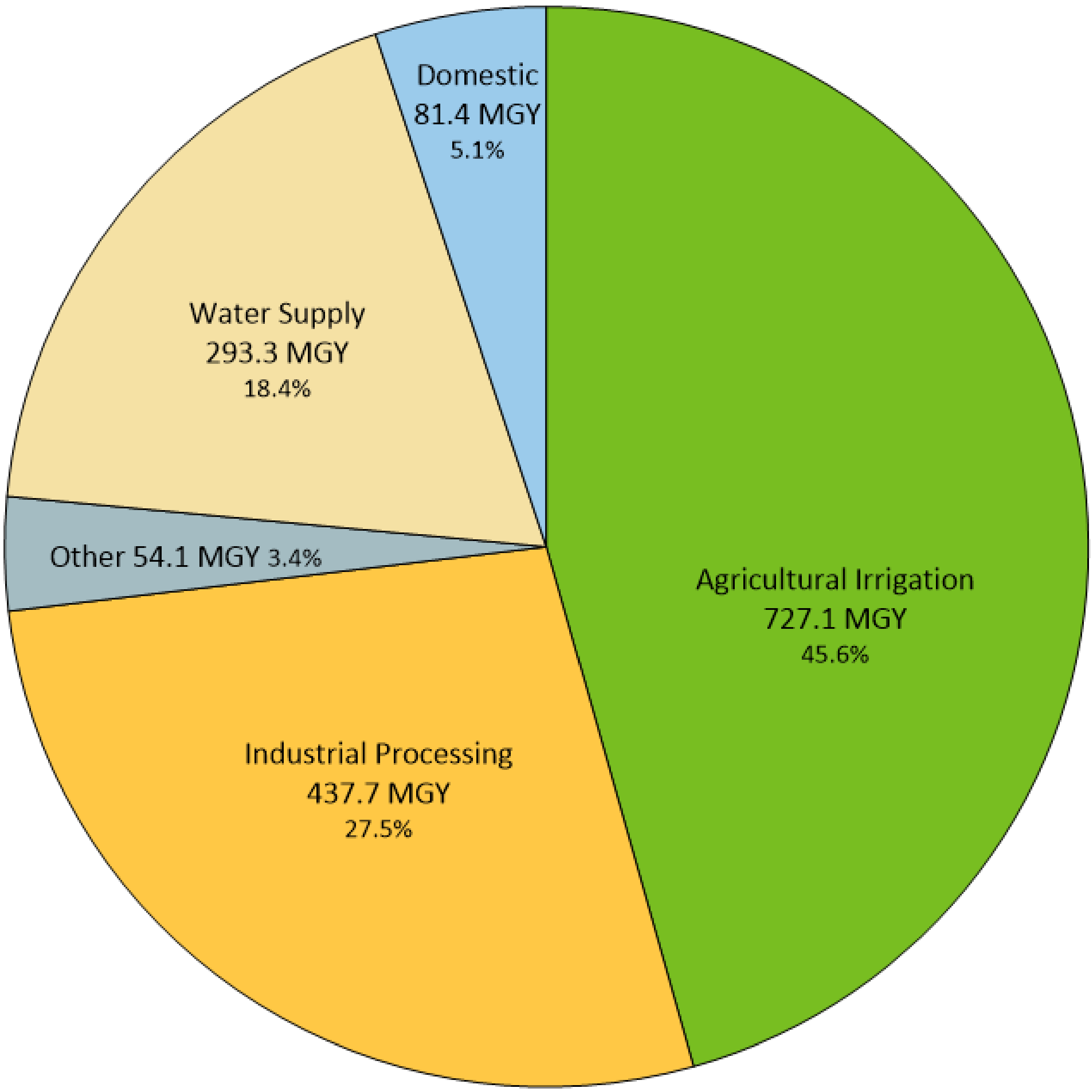

Figure 9. Water Use

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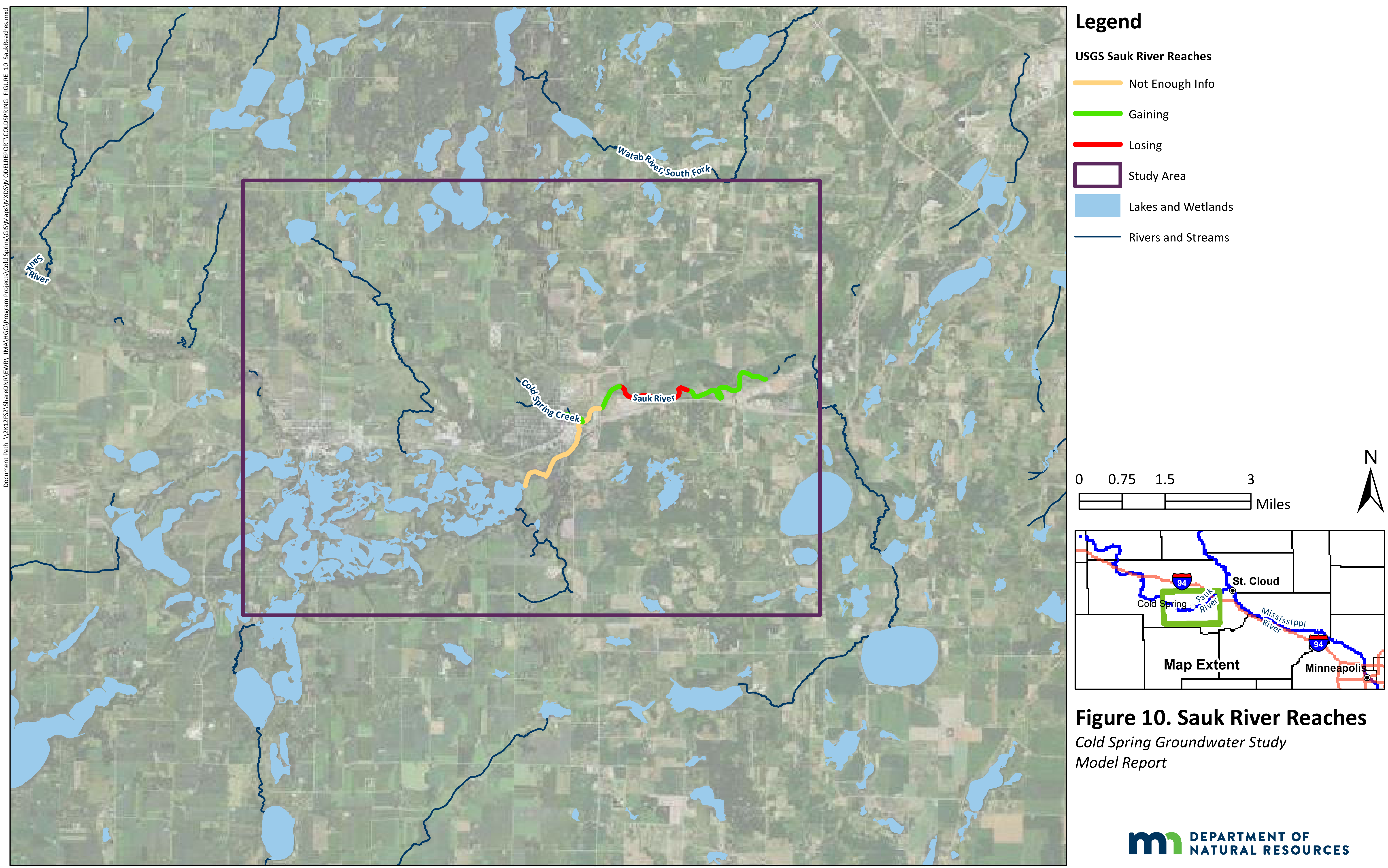

Figure 10. Sauk River Reaches

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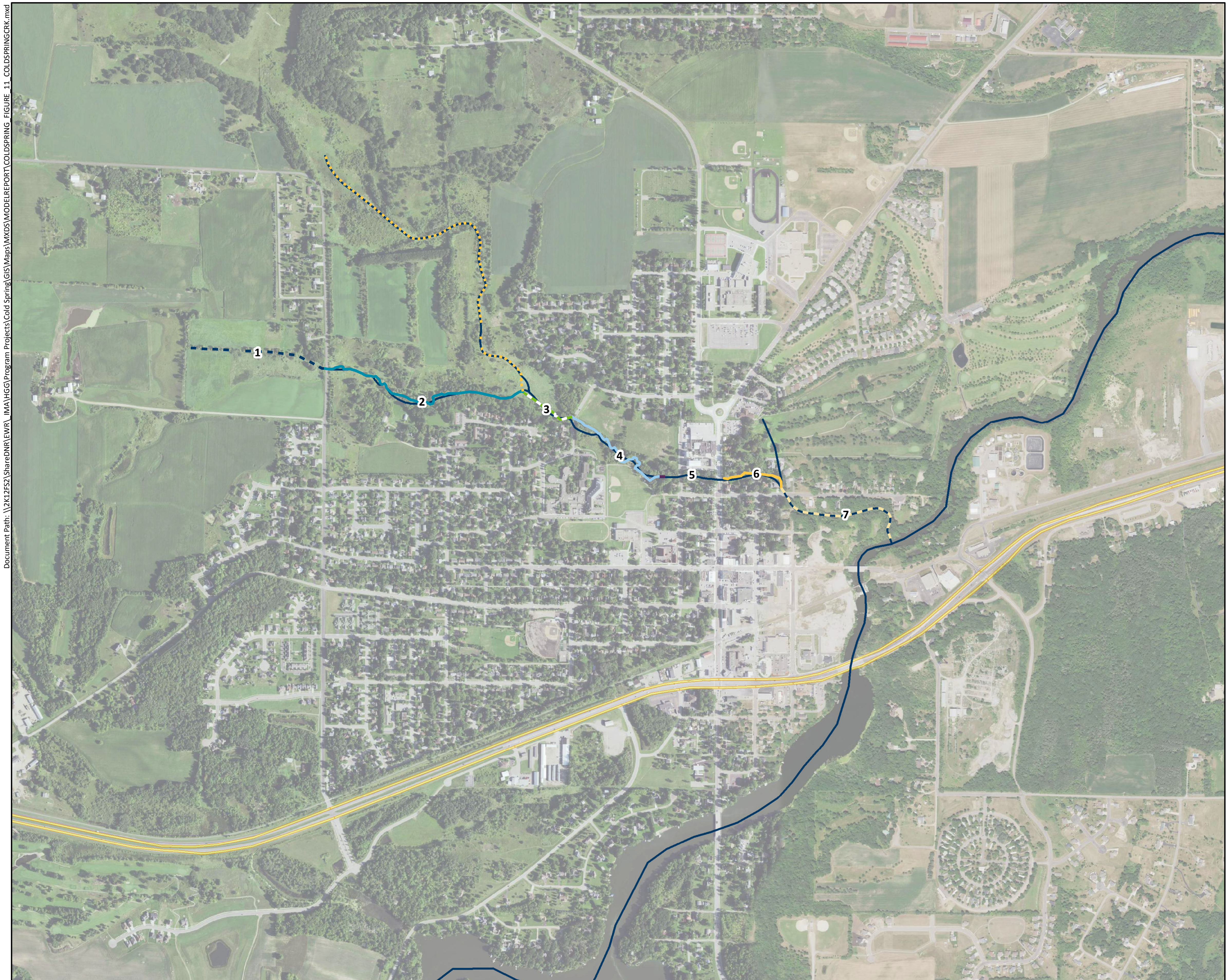

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Stream

Tributary Wetland
Cold Spring Reach 1
Cold Spring Reach 2
Cold Spring Reach 3
Cold Spring Reach 4
Cold Spring Reach 5
Cold Spring Reach 6
Cold Spring Reach 7

0 0.1 0.2 0.4 Miles

N

Figure 11. Cold Spring Creek Reaches

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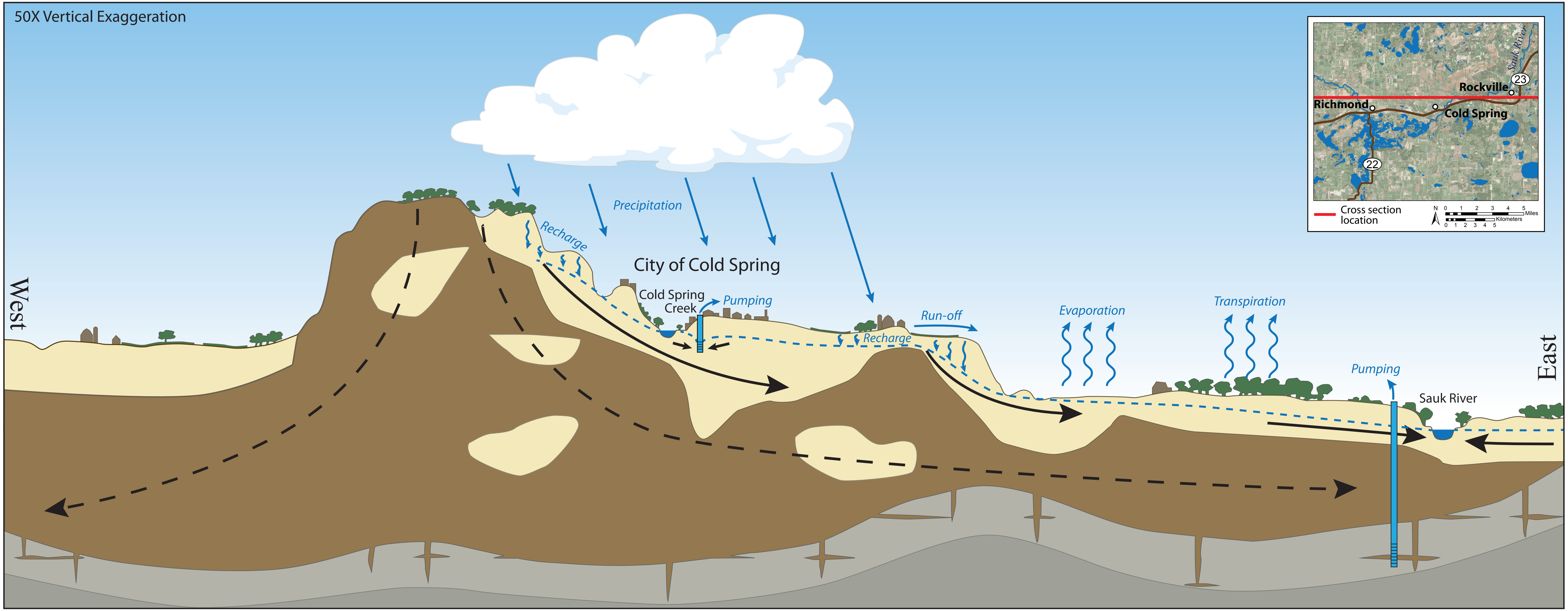

Assumed groundwater flow direction

Groundwater flow direction

Water table

Sand

Till

Fractured bedrock

Bedrock

Figure 12. Conceptual Model

Cold Spring Groundwater Study Model Report

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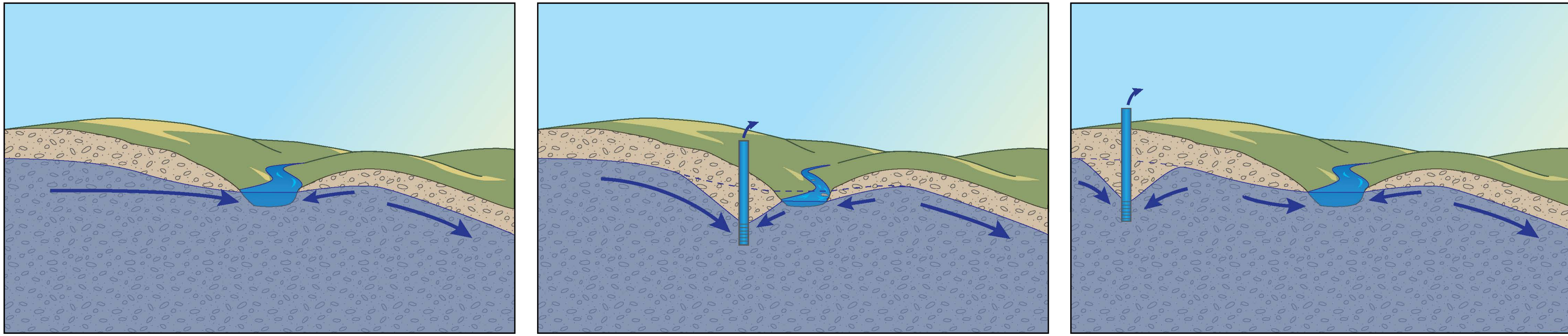
Natural State | *Pumping Near to Stream* | *Pumping Far From Stream*



In a natural state water flows to natural discharge points such as a stream or low points in the landscape.

When pumping takes place a cone of depression is formed. This is where the water table is below the natural water level. When this cone of depression is near a groundwater connected surface water body, water can be diverted from the surface water body.

When pumping takes place a cone of depression is formed. This is where the water table is below the natural water level. The further away the well is from a surface water body the less likely the cone of depression will remove water from the surface water body.

Figure 13. Pumping System

Cold Spring Groundwater Study
Model Report

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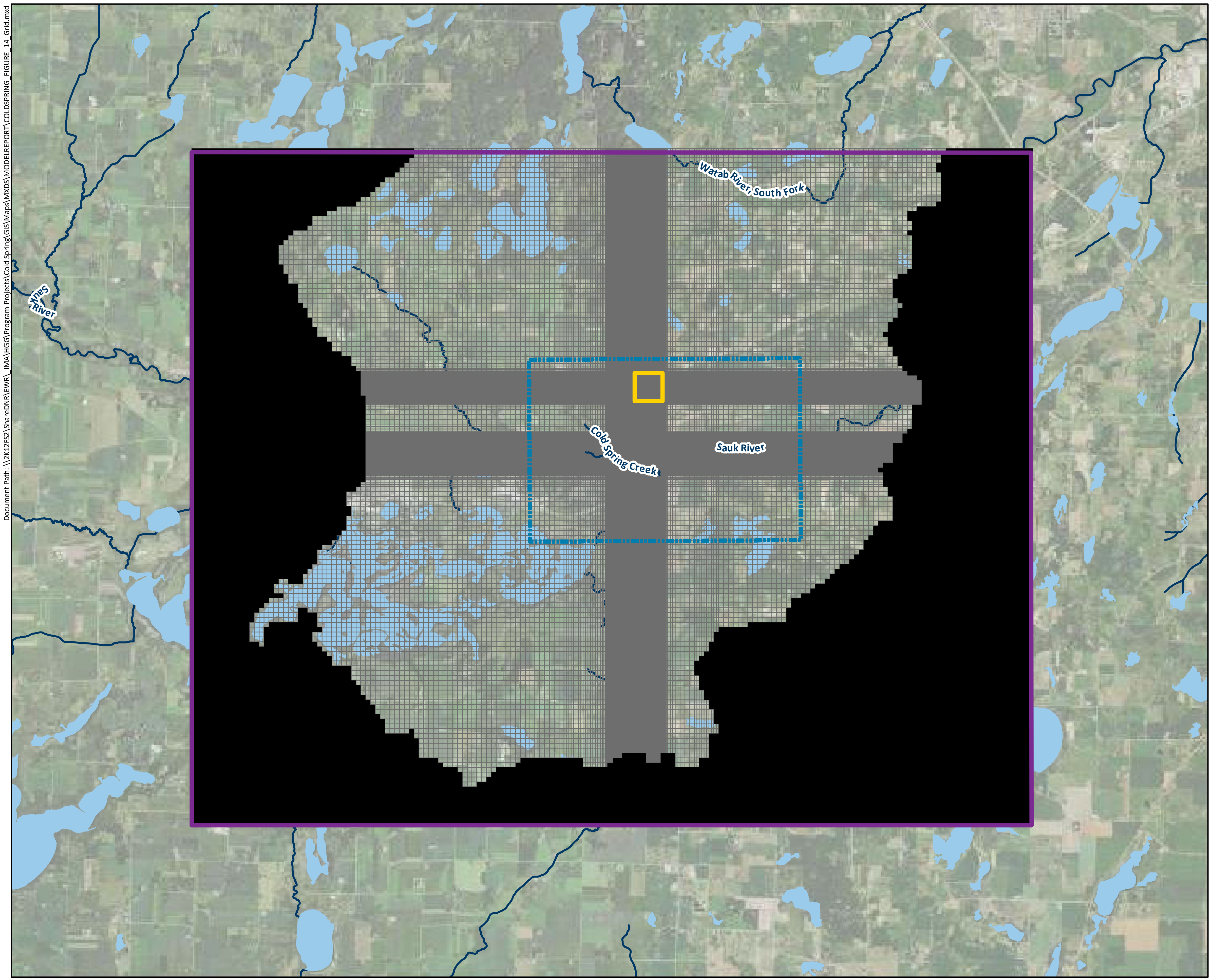

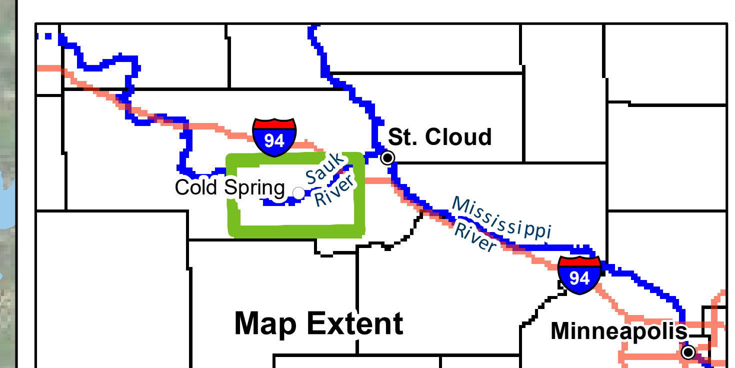

Figure 14. Numerical Model Grid

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Model Report

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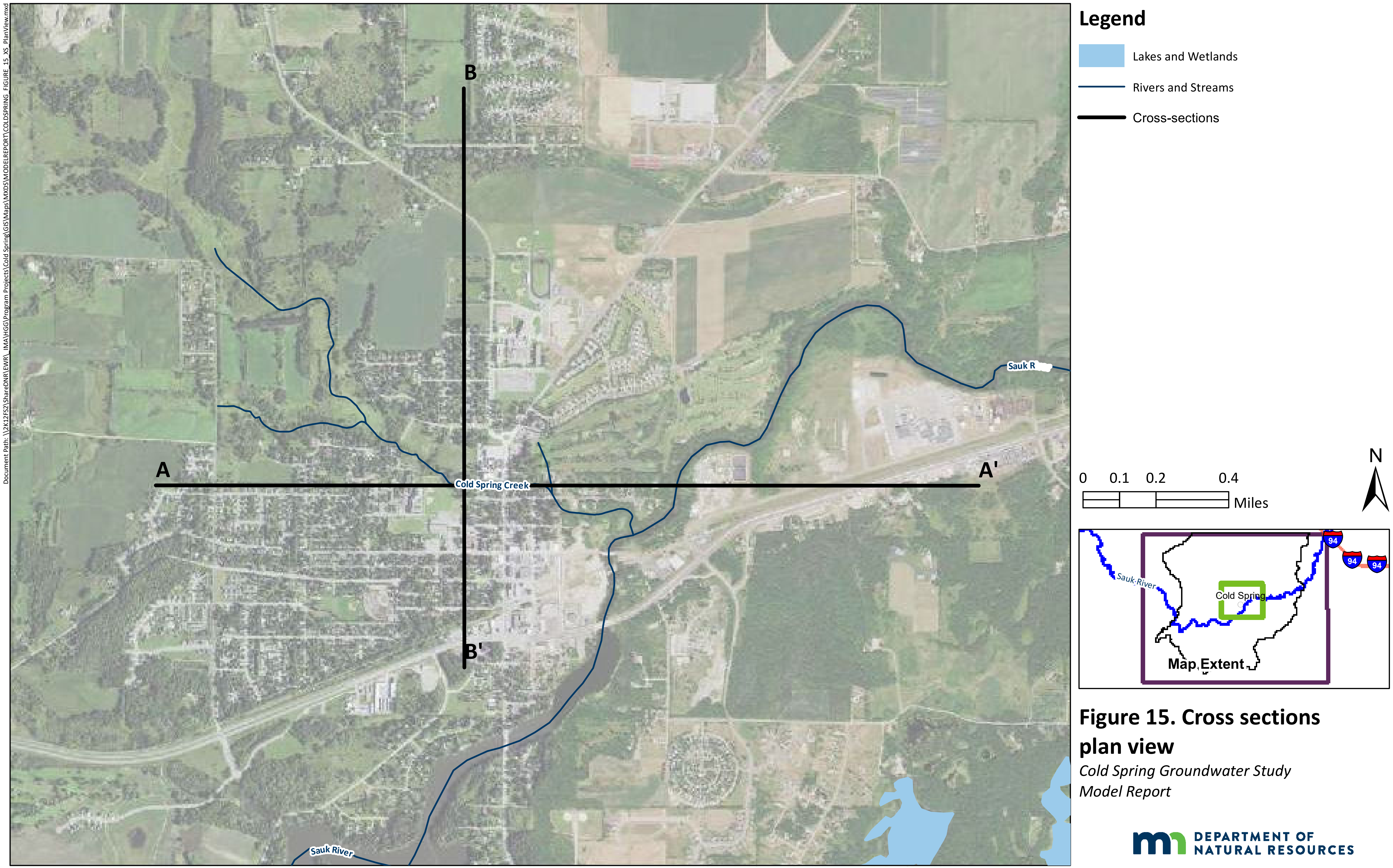

Figure 15. Cross sections plan view

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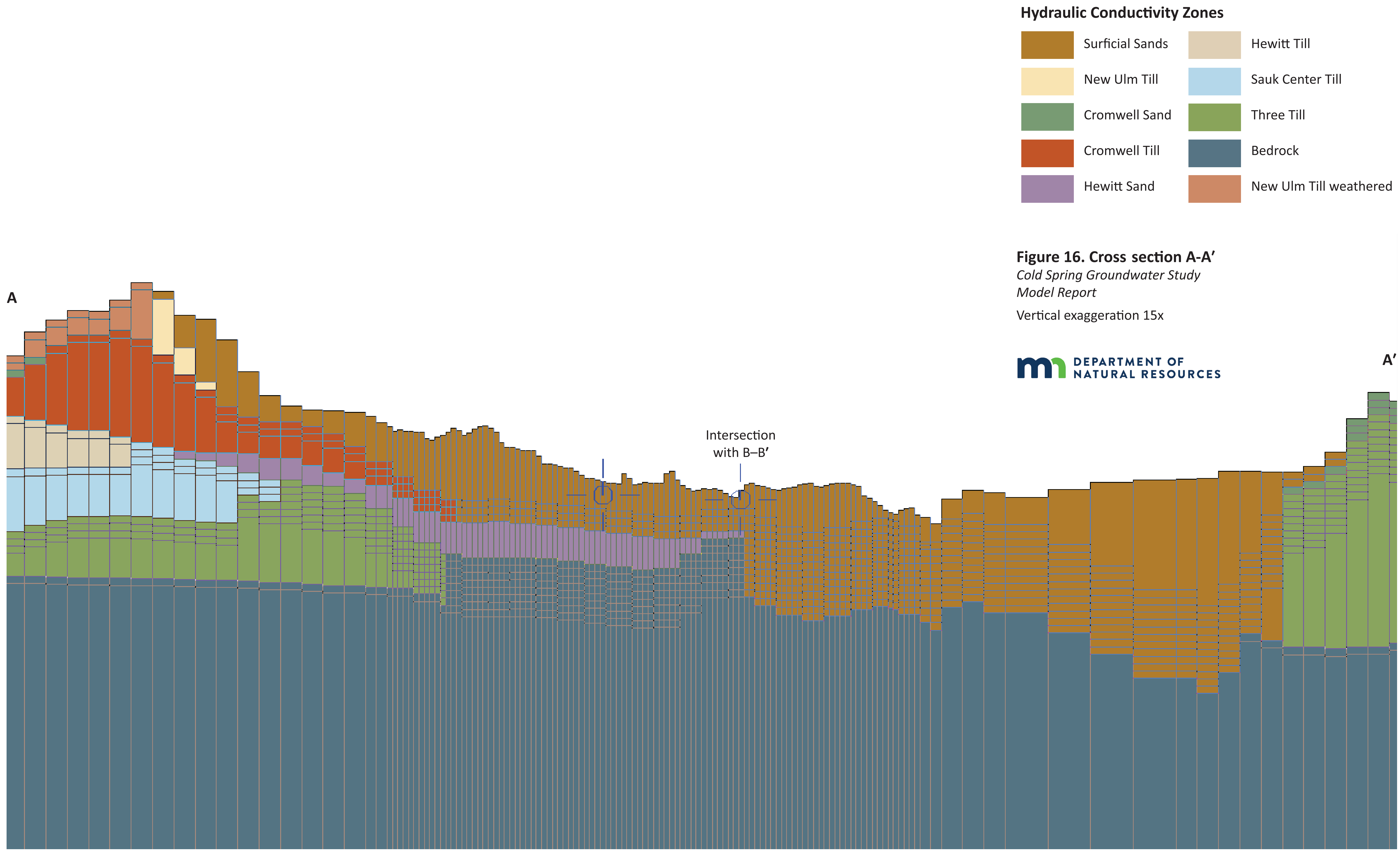

Figure 16. Cross section A-A′
Cold Spring Groundwater Study Model Report
Vertical exaggeration 15x

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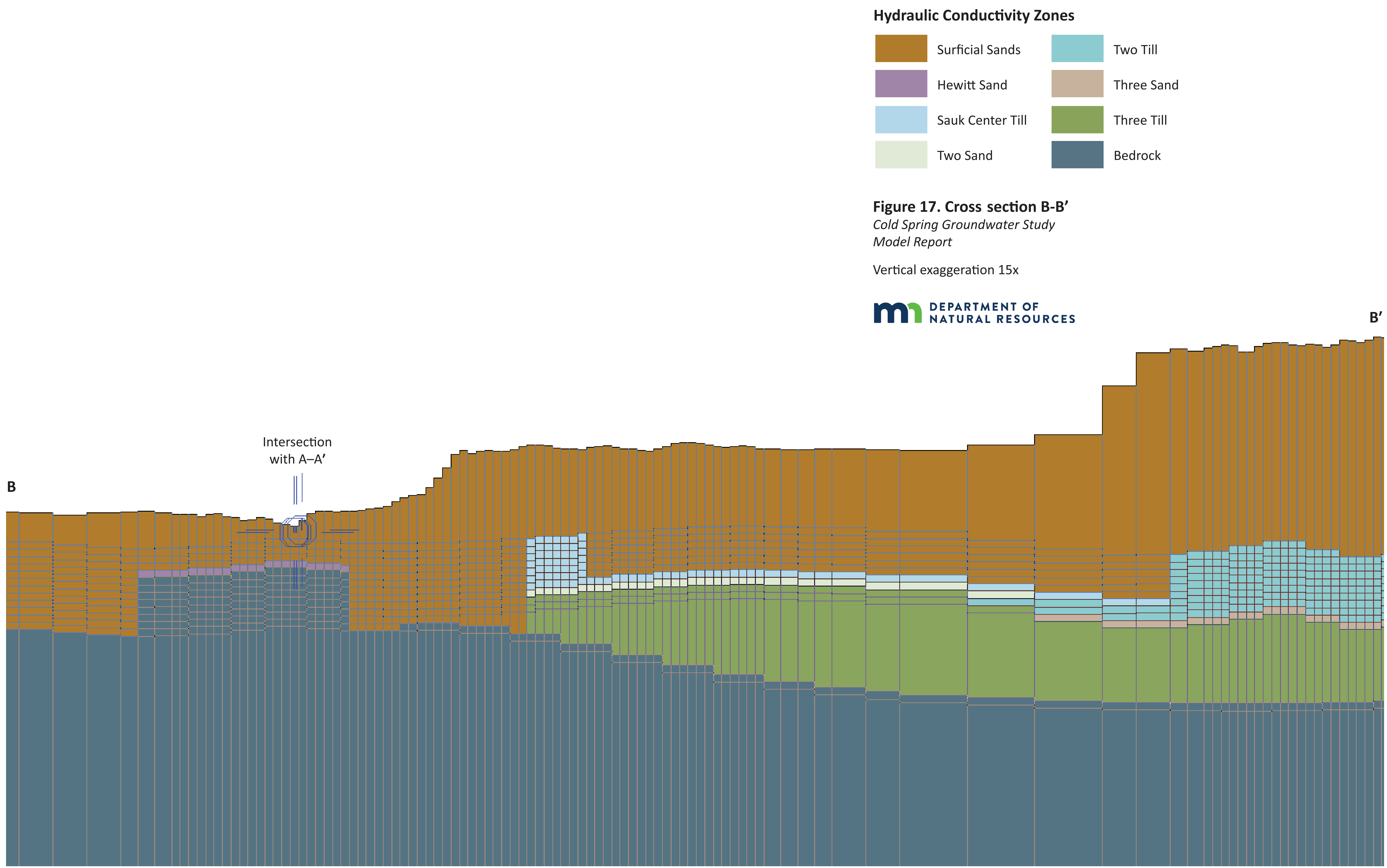

Figure 17. Cross section B-B′
Cold Spring Groundwater Study
Model Report

Vertical exaggeration 15x

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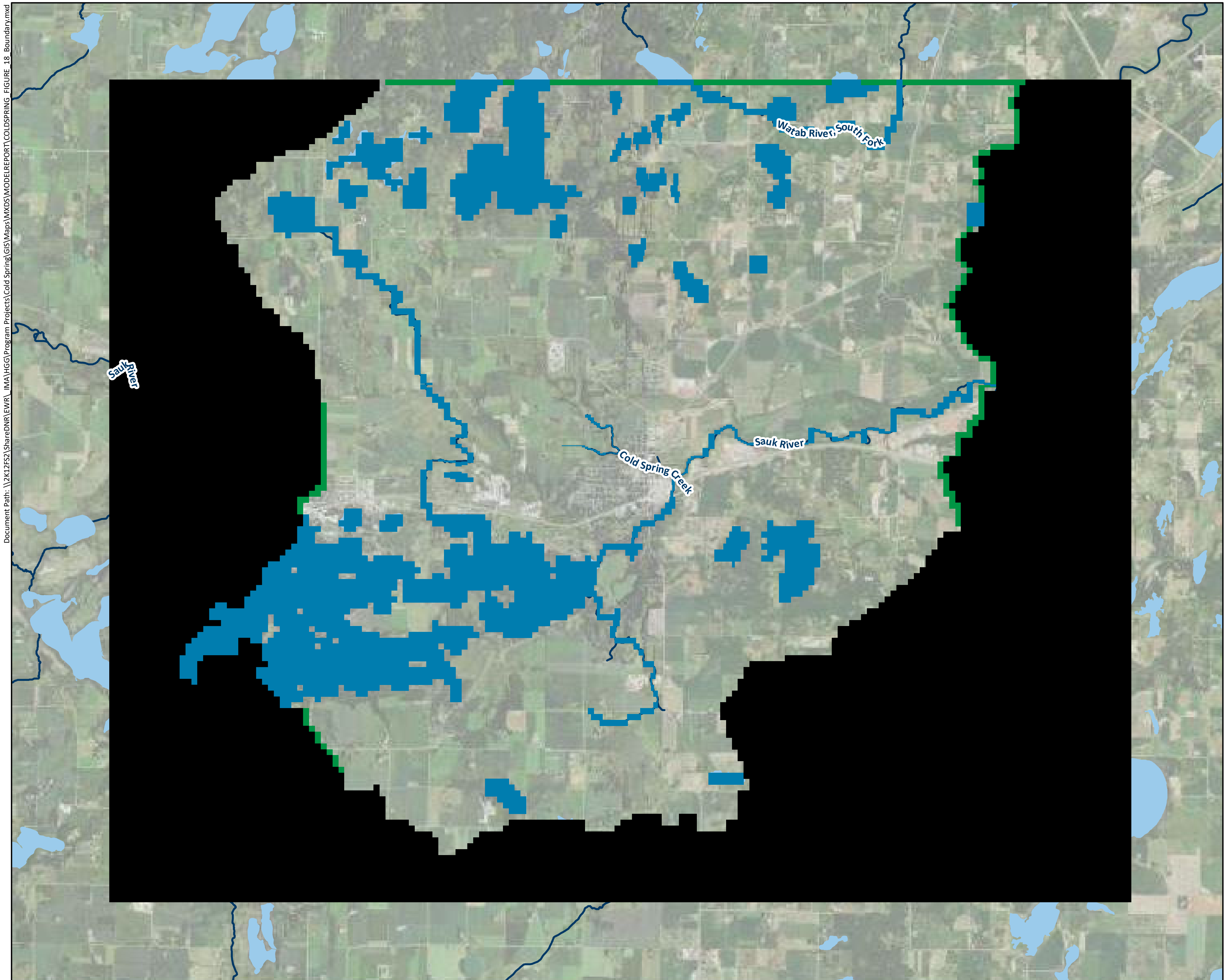

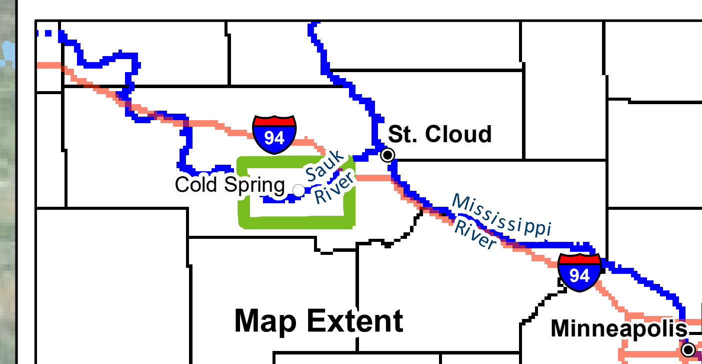

Figure 18. Model Boundaries

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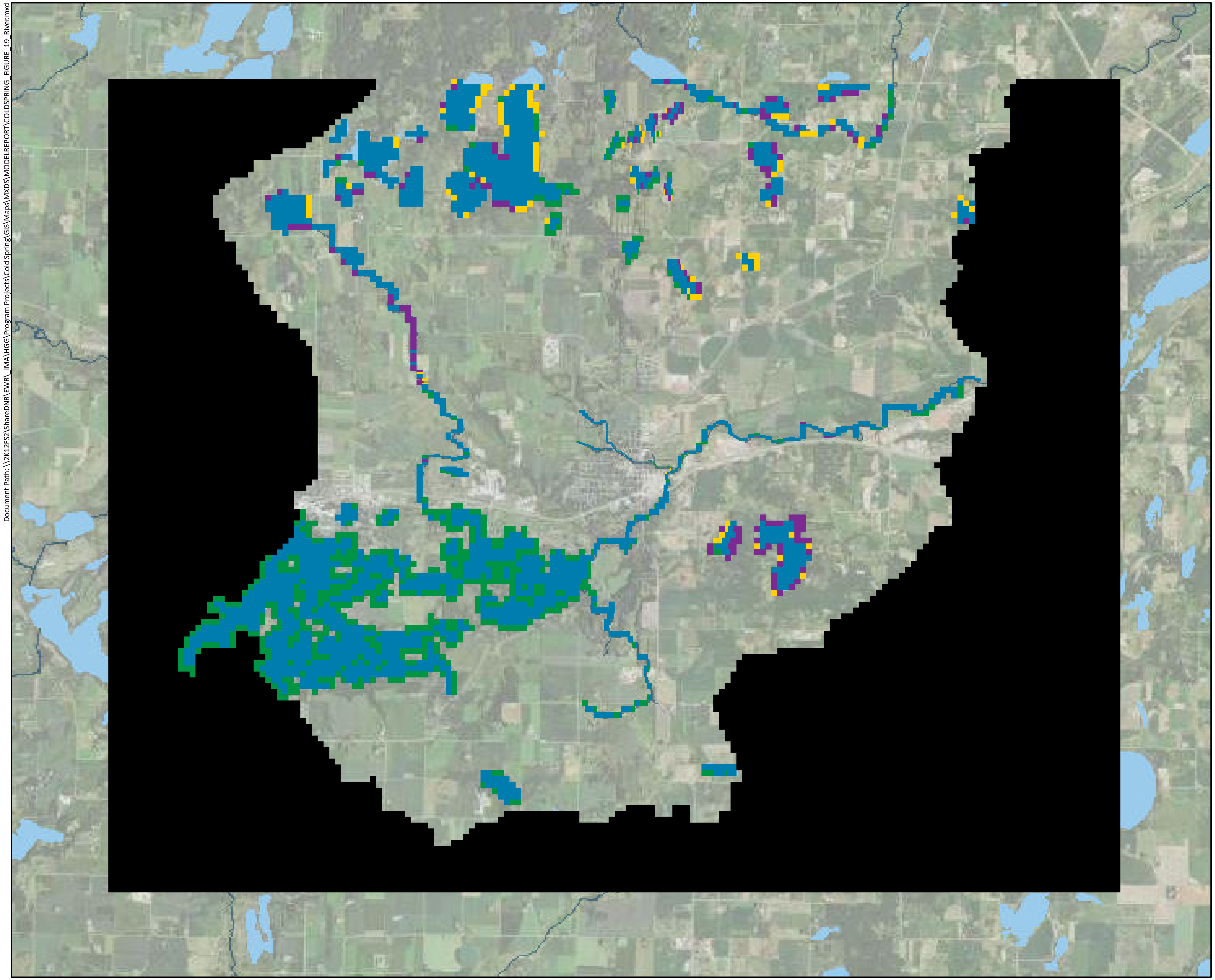

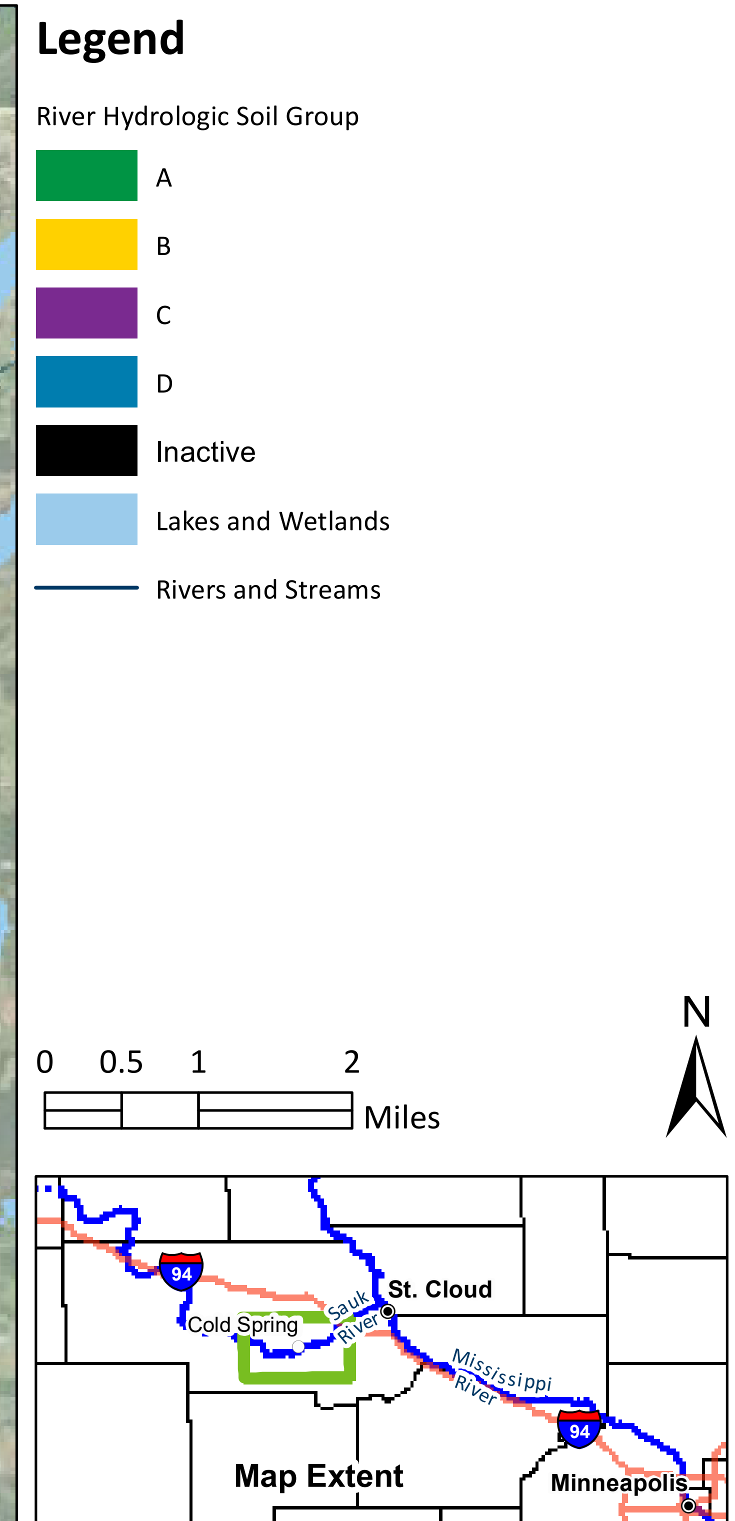

Figure 19. River Cell Groups

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Model Report

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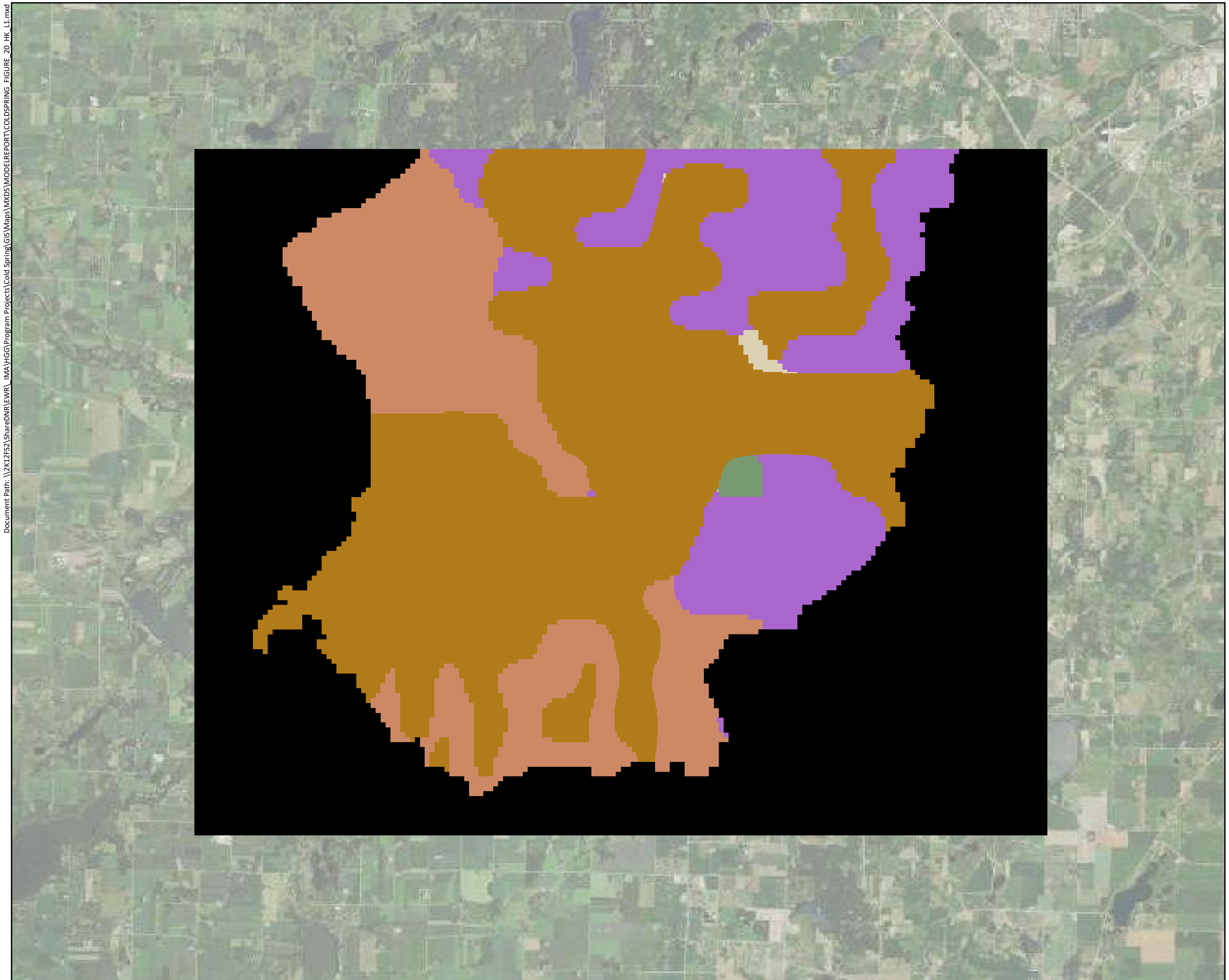

Legend

Hydraulic Conductivity Zones

- Surficial Sands (kx1/kz1)
- Cromwell Sand (kx3/kz3)
- Hewitt Till (kx6/kz6)
- New Ulm Till weathered (kx15/kz15)
- Cromwell Till weathered (kx16/kz16)

N

0 0.75 1.5 3 Miles

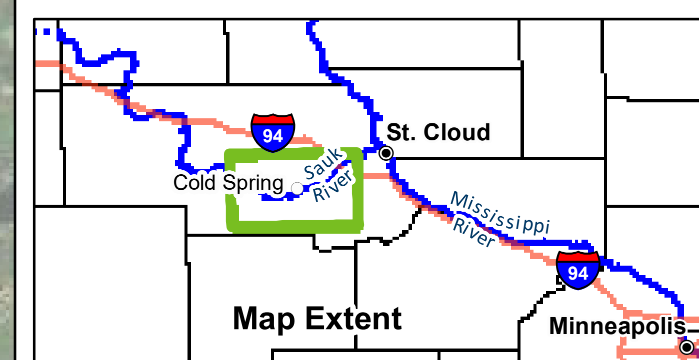

Figure 20. Layer 1 Zones

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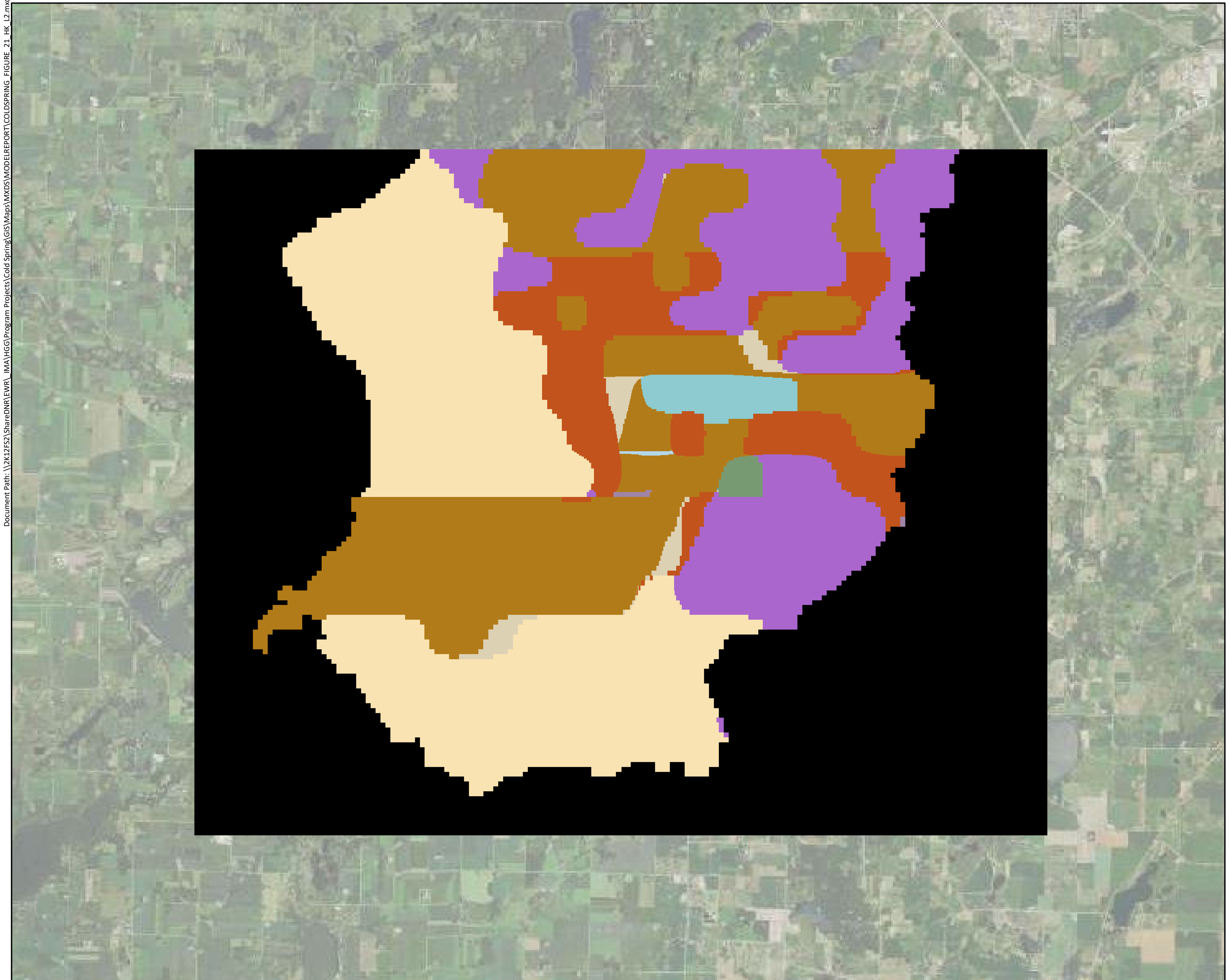

Legend

Hydraulic Conductivity Zones

- Surficial Sands (kx1/kz1)
- New Ulm Till (kx2/kz2)
- Cromwell Sand (kx3/kz3)
- Cromwell Till (kx4/kz4)
- Hewitt Sand (kx5/kz5)
- Hewitt Till (kx6/kz6)
- Sauk Center Till (kx8/kz8)
- Two Sand (kx9/kz9)
- Two Till (kx10/kz10)
- New Ulm Till weathered (kx15/kz15)
- Cromwell Till weathered (kx16/kz16)

0 0.75 1.5 3 Miles

N

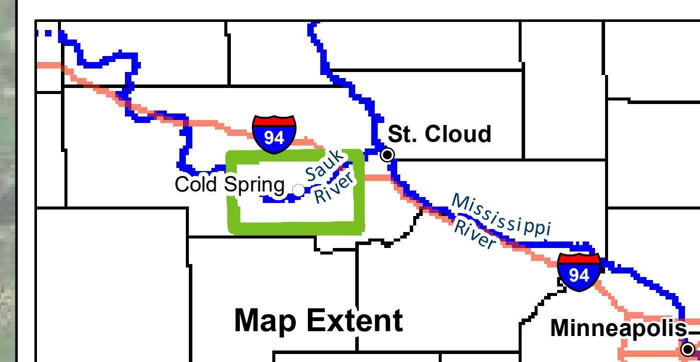

Figure 21. Layer 2 Zones

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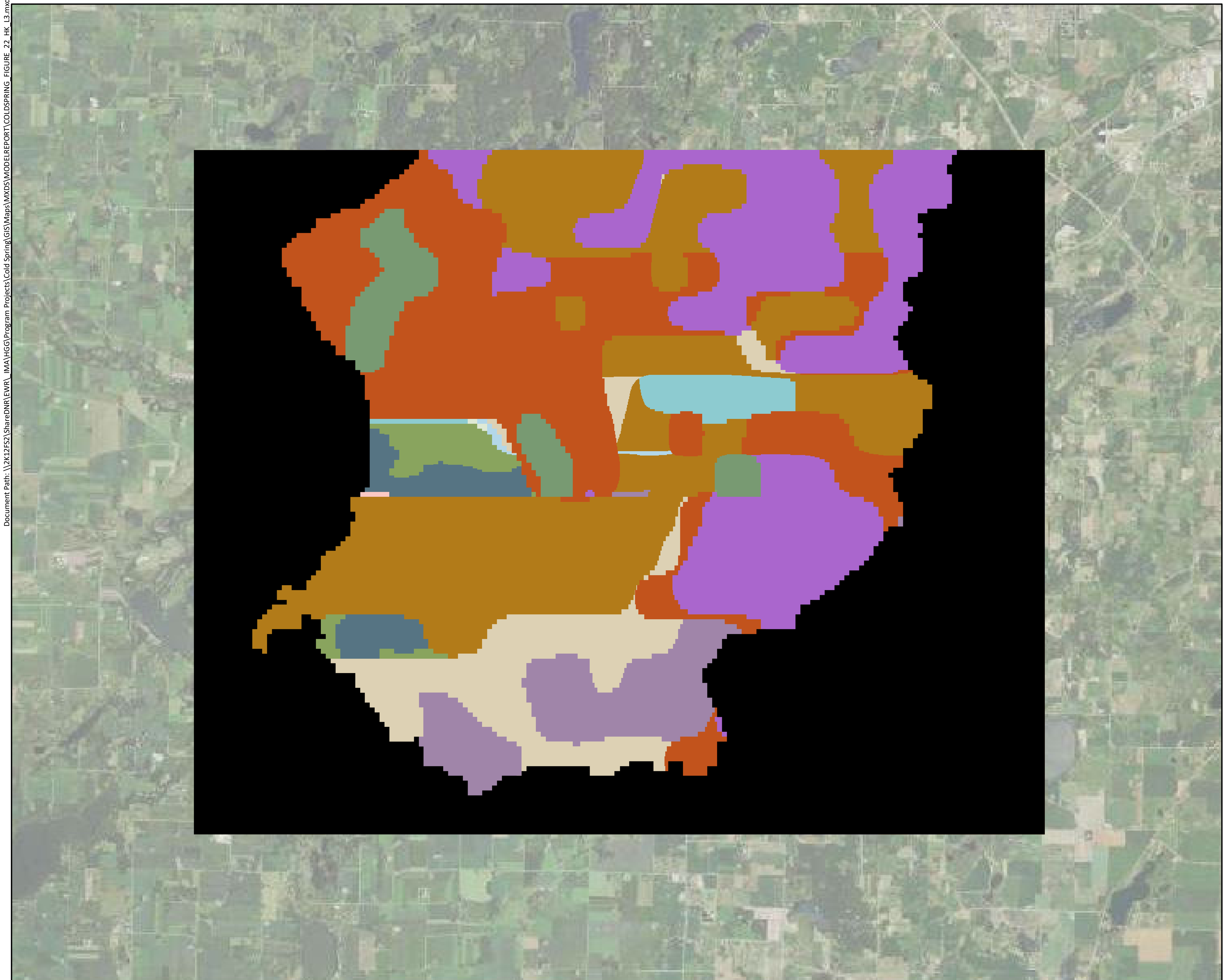

Legend

Hydraulic Conductivity Zones

- Surficial Sands (kx1/kz1)
- Cromwell Sand (kx3/kz3)
- Cromwell Till (kx4/kz4)
- Hewitt Sand (kx5/kz5)
- Hewitt Till (kx6/kz6)
- Sauk Center Till (kx8/kz8)
- Two Sand (kx9/kz9)
- Two Till (kx10/kz10)
- Three Till (kx12/kz12)
- Fractured Bedrock (kx13/kz13)
- Bedrock (kx14/kz14)
- New Ulm Till weathered (kx15/kz15)
- Cromwell Till weathered (kx16/kz16)

0 0.75 1.5 3 Miles

N

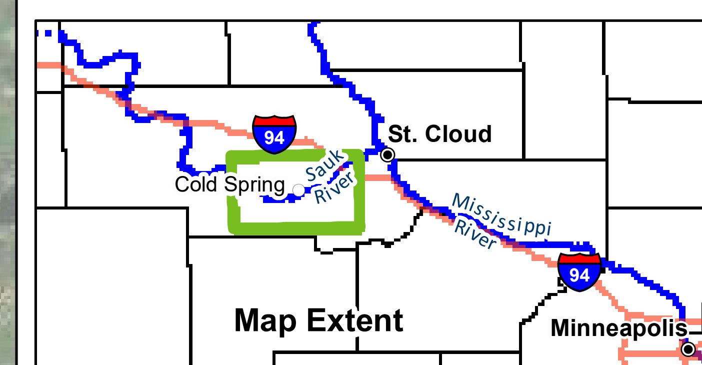

Figure 22. Layer 3 Zones

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Legend

Hydraulic Conductivity Zones

- Surficial Sands (kx1/kz1)
- Cromwell Till (kx4/kz4)
- Hewitt Sand (kx5/kz5)
- Hewitt Till (kx6/kz6)
- Sauk Center Till (kx8/kz8)
- Two Sand (kx9/kz9)
- Two Till (kx10/kz10)
- Three Till (kx12/kz12)
- Fractured Bedrock (kx13/kz13)
- Bedrock (kx14/kz14)

N

0 0.5 1 2 Miles

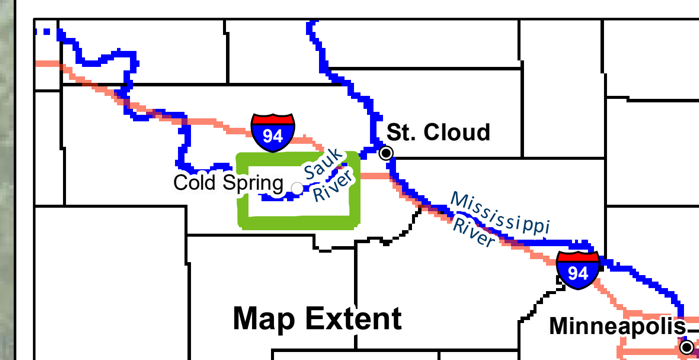

Figure 23. Layer 4 Zones

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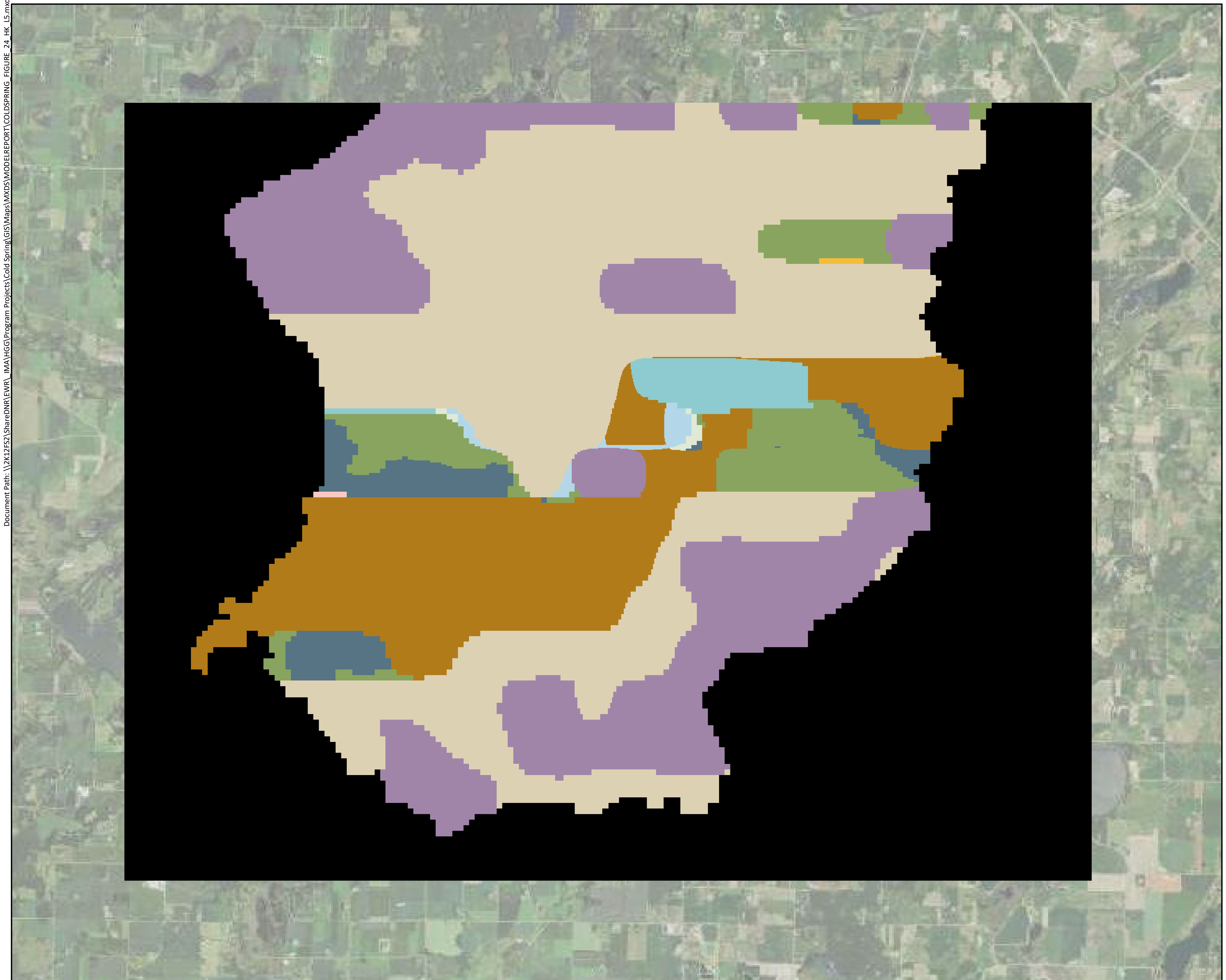
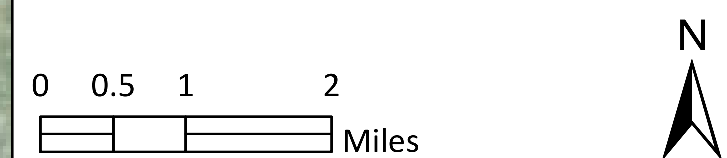


Legend

Hydraulic Conductivity Zones

- Surficial Sands (kx1/kz1)
- Hewitt Sand (kx5/kz5)
- Hewitt Till (kx6/kz6)
- Sauk Center Sand (kx7/kz7)
- Sauk Center Till (kx8/kz8)
- Two Sand (kx9/kz9)
- Two Till (kx10/kz10)
- Three Till (kx12/kz12)
- Fractured Bedrock (kx13/kz13)
- Bedrock (kx14/kz14)



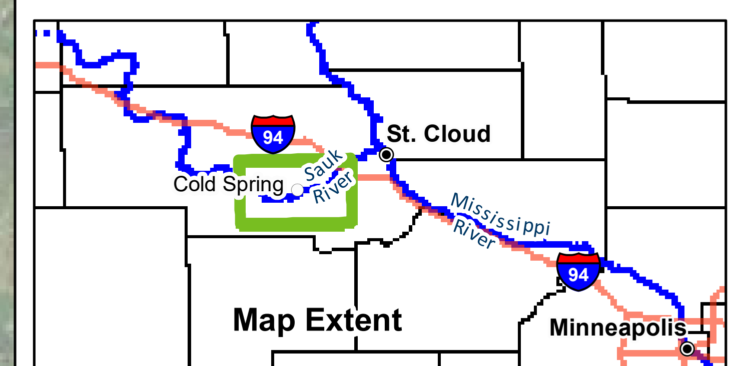


Figure 24. Layer 5 Zones

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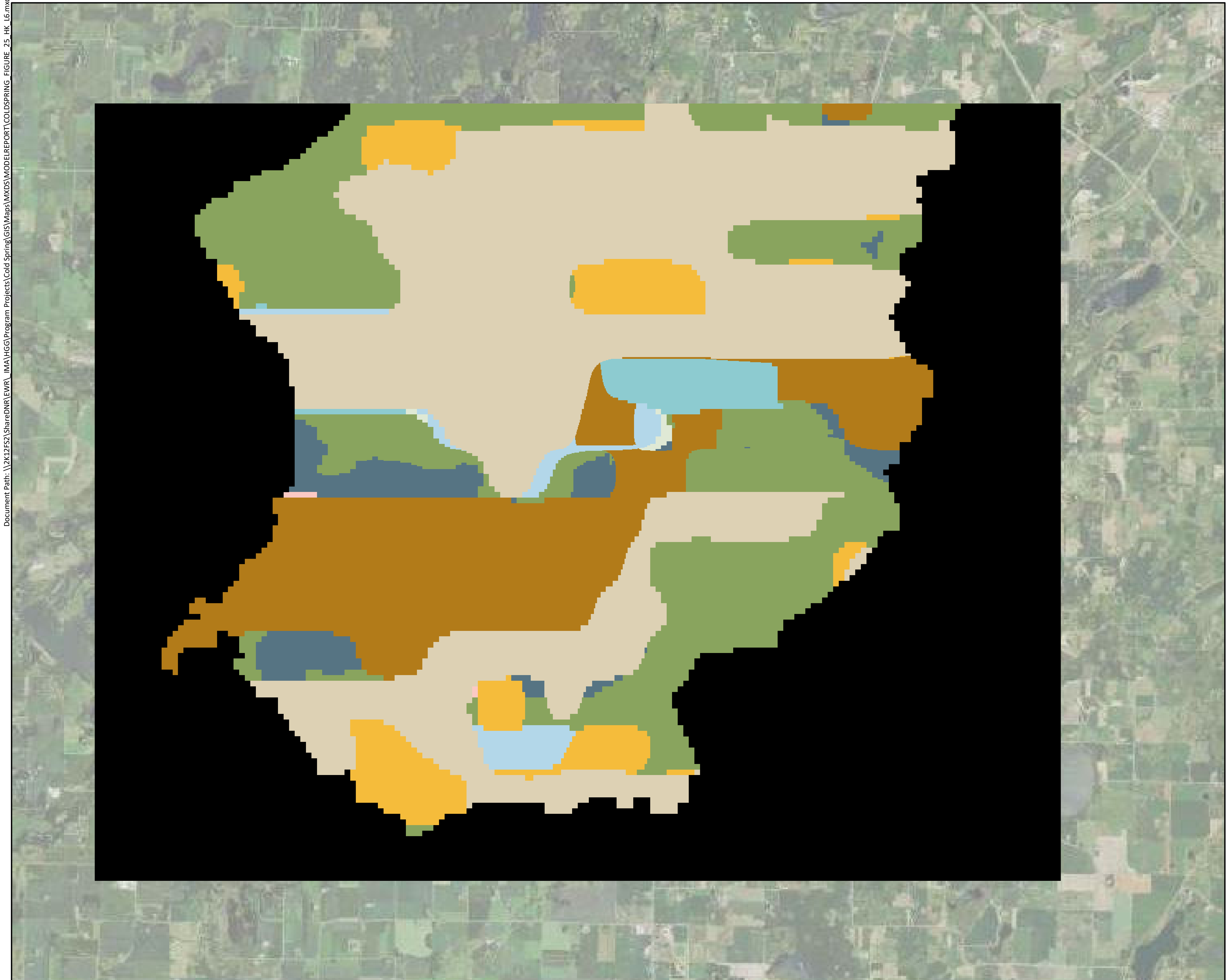

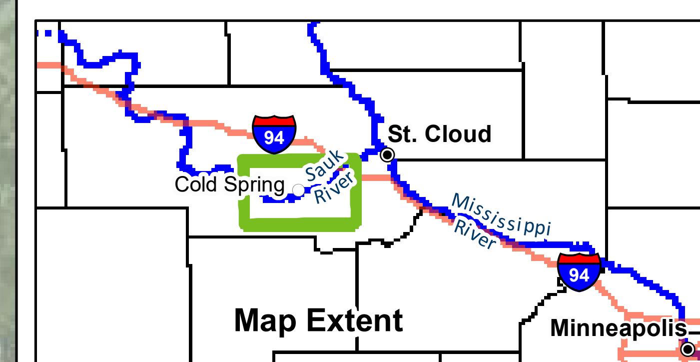

Figure 25. Layer 6 Zones

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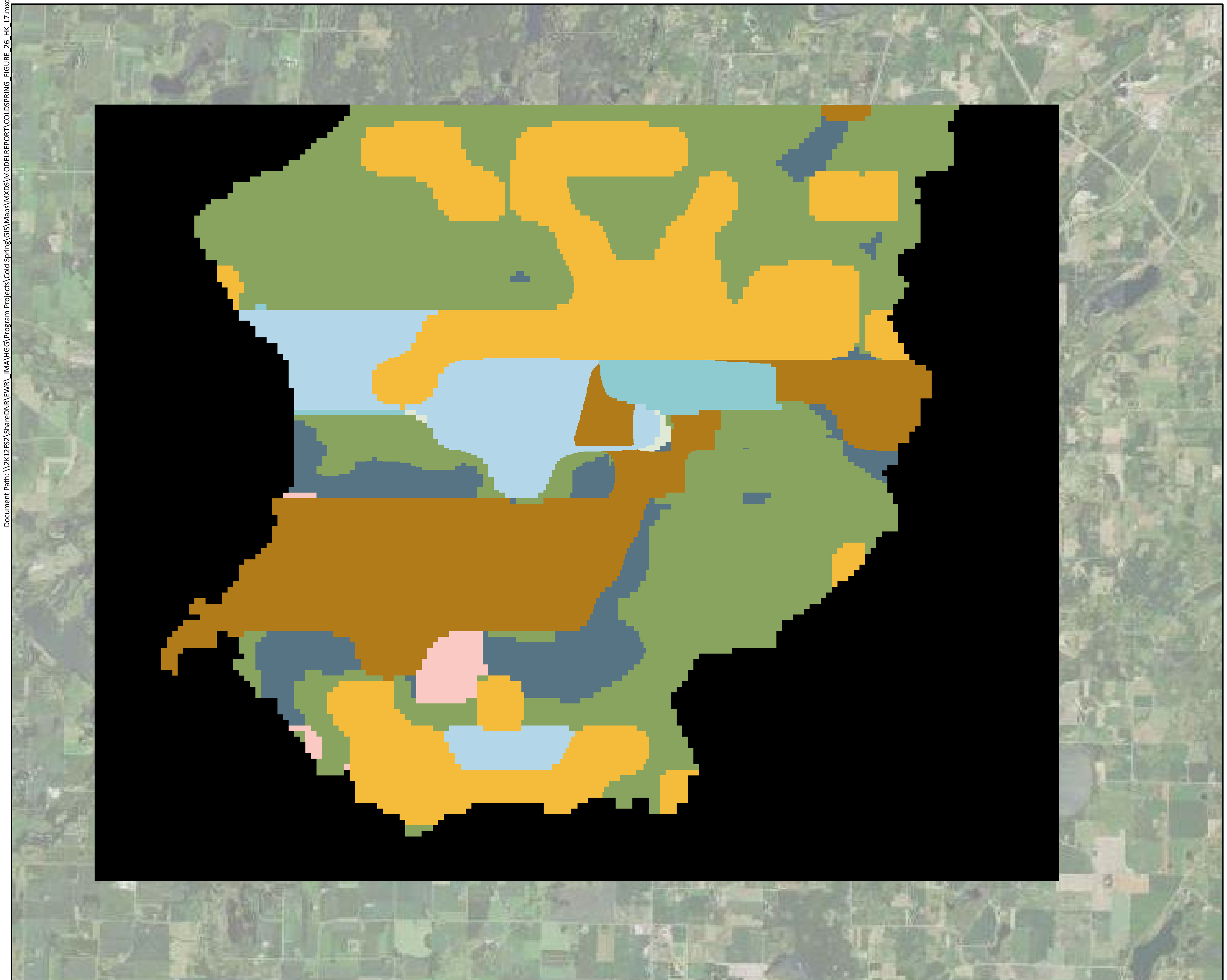
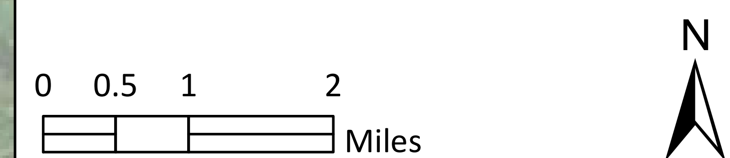


Legend

Hydraulic Conductivity Zones

- Surficial Sands (kx1/kz1)
- Sauk Center Sand (kx7/kz7)
- Sauk Center Till (kx8/kz8)
- Two Sand (kx9/kz9)
- Two Till (kx10/kz10)
- Three Sand (kx11/kz111)
- Three Till (kx12/kz12)
- Fractured Bedrock (kx13/kz13)
- Bedrock (kx14/kz14)
- Inactive



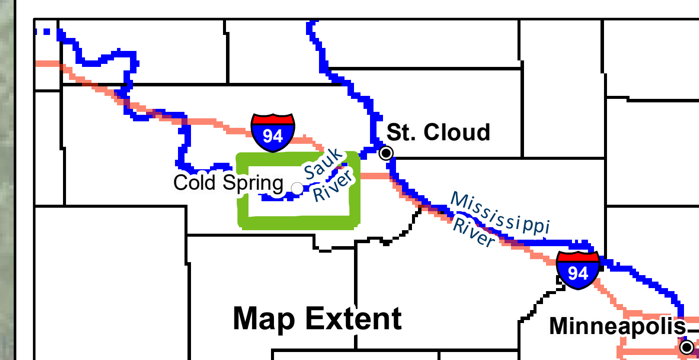


Figure 26. Layer 7 Zones

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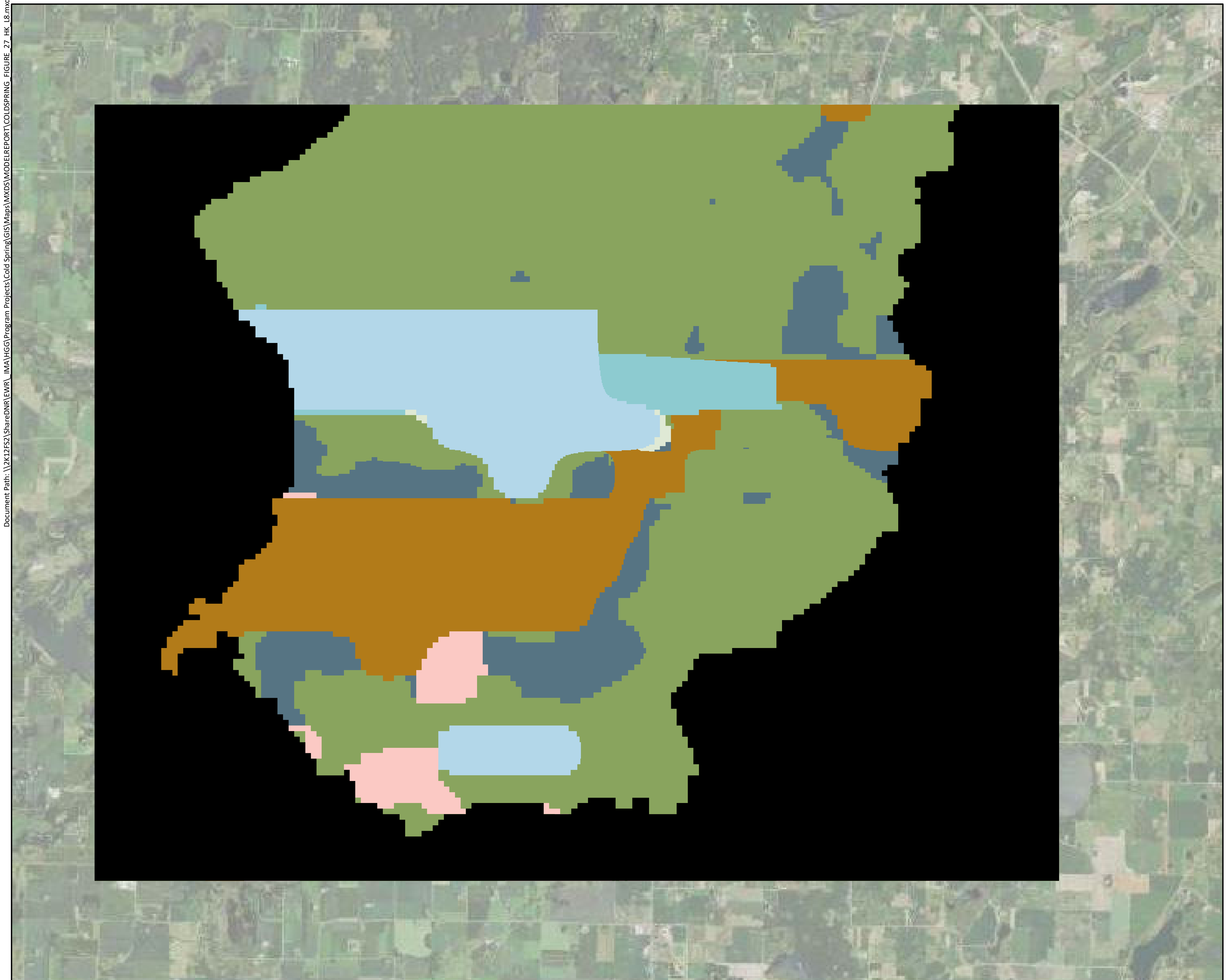

Legend

Hydraulic Conductivity Zones

- Surficial Sands (kx1/kz1)
- Sauk Center Till (kx8/kz8)
- Two Sand (kx9/kz9)
- Two Till (kx10/kz10)
- Three Sand (kx11/kz111)
- Three Till (kx12/kz12)
- Fractured Bedrock (kx13/kz13)
- Bedrock (kx14/kz14)
- Inactive

N

0 0.5 1 2 Miles

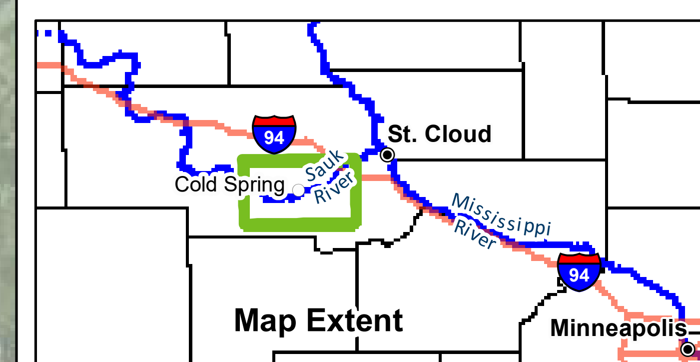

Figure 27. Layer 8 Zones

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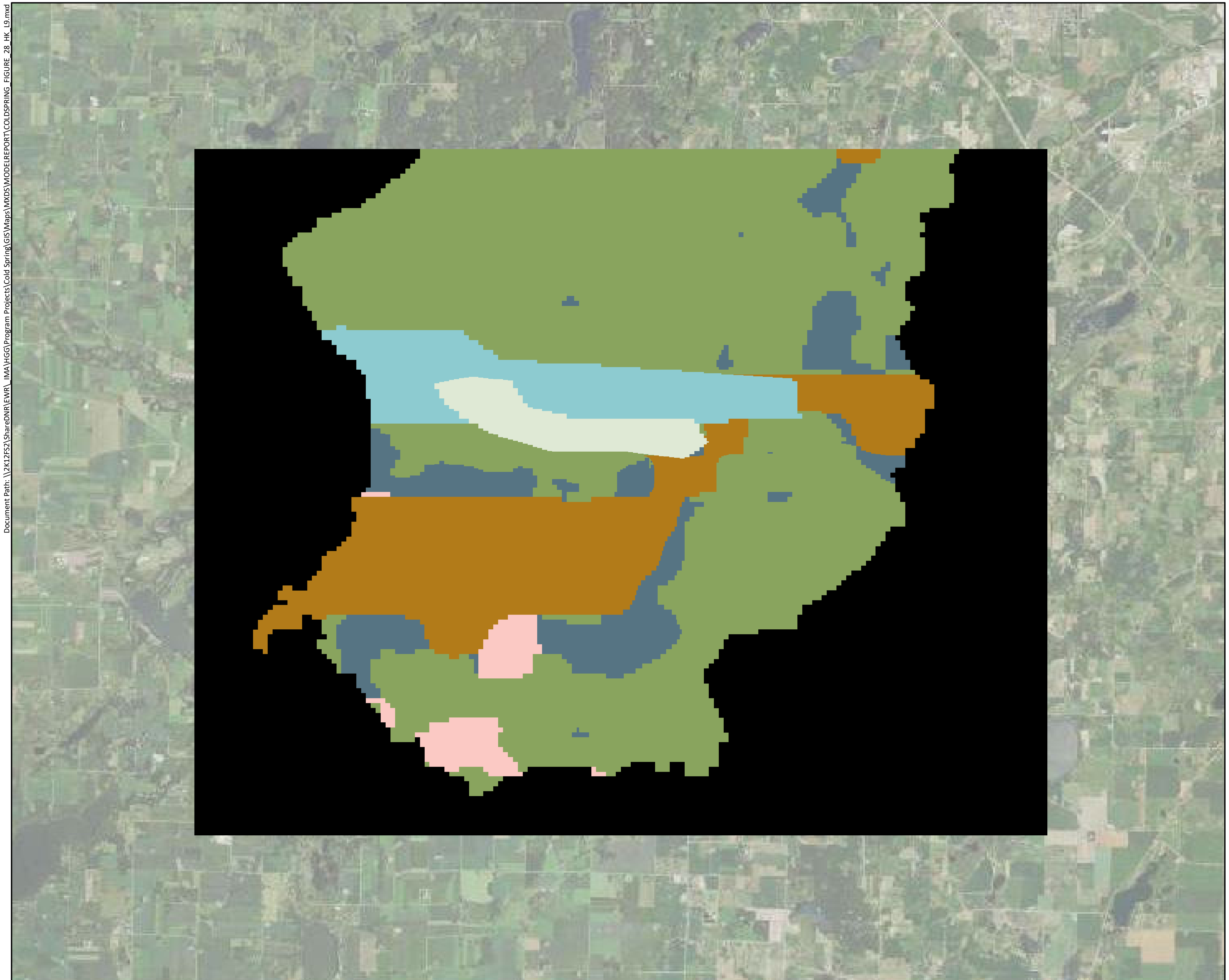

Legend

Hydraulic Conductivity Zones

- Surficial Sands (kx1/kz1)
- Two Sand (kx9/kz9)
- Two Till (kx10/kz10)
- Three Sand (kx11/kz111)
- Three Till (kx12/kz12)
- Fractured Bedrock (kx13/kz13)
- Bedrock (kx14/kz14)
- Inactive

0 0.75 1.5 3 Miles

N

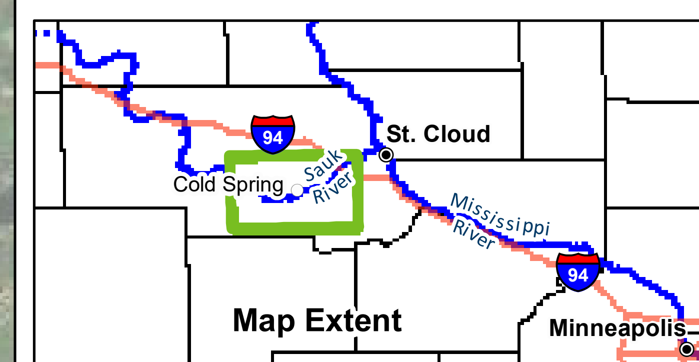

Figure 28. Layer 9 Zones

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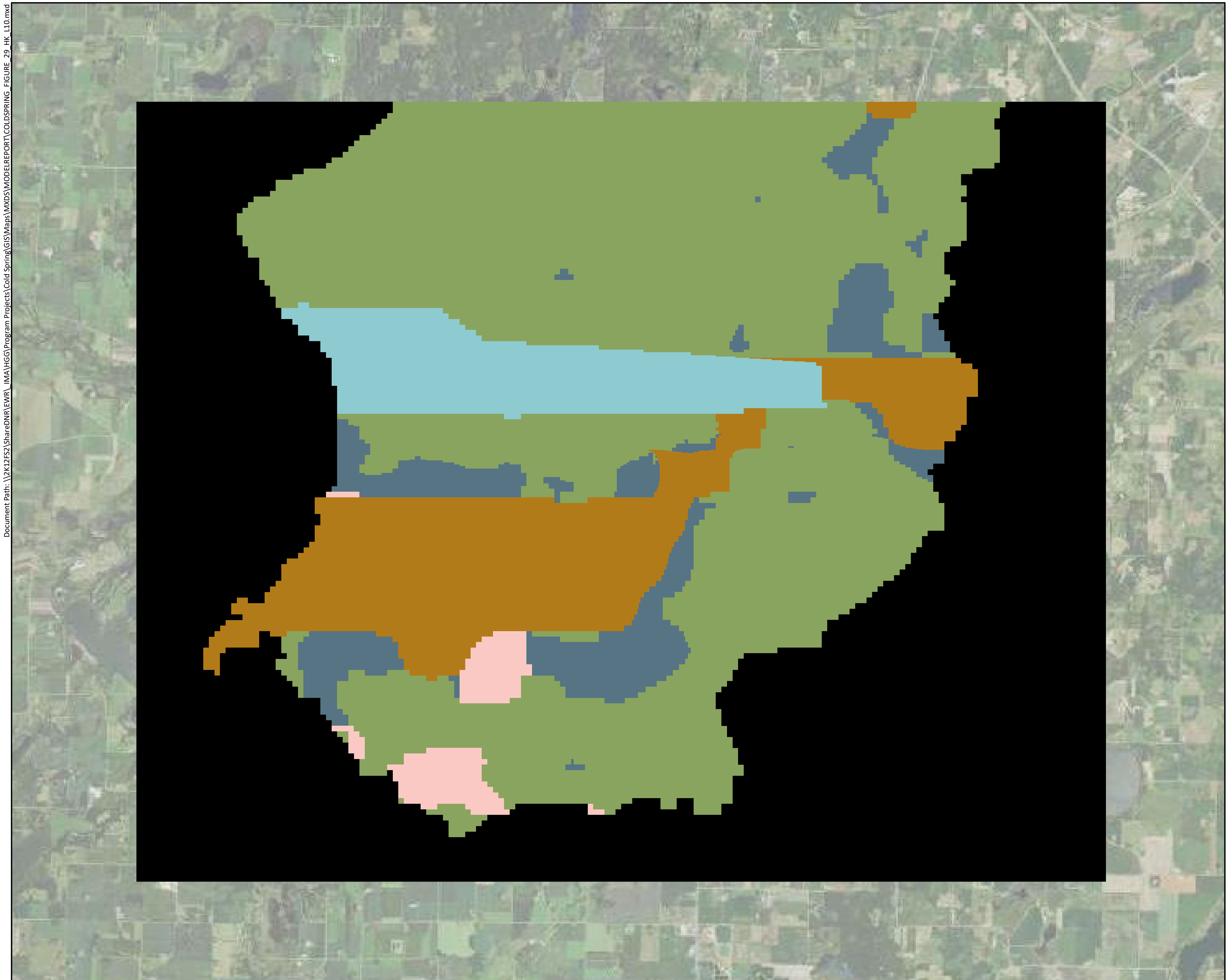
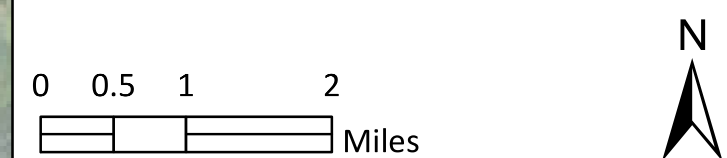


Legend

Hydraulic Conductivity Zones

- Surficial Sands (kx1/kz1)
- Two Till (kx10/kz10)
- Three Sand (kx11/kz111)
- Three Till (kx12/kz12)
- Fractured Bedrock (kx13/kz13)
- Bedrock (kx14/kz14)
- Inactive



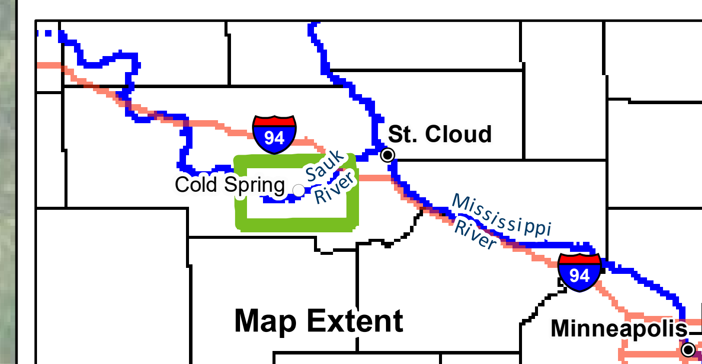


Figure 29. Layer 10 Zones

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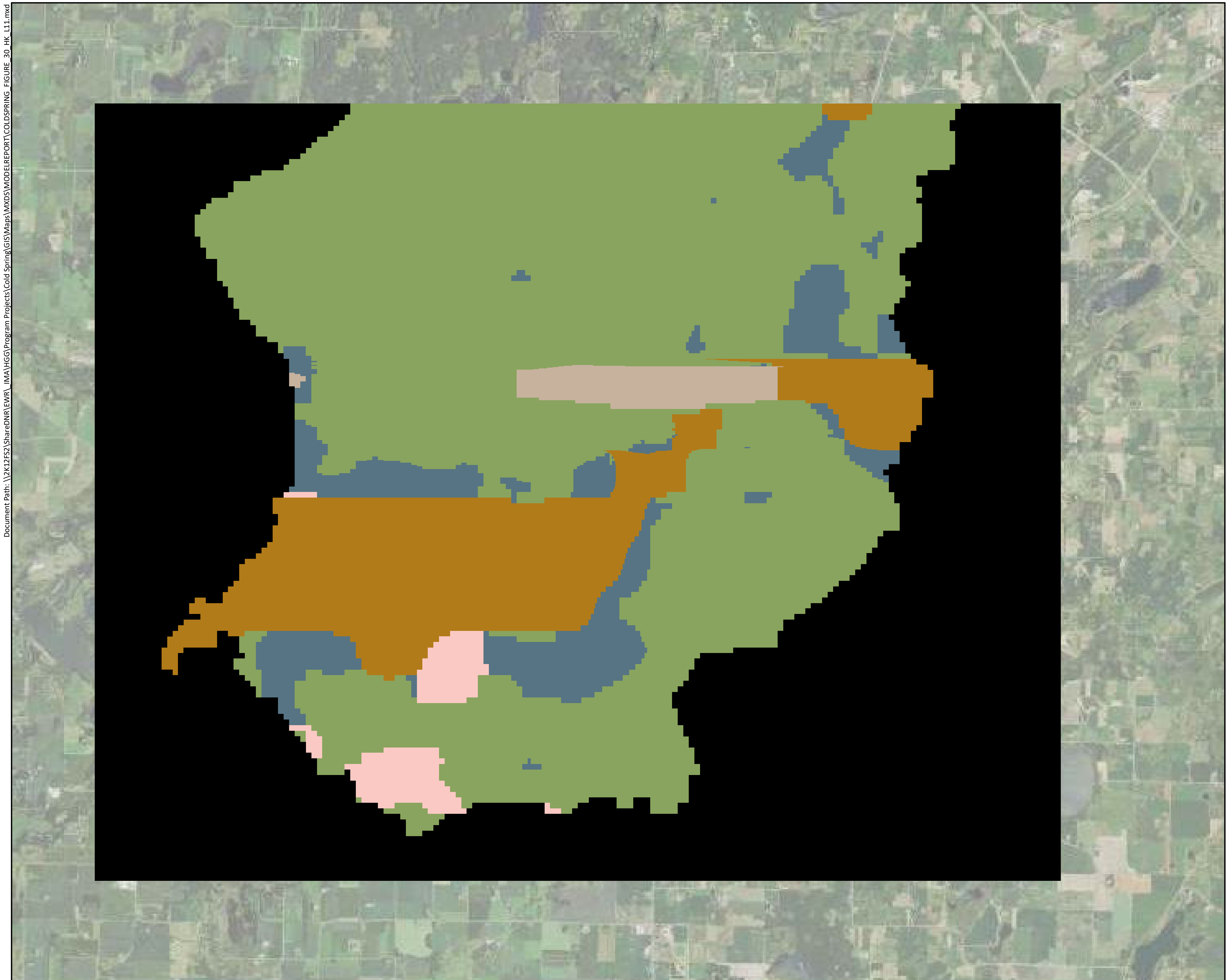

Legend

Hydraulic Conductivity Zones

- Surficial Sands (kx1/kz1)
- Three Sand (kx11/kz111)
- Three Till (kx12/kz12)
- Fractured Bedrock (kx13/kz13)
- Bedrock (kx14/kz14)
- Inactive

0 0.5 1 2 Miles

N

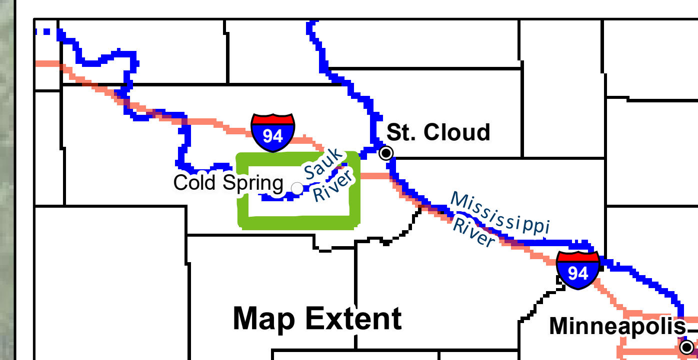

Figure 30. Layer 11 Zones

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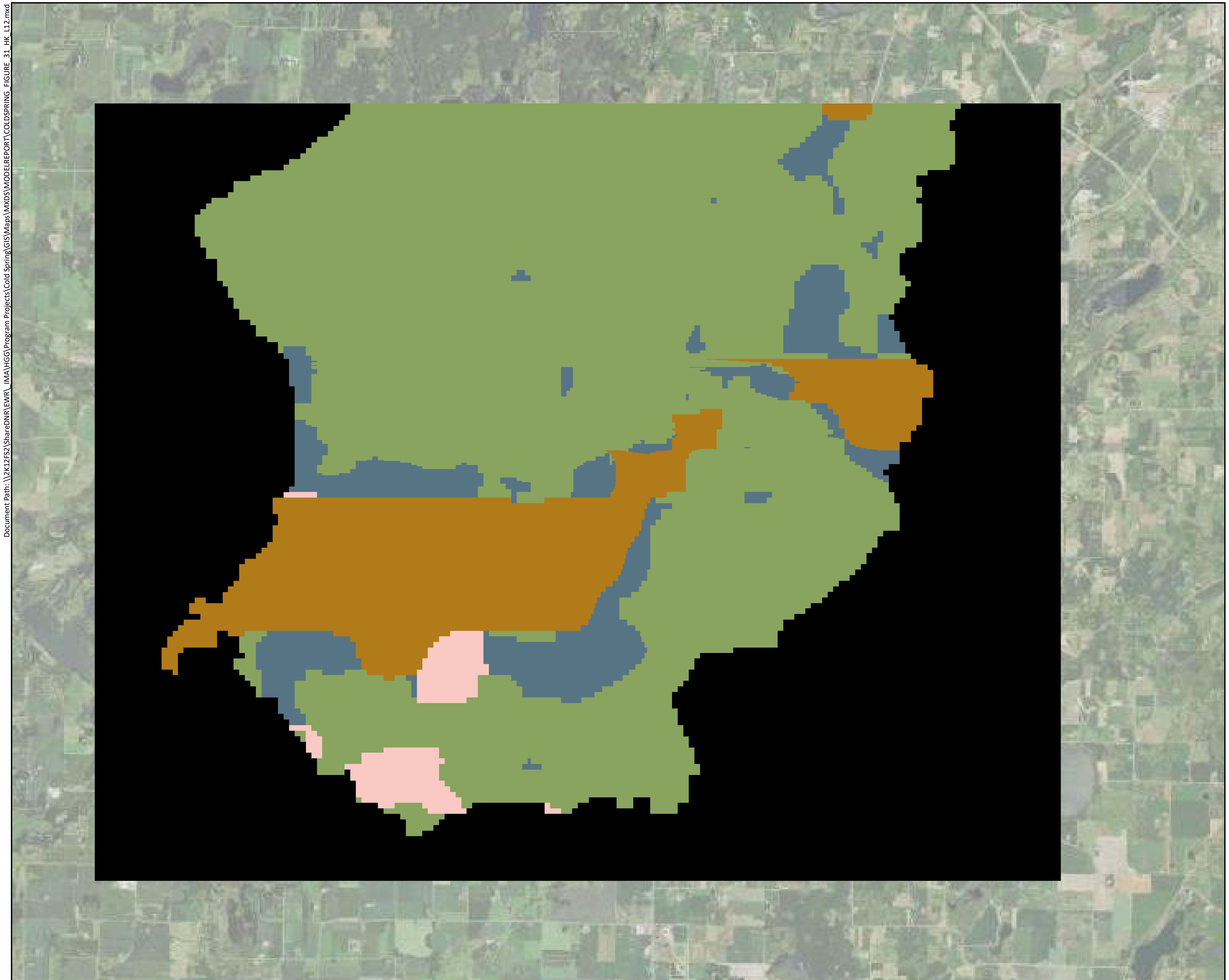
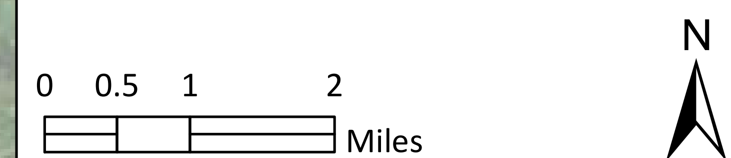


Legend

Hydraulic Conductivity Zones

- Surficial Sands (kx1/kz1)
- Three Till (kx12/kz12)
- Fractured Bedrock (kx13/kz13)
- Bedrock (kx14/kz14)
- Inactive



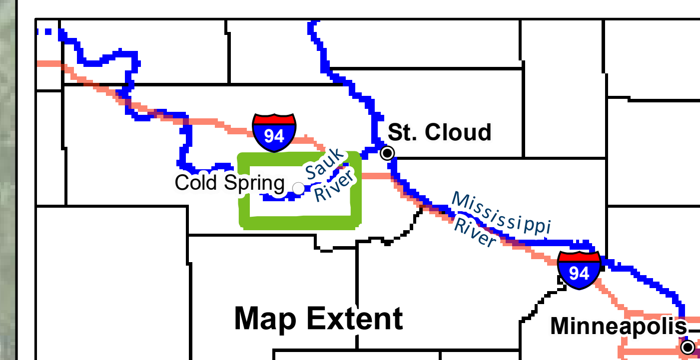


Figure 31. Layer 12 Zones

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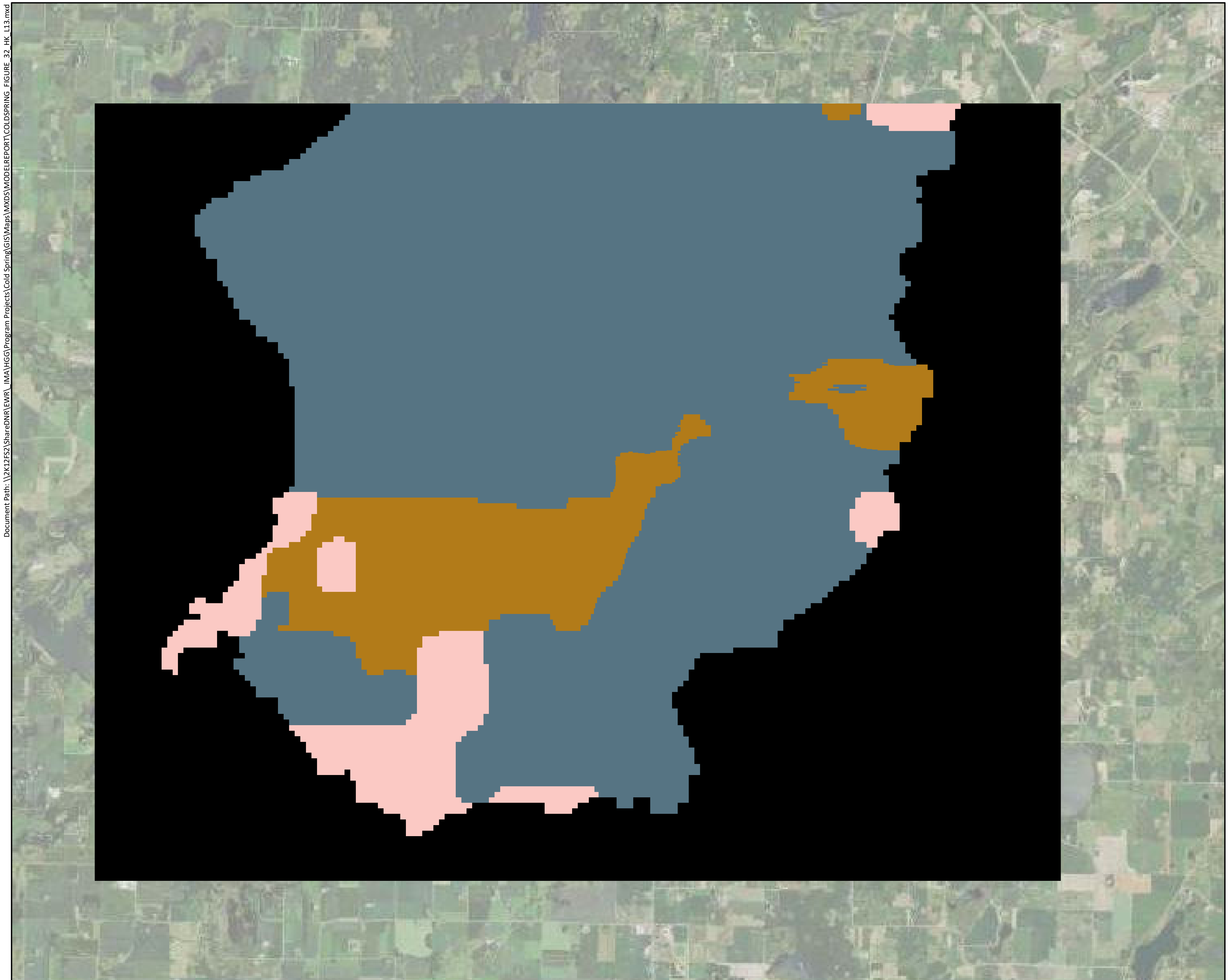

Legend

Hydraulic Conductivity Zones

- Surficial Sands (kx1/kz1)
- Fractured Bedrock (kx13/kz13)
- Bedrock (kx14/kz14)
- Inactive

N

0 0.5 1 2 Miles

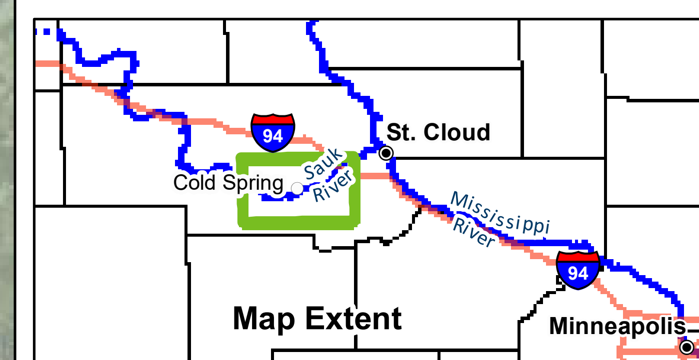

Figure 32. Layer 13 Zones

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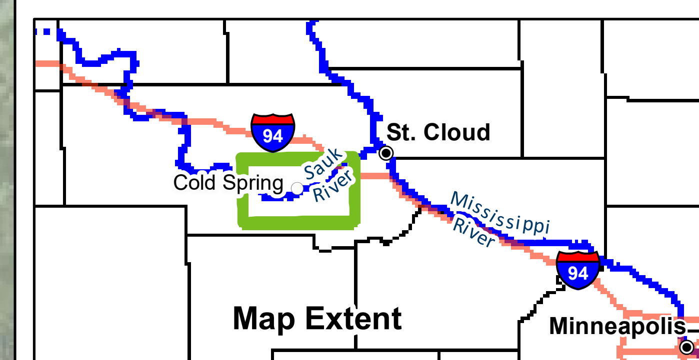

Figure 33. Layer 14 Zones

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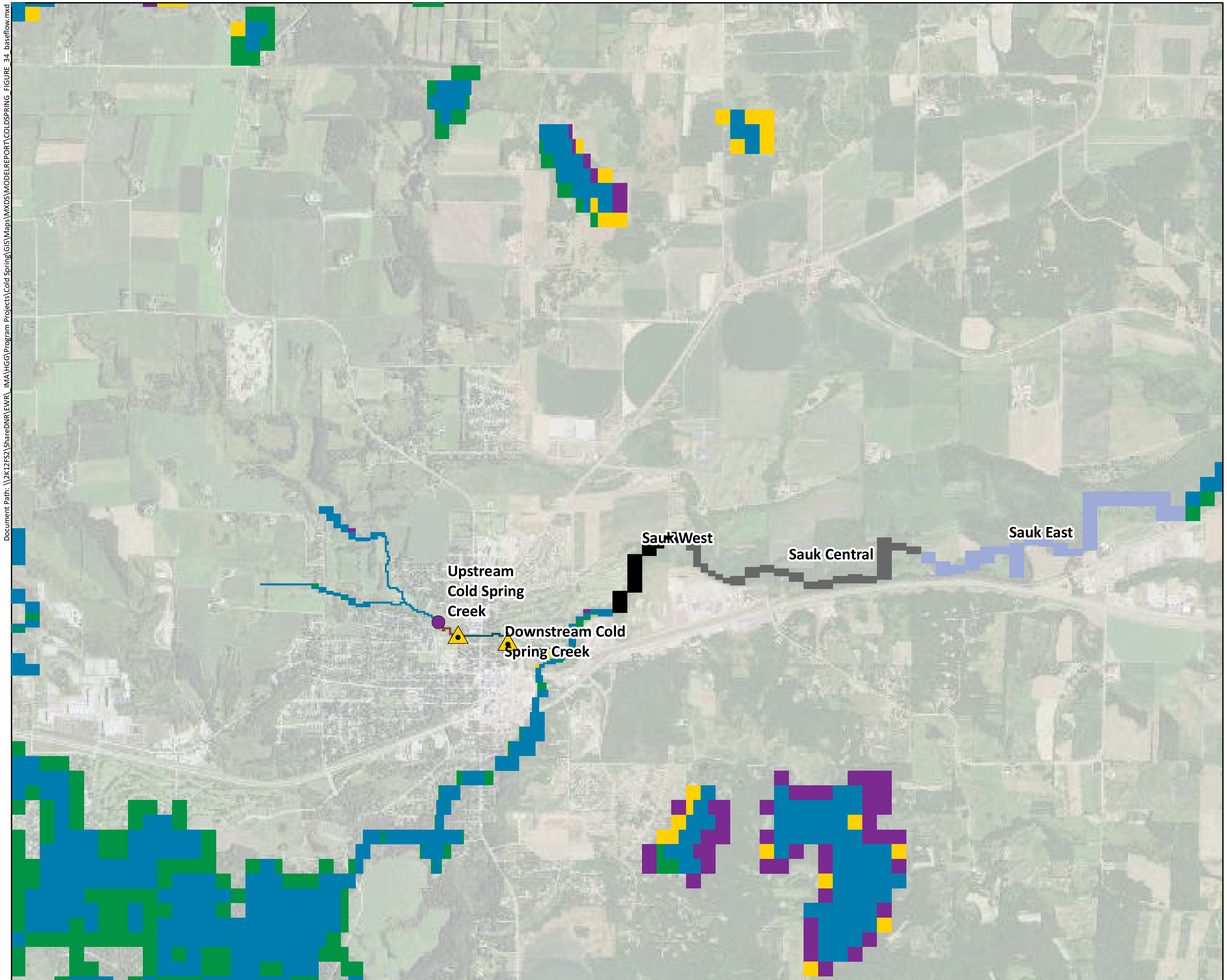

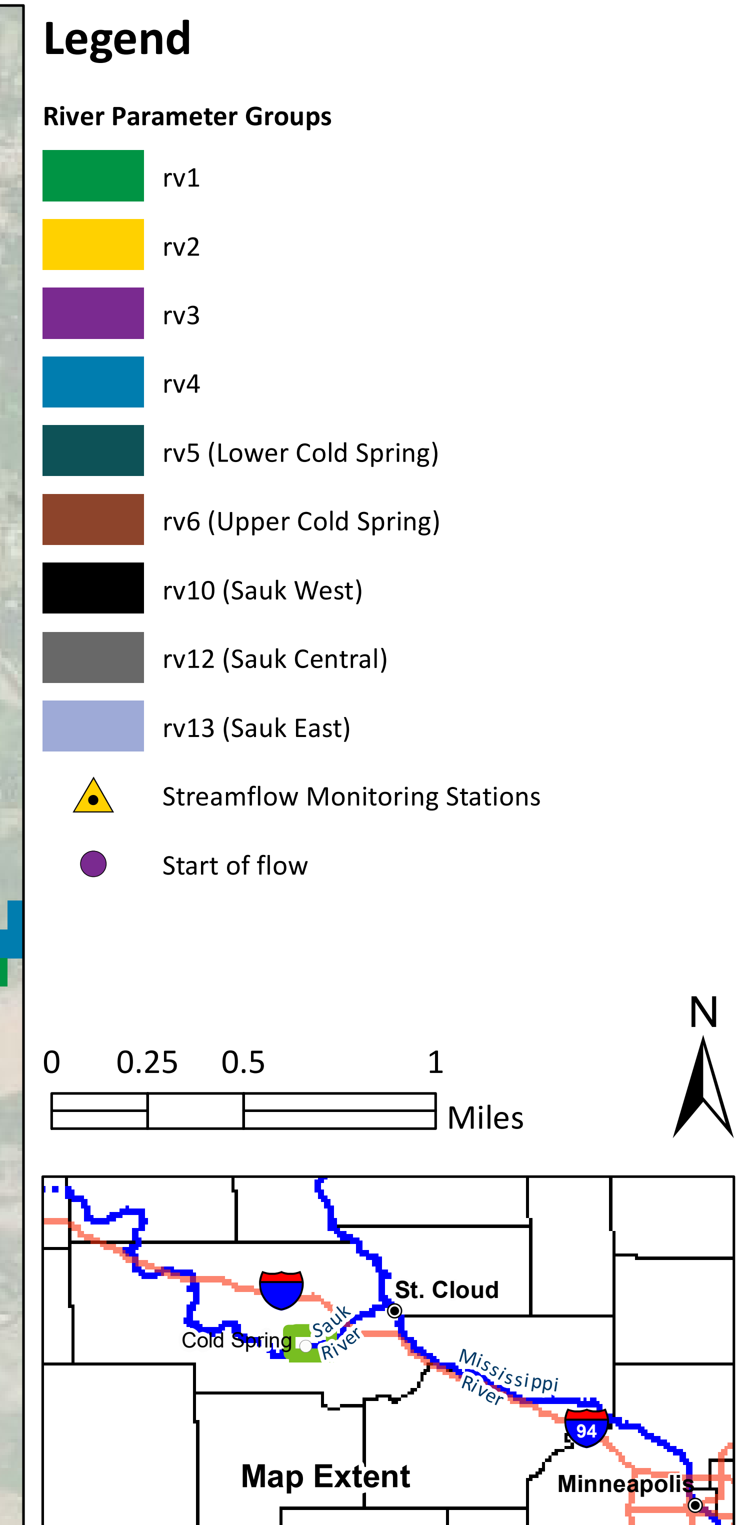

Figure 34. River cell groups and reaches

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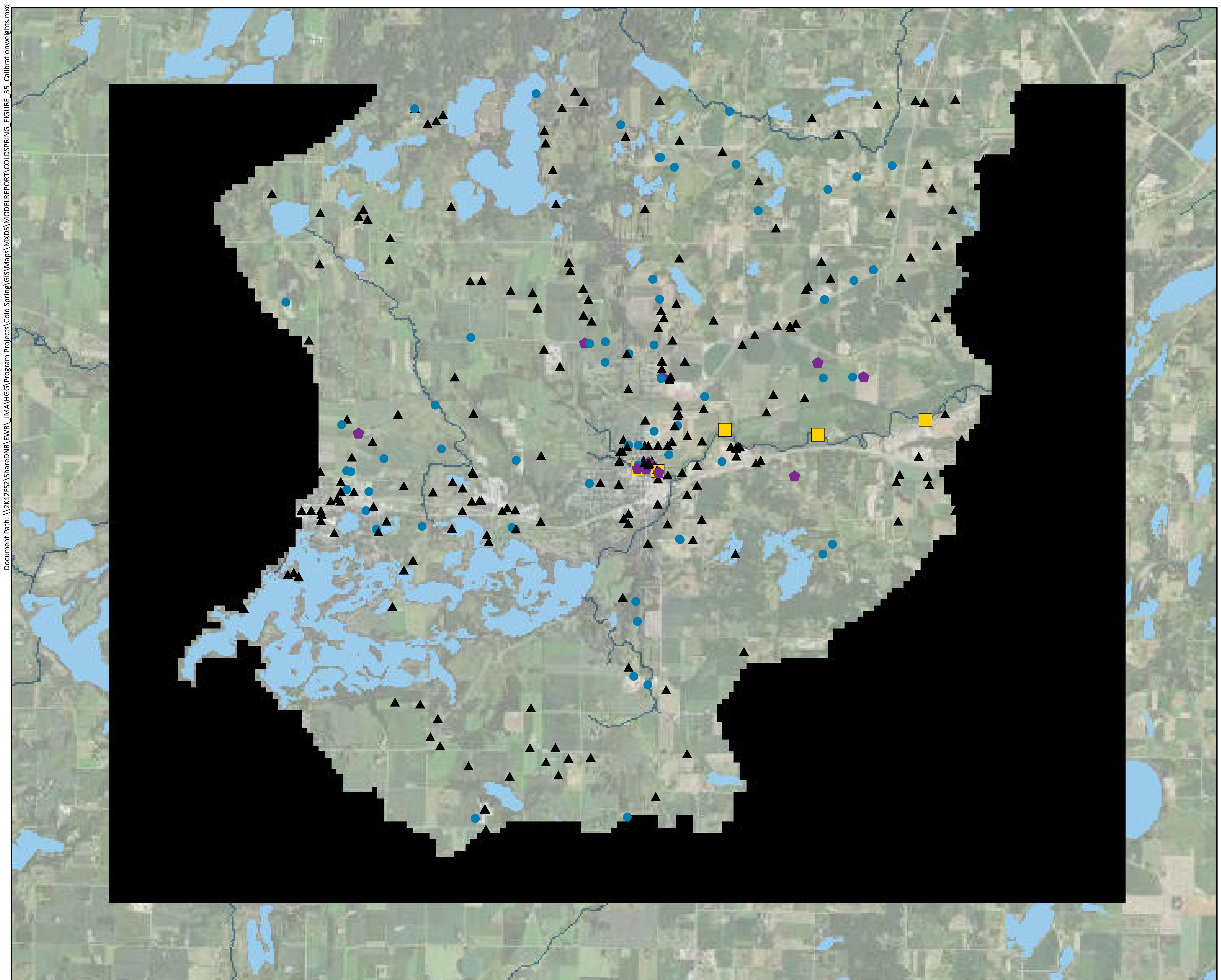

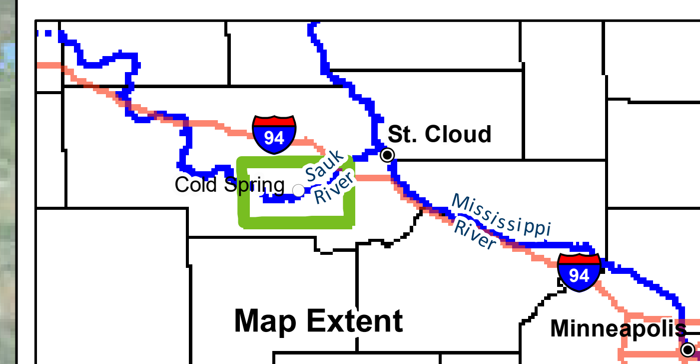

Figure 35. Calibration Groups

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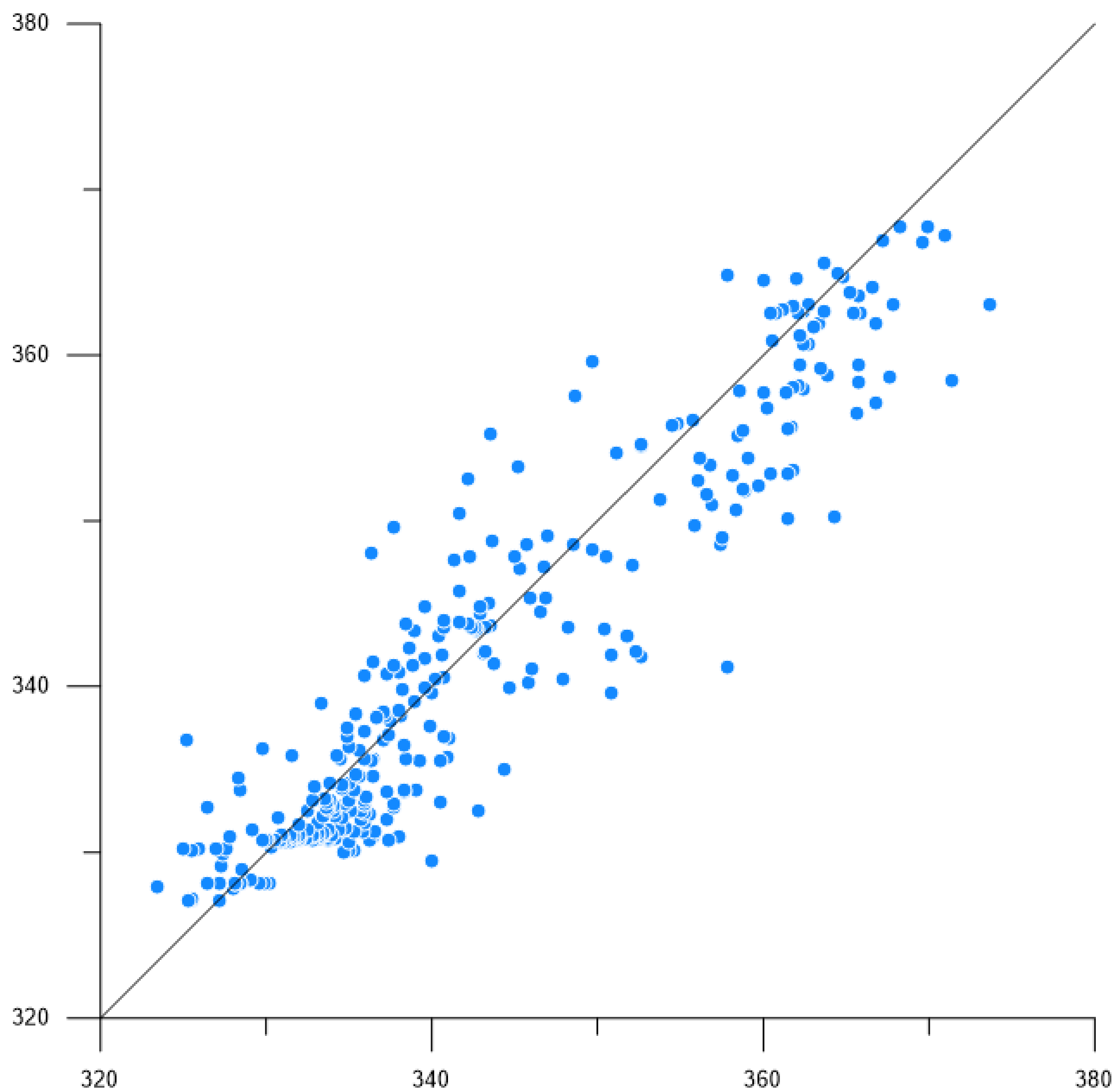

Figure 36. Observed versus Modeled Target Values

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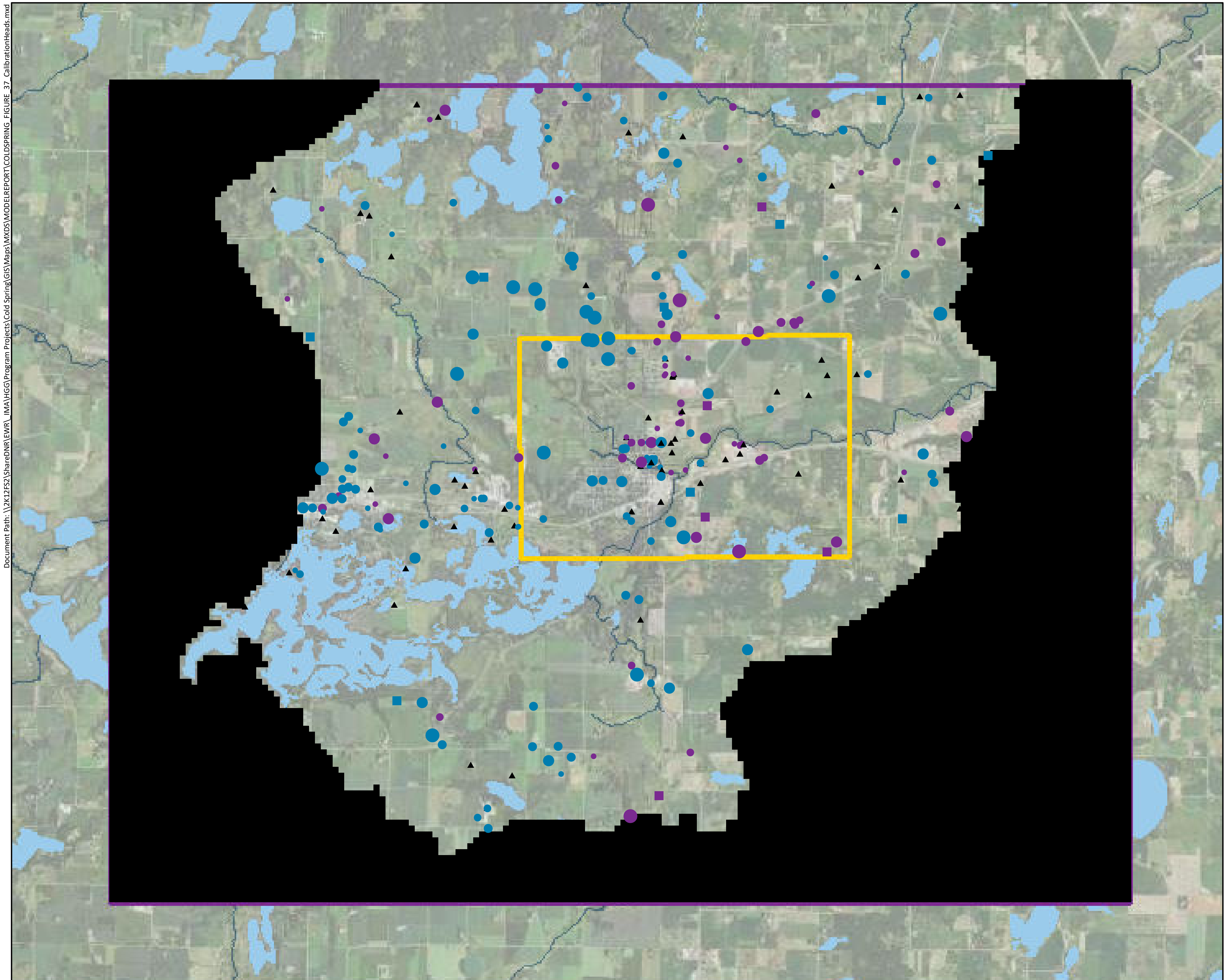
Document Path: \\2K12FS2\ShareDNR\EWR_IMA\HGG\Program Projects\Cold Spring\GIS\Maps\MXDS\MODELREPORT\COLDSPRING FIGURE_37_CalibrationHeads.mxd



Legend

Difference between modeled and observed (m)

- -17.0 - -10.0
- -9.9 - -7.0
- -6.9 - -5.0
- -4.9 - -3.0
- -2.9 - -2.0
- -1.9 - -1.0
- -0.9 - 1.0
- 1.1 - 2.0
- 2.1 - 3.0
- 3.1 - 5.0
- 5.1 - 7.0
- 7.1 - 10.0
- 10.1 - 12.0

Study Area

Area of Interest

0 0.5 1 2 Miles

N

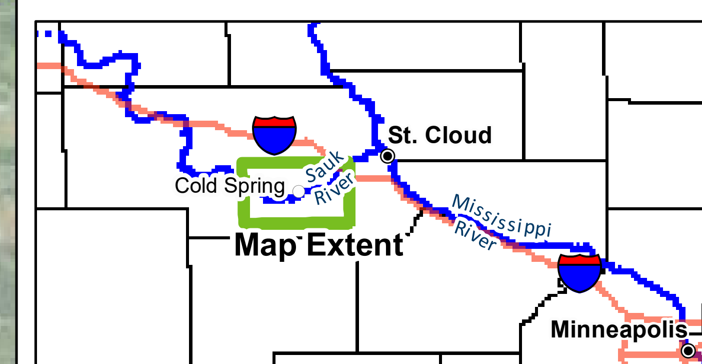


Figure 37. Head Targets

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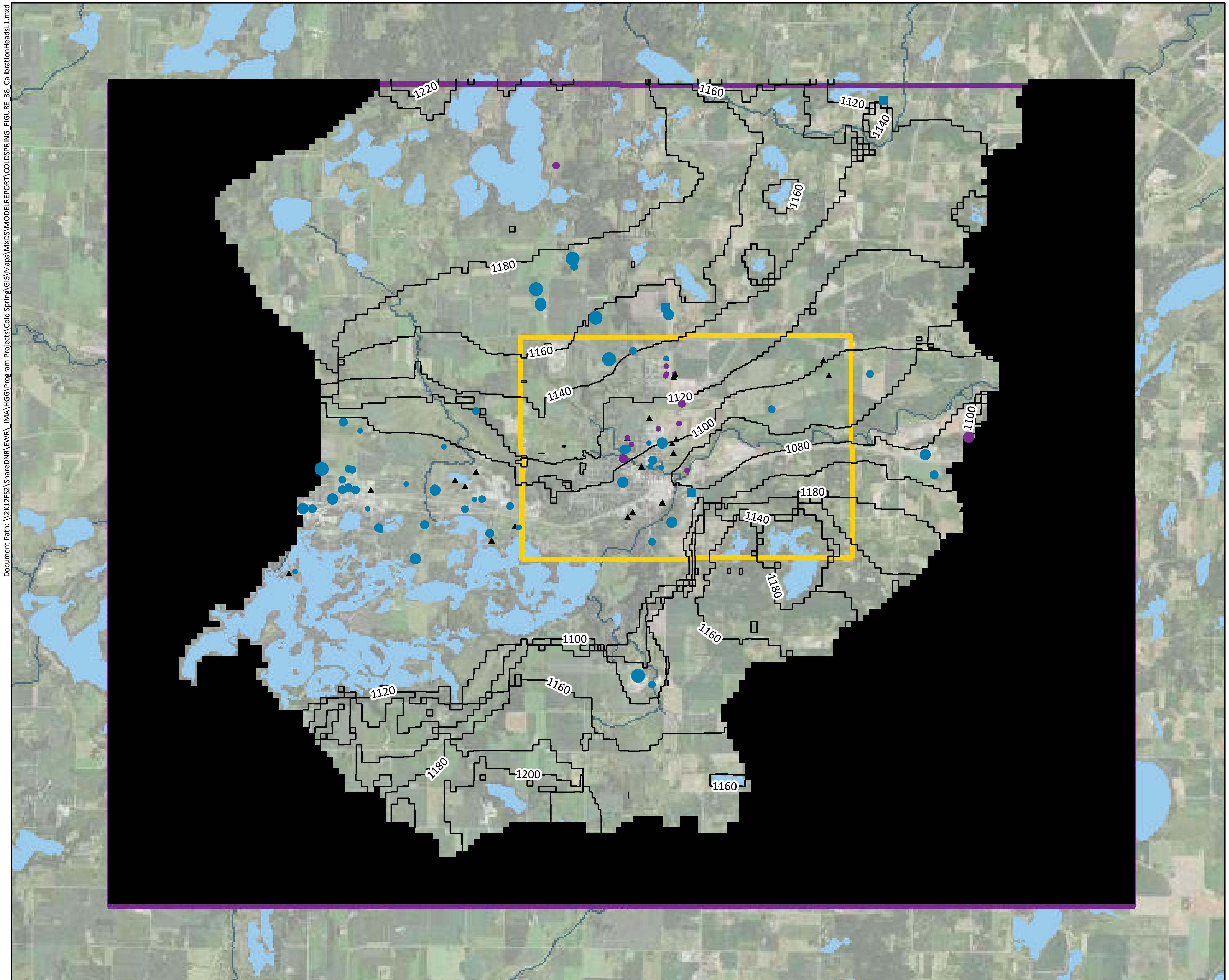

Legend

Difference between modeled and observed (m)

- -17.0 - -10.0
- -9.9 - -7.0
- -6.9 - -5.0
- -4.9 - -3.0
- -2.9 - -2.0
- -1.9 - -1.0
- -0.9 - 1.0
- 1.1 - 2.0
- 2.1 - 3.0
- 3.1 - 5.0
- 5.1 - 7.0
- 7.1 - 10.0
- 10.1 - 12.0

- Study Area
- Area of Interest
- Computed water level contours (ft)

0 0.5 1 2 Miles

N

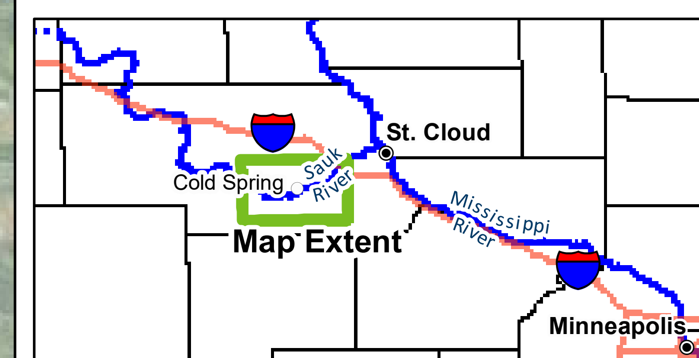

Figure 38. Water level and targets Layer 1

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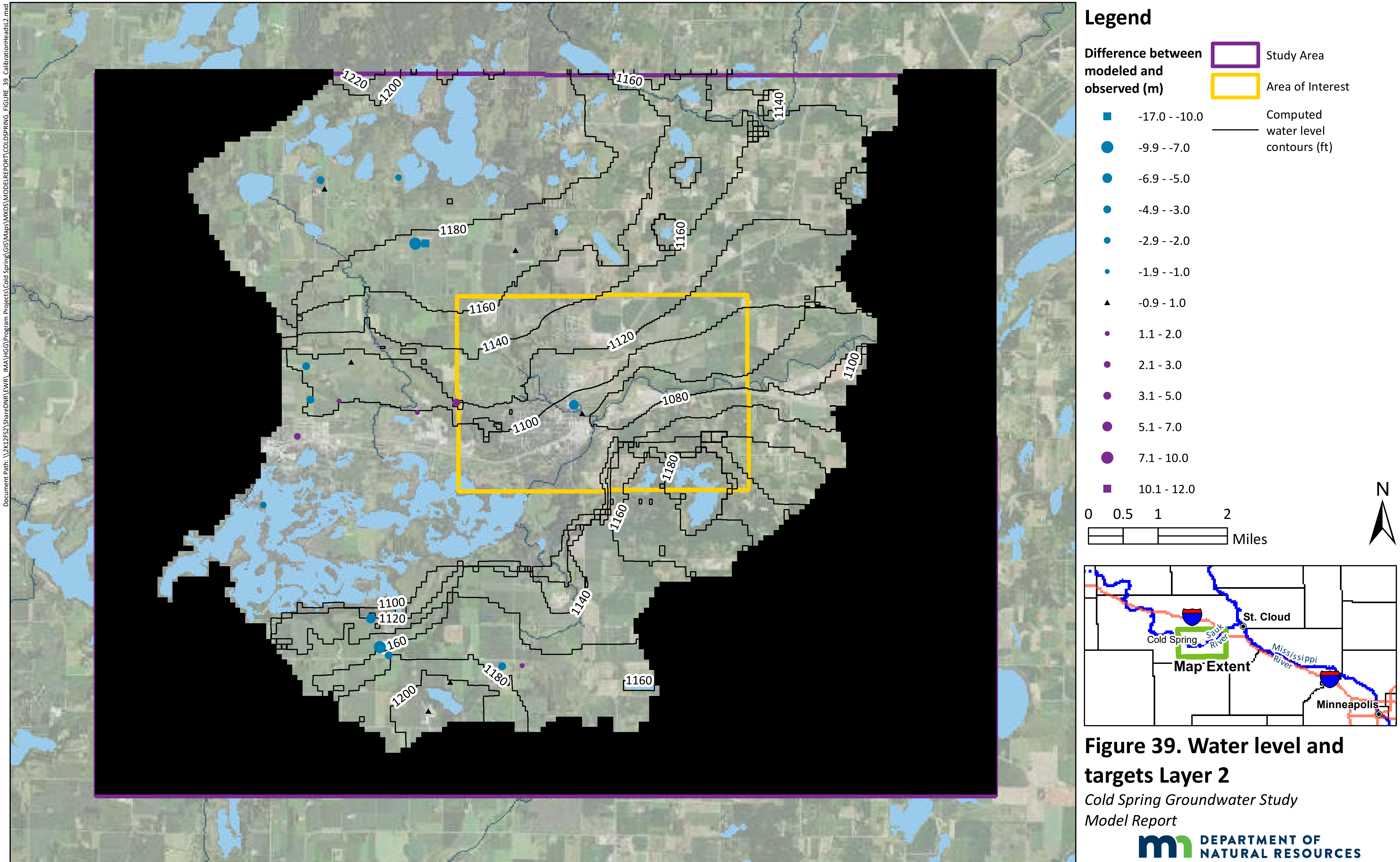

Figure 39. Water level and targets Layer 2

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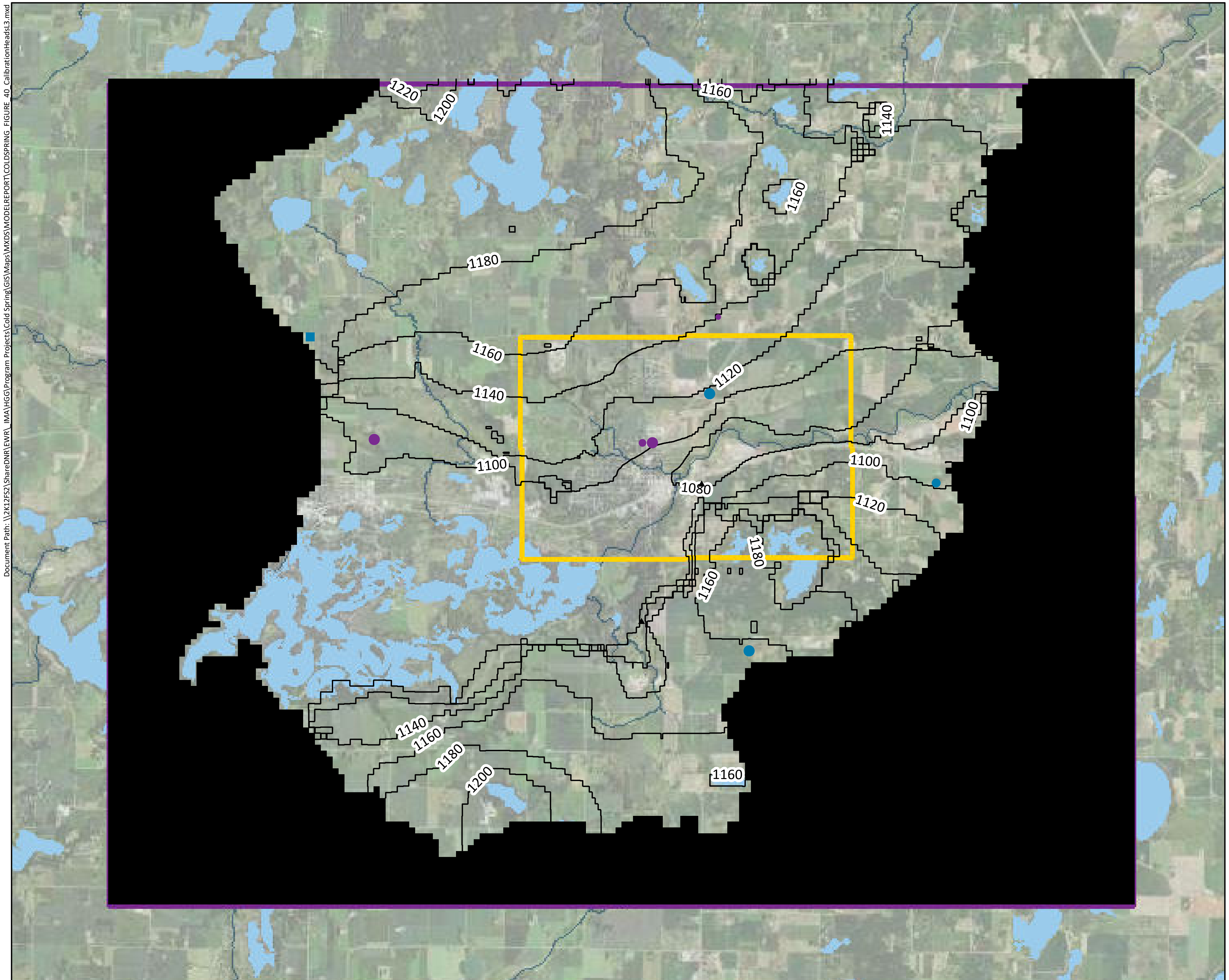

Legend

Difference between modeled and observed (m)

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- -9.9 - -7.0
- -6.9 - -5.0
- -4.9 - -3.0
- -2.9 - -2.0
- -1.9 - -1.0
- -0.9 - 1.0
- 1.1 - 2.0
- 2.1 - 3.0
- 3.1 - 5.0
- 5.1 - 7.0
- 7.1 - 10.0
- 10.1 - 12.0

Study Area

Area of Interest

Computed water level contours (ft)

0 0.5 1 2 Miles

N

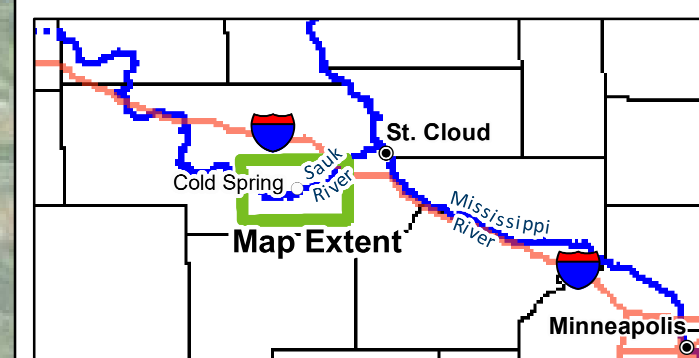

Figure 40. Water level and targets Layer 3

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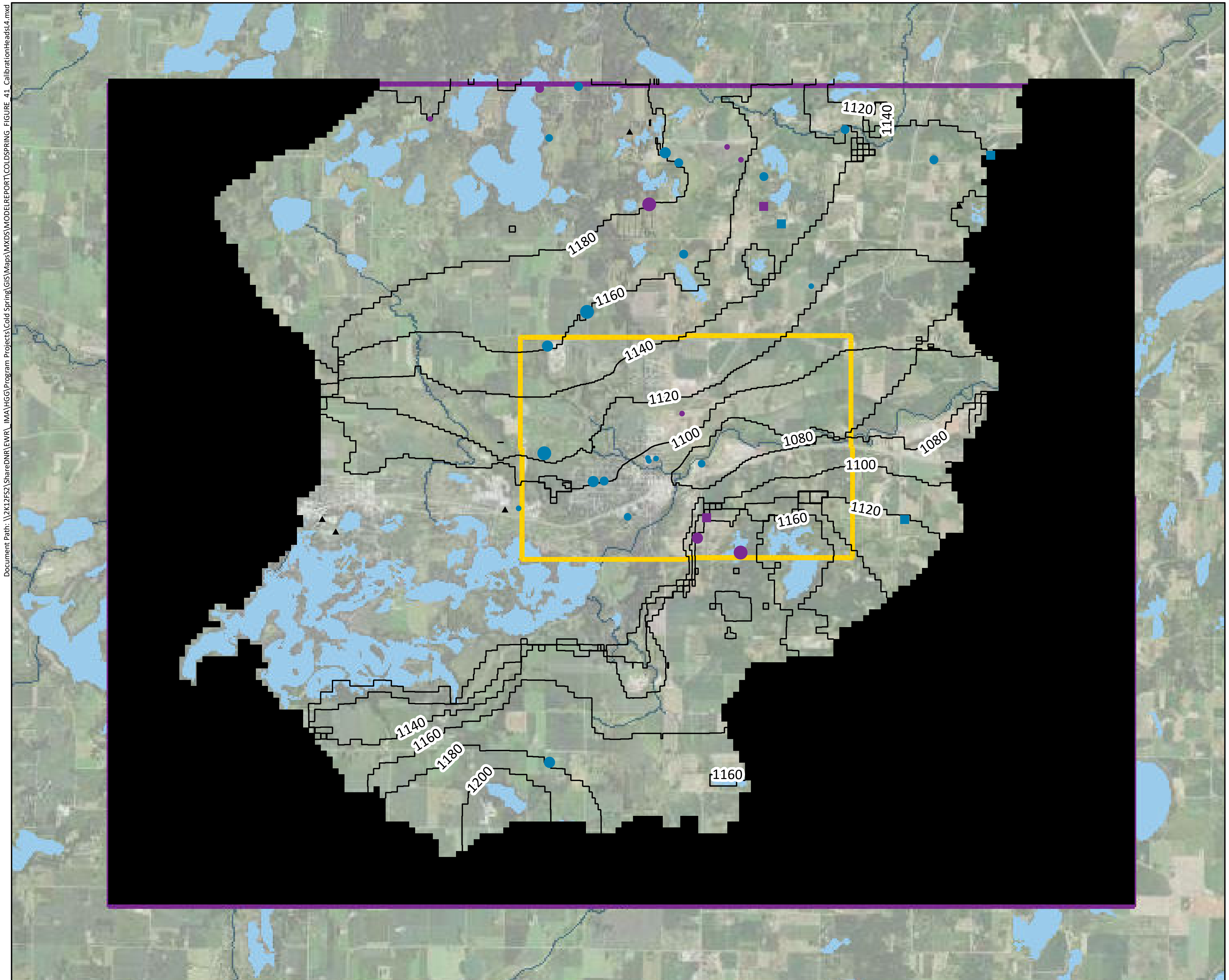

Legend

Difference between modeled and observed (m)

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- -9.9 - -7.0
- -6.9 - -5.0
- -4.9 - -3.0
- -2.9 - -2.0
- -1.9 - -1.0
- -0.9 - 1.0
- 1.1 - 2.0
- 2.1 - 3.0
- 3.1 - 5.0
- 5.1 - 7.0
- 7.1 - 10.0
- 10.1 - 12.0

Study Area

Area of Interest

Computed water level contours (ft)

0 0.5 1 2 Miles

N

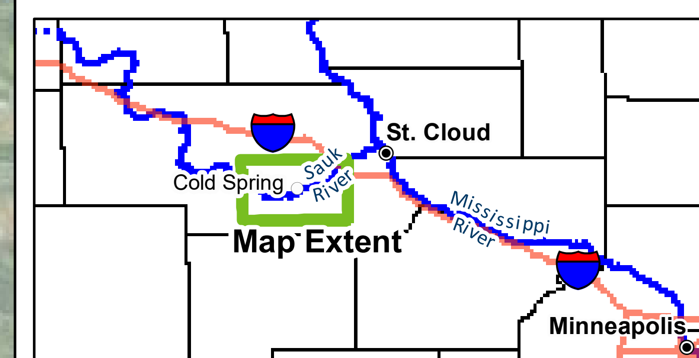

Figure 41. Water level and targets Layer 4

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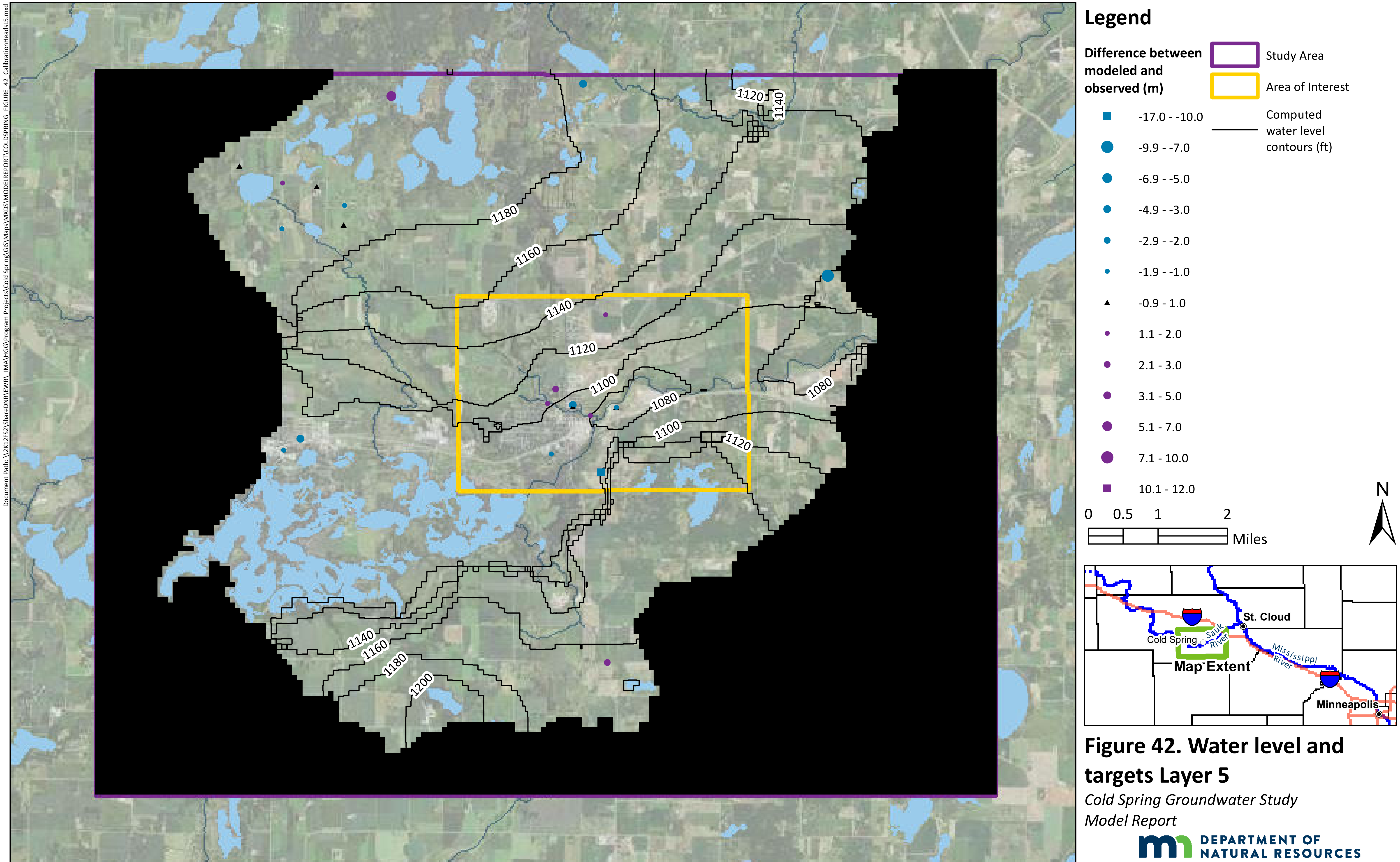

Figure 42. Water level and targets Layer 5

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Model Report

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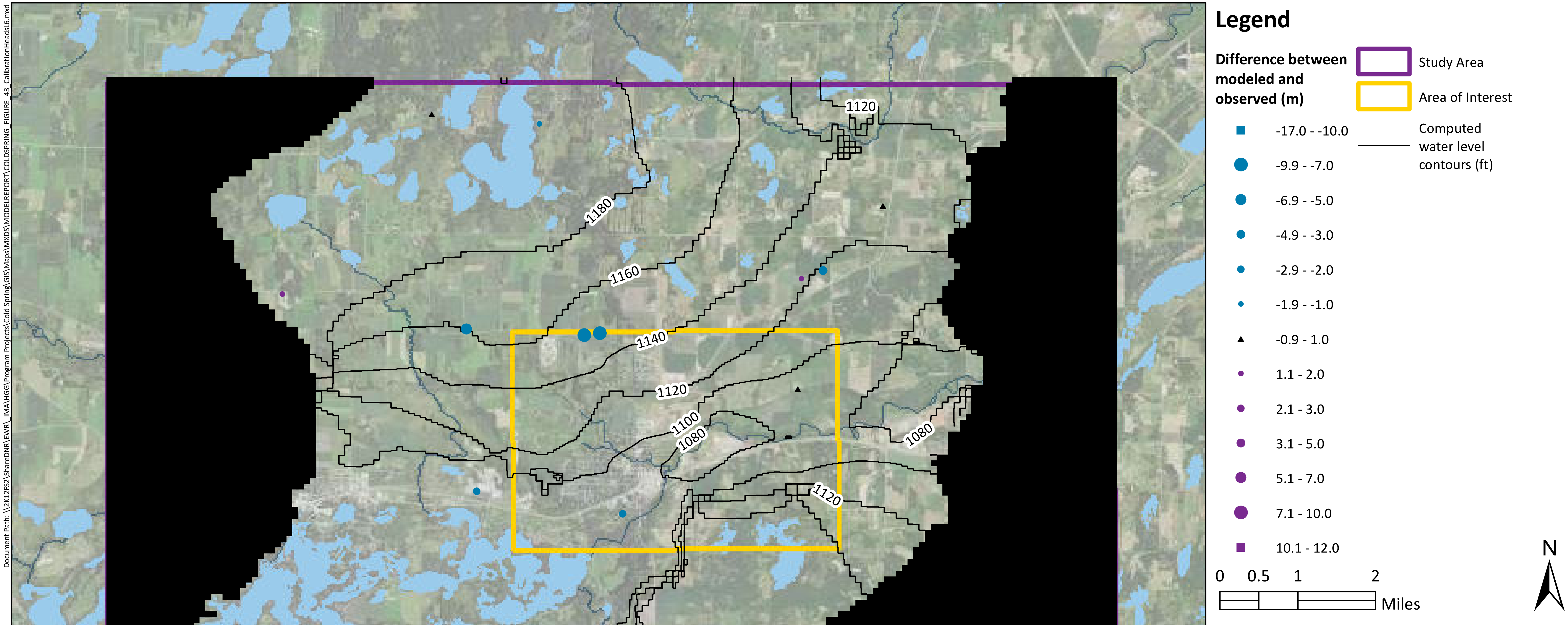

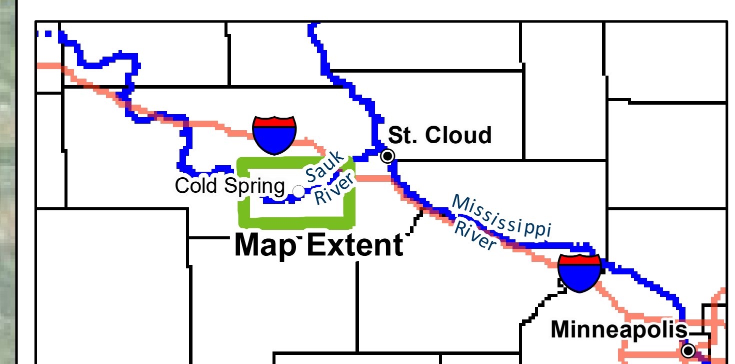

Figure 43. Water level and targets Layer 6

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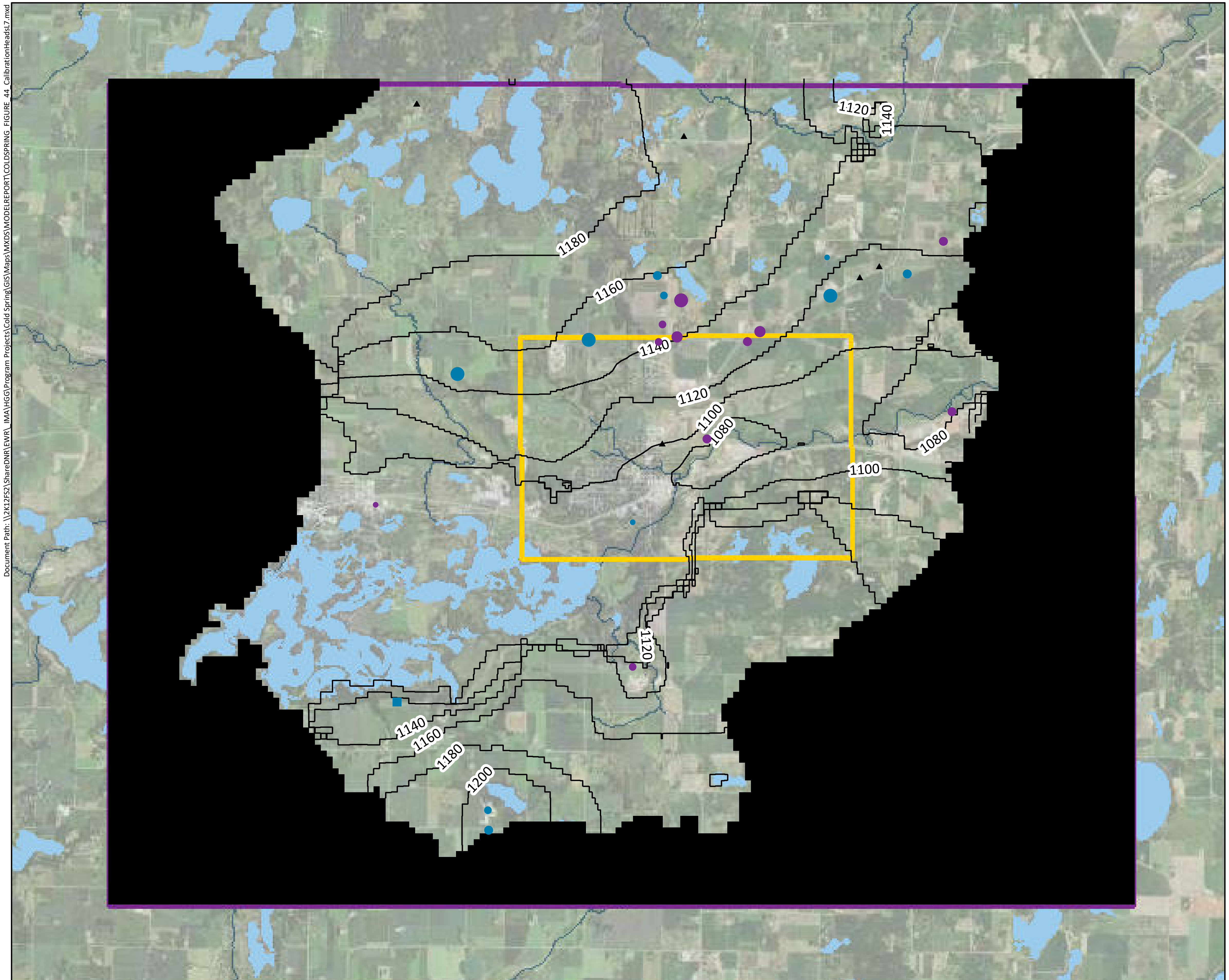

Legend

Difference between modeled and observed (m)

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- -9.9 - -7.0
- -6.9 - -5.0
- -4.9 - -3.0
- -2.9 - -2.0
- -1.9 - -1.0
- -0.9 - 1.0
- 1.1 - 2.0
- 2.1 - 3.0
- 3.1 - 5.0
- 5.1 - 7.0
- 7.1 - 10.0
- 10.1 - 12.0

Study Area

Area of Interest

Computed water level contours (ft)

0 0.5 1 2 Miles

N

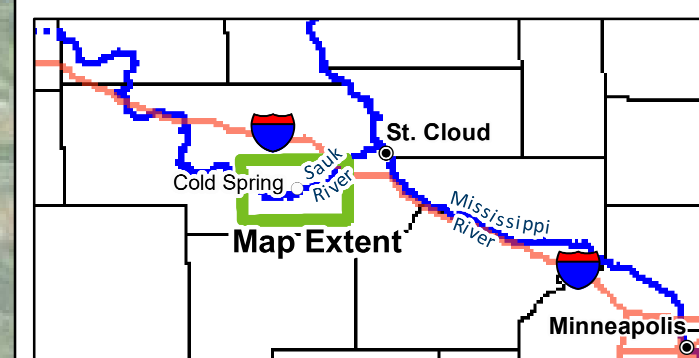

Figure 44. Water level and targets Layer 7

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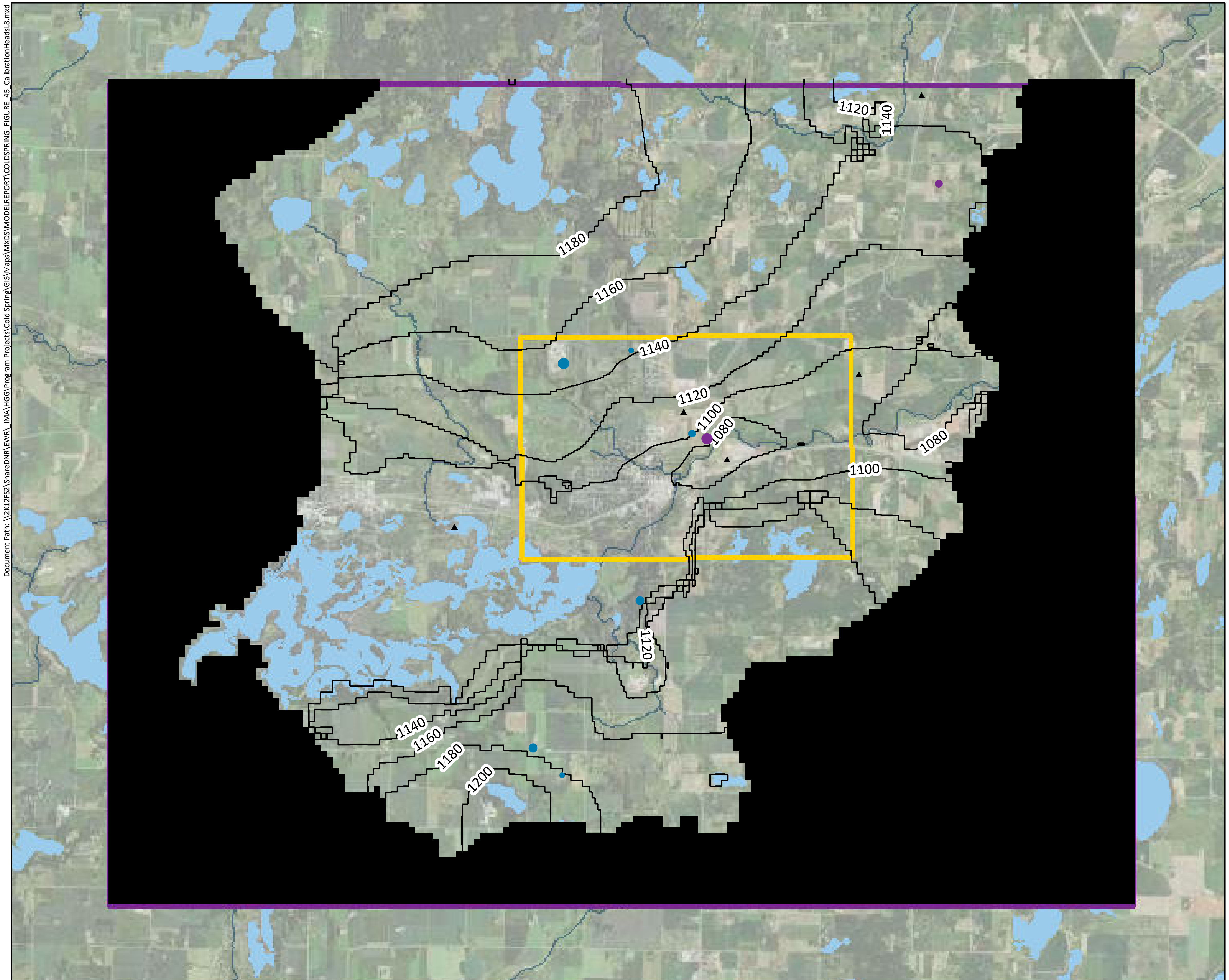

Legend

Difference between modeled and observed (m)

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- -4.9 - -3.0
- -2.9 - -2.0
- -1.9 - -1.0
- -0.9 - 1.0
- 1.1 - 2.0
- 2.1 - 3.0
- 3.1 - 5.0
- 5.1 - 7.0
- 7.1 - 10.0
- 10.1 - 12.0

Study Area

Area of Interest

Computed water level contours (ft)

0 0.5 1 2 Miles

N

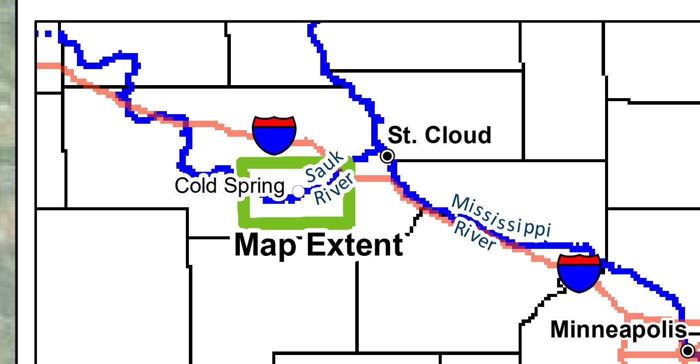

Figure 45. Water level and targets Layer 8

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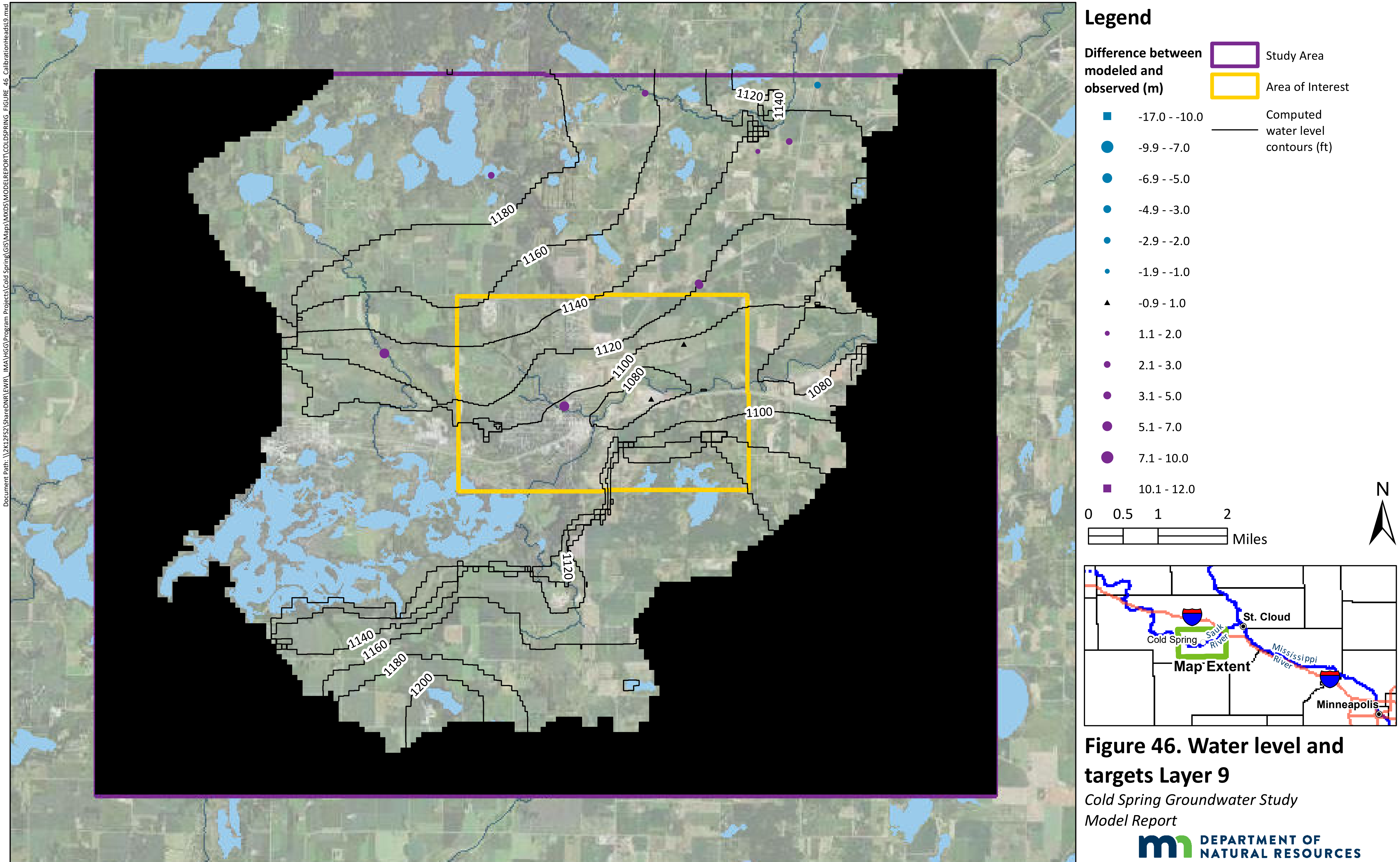

Figure 46. Water level and targets Layer 9

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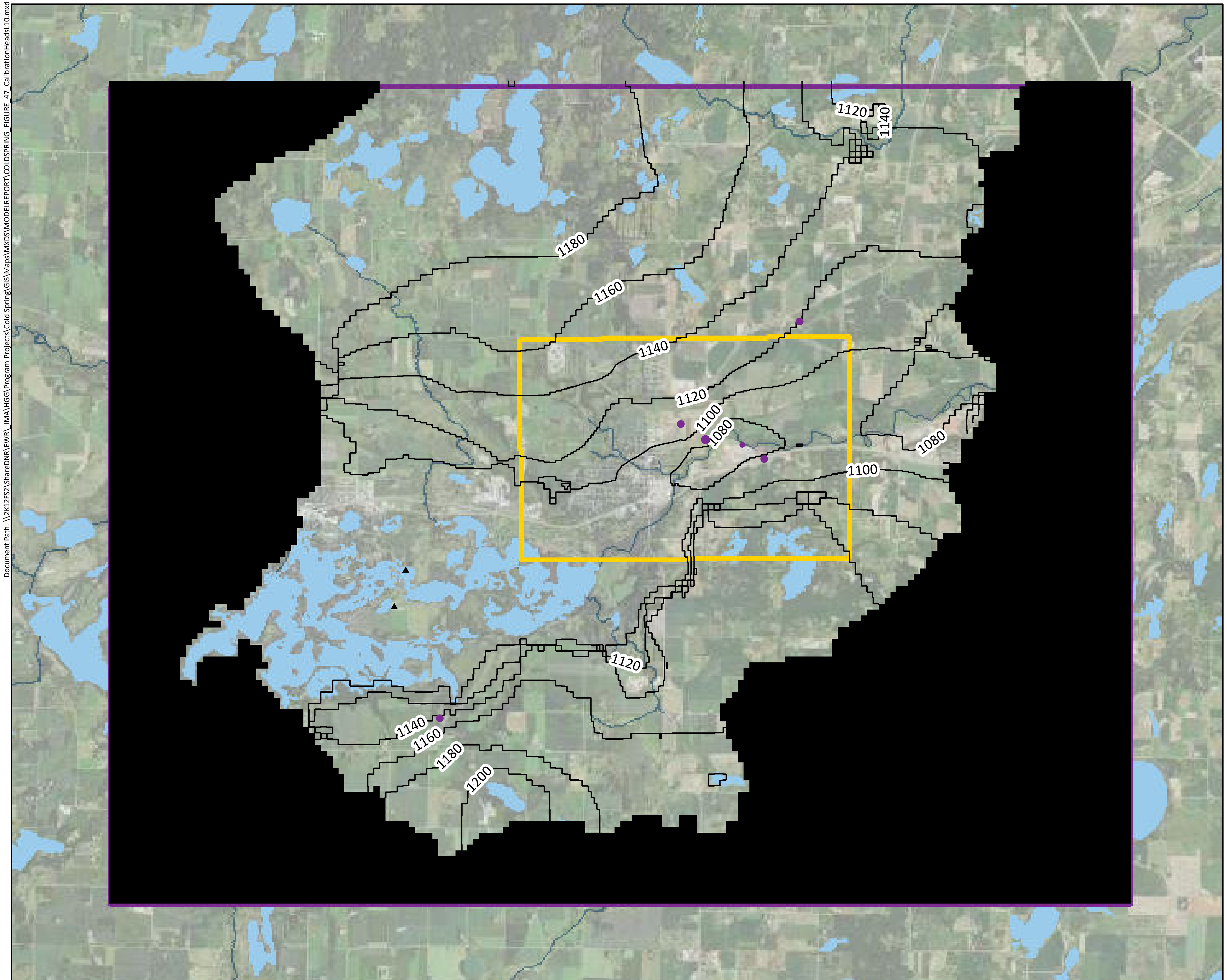

Legend

Difference between modeled and observed (m)

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- -9.9 - -7.0
- -6.9 - -5.0
- -4.9 - -3.0
- -2.9 - -2.0
- -1.9 - -1.0
- -0.9 - 1.0
- 1.1 - 2.0
- 2.1 - 3.0
- 3.1 - 5.0
- 5.1 - 7.0
- 7.1 - 10.0
- 10.1 - 12.0

- Study Area
- Area of Interest
- Computed water level contours (ft)

0 0.5 1 2 Miles

N

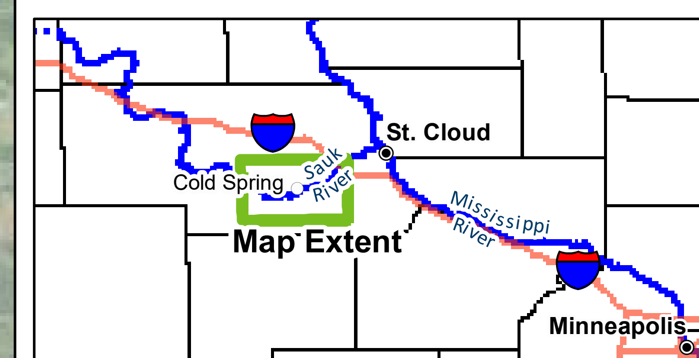

Figure 47. Water level and targets Layer 10

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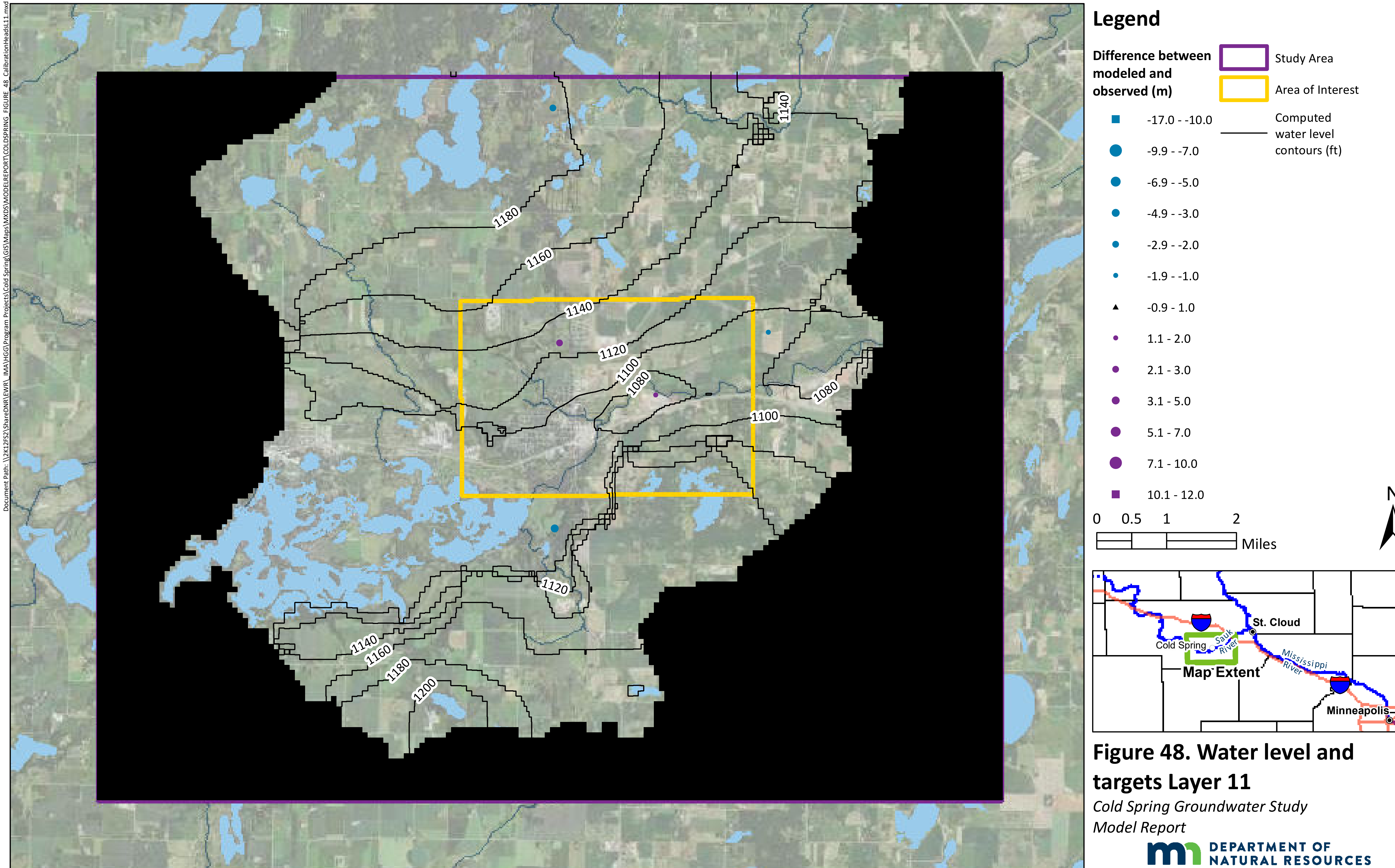

Figure 48. Water level and targets Layer 11

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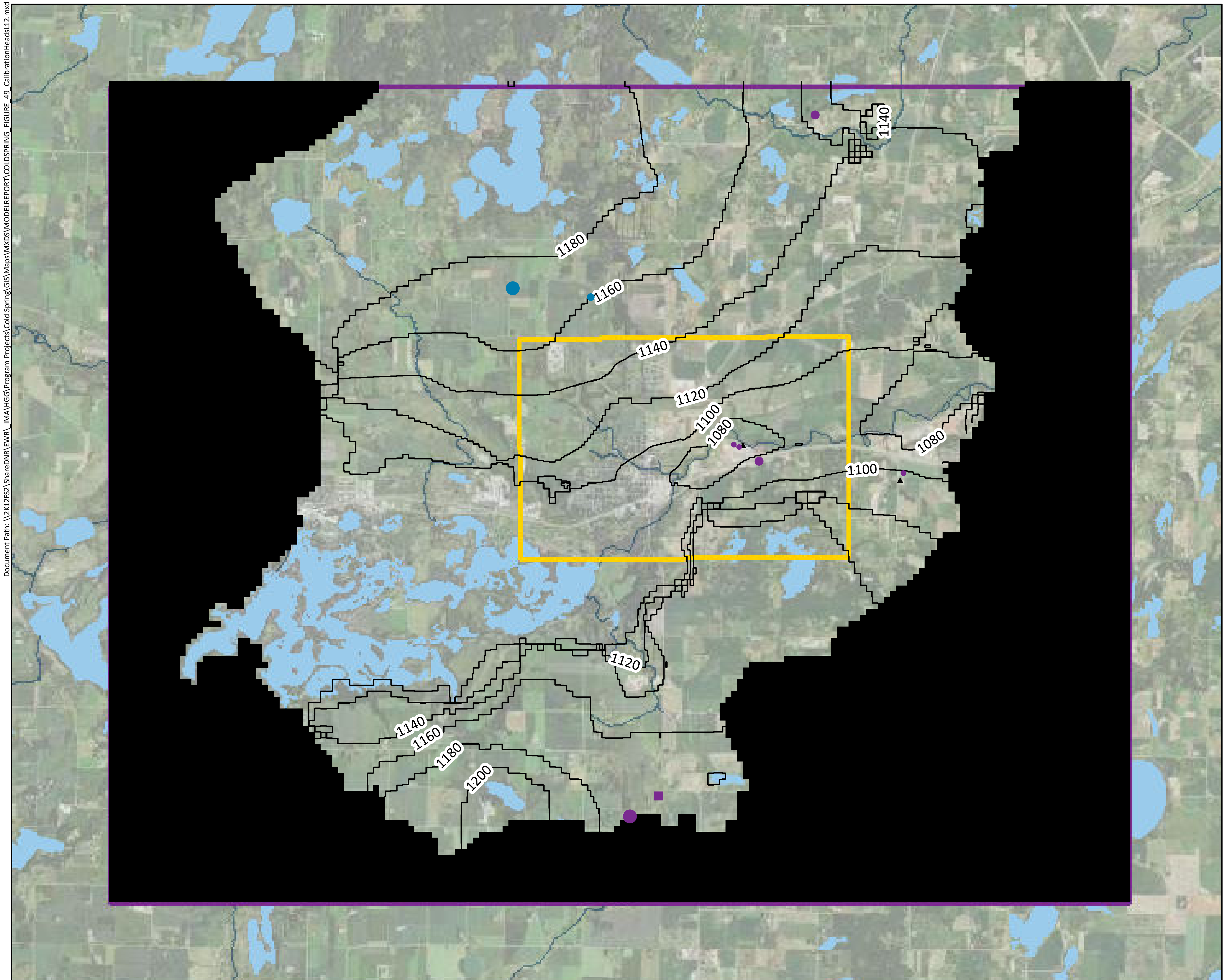

Legend

Difference between modeled and observed (m)

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- -9.9 - -7.0
- -6.9 - -5.0
- -4.9 - -3.0
- -2.9 - -2.0
- -1.9 - -1.0
- -0.9 - 1.0
- 1.1 - 2.0
- 2.1 - 3.0
- 3.1 - 5.0
- 5.1 - 7.0
- 7.1 - 10.0
- 10.1 - 12.0

Study Area

Area of Interest

Computed water level contours (ft)

0 0.5 1 2 Miles

N

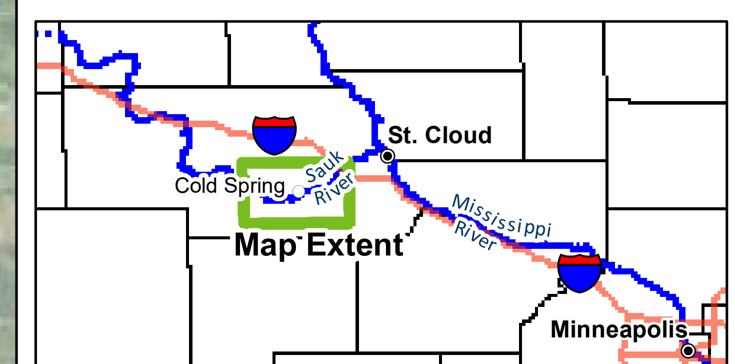

Figure 49. Water level and targets Layer 12

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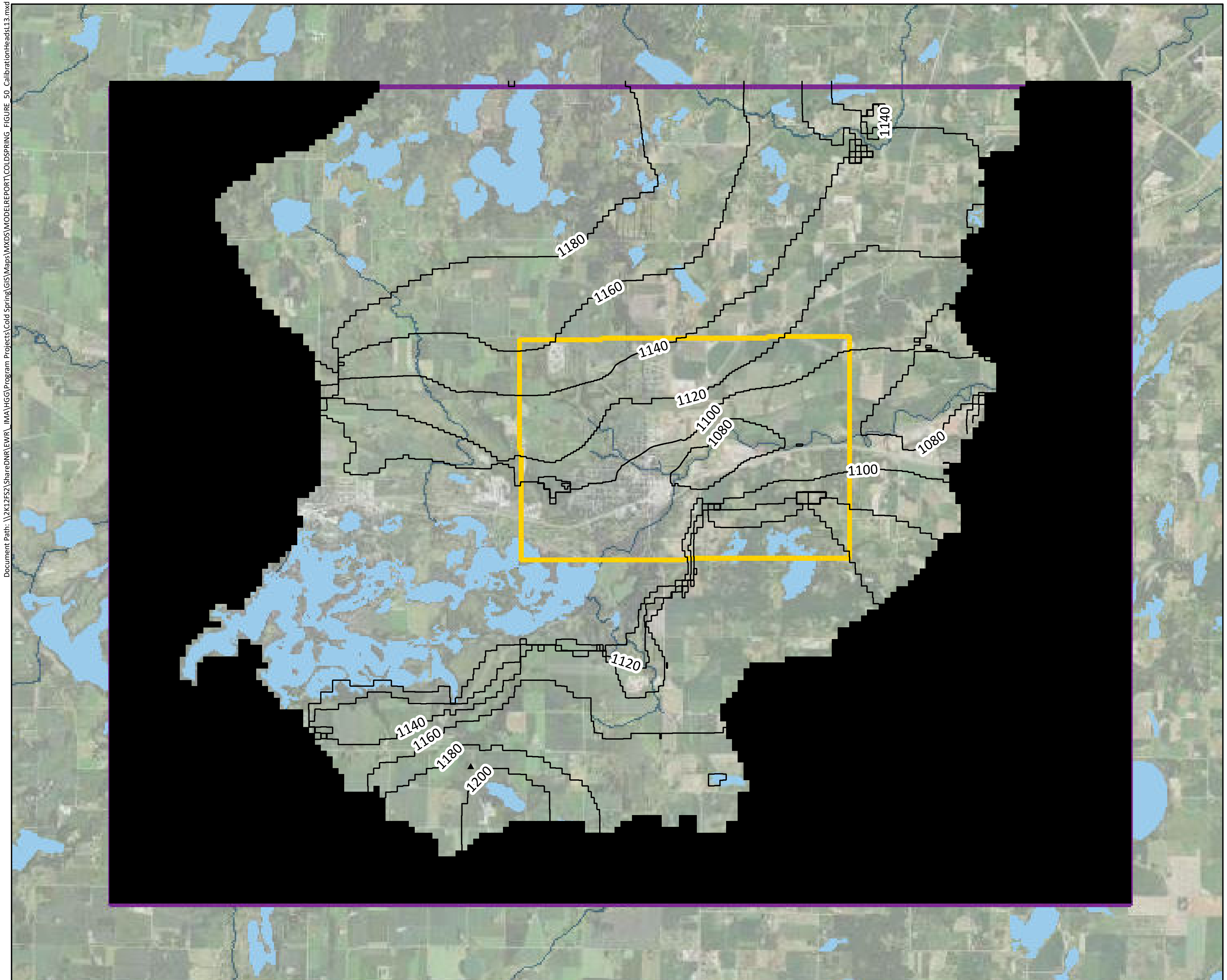

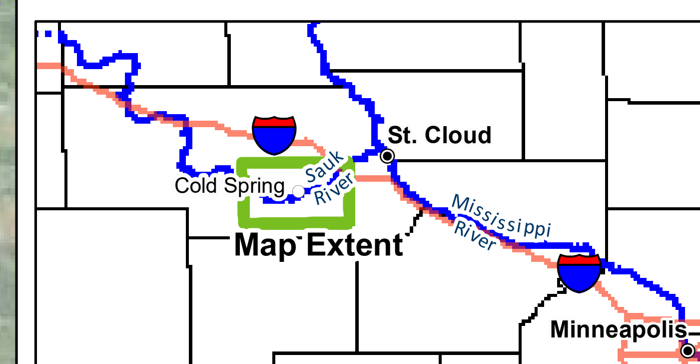

Figure 50. Water level and targets Layer 13

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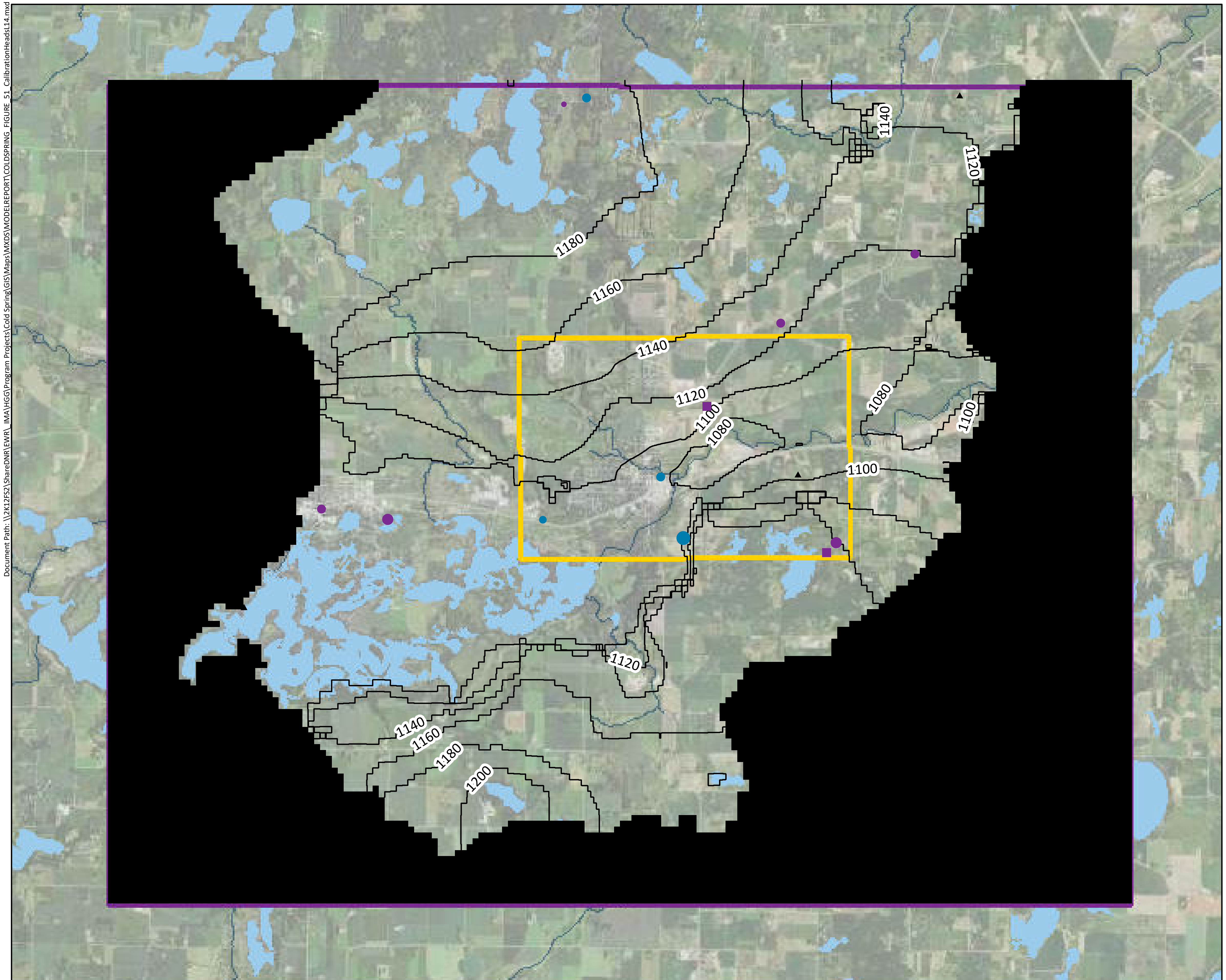

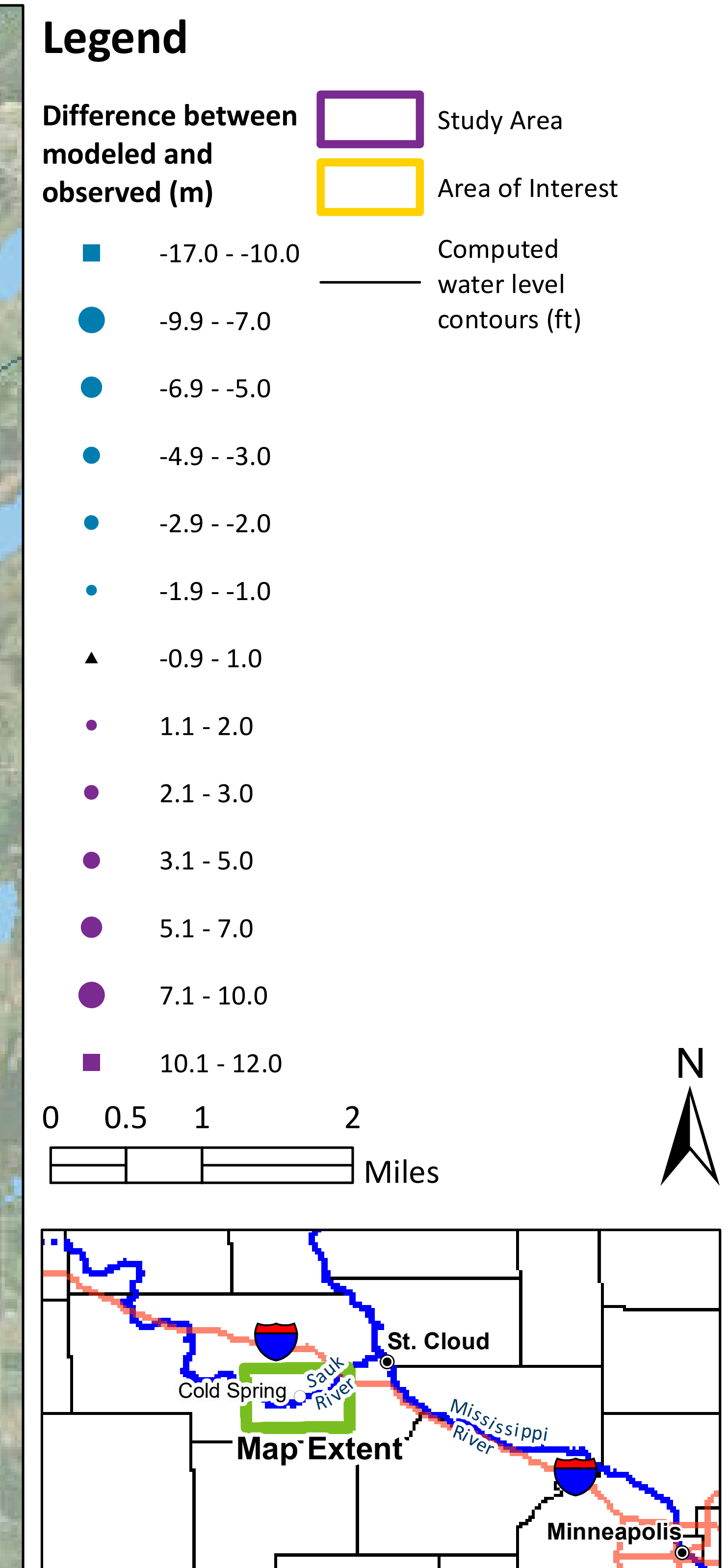

Figure 51. Water level and targets Layer 14

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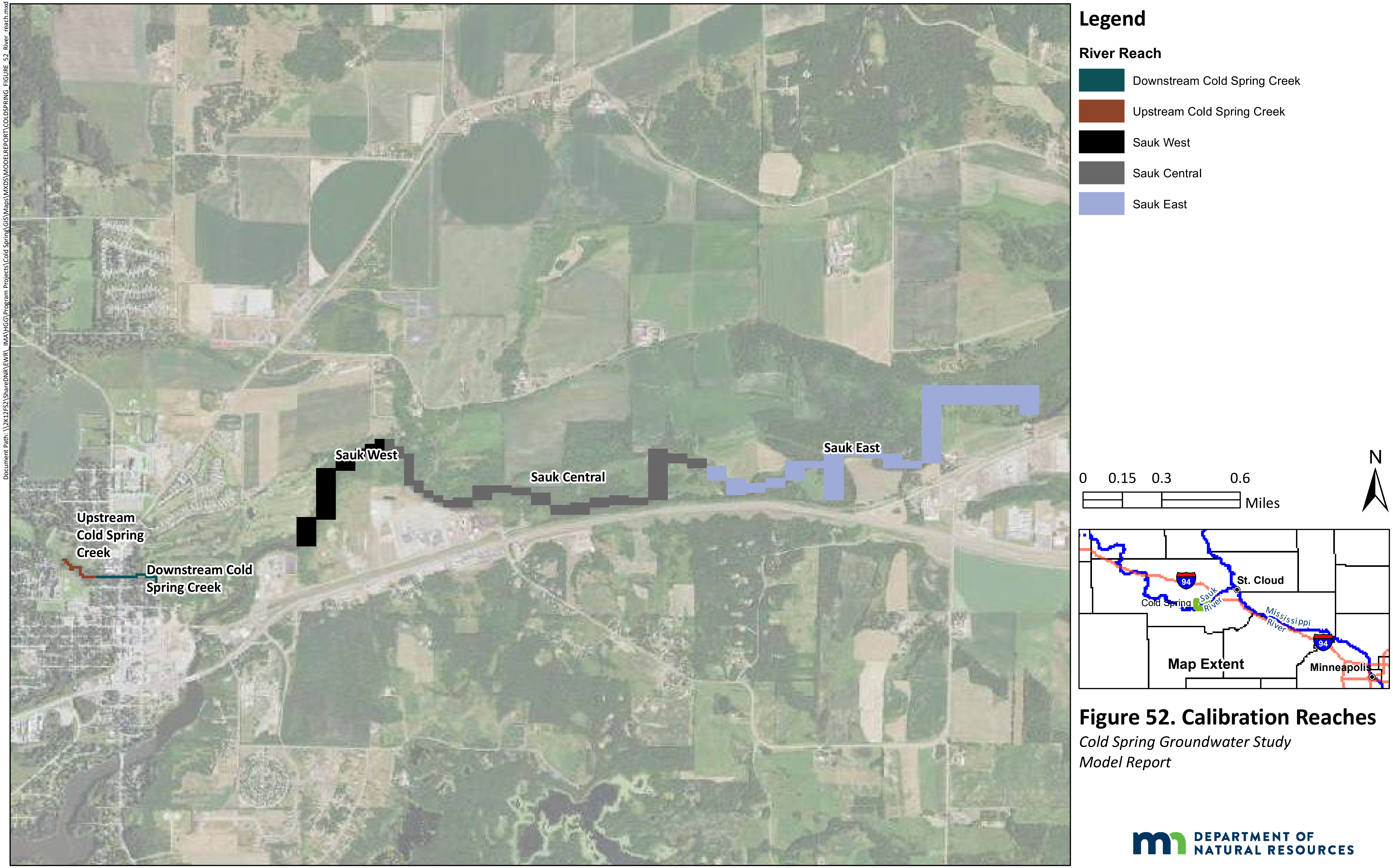

Figure 52. Calibration Reaches

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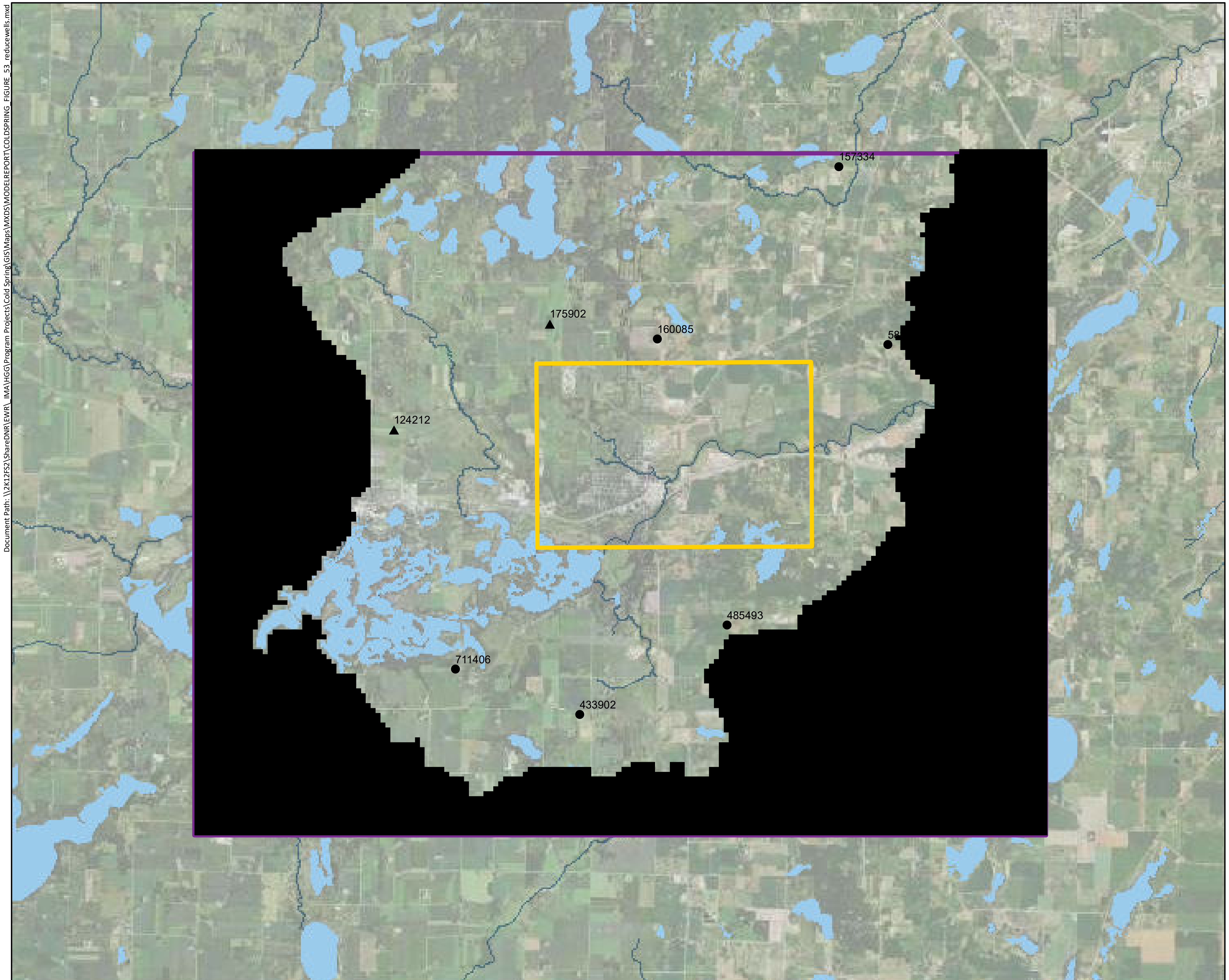

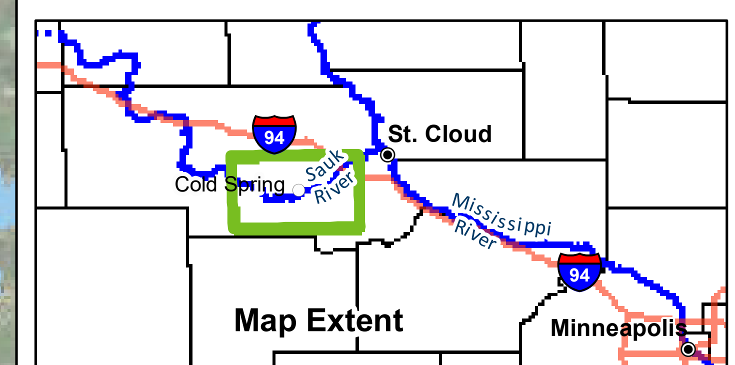

Figure 53. Reduced pumping wells

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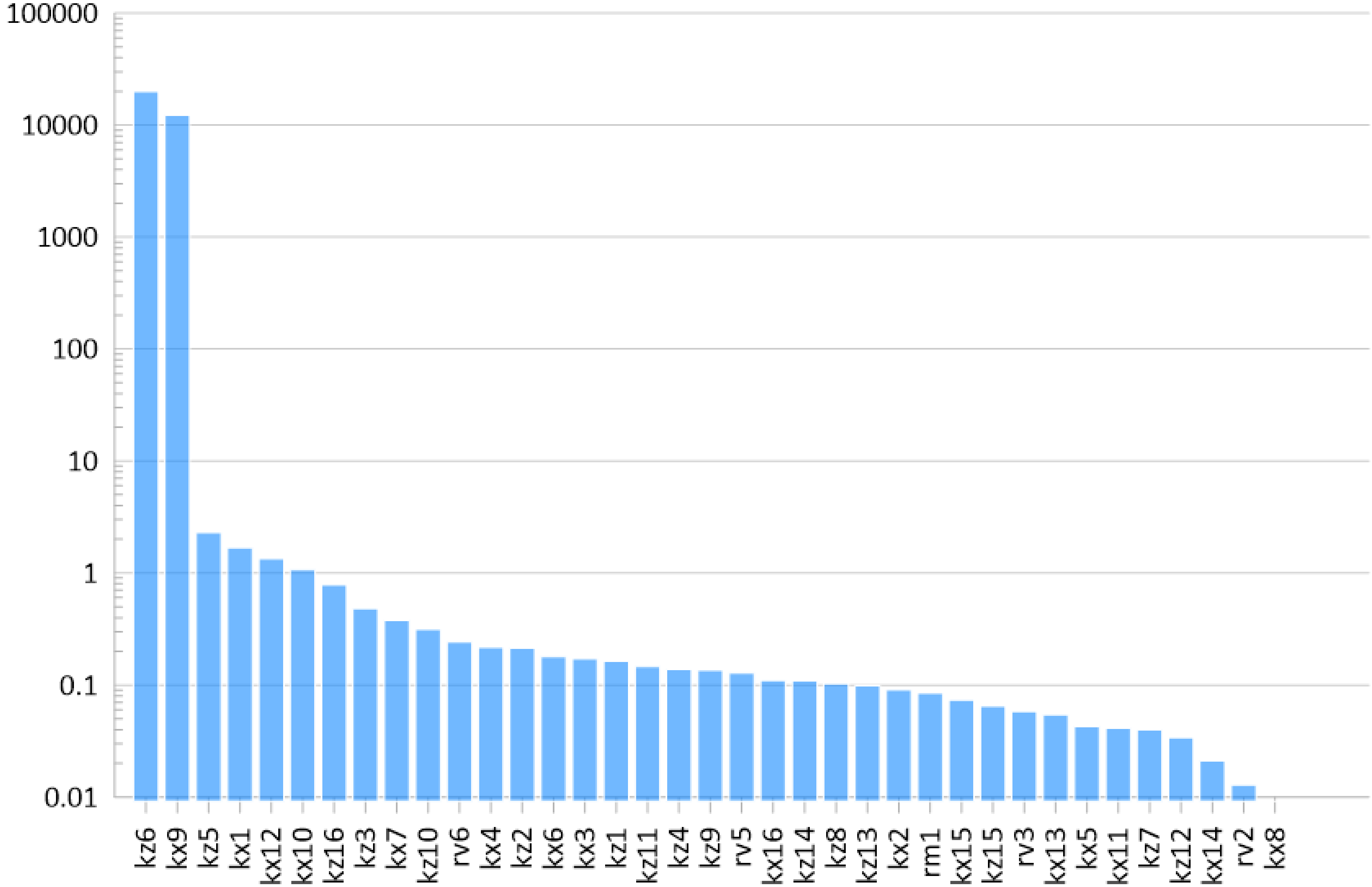

Figure 54. Parameter Sensitivities

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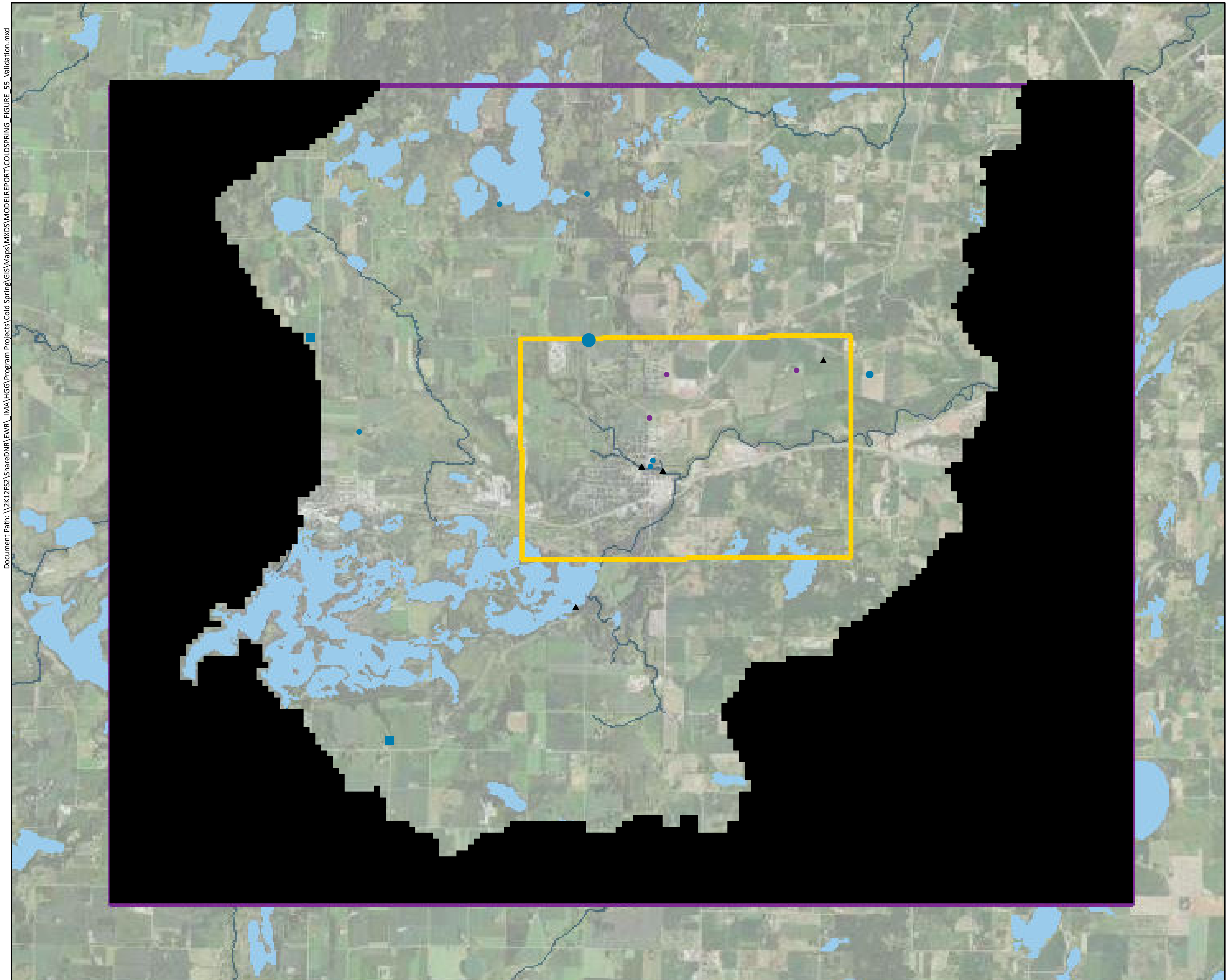

Legend

Difference between modeled and observed (m)

- -17.0 - -10.0
- -9.9 - -7.0
- -6.9 - -5.0
- -4.9 - -3.0
- -2.9 - -2.0
- -1.9 - -1.0
- -0.9 - 1.0
- 1.1 - 2.0
- 2.1 - 3.0
- 3.1 - 5.0
- 5.1 - 7.0
- 7.1 - 10.0
- 10.1 - 12.0

- Study Area
- Area of Interest

0 0.5 1 2 Miles

N

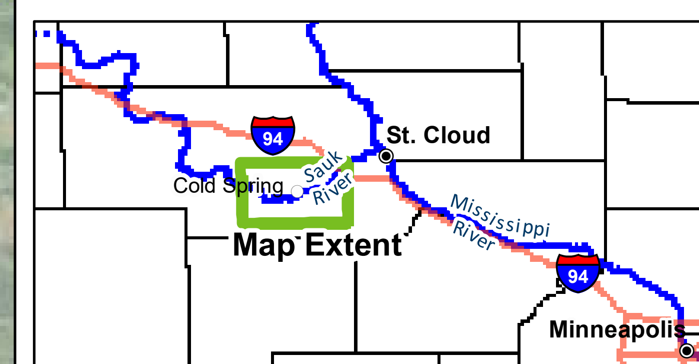

Figure 55. Validation Head Targets

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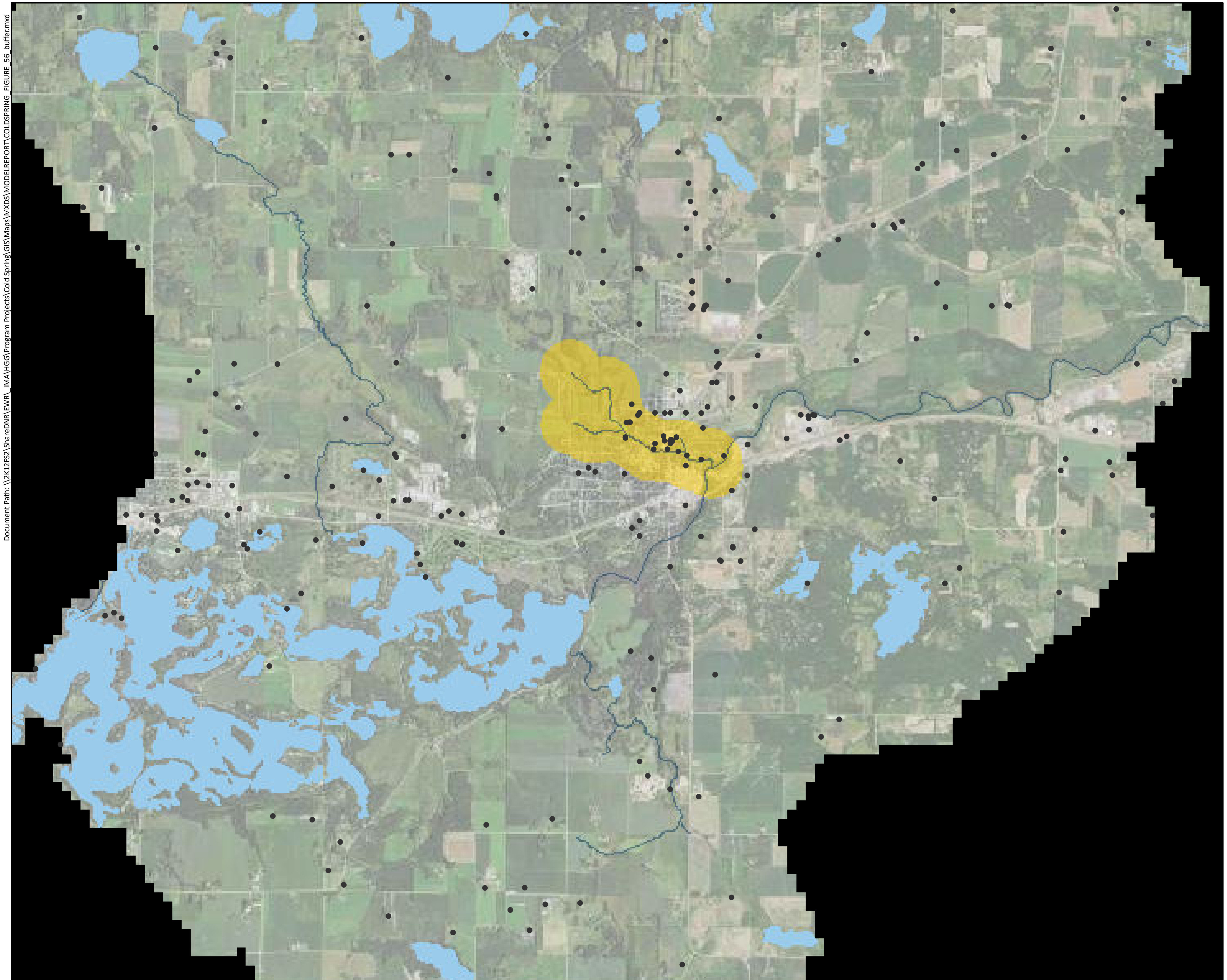

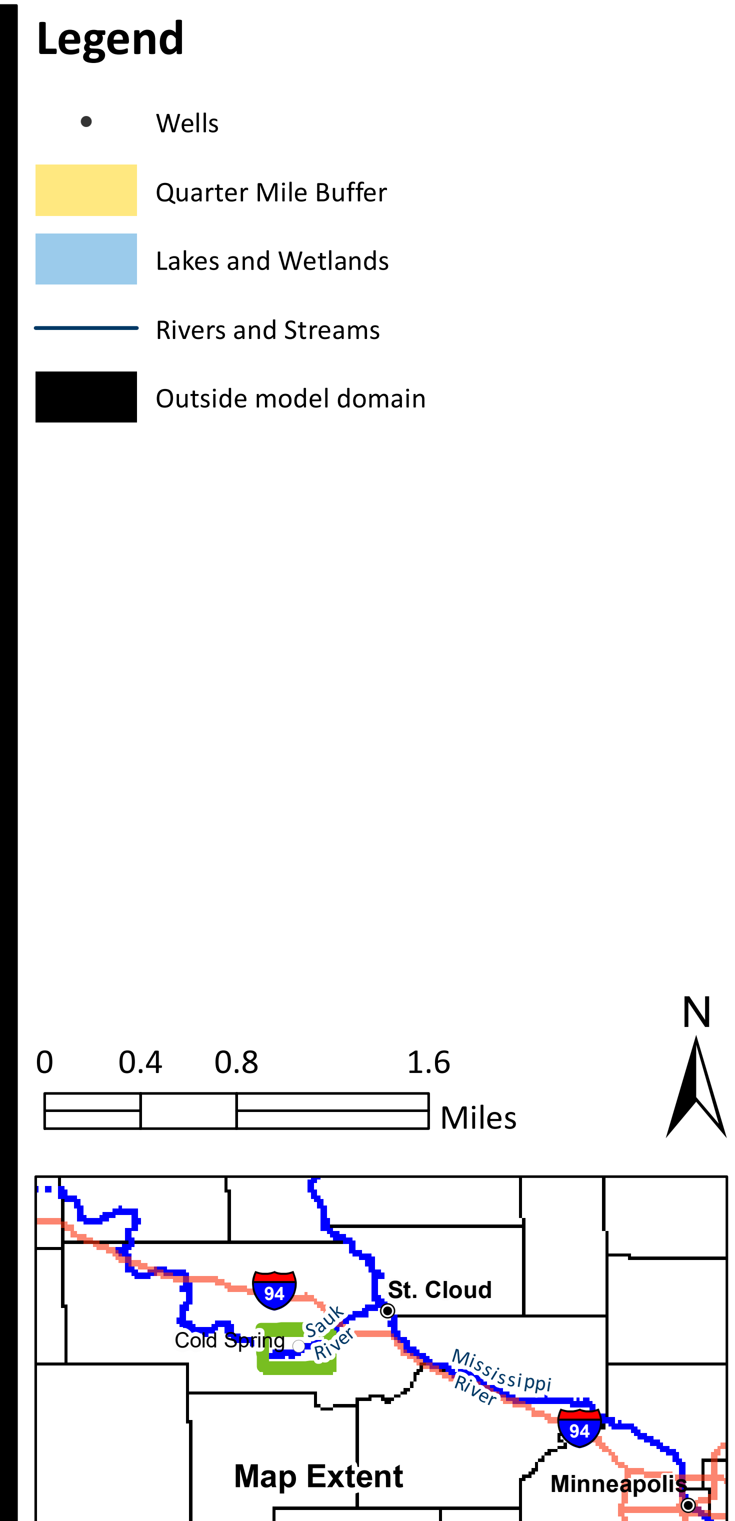

Figure 56. Quarter mile buffer

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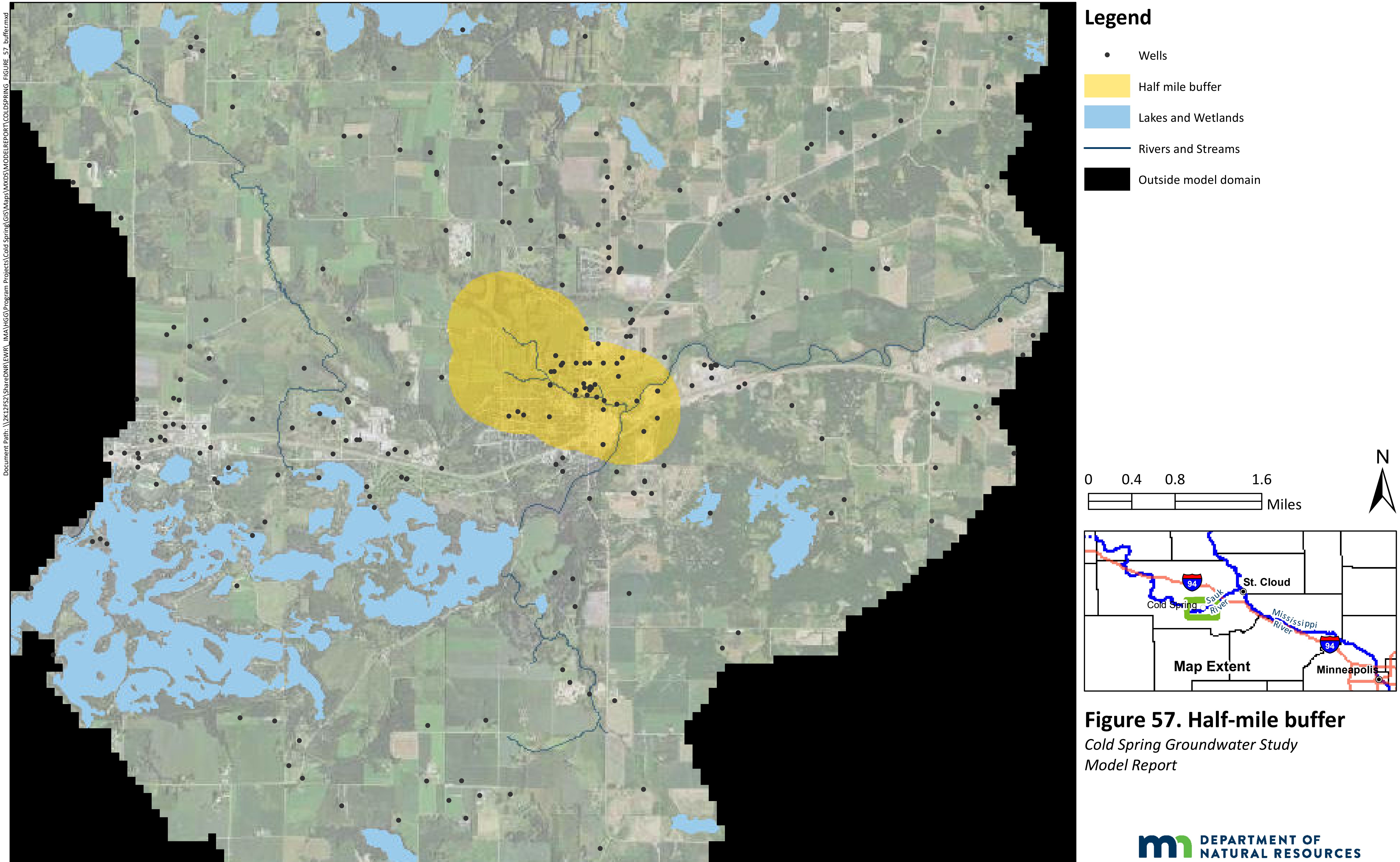

Figure 57. Half-mile buffer

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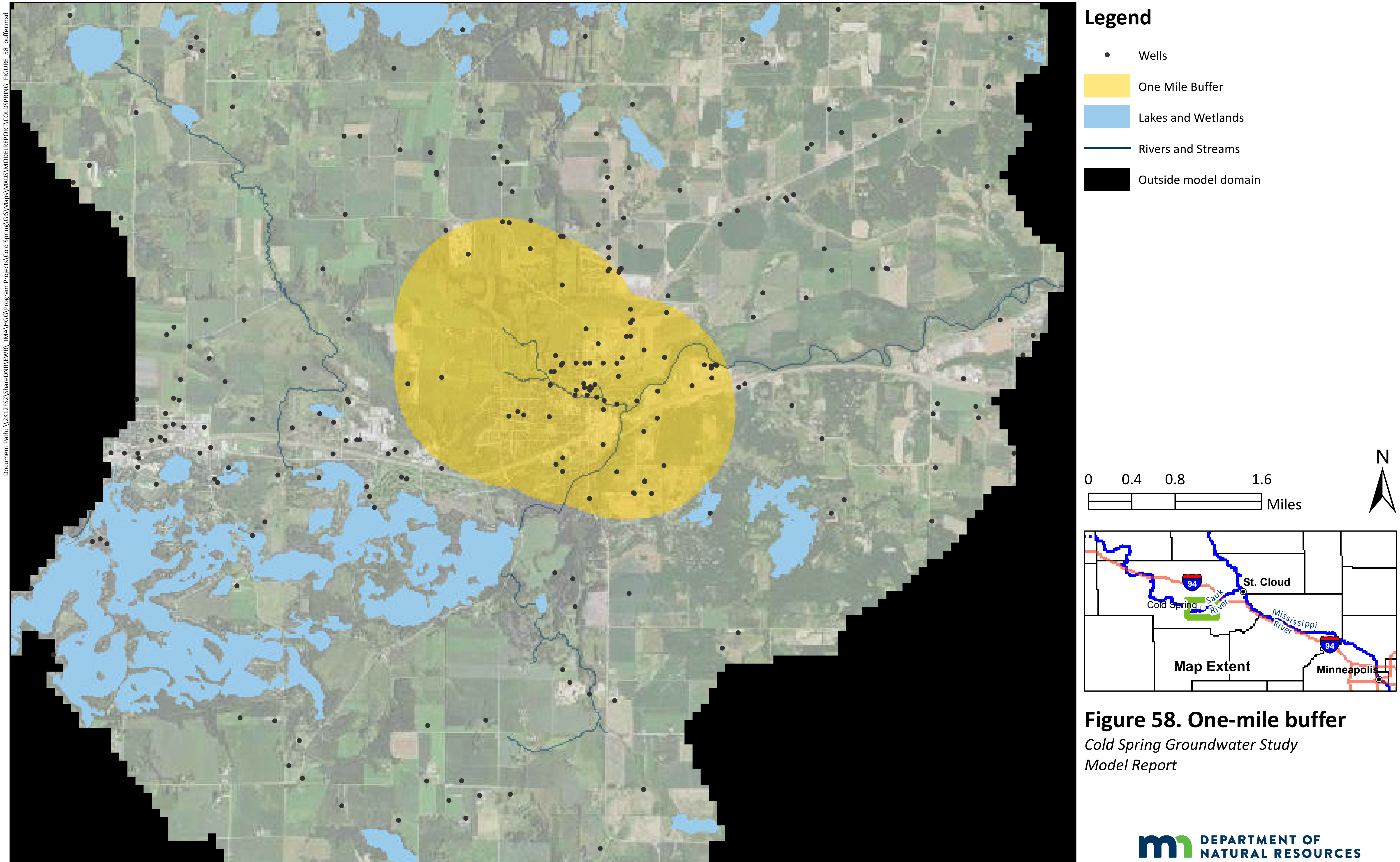

Figure 58. One-mile buffer

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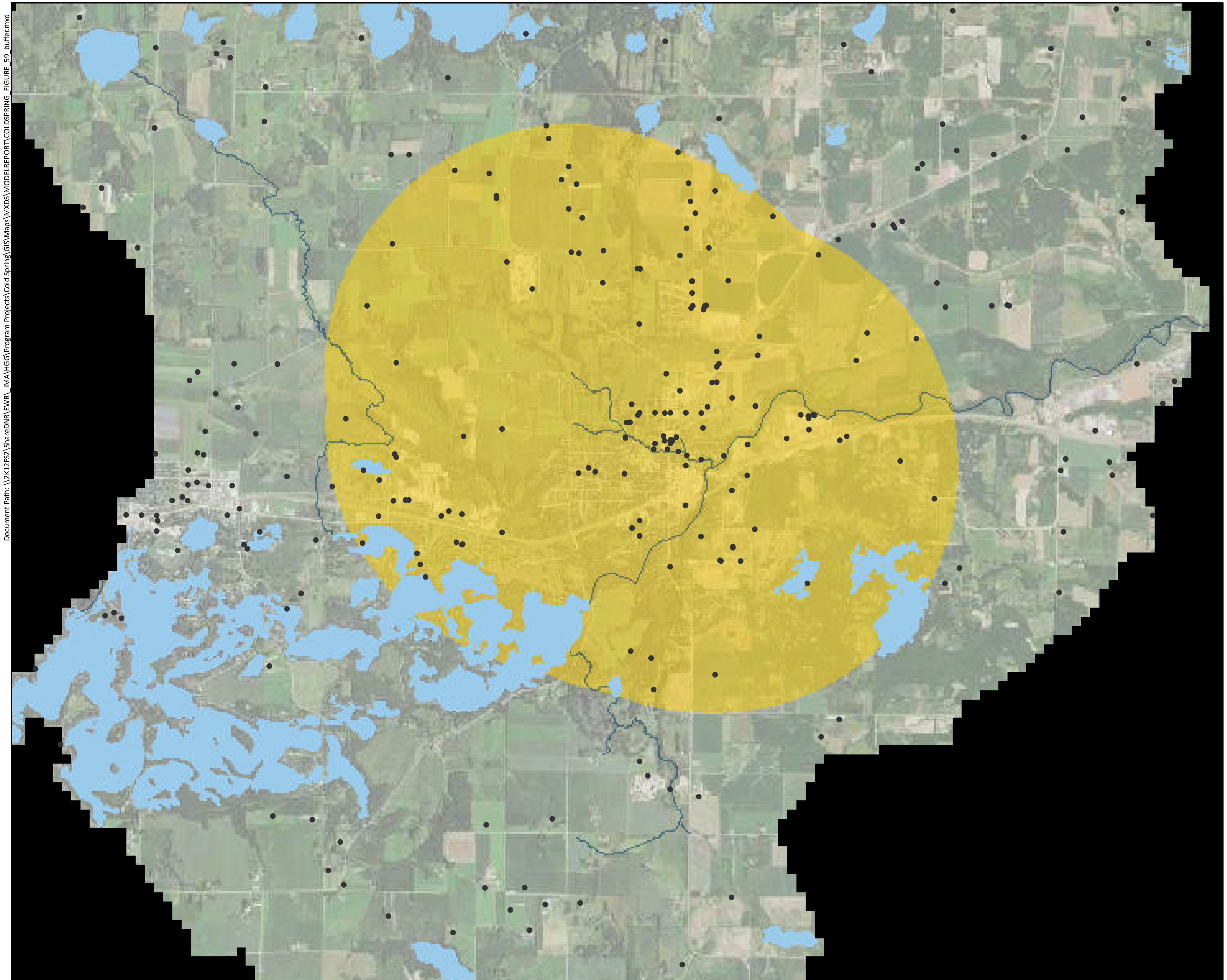

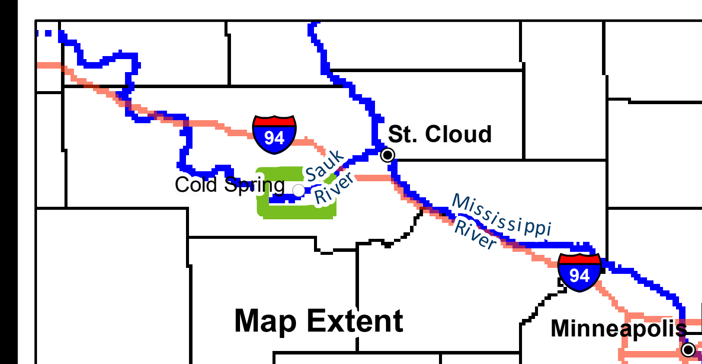

Figure 59. Two-mile buffer

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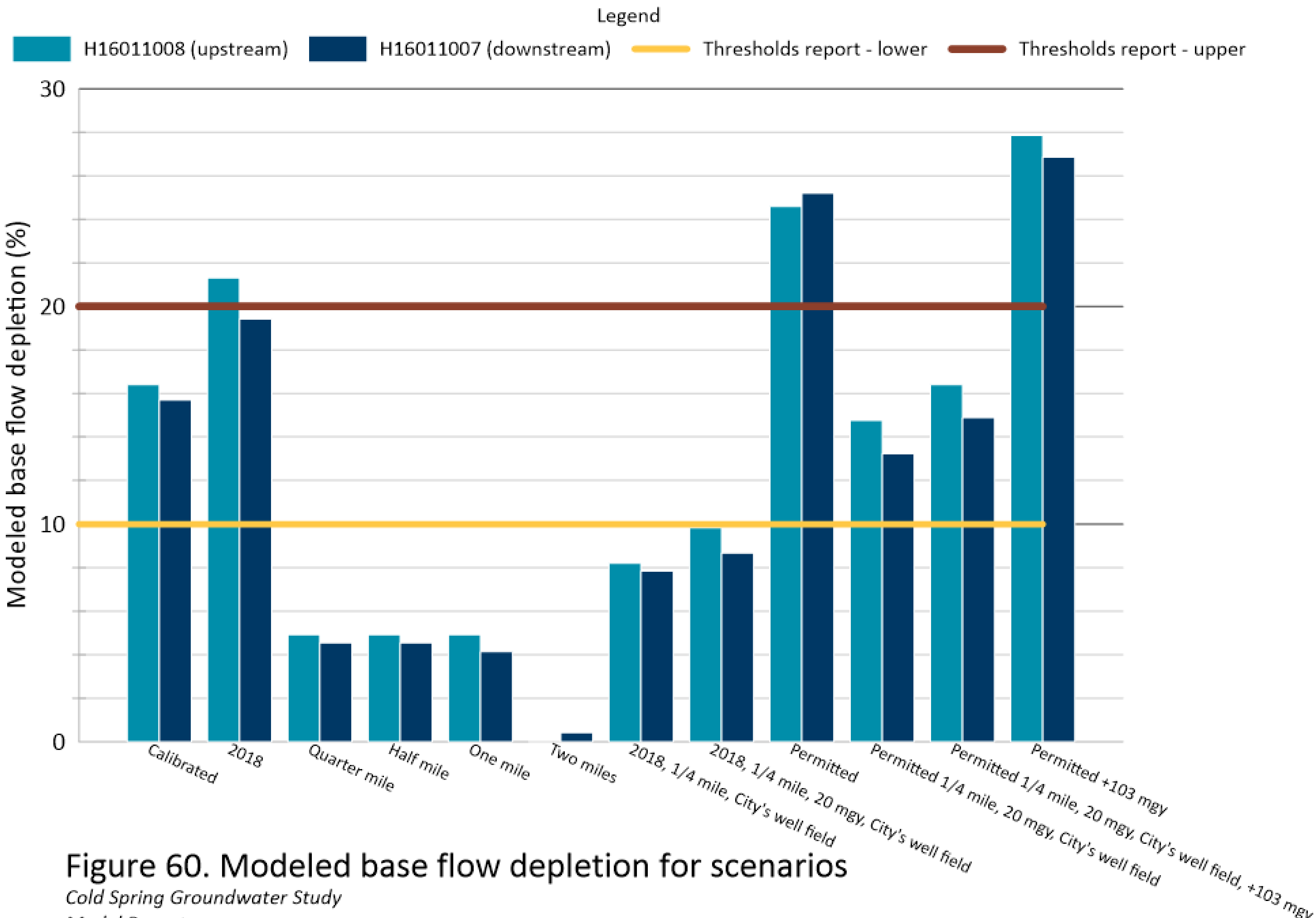

Figure 60. Modeled base flow depletion for scenarios

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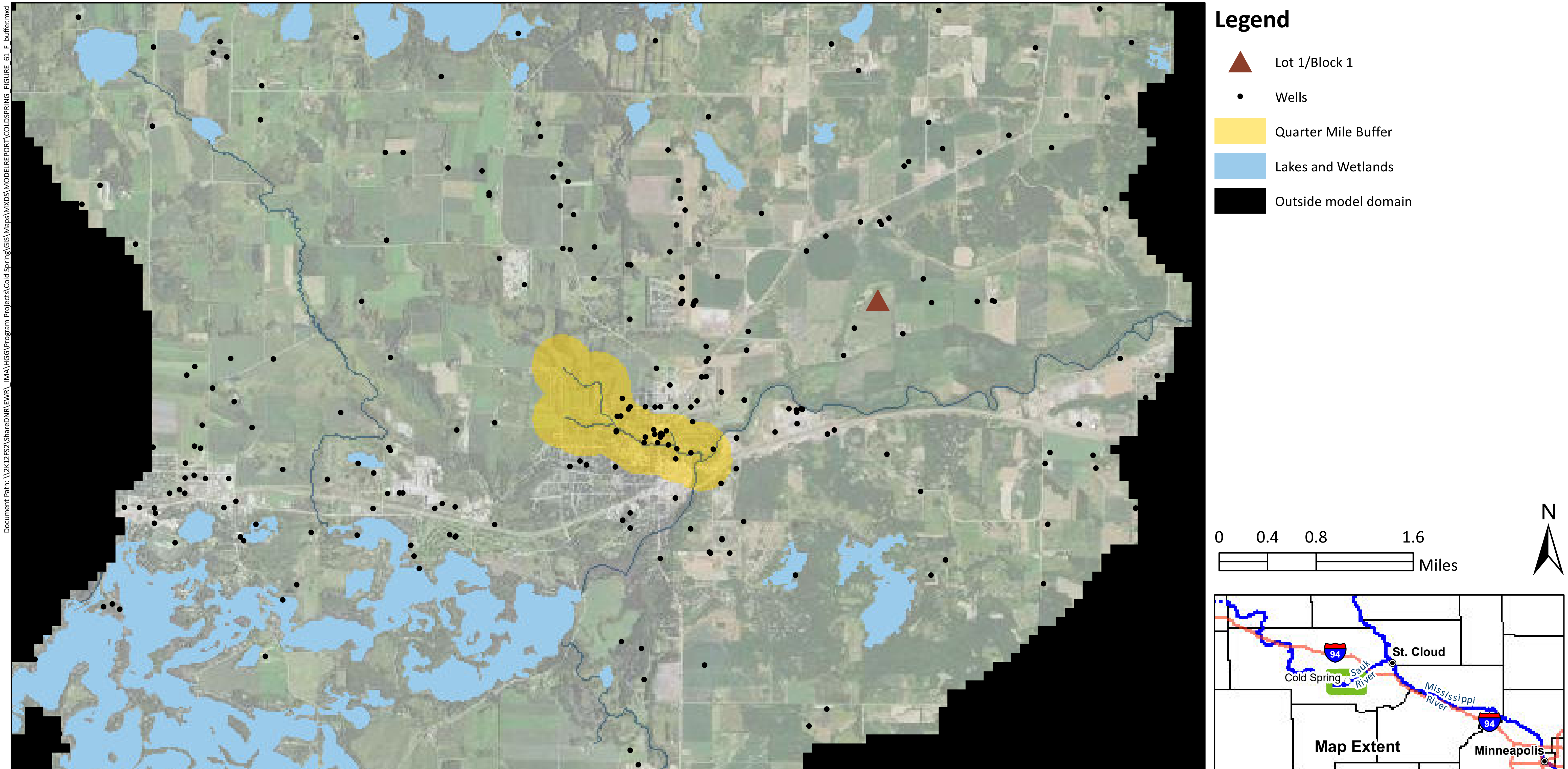

Figure 61. Additional site hypothetical water supply scenarios

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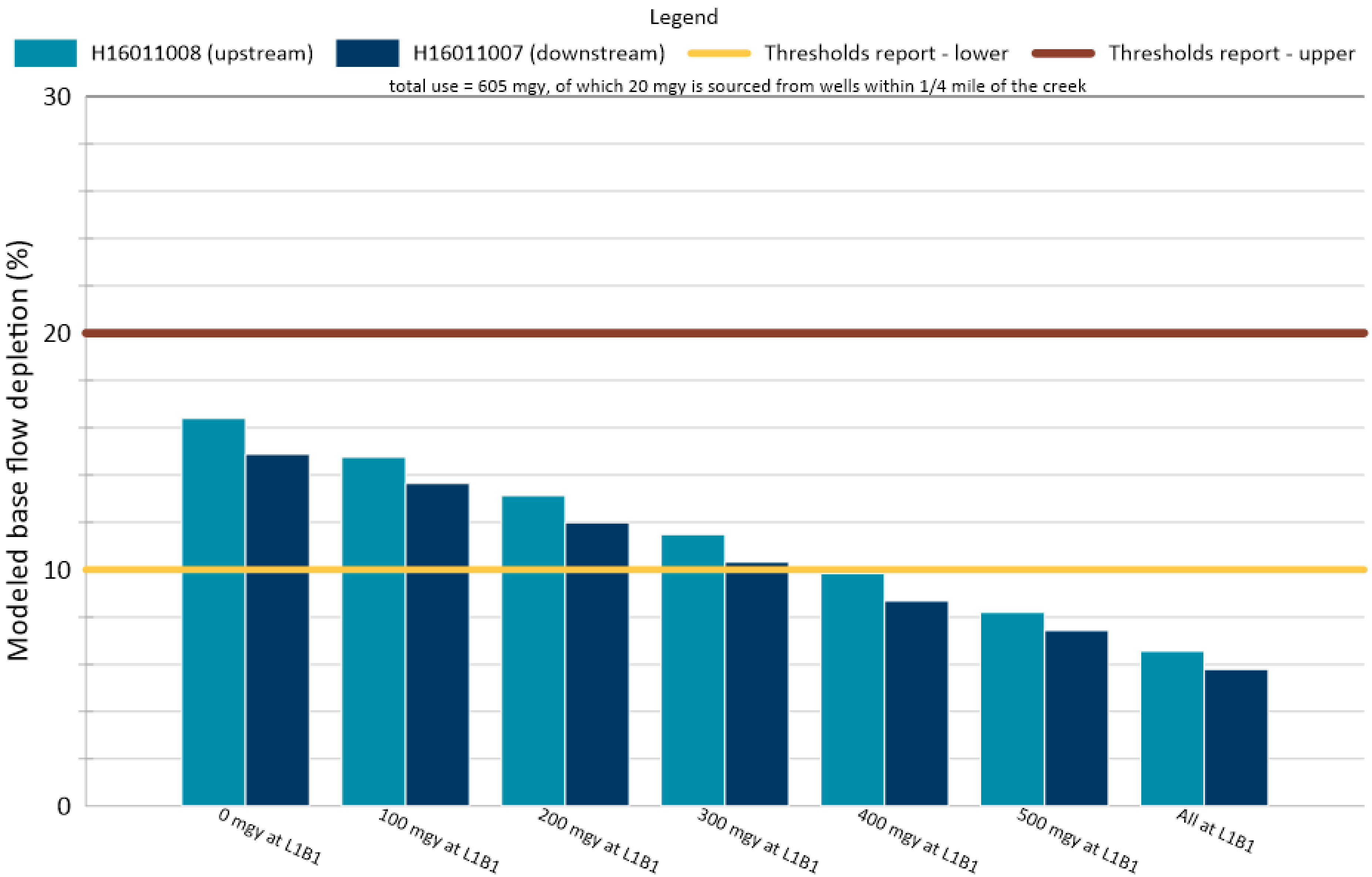

Figure 62. Modeled base flow depletion comparing existing well field and Lot 1/Block 1

8.0 List of abbreviations and glossary

aquifer—An underground layer of water-bearing permeable rock or unconsolidated materials (sand and gravel) from which groundwater can be extracted using a water well.

area of interest—The specific area of the model that is trying to answer questions.

base flow—The sustained flow (amount of water) in a stream that comes from groundwater discharge or seepage. Groundwater flows underground until it intersects the land surface where it becomes surface water in the form of springs, streams/rivers, lakes and wetlands. Base flow is the continual contribution of groundwater to rivers and is an important source of flow between rainstorms.

bedrock—The consolidated rock underlying unconsolidated surface materials such as soil or glacial sediment.

the City—City of Cold Spring Minnesota

cfy—

CHB—Constant head boundary

cone of depression—Where the potentiometric surface is lowered surrounding a well due to pumping.

CSBC—Cold Spring Brewing Company

CWI—County well index or Minnesota well index

data collection area—Defined area where the DNR will collect data to inform the final groundwater flow model.

DNR—Minnesota Department of Natural Resources

evaporation—The process by which water or other liquids change from liquids to a gas vapor. Evaporation can return infiltrated water to the atmosphere from upper soil layers before it reaches groundwater or surface water, and occur from leaf surfaces (interception), water bodies (lakes, streams, wetlands, oceans), or small puddled depressions in the landscape.

evapotranspiration—The combination of evaporation and transpiration. Loss of water to the atmosphere by evaporation from the soil and open bodies of water and transpiration by plants (water that is released from plants during photosynthesis).

gaining stream—A stream reach that receives a measureable percentage of its flow from groundwater.

GIS—Geographic information system

glacial—Relating to or derived from a glacier.

gpm—

groundwater—Water that collects or flows beneath the earth surface, filling the porous spaces in soil, sediment, and rocks.

hydraulic—Relating to water movement.

hydraulic conductivity—The rate at which groundwater flows through a unit cross-section of an aquifer.

hydraulic head (head) —The energy that causes groundwater to flow; the sum of the elevation head and the pressure head.

infiltration—The movement of water from the land surface into the subsurface under unsaturated conditions.

LiDAR—A detection system that works on the principle of radar, but uses light from a laser.

losing stream—A stream that loses a measureable percentage of its flow to groundwater.

mg—Million gallons

mgy—Million gallons per year

MDH—Minnesota Department of Health

MDOT—Minnesota Department of Transportation

MPCA—Minnesota Pollution Control Agency

MRCC—Midwest Regional Climate Center

MRLC—Multi-Resolution Land Characteristics Consortium

MWI—Minnesota Well Index: a database developed and maintained by the Minnesota Department of Health and Minnesota Geological Survey containing basic information for wells drilled in Minnesota such as location, depth, and static water level. The database contains construction and geological information from the well record (well log) for many wells. It is available online through the Minnesota Well Index mapping application).

NLCD—National Land Cover Dataset

NRCS—Natural Resources Conservation Service

numerical model—A computer model that uses MODFLOW or other source code to simplify real-world systems and use differential equations to calculate groundwater flow.

overland flow—The result of precipitation that does not infiltrate into the ground; often referred to as run-off.

potential recharge—The movement of water through soil below the root zone, but not necessarily to the groundwater system.

potentiometric surface—A surface representing the total head of groundwater in an aquifer and defined by the levels to which water will rise in tightly case wells.

Quaternary—Geologic time period that began 2.588 million years ago and continues to today. The Quaternary Period comprises the Pleistocene and Holocene epochs.

reach(es) — length of stream or river

recharge—The process through which water enters the groundwater system.

Steady-state model—Represents the equilibrium of average conditions where hydraulic heads and volume of water in storage do not change over time.

SWB—Soil-Water Balance

till—Unsorted glacial sediment deposited directly by ice. It is derived from the erosion and entrainment of rock and sediment over which the glacier has passed.

transmissivity—An aquifer's capacity to transmit water, determined by multiplying the hydraulic conductivity of the aquifer material by the thickness of the aquifer.

transpiration—The process by which plants take up water through their roots and then give off water vapor through their leaves (open stomata).

USDA—United States Department of Agriculture

USGS—United States Geological Survey

vertical anisotropy – hydraulic conductivity varies with the direction of measurement at a particular point, horizontal versus vertical

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Appendix A – Site history

Date	Activity
1952	First groundwater appropriation in Cold Spring area
May 1964	Cold Spring Brewery application for work in beds of public waters (1964-0492)
May 1966	City of Cold Spring files statement on appropriation of water (1966-6428) Groundwater: One 12-inch well 65 feet deep 350 gallons per minute (gpm) Surface Water: 2 pumps 2400 gpm
Dec 1975	City of Cold Spring applied for appropriation permit (1976-3179) Rate: 1160 gpm Appropriation: 138 mgy
Jun 1977	Commissioner’s order under section 97C.005: Permits issued after June 3, 1977, to appropriate water from streams designated trout streams, must be limited to temporary appropriations.
Summer 1980	Two dewatering projects to install sewer lines. First resulted in creek drying up between Fifth and Eighth Aves. Second did not dry up stream.
Aug 1980	City of Cold Spring installs culvert to direct storm water into Cold Spring creek
Sep 1980	DNR report on Cold Spring Brewery Creek notes the concern of groundwater/stream interactions. Recommends increased monitoring, aquifer tests, and cooperative pumping schedule.
Feb 1984	Cold Spring Brewery application (1984-3211) for wells 1 (253011, depth 51 feet) and 3 (718237, depth 58 feet;) 24 mgy for beer processing and cooling.
Mar 1988	Cold Spring Brewery application (1988-3220) for well 2 (440639 and 60 feet deep; 24 mgy)
1990	Minnesota Legislature adopted Minn. Stat 103G.285 (2012) which states appropriation “permits issued after June 3, 1977, to appropriate water from streams designated trout streams…must be limited to temporary appropriations” This provision required the DNR to give heightened protection to trout streams when evaluating surface-water appropriations.
Aug 1990	River Oaks Country Club application for permit (22 mgy)
Aug 1994	ISD 750 Irrigation permit 8.7 mgy
Jun 1995	City initiates Wellhead Protection Planning
Jul 1995	Gold’n Plump releases its “Groundwater Resources Evaluation – Wellhead Protection Area Delineation Report” that used MODFLOW to determine impacts from their well use to the City of Cold Springs Wellhead Protection Area.
1996	City Well 1 (241386) exceeds Nitrate HCML level of 10 parts per million
Aug 1997	Permit 1976-3179 is amended to increase appropriation from 138 mgy to 148 mgy at a rate of 1055 gpm.
Jan 1998	MPCA issued NPDES permit for once-through noncontact cooling water and reverse osmosis reject water. Maximum allowable discharge: 62,000 gpd (max 44,000 gpd) with 1/3 of discharge being reject reverse osmosis water and 2/3 being non-contact cooling water. Expiration date 12/31/2002
Nov 1998	City Well 4 constructed (614989)
Feb 1999	Request to transfer permits 1984-3211 and 1988-3220 from Cold Spring Brewing Co. to Gluek Brewing Company. Permit transferred under the name REFLO Inc. on June 24, 1999

Nov 1999	City Well 5 constructed (632093)
Unknown	Cold Spring Brewery applied for an amendment to add well #718237 and to increase authorized annual appropriations from 24 mgy to 80 mgy and to increase the combined pumping rate from 100 to 500 gpm (100 gpm for 253011 and 400 gpm from well 718237).
Apr 2000	Permit 1976-3179 is amended to add City Wells 4 and 5. Volume stays the same (148 mgy) but max rate changes to 2315 gpm.
2001	USGS Groundwater investigation and model
Dec 2002	City Well 6 constructed (686699)
Sep 2003	Permit 1976-3179 is amended to increase appropriation from 148 mgy to 210 mgy. Rate remains 2315 gpm. 6/21/2004 Permit 1976-3179 is amended to increase appropriations from 210 mgy to 250 mgy. Rate increases to 3115 gpm. Well 6 is added.
2005	Gluek Brewing and REFLO Inc. requested to amend permit 1984-3211 to increase its appropriation from 24 to 60 mgy. Well #253011 was shifted to a standby well and #718237 became the primary source of appropriation. The DNR authorized the appropriation.
2006	The City of Cold Spring leased City Well 1, located 435 ft. from Cold Spring Creek, to Gluek Brewing Co.
2006	REFLO Inc. for Gluek Brewing Co reported it had appropriated 65.5 mgy in 2005 (5.5 million over its authorized volume) and asked for an amendment to increase the volume to 80 mgy from well 718237
2006	Fish kill on Cold Spring Creek (unknown cause)
Mar 2006	DNR approved amendment of permit 1984-3211 to authorize 80 mgy at a pumping rate of 500 gpm and permit 1988-3220 to authorize 20 mgy at a pumping rate of 120 gpm
Dec 2006	Gluek Brewing Company proposed expansion, and City proposed the use of old well by brewery. DNR advises additional testing to make sure there is no impact on the trout stream as a result of using this well.
2009	Fish kill on Cold Spring Creek due to fire hydrant flush with chlorinated water
Apr 2009	Request by Cold Spring Brewery to amend Permit 1984-3211 to add well #241386 at 350 gpm and increase appropriation to 145 mgy. For the four previous years, they leased this well from the city and pumped volumes of 39.8, 132.8, 114.3, and 132.8 million gallons.
Jun 2009	The DNR reviews stream flow data and determines that base flow is reduced by pumping.
Aug 2009	The DNR tells Brewery they need to install loggers in observation wells 620734 and 620740 before the DNR can evaluate the April 2009 amendment request.
9/17 - 10/8/2009	Data loggers deployed at wells 620734 & 620740
Dec 2009	The DNR reviews monitoring results and determines that the drawdown from pumping reaches the trout stream

Jun 2010	Minn. Stat. 103G.287 Subdivision 2 is added that acknowledges the relationship of groundwater to surface-water resources and makes appropriations that will have a negative effect upon surface-water resources subject to 103G.285 (limited to temporary impacts).
Feb 2012	Permit is amended for 2 years to enable monitoring of impacts on the trout stream.
Mar 2012	Fisheries released a Stream Survey Report on Cold Spring Creek alternatively known as Brewery Creek. A stage logger was used to estimate discharge between 2002 and 2011 but was removed upon landowner's request.
Jan 2013	The DNR sends letter to Cold Spring Brewery Company stating the permit volume will not be reduced to 80 mgy from 145 mgy immediately because they have demonstrated progress towards finding a new water source.
Mar 2013	The DNR received letter from City of Cold Spring asking for a 10-month extension on the Cold Spring Brewery permit (expiring 12/31/2014 instead of 2/28/2014) because the Brewery asked the City to provide them with the water and the City could not find a location to build a new well field. They needed time to do so.
Apr 2013	The DNR responds to request for 10-month extension explaining MN Rules 6115.0750, subpart 2 prevents the extension of the permit. "..*a temporary permit is a one-time, limited life, not more than 12 months, nonrecurring appropriation of waters of the state. Requested time extensions shall be permitted but in no case shall the total length of time the permit remains in force exceed two years*."
Jun 2013	On June 18, 2013, Cold Spring Brewing Company submitted a written request to the DNR to extend Limited Permit 1984-3211 by 10 months to December 31, 2014. The letter requesting the extension was accompanied with numerous documents evidencing the Cold Spring Brewery's attempts to locate a new well field that would not adversely impact Cold Spring Creek or the City of Cold Spring's water supplies and that was not adversely impacted by nitrate concentrations.
Jul 2013	Minn. Stat. § 103G.285, subd. 1 (2012), authorizes the commissioner or his delegate to waive a limitation or requirement in subd. 5 for "just cause." The DNR approved the requested extension of Limited Permit 1984-3211 for "just cause." DNR sends letter to Cold Spring Brewing extending their permit 1984-3211 to December 31, 2014 with the following requirements: 1) new wells cannot impact Cold Spring Creek, 2) the brewery must provide DNR with the required information to evaluate new wells, 3) they must find ways to reduce pumping in existing wells that impact the Creek, and 4) permit 1984-3211 will be terminated after Dec 31, 2014.
Aug 2013	Cold Spring Brewing responded to letter saying they did not agree with terminating the permit after December 31, 2014. They wanted to go back to the original authorized volume of 24 mgy. One reason given was that they would need an additional 18.8 mgy from the City because they would have to RO treat the water first.
Aug 2013	Cold Spring Brewery sent letter to DNR with a check for $500 stating they wanted to hold a hearing to contest the termination of their permits if the DNR pursued that line of action.

Oct 2013	Cold Spring Brewery applied for a construction dewatering permit for 30 manifolded wells near the stream to use between 11/11/13 and 11/22/13 for a total of 6 mgy at a rate of 300 gpm. They planned to discharge the pumped water into the stream.
October 2014 - March 2015	The DNR collected groundwater level data in wells 620740 and 620735 and correlated it to stream monitoring data at stations H16011007 and H16011008. Cold Spring Brewery shuts down over the holiday. A drop in Creek water level was seen when pumping resumed. The fourth condition was later changed to the submission of monthly updates on the progress made to complete a new water supply system prior to December 31, 2014
Jul 2014	The DNR analyzed available data to determine if groundwater appropriations have a negative impact. It was concluded that all permitted pumping in the area combines to reduce flow by as much as 1 cfs (approximately one-third of what would otherwise be the creek's flow).
Nov 2014	The city of Cold Spring and Cold Spring Brewing Company submitted a progress plan and requested an extension to Limited Permit 1984-3211 for three years to December 31, 2017
Dec 2014	Findings of fact for permit 1984-3211 is completed concerning a request by Cold Spring Brewing Company to extend the limited permit to December 31, 2017 while it works with the city to develop a new well field.
Jul 2016	The DNR was directed by the Legislature to "conduct necessary monitoring of stream flow and water levels and develop a groundwater model to determine the amount of water that can be sustainably pumped in the area of Cold Spring Creek for area businesses, agriculture, and city needs." Additionally, the DNR was directed (by Legislature) to increase the authorized volume for the City of Cold Spring by 100 million gallons for a 10-million-gallon reduction in pumping from wells near Cold Spring Creek.
Aug 2016	Cold Spring Brewing and the City of Cold Spring agree to reductions of 3 mg on permit 1976-3179, 3 mg on permit 1984-3211 and 4 mg on 1988-3211 to meet the 10 mg reduction requirement for 100 mg increase in authorized volume for City of Cold Spring for five years.
Dec 2016	The City of Cold Spring's permit 1976-3179 was amended to appropriate up to 347 mgy, an increase of 100 mgy per legislative decree (less 3 mg as agreed upon with Cold Spring Brewing. The authorized volume will return to 250 mgy after 12/31/2021 unless other arrangements are approved. Cold Spring Brewing permits were also amended to reduce authorized volumes.

Appendix B – Cold Spring Soil-water-balance model

DEPARTMENT OF NATURAL RESOURCES

Cold Spring Groundwater Study

Soil-Water Balance Model

03/07/2018

Hydrogeology and Groundwater Unit

This study is Appendix B of the Cold Spring Groundwater Study Model

Executive summary

Groundwater recharge is a difficult component of the water budget to determine, and groundwater models are highly sensitive to recharge. Recharge in groundwater models can be estimated as a percentage of precipitation, can be numerically calculated using a program such as Soil-Water-Balance (SWB), and can be used as a calibration parameter. The Cold Spring groundwater model uses a combination of the SWB model and calibration approach to include the spatial distribution of recharge. The SWB modeling approach is discussed here and the calibration approach is discussed in the Cold Spring Groundwater Model Report.

The SWB model uses a modified approach of Thornthwaite-Mather soil-water balance. A key advantage is that it makes use of readily available geographic datasets including soil properties, land use, and daily weather data. These data were used to calculate spatially and temporally variable recharge estimates. Recharge can be affected by weather (precipitation and temperature), land use (due to evapotranspiration rates), and soil types.

Locally, the 10-year mean annual potential recharge rate from 2006–2018 was 10.2 inches per year. Generally, the higher potential recharge rates were near the existing and buried river channels and the sandy area directly north of the City of Cold Spring. Precipitation variability partially explains the differences in potential recharge.

1.0 Introduction

Groundwater recharge is one of the main boundary conditions in the development of a numerical model. Recharge is the main inflow into the groundwater system and replaces water loss through springs, streams, evapotranspiration, pumping, and outflow. While recharge is an important component of the hydrologic cycle and numerical models, it is difficult to estimate due to temporal and spatial differences. These differences can be due to changes in weather/climate, antecedent soil moisture, variation of soil permeability, evapotranspiration due to root depths, and land cover.

Various methods exist to estimate recharge that range in complexity from assuming a percentage of precipitation applied to the entire model domain to creating an integrated groundwater surface-water model. The assumption of a percent of precipitation requires minimal data and time, but is unable to take into account spatial differences. Whereas, an integrated groundwater surface-water model provides a model of the surface water and groundwater flow and includes spatial differences recharge, it requires extensive data, computing power, and time. The United States Geological Survey (USGS) Soil-Water Balance (SWB) model (Westenbroek, Kelson, Dripps, & Hunt, 2010) balances the data and time requirements with the need to include some of the spatial and temporal variability of recharge. SWB is soil-moisture estimation model, it estimates the amount of potential recharge to the aquifer system.

1.1 Model description

The Cold Spring SWB model was created to estimate the potential recharge in the vicinity of Cold Spring, Minnesota for input into the Cold Spring groundwater model. The Cold Spring groundwater model was developed to help quantify the cumulative impact of pumping on Cold Spring Creek.

The SWB model uses a modified Thornthwaithe-Mather soil water accounting method to calculate potential recharge for each grid cell by calculating the difference between the soil moisture and the sources and sinks (Westenbroek, Kelson, Dripps, & Hunt, 2010).

$$Recharge = Sources - Sinks - \Delta Soil\ Moisture$$

Sources of water include: precipitation, snowmelt, and inflow (runoff into cell) and sinks include interception, outflow (runoff out of cell), and evapotranspiration.

SWB is based on the runoff curve number method that is an empirical analysis of runoff from small catchments and hillslopes. It was developed by the Soil Conservation Service to approximate the amount of direct runoff from a precipitation event in a watershed. However, the curve number method does not calculate evapotranspiration that is necessary to calculate potential recharge. Curve numbers (CN) are assigned to specific land use types/soil type combinations and are used to calculate the maximum storage (S_{max}). This in turn is used to calculate the amount of runoff that occurs per daily precipitation event.

$$S_{max} = \frac{1{,}000}{CN} - 10$$

Before runoff occurs, an initial portion of the rainfall is lost to interception, depression storage, and infiltration. This *initial abstraction* is defined by the user as a percentage of the maximum storage rather than having the model calculate interception, depression storage, and infiltration separately.

$$Initial\ Abstraction\ = 0.2 * S_{max}$$

More runoff occurs if a smaller percent is abstracted. Once the rainfall has exceeded initial abstraction, then runoff is generated. Runoff from one cell becomes inflow for the next downgradient cell.

$$Runoff = \frac{(Precip - Initial\ Abstraction)^2}{(Precip + [S_{max} - Initial\ Abstraction])} \quad When\ Precip > Initial\ Abstraction$$

The initial curve numbers are adjusted by the SWB model as the soil water capacity changes to more accurately represent infiltration and runoff. They increase slightly when the soil is close to saturation and lower slightly during very dry conditions. Curve numbers can also be adjusted to account for frozen ground. When the ground is completely frozen no infiltration can take place. SWB calculates a running sum of when and how the air temperature deviates from the freezing point of water called the continuous frozen-ground index (CFGI). The calculation is dependent upon the ground condition on the previous day, the air temperature, and the depth of snow on the ground.

The final loss of water before it becomes potential recharge is evapotranspiration. Evapotranspiration (ET) takes place when groundwater is either close to the surface as evaporation or through plant uptake as transpiration. SWB allows the user to choose from five different methods to calculate evapotranspiration:

- Thornthwaite-Mather
- Jensen-Haise
- Blaney-Criddle
- Turc
- Hargreaves and Samani

The method of choice depends on the amount and quality of data available that is needed to make the calculation. This is used to calculate the change in soil moisture, potential evapotranspiration, accumulated potential water loss, and actual evapotranspiration. Recharge is the infiltration water that is not lost to evapotranspiration.

2.0 Model limitations and assumptions

2.1 Runoff curve method

The curve number method is designed for watershed scale (not field or grid cell scale) to calculate run off. Curve numbers also vary from event to event and the antecedent-soil-moisture condition only explains part of the variability (Hjelmfeldt, 1991). The curve numbers are based on an average experimental condition but the method was developed to evaluate floods rather than to simulate average daily flows (Westenbroek, Kelson, Dripps, & Hunt, 2010). The Thornthwaite-Mather soil-water balance method produces a sufficient estimate of recharge with readily available data.

SWB uses a land-cover lookup table to extract runoff and interception values. Curve numbers calculated by the USGS for the Minnesota SWB model (Smith, 2015) were used in the Cold Spring SWB model. The Minnesota SWB model was calibrated using watersheds throughout the state, including the Sauk River near St. Cloud, Minnesota. The Cold Spring model is included in the Sauk River near St. Cloud watershed.

2.2 Surface-water routing

SWB uses an eight directional flow-routing algorithm to determine how to route overland flow between the cells. Flow cannot be routed into more than one cell. Otherwise, the cell is considered to be a closed depression and all water in excess of soil moisture capacity contributes to recharge.

All runoff is assumed to infiltrate or be taken out of the model on the same day the precipitation (rainfall or snowmelt) occurred. Water in depressions is converted to recharge after ET and soil moisture demands are met. This could result in hundreds or thousands of inches per year of recharge being calculated. This is restricted by assigning a daily maximum recharge rate for each land-cover and soil group combination (Westenbroek, Kelson, Dripps, & Hunt, 2010).

The Cold Spring SWB model did not include surface-water routing. When surface-water routing was included the model predicted greater than 50 inches of recharge in an average year in low lying areas when daily maximum recharge rates were used. This amount of recharge was deemed unrealistic.

2.3 Performance around lakes and wetlands

The SWB model can over estimate recharge in areas where wetlands, lakes, springs, or other areas where the water table is close to the land surface. The model does not reject infiltrated water due to near-surface groundwater. The only way to minimize this is by specifying a maximum recharge rate for combined land use and soil types in the land use lookup table.

2.4 Time delays for infiltration

SWB does not account for interaction between groundwater and surface water so the time it takes for water to travel from the bottom of the root zone to the top of the water table is not accounted for. It is assumed that it instantaneously enters the aquifer. This is acceptable in the Cold Spring area as it is a surficial aquifer system and an infiltration delay is unlikely to have great impact.

CFGI allows the user to adjust the curve numbers to account for frozen ground and its impacts on the timing of infiltration. However, adjustments to the curve number are based on air temperatures and cannot differentiate between patches of ground that can differ in the timing of snowmelt due to effects like shade and orientation to the sun.

2.5 Climate data requirements

Climate data requirements are based on the evapotranspiration method used for the model. There are five available methods in SWB to calculate evapotranspiration. Most involve information that is only available through field study that not only requires a significant amount of time, but can also be financially prohibitive. This type of data includes daily average wind speed, daily average humidity, daily max relative humidity, and daily percentage of possible sunshine. The Thornwaite-Mather approach uses information that is readily available at most climate stations so this method was used for the Cold Spring SWB model.

Daily precipitation and temperature maximum, minimum, and average temperatures were readily available for use. Yearly climate variability will affect calculated potential recharge values so several years of data that represent the variability in climate should be used to determine a representative potential recharge value for the area over time.

2.6 Initial abstractions

SWB allows the user to choose an amount of precipitation that must fall before runoff occurs based on the maximum soil-moisture capacity. The amount that must fall is based on the curve numbers so it is directly related to land use type. The user can choose 20 percent of the maximum soil capacity (TR-55 method) or 5 percent of the maximum soil capacity (Hawkins method) as the initial abstraction. This means 20 percent or 5 percent of the amount of water the soil can hold must fall before any runoff occurs. The TR-55 method was chosen for the Cold Spring model because the method is suggested for rural landscapes.

3.0 SWB model input

3.1 Climatological input

The SWB has the option to use either data from a single climate station or use gridded files interpolated between multiple climate stations in the area. A single station was used for the Cold Spring model because there was insufficient data available from multiple stations to create gridded files. Daily data from the Collegeville station, located approximately 8.5 miles northeast of Cold Spring, was used due to its continuous record during the modeling period between January 2006 and December 2018 (Figure 1). Daily average temperature, precipitation, maximum temperature, and minimum temperature was compiled for model years. Trace and missing precipitation data was changed to zero precipitation and missing minimum and maximum temperature data was calculated by averaging between the temperature before and the temperature after. The dates were separated into month, day, and year. No additional manipulation of the date was necessary because SWB code converts between the Gregorian date and the Julian day number and also accounts for leap years.

3.2 Land use and land-cover input

The land use lookup table created for the model contains the National Resources Conservation Service (NRCS) curve number, rooting depth, interception, and maximum daily recharge information specific to each land use type (Appendix Table B-3, Land Use). This table uses the effective rooting depth, which is the depth where the plant extracts most of its moisture.

Land use cover information along with soil-water capacity is used to assign a maximum soil-moisture holding capacity and calculate runoff for each 30-meter cell in the model. The USGS National Land-cover Database (NLCD) was used to obtain land use information.

The NLCD 30-meter raster files and databases were downloaded from the USGS website for the years 1992, 2001, 2006, and 2011 for Stearns County. The GIS raster grids were imported into GIS and projected to North American Datum 1983 (NAD83) Universal Transverse Mercator Zone 15 North (UTM zone 15N) snapping and clipping to the model boundary. Because the model grid and the land use were 30-meter grids, there was no need to manipulate the land use data to match the model. The 2011 grid was exported from GIS into an ASCII file to be used in the model (Figure B-2). The land use categories used in the model, and their descriptions, are listed Table B-3.

The lookup table used by the USGS for their SWB model of Minnesota was used as a starting point for information relating to land use and soil types within the lookup table. Additional land use categories existed in the Cold Spring SWB model. Many of these were similar to uses already listed in the *Potential Groundwater Recharge for the State of Minnesota Using the Soil-Water-Balance Model, 1996-2010* look up table and the values were copied and used when available (Smith, 2015). The following additional land uses added to the USGS SWB model are listed in Table B-1 and the description for each land use type can be found in Table B-3.

Appendix Table B-1. New land use categories and relation to existing land use categories

New land use categories	Related existing land use categories
24 Developed high intensity	22 High intensity residential
31 Bare Rock/Clay	N/A
52 Shrub	51 Shrubland
71 Grassland	33 Transitional
90 Woody wetlands	91 Woody wetlands
95 Emergent wetlands	92 Emergent wetlands

3.3 Soil hydrologic group

The NRCS has grouped soils into hydrologic soil categories A, B, C, and D on the basis of infiltration capacity. Group A soils have the highest infiltration rate representing gravels and sands. Group D soils have the lowest infiltration rate representing clays.

A soil map of Stearns County was downloaded from the NRCS website (NRCS, 2017), projected to the project datum, NAD83 UTM Zone 15N, and clipped to the model grid using ArcGIS tools. The Soil Survey Geographic database (SSURGO) with the infiltration rates was joined to the soil layer. An additional field was created in the attribute table to convert the soil groups to a numerical lookup value that SWB could use. Soil type A was classified as 1, type B as 2, type C as 3 and types A/D, B/D, C/D, and D as 4. Gravel pits and quarries were not assigned a hydrologic soil category in the soils layer but were classified as 1 in this model. Bedrock and water was given a classification of 4. The soil layer was then converted to a 30-meter raster in GIS with a cell assignment of maximum combined area to ensure the soil type with the maximum area in the cell was assigned to that cell (Figure B-3).

3.4 Available soil water capacity

The SWB model uses the available soil water capacity and root depth information to calculate the maximum soil water holding capacity for use with runoff calculations for each cell. These data were obtained from the SSURGO database from the NRCS. The available soil water capacity varies with depth and the weighted mean of the available soil water capacity was calculated for each soil type.

3.5 Evapotranspiration and soil moisture

Thornthwaite-Mather method for estimating evapotranspiration was used because the data needed was readily available. This calculation does tend to slightly underestimate evapotranspiration; however, potential recharge values calculated did not appear to be out of the range of possibility.

The potential evapotranspiration (PE) is calculated using the Thornthwaite-Mather approach and is compared to precipitation.

- When precipitation is less than PE then the actual evapotranspiration is less than PE and is limited to the amount of water than can be taken from the soil, and the change is soil moisture is calculated.
- When precipitation is greater than PE then the actual evapotranspiration is equal to PE. The difference between the precipitation and PE is added to the soil moisture. If the new soil moisture value is above the soil storage capacity (S_{max}) then the excess moisture is converted to recharge.

3.6 Surface-water flow direction

SWB uses an eight direction flow-routing algorithm to determine how to route overland flow between the cells. A USGS 30-meter digital elevation model was used to create a flow direction grid in GIS. After a review of the model results, with and without the surface-water routing, it was decided that surface-water routing should not be included in the Cold Spring SWB model due to excessive infiltration in low lying areas.

Surface runoff routing was turned off for the final model runs, but the flow routing grids were developed and used in initial model discussions.

3.7 Other SWB inputs

A discussion of the additional SWB inputs follows.

3.7.1 Recharge limits

The maximum recharge rate for each of the soil type and land use combinations were taken from the *Potential Groundwater Recharge for the State of Minnesota Using the Soil-Water-Balance Model, 1996-2010* model look up table.

3.7.2 Precipitation

Precipitation is added to the model on a daily time scale in the form of rain and snow. SWB assumes rain has fallen as snow when the mean temperature minus one-third the difference between the daily high and low temperatures is less than or equal to the freezing point of water (Westenbroek, Kelson, Dripps, & Hunt, 2010).

$$Temperature_{mean} - 1/3(Temperature_{high} - Temperature_{low}) \leq 32°F$$

Snow is allowed to accumulate or melt based on a temperature index method where it is assumed that 1.5 mm (0.059 in) of snow melts per day per average degree Celsius that the maximum temperature is above the freezing point.

In a similar manner, frozen ground is tracked by a frozen ground index. The upper and lower bounds were set to 83 and 56 respectively. These values are the standard values from literature (Westenbroek, Kelson, Dripps, & Hunt, 2010). The model will ignore additional runoff due to frozen ground conditions if the bounds are not set.

3.7.3 Interception

A user specified volume of rainfall is assumed to be intercepted for each land use type and season. Any daily precipitation that exceed this specified volume is used to calculate potential recharge. The Cold Spring model used values ranging from 0 to 0.06 inches based on the land use type. The interception values were taken from the Minnesota SWB model (Smith, 2015).

3.7.4 Continuous frozen ground index

It was demonstrated through empirical research that the CFGI transition range between frozen and thawed ground is 56–83 C-days. Enhanced recharge is unlikely when CFGI values are below 56 and likely when above 83 C-days. (Molnau & Bissel, 1983, p. 112). SWB uses this upper and lower bound information along with climate data to calculate the probability of the ground being frozen on any given day. The curve number is adjusted linearly up or down based on the assumption that there is more runoff when the ground is frozen. The initial CFGI value was set to 100 with the assumption that the ground in Minnesota is frozen in January and has been for some time. The initial snow cover was set to 100 because it is likely in January the ground will be snow covered.

4.0 Model results

The SWB model was run for years 2006 through 2018 to simulate potential recharge rates for the Cold Spring study area. Annual potential recharge estimates for individual years and the mean 13-year annual potential recharge estimates were calculated for the Cold Spring study area.

4.1 Annual mean potential recharge estimates

Annual mean potential recharge ranged from 5.6 to 14.5 inches per year. The lowest recharge rate was in 2006 and the maximum potential recharge rate was in 2008 (Table B-2). Precipitation variability partially explains the differences in potential recharge, but other factors such as antecedent moisture condition and timing of precipitation are likely important. Figures B-4 through B-16 show the spatial distribution of potential recharge.

Appendix Table B-2. Annual recharge results for 2006 through 2018

Year	Mean Annual Potential Recharge
2006	5.6
2007	9.7
2008	14.5
2009	12.7
2010	8.9
2011	12.6
2012	6.6
2013	10.0
2014	12.4
2015	6.8
2016	7.5
2017	9.5
2018	5.9

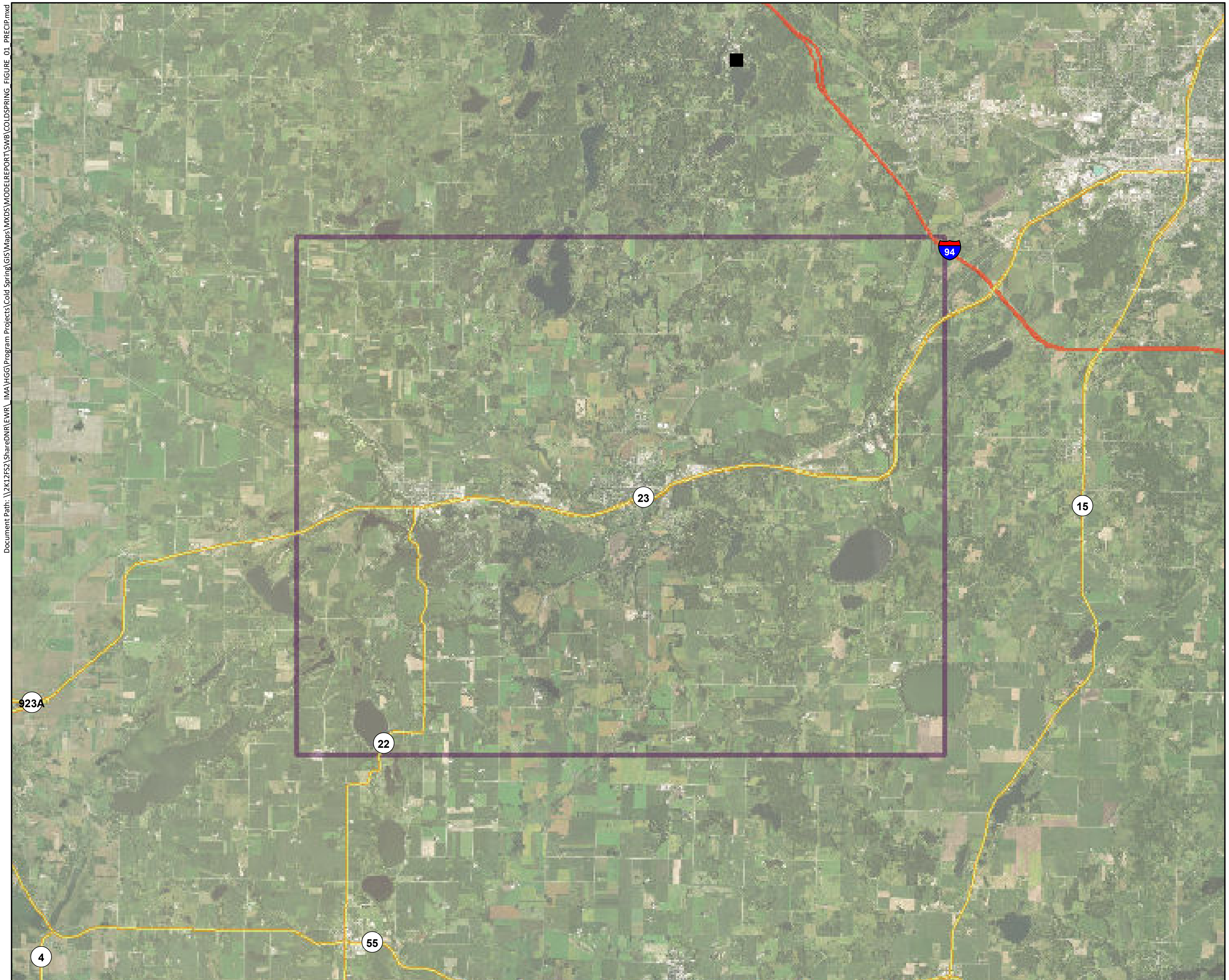
4.2 Mean annual potential recharge estimates

The 10-year mean annual potential recharge rate from 2006 to 2018 was 10.2 inches per year. The mean annual potential recharge rates ranged from 0 to 16 inches per year. In general, the higher potential recharge rates were in or near the existing surficial sands associated with the Sauk River valley and adjacent buried river channels (Figure B-17).

Summary

Groundwater recharge is one of the more difficult components of the water budget to determine, and is generally one of the more sensitive parameters in groundwater models. The Cold Spring SWB model uses a modified Thornthwaite-Mather soil water balance approach with components calculated on a daily basis. A key advantage to this approach is the commonly available geographic datasets including: soil properties, land use, and daily weather data are used to calculate spatially and temporally variable recharge estimates. These estimates provide a reasonable initial dataset to incorporate into the Cold Spring groundwater model and help to decrease the uncertainty of the groundwater model.

Figures B-1 through B-17

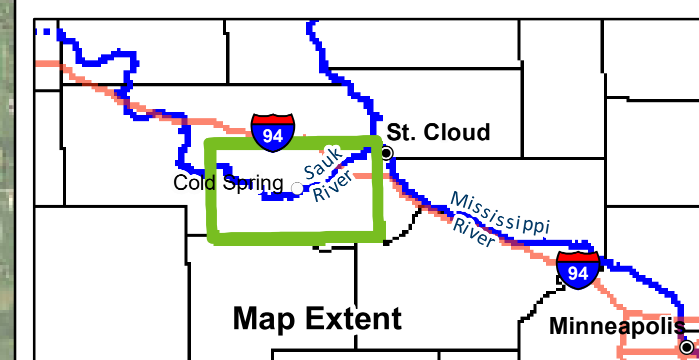


Legend

- College St. John Climate Monitoring Stations
- Interstate Highway
- State Highway
- Study Area

0 1 2 4 Miles

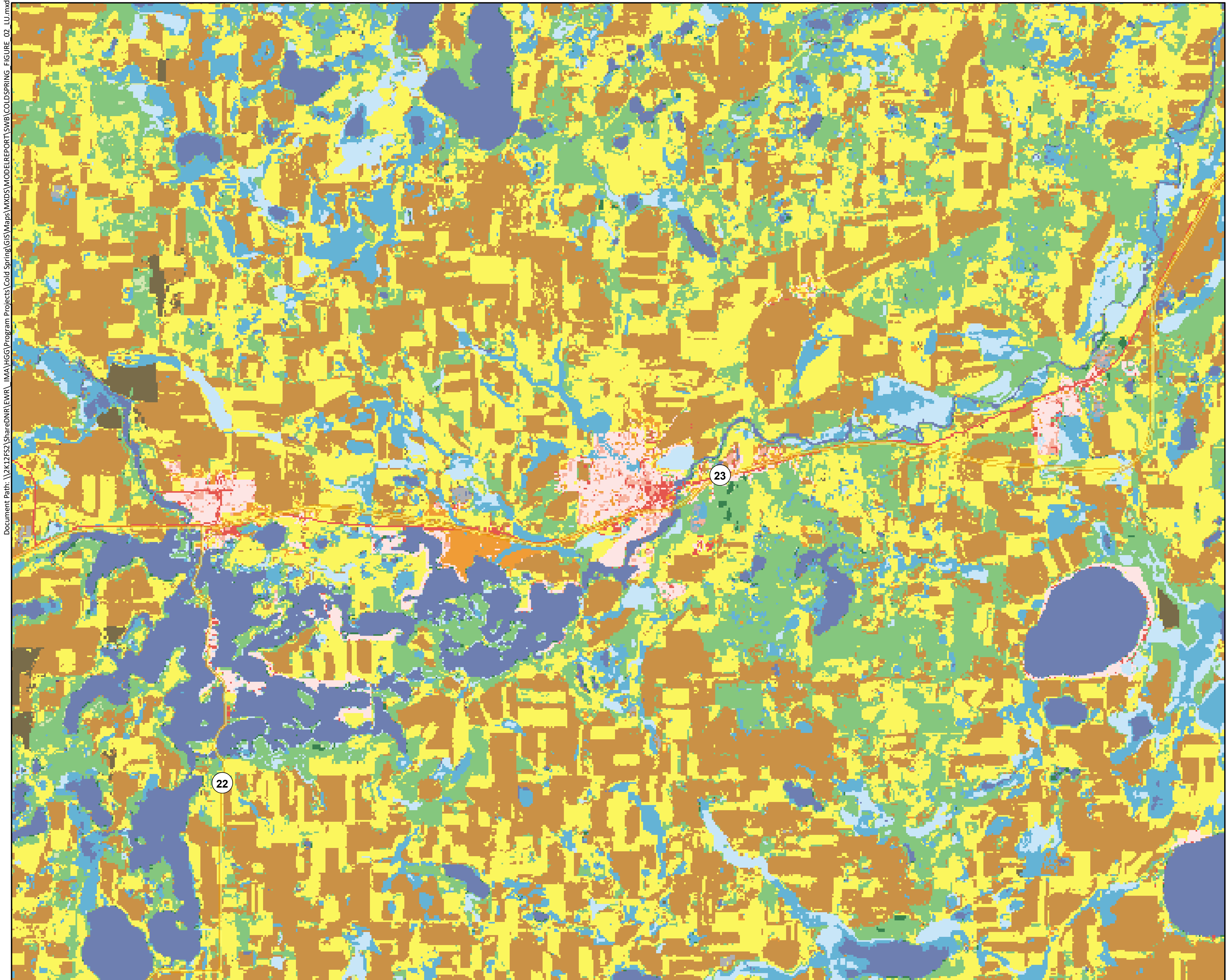
N



Appendix Figure B-1. Climate Station

Cold Spring Soil-water Balance Model Report

DEPARTMENT OF NATURAL RESOURCES



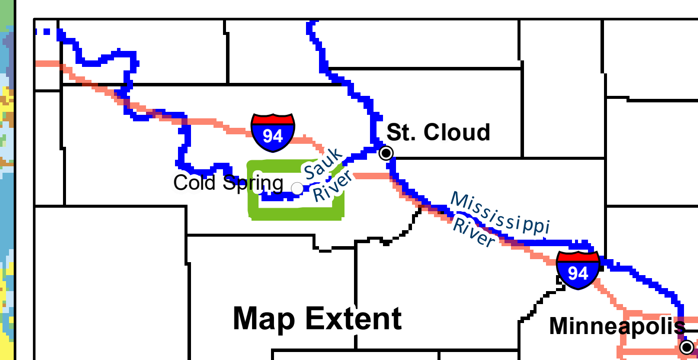
Legend

Land Use

- Open Water
- Low Intensity Residential
- High Intensity Residential
- Commercial, Industrail, Transportation
- Quarries, Strip Mines, Gravel Pits
- Transitional
- Dediduous Forest
- Evergreen Forest
- Mixed Forest
- Shrubland
- Pasture Hay
- Row Crops
- Small Grains
- Urban Recreational Grasses
- Woody Wetlands
- Emergent Herbaceous Wetlands
- Interstate Highway
- State Highway

N

0 0.5 1 2 Miles



Appendix Figure B-2. Land Use

Cold Spring Soil-water Balance Model Report

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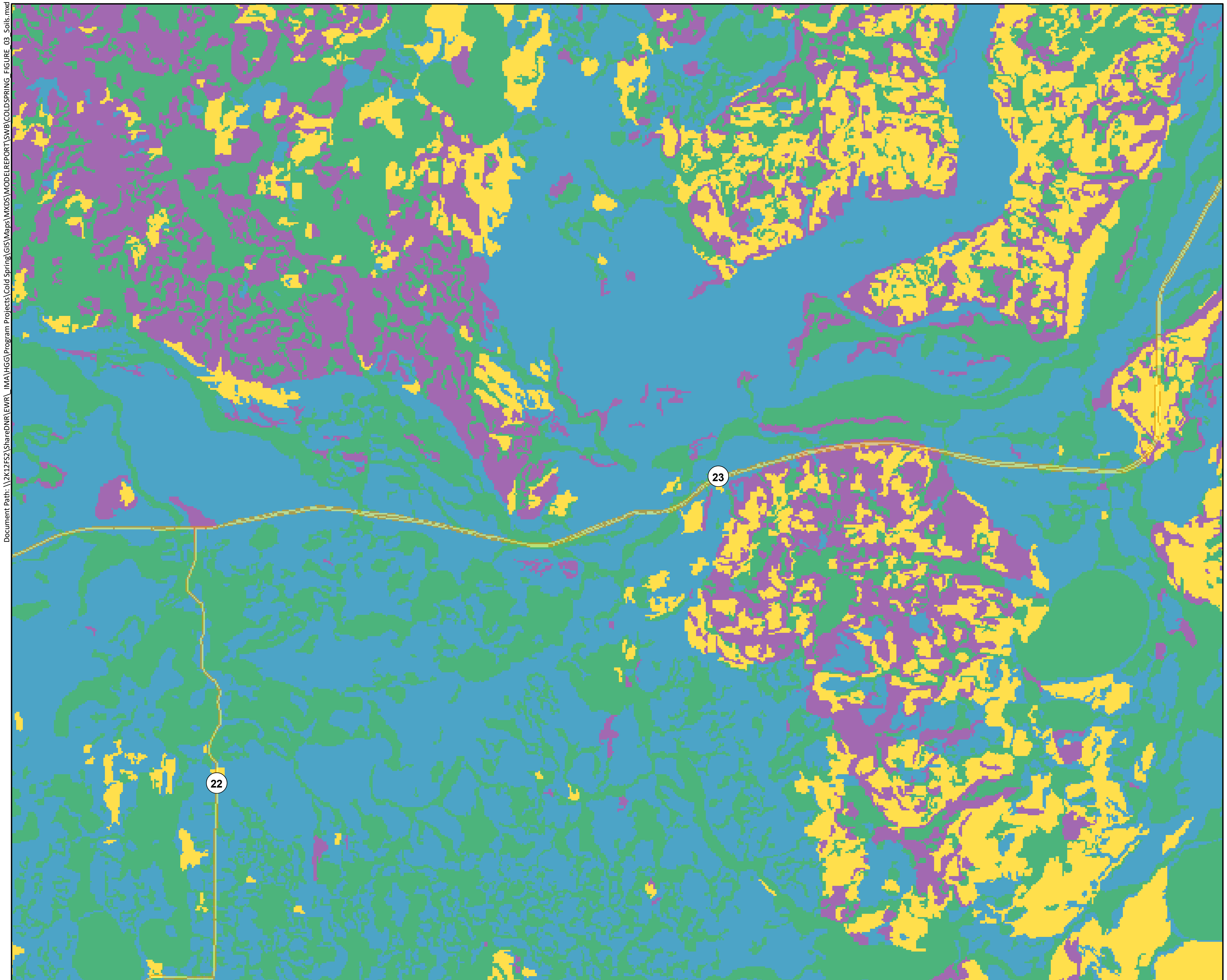


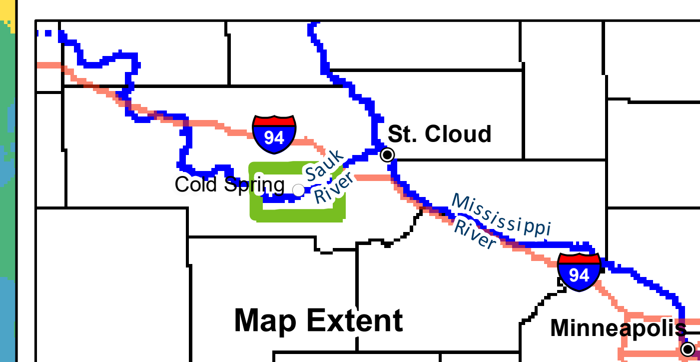
Legend

Soils

- A
- B
- C
- D
- Interstate Highway
- State Highway

0 0.5 1 2 Miles

N



Appendix Figure B-3. Soils

Cold Spring Soil-water Balance Model Report

DEPARTMENT OF NATURAL RESOURCES

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Legend

Interstate Highway

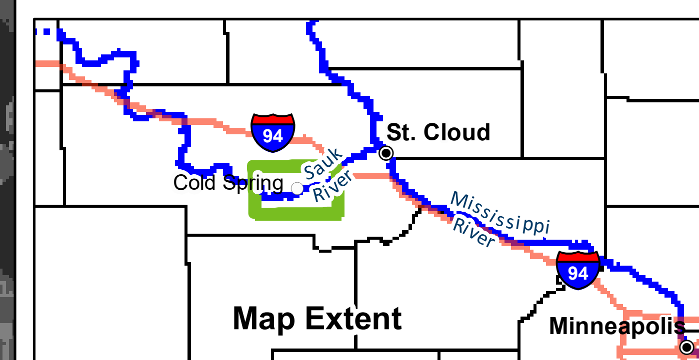
State Highway

Average annual recharge (inches)

- 0 - 3
- 3.01 - 6
- 6.01 - 9
- 9.01 - 12
- 12.1 - 15
- 15.1 - 18
- 18.1 - 21

0 0.5 1 2 Miles

N



Appendix Figure B-4. 2006 Recharge

Cold Spring Soil-water Balance Model Report

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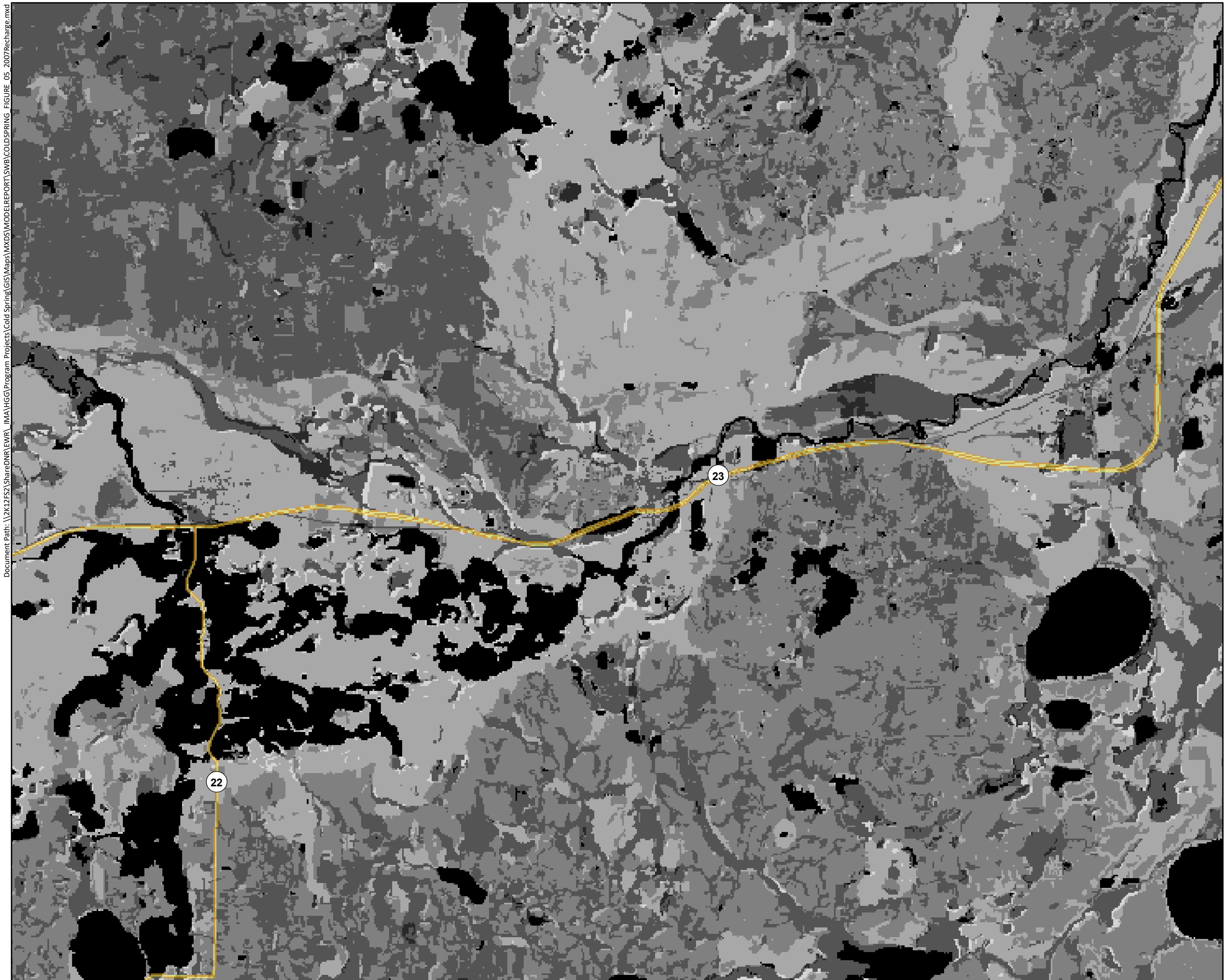


Legend

Interstate Highway

State Highway

Average annual recharge (inches)

0 - 3

3.01 - 6

6.01 - 9

9.01 - 12

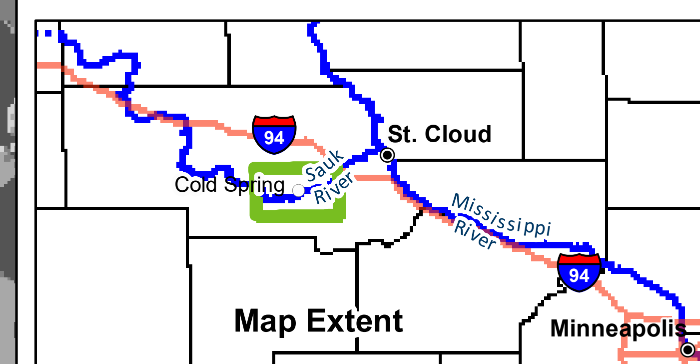
12.1 - 15

15.1 - 18

18.1 - 21

N

0 0.5 1 2 Miles



Appendix Figure B-5. 2007 Recharge

Cold Spring Soil-water Balance Model Report

DEPARTMENT OF NATURAL RESOURCES

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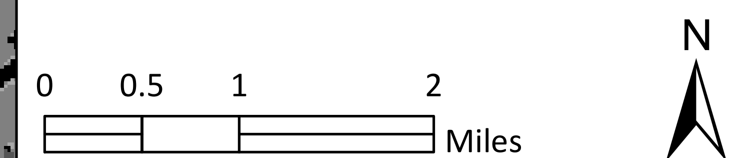
Legend

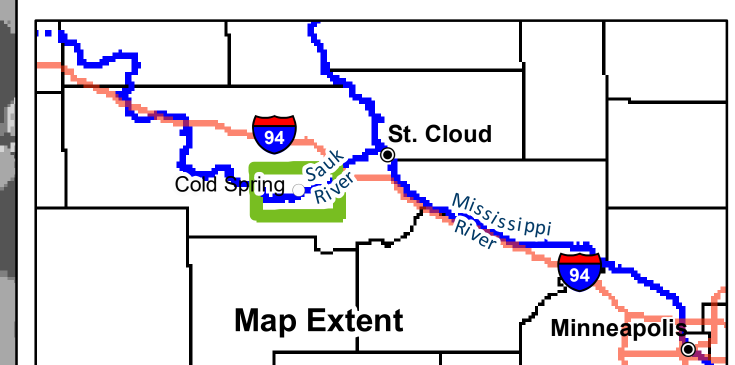
Interstate Highway

State Highway

Average annual recharge (inches)

0 - 3
3.01 - 6
6.01 - 9
9.01 - 12
12.1 - 15
15.1 - 18
18.1 - 21





Appendix Figure B-6. 2008 Recharge

Cold Spring Soil-water Balance Model Report

DEPARTMENT OF NATURAL RESOURCES

Legend

Interstate Highway

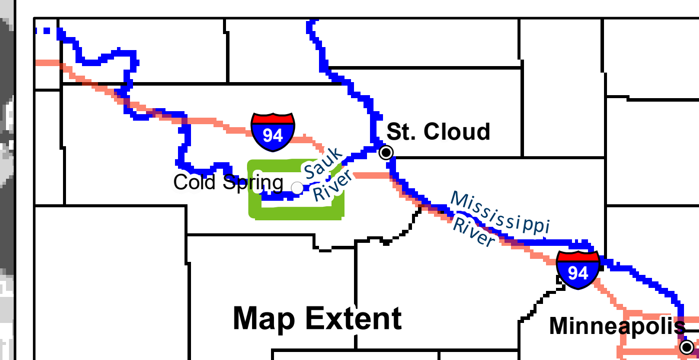
State Highway

Average annual recharge (inches)

0 - 3
3.01 - 6
6.01 - 9
9.01 - 12
12.1 - 15
15.1 - 18
18.1 - 21

0 0.5 1 2
Miles

N



Appendix Figure B-7.
2009 Recharge

Cold Spring Soil-water Balance Model Report

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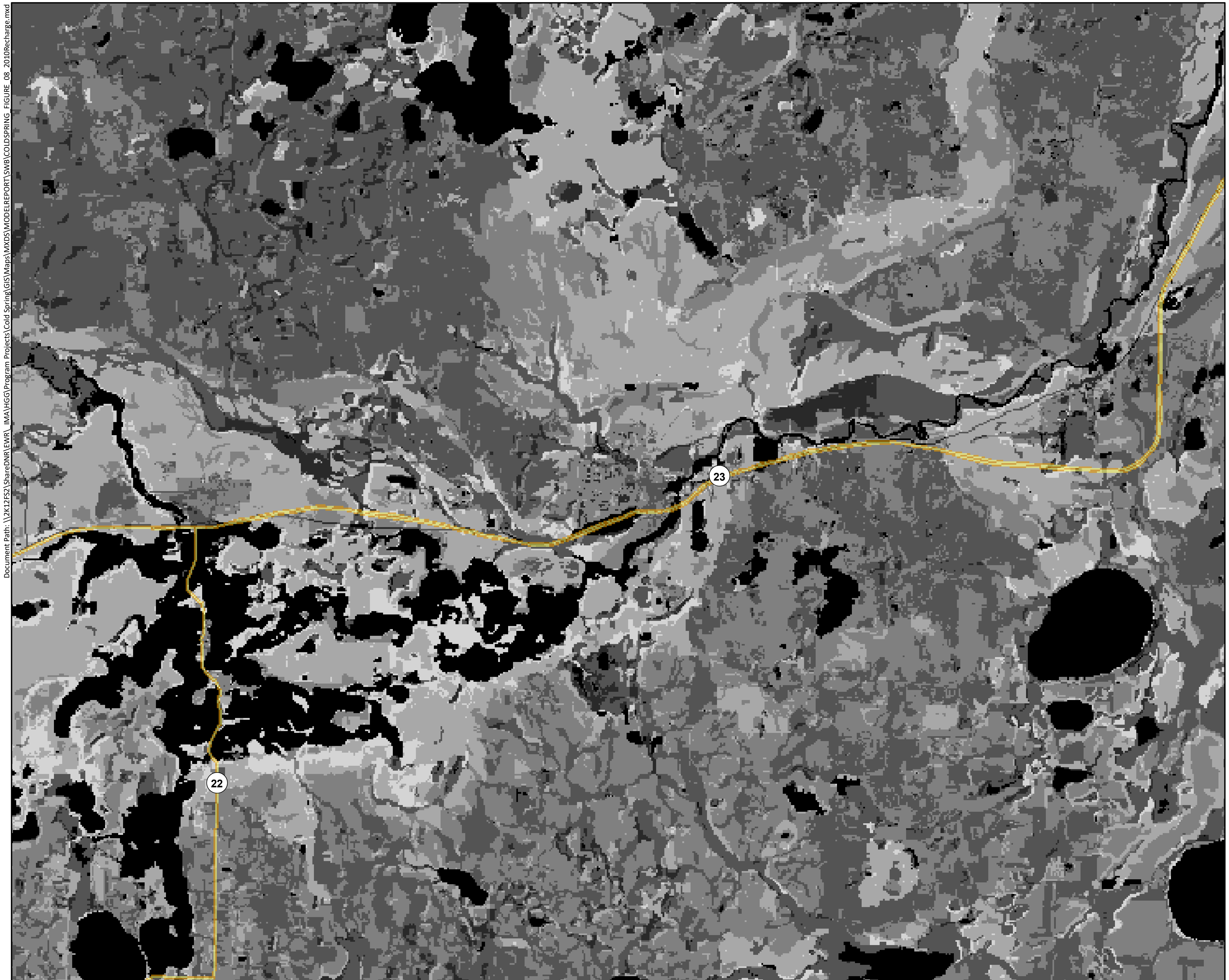


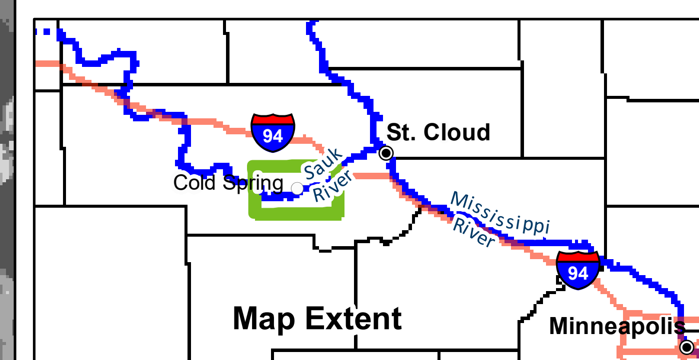
Legend

Average annual recharge (inches)

- 0 - 3
- 3.01 - 6
- 6.01 - 9
- 9.01 - 12
- 12.1 - 15
- 15.1 - 18
- 18.1 - 21
- Interstate Highway
- State Highway

0 0.5 1 2 Miles

N



Appendix Figure B-8. 2010 Recharge

Cold Spring Soil-water Balance Model Report

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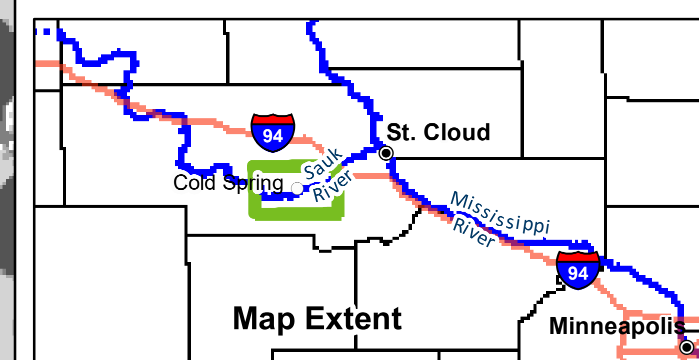

Appendix Figure B-9.
2011 Recharge

Cold Spring Soil-water Balance Model Report

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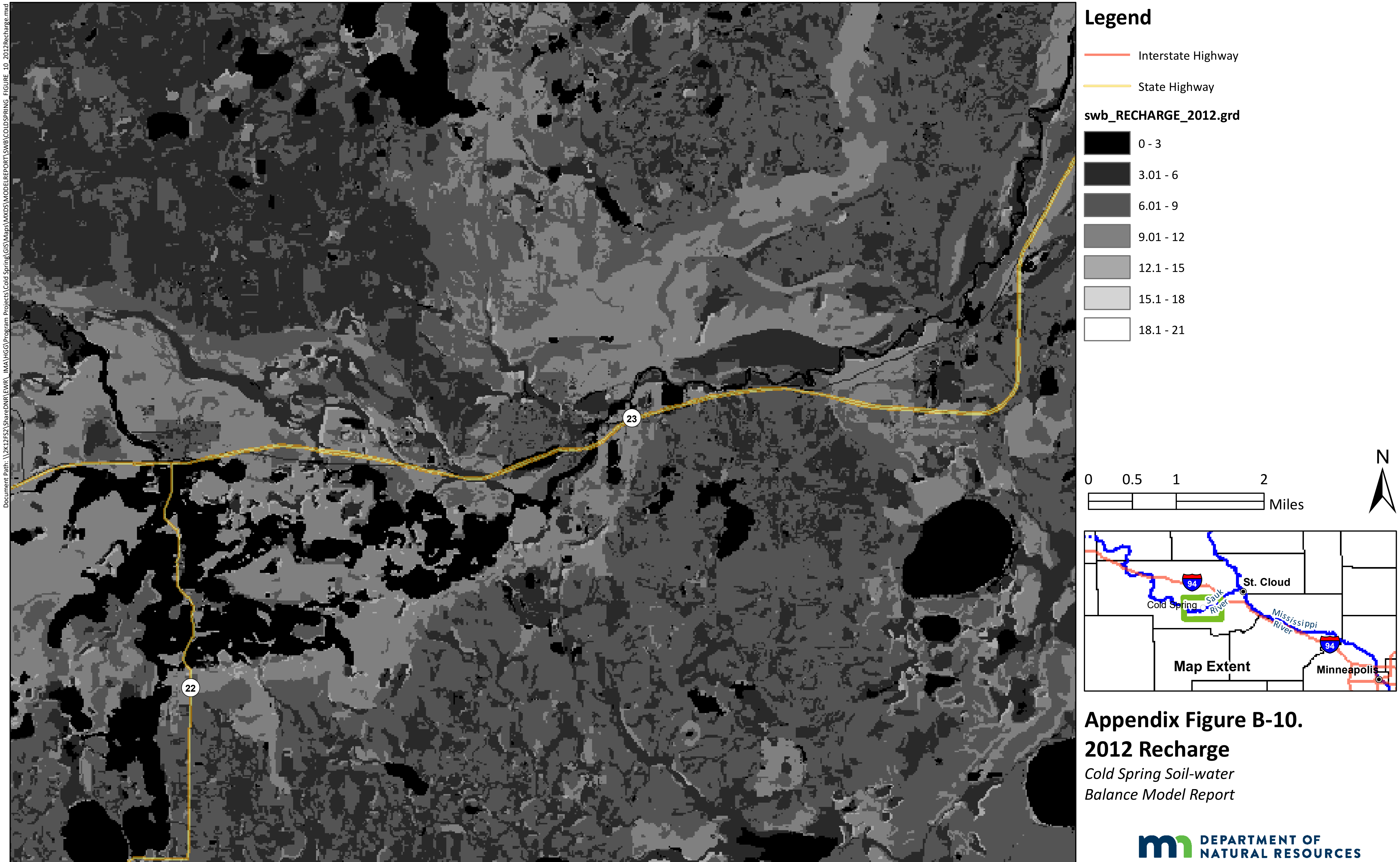


Appendix Figure B-10.
2012 Recharge

Cold Spring Soil-water Balance Model Report

DEPARTMENT OF NATURAL RESOURCES

Legend

Interstate Highway

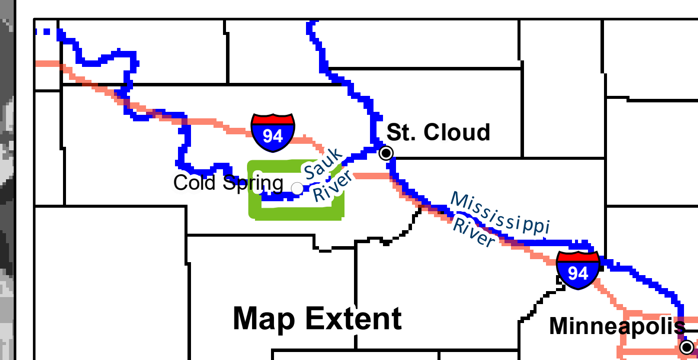
State Highway

Average annual recharge (inches)

- 0 - 3
- 3.01 - 6
- 6.01 - 9
- 9.01 - 12
- 12.1 - 15
- 15.1 - 18
- 18.1 - 21

0 0.5 1 2 Miles

N



Appendix Figure B-11. 2013 Recharge

Cold Spring Soil-water Balance Model Report

DEPARTMENT OF NATURAL RESOURCES

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Legend

Interstate Highway

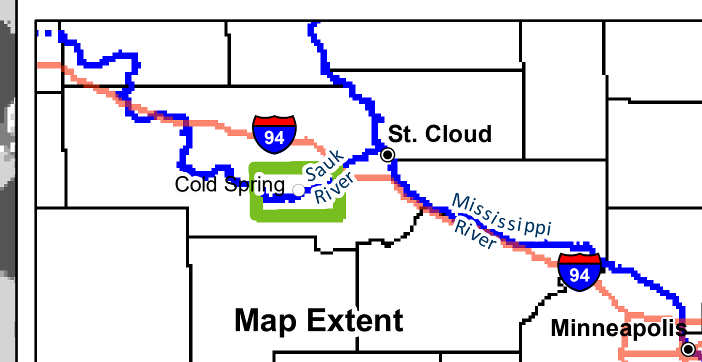
State Highway

Average annual recharge (inches)

0 - 3
3.01 - 6
6.01 - 9
9.01 - 12
12.1 - 15
15.1 - 18
18.1 - 21

N

0 0.5 1 2 Miles



Appendix Figure B-12. 2014 Recharge

Cold Spring Soil-water Balance Model Report

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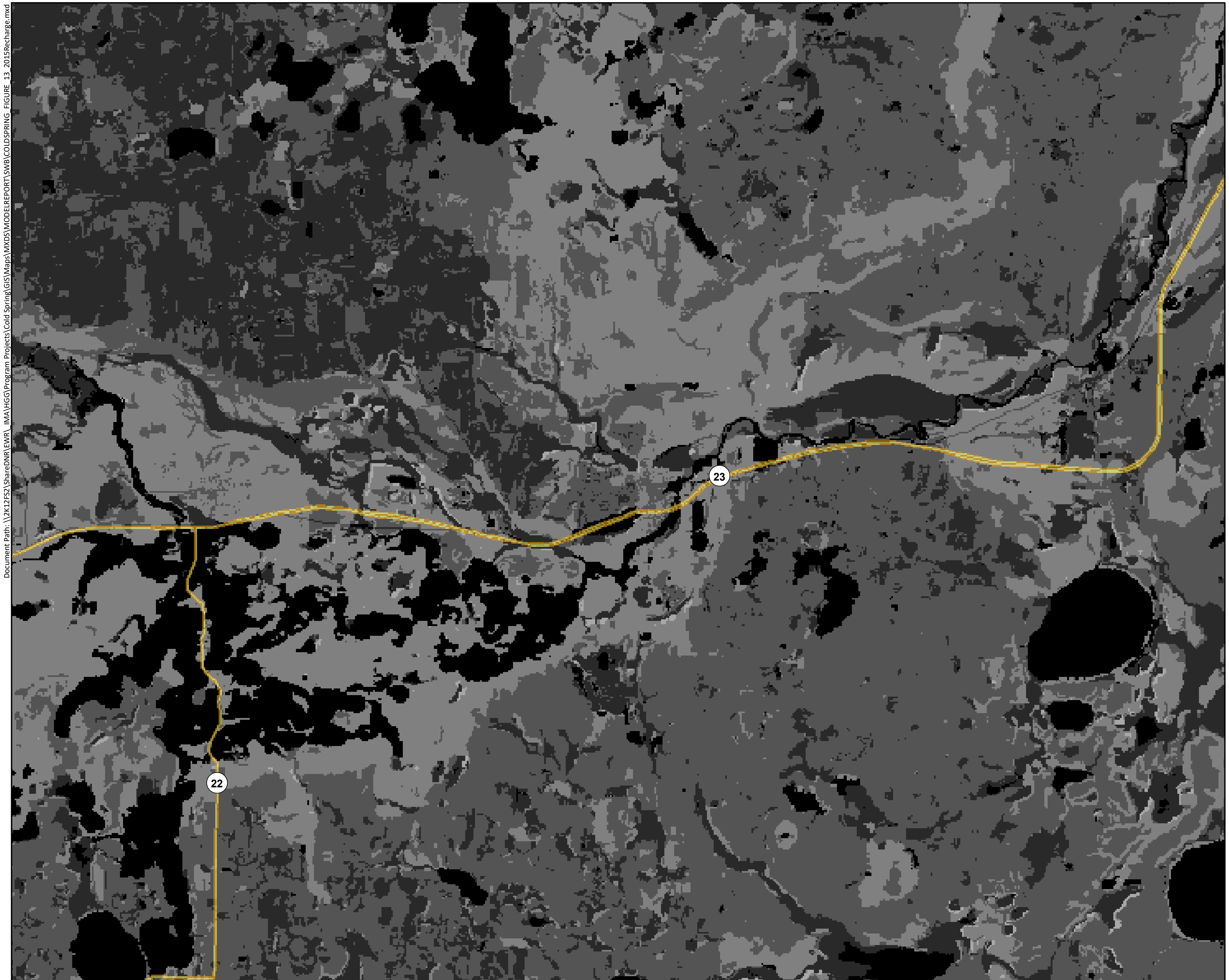

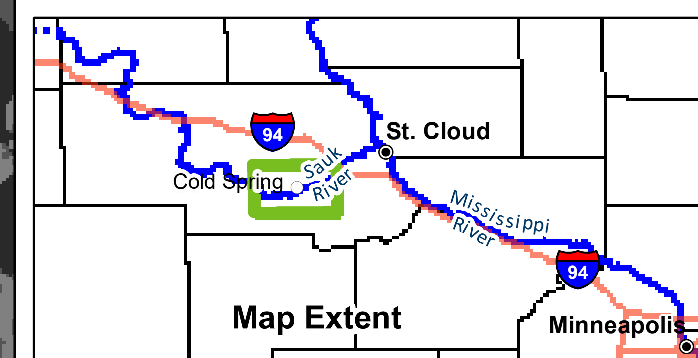

Appendix Figure B-13.
2015 Recharge

Cold Spring Soil-water Balance Model Report

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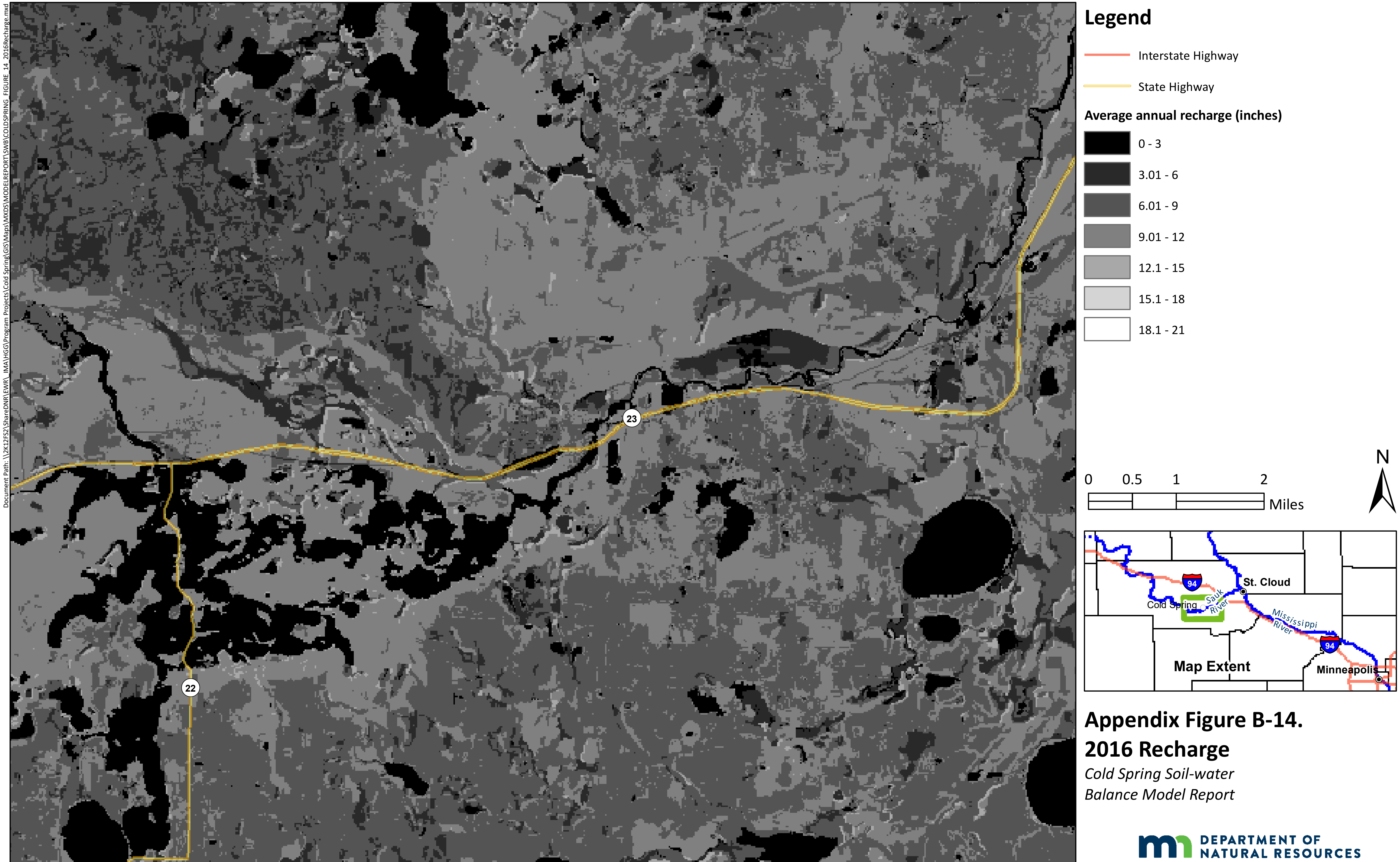

Appendix Figure B-14.
2016 Recharge

Cold Spring Soil-water Balance Model Report

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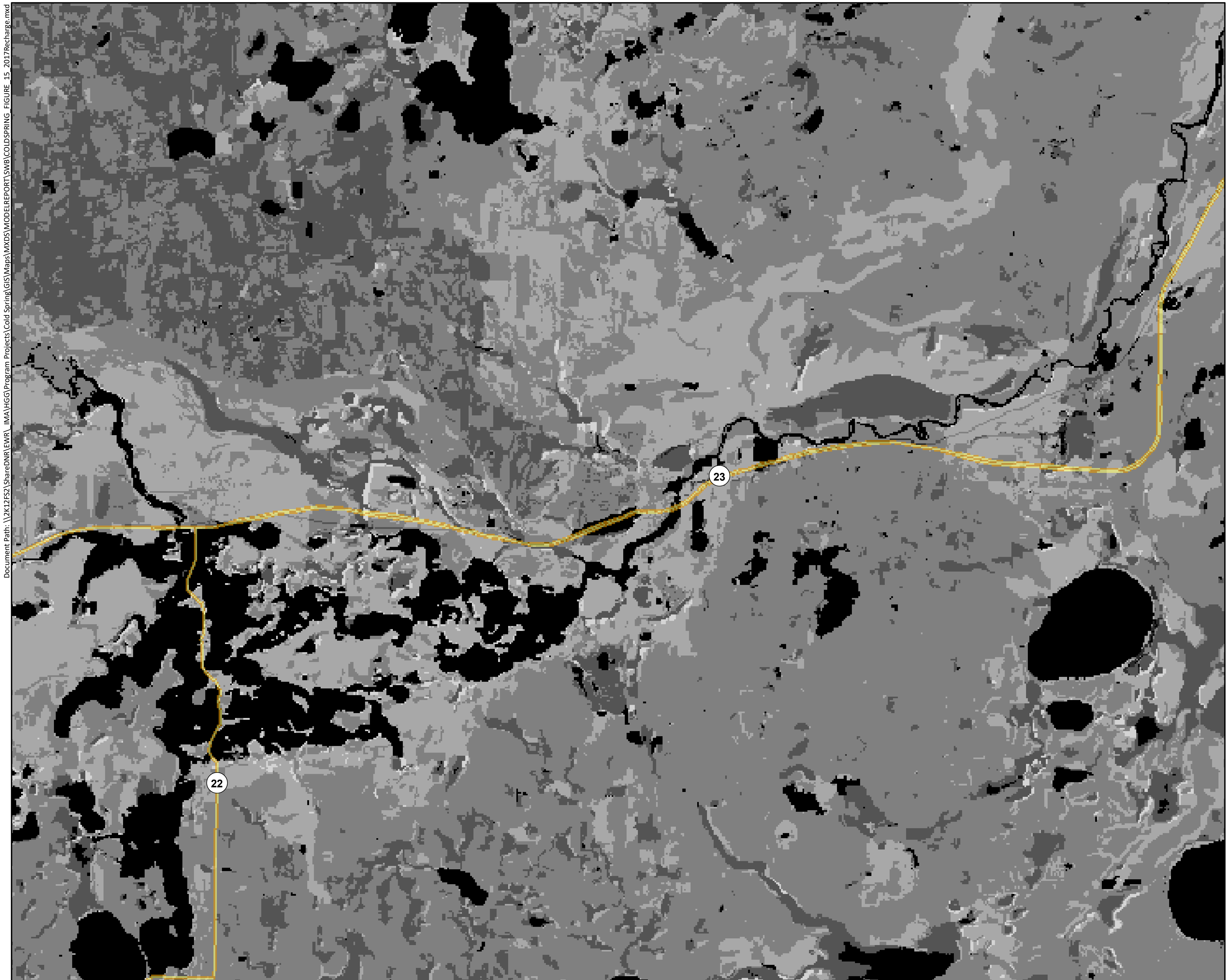


Legend

Interstate Highway

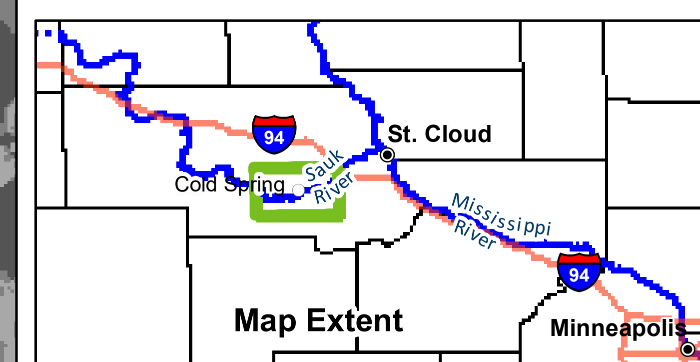
State Highway

Average annual recharge (inches)

- 0 - 3
- 3.01 - 6
- 6.01 - 9
- 9.01 - 12
- 12.1 - 15
- 15.1 - 18
- 18.1 - 21

0 0.5 1 2 Miles

N



Appendix Figure B-15. 2017 Recharge

Cold Spring Soil-water Balance Model Report

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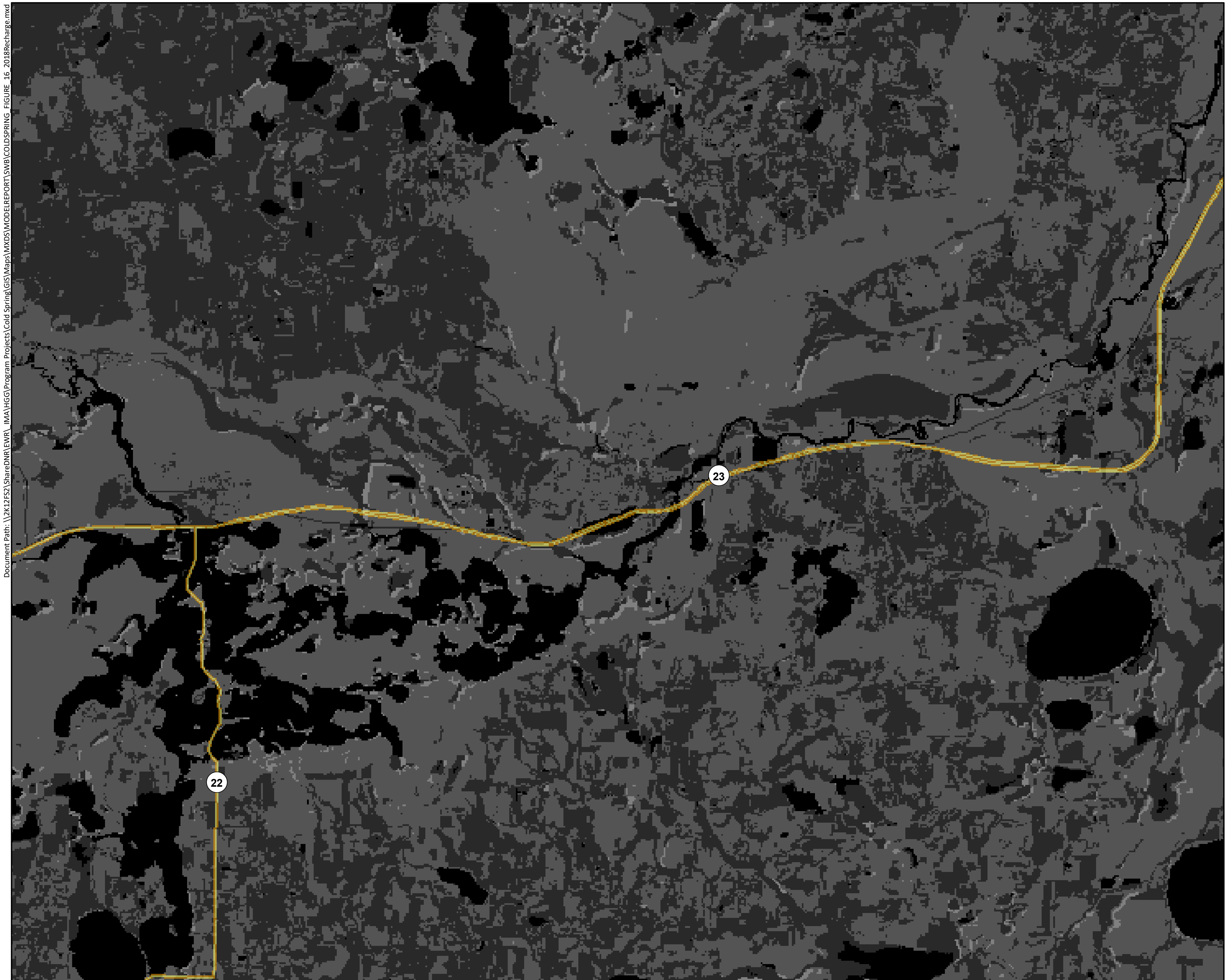
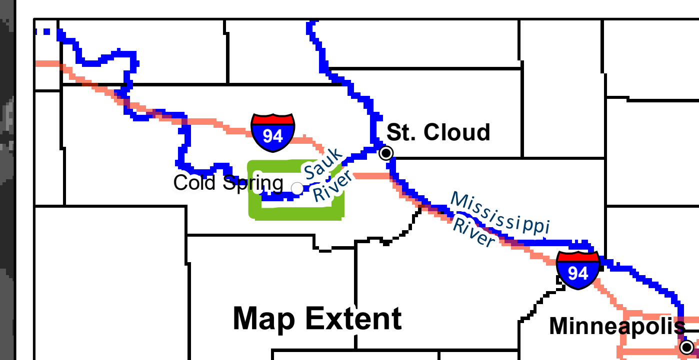




Appendix Figure B-16. 2018 Recharge

Cold Spring Soil-water Balance Model Report

DEPARTMENT OF NATURAL RESOURCES

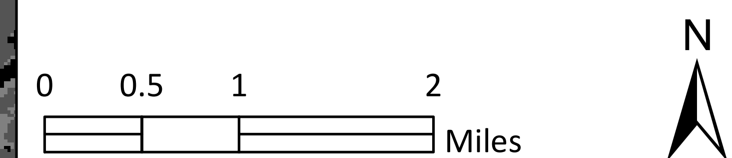
Legend

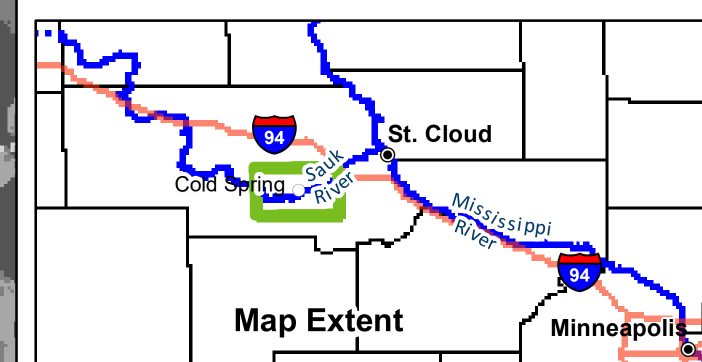
Interstate Highway

State Highway

Average annual recharge (inches)

0 - 3
3.01 - 6
6.01 - 9
9.01 - 12
12.1 - 15
15.1 - 18
18.1 - 21





Appendix Figure B-17. Average 2006 to 2018 Recharge

Cold Spring Soil-water Balance Model Report

DEPARTMENT OF NATURAL RESOURCES

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Appendix Table B-3: Land use

Appendix Table B-3. Land Use Look-up Table for Cold Spring

		Curve Numbers				Max Recharge(inches per day)				Interception		Root Zone Depth(feet)			
LU	Description (not used by Model)	A	B	C	D	A	B	C	D	Growing Season	Non Growing Season	A	B	C	D
11	Open Water	100	100	100	100	4.5	2.25	1.5	0.75	0	0	0	0	0	0
21	Low Intensity Residential	70	80	87	92	2.5	1.5	0.83	0.42	0.04	0	3.08	3.83	2.45	1.53
22	High intensity Residential	89	92	94	97	2.5	1.5	0.83	0.42	0.04	0	3.08	3.83	2.45	1.53
23	Commercial	89	92	94	97	2.5	1.5	0.83	0.42	0.04	0	3.08	3.83	2.45	1.53
32	Quarries/Mines	89	92	94	97	2.5	1.5	0.83	0.42	0.04	0	3.08	3.83	2.45	1.53
33	Transitional- Sparse vegetation	90	93	95	96	6	3.5	2.75	2	0.06	0	1	1	1	1
41	Deciduous Forest	90	93	95	96	6	3.5	2.75	2	0.06	0	1	1	1	1
42	Evergreen Forest	39	61	74	80	6	3.5	2.75	2	0.04	0.02	2.24	2.8	2.24	1.49
43	Mixed Forest	30	55	70	77	6	3.5	2.75	2	0.02	0	2.7	2.31	1.85	1.62
51	Shrubland	36	60	73	79	6	3.5	2.75	2	0.02	0.02	3.16	2.65	2.12	1.85
81	Pasture/Hay	33	58	72	78	6	3.5	2.75	2	0.02	0.02	2.93	2.48	1.99	1.74
82	Row Crops	39	61	74	80	6	3.5	2.75	2	0.04	0.02	2.45	3.06	2.45	1.63
83	Small Grains	39	61	74	80	6	3.5	2.75	2	0.04	0.02	2.45	3.06	2.45	1.63
85	Urban/Recreational Grass	39	61	74	80	6	3.5	2.75	2	0.04	0.02	2.24	2.8	2.24	1.49
91	Woody Wetlands	49	69	79	84	6	3.5	2.75	2	0.04	0.02	2.56	3.2	2.56	1.7
92	Emergent Herbaceous Wetlands	67	78	85	89	6	3.5	2.75	2	0.04	0	2.12	1.93	1.89	1.35

Land use descriptions for Table B-3

11 **Open Water—**areas of open water, generally with less than 25 percent or greater cover of water (per pixel).

12 **Perennial Ice and Snow—**All areas characterized by year-long cover of ice and/or snow.

21 **Low Intensity Residential—**Includes areas with a mixture of constructed materials and vegetation. Constructed materials account for 30-80 percent of the cover. Vegetation may account for 20 to 70 percent of the cover. These areas most commonly include single-family housing units. Population densities will be lower than in high intensity residential areas.

22 **High Intensity Residential**—Includes heavily built up urban centers where people reside in high numbers. Examples include apartment complexes and row houses. Vegetation accounts for less than 20 percent of the cover. Constructed materials account for 80-100 percent of the cover.

23 **Commercial, Industrial, Transportation**—Includes infrastructure (for example, roads, railroads, etc.) and all highways and all developed areas not classified as High Intensity Residential.

24 **Developed, High Intensity—**Includes highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to 100 percent of the total cover.

31 **Bare Rock, Sand, Clay**—Perennially barren areas of bedrock, desert, pavement, scarps, talus, slides, volcanic material, glacial debris, and other accumulations of earthen material.

32 **Quarries, Strip Mines, Gravel Pits**—Areas of extractive mining activities with significant surface expression.

33 **Transitional—**Areas of sparse vegetative cover (less than 25 percent that are dynamically changing from one land-cover to another, often because of land use activities. Examples include forest clearcuts, a transition phase between forest and agricultural land, the temporary clearing of vegetation, and changes due to natural causes (for example fire, flood, etc.)

41 **Deciduous Forest**—Areas dominated by trees where 75 percent or more of the tree species shed foliage simultaneously in response to seasonal change.

42 **Evergreen Forest**—Areas characterized by trees where 75 percent or more of the tree species maintain their leaves all year. Canopy is never without green foliage.

43 **Mixed Forest**—Areas dominated by trees where neither deciduous nor evergreen species represent more than 75 percent of the cover present.

51 **Shrubland**—Areas dominated by shrubs; shrub canopy accounts for 25-100 percent of the cover. Shrub cover is generally greater than 25 percent when tree cover is less than 25 percent. Shrub cover may be less than 25 percent in cases when the cover of other life forms (for example herbaceous or tree) is less than 25 percent and shrubs cover exceeds the cover of the other life forms.

52 **Shrub/Scrub**—Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20 percent of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.

61 **Orchards, Vineyards, Other**—Orchards, vineyards, and other areas planted or maintained for the production of fruits, nuts, berries, or ornamentals.

71 **Grasslands Herbaceous**—Areas dominated by upland grasses and forbs. In rare cases, herbaceous cover is less than 25 percent, but exceeds the combined cover of the woody species present. These areas are not subject to intensive management, but they are often utilized for grazing.

81 **Pasture Hay**—Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops.

82 **Row Crops**—Areas used for the production of crops, such as corn, soybeans, vegetables, tobacco, and cotton.

83 **Small Grains**—Areas used for the production of graminoid crops such as wheat, barley, oats, and rice.

84 **Fallow**—Areas used for the production of crops that are temporarily barren or with sparse vegetative cover as a result of being tilled in a management practice that incorporates prescribed alternation between cropping and tillage.

85 **Urban Recreational Grasses**—Vegetation (primarily grasses) planted in developed settings for recreation, erosion control, or aesthetic purposes. Examples include parks, lawns, golf courses, airport grasses, and industrial site grasses.

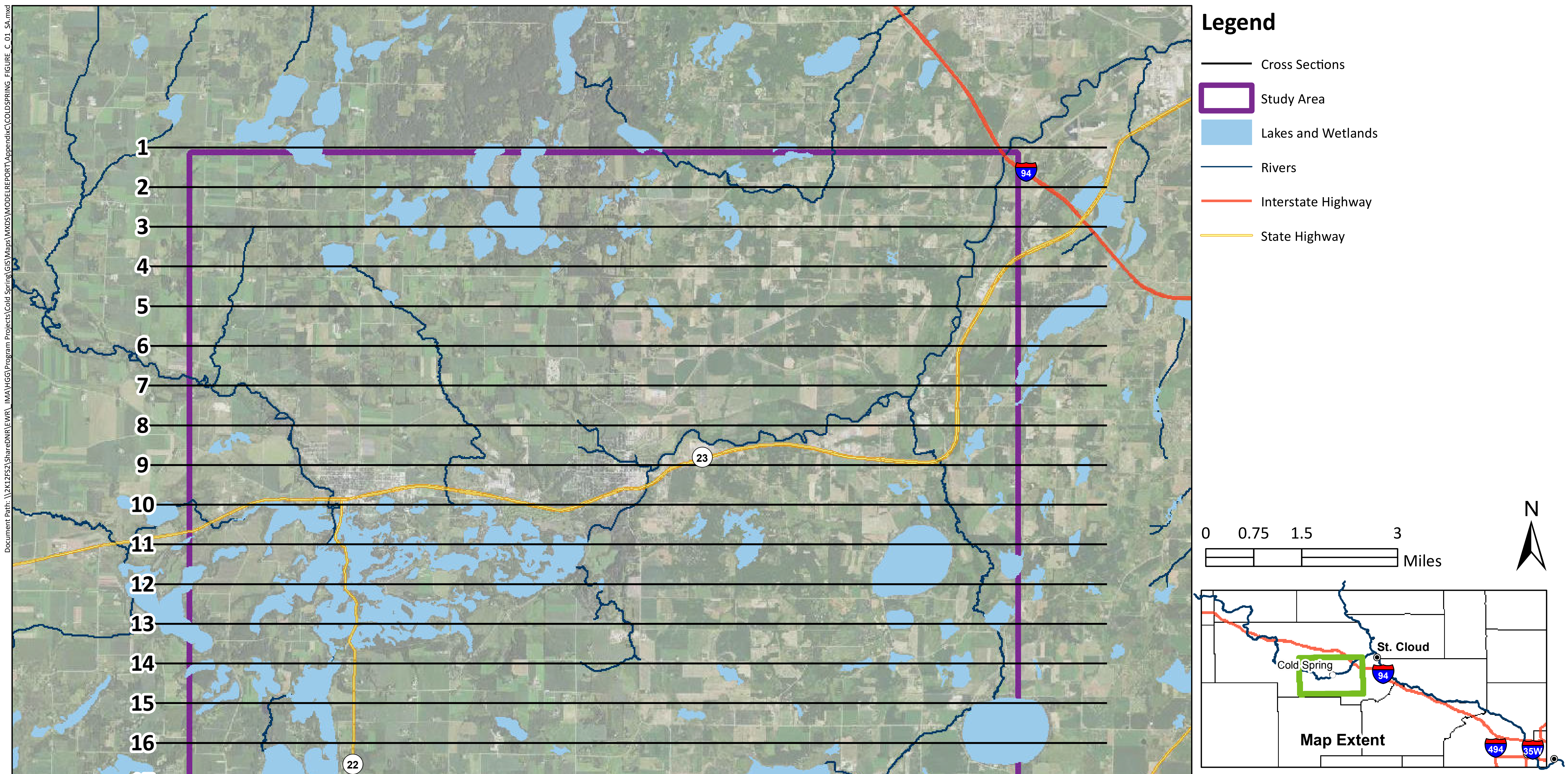
90 **Woody Wetlands**—Areas where forest or shrub land vegetation accounts for greater than 20 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

91 **Woody Wetlands**—Areas where forest or shrubland vegetation accounts for 25-100 percent of the cover and the soil or substrate is periodically saturated with or covered with water.

92 **Emergent Herbaceous Wetlands**—Areas where perennial herbaceous vegetation accounts for 75-100 percent of the cover and the soil or substrate is periodically saturated with or covered with water.

95 **Emergent Herbaceous Wetlands**—Areas where perennial herbaceous vegetation accounts for greater than 80 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water

Appendix C – Cross-sections



Appendix Figure C-1. Cross sections

Cold Spring Groundwater Study

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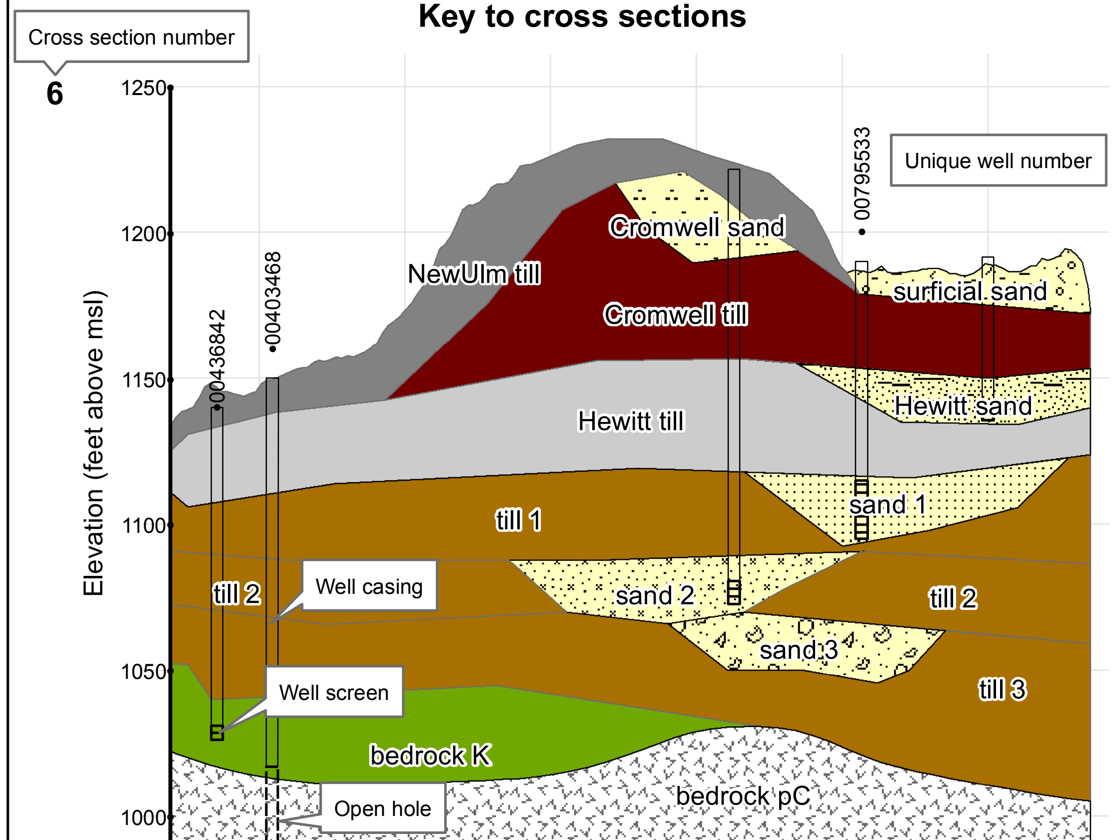
Key to cross sections



On portions of the cross sections where there are many closely spaced wells not all of the well unique numbers will appear. Not all of the well construction infomartion from the data base (CWI) are complete. Therefore some of the well parts (casing, screens or openhole sections) may not appear on the cross sections.

Hydrogeologic characteristics of units

- Surficial sand - unconfined (water table) aquifer
- New Ulm till - aquitard
- Cromwell sand - confined aquifer
- Cromwell till - aquitard
- Hewitt sand - confined aquifer
- Hewitt till - aquitard
- Sand 1 - confined aquifer above till 1
- Till 1 - undifferentiated glacial sediment of unknown origin. May be mostly aquitard.
- Sand 2 - confined aquifer above till 2
- Till 2 - undifferentiated glacial sediment of unknown origin. May be mostly aquitard.
- Sand 3 - confined aquifer above till 3
- Till 3 -- undifferentiated glacial sediment of unknown origin. May be mostly aquitard.
- Bedrock K - Cretaceous bedrock of sandstone, shale and mudstone. May be aquifer or aquitard.
- Bedrock pC - bedrock of Precambrian crystalline (igneous or metamorphic) rock. Maybe fractured and able to convey some water to wells.

Appendix Figure C-2. Cross section key

Cold Spring Groundwater Study

Model Report

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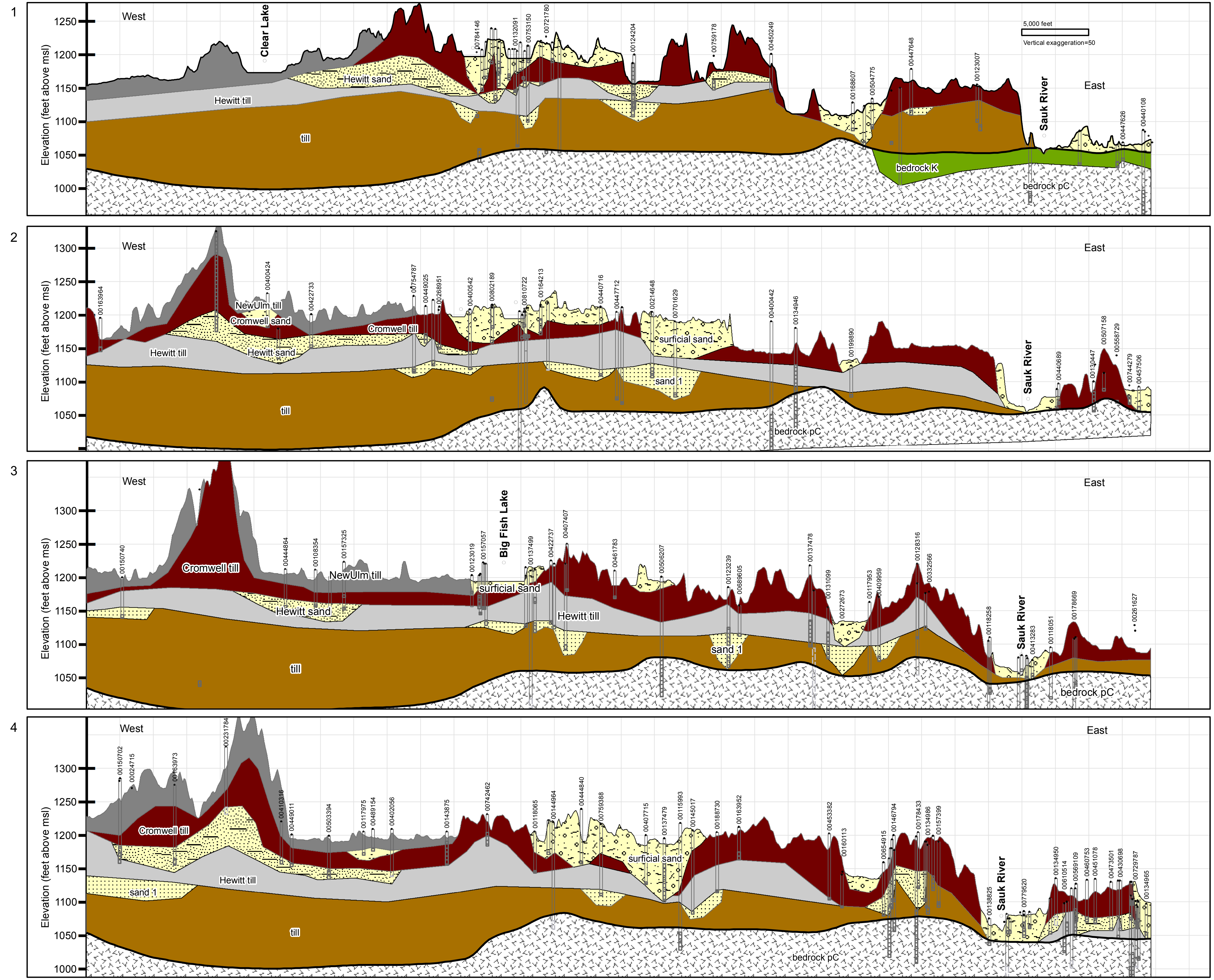

Appendix Figure C-3. Cross sections 1–4

Cold Spring Groundwater Study

Model Report

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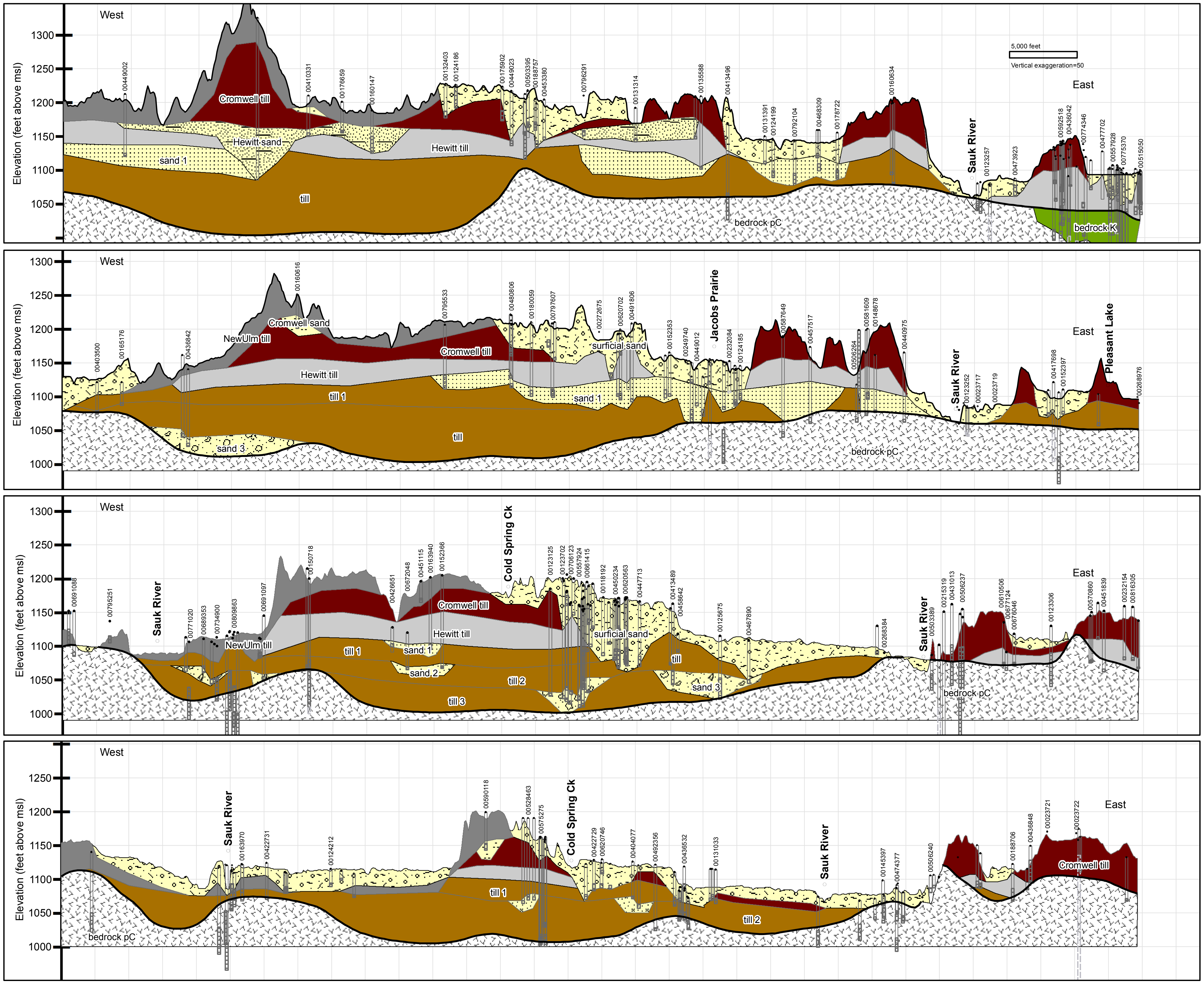
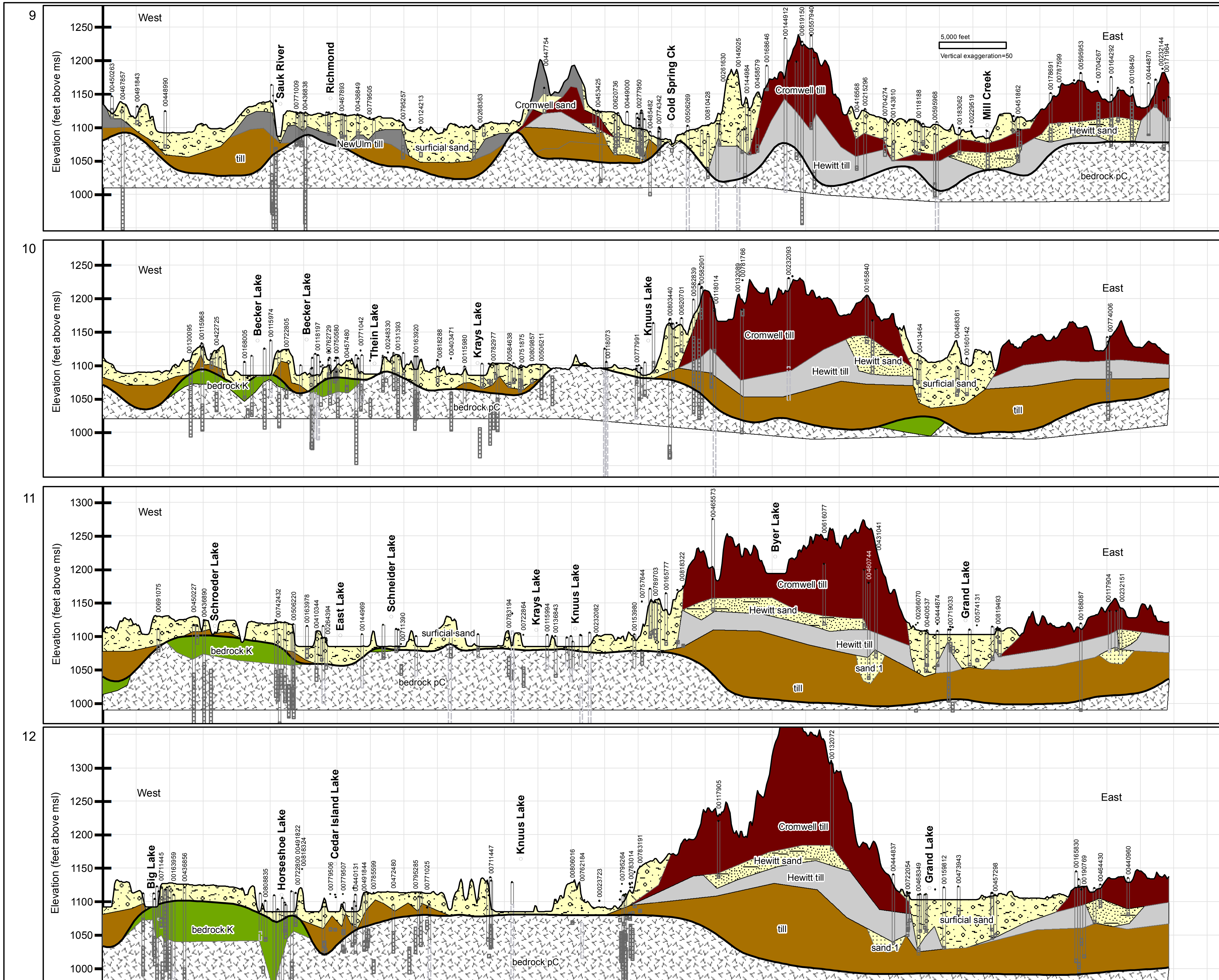


Appendix Figure C-4. Cross sections 5–8

Cold Spring Groundwater Study
Model Report

DEPARTMENT OF NATURAL RESOURCES



Appendix Figure C-5. Cross sections 9–12

Cold Spring Groundwater Study

Model Report

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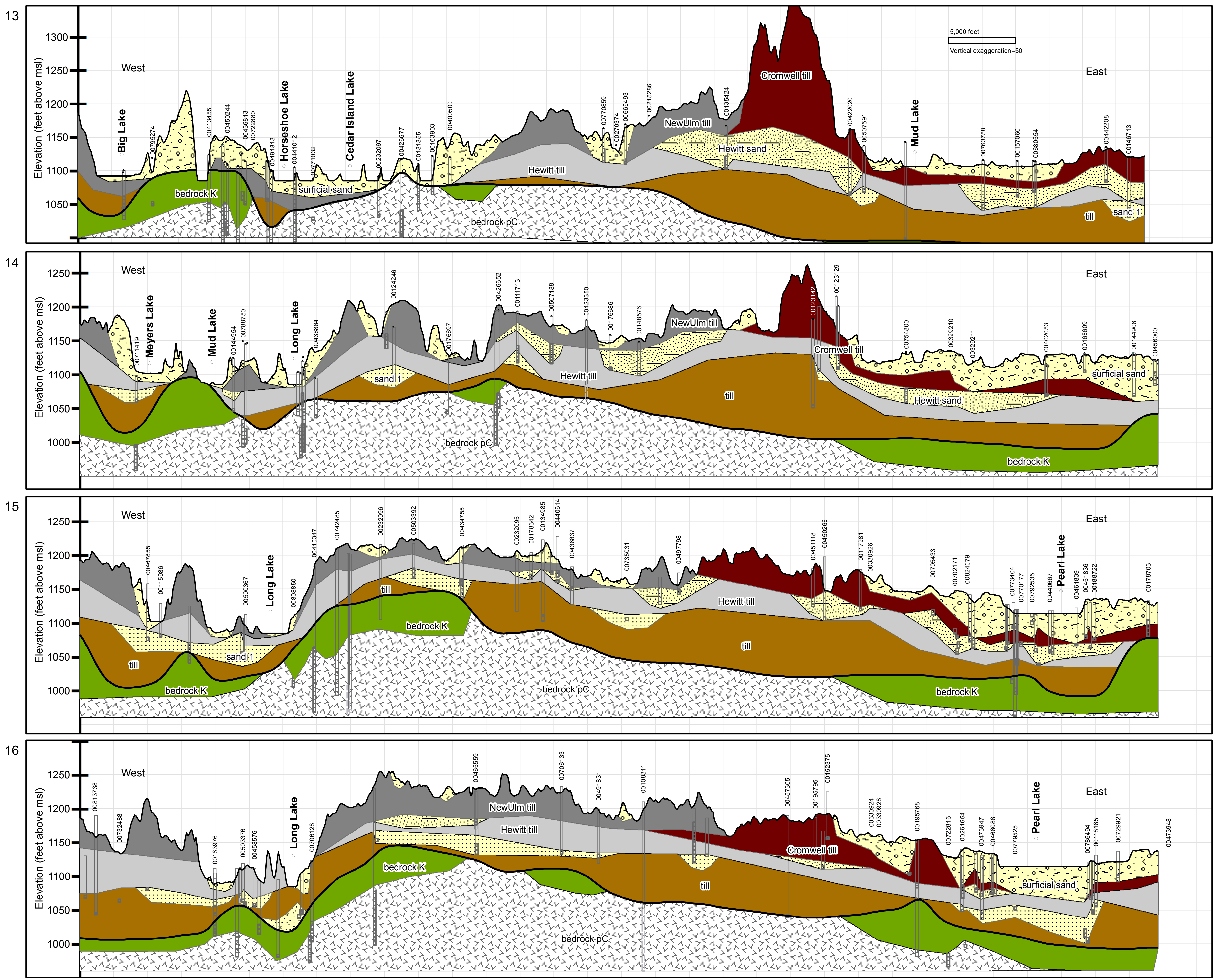

Appendix Figure C-6. Cross sections 13–16
Cold Spring Groundwater Study
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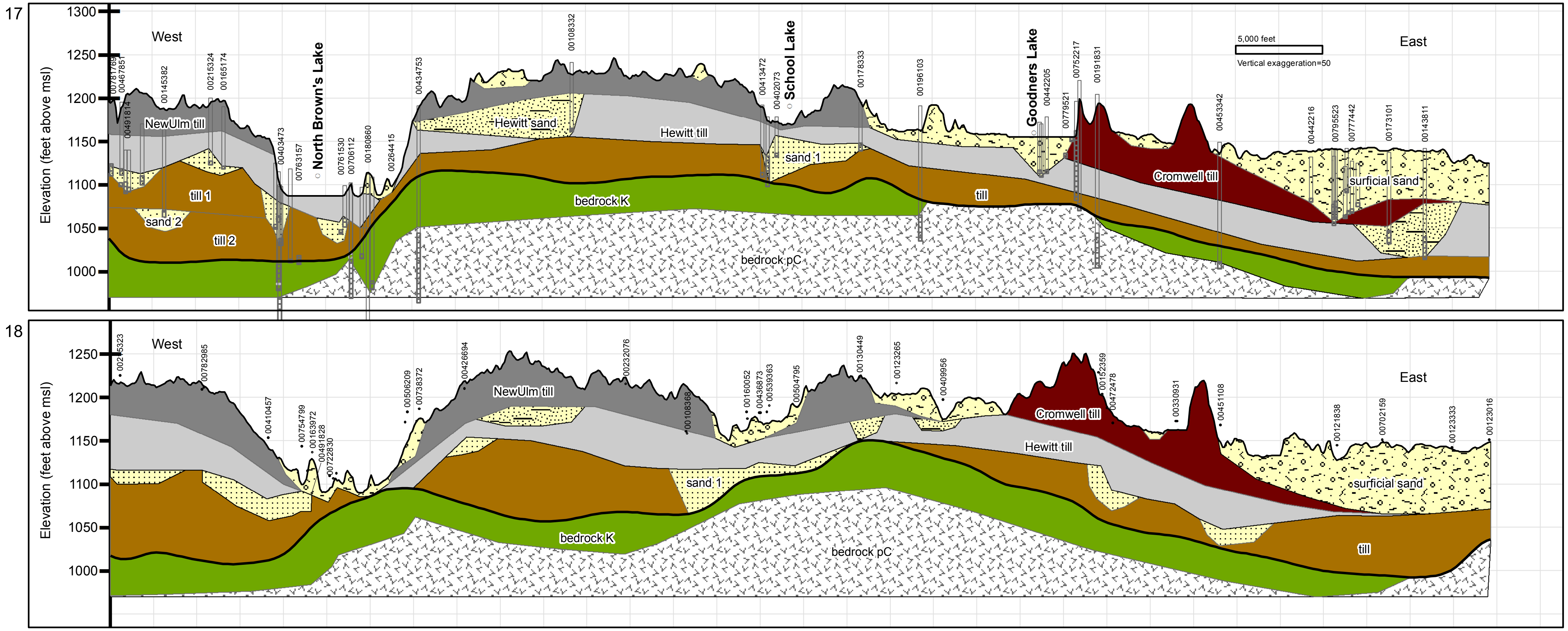

Appendix Figure C-7. Cross sections 17–18

Cold Spring Groundwater Study

Model Report

DEPARTMENT OF NATURAL RESOURCES

Appendix D – Sand modeling

Technical Memo

Date: 02/27/2018

To: Anneka Munsell

From: Bob Tipping, Minnesota Geological Survey (MGS)

RE: Quaternary Sand Modeling

Sand modeling uses well log driller's descriptions to interpolate buried sand lenses within unconsolidated geologic material. The resulting models are used by MGS geologists to help identify lithostratigraphic contacts (glacial till) within Minnesota's Quaternary deposits. Coded well driller's logs used in the sand model are contained in the state water well database, County Well Index (CWI). The well logs are split into five foot elevation intervals with a point at each split. The well log primary and secondary material attributes at each point are classified into one of three groups:

Fine-grained material (i.e.,'CLAY'),
Mixed fine and coarse-grained material (i.e.,CLAY+SAND; GRVL+CLAY), or
Coarse-grained material (i.e.,SAND, GRVL, COBL).

Each group is assigned a value:

- fine-grained material =1
- mixed material =2, and
- coarse material = 3.

Each 5-foot elevation interval point set is interpolated using 2-D ordinary probability kriging with a threshold material value of 2.5. The resulting sand likelihood raster (raster 1) is evaluated using a 2-D ordinary kriging predictive standard error raster (raster2), where areas with sparse data have a higher predictive standard error. Masking raster 1 with low predictive standard error areas of raster 2 results in a new probability raster (raster 3) where cells more than 1500 meters from a well location are typically assigned a null value.

For each 5 foot elevation interval, a grid regularly spaced points with (250 meter horizontal spacing) are assigned and elevation value and a probability values from raster 3. Once points lying above the land surface or below the bedrock surface have been removed, resulting gridpoints are merged to produce a 3 dimensional sand model.

Appendix E – Base flow analysis

DEPARTMENT OF NATURAL RESOURCES

Technical Memo

Date: 12/18/2019

To: Ellen Considine, Anneka Munsell

From: Zachary Moore, Joy Loughry - EWR Water Monitoring and Surveys Unit

RE: Cold Spring Groundwater Study – Requisition #: 2020-01

Introduction

This memo is in response to the Requisition for Technical Services #2020-01 dated 8/22/2019 requesting "Estimate(ed) base flow for Cold Spring Creek from 2014-2018 in the vicinity of H16011008 and H16011007 using at least three methods and complete technical memo describing the results."

The two continuous water level monitoring stations, H16011008 and H16011007 located on Cold Spring Creek, were installed 10/22/2014 by the Minnesota Department of Natural Resources (MN DNR). Site H16011008 is located approximately ¼ mile upstream of site H16011007. Before base flow could be estimated, staff had to process the data in order to create the continuous record of stream discharge at these stations. The records for calendar years 2014-2018 at both stations are finalized.

Appendix Table E-1. Stream gage periods of record and drainage area

Site	Water Level Period of Record	Drainage Area (mi^2)	Mean Basin Slope (%)
Cold Spring Creek at Cold Spring, 5th Ave (H16011008)	Oct. 2014 – Jan. 2019	4.00	2.90
Cold Spring Creek at Cold Spring, 2nd St N (H16011007)	Oct. 2014 – Jan. 2019	4.08	2.89

Methods

Using the mean daily flows, estimated base flow for 10/24/2014 – 1/1/2019 was calculated for both sites using the United States Geological Survey's (USGS) GW Toolbox software (Barlow and others, 2015). All 8 available separation methods were used and are outlined below. Details and citations for each method are in the GW Toolbox user manual (Barlow and others, 2015).

- PART
- HySEP - Fixed Interval
- HySEP - Local Minimum
- HySEP - Sliding Interval
- BFI - Standard
- BFI - Modified
- One parameter digital filter (BFLOW)
- Two Parameter digital Filter (TwoPRDF)

Parameters were based on suggestions from the literature and are outlined below.

One Parameter Filter Constant (α)

Explanation: Program default that is based on values cited in the literature.

Source: Barlow and others (2015)

Two Parameter Recession Constant (a)

Explanation: Calculated by the program

Source: Barlow and others (2015)

Two Parameter BFImax

Explanation: Calculated by the program

Source: Barlow and others (2015)

BFI Standard Partition Length (N, days)

Explanation: The literature suggests running the program with varying values of N (days) to find an inflection point. This analysis showed the inflection point at N=1. This is consistent with the observed data that show the flashiness of the system.

Source: Wahl and Wahl (1995)

BFI Standard Turning Point Test Factor (F)

Explanation: The literature states that "in practice, the value of 0.9 seems appropriate in most applications for which the BFI method is suitable."

Source: Wahl and Wahl (1995)

BFI Modified Daily Recession Index (K')

Explanation: Program default. Resulting estimates using this method were in line with other estimates so no modification was made to this value.

Source: Barlow and others (2015)

Appendix Table E-2. Parameter and value used for the analyses

Parameter	Value
One Parameter Filter Constant (α)	0.925 (default)
Two Parameter Recession Constant (a)	Calculated by program
Two Parameter BFImax	Calculated by program
BFI Standard Partition Length (N, days)	1
BFI Standard Turning Point Test Factor (F)	0.9 (default)
BFI Modified Daily Recession Index (K’)	0.97915 (default)

Because the hydrograph separation methods are subjective, the user manual for the USGS GW Toolbox software recommends using more than one method and then comparing the results. The manual also recommends using the resulting base flow estimates on time scales greater than daily, preferably monthly or yearly (Barlow and others, 2015).

Results

All 8 methods produced similar estimates of average base flow. It is recommended to use the median of all 8 methods. Results and basic statistics can be found in tables 3, 4 and 5.

Appendix Table E-3. Average streamflow, base flow, base flow percentage (BFP), and base flow index (BFI) using various estimation methods at gaging station H16011008 for 10/22/2014 - 1/1/2019

	Streamflow	Base flow	Base flow percentage	Base flow index
Method	CFS	CFS	(%)	(--)
PART	0.63	0.49	94.02	0.94
HySEP-Fixed	0.63	0.5	93.23	0.93
HySEP-LocMin	0.63	0.47	91.92	0.92
HySEP-Slide	0.63	0.5	93.08	0.93
BFIStandard	0.63	0.49	94.31	0.94
BFIModified	0.63	0.48	92.46	0.92
BFLOW	0.63	0.48	91.58	0.92
TwoPRDF	0.63	0.45	82.38	0.82
Mean	--	**0.48**	**91.62**	**0.92**
Min	--	**0.45**	**82.38**	**0.82**
Max	--	**0.50**	**94.31**	**0.94**
Median	--	**0.49**	**92.77**	**0.93**

Appendix Table E-4. Average streamflow, base flow, base flow percentage (BFP), and base flow index (BFI) using various estimation methods at gaging station H16011007 for 10/22/2014 - 1/1/2019

	Streamflow	Base flow	Base flow percentage	Base flow index
Method	CFS	CFS	(%)	(--)
PART	2.2	1.95	94.97	0.95
HySEP-Fixed	2.2	1.95	94.48	0.94
HySEP-LocMin	2.2	1.92	93.65	0.94
HySEP-Slide	2.2	1.95	94.28	0.94
BFIStandard	2.2	1.97	95.63	0.96
BFIModified	2.2	1.92	93.96	0.94
BFLOW	2.2	1.92	93.38	0.93
TwoPRDF	2.2	1.71	82.14	0.82
Mean	--	**1.91**	**92.81**	**0.93**
Min	--	**1.71**	**82.14**	**0.82**
Max	--	**1.97**	**95.63**	**0.96**
Median	--	**1.94**	**94.12**	**0.94**

Appendix Table E-5. Monthly median streamflow and base flow for all estimation methods at gaging station H16011008 for 10/22/2014 - 1/1/2019

	Streamflow	Base flow
Month	CFS	CFS
January	0.5	0.49
February	0.5	0.48
March	0.5	0.52
April	0.5	0.44
May	0.5	0.49
June	0.5	0.51
July	0.4	0.42
August	0.4	0.37
September	0.3	0.33
October	0.5	0.47
November	0.5	0.49
December	0.5	0.49

Appendix Table E-6. Monthly median streamflow and base flow for all estimation methods at gaging station H16011007 for 10/22/2014 - 1/1/2019.

	Streamflow	Base flow
Month	CFS	CFS
January	2.0	1.91
February	1.9	1.84
March	2.0	1.90
April	2.0	1.92
May	2.1	1.95
June	2.0	1.90
July	1.9	1.80
August	1.8	1.70
September	1.8	1.73
October	2.1	1.95
November	2.0	2.00
December	2.0	1.98

References

Barlow, P.M., Cunningham, W.L., Zhai, Tong, and Gray, Mark, 2015, U.S. Geological Survey groundwater toolbox, a graphical and mapping interface for analysis of hydrologic data (version 1.0)—User guide for estimation of base flow, runoff, and groundwater recharge from streamflow data: U.S. Geological Survey Techniques and Methods 3-B10, 27 p., https://dx.doi.org/10.3133/tm3B10

Lim, Kyoung Jae, Bernard A. Engel, Zhenxu Tang, Joongdae Choi, Ki-Sung Kim, Suresh Muthukrishnan, and Dibyajyoti Tripathy, 2005. Automated Web GIS Based Hydrograph Analysis Tool, WHAT. Journal of the American Water Resources Association 41(6):1407-1416. https://engineering.purdue.edu/mapserve/WHAT/

Wahl, K.L., and Wahl, T.L., 1995, Determining the flow of Comal Springs at New Braunfels, Texas, in Proceedings of Texas Water 95, August 16–17, 1995, San Antonio, Tex.: American Society of Civil Engineers, p. 77–86.

Appendix F – Model well files

Appendix F contains the WEL file formatted for MODFLOW-NWT.
These are not intended to be read using a screen reader.

```
# MODFLOW2000 Well Package
PARAMETER  0  0
      851        50   AUX IFACE
SPECIFY 1.000000e-003
      851         0            Stress Period 1
        8         3      243-2.4963572        0
        9         3      243-6.0853291        0
       10         3       243-6.0853291        0
       11         3       243-6.0853291        0
       12         3       243-1.5053554        0
        9         4      245-0.000e+00        0
       10         4       245-0.000e+00        0
        9         5      209-3.3916695        0
       10         5       209-4.3203850        0
       11         5       209-4.3203850        0
       12         5       209-7.7203608        0
       12         6       226-0.000e+00        0
       13         6       226-0.000e+00        0
       14         6       226-0.000e+00        0
        4         7       55-0.000e+00        0
        5         7       55-0.000e+00        0
        6         7       57-0.000e+00        0
        7         7       57-0.000e+00        0
       11         7       112-0.6369280        0
       12         7       112-5.1632519        0
        4         9      230-3.671e-06        0
        5         9      230-1.823e-05        0
        6         9      230-1.067e-04        0
        7         9      230-0.3218170        0
        8         9      230-0.3218170        0
        9         9      230-0.3218170        0
       10         9       230-0.3218170        0
       11         9       230-0.3218170        0
       12         9       230-0.3218170        0
       13         9       230-3.271e-06        0
       14         9       230-4.593e-05        0
        4        13       167-3.4457200        0
        4        14       211-2.188e-04        0
        5        14       211-5.997e-03        0
        6        14       211-7.183e-03        0
        7        14       211-40.375999        0
        9        14       240-10.837169        0
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       11        14        240-20.246141        0
       12        14        240-30.896128        0
       13        14        240-2.058e-04        0
       14        14        240-2.129e-04        0
        4        14       245-3.686e-07        0
        5        14       245-2.090e-06        0
```

6	14	245-8.917e-06	0
7	14	245-0.3940856	0
1	15	76-0.1613772	0
2	15	76-0.0328738	0
3	15	76-0.0328738	0
4	15	76-1.449e-07	0
9	16	233-0.2310040	0
10	16	233-0.2951714	0
11	16	233-0.1935705	0
8	18	246-0.1590690	0
9	18	246-0.3104831	0
10	18	246-0.2875299	0
2	21	59-4.8297210	0
3	21	59-2.358e-06	0
4	21	59-1.478e-05	0
5	21	59-3.030e-05	0
6	21	59-1.654e-06	0
2	22	44-0.2206009	0
3	22	44-80.856598	0
4	22	145-0.000e+00	0
5	22	145-0.000e+00	0
6	22	145-0.000e+00	0
7	22	145-0.000e+00	0
8	22	145-0.000e+00	0
9	22	145-0.000e+00	0
10	22	145-0.000e+00	0
11	22	145-0.000e+00	0
12	22	145-0.000e+00	0
4	22	217-0.000e+00	0
5	22	217-0.000e+00	0
6	22	217-0.000e+00	0
7	22	217-0.000e+00	0
8	22	217-0.000e+00	0
9	22	217-0.000e+00	0
10	22	217-0.000e+00	0
11	22	217-0.000e+00	0
12	22	217-0.000e+00	0
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6	23	43-24.108580	0
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3	24	45-0.000e+00	0
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8	31	227-0.2206430	0
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2	32	81-56.813648	0
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7	32	236-74.711090	0
8	32	236-8.952e-06	0
2	34	62-0.000e+00	0

3	34	62-0.000e+00	0
4	34	62-0.000e+00	0
7	34	241-104.54000	0
2	35	86-0.000e+00	0
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6	35	86-0.000e+00	0
7	35	86-0.000e+00	0
8	35	86-0.000e+00	0
12	36	69-33.947300	0
1	36	73-175.62434	0
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3	36	73-1.796e-06	0
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5	36	73-2.309e-05	0
6	36	73-1.208e-04	0
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10	37	165-1.4854203	0
6	38	31-7.9239221	0
7	38	31-4.0732780	0
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4	39	74-0.000e+00	0
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5	40	247-1.238e-06	0
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7	40	247-1.1314676	0
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11	41	223-58.478020	0
12	41	223-100.02252	0
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14	42	220-0.000e+00	0
9	42	222-0.8726515	0

10	42	222-0.9935466	0
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9	42	222-2.7270327	0
10	42	222-3.1048293	0
11	42	222-3.1048293	0
12	42	222-0.5268286	0
7	43	216-131.43686	0
8	43	216-2.7901404	0
6	44	62-5.882e-05	0
7	44	62-18.733141	0
7	45	183-3.1289301	0
7	45	86-0.000e+00	0
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9	45	86-0.000e+00	0
10	45	86-0.000e+00	0
6	45	88-0.000e+00	0
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10	61	198-7.2561808	0
8	68	78-1.0951586	0
9	68	78-5.1507311	0
10	68	78-24.246410	0
8	82	233-1.3852731	0
9	82	233-20.317516	0
10	82	233-20.317516	0
11	82	233-20.317516	0
12	82	233-20.317516	0
13	82	233-20.317516	0
14	82	233-1.428e-04	0
2	108	50-0.000e+00	0
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3	108	218-0.9301773	0
1	112	186-0.000e+00	0
2	112	186-0.000e+00	0

3	112	186-0.000e+00	0
3	137	136-0.000e+00	0
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7	137	163-0.000e+00	0
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11	137	163-0.000e+00	0
12	137	163-0.000e+00	0
5	131	202-0.000e+00	0
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5	157	70-0.000e+00	0
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13	161	216-0.000e+00	0
14	161	216-0.000e+00	0
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2	173	63-0.000e+00	0
3	173	63-0.000e+00	0

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5	173	63-0.000e+00	0
6	173	63-0.000e+00	0
7	173	63-0.000e+00	0
12	177	241-0.000e+00	0
13	177	241-0.000e+00	0
14	177	241-0.000e+00	0
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3	180	246-1.883e-05	0
4	180	246-1.738e-05	0
4	186	92-0.000e+00	0
5	186	92-0.000e+00	0
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2	187	110-0.000e+00	0
3	188	201-0.000e+00	0
4	188	201-0.000e+00	0
5	188	201-0.000e+00	0
3	188	246-0.000e+00	0
4	188	246-0.000e+00	0
1	190	40-0.000e+00	0
1	190	45-0.000e+00	0
2	190	45-0.000e+00	0
1	190	56-0.000e+00	0
2	190	56-0.000e+00	0
3	190	56-0.000e+00	0
4	190	56-0.000e+00	0
1	189	61-0.000e+00	0
2	189	61-0.000e+00	0
3	189	61-0.000e+00	0
4	189	61-0.000e+00	0
5	189	61-0.000e+00	0
2	191	40-5.196e-06	0
3	191	40-1.4075249	0
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12	191	40-1.4075249	0
13	191	40-1.4075249	0
14	191	40-2.016e-05	0
1	191	198-0.000e+00	0
2	191	198-0.000e+00	0

3	191	198-0.000e+00	0
5	192	40-0.000e+00	0
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13	192	40-0.000e+00	0
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2	192	63-61.818863	0
3	192	63-58.207066	0
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2	192	64-2.4012685	0
3	192	64-1.3607424	0
1	192	163-0.000e+00	0
2	192	163-0.000e+00	0
3	192	163-0.000e+00	0
4	192	163-0.000e+00	0
1	192	163-0.000e+00	0
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2	192	163-0.000e+00	0
1	193	44-0.000e+00	0
2	193	44-0.000e+00	0
7	193	46-0.000e+00	0
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9	193	46-0.000e+00	0
1	193	69-64.165886	0
2	193	69-2.7665174	0
5	194	37-43.110760	0
6	194	37-55.178658	0
7	194	37-55.178658	0
8	194	37-31.534925	0
1	194	123-0.000e+00	0
2	194	123-0.000e+00	0
3	194	123-0.000e+00	0
4	195	37-0.000e+00	0
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10	195	37-0.000e+00	0
11	195	37-0.000e+00	0
14	195	74-0.000e+00	0

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8	196	59-0.000e+00	0
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2	196	69-5.6202750	0
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2	197	47-0.5804768	0
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1	197	70-46.027500	0
2	197	70-13.140133	0
3	197	70-4.9141650	0
10	197	199-0.000e+00	0
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11	198	193-0.000e+00	0
3	200	66-0.000e+00	0
4	200	66-0.000e+00	0
5	200	66-0.000e+00	0
6	200	66-0.000e+00	0

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8	200	66-0.000e+00	0
9	200	66-0.000e+00	0
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9	209	133-0.000e+00	0
10	209	133-0.000e+00	0
11	209	133-0.000e+00	0
3	212	135-0.000e+00	0
4	212	135-0.000e+00	0
5	212	135-0.000e+00	0
12	216	216-12.172400	0
7	220	123-0.1508629	0
8	220	123-0.1909558	0
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11	220	123-0.1909558	0
12	220	123-0.1909558	0
13	220	123-0.1909558	0
14	220	123-0.6241122	0
1	222	130-159.70380	0
2	222	130-2.684e-06	0
3	222	130-1.956e-04	0
1	223	149-0.000e+00	0
2	227	54-2.2896671	0
3	227	54-1.536e-04	0
4	227	54-8.921e-05	0
3	227	82-2.1239800	0
10	229	57-0.8336574	0
11	229	57-1.0674280	0
12	229	57-1.5440242	0
13	229	57-1.085e-05	0
14	229	57-1.195e-04	0
2	234	57-0.000e+00	0
3	234	57-0.000e+00	0
4	234	57-0.000e+00	0
8	234	73-0.4218813	0
9	234	73-71.846222	0
2	236	81-2.493e-05	0
3	236	81-5.4751587	0
4	236	81-1.0834265	0
2	244	65-2.7999830	0

3	244	65-2.1581054	0
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5	244	65-1.5775665	0
7	248	65-12.285700	0
1	71	168-815.66174	0
2	71	168-0.0309246	0
3	71	168-0.0173356	0
12	138	209-948.42810	0
13	138	209-8.809e-04	0
1	145	111-0.000e+00	0
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3	150	178-0.000e+00	0
4	150	178-0.000e+00	0
1	158	111-0.000e+00	0
2	158	111-0.000e+00	0
3	158	111-0.000e+00	0
5	159	110-4.2997122	0
6	159	110-152.72841	0
7	159	110-152.72841	0
8	159	110-25.990482	0
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3	161	151-0.000e+00	0
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6	161	151-0.000e+00	0
8	159	206-48.892181	0
9	159	206-67.514000	0
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12	159	206-57.239826	0
4	161	145-389.22711	0
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1	84	228-73.079597	0
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2	197	70-23.888493	0
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13	8	242-7.329e-04	0
14	8	242-2.215e-05	0
3	132	46-13.522614	0
4	132	46-25.090387	0
6	34	229-3.280e-04	0
7	34	229-303.24667	0
12	139	212-8.3765697	0
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5	40	86-84.051331	0
6	40	86-133.45245	0
4	26	69-79.020401	0
4	2	74-0.000e+00	0
4	2	83-0.000e+00	0
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9	3	163-0.000e+00	0
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12	3	163-0.000e+00	0
5	3	165-1.2299998	0
6	3	165-38.352501	0
7	3	165-38.352501	0
8	3	165-38.352501	0
9	3	165-38.352501	0
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14	4	86-0.000e+00	0
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7	5	53-4.8722901	0
7	5	53-0.000e+00	0
14	5	79-0.000e+00	0
12	5	209-120.62300	0
5	6	58-0.000e+00	0
6	8	75-0.000e+00	0
4	9	119-5.3794298	0
7	10	193-168.27499	0
4	11	75-0.5486250	0
4	12	206-0.7002435	0
5	12	206-8.9997435	0
6	12	206-77.017509	0
4	13	164-0.000e+00	0
5	13	164-0.000e+00	0
4	13	255-34.522999	0
4	17	217-0.000e+00	0
5	19	28-14.269400	0
11	19	229-0.000e+00	0
12	19	229-0.000e+00	0
9	21	77-0.000e+00	0
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11	21	77-0.000e+00	0
5	22	37-1.7855560	0
6	22	37-68.189644	0
4	22	250-0.000e+00	0
6	23	239-0.5112900	0
7	23	239-0.5112900	0
4	25	220-11.808400	0
5	27	49-75.720703	0
7	28	247-2.9777751	0
8	28	247-2.9777751	0

9	28	247-2.9777751	0
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5	31	37-4.9397001	0
5	31	49-0.000e+00	0
6	31	49-0.000e+00	0
1	31	81-78.548302	0
2	34	64-0.000e+00	0
3	34	64-0.000e+00	0
4	34	64-0.000e+00	0
7	34	233-50.352001	0
6	35	225-4.337e-04	0
7	35	225-62.633999	0
8	35	225-7.6542673	0
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2	37	84-2.482e-06	0
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2	41	171-0.000e+00	0
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4	41	204-83.784599	0
5	41	204-8.056e-04	0
3	45	35-13.348500	0
6	45	93-5.174e-05	0
7	45	93-8.1078386	0
7	46	213-170.57500	0
4	47	75-52.360001	0
1	50	123-0.000e+00	0
8	50	121-1.8118100	0
1	62	93-0.000e+00	0
1	63	227-0.000e+00	0
7	82	60-0.6585580	0
11	82	234-28.385401	0
12	82	234-28.385401	0
13	82	234-28.385401	0
1	82	235-0.000e+00	0
11	98	122-0.9883550	0
3	104	202-0.000e+00	0
4	104	202-0.000e+00	0
5	104	202-0.000e+00	0
9	104	219-0.0967663	0
10	104	219-0.0967663	0

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12	104	219-90.847275	0
6	105	225-8.5732002	0
7	105	225-8.5732002	0
1	107	190-0.000e+00	0
14	107	202-16.685900	0
1	108	63-0.000e+00	0
2	108	63-0.000e+00	0
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6	108	190-0.000e+00	0
7	108	190-0.000e+00	0
7	108	249-0.000e+00	0
8	108	249-0.000e+00	0
2	109	41-1.801e-04	0
3	109	41-88.020821	0
1	109	146-0.000e+00	0
1	111	40-0.000e+00	0
10	112	190-0.000e+00	0
11	112	190-0.000e+00	0
12	112	190-0.000e+00	0
1	120	43-0.000e+00	0
8	124	198-0.000e+00	0
1	129	251-0.000e+00	0
1	137	145-0.000e+00	0
3	137	150-12.532467	0
4	137	150-12.532467	0
5	137	150-12.532467	0
1	137	163-0.000e+00	0
1	137	176-0.000e+00	0
1	131	182-0.000e+00	0
2	131	182-0.000e+00	0
8	131	202-0.000e+00	0
2	153	42-22.785101	0
4	151	74-3.2832408	0
5	151	74-11.536860	0
1	152	244-0.000e+00	0
1	152	244-0.000e+00	0
10	157	217-0.000e+00	0
11	157	217-0.000e+00	0
12	157	217-0.000e+00	0
5	164	201-0.000e+00	0
6	164	201-0.000e+00	0
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1	173	42-0.000e+00	0
2	173	42-0.000e+00	0
3	173	42-0.000e+00	0
1	175	63-0.000e+00	0
4	185	90-0.000e+00	0
14	179	223-0.000e+00	0

1	188	51-0.000e+00	0
2	188	51-0.000e+00	0
1	186	59-0.000e+00	0
4	187	88-0.000e+00	0
12	186	240-0.000e+00	0
1	189	41-0.000e+00	0
1	190	42-0.000e+00	0
1	192	38-0.000e+00	0
6	192	64-2.2105949	0
7	192	64-2.2105949	0
1	193	33-0.000e+00	0
1	193	35-0.000e+00	0
14	193	37-0.000e+00	0
4	193	68-1.8265966	0
5	193	68-1.8265966	0
6	193	68-1.8265966	0
4	193	70-0.3191077	0
5	193	70-0.3191077	0
6	193	70-0.3191077	0
1	193	250-2.2712500	0
1	194	61-0.000e+00	0
14	195	48-0.000e+00	0
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5	195	116-0.000e+00	0
6	195	116-0.000e+00	0
4	195	202-0.000e+00	0
4	195	241-0.000e+00	0
1	196	54-0.000e+00	0
6	196	123-0.000e+00	0
7	196	123-0.000e+00	0
7	196	123-0.000e+00	0
8	196	123-0.000e+00	0
1	196	176-0.000e+00	0
4	197	39-3.3582714	0
5	197	39-3.3582714	0
6	197	39-3.3582714	0
7	197	39-3.3582714	0
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2	197	46-0.000e+00	0
3	197	46-0.000e+00	0
1	198	65-0.000e+00	0
14	198	194-0.000e+00	0
4	198	200-0.000e+00	0
1	199	66-0.000e+00	0
1	199	149-0.000e+00	0

14	199	229-0.000e+00	0
4	201	211-0.000e+00	0
14	201	228-0.000e+00	0
1	202	53-0.000e+00	0
4	202	240-0.6585580	0
1	204	31-0.000e+00	0
1	204	32-0.000e+00	0
10	204	51-0.000e+00	0
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13	204	51-0.000e+00	0
11	208	115-0.000e+00	0
12	208	115-0.000e+00	0
13	208	115-0.000e+00	0
14	208	115-0.000e+00	0
14	210	24-0.000e+00	0
10	210	49-7.8356671	0
11	210	49-7.8356671	0
12	210	49-7.8356671	0
13	210	49-7.8356671	0
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11	211	188-6.8977156	0
12	211	188-13.257639	0
3	218	214-0.2651517	0
4	218	214-0.2651517	0
5	218	214-3.3214867	0
6	224	174-33.947399	0
7	226	49-139.33900	0
6	227	73-0.000e+00	0
2	232	55-2.4983699	0
6	234	77-0.000e+00	0
5	235	198-0.0985244	0
4	236	75-33.447189	0
5	236	75-36.071877	0
6	236	75-2.2886333	0
2	236	88-1.4235797	0
3	236	88-1.735e-03	0
4	236	88-1.735e-03	0
13	237	62-15.764176	0
14	237	62-1.824e-03	0
2	239	69-0.1970490	0
8	239	77-3.4981401	0
12	242	160-6.8687100	0
7	245	65-50.498100	0
6	246	63-58.470100	0
1	61	168-0.000e+00	0

1	61	168-0.000e+00	0
1	61	169-0.000e+00	0
1	82	169-0.000e+00	0
1	84	179-475.40601	0
1	86	179-0.000e+00	0
1	82	180-0.000e+00	0
1	82	181-544.37500	0
1	129	116-0.000e+00	0
1	129	116-0.000e+00	0
5	137	123-0.000e+00	0
6	137	123-0.000e+00	0
1	145	115-0.000e+00	0
1	139	121-0.000e+00	0
11	139	211-92.085716	0
12	139	211-282.94528	0
12	141	211-468.73199	0
4	157	144-547.44244	0
5	157	144-13.691566	0
4	158	155-87.328918	0
5	158	155-0.4752562	0
6	158	155-14.818914	0
7	158	155-14.818914	0
1	160	150-0.000e+00	0
1	160	150-0.000e+00	0
9	163	136-0.000e+00	0
10	163	136-0.000e+00	0
1	168	147-0.000e+00	0
5	163	150-0.000e+00	0
1	170	156-0.000e+00	0
2	170	156-0.000e+00	0
5	177	176-0.000e+00	0
6	177	176-0.000e+00	0
7	177	176-0.000e+00	0
8	177	176-0.000e+00	0
1	174	196-0.000e+00	0
2	174	196-0.000e+00	0
3	174	196-0.000e+00	0
4	174	196-0.000e+00	0
14	183	163-0.000e+00	0
7	34	156-16.853701	0
1	142	57-3.7996099	0
2	142	57-5.777e-09	0
4	15	185-3.4457200	0
10	138	212-0.000e+00	0
11	138	212-0.000e+00	0
12	138	212-0.000e+00	0
9	152	211-109.21467	0
10	152	211-109.21467	0
11	152	211-109.21467	0

2	108	45-0.000e+00	0
1	84	167-0.000e+00	0
2	84	167-0.000e+00	0
3	84	167-0.000e+00	0
4	84	167-0.000e+00	0
5	84	167-0.000e+00	0
6	84	167-0.000e+00	0
1	117	158-0.000e+00	0
2	117	158-0.000e+00	0
1	168	135-0.000e+00	0
2	174	164-0.000e+00	0
3	174	164-0.000e+00	0
4	174	164-0.000e+00	0
6	192	227-0.000e+00	0
7	192	227-0.000e+00	0
8	192	227-0.000e+00	0
9	192	227-0.000e+00	0
10	192	227-0.000e+00	0
11	192	227-0.000e+00	0
12	192	227-0.000e+00	0
13	192	227-0.000e+00	0
12	246	121-0.000e+00	0
13	246	121-0.000e+00	0

Appendix G – Response to comments

Comment 1: Where are the two outlier head targets located?

These two outlier head targets are located in bedrock. One is located near the northeastern edge of the model, and the other is located just southeast of Greystone Rd and CSAH 2 in the area of interest. Bedrock aquifer properties are not well understood, and we do not expect to be able to precisely match targets in bedrock wells.

Comment 2: More explanation on the base flow method should be put into the report itself regarding methodology, not just the appendix. Explain two different sets of data (base flow from 2006-2015 and streamflow from 2014-2016.)

Additional explanation has been added to section 4.5.3 Calibration Targets.

Comment 3: Can increase in base flow be correlated to layers in the model?

Yes, the difference between upstream and downstream base flow appears to come from zone 5 (Hewitt Sand), as shown on the cross sections on figures 16 and 17.

Comment 4: Which layer contributes the most flow?

Layers 1 and 5 contribute the most flow to Cold Spring Creek (surficial sand and Hewitt sand, respectively).

Comment 5: Did you look at how much Riv10 influences the area of interest? Is it worth having it in the report? Is it order of magnitude in its influence?

Heads throughout the model are sensitive to Riv10. It is likely that heads throughout the model are sensitive to Riv10 because the Sauk River is the major discharge point for groundwater in the area. Along Cold Spring Creek changing the Riv10 parameter by an order of magnitude causes less than 1 percent of change of base flow to the creek.

Comment 6: How about Kx4? How connected is it to the decision tree?

Kx4 contributes about 2 percent of the total flow to the area of interest. When Kx4 is changed by an order of magnitude, base flow in Cold Spring Creek changes by about 20 percent. This parameter is sensitive and contributes to the total flow in the area of interest, however both Cold Spring Creek and the area of interest are relatively insensitive to this parameter.

Comment 7: Why did you choose these scenarios? You should put the rationale in the report.

Description of why these scenarios were chosen can be found in section 5.0.

Comment 8: Don’t use slash (u/s & d/s).

Removed “u/s” and “d/s” in the report and replaced with “upstream” and “downstream”.

Comment 9: For scenarios, how was the added flow distributed between 4, 5, & 6?

The total was divided evenly among the three wells.

Comment 10: What is the breakdown of volumes (city and brewery) removed in scenarios 2 and 3? The volume applied to the city wells 4 5, and 6?

153.5 mgy was removed from the brewery wells and 39.5 mgy from the City; these were the volumes reported to the DNR as part of the permit requirements. The total additional volume applied to City wells 4, 5, and 6 is described in section 5.0.

Comment 11: You are using two measuring points (us & ds). These are reaches, not points. Have you thought of the implication of those two points and what comes next? This needs to be addressed in the technical report. Urge those who make the decisions to think about that. It's not insignificant.

The two measuring points each represent the reach of the stream that is immediately upstream of the point. Two points/reaches were chosen because it is not practical to discretize the stream into very short (e.g., less than several-hundred-foot-long) reaches and understand what happens along each of those reaches. However, it may be advantageous to use two measuring points instead of just one. In general, upstream and downstream reaches, with their different flowrates, widths, and depths, provide different habitats. Upstream reaches, with lower flow rates, are expected to be more sensitive to base flow depletion, whereas downstream reaches are less sensitive but are an indicator of an entire watershed's health. To balance the desirability of protecting a range of habitat against the practicability of regulating very short stream reaches, we chose to measure model predictions at two measuring points, which each represent a stream reach.

Comment 12: Discuss the 1000' selection in the report.

The intention of running these scenarios was to explore questions about the effect of pumping close to the creek. 1000' was an arbitrary distance, chosen to evaluate the effect of pumping close to the stream. We agree that a distance of 1000' may unintentionally connote a relationship to a regulatory requirement. To avoid confusion, the model scenarios now examine the effect of pumping within ¼, ½, 1, and 2-mile distances from the stream. This selection is discussed in section 5.0 in the report.

Comment 13: Is there any real value in talking about the downstream Sauk River numbers in the report? It provides outliers that are prominent on the tables. Maybe they should be put in the appendix instead.

These numbers are described in Section 4.5.3.

Comment 14: Buried sand under creek with unit on top with strong effect. Cross-section may be useful where large increase in flow over 3 blocks.

The geology Cross sections added as figures 16 and 17.

Comment 15: For scenarios, did you use 2016 total amount reported? What was it? Or did you use total permitted 2016 pumping?

For scenarios we used the total pumping reported by permit holders for 2016 as part of their water permit.

Comment 16: Check 2014 to 2016 pumping to model to allow base flow and pumping to match.

This is discussed in section 4.7

Comment 17: Run a 2017 scenario to check for over calibrations

This is described in section 4.7

Comment 18: Include a map to accompany the scenarios with the 1000' boundary

Figures 41 through 44 were added to the report to illustrate distances from the creek.

Comment 19: Create a figure describing hydraulic conductivity for each layer in the report.

Figures 17 through 30 were added to the report to illustrate hydraulic conductivity in each layer.

Comment 20: State how Kx and Kz are tied in the report and include figures of Kz.

Section 4.3.4 describes how vertical and horizontal hydraulic conductivities are tied, and figures 20 through 33 describe both horizontal and vertical hydraulic conductivity.

Comment 21: Is zone 9 in layer 8 confined?

Yes

Comment 22: Increased flow from your upstream to your downstream Cold Spring Creek flow measurements are due, in large part, to a strong upward hydraulic head gradient over those 3 blocks. In retrospect makes sense - looking at the history of Cold Spring says the brewery was built on the city's namesake spring. Supported also by well logs, peat deposits mapped on the Stearns County Atlas near the site, and sand body below Cromwell till hydraulic conductivity zone from your subsurface model that runs approximately below the creek.

The buried sand must be somewhat continuous into the highlands area west to be connected to higher hydraulic head. Maybe already mapped that way in your model? At any rate, your model should show an upward flux through cells below the creek in this area - which given that the creek flow measurements were a primary calibration target, could explain why the model is sensitive to the Cromwell hydraulic conductivity parameter.

The buried sand unit is somewhat continuous to the west and there is an upward gradient to the creek when it is no longer confined as shown in figures 16 and 17 (Hewitt sand, Kx5). As described in response to comment 6, while the model is sensitive to Cromwell till hydraulic conductivity (Kx4) the creek itself is rather insensitive when compared to the hydraulic conductivity of the Hewitt sand (Kx5).

Comment 23: The observed and model-calculated flows for the Sauk River do have some disparity. I believe this was discussed at the last TAG meeting, but I don't recall how it was addressed. Is there a plan to get the model and observed values to calibrate better? Or is the emphasis on hitting the flows on Cold Spring Creek the main priority (for which the model appears to be close)? What anticipated changes would you expect would be necessary to better calibrate the Sauk River flows? Are there parameters that could be adjusted within the realm of reality to achieve better calibration and, if so, what parameters? Or would other changes be needed to hit the observed values?

As discussed in the TAG meeting, the flows for the Sauk River were the values used in the USGS report (Lingren, 2001). Model report sections 2.4.2 and 4.5.3 discuss the base flow values used in the report. Fitting base flow in Cold Spring Creek was the priority during model calibration. We do not anticipate making any changes to better match flow in the Sauk River, as the streamflow data from the Sauk River has relatively high error associated with it.

Comment 24: This is probably more related to how the model is used, but in talking with the City there is an interest in knowing the impacts of other permitted wells on the creek (e.g., farm irrigation wells, Gold'n Plump wells, etc.). It would be interesting to see what impact is observed at the creek when those wells are shut off versus the impact observed when they are on. While the impact might be expected to be small, it's something there is interest in knowing about… plus it could help judge the sensitivity of the model to pumping changes (near the area of focus) besides just changes to the City's wells.

Section 5.0 was revised to help evaluate impacts of other permitted wells away from the creek.

Addendum 1 – Correction to Cold Spring Groundwater Study Model Report

Memorandum

Date: 10/1/2020

To: Nicola Blake-Bradley, Area Hydrologist
Constance Holth, Hydrologist Supervisor
Tim Crocker, District Manger
Dan Lais, Regional Manger

Cold Spring Technical Advisory Group

From: Anneka Munsell, Groundwater Modeler
Ellen Considine, Hydrologist Supervisor
Jay Frischman, Groundwater Unit Supervisor
Jason Moeckel, IMA Section Manager

RE: Correction to Cold Spring Groundwater Study Model Report

This memorandum describes a correction to the Cold Spring Groundwater Study model report issued in January 2020 by the Department of Natural Resources (DNR). Base flow had been calculated incorrectly in the report, which caused base flow depletion to be miscalculated by -2.1 to 1.1 percent. The magnitude of the correction is such that the overall conclusions of the report remain the same.

The original report text and the corrected text are shown below. Correcting the calculation required an additional model scenario: the 2014 through 2018 pumping scenario, which is also described below. The original report, dated January 17, 2020, has been revised and re-issued.

At the City's request, the Site previously referred to as the "Froehle" site is now referred to as the "Lot 1/Block 1" site.

Calculating percent reduction in base flow - *original text from report*

All model scenarios were compared to a **no pumping** model run in which no wells were pumped to calculate base flow in Cold Spring Creek under a natural condition. The depletion in base flow (*depletion*) for each scenario was calculated by subtracting the base flow in a given scenario ($base\ flow_{scenario\ x}$) from the base flow in the **no pumping** model run ($base\ flow_{no\ pumping}$). This depletion in base flow is the amount of groundwater diverted from Cold Spring Creek to pumping wells.

$$depletion = base\ flow_{no\ pumping} - base\ flow_{scenario\ x}$$

It is common practice for a prediction to be presented not in absolute terms, but as a difference relative to the base case (Barnett, et al., 2012). The base case of the Cold Spring model is the measured base flow (Appendix E) plus the modeled depletion, as calculated in the previous equation. The equation below was used to calculate the percent difference of the model results.

$$Percent\ difference = \frac{depletion}{base\ flow_{measured} + depletion}$$

Calculating percent reduction in base flow - *corrected text*

To calculate base flow depletion it is first necessary to determine how much base flow would be present in the stream, absent pumping (i.e., the reference base flow). The reference base flow is calculated using both model results and field-based data, as follows:

$$reference\ depletion = base\ flow_{no\ pumping} - base\ flow_{2014-2018}$$

In the equation above, "reference depletion" is a modeled value which represents the average base flow depletion during the period from 2014 through 2018. The reference depletion is then added to the base flow measured in the creek over the same time period (2014 through 2018) to calculate the "reference base flow", as follows.

$$reference\ base\ flow = base\ flow_{measured} + reference\ depletion$$

The "reference base flow" represents how much base flow, on average, would have been in the creek over the period from 2014 through 2018 without pumping. Using field data to calculate the reference base flow (instead of simply using the results of the base flow from the no-pumping model scenario) minimizes the impact of model error on the calculation of depletion.

Base flow depletion for each of the model scenarios was calculated as follows:

$$depletion_{scenario\ x} = \ base\ flow_{no\ pumping} - base\ flow_{scenario\ x}$$

It is common practice for a prediction to be presented not in absolute terms but as a difference relative to the base case (Barnett, et al., 2012). For the Cold Spring model, the base case is the reference base flow defined above. The percent difference in base flow was calculated using the equation below:

$$Percent\ difference_{scenario\ x} = \frac{depletion_{scenario\ x}}{reference\ base\ flow}$$

Cumulative impact scenarios – *original text from report (no correction required)*

To determine the current cumulative impact of groundwater withdrawal on Cold Spring Creek and to calculate the effect of pumping distance and volume on the creek, five scenarios were simulated (results in Table 14):

Scenario 1 (Calibrated): All wells were pumped at the average 2006-2018 pumping rates, i.e., this is what the calibrated model calculates.

Scenario 2 (2018): All wells were pumped at 2018 pumping rates, averaged over the year.

Scenario 3 (1/4 mile): All wells within ¼ mile of Cold Spring Creek were turned off and the rest of the wells in the model domain were pumped at 2018 rates.

Scenario 4 (half mile): All wells within ½ mile of Cold Spring Creek were turned off and the rest of the wells in the model domain were pumped at 2018 rates.

Scenario 5 (one mile): All wells within 1 mile of Cold Spring Creek were turned off and the rest of the wells in the model domain were pumped at 2018 rates.

Scenario 6 (two miles): All wells within 2 mile of Cold Spring Creek were turned off and the rest of the wells in the model domain were pumped at 2018 rates

Addendum Table 1- 1. Simulated base flow in Cold Spring Creek for scenarios 1 through 6 – *both ORIGINAL values from report and CORRECTED values shown*

Scenario	Simulation	Pumping volume (mgy)	Upstream reach H16011008 (cfs)	Depletion over upstream reach (cfs)	*ORIGINAL* Upstream reach % difference	*CORRECTED* Upstream reach % difference	Downstream reach H16011007 (cfs)	Depletion over downstream reach (cfs)	*ORIGINAL* Downstream reach % difference	*CORRECTED* Downstream reach % difference
	Measured (from field data)	**--**	***0.49***	**--**	**--**	**--**	***1.94***	--	--	--
	No pumping	0	0.52	--	--	--	2.13	--	--	--
	2014-2018	1150	0.4	0.12	--	--	1.65	0.48	--	--
1	Calibrated	1199	0.42	0.1	16.9	16.4	1.75	0.38	16.4	15.7
2	2018	1313	0.39	0.13	21.0	21.3	1.66	0.47	19.5	19.4
3	Quarter mile	1125	0.49	0.03	5.8	4.9	2.02	0.11	5.4	4.5
4	Half mile	1121	0.49	0.03	5.8	4.9	2.02	0.11	5.4	4.5
5	One mile	811	0.49	0.03	5.8	4.9	2.03	0.1	4.9	4.1
6	Two miles	377	0.52	0	0.0	0.0	2.12	0.01	0.5	0.4

For Scenarios 2 through 5, MODFLOW reduced the specified pumping by 17.3 mgy (179.21 m3/day). For Scenario 6, MODFLOW reduced the specified pumping by 0.9 mgy (9.16 m3/day). The pumping volume shown in the table is what was modeled after the automatic reduction.

Hypothetical water supply scenarios at the City's wellfield – *original text from report (no correction required)*

Six model scenarios were simulated to demonstrate the effect of different pumping regimes at the City's existing wellfield. These scenarios are not intended to be prescriptive, but rather to help understand how different pumping configurations affect Cold Spring Creek. Results are shown in Addendum Table 1-2.

Scenario 7 (2018, ¼ mile, the City's well field): All wells within ¼ mile of Cold Spring Creek are turned off. City wells 4, 5, and 6 supply the 2018 demand from the wells within ¼ mile of Cold Spring Creek split evenly among the three wells.

Scenario 8 (2018, ¼ mile, 20 mgy, the City's well field): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (440639 and 718237, because these are the two wells with reported pumping in 2018) and City well 3. City wells 4, 5, and 6 supply the remaining 2018 demand from the wells within ¼ mile of Cold Spring Creek (188 mgy minus 20 mgy).

Scenario 9 (Permitted): All wells within the model domain pump maximum permitted volume, averaged over the year.

Scenario 10 (Permitted, ¼ mile, 20 mgy, the City's well field): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek (505 mgy minus 20 mgy).

Scenario 11 (Permitted, +103 mgy): All wells within the model domain pump maximum permitted volume, averaged over the year. City wells 4, 5, and 6 supply an additional 103 mgy.

Scenario 12 (Permitted, ¼ mile, 20 mgy, the City's well field, +103 mgy): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek and supply an additional 103 mg (505 mgy minus 20 mgy plus 103 mgy).

Addendum Table 1- 2. Simulated base flow in Cold Spring Creek for scenarios 7 through 12 – *both ORIGINAL values from report and CORRECTED values shown*

Scenario	Simulation	Pumping volume (mgy)	Upstream reach H16011008 (cfs)	Depletion over upstream reach (cfs)	ORIGINAL Upstream reach % difference	CORRECTED Upstream reach % difference	Downstream reach H16011007 (cfs)	Depletion over downstream reach (cfs)	ORIGINAL Downstream reach % difference	CORRECTED Downstream reach % difference
	Measured	**--**	***0.49***	**--**	**--**	**--**	***1.94***	**--**	**--**	**--**
	No pumping	0	0.52	--	--	--	2.13	--	--	--
	2014-2018	1150	0.4	0.12	--	--	1.65	0.48	--	--
7	2018, ¼ mile, the City's well field	1313	0.47	0.05	9.3	8.2	1.94	0.19	8.9	7.9
8	2018, ¼ mile, 20 mgy, the City's well field	1313	0.46	0.06	10.9	9.8	1.92	0.21	9.8	8.7
9	Permitted	2377	0.37	0.15	23.4	24.6	1.52	0.61	23.9	25.2
10	Permitted, ¼ mile, 20 mgy, the City's well field	2377	0.43	0.09	15.5	14.8	1.81	0.32	14.2	13.2
11	Permitted, +103 mgy	2480	0.35	0.17	25.8	27.9	1.48	0.65	25.1	26.9
12	Permitted, ¼ mile, 20 mgy, the City's well field, +103 mgy	2480	0.42	0.1	16.9	16.4	1.77	0.36	15.7	14.9

For Scenarios 9 through 12, MODFLOW reduced the specified pumping by 129 mgy (1338 m3/day). The pumping volume shown in the table is what was modeled after the automatic reduction.

Hypothetical water supply scenarios at Lot 1/Block 1 – *original text from report (no correction required)*

Six model scenarios were simulated to demonstrate the effect of shifting water supply demand to a potential new well field. These scenarios are not intended to be prescriptive, but rather to help understand how different pumping configurations affect Cold Spring Creek. Results are shown in Addendum Table 1-3.

Scenario 13 (Permitted, ¼ mile, 20 mgy, +103 mgy Lot 1/Block 1): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek. The Lot 1/Block 1 site supplies an additional 103 mgy from test well (unique number 00812233).

Scenario 14 (Permitted, ¼ mile, 20 mgy, +103mgy, 200 mgy Lot 1/Block 1): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek minus 97 mgy. The Lot 1/Block 1 site supplies the 97 mgy from the City's wells and an additional 103 mgy from test well (unique number 00812233).

Scenario 15 (Permitted, ¼ mile, 20 mgy, +103mgy, 300 mgy Lot 1/Block 1): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek minus 197 mgy. The Lot 1/Block 1 site supplies the 197 mgy from the City's wells and an additional 103 mgy from test well (unique number 00812233).

Scenario 16 (Permitted, ¼ mile, 20 mgy, +103mgy, 400 mgy Lot 1/Block 1): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek minus 297 mgy. The Lot 1/Block 1 site supplies the 297 mgy from the City's wells and an additional 103 mgy from test well (unique number 00812233).

Scenario 17 (Permitted, ¼ mile, 20 mgy, +103mgy, 500 mgy Lot 1/Block 1): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and City well 3. City wells 4, 5, and 6 supply the remaining permitted demand from the wells within ¼ mile of Cold Spring Creek minus 397 mgy. The Lot 1/Block 1 site supplies the 397 mgy from the City's wells and an additional 103 mgy from test well (unique number 00812233).

Scenario 18 (Permitted, ¼ mile, 20 mgy, +103mgy, all Lot 1/Block 1): All wells within ¼ mile of Cold Spring Creek are turned off, except 20 mgy is pumped from brewery wells (253011, 440639, and 718237) and the Lot 1/Block 1 site supplies the remaining demand and an additional 103 mgy from test well (unique number 00812233).

Addendum Table 1- 3. Simulated base flow in Cold Spring Creek for scenarios 13 through 18 - *both ORIGINAL values from report and CORRECTED values shown*

Scenario	Simulation	Pumping volume (mgy)	Upstream reach H16011008 (cfs)	Depletion over upstream reach (cfs)	ORIGINAL Upstream reach % difference	CORRECTED Upstream reach % difference	Downstream reach H16011007 (cfs)	Depletion over downstream reach (cfs)	ORIGINAL Downstream reach % difference	CORRECTED Downstream reach % difference
	Measured	**--**	***0.49***	**--**	**--**	**--**	***1.94***	**--**	**--**	**--**
	No pumping	0	0.52	--	--	--	2.13	--	--	--
	2014-2018	1150	0.4	0.12	--	--	1.65	0.48	--	--
13	Permitted, ¼ mile, 20 mgy, +103 Lot 1/Block 1	2480	0.43	0.09	15.5	14.8	1.8	0.33	14.5	13.6
14	Permitted, ¼ mile, 20 mgy, +103, 200 mgy Lot 1/Block 1	2480	0.44	0.08	14.0	13.1	1.84	0.29	13.0	12
15	Permitted, ¼ mile, 20 mgy, +103 mgy, 300 mgy Lot 1/Block 1	2480	0.45	0.07	12.5	11.5	1.88	0.25	11.4	10.3
16	Permitted, ¼ mile, 20 mgy, +103 mgy, 400 mgy Lot 1/Block 1	2480	0.46	0.06	10.9	9.8	1.92	0.21	9.8	8.7
17	Permitted, ¼ mile, 20 mgy, +103 mgy, 500 mgy Lot 1/Block 1	2480	0.47	0.05	9.3	8.2	1.95	0.18	8.5	7.4
18	Permitted, ¼ mile, 20 mgy, +103 mgy, all Lot 1/Block 1	2480	0.48	0.04	7.6	6.6	1.99	0.14	6.7	5.8

For Scenarios 13 through 18, MODFLOW reduced the specified pumping by 128.9 to 129.2 mgy (1,337 m3/day to 1340 m3/day). The pumping volume shown in the table is what was modeled after the automatic reduction.