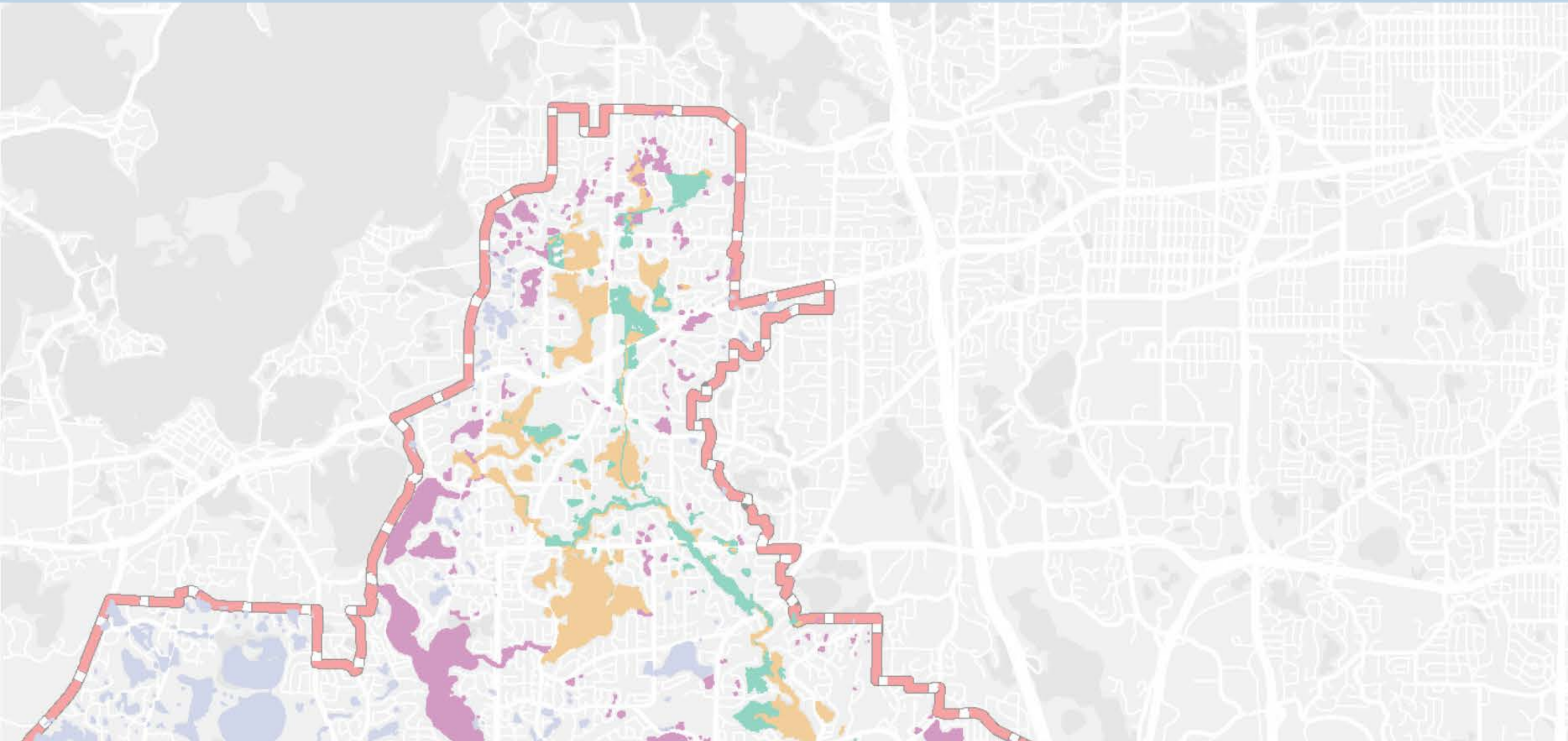
Regional Groundwater / Surface Water Interaction Study



Prepared for
Riley Purgatory Bluff Creek Watershed District

December 2017

RILEY PURGATORY BLUFF CREEK WATERSHED DISTRICT
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RILEY
PURGATORY
BLUFF CREEK
WATERSHED DISTRICT

December 2017

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Certification

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

_______________________________ ____12/28/2017____

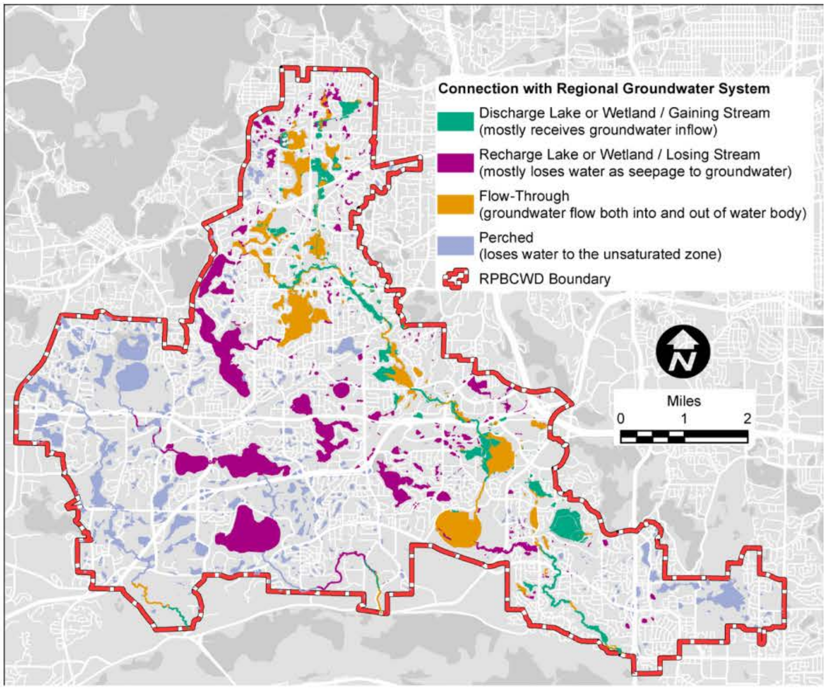
Evan G. Christianson Date

PG # 51379

Regional Groundwater/Surface Water Interaction Study
Executive Summary

SUMMARY

A groundwater/surface water interaction and slope stability study was performed for the Riley Purgatory Bluff Creek Watershed District (District). This study used publically available GIS datasets to evaluate: 1) the connection of regional groundwater and surface water across the district; 2) the vulnerability of surface waters to changes in the groundwater system; 3) areas that are most conducive for large-scale infiltration; and 4) the current slope stability across the District and areas where the risk of slope failure is greatest in the presence of increased infiltration.

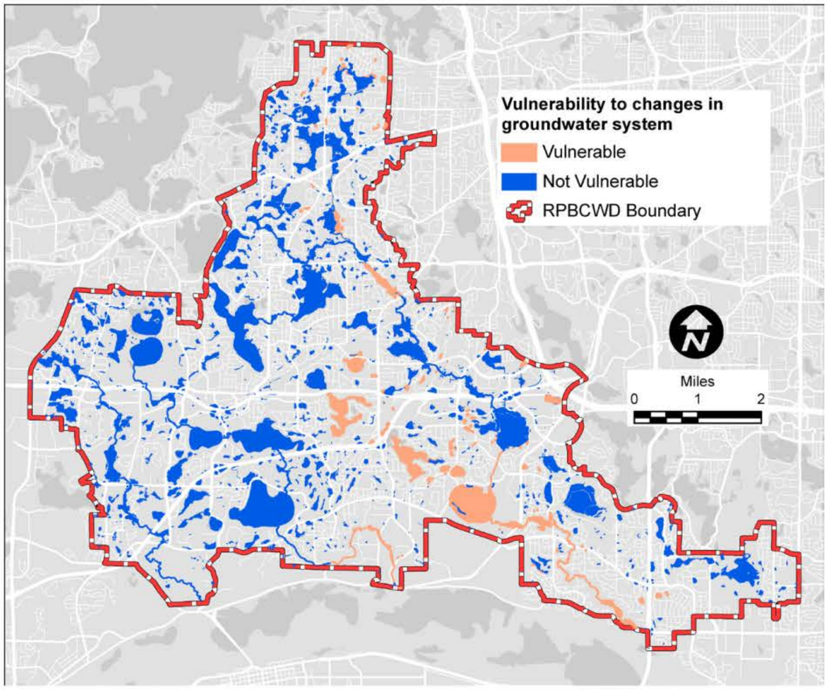


REGIONAL GROUNDWATER/ SURFACE WATER INTERACTION

Surface water features in the western part of the District interact with groundwater differently than surface waters in the eastern and northern part of the District. In the west, lakes and wetlands are mostly perched or recharge the groundwater system. In the east and north, lakes and wetlands mostly gain water from the groundwater system or are flow-through features

VULNERABILITY OF SURFACE WATERS TO CHANGES IN THE REGIONAL GROUNDWATER SYSTEM

Surface waters in the southcentral part of the District are most vulnerable to changes in the groundwater system. Surface water features in the western part of District are less vulnerable.



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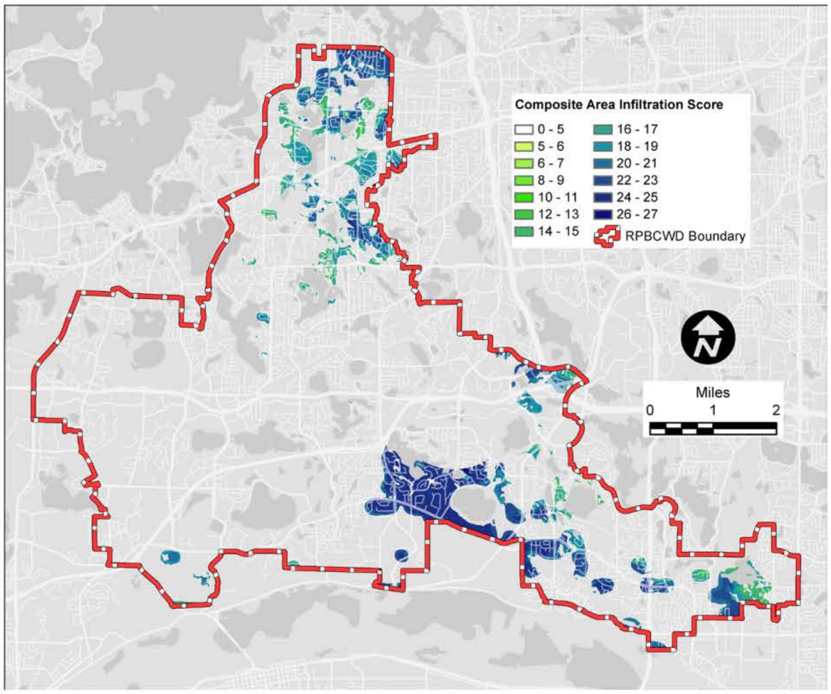


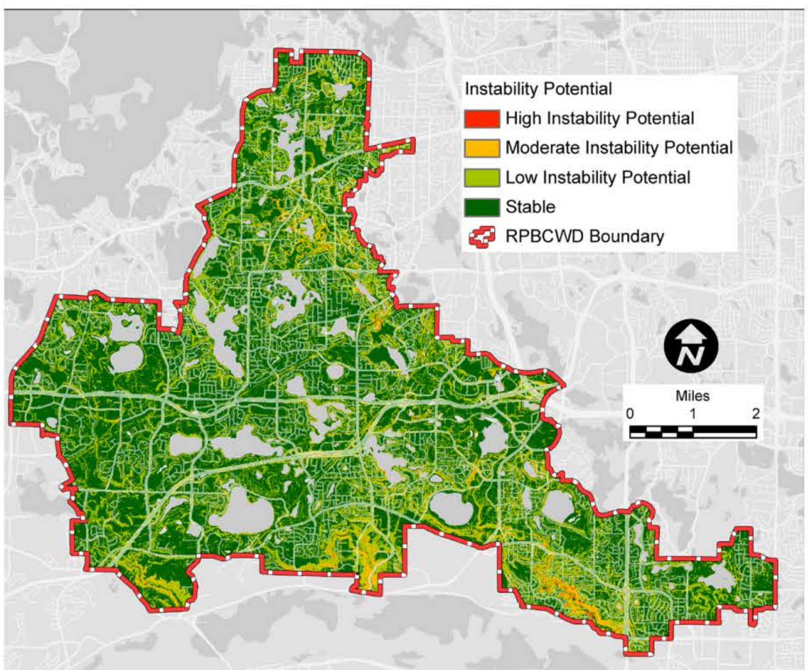
AREAS BEST SUITED FOR LARGE-SCALE INFILTRATION

For large-scale infiltration, areas in the northern and southeastern part of the District were identified as being the best potential locations.

Areas west and southwest of Staring Lake, north of County Road 62, and southwest of Hyland Lake were identified as some of the best areas suited for large scale infiltration.

SLOPE STABILITY

The banks of Riley and Purgatory Creek are most vulnerable to slope instability due to increased infiltration near steep slopes.



RECOMMENDATIONS

- Establish baseflow thresholds for the creeks within the District
- Establish either lake stage or outlet discharge, thresholds for lakes identified as vulnerable to changes in the groundwater system.
- Establish target hydrographs for wetlands identified as vulnerable to changes in the groundwater system.
- Re-establish a monitoring well network within the District and implement a monitoring program.
- Develop a fully coupled groundwater-surface water model for the District.
- Establish a formal process for tracking groundwater data submitted to the District with permit applications.

2.0 Introduction

Understanding the interaction between groundwater and surface water is important for the sustainable management and protection of water resources in the Riley Purgatory Bluff Creek Watershed District (District). How groundwater and surface water interact affects how they may respond to seasonal changes (such as drought), long-term climate change, or groundwater pumping. Changes in the groundwater system may affect water levels, stream flow, and water quality. One strategy for the preservation and restoration of the groundwater system is to enhance groundwater recharge through the infiltration of stormwater.

This report:

- Discusses how regional groundwater and surface water interact across the District and identifies surface waters that may be susceptible to changes in groundwater levels.
- Identifies areas best suited for large-scale infiltration to help replenishing stressed aquifers and/or help offset potential impacts to surface water from increased groundwater pumping.
- Identifies areas within the District where large-scale infiltration may result in increased slope instability.

The susceptibility of surface waters to changes in groundwater levels has been a topic of great interest for water bodies across the Twin Cities metro area in general. Record low water levels in White Bear Lake have, in part, been attributed to increased groundwater pumping in the area (Jones, 2013). In 2012, the Minnesota State Legislature gave the Minnesota Department of Natural Resources (MNDNR) authority to designate groundwater management areas to "ensure sustainable use of groundwater that protects ecosystems, water quality, and the ability of future generations to meet their own needs" (MN 103G.287 Subd. 4). With this new authority, the MNDNR initiated three pilot groundwater management areas (GWMAs); Straight River Area, Bonanza Valley, and the North and East Metro. These pilot GWMAs were established in areas of greatest concern regarding ground water impacts to surface waters and to learn how to establish GWMAs in other areas facing groundwater management issues.

The groundwater management plan for the North East Metro was released by the MNDNR in November 2015 and outlines the actions the MNDNR will take to sustainably manage groundwater in the area (MNDNR, 2015). This management plan offers some insight to how a GWMA might be implemented in the area of the District sometime in the future. The two most important items in the groundwater management plan as it relates to this report are:

- The MNDNR will work with watershed districts to evaluate lakes and basins in the GWMA that are susceptible to changing groundwater levels. The MNDNR will develop thresholds to determine negative impacts to basins and wetlands.

- The MNDNR will promote groundwater recharge in the GWMA and work with watershed districts to identify important groundwater recharge areas and opportunities to enhance recharge

The Carver County 2016-2025 Groundwater Plan (Carver County Public Services Division, 2016) lists three goals related to groundwater management:

- Prevent groundwater contamination
- Ensure the County's groundwater supply
- Protect groundwater dependent natural resources.

Work completed as part of this project supports all three goals, particularly goals 2 and 3. As stated in the county plan an objective to achieve goal three is to increase the County's understanding of groundwater and surface water interactions. Section 3.0 of this report describes a classification of groundwater and surface water interaction across the District. As described in Section 4 of this report, some areas of the District have good potential for large-scale infiltration. Promoting infiltration in these areas can help to ensure the County's water supply by both recharging aquifers and offsetting potential negative impacts to surface water resources from increased pumping.

3.0 Evaluation of Regional Groundwater/Surface Water Interaction

To evaluate regional groundwater/surface water interaction across the District, publicly available data sets were compiled and further analyzed. A number of different agencies and organizations collect groundwater, surface water, and other environmental data throughout the District for many different purposes.

Some of the major datasets compiled and used for this study include:

- Surficial and bedrock geology
- Lake bathymetry
- Surface topography and morphology
- Observation well data
- Well records and boring logs
- Soil surveys
- Data from the Twin Cities Metropolitan Area Groundwater Flow Model (Metro Model 3)
- Current water use and projected water demand

Evaluating the relationship between surface waters and groundwater involves the following three fundamental steps:

1. Determining whether a connection between surface water and groundwater is likely or not
2. Categorizing the connection based on how groundwater and surface water interact
3. Evaluating the degree of influence groundwater has on individual surface water features and if the surface water is vulnerable to changes in the groundwater system — either pumping-induced or resulting from longer climatic changes.

How vulnerable a surface water feature is to changes in the groundwater system depends on a combination of how groundwater and surface water interact, physical characteristics of the water body (depth, bed permeability), local geology, and sensitivity of biota.

3.1 Regional Groundwater Table

To evaluate the connection of surface water features to the regional groundwater system a map of the regional groundwater table surface was created (Figure 1). The regional groundwater table is different than a map of the phreatic surface (upper-most surface of saturation) in that the phreatic surface includes perched groundwater zones (sits above the regional water table) and small local groundwater flow systems. Inclusion of perched groundwater zones is not appropriate for this study as they likely show no response to changes in the regional groundwater flow system. Small local groundwater flow systems may interact with some surface water features; however, the scale of this study and density of available data do not support evaluation of local groundwater flow systems or their interaction with surface waters.

To construct the regional groundwater table map, water-level data from a number of different sources were compiled. The main sources of data included; MNDNR water table observation wells and static water levels from the Minnesota County Well index (CWI). Historical water levels from District monitoring wells that are no longer monitored were also reviewed. Results from the Metro Model 3 groundwater model (Metropolitan Council, 2014) and reaches of streams known to be well connected with groundwater were also used to where data from other sources were sparse. Surface elevations from lakes and wetlands are commonly used in defining the water table surface; however, they were not used for this study as they would skew the intended purpose of the regional groundwater table map – evaluating the potential connection of surface water features to regional groundwater.

All water level data went through a series of preprocessing and filtering steps to eliminate outliers and remove water-level data points that represent perched zones. The majority of the data processing focused on the static water levels from the CWI. The CWI is a valuable source of data as it extensively covers the District; however, the disadvantage of the CWI is the large degree of erroneous and conflicting data. Sources of error include: inaccuracy of water level measurement, well location, and well elevation; misidentification of hydrostratigraphic units, and water levels affected by season and/or year of installation. Given these sources of unavoidable uncertainty, water levels are typically assigned a likely error of +/- 20 feet. It is not uncommon to find two nearby measurements in the same aquifer with substantially different values.

The following steps were used to filter the CWI data:

1. Wells not screened near the groundwater table, or wells open to multiple aquifers, were removed by reviewing screened formation, screened interval and static water level.

2. Cross validation was performed to remove outliers. Cross validation compares an observed value to that of an estimated, or interpolated, value at the location of the observed value. Locations with discrepancies larger than 20 feet between interpolated and observed values were investigated and removed based on analysis of local topography and surface water features.

3. Locally perched groundwater was removed. In areas of localized high groundwater, the surrounding geology was evaluated to determine if the data represented an area of perched groundwater and if the data point should be removed.

4. Steps 1-3 were repeated several times until all outliers were removed and a satisfactory regional groundwater table surface was established (Figure 1).

3.2 Connection of Surface Water with the Regional Groundwater System

A surface water feature is considered to be in connection with the regional groundwater system if the regional water table intersects (or nearly intersects) the surface water feature. The fact that a surface water feature is hydraulically connected to the groundwater system does not necessarily mean that it is vulnerable to changes in the groundwater system but is the first step in the evaluation.

Surface water features not connected to the regional groundwater system are considered perched. Perched features were identified by comparing the regional groundwater table elevation to the elevation of the bottom of the surface water feature (e.g., elevation of the lake at maximum depth). Bottom elevations for features were determined in several ways. For lakes, bathymetry data were used to define bottom elevations. For features without bathymetry data, such as wetlands, depth estimates were based on Cowardin class (Cowardin et al., 1979) as defined in the NWI dataset.

Surface water features greater than 25 feet above the regional water table were considered to be perched. The connection between groundwater and surface water was considered to be indeterminate for surface water features 5 feet to 25 feet above the regional water table. For these features the hydraulic connection between groundwater the surface water may be seasonal, or the data are simply not sufficient to definitively say the feature is perched above the regional groundwater table. Surface water features less than 5 feet above the regional groundwater table surface are generally considered connected to the regional groundwater system.

3.3 Classification of Groundwater/Surface Water Interaction

Each surface water feature was categorized based on how groundwater and surface water interact (Figure 2). How they interact can aid in management or monitoring of individual features. This analysis involved comparing the surface water elevation for each feature to the regional groundwater table. Surface water elevations were obtained from LIDAR data. LIDAR stage data allows for consistency across all surface water features.

Table 1 describes each interaction type and qualifiers used in defining the interaction type for each feature. It is important to note when reading about these types of interactions that the terminology may seem counter-intuitive from the perspective of surface water. For this discussion, a "discharge" lake refers to the case where groundwater is discharging *into* the lake, and a "recharge" lake refers to the case where groundwater is recharged by water flowing *out of* the lake into groundwater.

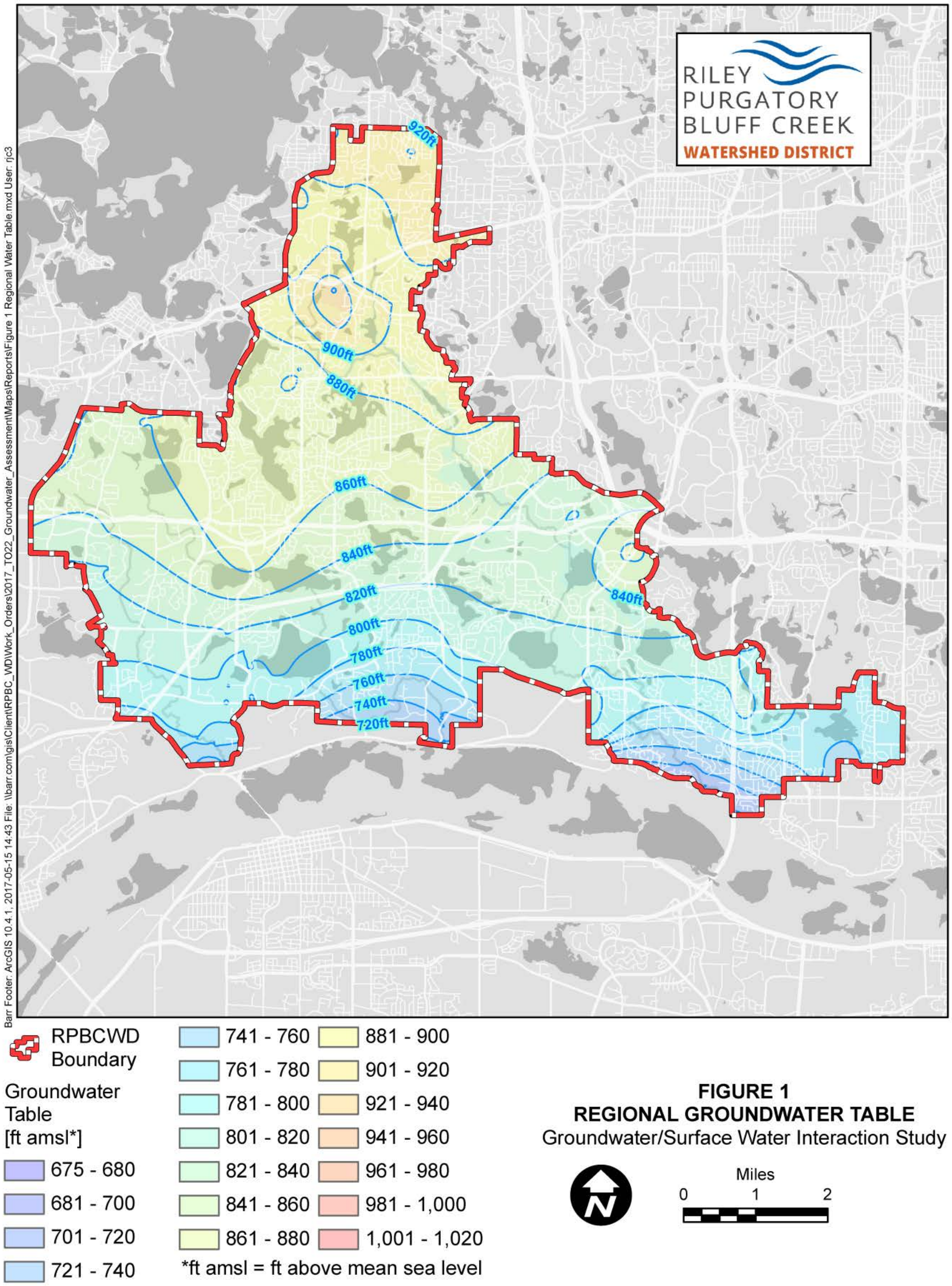


Figure 1 Regional Groundwater Table

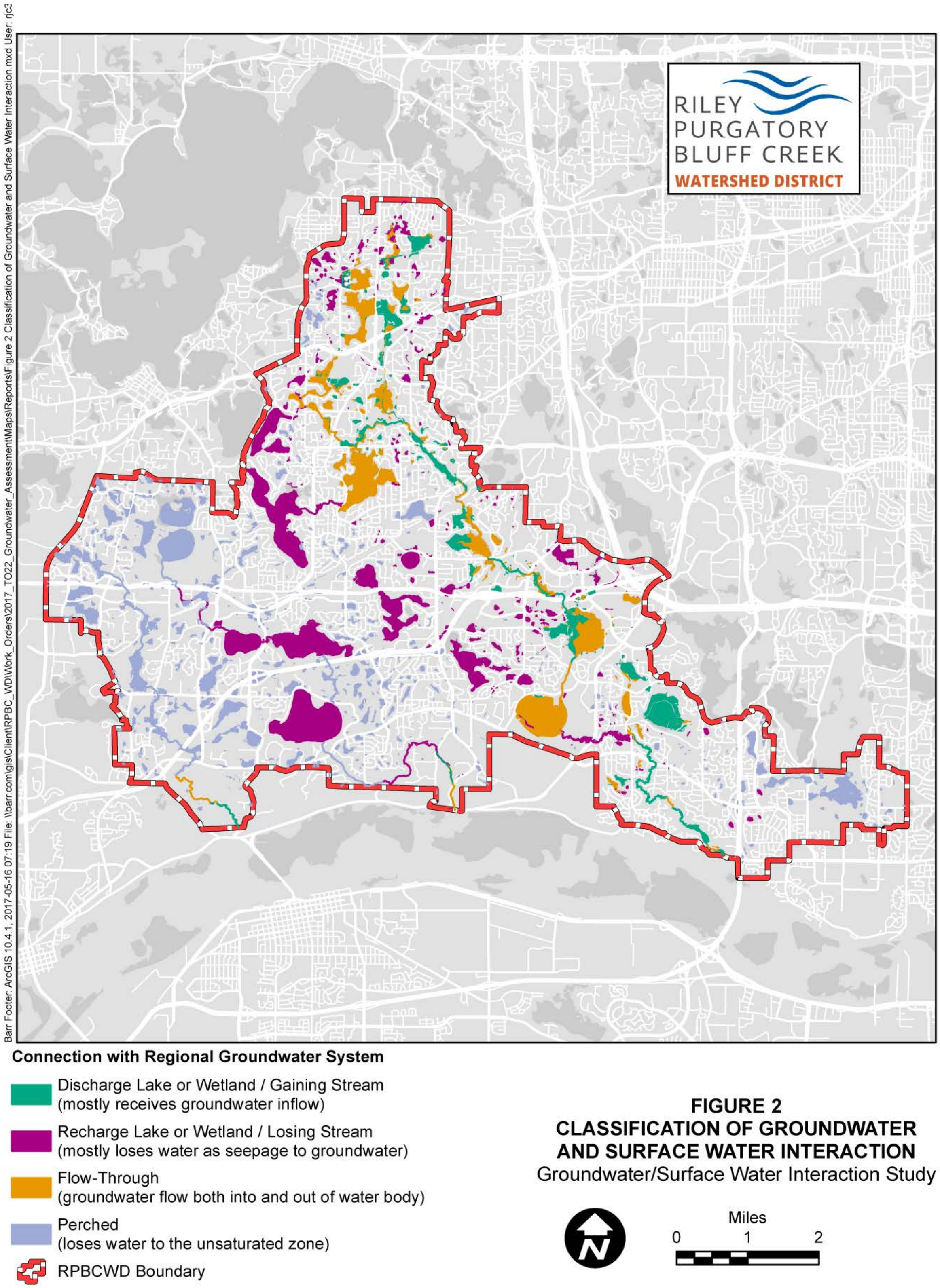
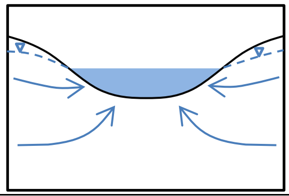
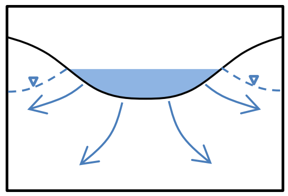
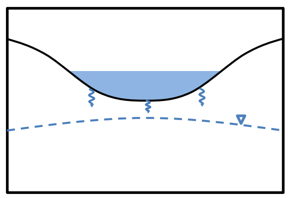
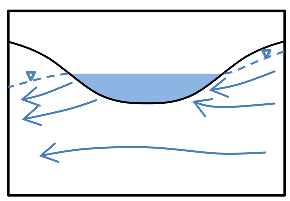
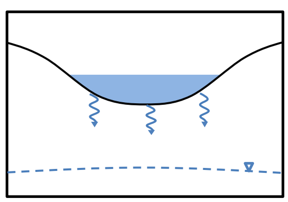
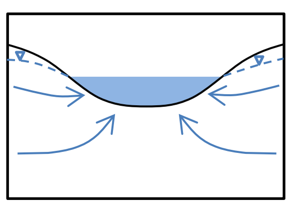
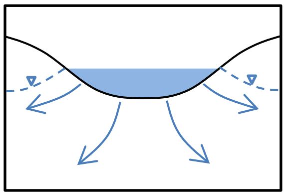
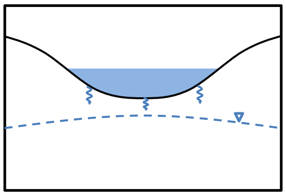
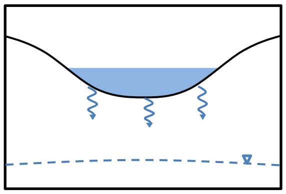


Figure 2 Classification of Groundwater and Surface Water Interaction

Table 1 Groundwater/surface water interaction classes

Type	Description		Qualifiers
Discharge lake/wetland	Mostly receives groundwater inflow		Connected to groundwater, surface water elevation below regional groundwater table
Recharge lake/wetland or Indeterminate	Connected to groundwater. Mostly loses water as seepage to groundwater		Groundwater connection is indeterminate, regional groundwater table lower than surface water elevation. Uncertainty in regional groundwater table makes it difficult to distinguish between features that are connected and those that are disconnected to groundwater.
	Disconnected to groundwater. Water table slightly below lake bottom. Fluctuations in the water table can affect the flow dynamics out of lake.		
Flow-through lake/wetland	Groundwater flow both into and out of lake/ wetland		Connected to groundwater, surface water elevation above or equal to regional groundwater table
Perched lake/ wetland with deep water table	Water table deep below feature. Loss of water into the unsaturated zone. Change in water table has no effect on feature		Disconnected from groundwater
Graining Stream	Groundwater flow into stream		Connected to groundwater, surface water elevation below regional groundwater table

Type	Description		Qualifiers
Losing Stream or Indeterminate	Mostly loses water to aquifer system		Groundwater connection is indeterminate, regional groundwater table lower than surface water elevation. Uncertainty in regional groundwater table makes it difficult to distinguish between features that are connected and those that are disconnected from groundwater.
	Water table slightly below stream bottom. Loss of water to the unsaturated zone. Fluctuations in the water table can affect the flow dynamics out of the stream.		
Perched Stream with deep water table	Water table deep below stream bottom. Loses water to the unsaturated zone. Change in water table has no effect on stream.		Disconnected from groundwater

3.4 Vulnerability to Changes in Groundwater Flow System

To evaluate the potential vulnerability of surface water features to changes in the groundwater flow system each was classified based on the geologic setting and specific characteristics of the feature itself (Figure 3).

Surface waters classified as perched or disconnected are inherently not vulnerable to changes in the regional groundwater system but may be highly sensitive to hydrologic changes in their watershed. While these features lose water to groundwater, the rate of loss is not dependent on groundwater levels. Losing streams or recharge lakes maybe vulnerable to changes in the groundwater system because the rate of flow from the surface water to groundwater may be controlled by the groundwater system. A drop in the groundwater table, or hydraulic head of the upper aquifer, may cause an increase in the loss of water to the groundwater system.

The properties of geologic units beneath a surface water feature affects the way that feature responds to changes in the regional groundwater system, either from pumping or climatic changes. It is assumed that a lake that sits directly within low permeability glacial till is likely influenced very little by changes in regional groundwater levels, with the lake water-budget more likely controlled by surface water flows. The presence of low permeability sediments may attenuate or eliminate effects of groundwater pumping, depending on their hydraulic properties, thickness, and horizontal extent. Alternatively, a lake that sits within a higher permeability sand and gravel glacial outwash is likely very sensitive to regional groundwater changes and a larger component of the water budget for the lake is likely controlled by groundwater flows.

The bathymetry, or geometry, of a lake basin is important in determining potential impacts from groundwater pumping. While the bathymetry plays no role in determining if a lake is vulnerable or not, it does indicate how changes in the groundwater table may impact the lake. Lakes with wide littoral zones have a greater potential of being negatively impacted by changes in water levels. Lakes that are less than 5 feet deep over more than 20% of the total surface area are considered to be more sensitive to changes in lake level. These lakes are generally disproportionately shallow as indicated by the relative hypsographic curves (depth vs. area) presented in Appendix A. Many of these lakes may be relatively deep but tend to have broad, shallow shorelines. Lakes that are considered vulnerable to changes in the groundwater system and fall within these criteria may require greater priority in setting up potential monitoring and/or management plans. While bathymetric data are not available for most wetlands, it is assumed that all wetlands are less than 5 feet deep over more than 20% of their surface area and are therefore considered to be similarly vulnerable as lakes that fall into this category.

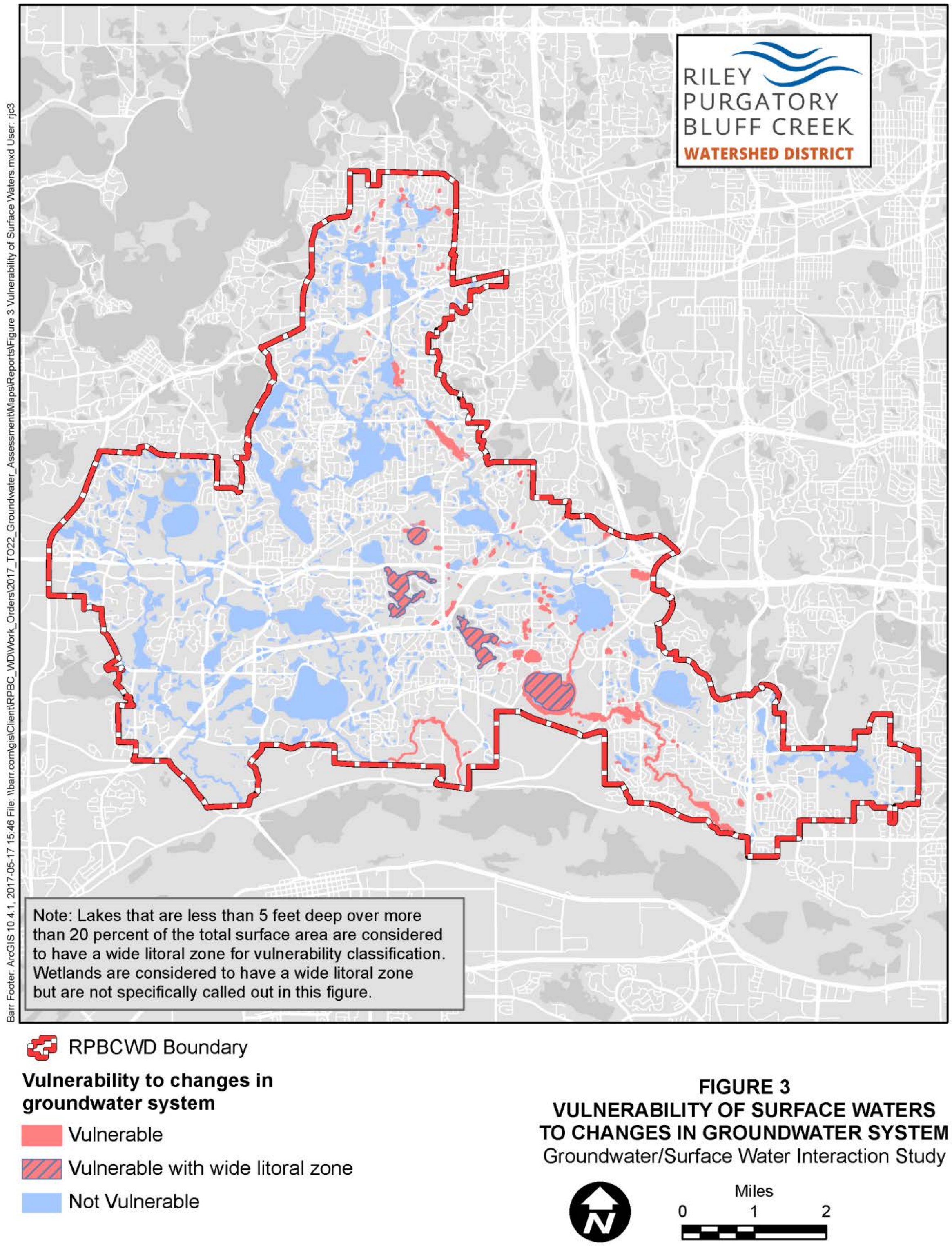


Figure 3 Vulnerability of Surface Waters to Changes in Groundwater System

4.0 Opportunities for Large Scale Groundwater Recharge

Data compiled and developed to assess the connection of surface water to the regional groundwater system were used to identify opportunities for large scale groundwater recharge via infiltrating stormwater. Areas for large scale infiltration are identified to improve resiliency of surface waters and the effect of changes in the groundwater system while also achieving stormwater runoff volume reductions, stream-flow volume reductions, and water quality improvements. The effectiveness of infiltrating stormwater to enhance groundwater recharge is dependent on several factors, including:

- Local geology (e.g., surficial soils, and geology of the unsaturated zone)
- Depth to groundwater
- Proximity to surface waters
- Volume of stormwater available

Infiltrating in some areas may have more benefit than other areas. For example, if infiltrating to replenish the Prairie du Chien aquifer, the presence of confining units above the Prairie du Chien aquifer (e.g., Decorah Shale) may prevent any positive impact. Infiltration can also be used to help offset impacts occurring, or projected to occur, due to increased pumping. For example, infiltrating to increase baseflow to a stream or increase groundwater inflow to a lake. These infiltration strategies are highly dependent on proximity to such features.

The quality of water is also a concern for infiltrating stormwater to enhance recharge to drinking water aquifers. As part of our analysis, we reviewed existing water supply management areas and aquifer vulnerability mapping done as part of individual communities' wellhead protection plans.

4.1 Methodology Used to Rank Areas for Focused Infiltration

To identify areas most suitable for large-scale infiltration, a scoring system was developed to help weigh the different types of data that must be considered. This process helps to rank areas of the District where large-scale infiltration projects should be considered. While the process considers as much information as possible, site-specific data such as geologic borings, piezometers, and other engineering studies will be required prior to implementing any large-scale infiltration at a specific site. The scale and scope of this study were focused on identification of areas of the watershed best suited for large-scale infiltration practices. This study does not consider site-specific details such as site access, aesthetics, and fit with surrounding infrastructure. In addition, the study is not designed to evaluate smaller-scale infiltration practices such as rain gardens, or stormwater management through infiltration at individual development sites. These practices should continue to be pursued through the District.

The scoring system developed for this study maps and ranks all different information to consider when identifying locations for infiltration. All data are mapped to a 3 meter by 3 meter grid and then assigned a score. For example, areas with sandy soils receive a higher score than areas with clay soils. Scores for each dataset (e.g., soils, depth to regional groundwater table, bedrock geology, etc.) are then added together to obtain a composite (total) score. The composite score allows for ranking different areas of the watershed that are most suitable for large-scale infiltration, higher scores indicating more suitable areas. In some instances, certain components suggest that large-scale infiltration should perhaps not occur in certain areas. For example, areas where the regional groundwater table is very near the ground surface are not suitable for large-scale infiltration. The shallow regional groundwater table dramatically limits the ability to infiltrate large volumes of water, even if very sandy soils exist. In the final composite score these areas receive a score of zero. The 3 meter by 3 meter grid is used as it is the smallest scale of the input data used (Lidar topography data). Some data sets are originally at a much coarser scale but were resampled to the 3 meter by 3 meter grid. The resampling was done to allow for consistent input to the scoring system but does not mean that all datasets are accurate to such a fine scale.

4.1.1 Depth to Regional Groundwater Table

The Minnesota Pollution Control Agency (MPCA) requires a minimum separation of 3 feet between the bottom of an infiltration practice and the elevation of the seasonally high water table. However, depth to water table should be much greater in most instances. Infiltration of water will form a mound at the water table below the site of infiltration. If the mound becomes too high the effectiveness of the infiltration practice can be compromised. Also, in some instances if mounding at the water table gets too high it may have negative consequences for nearby structures; for example, wet basements, or development of unstable soils. The size of the mound that will develop below an infiltration practice is a function of the permeability (hydraulic conductivity) of soils and infiltration rate.

A map of the depth to the regional groundwater table is shown on Figure 4. The following scoring system was used for depth to the regional groundwater table in ranking areas conducive to large-scale infiltration (Figure 5):

- 3 points = Depth to regional groundwater table > 20 feet
- 2 points = Depth to regional groundwater table > 15 feet and < 20 feet
- 1 point = Depth to regional groundwater table > 10 feet and < 15 feet
- 0 points = Depth to regional groundwater table < 10 feet
- Area not suitable for large scale infiltration regardless of other information where depth to regional groundwater table < 5 feet

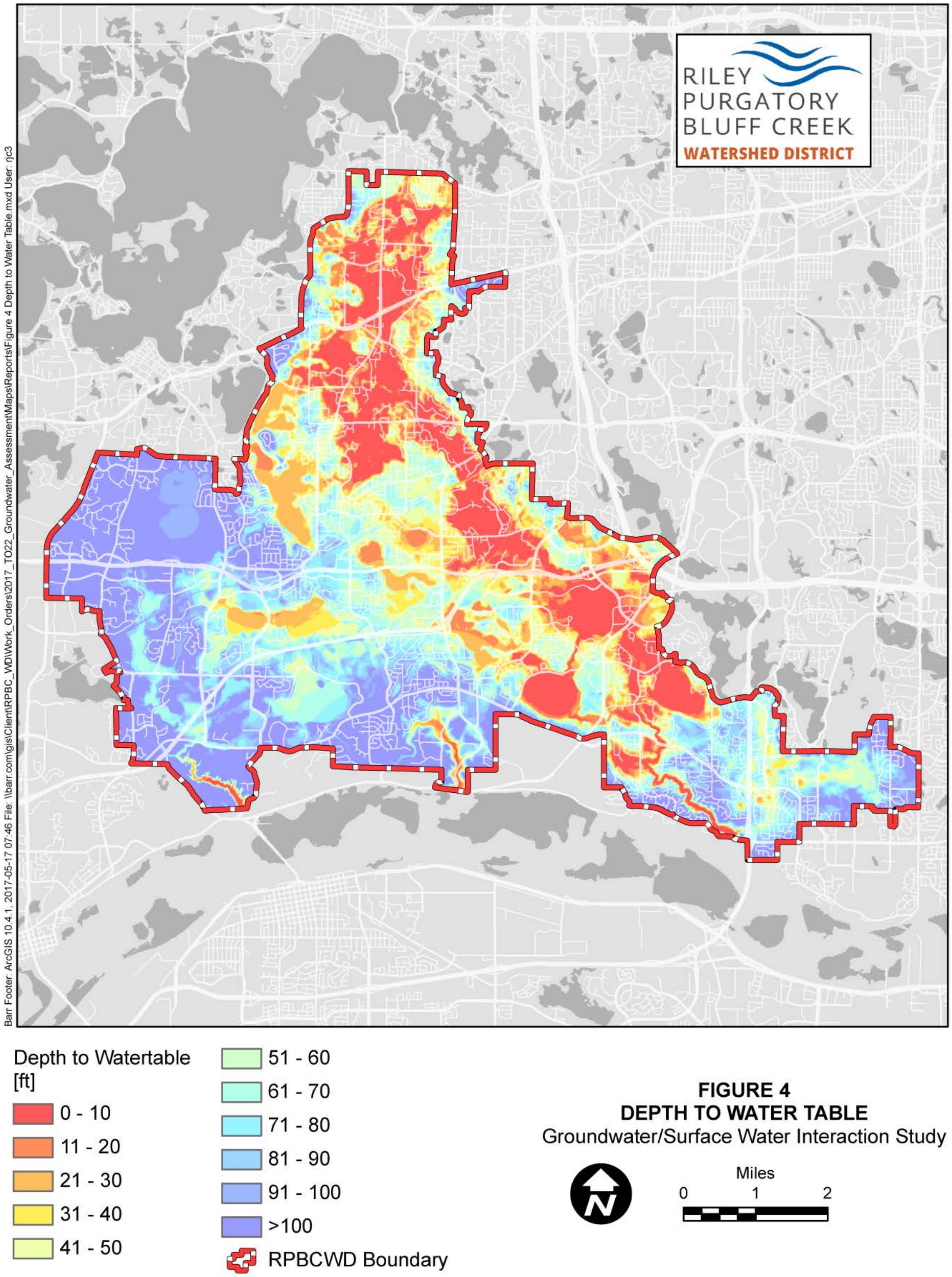


Figure 4 Depth to Water Table

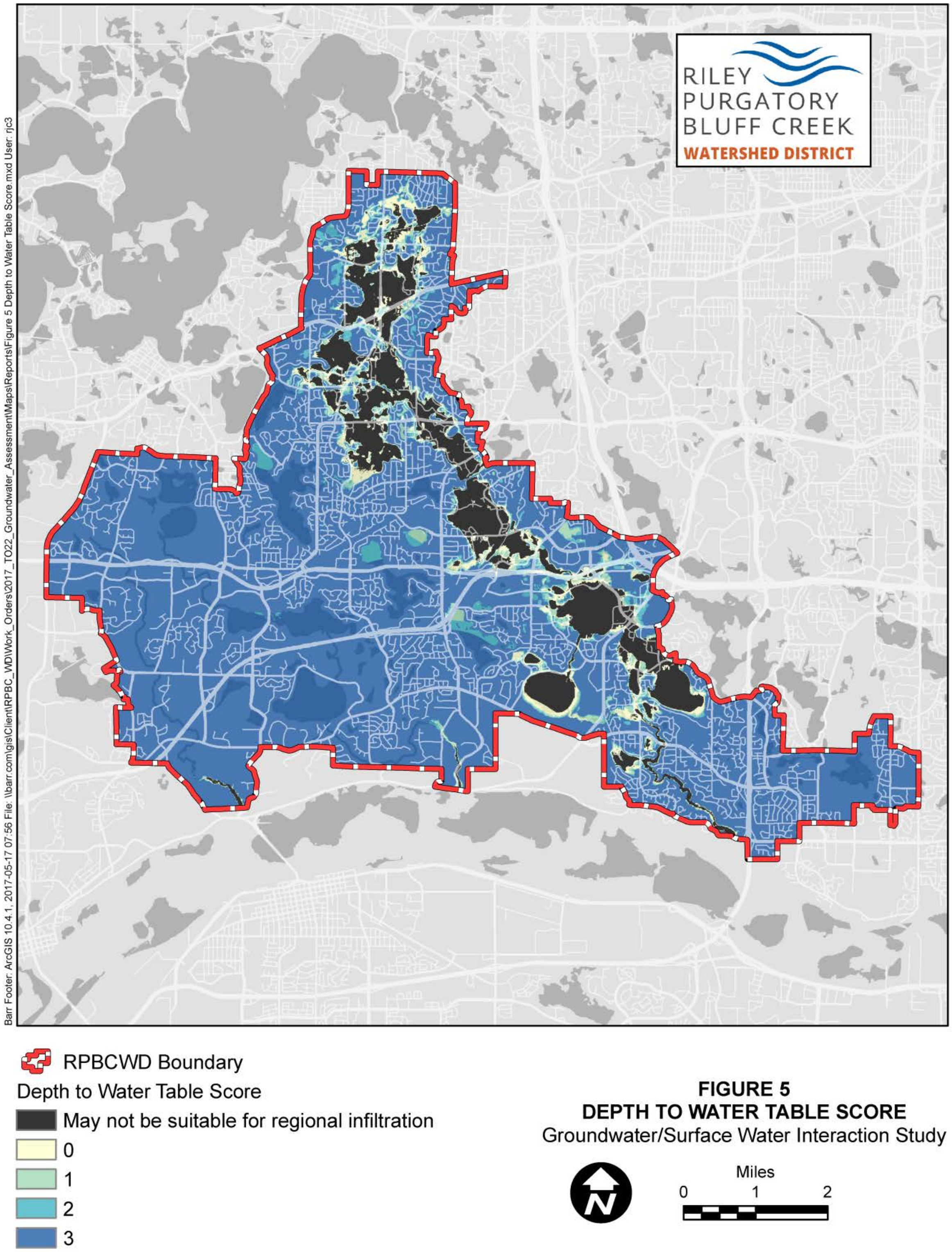


Figure 5 Depth to Water Table Score

4.1.2 Soils

Hydrologic soil types, as mapped by the Natural Resources Conservation Services (NRCS), are shown on Figure 6. Hydrologic soil groups (A, B, C, D) are grouped primarily to assess the runoff potential of a soil but can also be used to assess the ability of a soil to infiltrate water. In general, soils in hydrologic soil group A have the greatest capacity to infiltrate water and soils in group D have the least capacity.

Hydrologic Soil Group A—(Low runoff potential): Group A soils have a high infiltration rate and are typically composed of more than 90 percent sand and gravel.

Hydrologic Soil Group B—(Moderately low runoff potential): Group B soils have a moderate infiltration rate and are typically composed of 50-90 percent sand.

Hydrologic Soil Group C—(Moderately high runoff potential): Group C soils have a slow infiltration rate and are composed of less than 50 percent sand.

Hydrologic Soil Group D—(High runoff potential): Group D soils have a very slow infiltration rate and are composed of more than 40 percent clay. These soils have of combination of high swelling potential, a permanently high water table, and a clay layer at or near the surface.

Dual hydrologic groups, A/D, B/D, and C/D, are soils that are considered D soils primarily because of a high water table. However, if the soil were drained it would be classified into a different group. The first group listed for dual hydrologic group soils is for a drained condition. For the purpose of infiltration all dual hydrologic groups are considered as D soils.

Some areas of the District have unclassified soil hydrologic classes. The lack of classification is primarily due to land development prior to NRCS surveying. Unclassified soils were given a score of zero in the scoring system, allowing these areas to still be considered but also allowing for the uncertainty in the soil conditions to still be accounted for.

The following scoring system was used for hydrologic soil groups in ranking areas conducive to large-scale infiltration (Figure 7):

- Group A = 4 Points
- Group B = 2 Points
- Group C and Undefined = 0 Points
- Group D (also A/D, B/D, and C/D) = May not be suitable for large-scale infiltration without site specific analysis

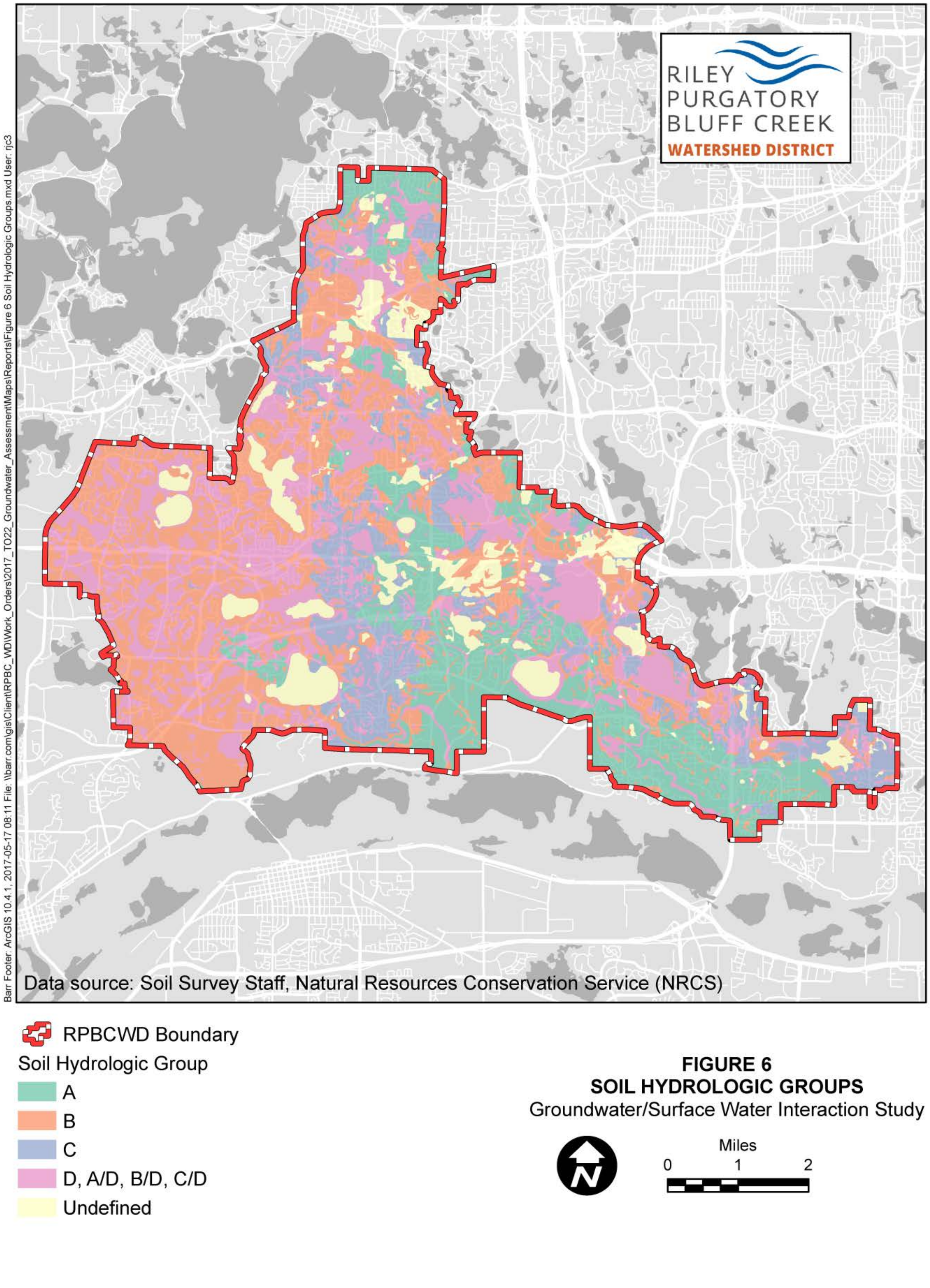


Figure 6 Soil Hydrologic Groups

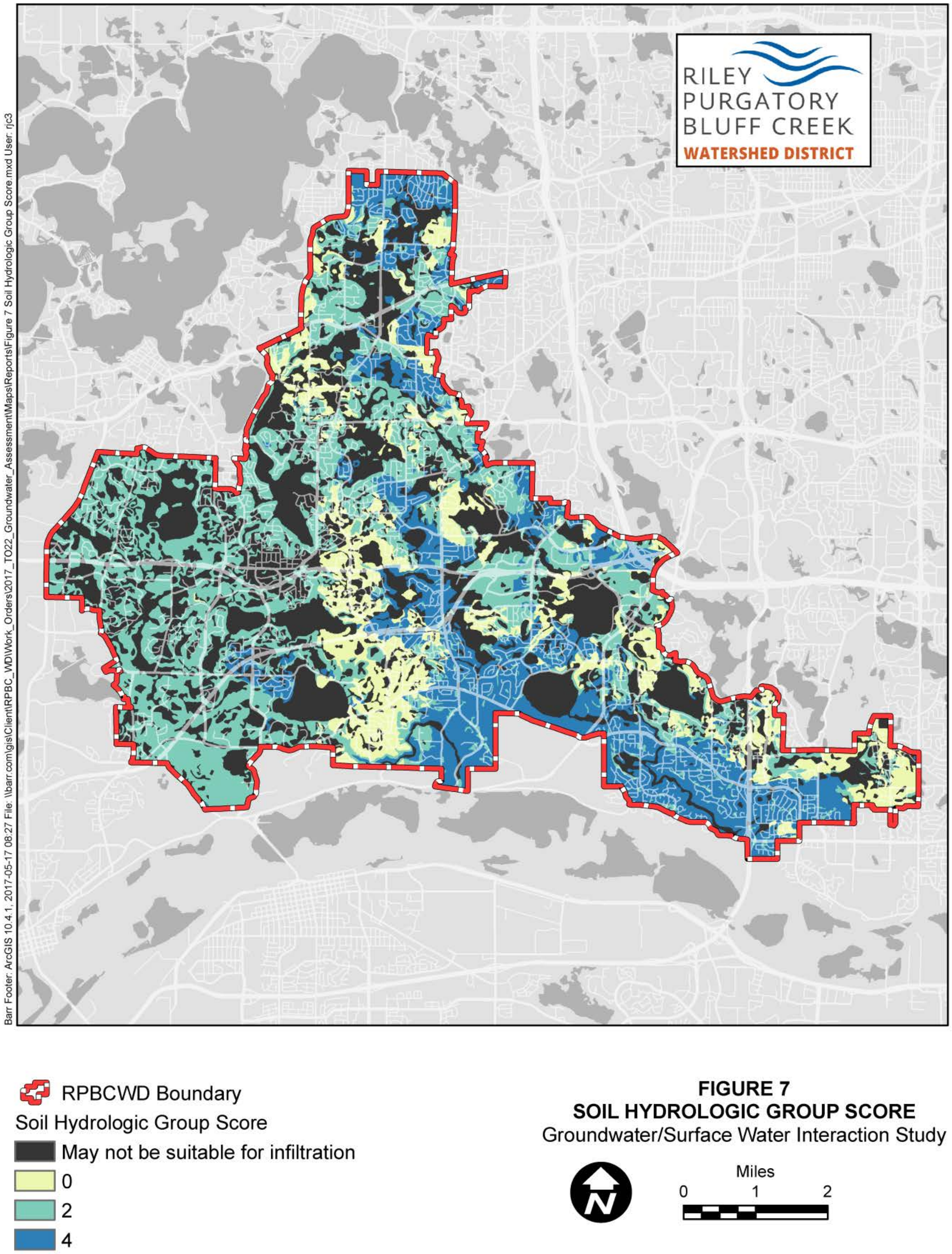


Figure 7 Soil Hydrologic Group Score

4.1.3 Surficial Geology

Surficial geology, simplified and grouped by lithology (e.g., sand, silt) as mapped by Meyer (2007), is presented on Figure 8. When infiltrating large volumes of water (typically above the water storage capacity of the soil zone) the surficial geology often plays a larger role than soil hydrologic group in determining the infiltration capacity of an area. Surficial geology shown on Figure 8 is a generalization of the type of material from ground surface to a depth of approximately 20 feet. This is in contrast to the hydrologic soil groups that are classified based on soil properties from ground surface to a depth of approximately 40 inches. Also, in areas where soils have not been assigned a hydrologic soil class, use of the surficial geology helps to fill this gap.

The following scoring system was used for surficial geology in ranking areas conducive to large-scale infiltration (Figure 9):

- Sand = 2 points
- Glacial Till (Diamicton) = 1 points
- Unspecified = 0 Points
- Organic, Clay = May not be suitable for large-scale infiltration without site specific analysis

4.1.4 Bulk Unsaturated Hydraulic Conductivity

To capture the ability of sediments at depth to transmit water, the bulk hydraulic conductivity of the unsaturated zones was considered. Data compiled by Tipping (2011) which mapped textural characteristics of the Quaternary sediments in the eleven-county metropolitan area and correlated those textures to representative ranges in hydraulic conductivity values (Table 2) was implemented into the scoring system. The material types classified by Tipping (2011) are mapped as a matrix of points spaced 820 feet (250 meters) apart in the horizontal direction and 20 feet apart in the vertical direction. The point data set from Tipping (2011) was converted to a series of raster grids, each representing material types along a single elevation (each elevation raster was spaced 20 feet apart). The raster grids were then resampled to a grid spacing of 3 meters by 3 meters to be consistent with other datasets used the scoring system. Equations 3-1 and 3-2 (Anderson and Woessner, 1992) were used to calculate an effective bulk vertical hydraulic conductivity of the unsaturated zone. (Figure 10).

$$(K_z)_{i,j} = \frac{B_{i,j}}{\sum_{g=1}^{m} \frac{b_{i,j,g}}{Kz_{i,j,g}}} \qquad \textbf{(Eqn. 3-1)}$$

$$B_{i,j} = \sum_{g=1}^{m} b_{i,j,g} \qquad \textbf{(Eqn. 3-2)}$$

where:

$B_{i,j}$ is the thickness of a model cell
$b_{i,j,g}$ is the thickness of an individual material type
$Kx_{i,j,g}$ is the horizontal hydraulic conductivity of an individual material type
$Kz_{i,j,g}$ is the vertical hydraulic conductivity of an individual material type

Table 2 Representative hydraulic conductivity values by material type

Material Type	Representative Hydraulic Conductivity		Material Type	Representative Hydraulic Conductivity	
	(ft/day)	(in/hr)		(ft/day)	(in/hr)
Loam to Clay Loam	1.0	0.5	Sandy Silt	3.0	1.5
Loam to Sandy Loam	1.7×10^{-3}	8.5×10^{-4}	Loam to clay loam – deep	0.5	0.3
Loam, silt rich, silt and clay	1.4	0.7	Loam to sandy loam – deep	8.65×10^{-6}	1.73×10^{-5}
Loam to sandy clay loam	2.0×10^{-3}	1.0×10^{-3}	Loam, silt rich; silt and clay – deep	2.8×10^{-3}	1.4×10^{-3}
Sand and Gravel	1.5	0.7	Loam to sandy clay loam – deep	1.23×10^{-5}	2.45×10^{-5}
Fine Sand	707.0	353.5	Data from Tipping (2011)		

Areas of high hydraulic conductivity are preferable for infiltration. Low hydraulic conductivity materials slow infiltration and are less desirable.

The following scoring system was used for bulk vertical hydraulic conductivity in ranking areas conducive to large-scale infiltration (Figure 11):

- > 10 ft/day = 3 points
- 1 to 10 ft/day = 2 points
- 0.1 to 0.9 ft/day = 1 point
- < 0.1 ft/day = May not be suitable for large-scale infiltration without site specific analysis

4.1.5 Shallow Bedrock Confining Units

Shallow bedrock confining units restrict movement of water to deeper aquifers. Infiltration in these areas may be suitable for some goals such as sustaining base flow in a stream. However, these areas are not good candidates if the goal is to help replenish deeper bedrock aquifers. A map of the upper most bedrock unit is shown on Figure 12. Shallow bedrock confining units include: the Platteville and Glenwood Formation and the base of St. Peter Sandstone.The following scoring system was used for presence of shallow bedrock confining units (Figure 13):

- 3 points = Prairie du Chien, Jordan, Tunnel City or St. Lawrence is upper most bedrock unit
- 2 points = St. Peter Sandstone is upper most bedrock (basal St. Peter Confining unit present)
- 1 point = Platteville or Glenwood Formation is upper most bedrock (basal St. Peter and Platteville or Glenwood confining units present)

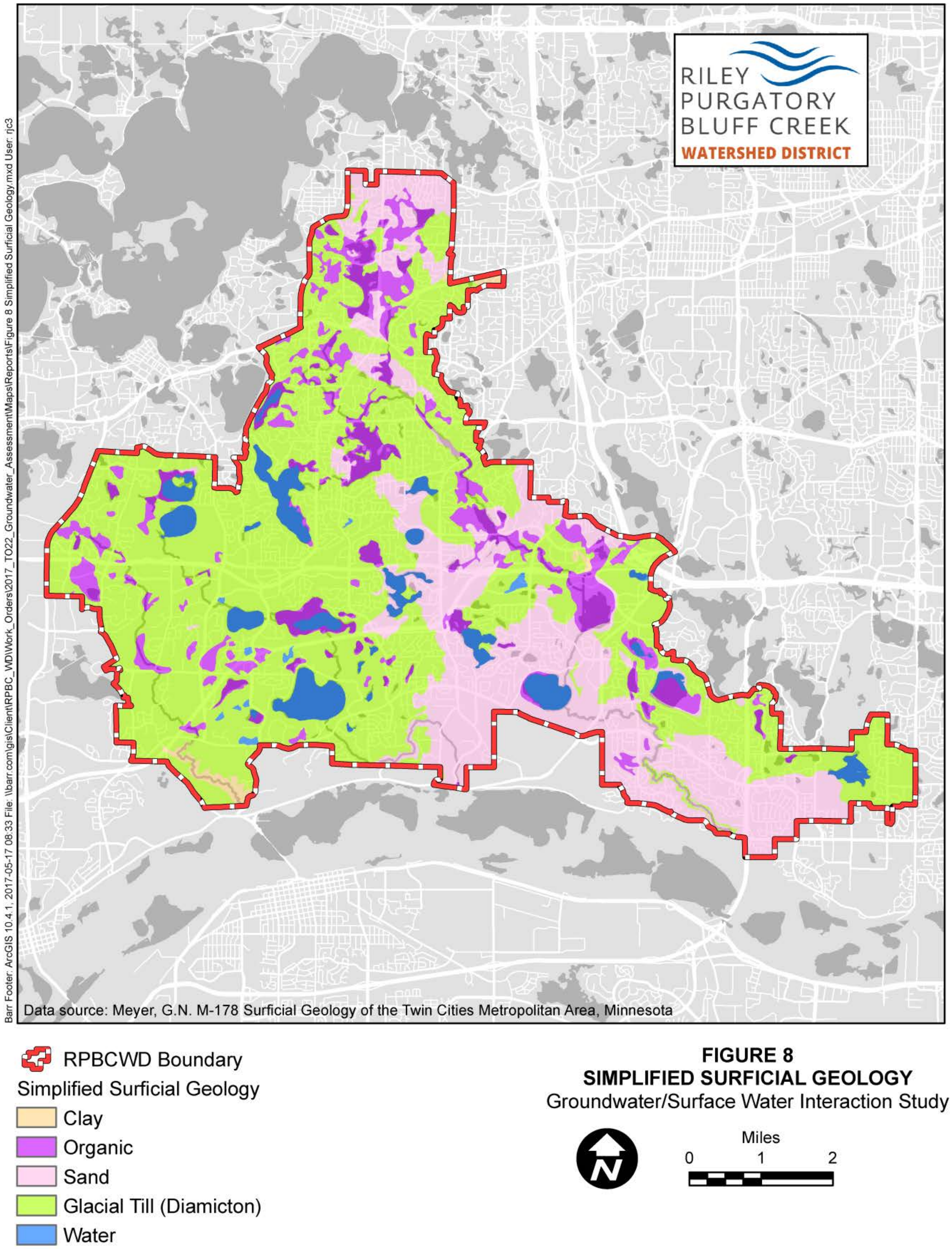


Figure 8 Simplified Surficial Geology

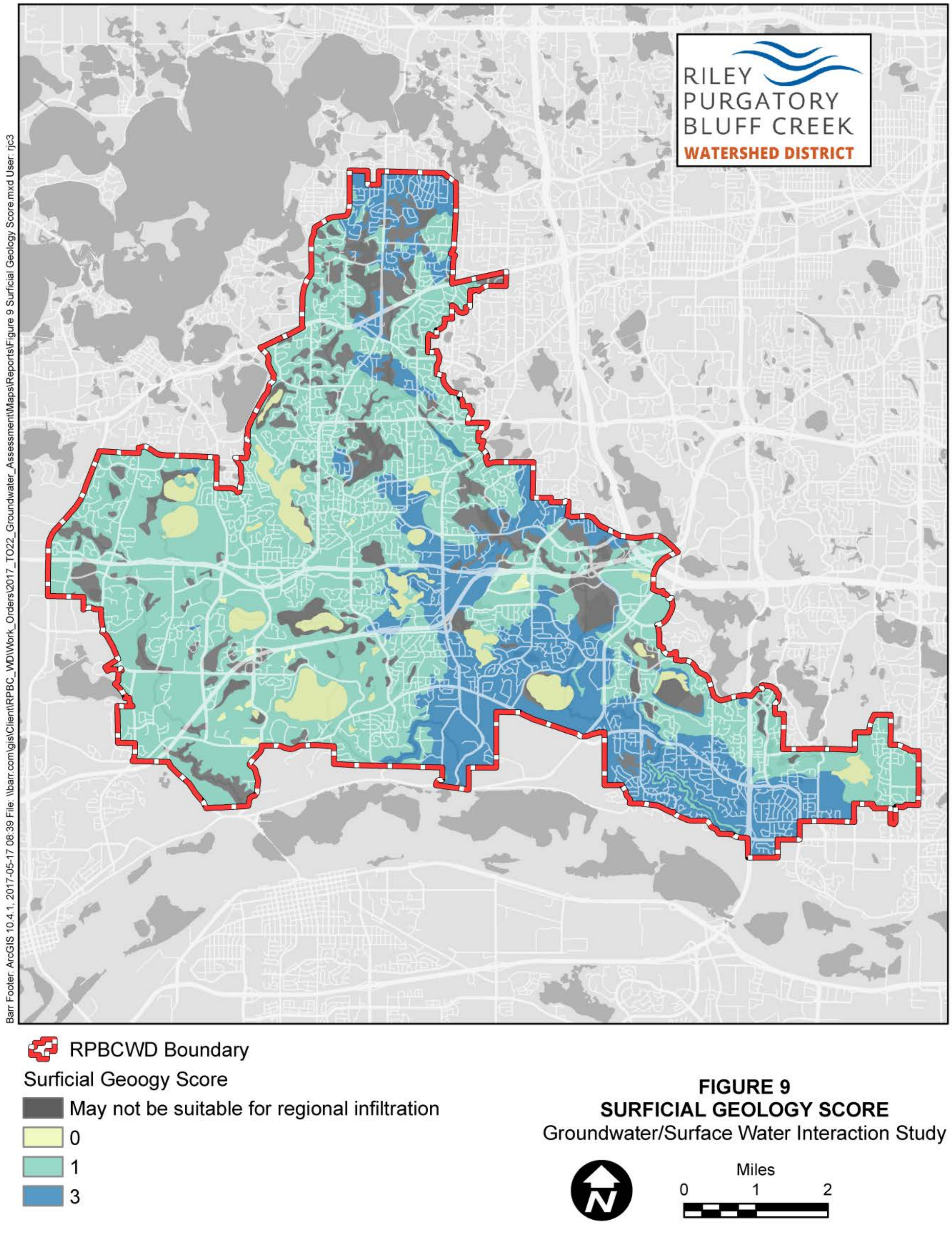


Figure 9 Surficial Geology Score

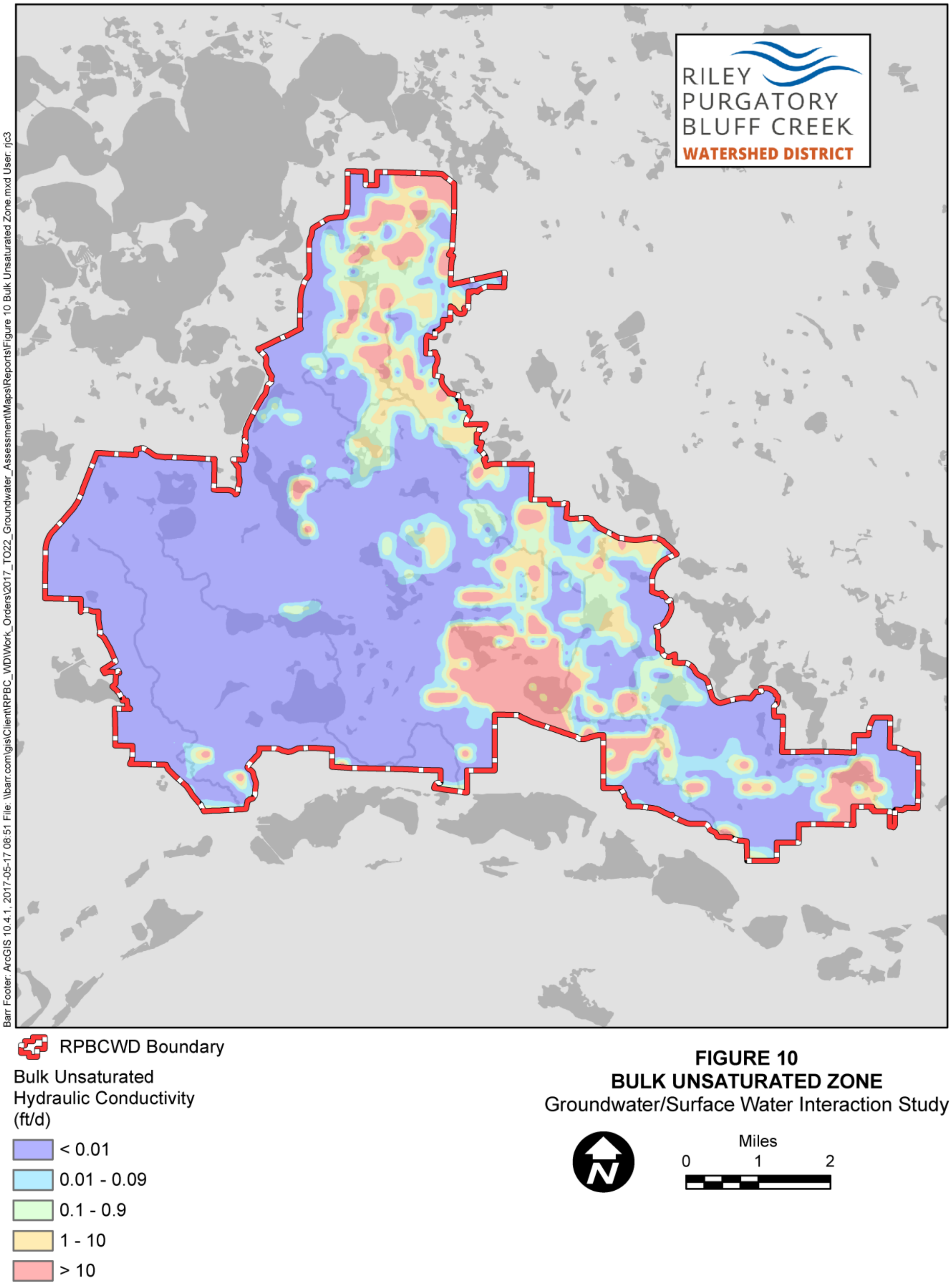


Figure 10 Bulk Unsaturated Zone Hydraulic Conductivity

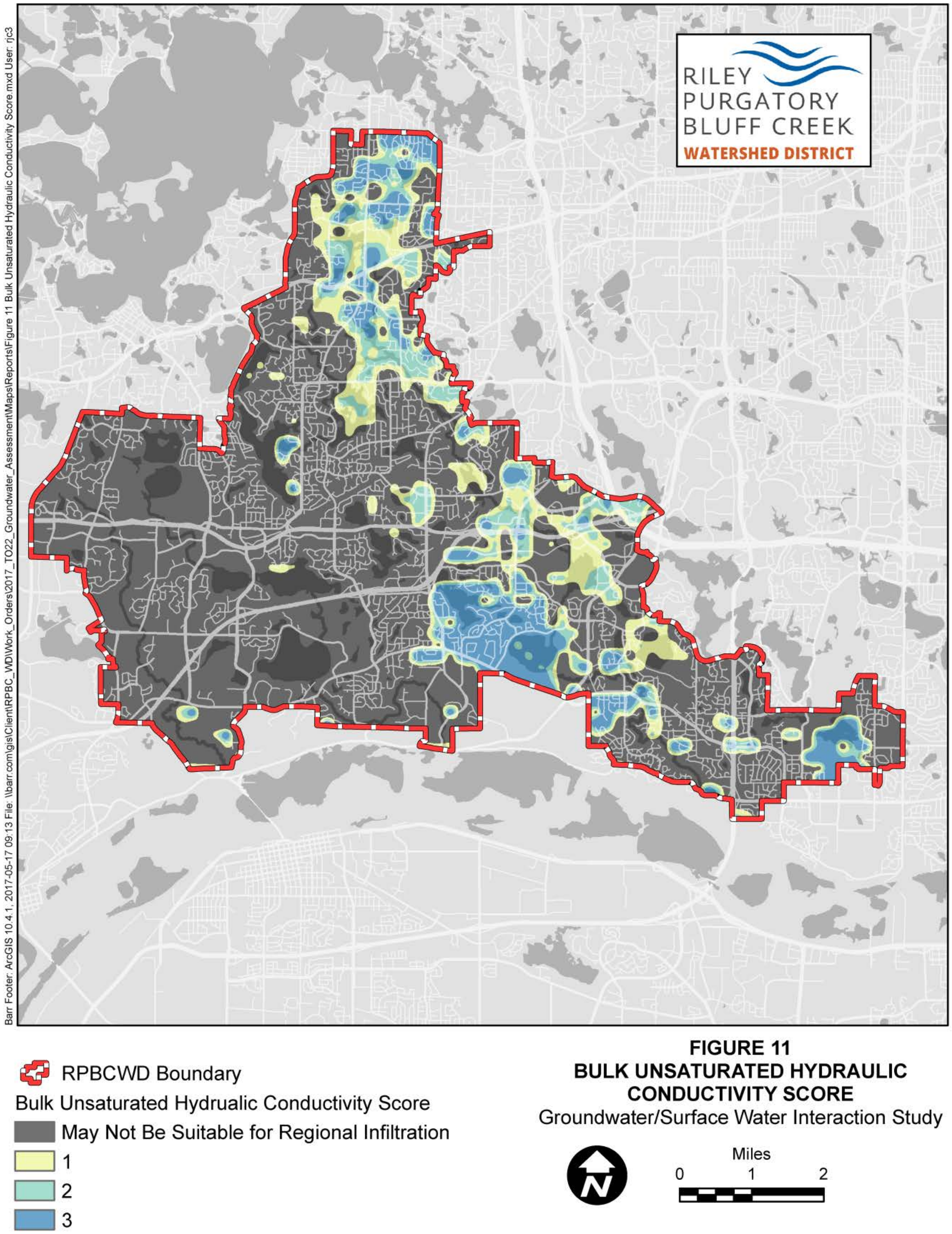


Figure 11 Bulk Unsaturated Hydraulic Conductivity Score

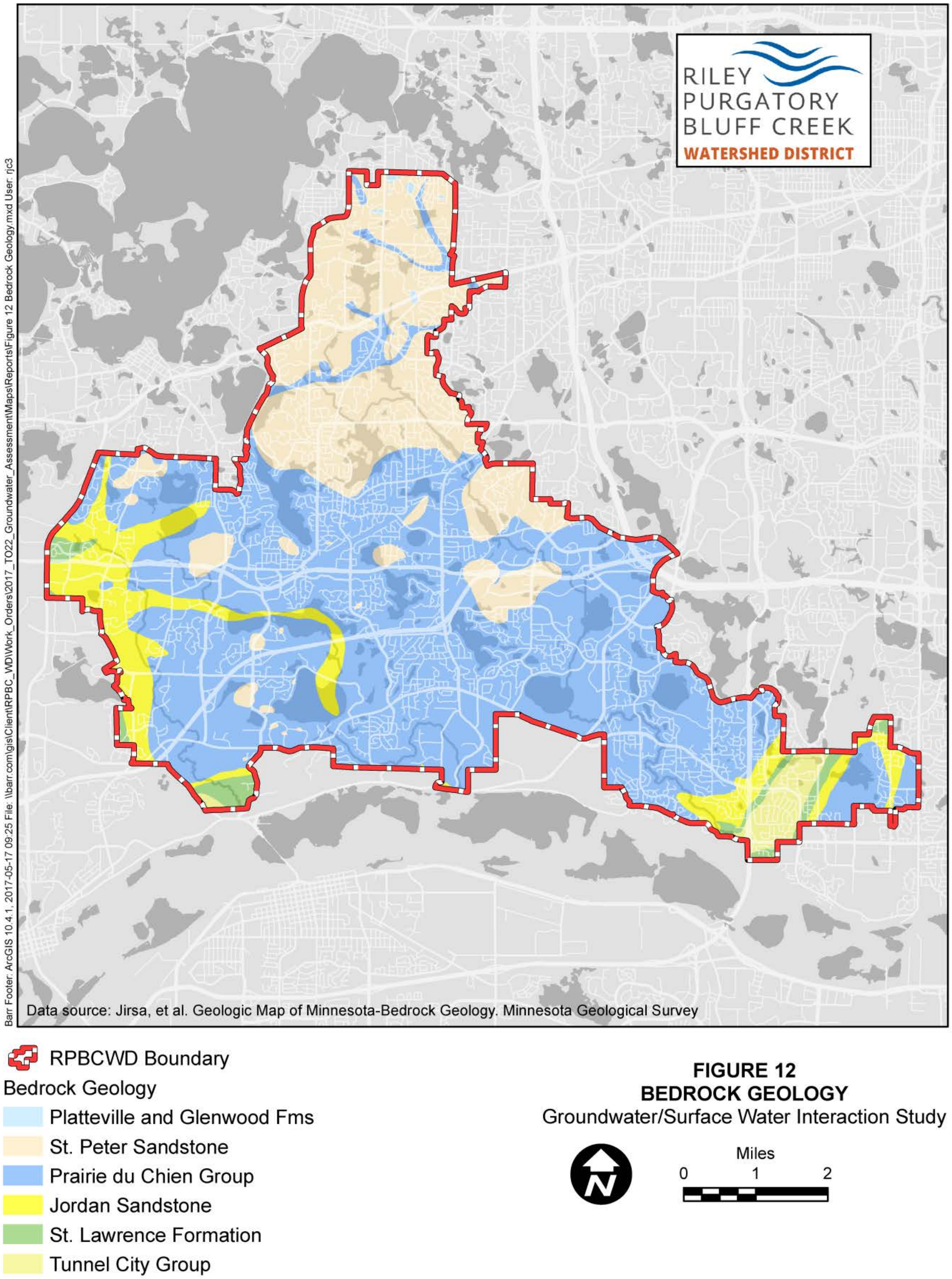


Figure 12 Bedrock Geology

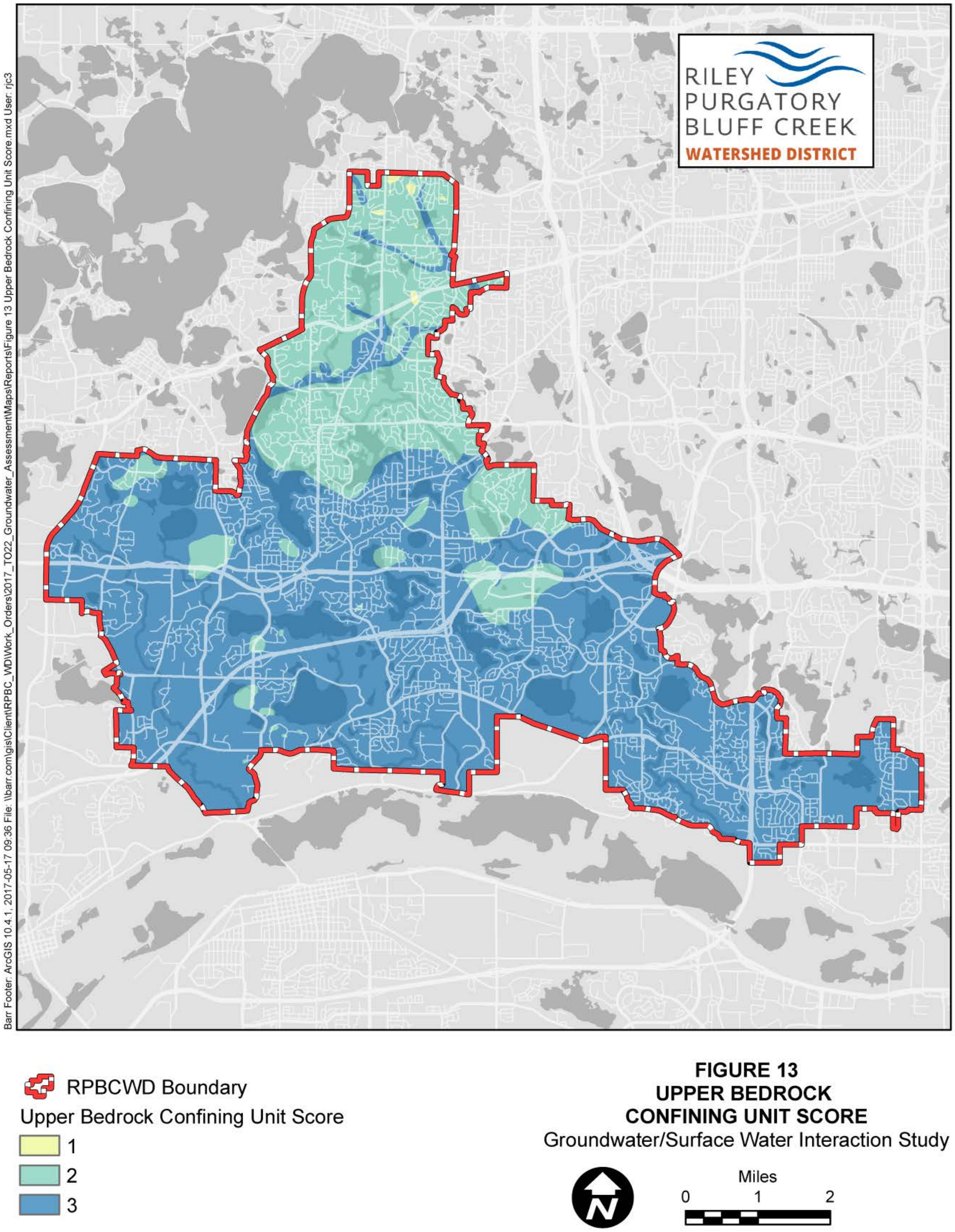


Figure 13 Upper Bedrock Confining Unit Score

4.1.6 Drinking Water Supply Management Areas

The majority of the communities in the District use groundwater as their municipal water source (Figure 14). Bloomington, in the far eastern corner of the district, uses both its own groundwater wells and surface water purchased from Minneapolis as a water source. The Minnesota Department of Health regulates municipal water supplies and has guidance regarding infiltration of stormwater in vulnerable drinking water supply management areas (DWSMAs) (Figure 15). The vulnerability of DWSMAs are classified into five groups: very-high, high, moderate, low, and very-low. Vulnerability is based on how easily groundwater may be impacted by activities at the surface. Local geology and geochemical data are used to assess how quickly water infiltrating at the surface may reach a water supply source aquifer.

Aquifer vulnerability assessments are used to:

1. Assess the level of risk that land use may have on groundwater entering a public water supply
2. Guide efforts to inventory potential contaminant sources
3. Define measures to control potential contaminant sources

Composite aquifer vulnerabilities within DWSMAs are shown on Figure 15. Because stormwater may contain contaminants that could lead to adverse health effects, the Minnesota Department of Health stresses that care be exercised in planning projects that involve infiltrating stormwater in DWSMAs, especially if the aquifer vulnerability is moderate, high, or very-high. There is generally little concern for potential impacts to a drinking water aquifer from infiltration within a DWSMA if the aquifer vulnerability is classified as very-low or low. Infiltration within a DWSMA with aquifer vulnerability of very-high, high, or moderate is considered appropriate if:

- The receiving aquifer does not exhibit facture or solution enhanced groundwater flow.
- The infiltration site is not in a 1-year capture zone.
- The land uses for the infiltration site and water drained to the site are forest, parkland, open space, low density residential, high density residential, golf course, or agricultural. Commercial, industrial, municipal, and transportation corridors may be acceptable if an emergency spill response plan is acceptable. MPCA does not allow infiltration of runoff from potential stormwater hotspots (PSHs).
- Infiltrated water is able to meet federal drinking water standards through pre-treatment, secondary containment, or natural attenuation in the unsaturated zone.

The following scoring system was used for DWSMA vulnerability (Figure 16):

- High and Very High = 1 point
- Moderate = 2 points
- Low and Very low = 3 points
- Not in a DWSMA = 4 points
- 1-year capture zones = Area may not be suitable for large-scale infiltration without site specific analysis

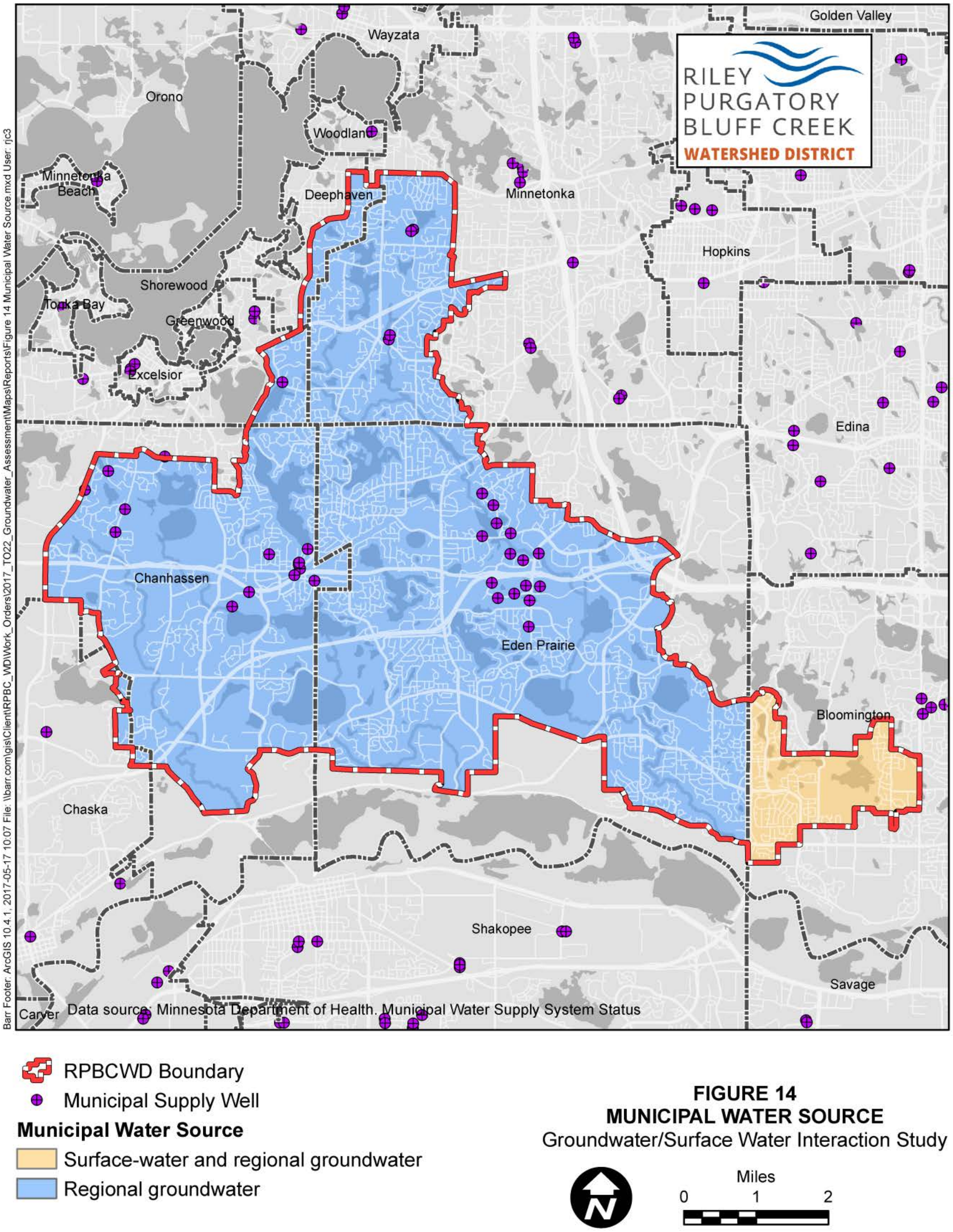


Figure 14 Municipal Water Source

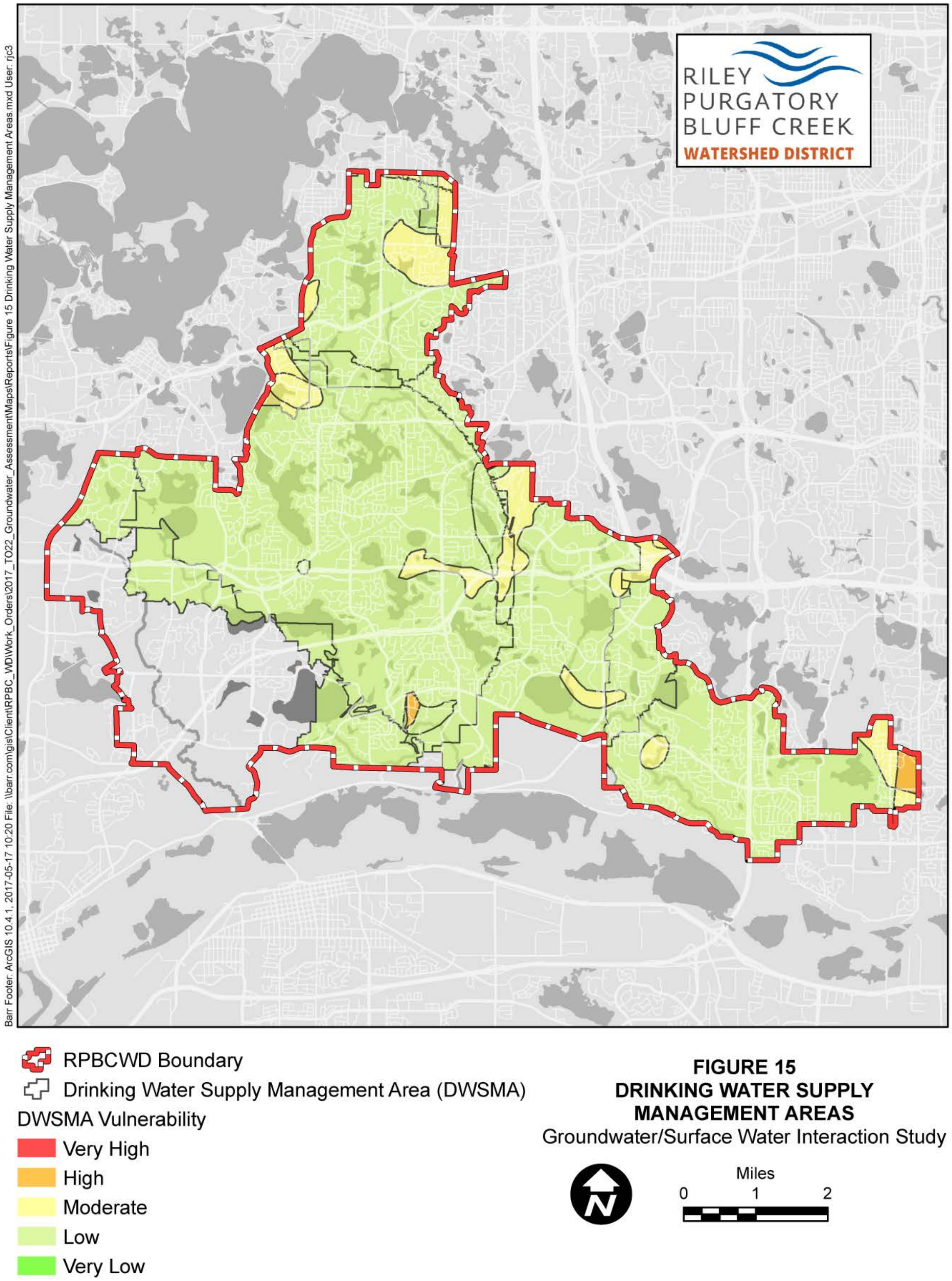


Figure 15 Drinking Water Supply Management Areas

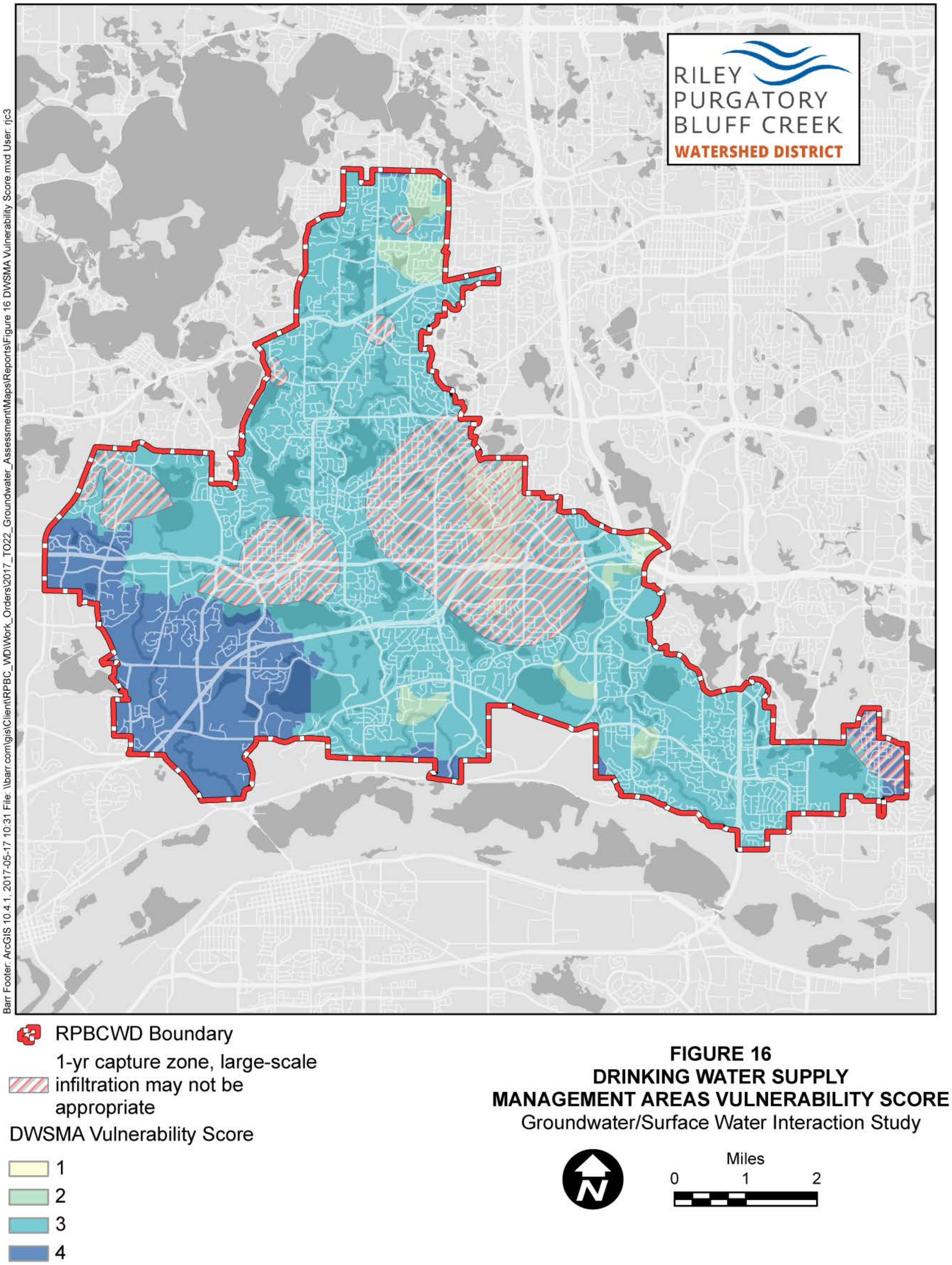


Figure 16 Drinking Water Supply Management Areas Vulnerability Score

4.1.7 Karst Areas

Karst is a type of landscape that develops when soluble bedrock is dissolved by water. Most of southeast Minnesota in underlain by carbonate bedrock that is conducive to karst development. The MPCA classifies karst into three categories; active, transition, and covered. The classification depends on the depth to bedrock (Figure 17); active karst occurs where the depth to the bedrock is less than 50 feet, transition karst where depth to the bedrock is between 50 and 100 feet and covered karst where the depth to bedrock is more than 100 feet. Classifications are shown on Figure 18. Karst areas, in particular active karst areas, are of concern for infiltrating large volumes. Excessive volumes of water may help to dissolve carbonate bedrock enlarging fractures and caverns leading to eventual collapse. The weight of any ponded water may also lead to collapse of any existing or filled karst features. A recent and well-known example of this is the collapse event at the Dancing Waters development in Woodbury in October, 2005. The MPCA does not define specific rules regarding infiltrating stormwater in karst areas. However, additional pre-treatment may be necessary and site-specific geotechnical investigations are typically required. In general, karst formation is of little concern across the District; a few small areas of transition karst exist in the northern part of the district. No areas of active karst are present.

The following scoring system was used for presence of karst areas (Figure 19):

- Active Karst = 1 point (note: not present in District)
- Transition Karst = 2 points
- Covered Karst or No Karst = 3 points

4.1.8 Areas of Potential Future Groundwater Drawdown

The Metropolitan Council conducts water supply planning for the Twin Cities metro area. Current projections of population and water demand for the District for 2020, 2030, and 2040 are shown in Table 3 below.

Table 3 Projected population and water use for the district

	2020	2030	2040
Population Served	259,902	284,557	316,123
Total Population	268,400	293,800	318,500
Projected Average Daily Water Use (Million Gallons)	6.15	6.74	7.49
Total Per Capita Water Use (Gal/Person/Day)	142	142	142

Source: Metropolitan Council. 2015. Water Supply Master Plan

The Metropolitan Council uses demand projections and a groundwater flow model (Metro Model 3) to assess potential groundwater drawdowns under future conditions. The Metropolitan Council does not estimate impacts to surface waters as a result of the increased pumping. However, in general it is expected that areas of greater drawdown will have greater impacts to surface waters that are connected to the groundwater system. Figure 20 shows the projected drawdown in the Prairie du Chien – Jordan

Aquifer for 2040. In general the east-central and west-central areas of the District are projected to have the greatest future drawdown. Potential drawdown in the eastern part of the District is more likely to influence surface water as they are more vulnerable to changes in the groundwater system (Figure 2 and Figure 3).

The following scoring system was used for areas of projected drawdown in the Prairie du Chien- Jordan Aquifer (Figure 21):

- < 5 feet = 0 points
- 5 to 10 feet = 1 point
- 10 to 20 feet = 2 points
- 20 to 30 feet = 3 points
- 30 to 40 feet = 4 points

4.2 Results of Infiltration Area Assessment

The results of the assessment of areas of the District most suitable for large-scale infiltration are presented on Figure 22. The areas darkest blue in color on Figure 22 are areas that scored the highest, indicating they are most suitable for large-scale infiltration. Areas in lighter green on Figure 20 are suitable for large-scale infiltration but may have some limitations. Areas shown in gray or with no color on Figure 20 may not be suitable for large-scale, focused infiltration. These areas, while not best for large-scale infiltration, may still be suitable for smaller scale, site specific infiltration which has historically been done in many parts of the District.

Figure 22 can be used to guide planning for large-scale infiltration projects across the District. However, site-specific data and engineering studies are necessary prior to implementation of any large-scale infiltration projects. Site-specific data necessary as part of project design include: geologic borings, water table elevations from site-specific piezometers, and hydraulic conductivity data for soils and unconsolidated sediments at the site. In addition, site specific infiltration data is critical to the viability of the perched/surficial systems and should continue to be pursued though the District. Additionally, hydraulic analysis/modeling will be necessary to obtain volumes and rates of water that will be routed to an infiltration area and groundwater modeling will likely be needed to assess infiltration capacity along with the size and extent of a groundwater mound that may develop at the water table.

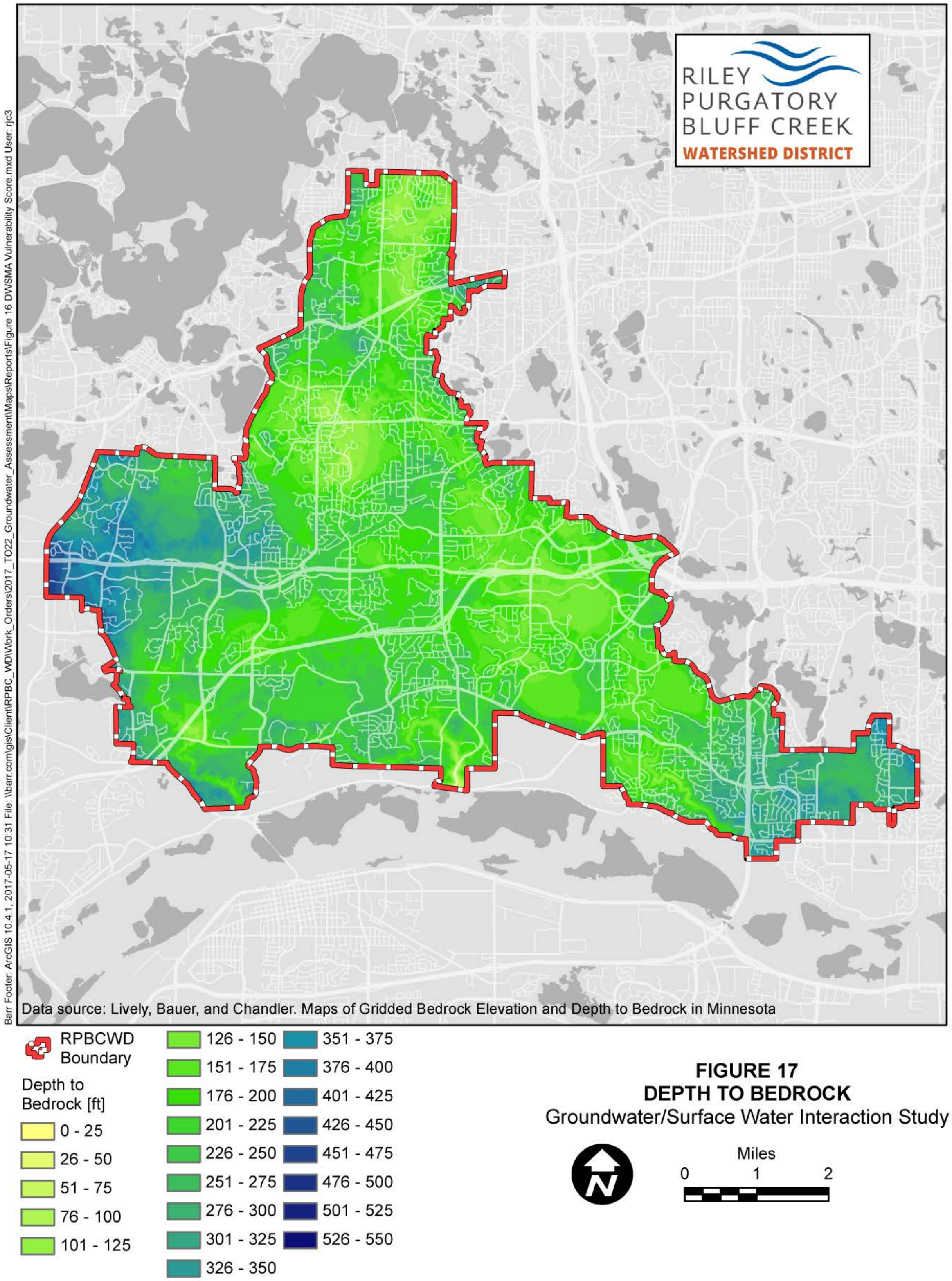


Figure 17 Depth to Bedrock

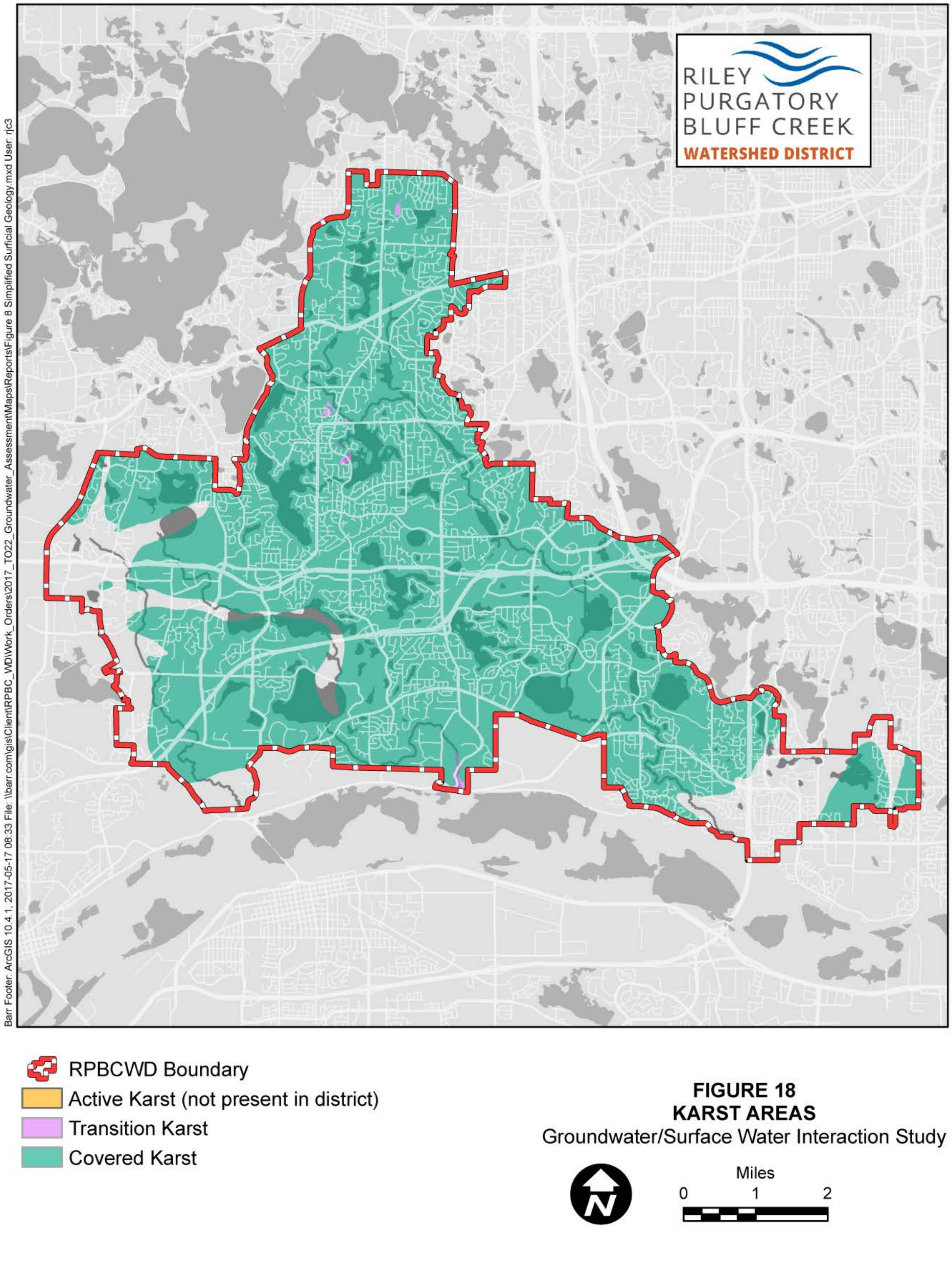


Figure 18 Karst Areas

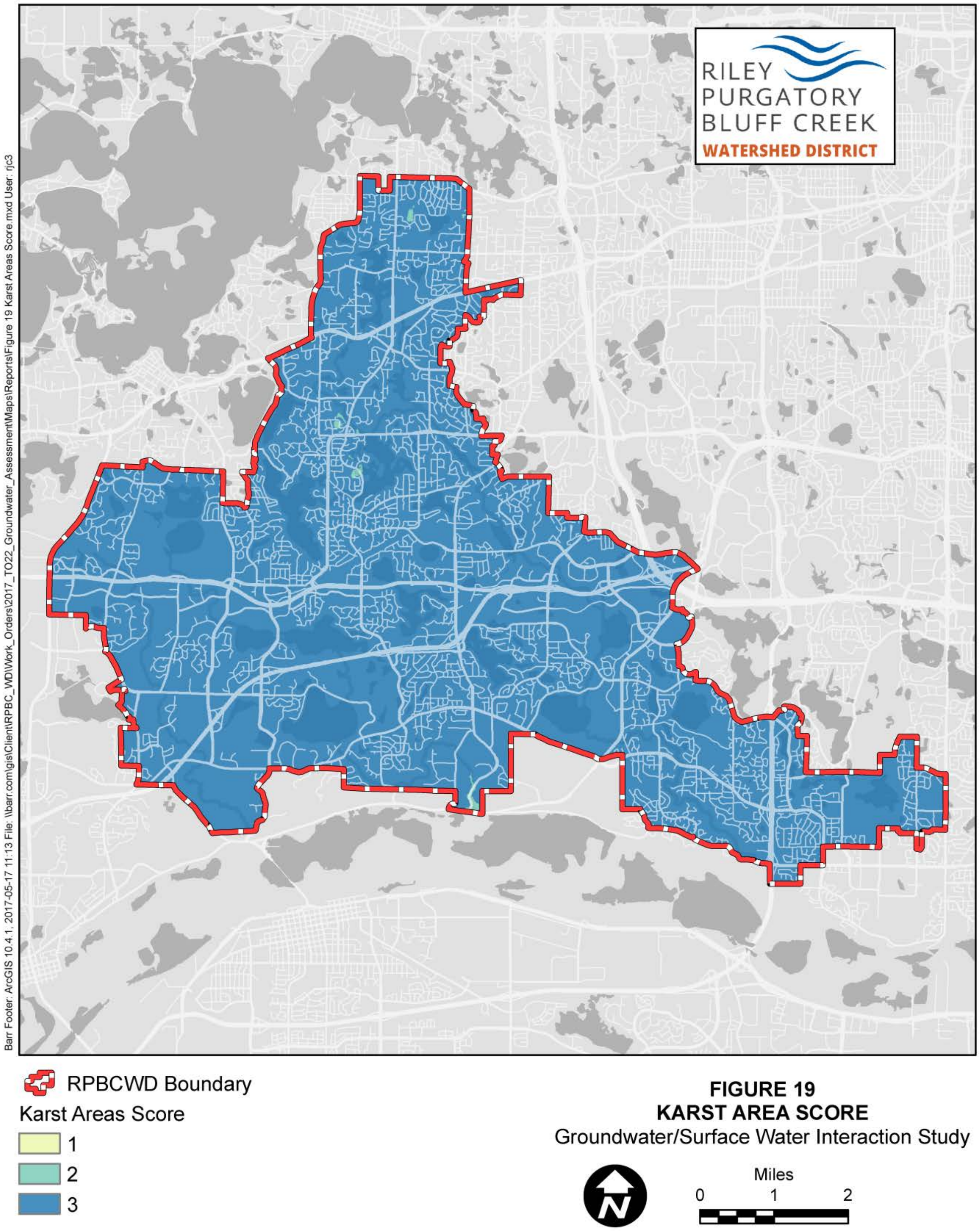


Figure 19 Karst Area Score

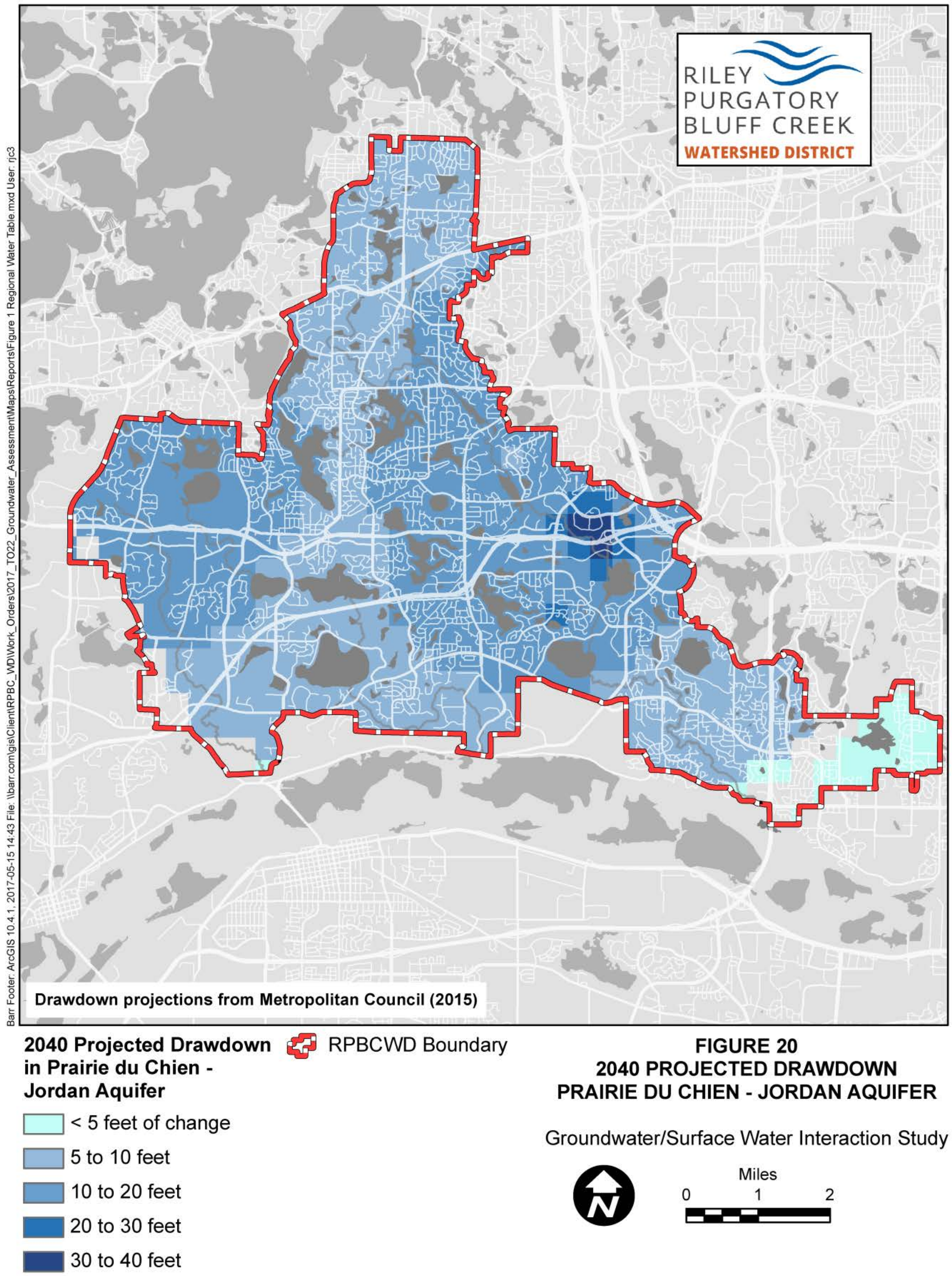


Figure 20 2040 Projected Drawdown in Prairie du Chien - Jordan Aquifer

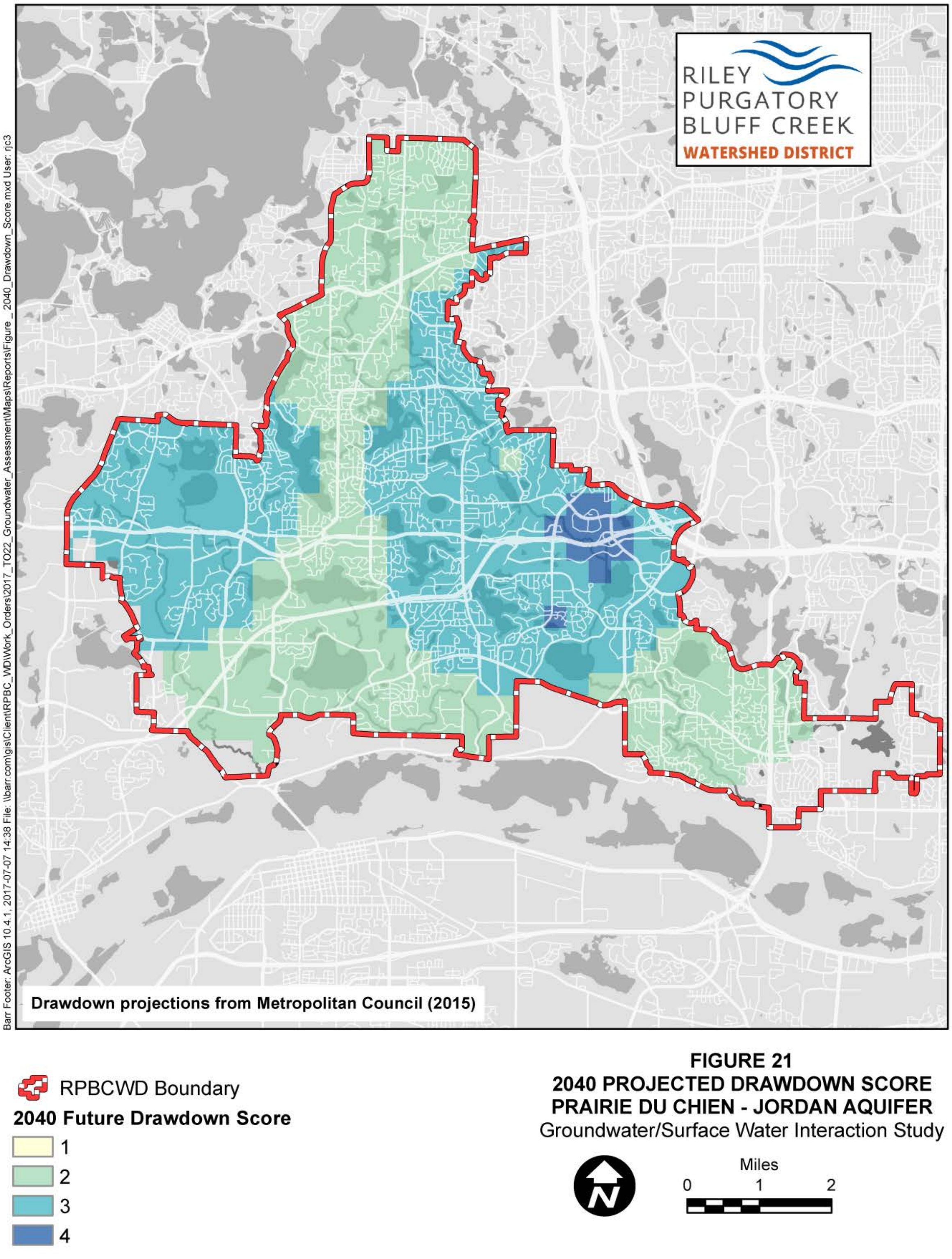


Figure 21 2040 Projected Drawdown Score Prairie du Chien - Jordan Aquifer

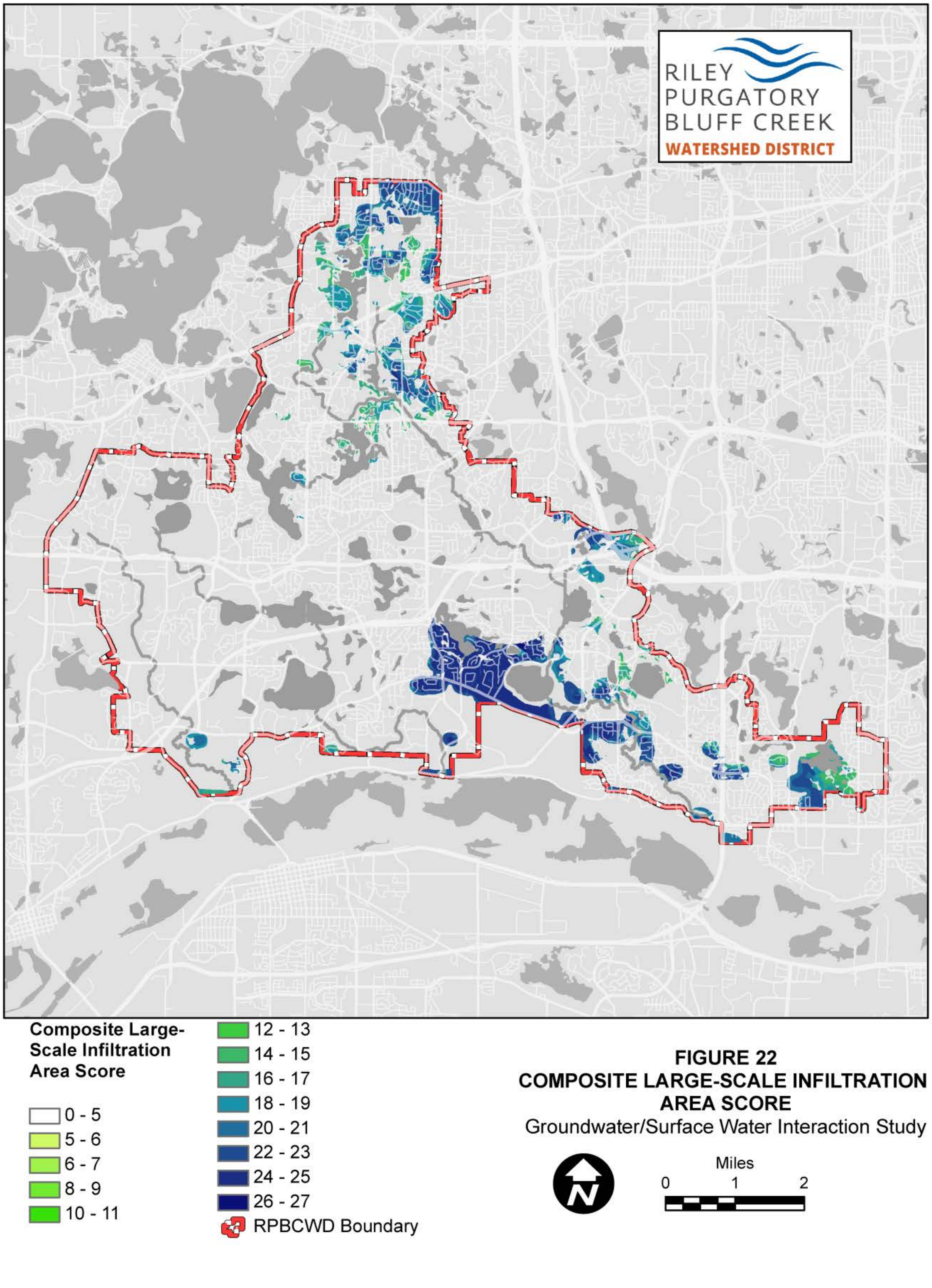


Figure 22 Composite Large Scale Infiltration Area Score

5.0 Potential for Slope Instability Due to Infiltration

The potential for slope instability due to increased infiltration was evaluated using publically available soil property and topography data as well as regional groundwater elevation data as described in Section 3.1. Soil properties, slope geometries, and the groundwater elevation data were used to construct a physically based slope-failure model which fully covers the extent of the District. The slope failure model was used to estimate the current stability of slopes within the District as well as estimate the stability effects of increasing infiltration. The model was also used to estimate the maximum amount of water which could be safely infiltrated on a given slope without inducing slope instability.

5.1 Methodology Used to Rank Potential For Slope Instability

The slope instability model (Okimura, 1985) included parameters which defined the engineering properties of the surficial soils within the District as well as the surface slope and groundwater table geometries. Soil property data were taken from the Soil Survey Geographic Database (SSURGO) provided by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS). LiDAR data used in the model was taken from publicly available datasets provided by the Minnesota Department of Natural Resources (MnDNR).

5.1.1 Data Availability and Processing

Data from the SSURGO database were downloaded within the District boundaries to a depth of 200 cm. The NRCS Soil Data Viewer tool was used to apply the average Unified Soil Classification System (USCS) soil type to all the surficial soil polygons within the District. A map of the USCS soil types is shown in Figure 23.

Though extensive, the SSURGO dataset does not directly include the geotechnical properties of interest for this study. The key parameters required for the slope stability model are the internal friction angle, cohesion, unsaturated unit weight, and saturated unit weight of the soil. The friction angle and cohesion used are shown in Table 4 (based on NRCS data)

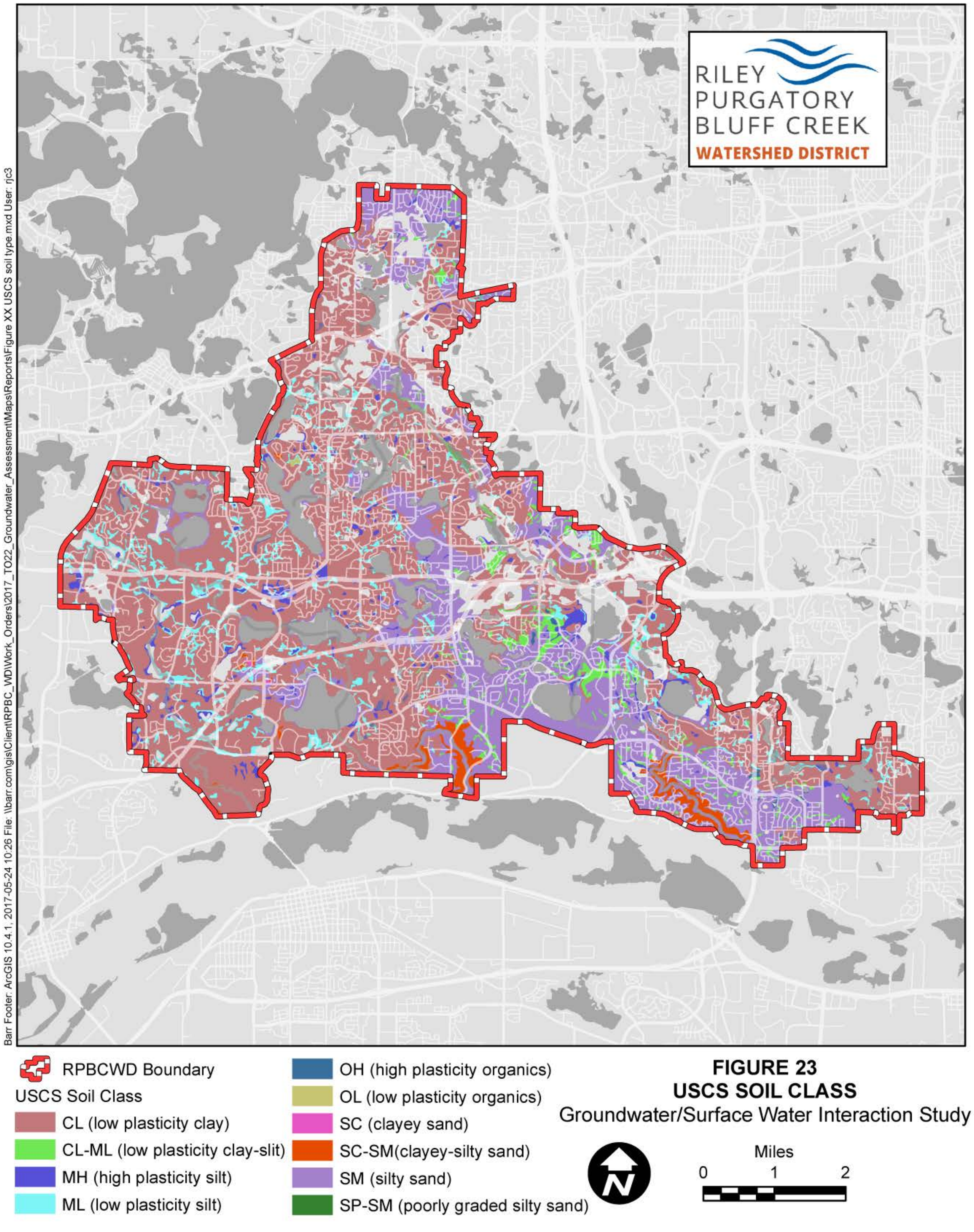


Figure 23 USCS Soil Class

Table 4 Relationship between soil type and internal angle of friction

USCS Soil Class	Description	Friction angle, θ (°)	Cohesion, C (kPa)
GW	well-graded gravel, fine to coarse gravel	40	0
GP	poorly graded gravel	38	0
GM	silty gravel	36	0
GC	clayey gravel	34	0
GM-GL	silty gravel	35	0
GC-CL	clayey gravel with many fines	29	3
SW	well-graded sand, fine to coarse sand	38	0
SP	poorly graded sand	36	0
SM	silty sand	34	0
SC	clayey sand	32	0
SM-SL	silty sand with many fines	34	0
SC-CL	clayey sand with many fines	28	5
ML	silt	33	0
CL	clay of low plasticity, lean clay	27	20
CH	clay of high plasticity, fat clay	22	25
OL	organic silt, organic clay	25	10
OH	organic clay, organic silt	22	10
MH	silt of high plasticity, elastic silt	24	5

The unit weight and saturated unit weight of the USCS soil types were assigned based on data provided in Peck, Hanson, and Thornburn (1974)

Table 5 Relationship between soil type and unit weight

Soil Type	Unit Weight lb/ft^3	Saturated Unit Weight lb/ft^3
Uniform sand (loose)	90	118
Uniform sand (dense)	109	130
Well-graded sand (loose)	99	124
Well-graded sand (dense)	116	135
Windblown silt (loose)	85	116
Glacial till	132	145
Soft glacial clay	76	110
Stiff glacial clay	106	129
Soft slightly organic clay	58	98
Soft very organic clay	43	89
Soft montmorillonitic clay	27	80

Where SSURGO data were unavailable, soil parameters with poor geotechnical engineering properties were assumed. It is important to note that all data obtained from the SSURGO database provides only estimates of soil characteristics—both in their spatial extent and their specific values. Additionally, estimates of soil properties are based on literature averages. Any specific project design or analysis would require more accurate and spatially-precise values from site-specific soil testing (LRRB, 2017).

5.1.2 Slope Failure Model

The slope stability model chosen for this analysis is a simplified infinite-slope model in which the failure plane is assumed to be an infinite slice parallel to the ground surface. The model is applied to every 3m by 3m grid cell within the District.

Using the infinite slope theory, one can determine conditions under which a soil layer with a thickness of *Z* and a saturated thickness *h* will slip over a plane parallel to the surface, which has a slope angle of θ with the horizon (Figure 24). A map of slope angle throughout the District is shown in Figure 25. The slipping conditions can be determined using Coulomb's law of friction. For a given model cell, the factor of safety (*FS*) for a slope can be determined from Equation 5-1 (Okimura, 1985).

$$FS = \frac{\hat{C}+[(\gamma_{sat}-\gamma_{w})*h+\gamma*(Z-h)]\cos^{2}\theta*\tan\hat{\varphi}}{[\gamma_{sat}*h+\gamma\,(Z-h)]*\sin\theta*\cos\theta} \quad \textbf{(Eqn. 5-1)}$$

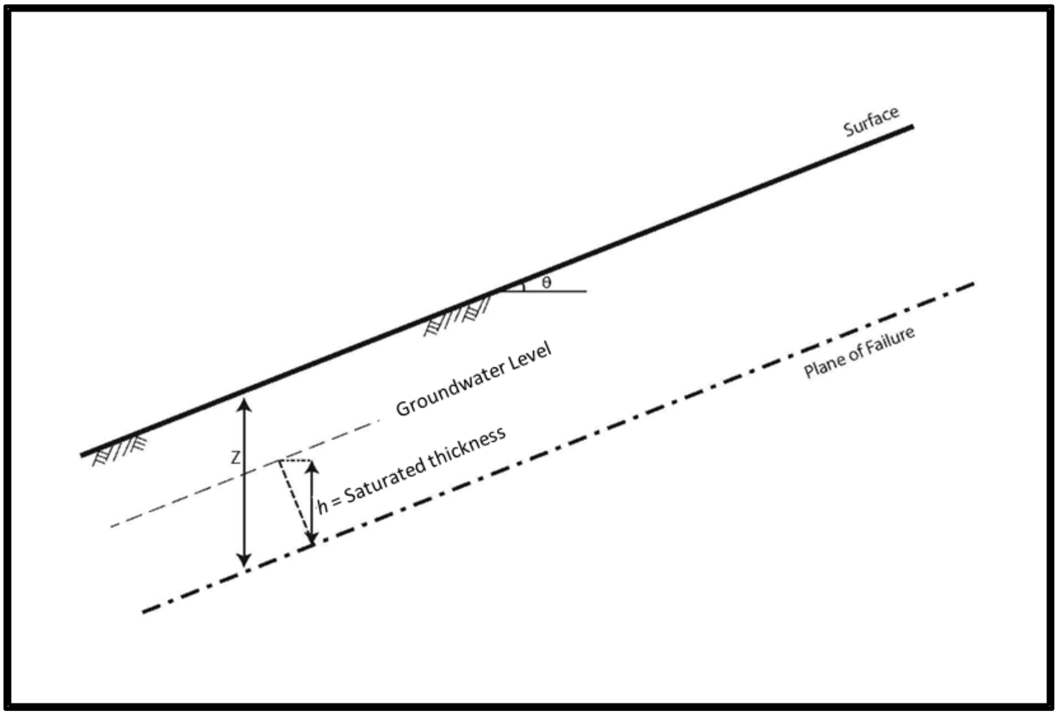


Figure 24 Schematic for infinite slope theory

In Equation 5-1, FS is the factor of safety, where a value less than 1 indicates an unstable slope and value greater than 1 indicates a stable slope, $\hat{C}$ is the effective cohesion, γ is the specific weight of soil under normal conditions, γ_{sat} is the specific weight of saturated soil, γ_{w} is the specific weight of water, Z is the depth of sliding block, h is saturated thickness of the block, θ is the slope angle, and $\hat{\varphi}$ is the effective internal angle of friction.

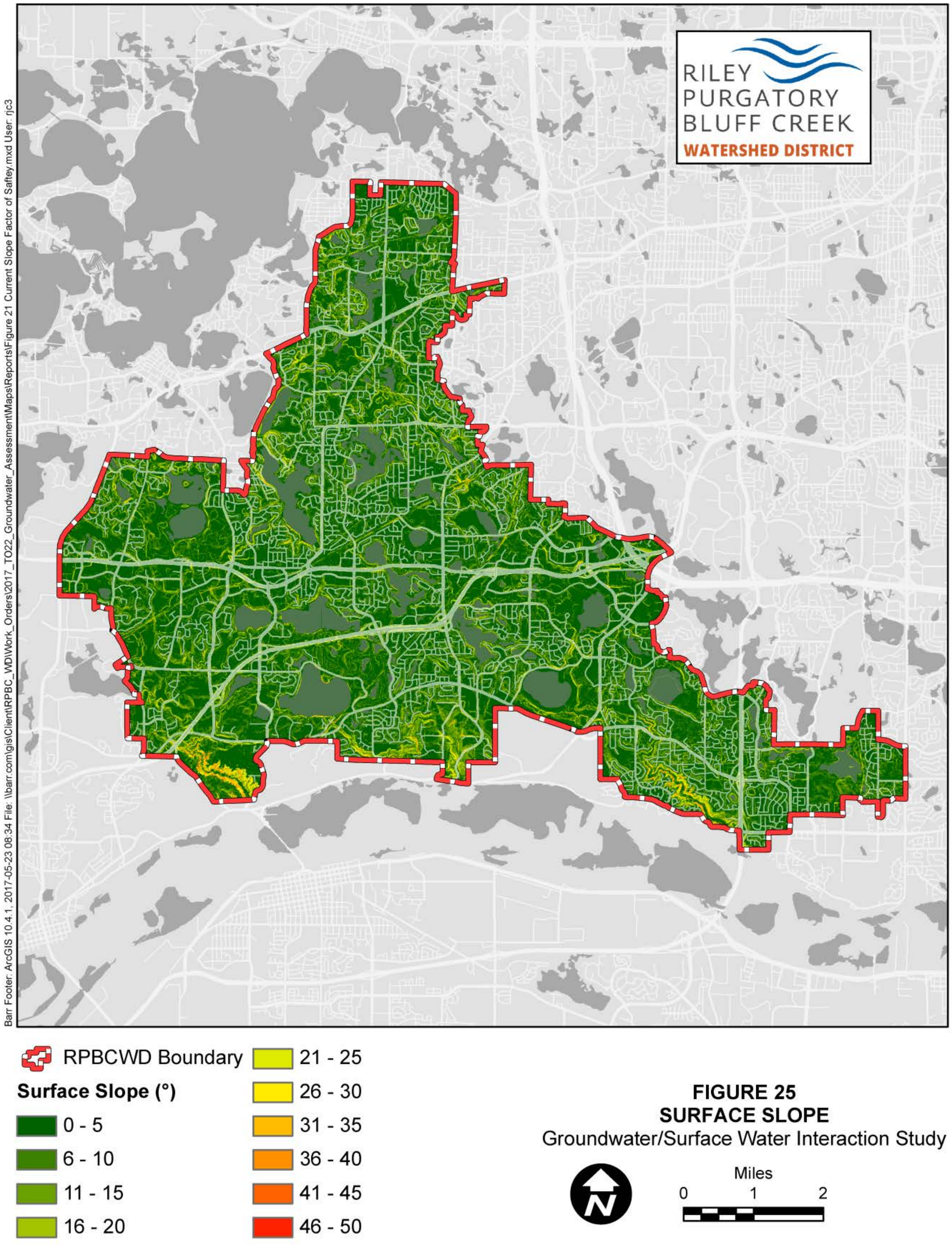


Figure 25 Surface Slope

The value for the depth of sliding block (Z) is generally unknown until slope failure occurs and site specific investigations are conducted. Antidotal evidence, based on review of historic landslide information, suggests that most shallow landslides are less than 2 meter deep. Barr (2017), utilizing a similar modeling approach to evaluate slope failure in Sibley and Carleton counties, found that a Z value of 6 feet (1.8 meters) was adequate in their validation analysis of comparing model susceptibility to historical slope-failure. Therefore, a 2 meter deep sliding block was be assumed uniformly across the project area when estimating the initial stability conditions. If site-specific information is available on likely failure surface geometry, it can be input into the model for a more accurate estimate.

The initial values for the saturated thickness *(h)* are taken from the current regional groundwater table determined in Section 3.1. If the groundwater table intersects the sliding block, the saturated thickness of the block is calculated from the difference between the surface of the groundwater table and the bottom of the sliding block. If an infiltration project produces a steady state head increase within the sliding block, the head increase is added to saturated thickness. For example, if an infiltration project was estimated to produce 1 meter of mounding in the infiltration area, 1 meter of saturated thickness would be added to model at that location. The infiltration areas and volumes are defined by a shapefile so new projects can be quickly modeled and the slope stability model updated.

As saturated thickness increases, the factor of safety of the slope decreases due to increasing unit weight of the failure slice and decreasing frictional force due to increasing pore pressure. Equation 5-1 can be rearranged to solve for the minimum saturated thickness *(h_{cr})* at which failure will occur (Equation 5-2). The pre-existing saturated thickness (*h)* from intersection of the failure slice and water table is then subtracted from the minimum saturated thickness (Equation 5-3) to give the maximum allowable increase in saturated thickness due to infiltration:

$$h_{cr} \geq \frac{\frac{\hat{C}}{\gamma_w}+\frac{\gamma_{sat}}{\gamma_w}*Z*\cos^2\theta*(\tan\hat{\varphi}-\tan\theta)}{\cos^2\theta*\left[\left(\frac{\gamma_{sat}}{\gamma_w}-\frac{\gamma}{\gamma_w}\right)*(\tan\theta-\tan\hat{\varphi})+\tan\hat{\varphi}\right]} \qquad \textbf{(Eqn.5-2)}$$

$$h_{cr,inf} = h_{cr} - h \qquad \textbf{(Eqn. 5-3)}$$

In Equation 5-2, h_{cr} is the critical depth of saturation for the soil layer. The value of h_{cr} gives the maximum allowable saturated thickness within the cell before instability is induced. For example, if an area reports h_{cr} values of 1.5m, the cell can maintain 1.5 meter of saturated thickness without the slope becoming unstable. Equation 5-3 gives the saturated depth available for infiltration where $h_{cr,inf}$ is the saturated depth in the cell remaining for infiltration after accounting for the thickness already saturated by the water table. Though these results cannot be used to determine the maximum allowable *rate* of infiltration (which is a more complex function of regional groundwater flow and requires site specific data and modeling), it does give estimates of areas which are conducive to infiltration and areas where infiltration will likely lead to slope instability.

5.2 Results of Slope Instability Assessment

The results of the slope instability assessment were used to estimate the current stability conditions and the critical saturation depth in the District. Additionally, the application of the model for estimation of infiltration impacts was demonstrated for a hypothetical infiltration project.

The current stability conditions are presented in Figure 26. Areas shown in red have high instability potential while areas shown in green are stable and are expected to have no instability issues. As would be expected, less stable slopes are located around the steep banks of the Riley, Purgatory, and Bluff Creeks. These locations have shallow regional water tables and soil types that are prone to failure. Slope angle is the primary factor in determining the potential for instability of slopes within the District. Soil properties and the level of the regional groundwater table play import roles, but generally only under specific circumstances (soils with poor engineering properties, very shallow water table). Therefore, the slope of the ground surface (Figure 25) can be used in conjunction with current stability conditions (Figure 26) in planning infiltration projects with regard to instability potential.

The critical saturation depth is shown in Figure 27. Regions shown in red and orange have very limited infiltration capacity before instability is induced while regions shown in green can receive greater infiltration without becoming unstable. Similar to the current stability estimates, locations with limited infiltration capacity are situated near the steep slopes along the creeks. The areas with limited infiltration capacity make up only a small portion of the District and have little influence on the overall area available for infiltration within the District. The composite infiltration area score (Figure 22) with areas of a critical saturation depth of less than 10 feet is shown on Figure 27.

The stability model can also be used to estimate the stability impacts of infiltration projects. To demonstrate, a hypothetical infiltration project was simulated within the southwest corner of the District. The results of this example are presented in Figure 29. At initial conditions before infiltration is modeled, the slopes within the infiltration area mostly in the low instability potential and stable stability classifications. Saturation increases of 1 meter and 2 meter are then added to the model. As the saturation depth is increased, the stability of the infiltration area decreases. With 2 meter of saturation, a significant portion of the infiltration area has decreased in stability to moderate instability potential. This tool can be used to quickly approximate areas within the District which will remain stable for various infiltration projects.

Figure 27 can be used be to guide feasibility studies of infiltration sites with respect to slope stability throughout the District. However, site-specific slope stability analysis and groundwater modeling should be performed prior to implementation of any large-scale infiltration projects.

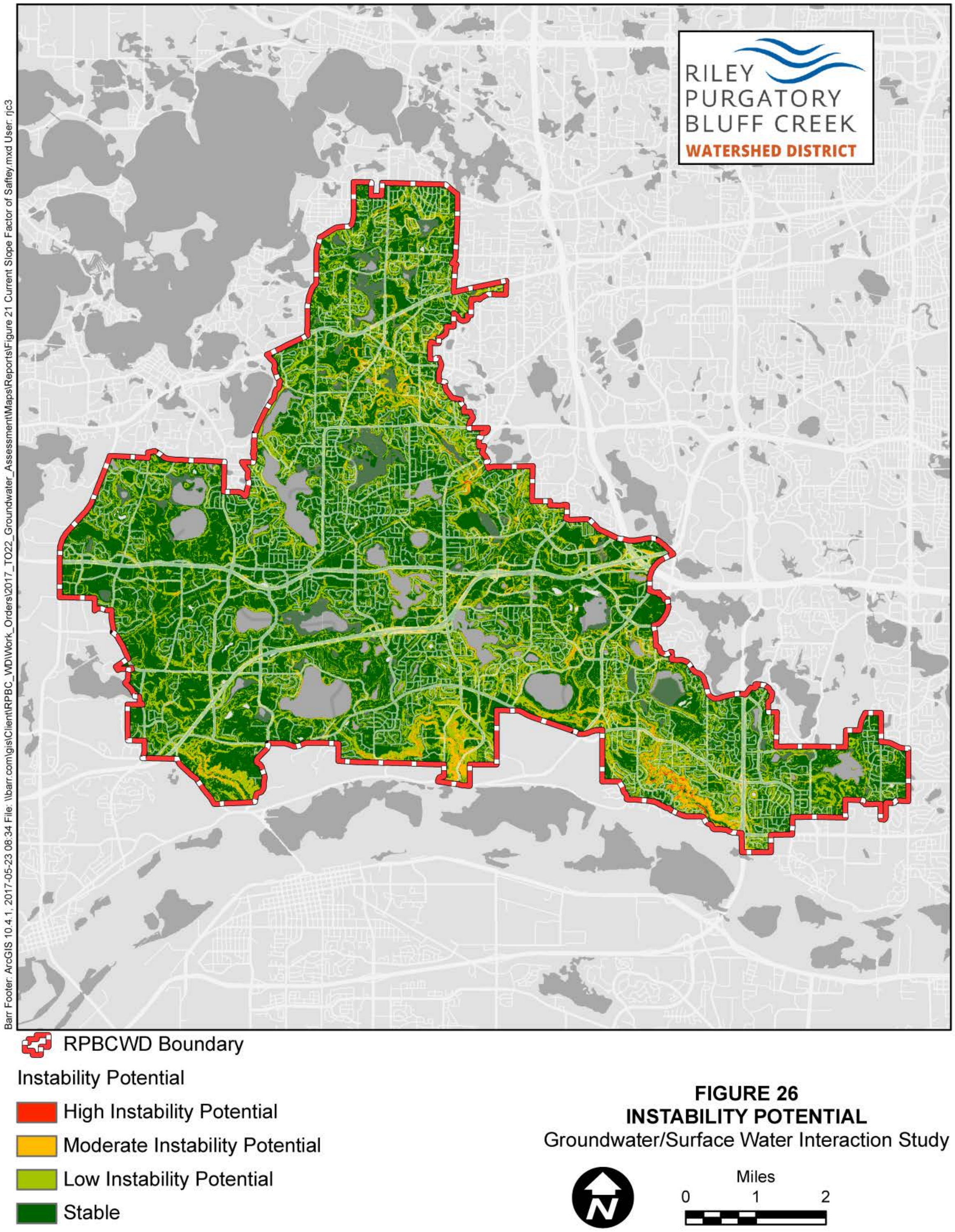


Figure 26 Instability Potential

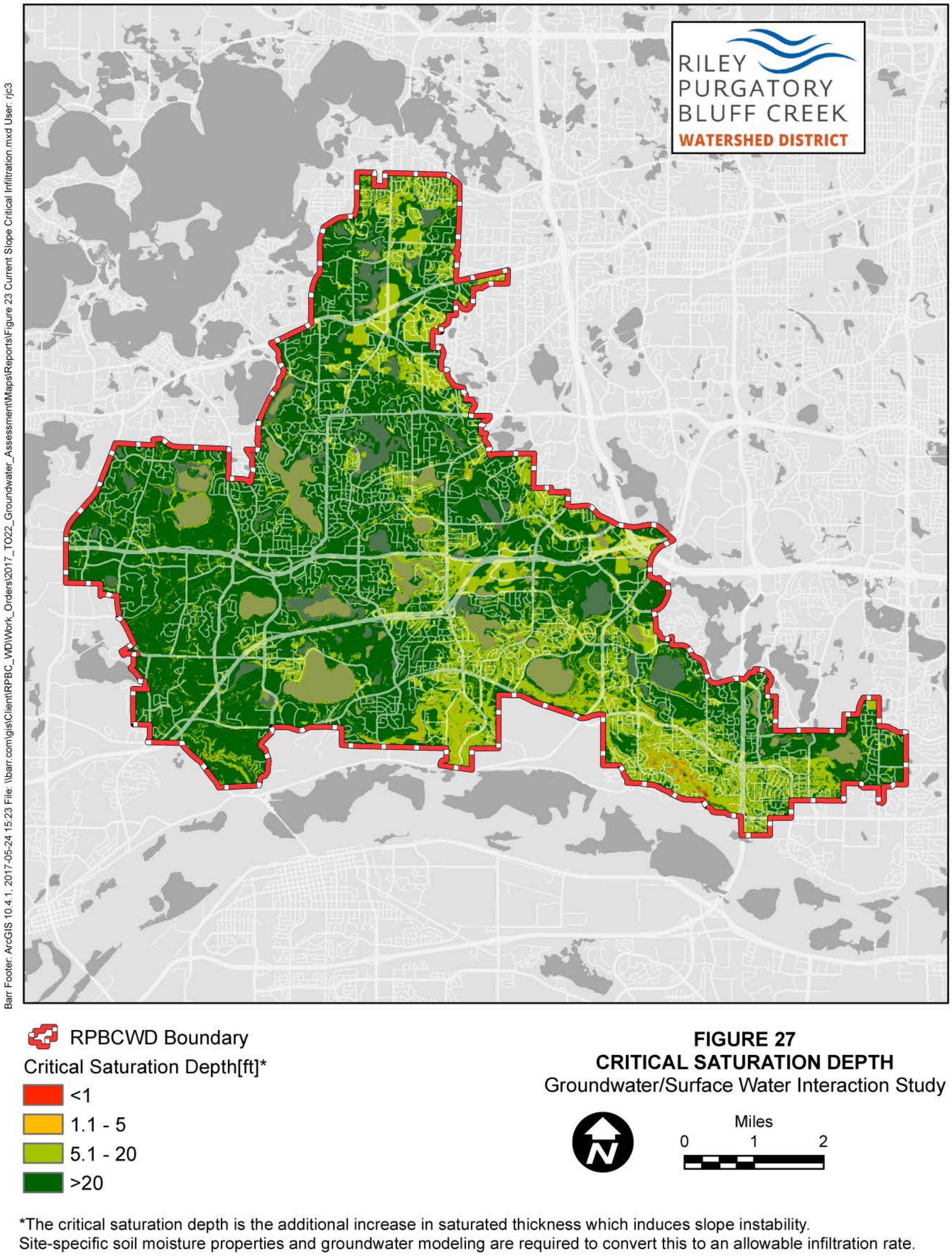


Figure 27 Critical Saturation Depth

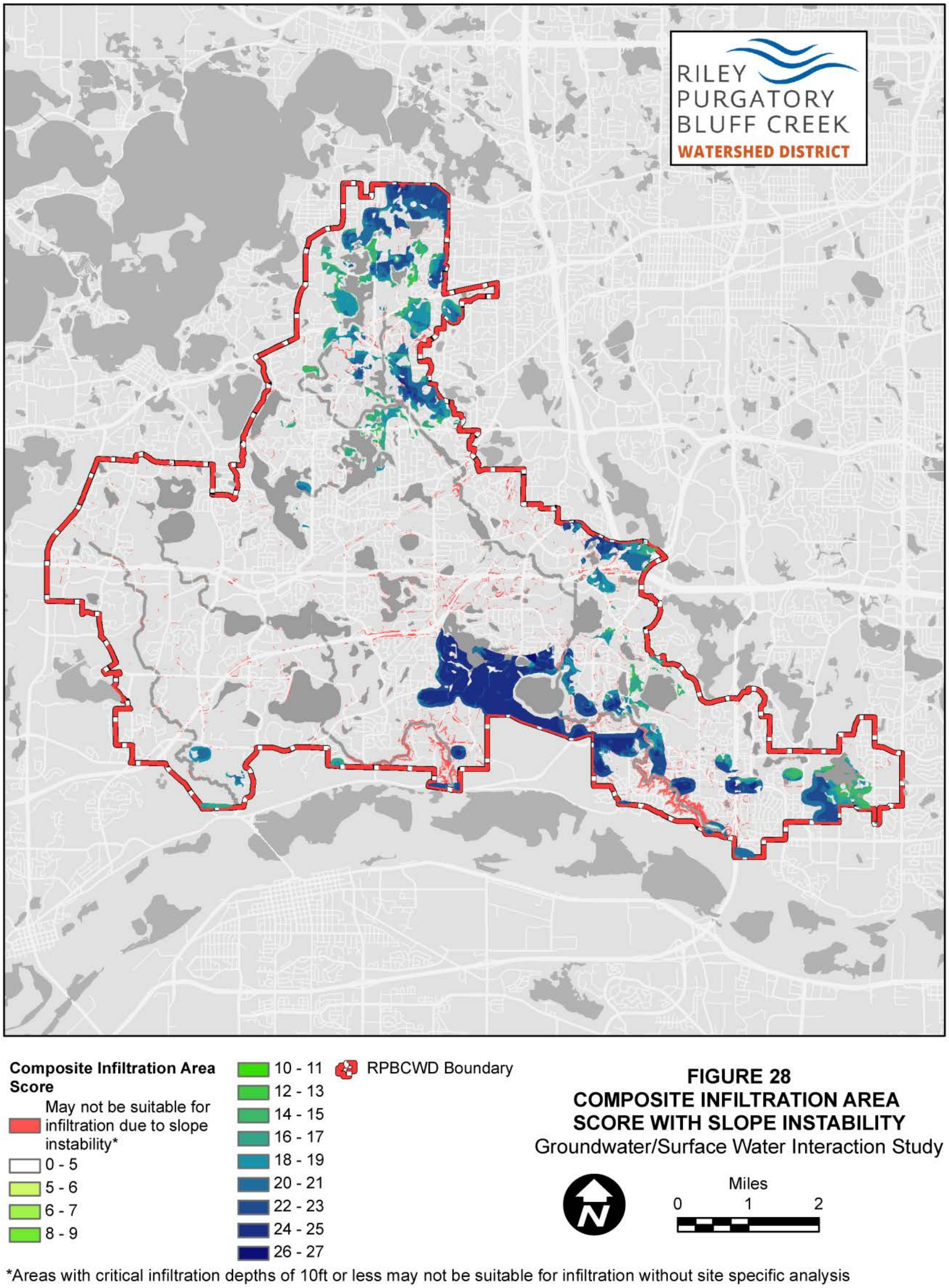


Figure 28 Composite Infiltration Area Score with Slope Instability

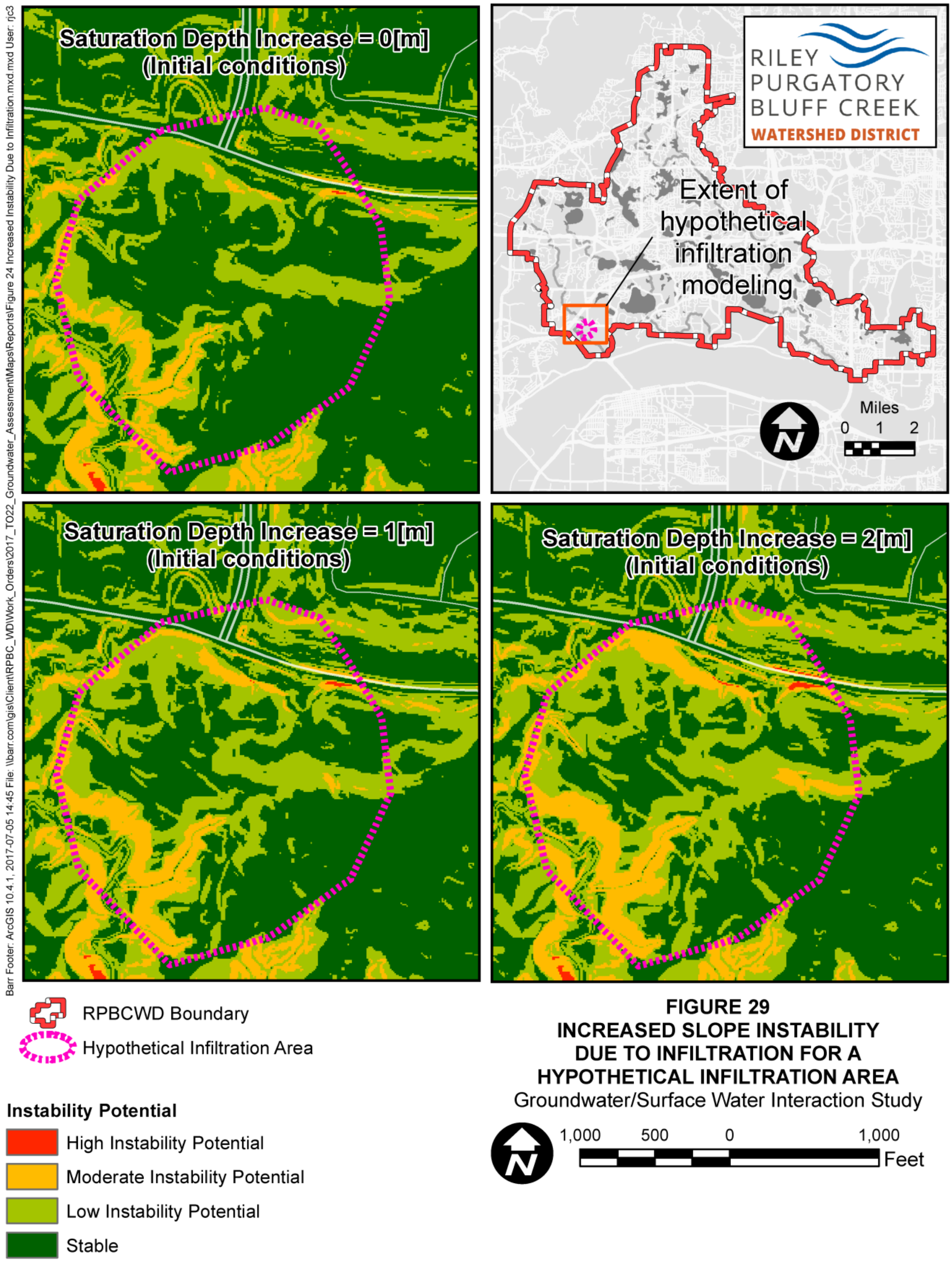


Figure 29 Increased Slope Instability Due to Infiltration for a Hypothetical Infiltration Area

6.0 Conclusions and Recommendations

The results of this study indicate that local geologic controls greatly influence the groundwater surface water interaction, the vulnerability of surface waters to changes in the groundwater system, and areas most suitable for large-scale infiltration.

Surface water features in the western part of the District interact with groundwater differently than surface waters in the eastern part of the District. In the western part of the District many surface water features are classified as perched, recharge lake/wetland, or losing streams (Figure 2). In the eastern and northern parts of the District many surface waters are classified as flow-through or discharge (Figure 2). The primary driver for these regional differences is extensive areas of low permeability glacial till in the western part of the district and larger areas of higher permeability sands in the eastern and northern part of the District.

The regional differences in how groundwater and surface water interact also are present in the potential vulnerability of surface waters to changes in the groundwater system. Surface waters in the south central part of the District are most vulnerable to changes in the groundwater system; surface water features in the western part of District are less vulnerable (Figure 3).

For large-scale infiltration, areas in the northern and southeastern part of the District were identified as being the best locations (Figure 22). Much of the western part of the District scored low in the analysis because of the extensive low permeability till. Areas west and southeast of Staring Lake, north of County Road 62, and southwest of Hyland Lake were identified as some of the areas best suited for large scale infiltration.

The results of the slope stability model show that the banks of Riley and Purgatory Creek are most vulnerable to slope instability due to increased infiltration. Slope is the primary factor in determining potential for slope instability, with soil type and depth to regional water table playing secondary rolls.

The following recommendations were developed based on the results of this study:

- Establish baseflow thresholds for the creeks within the District. The Minnesota DNR suggests establishing a threshold of 10-15% the median low flow (MNDNR, 2016). Generally, the median low flow occurs in August. The downstream reaches of Riley Creek and Purgatory were identified as most vulnerable to changes in the groundwater system and should be prioritized as such for establishing baseflow thresholds.
- Establish thresholds, either lake stage or outlet discharge, for lakes identified as vulnerable to changes in the groundwater system.
- Establish target hydrographs for wetlands identified as vulnerable to changes in the groundwater system.

- Re-establish a monitoring well network within the District and implement a monitoring program. Priority should be given to those areas that have been identified as areas of projected future drawdown from the Metropolitan Council (Figure 21) and areas near surface waters that were classified as vulnerable to changes in the groundwater system (Figure 3).
- Develop a fully coupled groundwater-surface water model for the District. To fully understand how surface waters are affected by changes in the groundwater system and how infiltration will affect the groundwater system and nearby surface waters a model capable of tracking the full water balance, for both groundwater and surface water is necessary.
- Consider establishing a formal process for tracking groundwater data submitted to the District with permit applications. This would include water level measurements and associated boring records into a GIS style database

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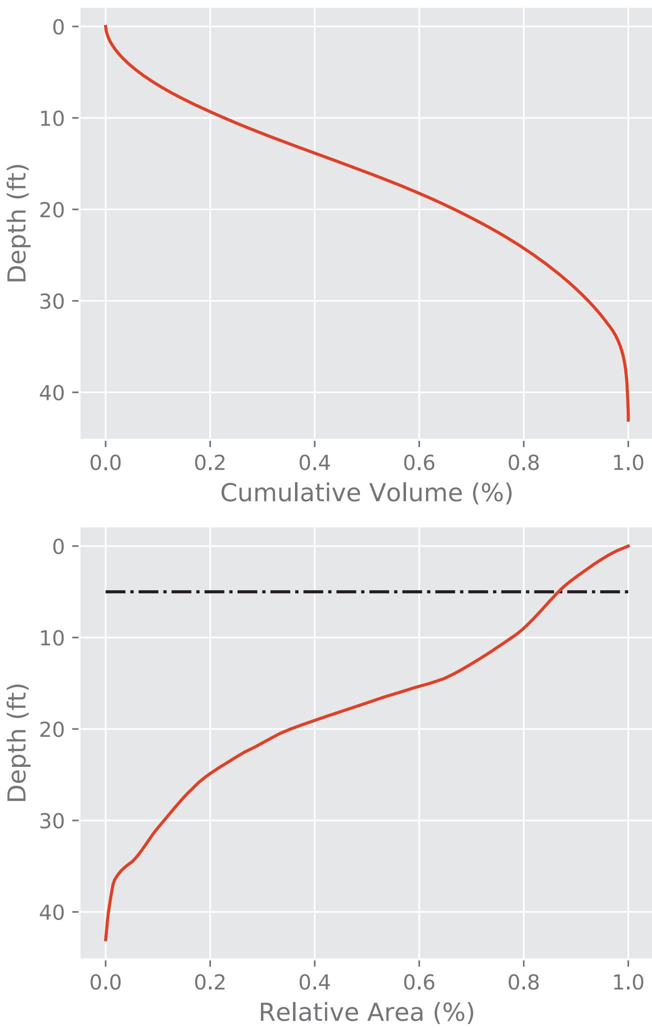
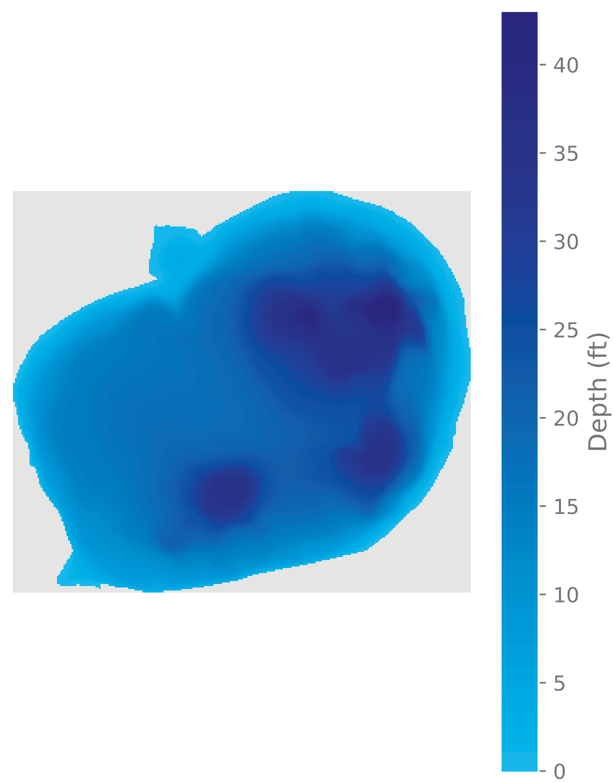
Appendix A

Basin Bathymetry and Geometry

Ann Lake



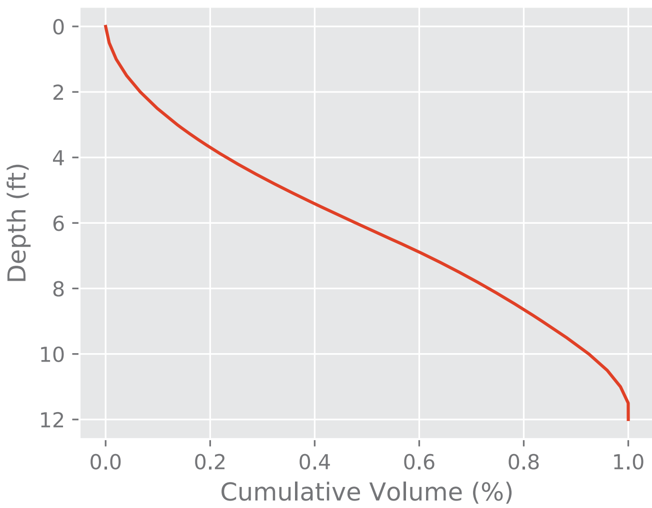


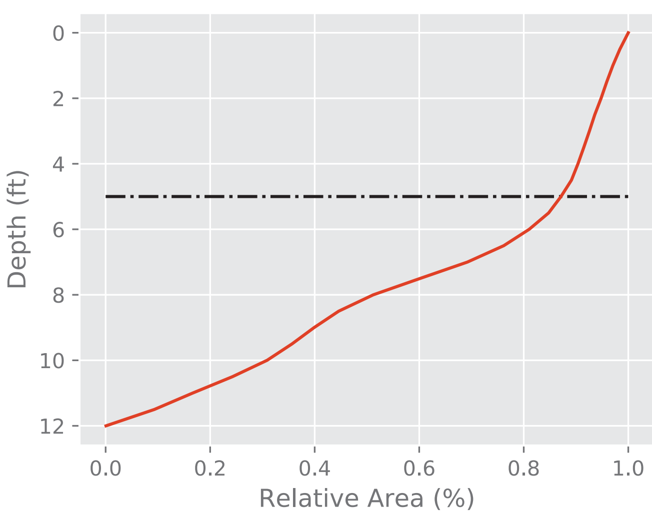
Percent area less than 5 feet deep: 13.3

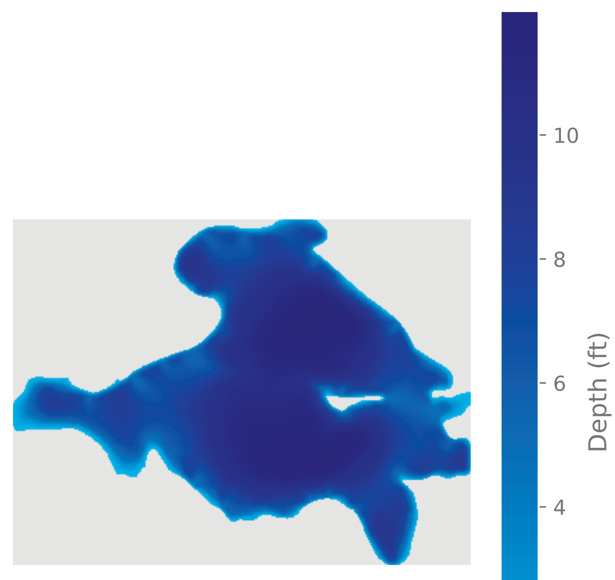
Maximum depth: 43 feet

Mean depth: 17.3 feet

Hyland Lake





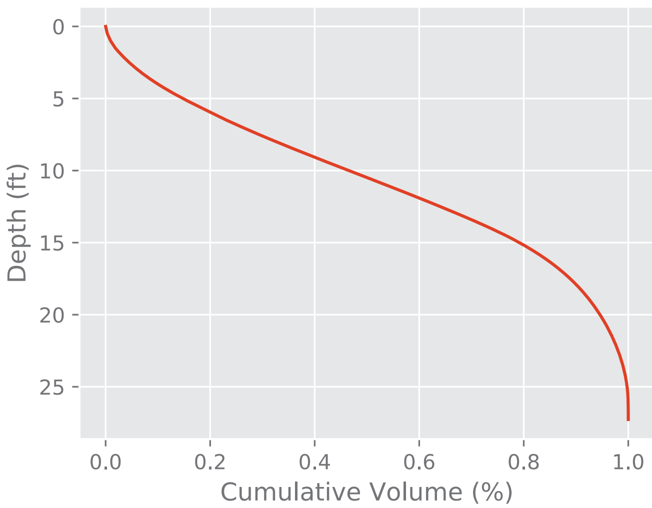


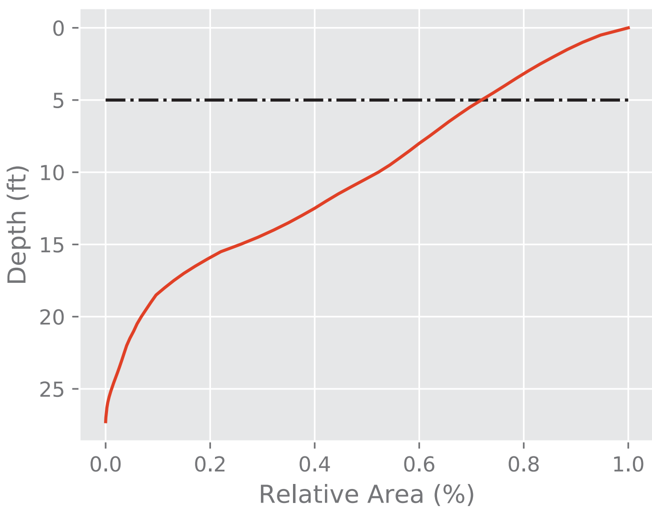
Percent area less than 5 feet deep: 12.9

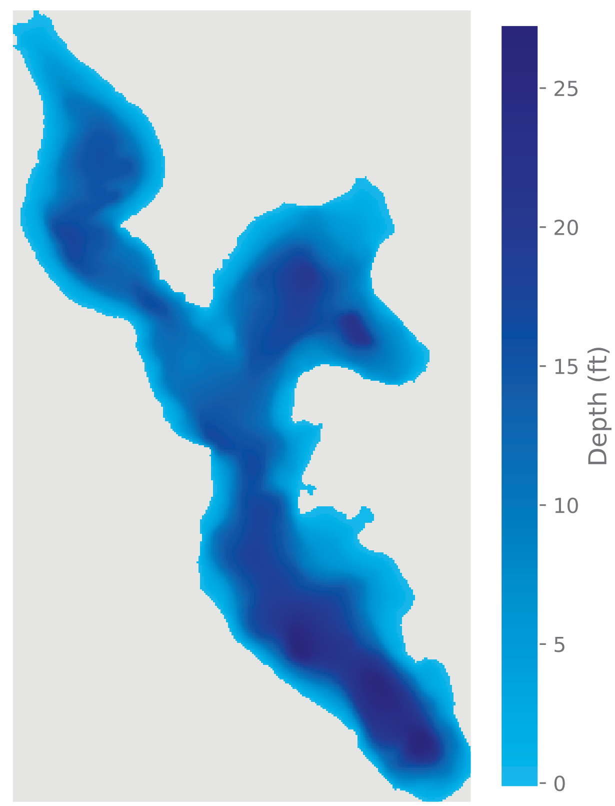
Maximum depth: 12 feet

Mean depth: 8.0 feet

Lotus Lake





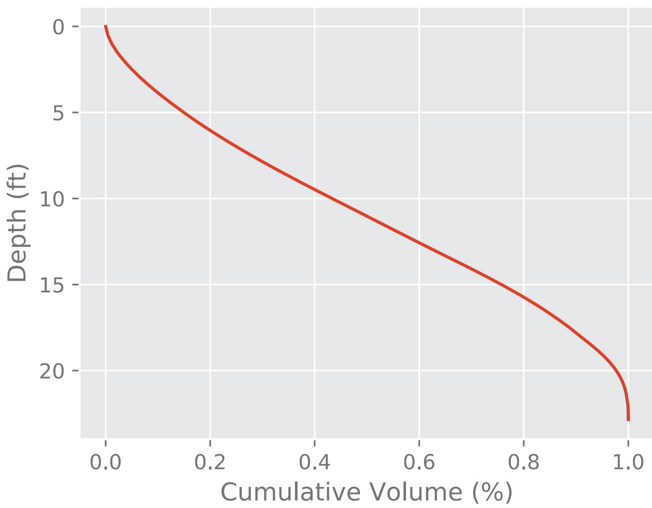


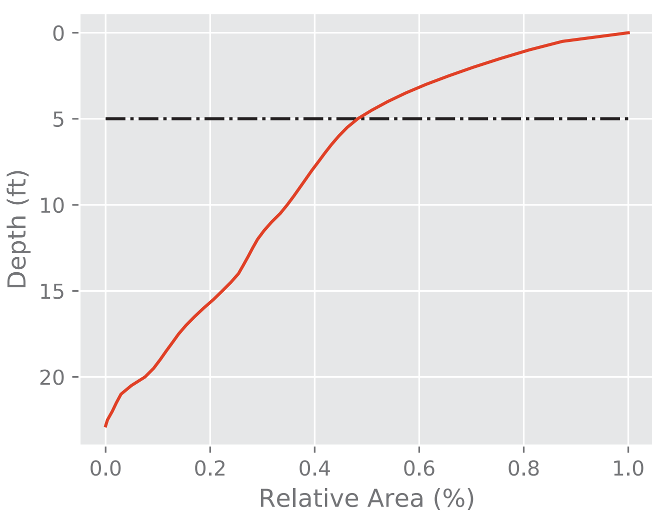
Percent area less than 5 feet deep: 28.1

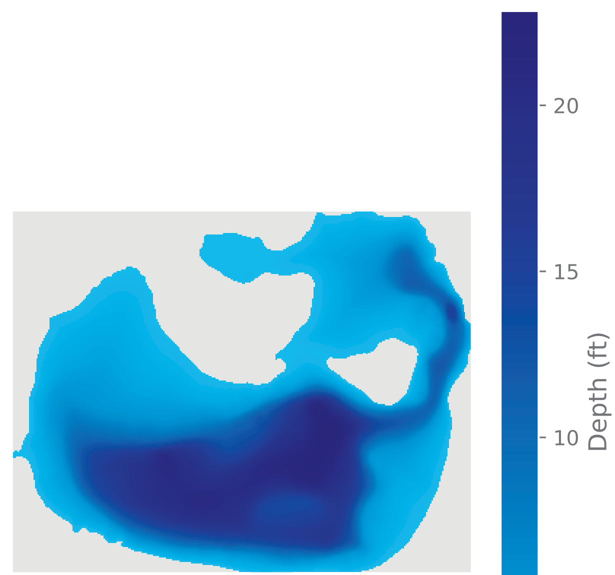
Maximum depth: 27 feet

Mean depth: 10.1 feet

Lucy Lake





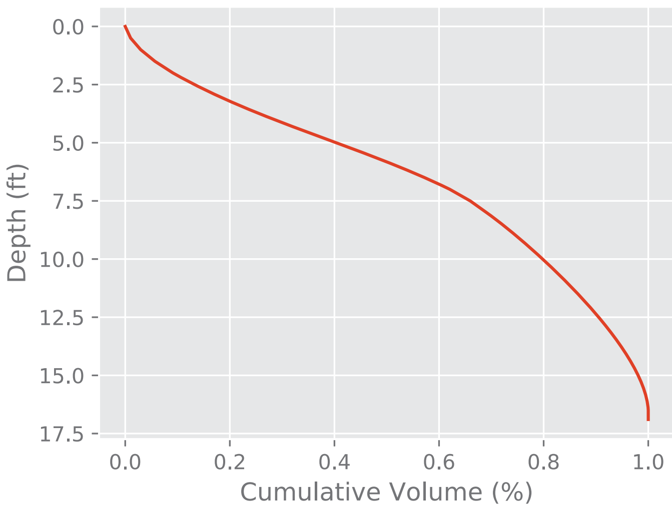


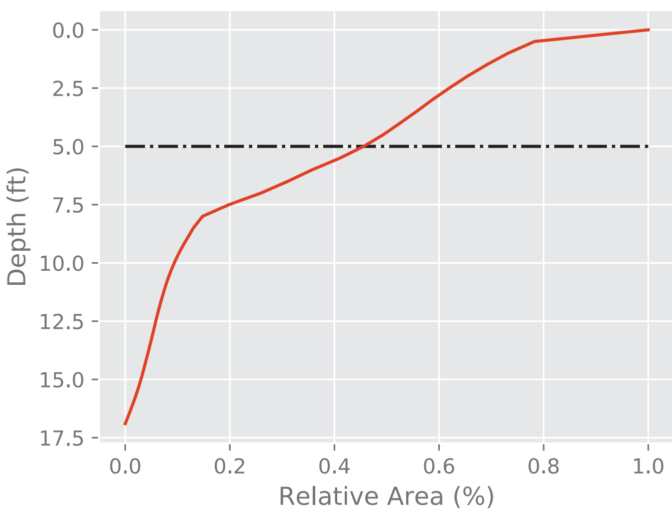
Percent area less than 5 feet deep: 51.8

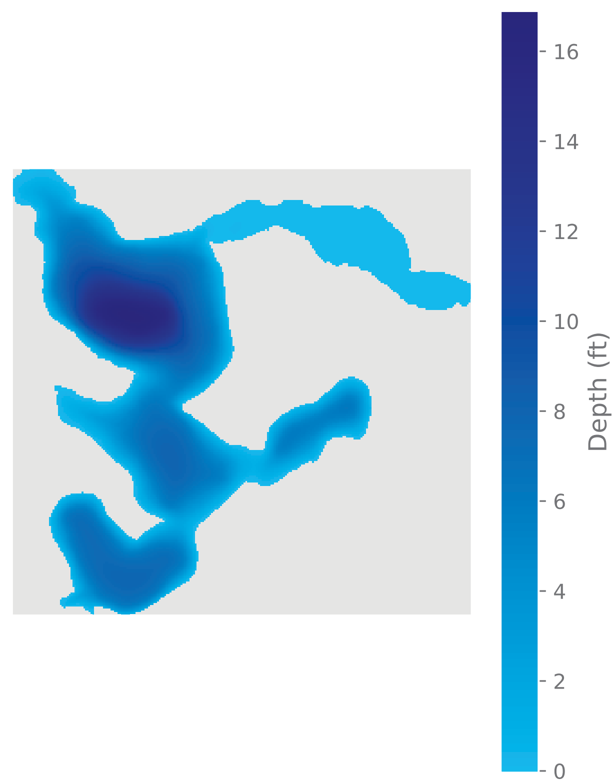
Maximum depth: 23 feet

Mean depth: 7.6 feet

Mitchell Lake





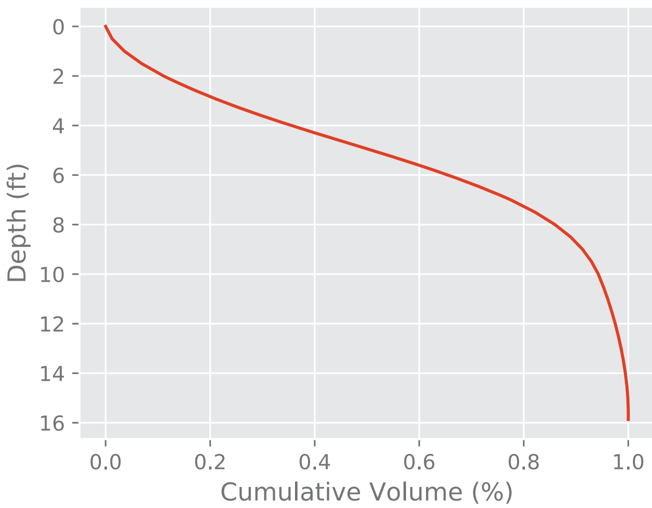


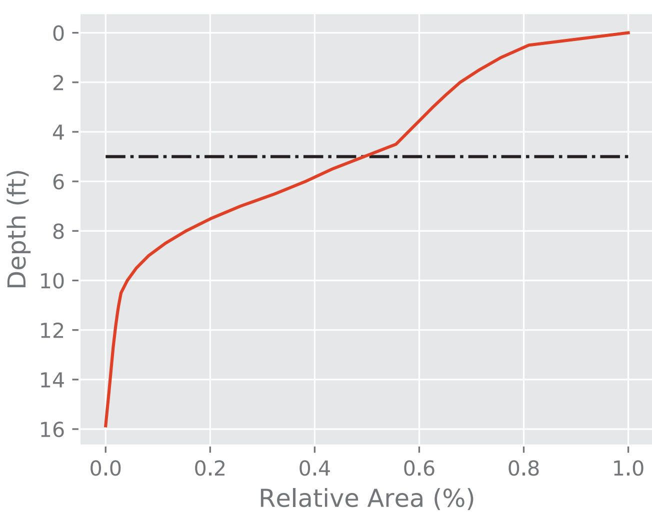
Percent area less than 5 feet deep: 54.4

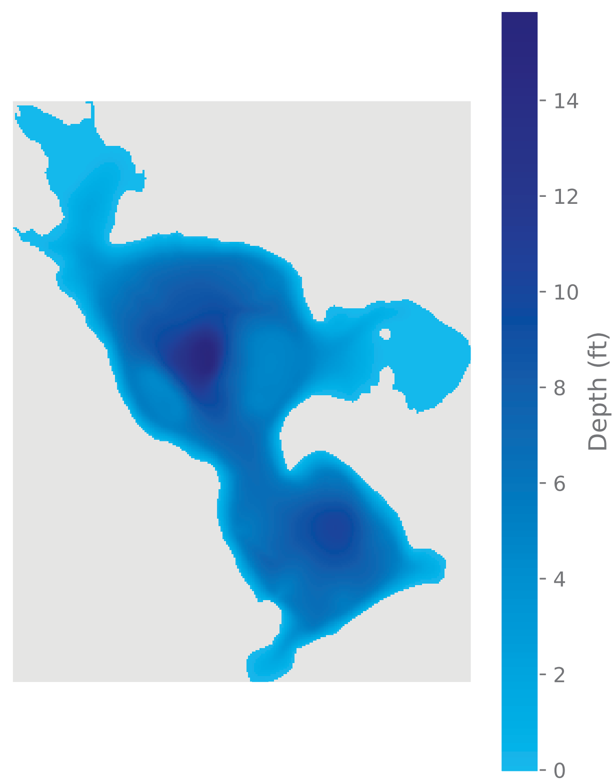
Maximum depth: 17 feet

Mean depth: 4.6 feet

Red Rock Lake





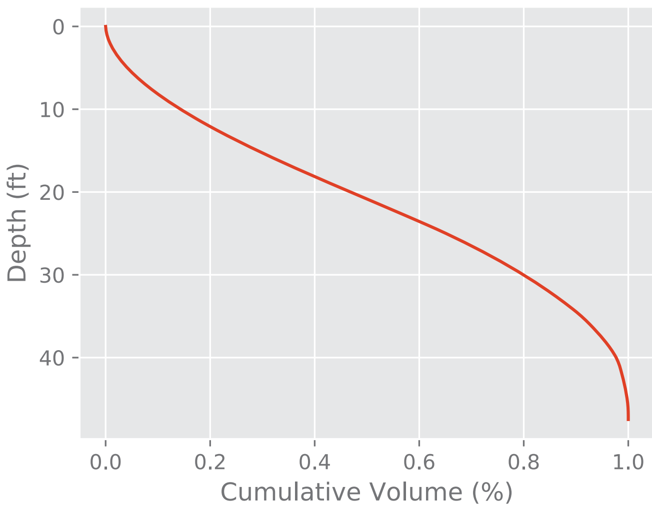


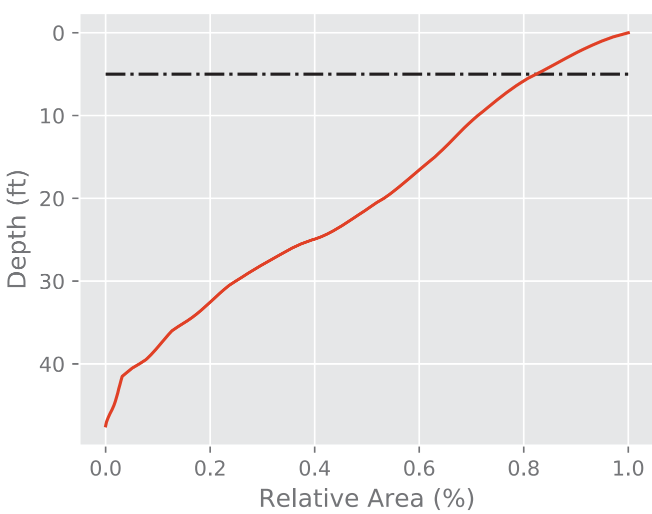
Percent area less than 5 feet deep: 50.5

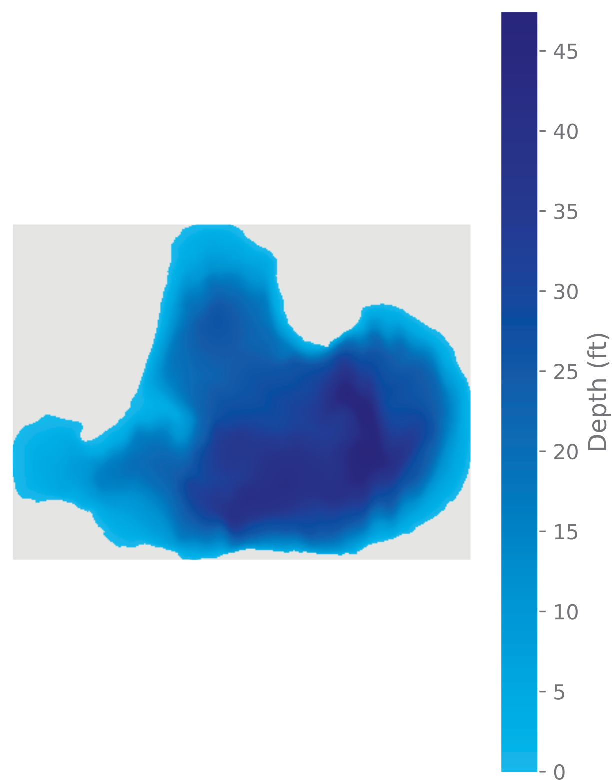
Maximum depth: 16 feet

Mean depth: 4.5 feet

Riley Lake





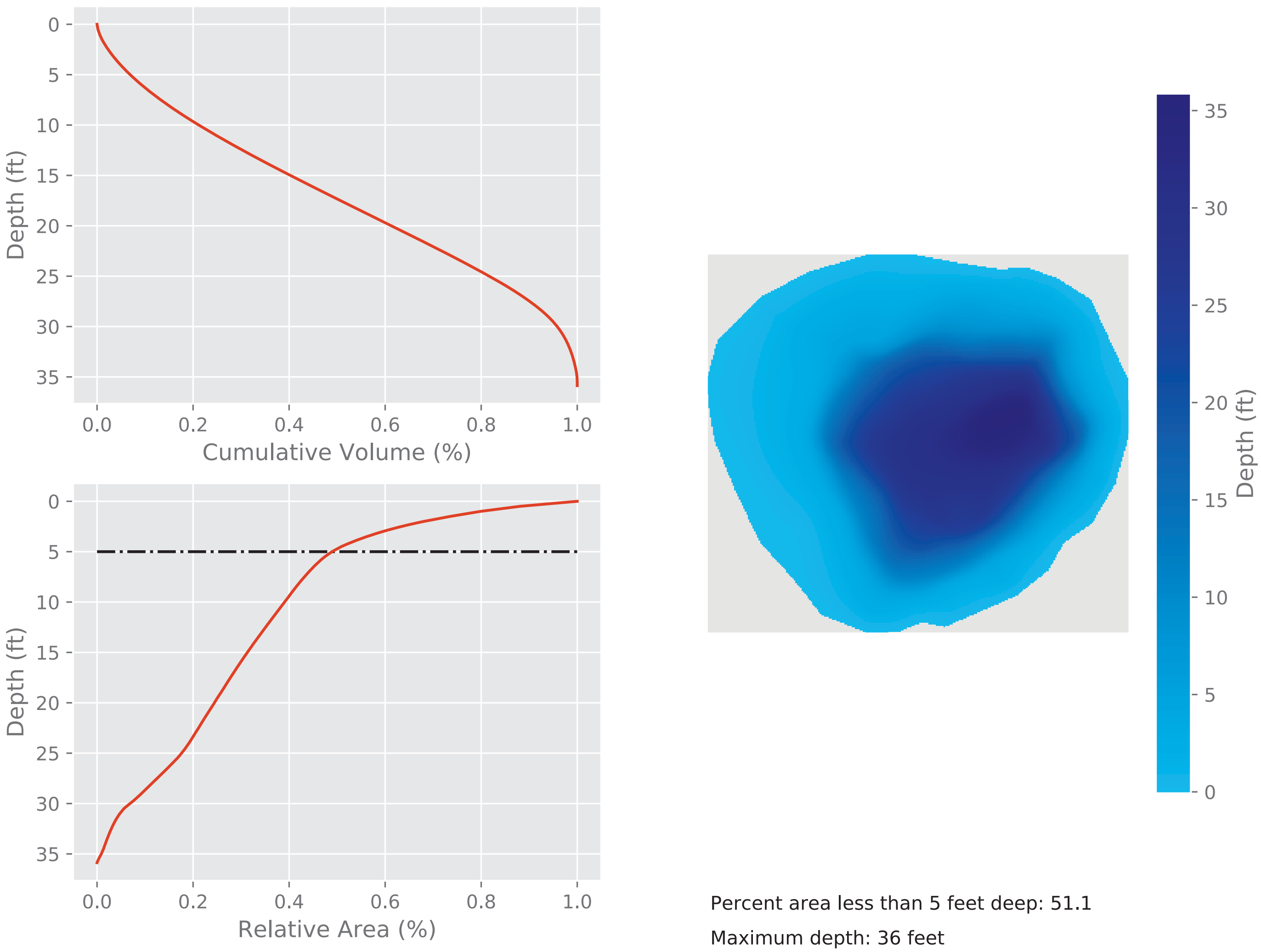


Percent area less than 5 feet deep: 17.6

Maximum depth: 47 feet

Mean depth: 20.2 feet

Round Lake

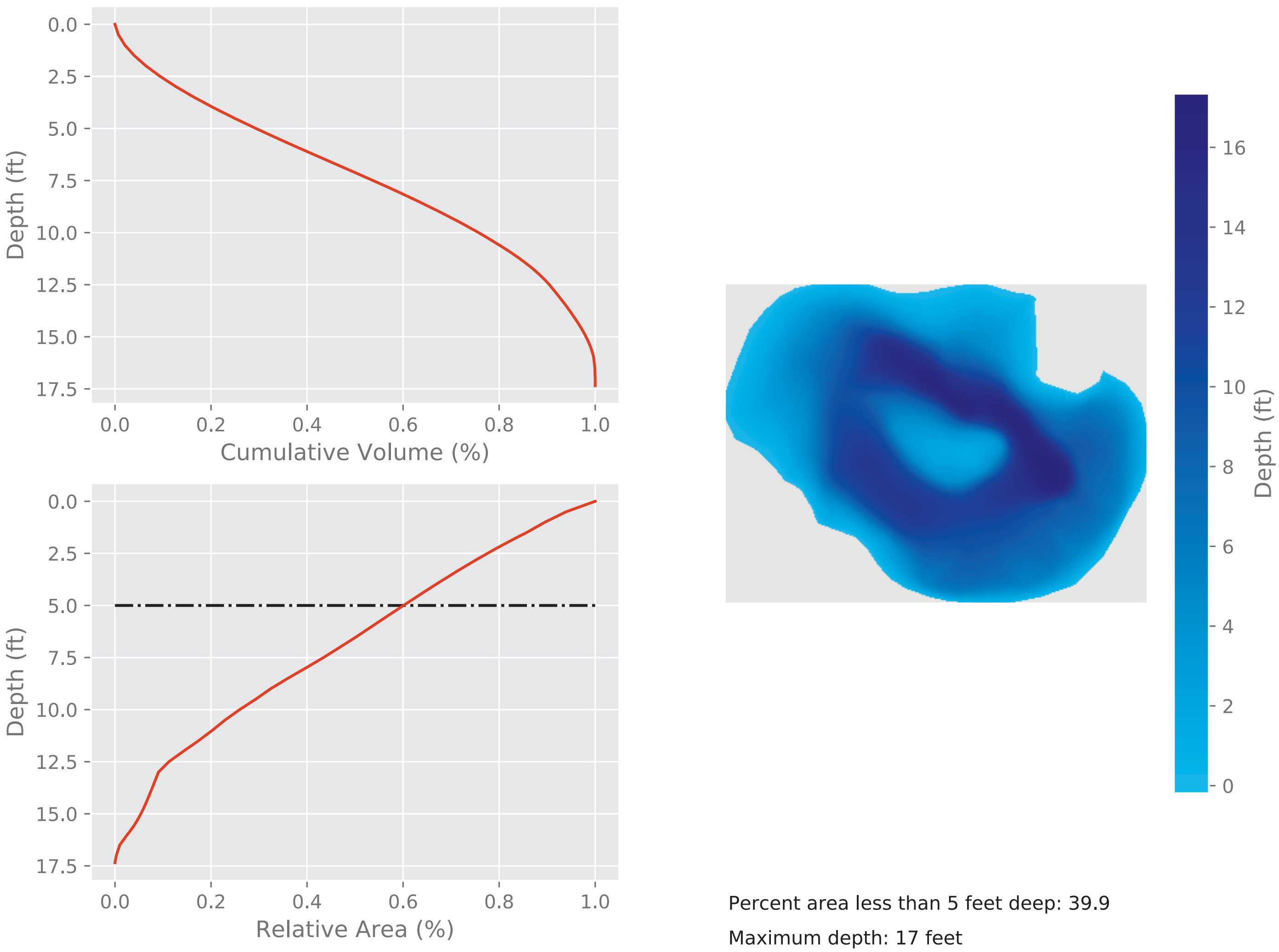


Percent area less than 5 feet deep: 51.1

Maximum depth: 36 feet

Mean depth: 10.5 feet

Staring Lake

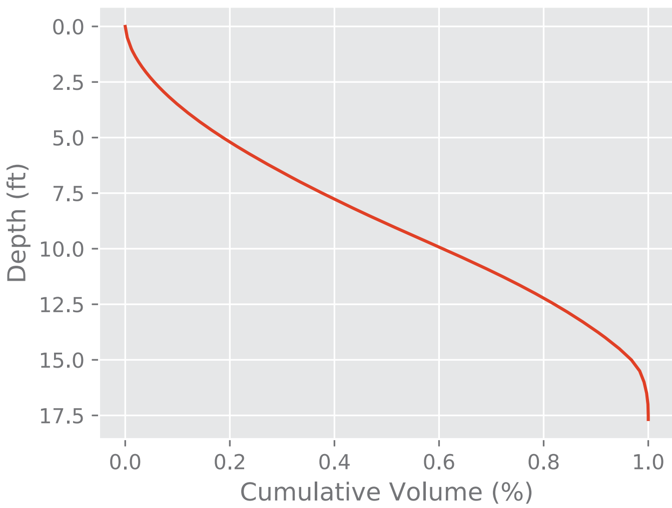


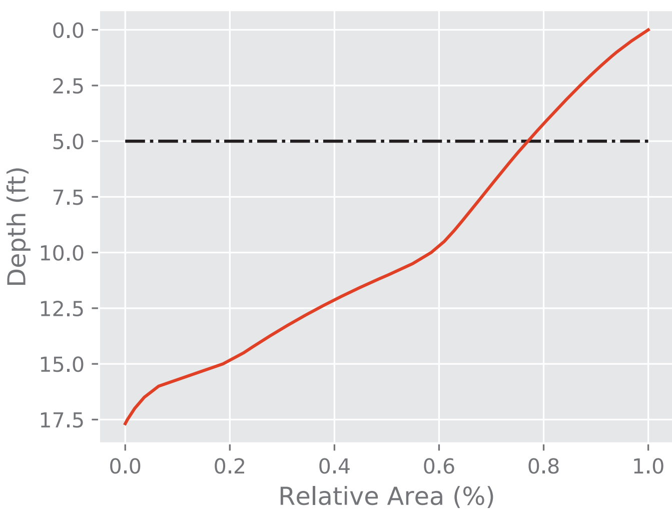
Percent area less than 5 feet deep: 39.9

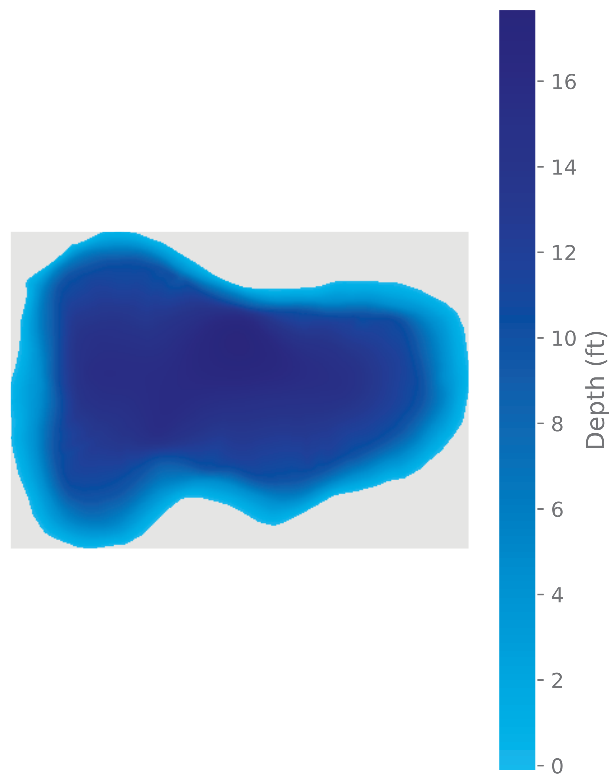
Maximum depth: 17 feet

Mean depth: 6.8 feet

Susan Lake







Percent area less than 5 feet deep: 23.0

Maximum depth: 18 feet

Mean depth: 9.8 feet