COMPILATION GEOLOGIC MODEL FOR CANNON RIVER WATERSHED

Steenberg, J.R., Retzler, A.J., Hamilton, J.D., and Francis, S. W.

Minnesota Geological Survey, 2609 West Territorial Road, St. Paul, MN, 55114, USA

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Minnesota Geological Survey
Harvey Thorleifson, Director

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Executive Summary

This report summarizes the compilation of geologic datasets to support watershed planning efforts. It is part of a two-year pilot project conducted by the Minnesota Geological Survey (MGS) for the Minnesota Department of Health (MDH) Groundwater Restoration and Protection Strategies (GRAPS) program. Our goal was to provide a compilation of both surface and subsurface geologic data within the Cannon River Watershed Board of Water and Soil Resources (BWSR) One Watershed One Plan (1W1P) boundary in a format suitable for both modelers and the general public. Geologic data for the Zumbro, St. Louis, Missouri and Redeye River Watersheds were also compiled as part of this project and presented in individual reports (Steenberg and others, 2021a,b; Steenberg and others, 2022a,b).

The GRAPS program helps local planning efforts prioritize groundwater quality and quantity concerns and provides strategies and actions for protection and restoration (https://www.health.state.mn.us/communities/environment/water/cwf/localimplem.html#HowDoesGRAPS). An MDH GRAPS report is a collection of maps and data describing conditions in a watershed. Eighteen watersheds in Minnesota currently have a GRAPS report for local organizations to use for developing their watershed plans including the Cannon River Watershed ("Cannon River Watershed (07040002) Groundwater Restoration and Protection Strategies Report", 2017). Many state agencies (Board of Water and Soil Resources (BWSR); Minnesota Department of Agriculture (MDA); Minnesota Department of Natural Resources (MNDNR); Minnesota Pollution Control Agency (MPCA)) work together to gather data and create these reports collaboratively. The general geologic information in these reports is not the most detailed information available from the MGS.

The MGS is a nonregulatory research and service arm of the School of Earth and Environmental Sciences at the University of Minnesota. MGS leads a variety of mapping and research activities for the state of Minnesota to support the stewardship of water, land, and mineral resources. The MGS County Geologic Atlas (CGA) mapping program produces maps that depict the distribution of sediments and bedrock in the subsurface and define their boundaries and geologic names (https://cse.umn.edu/mgs/county-geologic-atlas). Our detailed mapping program is widely used and recognized in the state. However, when planning at larger scales that involve several counties (i.e., a watershed), it can be problematic for users to create seamless geologic and hydrogeologic datasets in a Geographic Information System (GIS) environment. This pilot project was set up to address this need for the GRAPS program.

Seamless geologic products across the Cannon River Watershed are based on previously published CGAs, in-progress CGA mapping and new interpolated models in areas where mapping has not been completed yet. Revisions were made along boundaries to achieve consistency across the watershed. These products were transferred into a web-based 3D model (https://arcg.is/09OS1L0) so they could be readily visualized and used outside of a GIS environment by water planners, other state agencies involved in the GRAPS process, and the public. Geologic datasets are provided in the supplementary files of this report in a format suitable for groundwater-surface water modeling. All features are documented with metadata. Basic instructions on how to use the web-based 3D model are also provided in this report.

Introduction

The goal of the Minnesota Geological Survey (MGS) and Minnesota Department of Health (MDH) Groundwater Restoration and Protection Strategies (GRAPS) two-year pilot project was to provide a compilation of both surface and subsurface geologic data within selected Board of Water and Soil Resources (BWSR) One Watershed One Plan (1W1P) boundaries in a format suitable for both modelers and the general public. This report focuses on the Cannon River Watershed in southeast Minnesota (Fig. 1). Separate reports describe the results for the Zumbro, St. Louis, Missouri and Redeye River Watersheds (Steenberg and others, 2021a,b; Steenberg and others, 2022a,b). This report documents the steps taken to compile MGS mapping in the Cannon River Watershed for the unconsolidated Quaternary sediments into a texture-based point model and a series of bedrock layers.

Maps from the County Geologic Atlas (CGA) mapping program were used to compile the most up-to-date geologic information in the Cannon River Watershed. A full CGA contains two major components, designated as “Part A” and “Part B”. Part A is completed by the MGS and includes a package of maps that depict the distribution of sediments and rocks in the subsurface, define their boundaries and geologic names and provide the data used in the creation of the maps (https://cse.umn.edu/mgs/county-geologic-atlas). Supplemental digital and GIS data used in the creation of the maps and all associated geologic products are available for download on our website (https://conservancy.umn.edu/handle/11299/57196). Part B is produced by the Minnesota Department of Natural Resources (MNDNR) and contains detailed groundwater information including hydrogeologic setting, aquifer distribution, pollution sensitivity, groundwater recharge and subsurface flow within the county. Together, this information can be used to make land-use decisions that consider aquifer sensitivity, water quality, and sustainability. This report summarizes the geologic setting and provides a short description of the geologic materials in the watershed. CGA products, however, should be consulted for more detailed information including the geologic setting, geologic data utilized, detailed map unit descriptions, and hydrogeologic properties.

CGAs published prior to the late 2000s generally contain limited GIS data. Modern CGAs include a package of continuous raster surfaces for use in GIS applications for each of the individual map units. Surfaces represent the elevation of the tops and bottoms of the mapped units, and their thicknesses. A raster is a spatial dataset that consists of a matrix of equally-sized cells (or pixels) arranged in rows and columns. Each cell contains an attribute value and location coordinates. They are a powerful GIS tool used to accurately depict the subsurface geologic environment and provide a modeling framework to spatially analyze geology and groundwater.

The Cannon River Watershed spans nine southeast Minnesota counties (Goodhue, Dakota, Rice, Steele, Le Sueur, Waseca, Freeborn, Scott and Blue Earth) and covers an area of approximately 1460 square miles (3780 square kilometers). For this project we've also included the northern section of the Zumbro River Watershed in portions of Waseca and Goodhue counties for groundwater modeling purposes and to cover areas not previously addressed in last year's Zumbro project. Goodhue, Dakota, Rice, Steele, Scott and Blue Earth counties have been mapped as part of the CGA program (Balaban and others, 1990; Hobbs and others, 1995; Setterholm and others, 1998, 2006; Runkel and others, 2001, 2011; Retzler and others, in press), however, they have been individually published over several decades ranging from 1990 to present day and vary in GIS data availability. Counties without a CGA have been mapped in less detail for regional studies and statewide compilations (Bloomgren, 1993; Jirsa and others, 2011; Lusardi and others, 2019).

Geologic Setting

Beneath the land surface, the Cannon River Watershed is composed of unconsolidated Quaternary deposits (<2.6 Ma) and layers of sandstone, shale, and carbonate rock formations from the Paleozoic Era deposited during the Cambrian, Ordovician and Devonian periods (~505-382 Ma). Unconsolidated Quaternary sediments range in thicknesses from 0-458 feet (140 meters). They are thickest in the western part of the watershed and thin to the northeast part of the watershed where bedrock is near the land surface (Fig. 2). Areas with the thickest sediments overlie deeply incised bedrock valley systems in Le Sueur County and the Mississippi River Valley in Goodhue County. Unconsolidated Quaternary sediments are glaciogenic in origin and are derived from bedrock and pre-existing sediments in areas north (Rainy provenance), northwest (Winnipeg and Riding Mountain provenances), and northeast (Superior provenance) of the study area. Materials of each provenance were transported and emplaced along the southern margin of the Laurentide Ice Sheet throughout multiple phases of glacial advance and retreat. Loam-textured diamicton (primarily till—i.e., unsorted sediment deposited directly in contact with glacial ice) is the principal glacial deposit within the watershed, though channelized sand and gravel exists, both at the surface and within the subsurface, in the form of ice-contact (eskers, hummocks, kames) and proglacial (outwash) meltwater deposits. Post-glacial sediments including lake sediment, terrace alluvium, colluvium and floodplain alluvium are also present and are composed of various textures.

Most till and fine-grained glaciolacustrine sediments do not readily transmit water, and hence they behave as aquitards that restrict the flow of groundwater into and out of subsurface aquifers. Alternatively, glaciogenic sand and gravel deposits tend to be highly transmissive and are typically regarded as potential aquifers capable of storing large volumes of groundwater and yielding adequate flow to a well. Quaternary wells are common in the south and west areas of the watershed where glacial deposits are thick and buried sand and gravel aquifers are present. Quaternary sediments, however, are discontinuous and vary in thickness, elevation, and extent over relatively short distances, and hence the majority of wells inside the map area are set within bedrock aquifers. Overlying unconsolidated materials control the rate at which bedrock aquifers are recharged and can influence groundwater chemistry during infiltration.

The various unconsolidated deposits described above that occur within roughly 10 feet (3 meters) of the lowermost soil horizon are depicted in Fig. 3A by their USDA texture. For visualization purposes, these units were simplified further in our online 3D model into four categories that represent sand (sorted coarse-grained sediments), mixed (variable proportions of both sorted and unsorted coarse- and fine-grained sediments), clay (sorted fine-grained sediments), and bedrock (Fig. 3B). A total of 40 units were differentiated within the Cannon River Watershed, including 22 surficial and 27 subsurface units (Table 1) with some units occurring in both.

Eighteen individual bedrock formations are mapped and differentiated in the Cannon River Watershed beneath the Quaternary sediment (Fig. 4). The uppermost layers are dominated by carbonate bedrock and the deepest layers are dominated by sandstone. Paleozoic bedrock formations contain a significant amount of groundwater that provides the water supply for the region. Properties within the bedrock formations control the direction and speed of groundwater flow. More permeable units such as sandstone or carbonate rock containing fractures and voids are aquifers and easily transmit water. Layers with more shale and fine-grained material are less permeable and commonly do not transit water as easily. These layers act as aquitards and protect underlying aquifers. Groundwater is well-connected to surface water in parts of the watershed where unconsolidated sediments are thin to absent, have less clay content, and/or underlying bedrock aquifers are present at the land surface. Small, patchy deposits of Mesozoic (Upper Cretaceous) bedrock are known in areas throughout the Cannon River Watershed but were not considered here as they do not play a significant role in the groundwater system.

Methods

To create a texture-based point model across the watershed individual MGS geologic datasets were first synthesized, compiled and edge-matched into seamless datasets and maps. Compiled products for the Cannon River Watershed were developed into an ArcGIS Online 3D model so they could readily be visualized and used by water planners, other state agencies involved in the GRAPS process, and the public. Because methods for mapping Quaternary sediment and bedrock layers differ, the compilation process for these datasets also differed. Below is a description of the compilation methods used for both bedrock and Quaternary sediment, as well as the visualization methods used in the online 3D model. Explanatory text in the CGAs should be consulted for more detailed MGS mapping methodology. It is beyond the scope of this report to provide full descriptions of these units, however the reader is directed to the source materials outlined in this section for complete accounting of all geologic information.

Watershed-scale Compilation of Bedrock Topography and Bedrock Geology

Bedrock topography represents the elevation of the bedrock surface and the bottom of the unconsolidated sediments. Bedrock topography is contoured by a geologist in map view at 25- to 50-foot contour intervals. Existing datasets were compiled and edge-matched, including bedrock topography contours from the statewide compilation of Jirsa and others (2011) and references therein, the 10-county Bedrock Geology map of Mossler (2013) and Retzler (in press) (Table 2). These contours were transformed into a raster surface using the “Topo to Raster” tool in ESRI ArcMap 10.7. The bedrock topography raster was set to be equal or less than that of the land surface 30-meter DEM.

A similar approach was used for the creation of unit surfaces that depict the individual bedrock formations. Existing contour lines from previous maps were compiled into one shapefile for the elevation of the top of the Jordan Sandstone (Table 2). Contours were edited to match along county edges. Revised contour mapping focused on the faulted areas within Wabasha, Goodhue and Rice Counties to more accurately depict the geologic structure in the watershed. Contouring was done at 25-foot (7.6-meter) intervals and a unit surface was subsequently constructed using the “Topo to Raster” tool in ArcMap 10.7. Using the unit surface of the top of the Jordan Sandstone as a reference, unit surfaces for all other bedrock units were calculated by adding or subtracting their estimated thicknesses. In some cases, isopach surfaces (i.e., surfaces depicting the thickness of a mapped unit across a region) were also used to derive unit surfaces for any bedrock unit with significant thickness variations across the Cannon River Watershed. These units include the Mt. Simon Sandstone, Eau Claire Formation, Tunnel City, St. Lawrence Formation, Prairie du Chien Group and Decorah and Maquoketa Formation. The bedrock layers are depicted in this dataset as a series of rasters representing elevations of the top and bottom of each unit, their thickness, as well as the bedrock topography. All raster surfaces can be viewed 2-dimensionally or 3-dimensionally in a GIS environment or through our online 3D model.

Watershed-scale Compilation of Surficial Quaternary (Unconsolidated) Sediments

To create the seamless surficial geology map across the watershed, 1:100,000 scale geologic contacts from the digital database D-1 (https://mngs-umn.opendata.arcgis.com) were combined with those from the more recent map completed in Steele County (Retzler and others, in press). The digital database D-1 contains lines, labels, and polygons that were compiled and edge-matched from all previous MGS Quaternary maps and is a digital companion to the statewide map of Quaternary geology (Lusardi and others, 2019). Unit identifiers from the Steele CGA updated mapping were modified to match the D-1 schema. With the exception of post-glacial materials, all Quaternary deposits are assigned to lithostratigraphic units defined in Johnson and others (2016).

All previous MGS Quaternary maps in this area were compiled using descriptions and samples collected from exposures, gravel pits, road cuts, water-well cuttings, rotary-sonic cores and soil-auger borings. These descriptions and samples, as well as engineering test borings from various organizations, are part of the MGS Quaternary Data Index (QDI). Geologic interpretations were also supported by the soil map of the region (Natural Resources Conservation Service, 2014), and well logs from the County Well Index (CWI). Map units are distinguished from one another by texture, lithology of the very coarse-grained sand fraction (1-2 millimeters), stratigraphic position, and landscape position.

Watershed-scale Compilation of Subsurface Quaternary (Unconsolidated) Sediments

Below the near surface (surficial) sediments, different layers of till and outwash deposits are present at depth in the subsurface. Mapping the subsurface Quaternary layers is part of a modern County Geologic Atlas product. Subsurface Quaternary mapping is accomplished by creating a set of east-west cross sections to depict the various layers. Coordinates and elevations from the geologic unit contacts are extracted from the cross sections in GIS and interpolated into unit surfaces (tops, bottoms and thicknesses). Unit bases are used to build a Quaternary geologic model from youngest to oldest units. The land surface is cut by progressively older units, with the younger eroded surface becoming the top of the unit below. Steele County is the only county in the watershed with Quaternary subsurface mapping that defines the Quaternary formations and textures. No new Quaternary subsurface mapping outside of Steele County was completed for this project. To define the texture of the subsurface

Quaternary materials in the watershed outside of Steele County interpolation models were run that incorporate drillers descriptions from water-well information. Information outside of Steele County only defines texture and does not assign the texture to a particular unit.

Texture-based Point Model

The unconsolidated sediments above bedrock are depicted in this dataset as a series of points referred to as a texture-based point model. Texture is reported based on the percent sand, silt and clay as one of the twelve recognized United States Department of Agriculture (USDA) soil texture classes (Soil Science Division Staff, 2017). We have also included gravelly sand in our descriptions, as these are important properties for modeling groundwater flow in the subsurface, despite not being recognized as official USDA textures (Table 3). The texture-based point model can be viewed 2-dimensionally or 3-dimensionally in a GIS environment or through our online 3D model (Fig. 5, https://arcg.is/09OS1L0). The texture-based point model for our online 3D model generalized these textures further into sand, mixed (variable amounts of clay and sand), and clay (Table 3).

The texture-based point model was created to visualize textures at and below the ground surface, down to bedrock (Fig.5). The model points are at a 250-meter (820-foot) regularly-spaced interval with 5-foot (1.5-meter) vertical spacing across the watershed. All points are uniquely identified with a ‘Unique_ID’ attribute that concatenates its UTM coordinate and elevation. There are nearly 1.4 million points in the model. The model was produced in three modeling stages that were subsequently combined. The three modeling stages are referred to as the “surficial model”, “subsurface model”, and the “interpolated model”. The surficial model points used the surficial geologic map created for this project. The map was intersected with the uppermost point in the matrix, at ground elevation, and assigned the respective map unit label and associated texture. The subsurface model points were intersected with the 27 subsurface rasters within Steele County. Points were assigned the respective map unit label and associated texture if their elevation was within the elevation range of the top and bottom of a particular Quaternary unit surface.

The interpolated point model was constructed, using ESRI ArcGIS Pro, by applying ordinary kriging estimation and prediction standard error methods on the current lithology data listed in the CWI stratigraphy table to estimate the likelihood of sand, mixed or clay (Tipping, 2019). Well data was assigned a ‘kclass’ value of 1 (fine-grained material, clay loam), 2 (mixed material, sandy loam), or 3 (coarse-grained material, gravel and/or sand) (Table 4). Data were then interpolated using ordinary kriging separately for the likelihood of ‘kclass’ > 2.5 = sand and the likelihood of ‘kclass’ < 1.5 = clay. For the mixed values, a third process was run where mixed values (sandy loam, loamy sand) = 1 and all other values= 0. Ordinary indicator kriging was run to produce the likelihood of ‘kclass_mix’ > 0.75 = mixed. Prediction standard error methods were used to limit interpolation based on data density. This method identifies locations where there isn’t enough data for the interpolated model process to estimate the likelihood of sand, mixed material, or clay. Any points not assigned to a value from the interpolation process because of lack of data are shown as an unknown value. Remaining points are assigned their likelihood of occurrence in the field ‘spot’ (% likely) in the point model attribute tables. In the case of overlapping values (i.e., the same point location within the interpolated model), sand overwrites clay or mixed, and mixed overwrites clay. The surficial, subsurface, and interpolated models are separate modeling processes to interpret the texture at any given point in the subsurface. These separate modeling processes were combined into one point model with no overlapping points based on the following hierarchy: the surficial model overrides the subsurface model, which overrides the interpolated model.

3D Visualization Methods

A 3D geologic model for the Cannon River Watershed was built using ESRI ArcGIS Pro 2.9 and the data described above (Fig. 5). For the bedrock, each top and bottom unit surfaces were converted into triangular irregular network (TIN) datasets using the “Raster to TIN” tool. Each TIN was configured with a Z Tolerance value of 10 (to balance precision with 3D drawing performance) and a Z factor of 6.096 (to convert the z-axis elevation values to meters while exaggerating the scale 20 times). The top and bottom TINs, along with the polygon delineating the Cannon River Watershed, were used to create a 3D multipatch of each bedrock unit using the “Extrude Between” tool.

For the Quaternary, the surficial geology polygons were reclassified based on the USDA texture into four generalized textural categories (clay, mixed, sand, and bedrock) (Fig. 3B, Table 1 and 3). Each of the four textural categories were then exported as 2D polygon layers. To better visualize the subsurface data, a subset of the texture-based point model was created, and its vertical z-axis values converted to meters and exaggerated 20 times. Because points in Steele County were the only data in the Cannon River Watershed based on more detailed subsurface CGA mapping, a finer subset spacing was used in this area (1000 x 1000 meters [3281 x 3281 feet] and 20 feet [6.1 meters] in the vertical). Elsewhere, the subset was spaced at 1250 x 1250 meters [4101 x 4101 feet] and 40 feet [12.2 meters] in the vertical. Each of the four textural categories were then exported as 3D point layers.

Depth to bedrock was also included in the 3D model and was calculated by subtracting the bedrock topography raster from the land surface DEM. The resultant raster was then reclassified into 50-foot (15.2-meter) intervals and converted into a 2D polygon layer.

The derivative bedrock and Quaternary data were compiled into an ArcGIS Pro Local Scene with the “Ground” reference layer set as a 20x vertically-exaggerated, 30-meter (98-foot) land surface DEM. This DEM was originally sourced from 1-meter lidar data supplied by the MNDNR and converted from feet to meters. The ArcGIS Pro Local Scene was then shared to ArcGIS Online as a web scene and imported into a web app, where further adjustments were made for accessibility and optimization.

Using the Web-based 3D Model

The web-based 3D model (https://arcg.is/09OS1L0) is meant to be a visualization tool for water planners, other state agencies involved in the GRAPS process, and the general public. It is made readily accessible in a browser, requiring no GIS software. The model is separated into four parts: depth to bedrock, surficial glacial geology, subsurface glacial geology, and bedrock geology. The depth to bedrock layer is shown as 2D polygons classified in 50-foot (15.2-meter) intervals. The surficial and subsurface glacial geology has been simplified into four textural categories of clay, mixed, sand, and bedrock. Each category is a separate layer in the model that can be turned on/off independently of the others. The surficial geology is shown as 2D polygons and represents the unconsolidated glacial sediments within a few meters of the land surface and where bedrock is within a few meters of the land surface. The polygons are shown with slight transparency to allow users to peer through them at underlying data. Below these polygons are the 3D point data representative of the subsurface glacial geology from the base of the surficial deposits down to the top of bedrock. Because data derived from subsurface CGA mapping are more detailed than those interpolated from water well information, a finer spacing of points is shown in Steele County than elsewhere in the watershed (see previous section “3D Visualization Methods” for spacing measurements). Below the point data lie the 3D bedrock layers representing the mappable Paleozoic units in the Cannon River Watershed. Each bedrock unit is a separate layer in the model that can be tuned on/off independently of the others. To better visualize thinner geologic units at this scale, the 3D model is exaggerated 20 times in the vertical and the surficial geology, subsurface geology and bedrock datasets are vertically offset from one another and from the ground surface to prevent data overlap. Furthermore, a Geographic References layer and three different Basemap layers are included for reference. The Geographic References layer is an overlay of geographic boundaries, roads, city names and various other geographic features, so the user can readily identify or search by surface areas of interest.

Upon each initial access, the web-based 3D model loads from a plan- (or map-) view perspective. You can return to this view by clicking the *Home* button on the left side of the map window. You can zoom in or out using the buttons on the left side of the map window, by scrolling a mouse wheel, or by pinching in/out with two fingers when viewed from a touch-compatible device. To rotate the 3D model, right-click and drag your cursor within the map window or press with two fingers and drag across the map window when viewed from a touch-compatible device. You can also change your primary navigation setting by clicking on the *Navigate* button on the left side of the map window. Above the *Navigate* button is a *My Location* button that will detect your physical location and zoom the map to it based on available network or GPS location. You can use the *Search Box*, located in the upper right corner, to zoom to a specific address or geographic location. Just below the *Search Box* is the *Reset Compass Orientation* button (to reset the compass orientation of the map view) and the *Full Screen* button (to view the 3D web model in full screen).

To the left of the map window lies the widget window containing 5 widgets: *Legend*, *Layer List*, *Measurement*, *Share* and *About*. The *Legend* acts as the map key, indicating the symbol type and color for features currently displayed in the map window. This is especially useful for discerning the textural categories of the Quaternary data and the various bedrock units, and is the primary widget shown upon each initial access to the web model. The *Layer List* shows all the available layers contained within the 3D web model and gives users the ability to turn on and off each layer by clicking the checkbox. Note that only one Basemap layer can be turned on at a time. The *Measurement* widget contains tools that allow you to measure the area or distance of a user-defined polygon or line in the map window. The *Share* widget contains a shortened URL that can be copied and shared with others to quickly access this 3D web model, along with options to embed this model on a separate website. Lastly, the *About* widget gives a summary of the model, its intended purpose, and acknowledgement of funding.

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Figure Captions

Figure 1. Watershed map of Minnesota highlighting the location of the Cannon River Watershed in southeast Minnesota. Gray lines show the One Watershed One Plan watershed boundaries, and the red line depicts the Cannon River Watershed.

Figure 2. Depth to bedrock or thickness of the unconsolidated (Quaternary) sediments in the Cannon River Watershed generated from subtracting the bedrock topography raster from the land surface raster. Thickness of unconsolidated deposits are depicted in the legend in 50-foot intervals. Thicker sediments are represented by brown, gray and white colors and areas of thin sediments are light blue and light green.

Figure 3. A) Surficial geology map of the Cannon River Watershed compiled for this project. Textures of the Quaternary units are differentiated by colors shown in the legend and defined in Table 1. B) Surficial geology map of the Cannon River Watershed simplified into four texture classes of sand, clay, mixed (variable amounts of clay and sand), and bedrock as shown in the online 3D model (https://arcg.is/09OS1L0).

Figure 4. Bedrock geology map of the Cannon River Watershed compiled for this project. Bedrock faults are shown in black. Bedrock layers are differentiated by colors shown in the legend.

Figure 5. The 3D geologic map for the Cannon River Watershed with only subsurface data displayed. This image shows the texture-based point model for the Quaternary sediments in four generalized texture categories (clay, mixed, sand, and bedrock) as well as the underlying bedrock geologic units.

Table 1. Quaternary map units showing map unit type, name, label, texture, and generalized texture. Unit labels for this compilation are consistent with the statewide Quaternary mapping of S-23 (Lusardi and others, 2019) and are different than the Steele CGA and noted in the table.

Table 2. Reference table for the different MGS sources used to create the different pieces of this geologic model.

Table 3. USDA texture table of possible textures for each mapped unit and their generalized texture into sand, mixed, or clay. This generalization is consistent for all GRAPS watershed models created by MGS.

Table 4. CWI table of lithologies from the stratigraphy information in CWI with our K class interpretation (1, 2, or 3) for use in the interpolated model.

Figure 1.

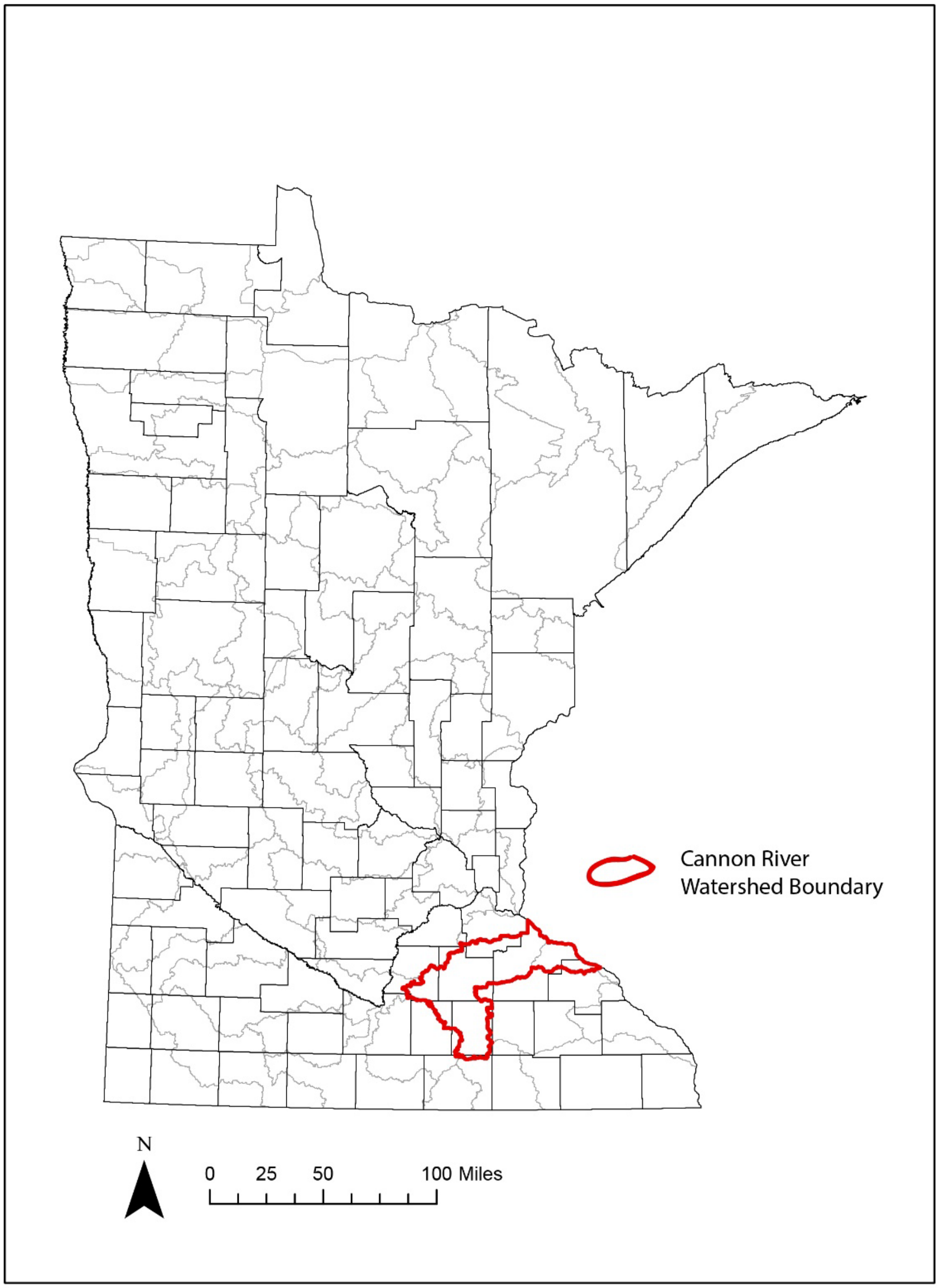

Figure 2

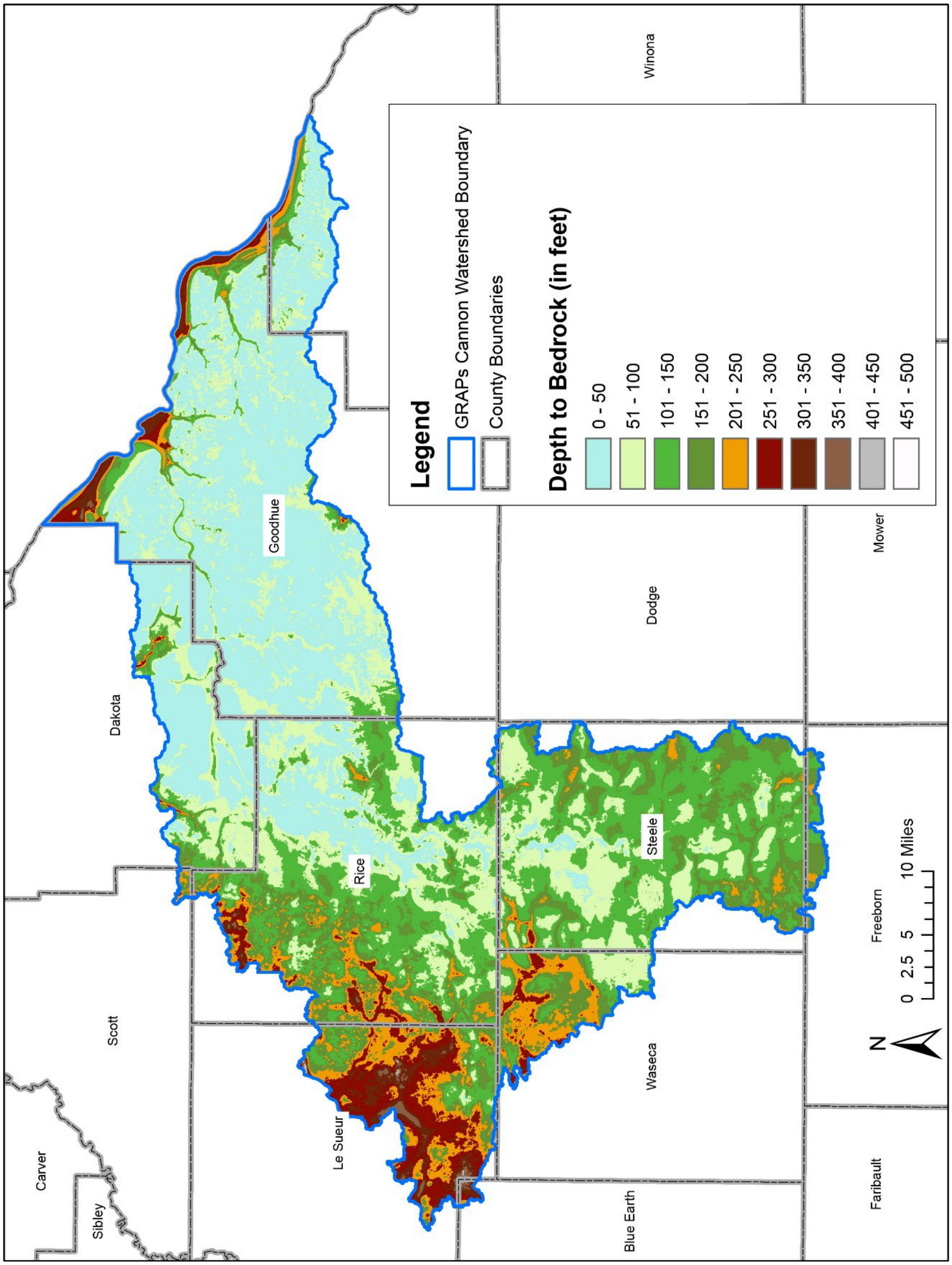
Legend
GRAPs Cannon Watershed Boundary
County Boundaries
Depth to Bedrock (in feet)
0 - 50
51 - 100
101 - 150
151 - 200
201 - 250
251 - 300
301 - 350
351 - 400
401 - 450
451 - 500
Winona
Goodhue
Dakota
Dodge
Mower
Rice
Steele
Scott
Freeborn
Waseca
Le Sueur
Carver
Sibley
Blue Earth
Faribault
N
0 2.5 5 10 Miles

Figure 3A

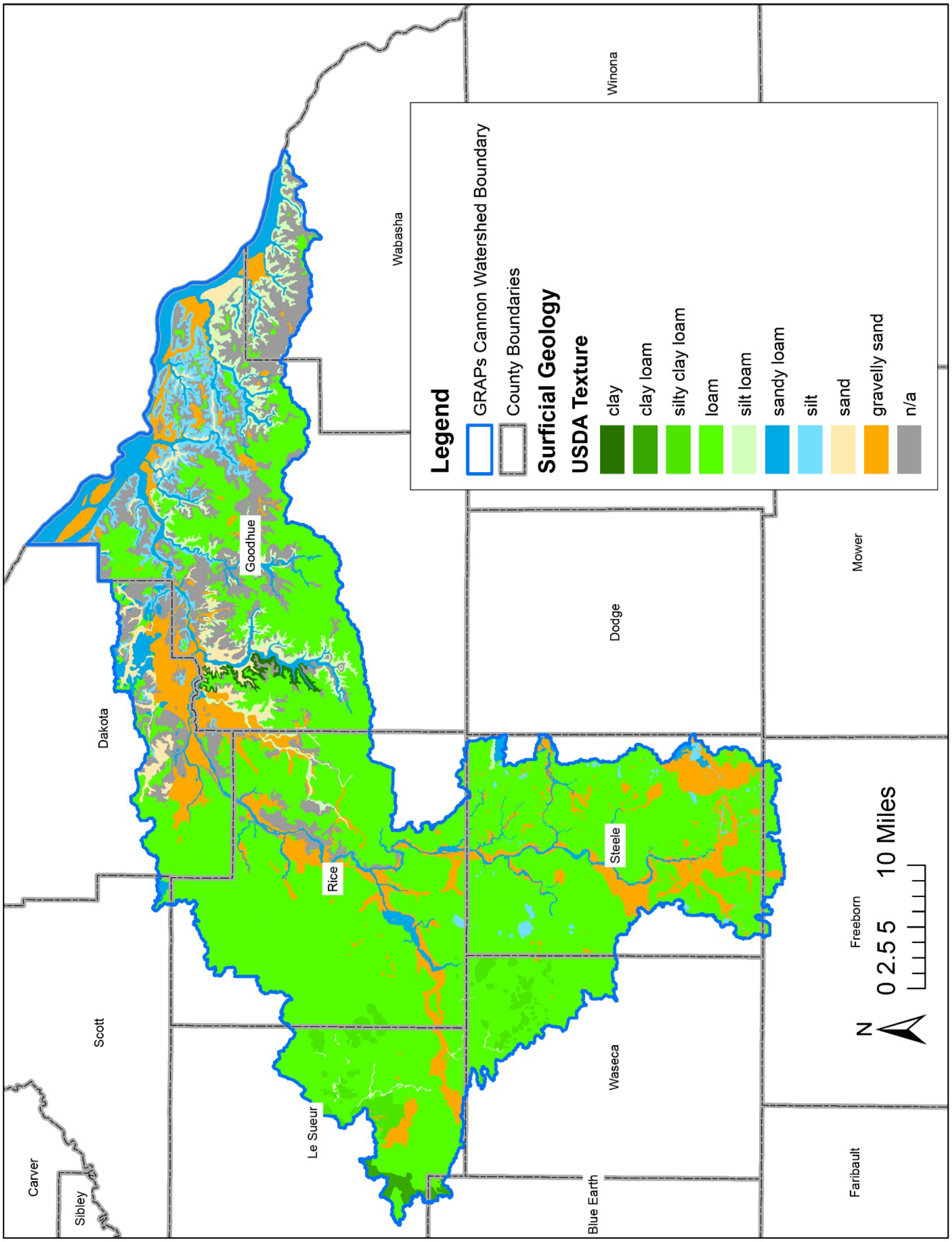
Legend
GRAPs Cannon Watershed Boundary
County Boundaries
Surficial Geology
USDA Texture
clay
clay loam
silty clay loam
loam
silt loam
sandy loam
silt
sand
gravelly sand
n/a
Winona
Wabasha
Goodhue
Dakota
Dodge
Mower
Rice
Steele
Scott
Freeborn
Waseca
Le Sueur
Carver
Sibley
Blue Earth
Faribault
N
0 2.5 5 10 Miles

Figure 3B

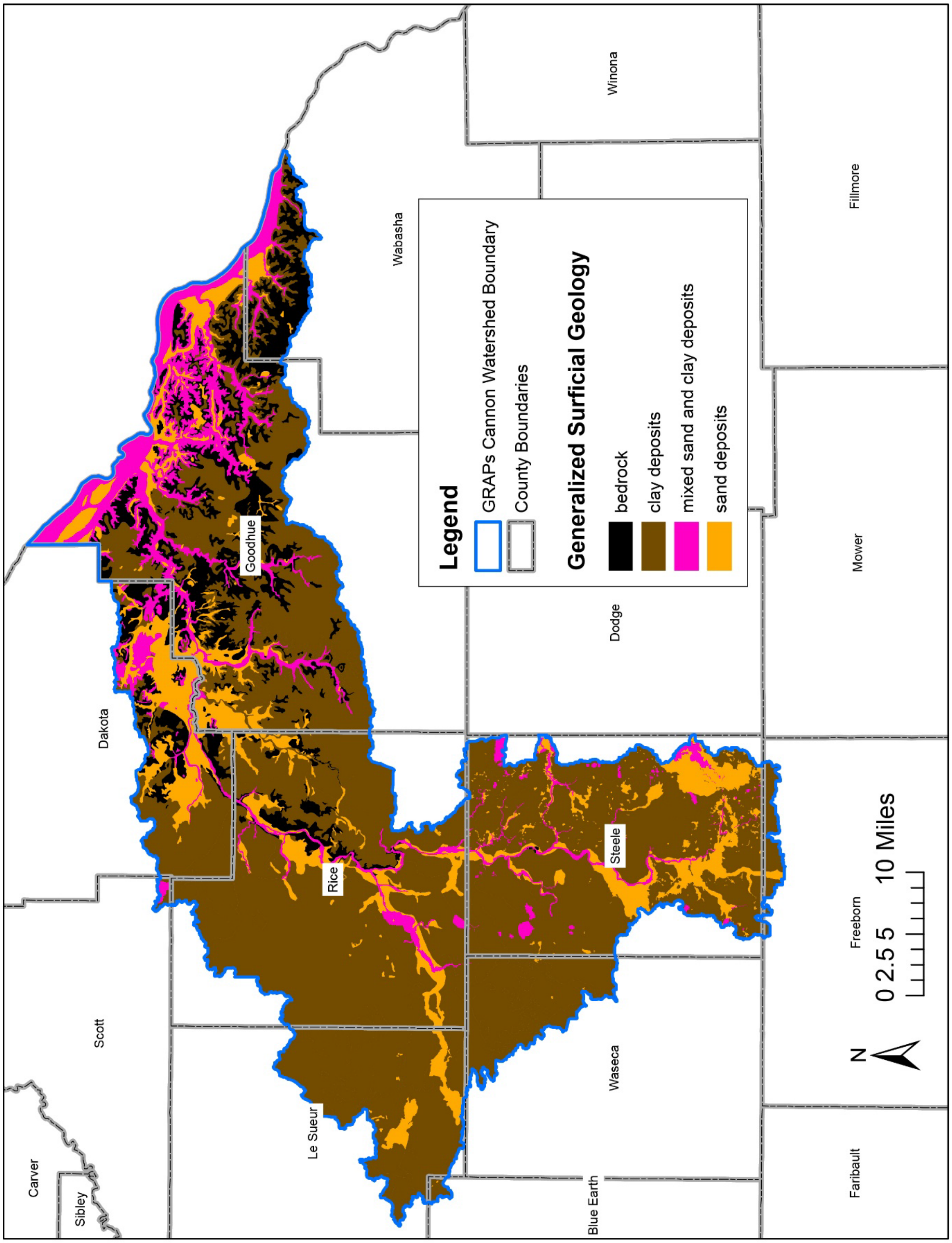
Legend
GRAPs Cannon Watershed Boundary
County Boundaries
Generalized Surficial Geology
bedrock
clay deposits
mixed sand and clay deposits
sand deposits
Carver
Sibley
Scott
Dakota
Goodhue
Wabasha
Winona
Le Sueur
Rice
Dodge
Steele
Waseca
Blue Earth
Faribault
Freeborn
Mower
Fillmore
N
0 2.5 5 10 Miles

Figure 4

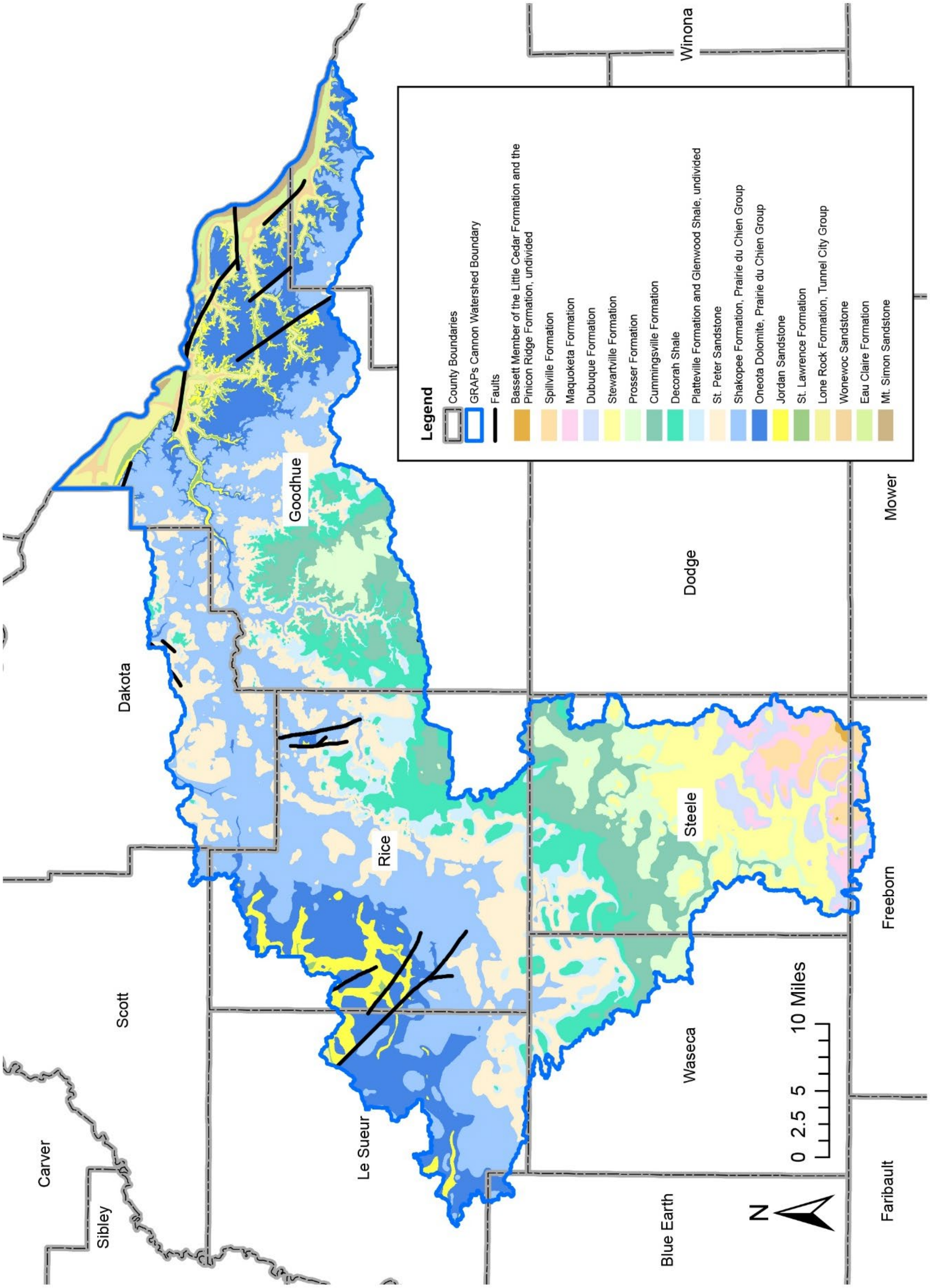
Legend
County Boundaries
GRAPs Cannon Watershed Boundary
Faults
Bassett Member of the Little Cedar Formation and the Pinicon Ridge Formation, undivided
Spillville Formation
Maquoketa Formation
Dubuque Formation
Stewartville Formation
Prosser Formation
Cummingsville Formation
Decorah Shale
Platteville Formation and Glenwood Shale, undivided
St. Peter Sandstone
Shakopee Formation, Prairie du Chien Group
Oneota Dolomite, Prairie du Chien Group
Jordan Sandstone
St. Lawrence Formation
Lone Rock Formation, Tunnel City Group
Wonewoc Sandstone
Eau Claire Formation
Mt. Simon Sandstone
Winona
Goodhue
Dakota
Dodge
Mower
Steele
Rice
Scott
Freeborn
Waseca
Carver
Le Sueur
Sibley
Blue Earth
Faribault
N
0 2.5 5 10 Miles

Figure 5.

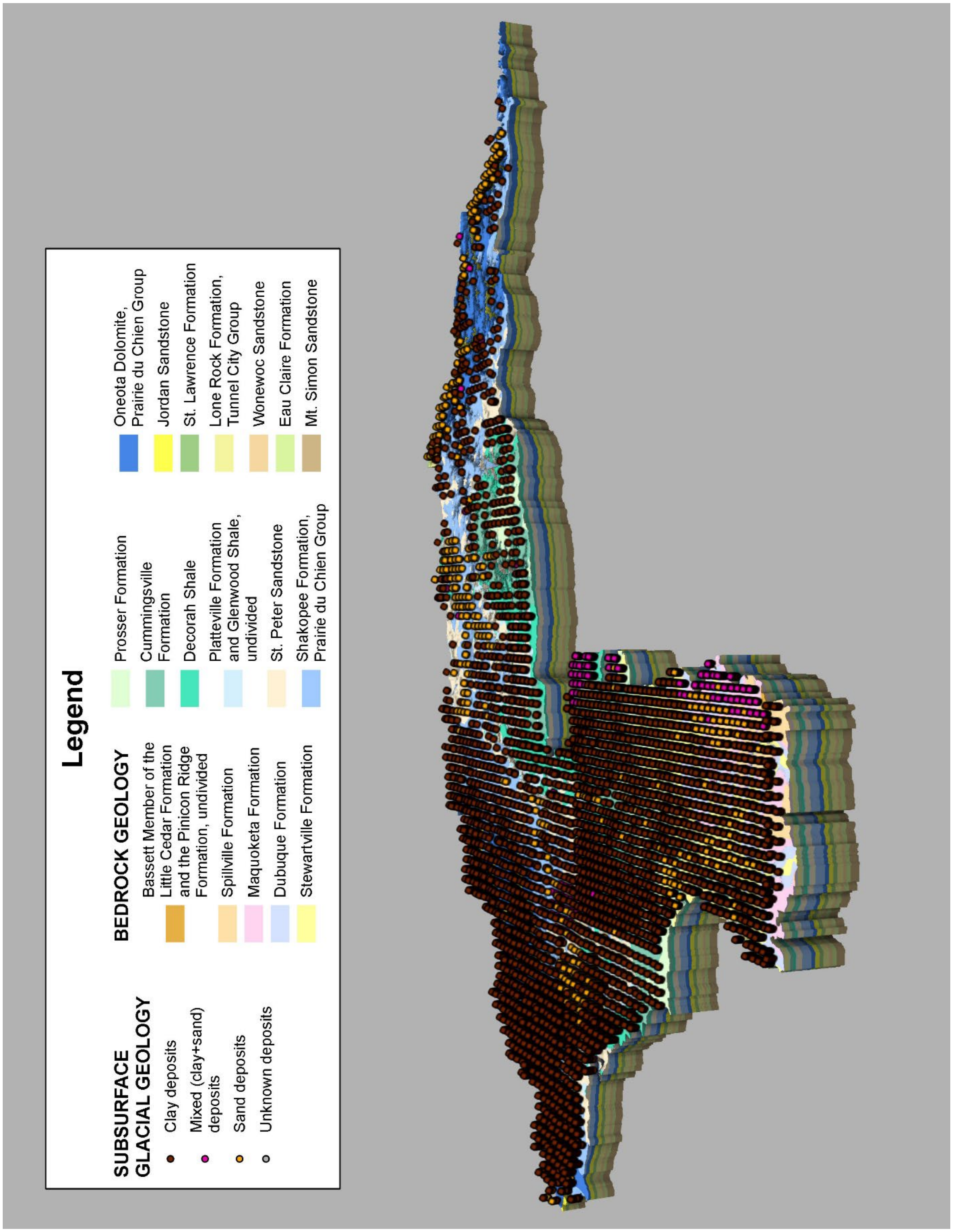
Legend
SUBSURFACE GLACIAL GEOLOGY
● Clay deposits
● Mixed (clay+sand) deposits
● Sand deposits
● Unknown deposits
BEDROCK GEOLOGY
Bassett Member of the Little Cedar Formation and the Pinicon Ridge Formation, undivided
Spillville Formation
Maquoketa Formation
Dubuque Formation
Stewartville Formation
Prosser Formation
Cummingsville Formation
Decorah Shale
Platteville Formation and Glenwood Shale, undivided
St. Peter Sandstone
Shakopee Formation, Prairie du Chien Group
Oneota Dolomite, Prairie du Chien Group
Jordan Sandstone
St. Lawrence Formation
Lone Rock Formation, Tunnel City Group
Wonewoc Sandstone
Eau Claire Formation
Mt. Simon Sandstone

Table 1.

Map type		Map Label	Lithostratigraphic Formation/Member	Unit type	USDA texture	Generalized 3D model texture	Steele CGA Unit Code
Subsurface	*Surficial*	al	Post-glacial	Floodplain Alluvium	Gravelly sand, sandy loam, silt, silt loam, loamy sand	Sand, mixed, clay	Qal
	Surficial	co	n/a	Colluvium	Clay, silt, silt loam	Clay, mixed	--
	Surficial	tef	n/a	Glaciolacustrine	Silt	Mixed	--
	Surficial	te	n/a	Terrace alluvium	Gravelly sand, sand	Sand	--
Subsurface	*Surficial*	hls	n/a	Lake Sediment	Silt	Mixed	Qlc
Subsurface	*Surficial*	nui	New Ulm Formation, undifferentiated	Ice Contact Glaciofluvial	Gravelly sand, loam	Sand, clay	Qnc
Subsurface	*Surficial*	glc	New Ulm Formation, undifferentiated	Lake Sediment	Silt, clay loam, silty clay loam, silt loam, silty clay	Mixed, clay	Qnl
Subsurface	*Surficial*	nuo	New Ulm Formation, undifferentiated	Outwash	Gravelly sand	Sand	Qno
	Surficial	nhh	New Ulm Formation, Heiberg Member	Hummocky Till	Loam	Clay	Qhh
	Surficial	nhm	New Ulm Formation, Heiberg Member	Collapsed Till	Loam	Clay	Qhm
Subsurface	*Surficial*	nh, nh1	New Ulm Formation, Heiberg Member	Till	Loam	Clay	Qht1
Subsurface		nho	New Ulm Formation, Heiberg Member	Outwash	Sand	Sand	Qhs
Subsurface		nh2	New Ulm Formation, Heiberg Member	Till	Loam	Clay	Qht2
	Surficial	nlh	New Ulm Formation, Villard Member	Hummocky Till	Loam	Clay	--
Subsurface		nlo1	New Ulm Formation, Villard Member	Outwash	Sand	Sand	Qvs1
Subsurface		nl1	New Ulm Formation, Villard Member	Till	Loam	Clay	Qvt1
Subsurface		nlo2	New Ulm Formation, Villard Member	Outwash	Sand	Sand	Qvs2
Subsurface		nl2	New Ulm Formation, Villard Member	Till	Loam	Clay	Qvt2
Subsurface		nmo	New Ulm Formation, Moland Member	Outwash	Sand	Sand	Qms
Subsurface	*Surficial*	nm	New Ulm Formation, Moland Member	Till	Loam, sandy loam	Clay, mixed	Qmt
	Surficial	nt	New Ulm Formation, Twin Cities Member	Till	Sandy loam	Mixed	--

	Surficial	rfo	River Falls Formation	Outwash	Gravelly sand	Sand	--
	Surficial	rfi	River Falls Formation	Till, sand and gravel	Sandy loam	Mixed	--
Subsurface	*Surficial*	bvo	Browerville Formation	Outwash	Sand	Sand	Qbs1
Subsurface	*Surficial*	bv	Browerville Formation	Till	Loam	Clay	Qbt1
Subsurface		rco	Rose Creek Formation	Outwash	Sand	Sand	Qrs
Subsurface		rc	Rose Creek Formation	Till	Loam	Clay	Qrt
Subsurface		lho	Lake Henry Formation, Meyer Lake Member	Outwash	Sand	Sand	Qls
Subsurface		lm	Lake Henry Formation, Meyer Lake Member	Till	Loam	Clay	Qlt
Subsurface		ell	Elmdale Formation	Glaciolacustrine	Silty clay	Clay	Qel
Subsurface		elo1	Elmdale Formation	Outwash	Sand	Sand	Qes1
Subsurface		el1	Elmdale Formation	Till	Silt loam	Clay	Qet1
Subsurface		elo2	Elmdale Formation	Outwash	Sand	Sand	Qes2
Subsurface		el2	Elmdale Formation	Till	Silt loam	Clay	Qet2
	Surficial	pio	Pierce Formation	Outwash	Gravelly sand	Sand	--
	Surficial	pi	Pierce Formation	Till	Loam	Clay	--
Subsurface		uno	Undifferentiated sand and gravel	Outwash	Sand	Sand	Qus
Subsurface		und	Undifferentiated Pleistocene sediment	Unknown	Unknown	Unknown	Qup
	Surficial	sb	n/a	Thin sediment over bedrock	n/a	Bedrock	--
	Surficial	b	Bedrock	Bedrock	n/a	Bedrock	Ou

Table 2.

Dataset	Sources	Areas
Bedrock Topography	Bedrock Geology of the Twin Cities Ten-County Metropolitan Area (Mossler, 2013)	Dakota and Scott Counties
	S-21 Bedrock Geology of Minnesota (Jirsa and others, 2011)	Le Sueur, Rice, Goodhue, Wabasha, Blue Earth, Waseca, Freeborn
	Steele County Bedrock Topography (Retzler and others, in press)	Steele County
Bedrock Geology	Bedrock Geology of the Twin Cities Ten-County Metropolitan Area (Mossler, 2013)	Dakota and Scott Counties
	Zumbro GRAPS compilation (Steenberg and others, 2021)	Rice, Goodhue, Wabasha Counties
	Steele Bedrock Geology (Retzler and others, in press)	Steele and Freeborn County
	Waseca Bedrock Geology (Bloomgren, 1993)	Waseca County
	Blue Earth Bedrock Geology (Runkel and others, 2011)	Blue Earth County
	Goodhue CGA (Setterholm and others, 1998)	Goodhue County
	Wabasha CGA (Runkel and others, 2001)	Wabasha County
Surficial Geology	D-1 Surficial Geology of Minnesota (2021)	Dakota, Scott, Le Sueur, Rive, Goodhue, Wabasha, Blue Earth, Waseca, and Freeborn Counties
	Steele Surficial Geology (Retzler and others, in press)	Steele County
Quaternary Subsurface	Steele Quaternary Stratigraphy (Retzler and others, in press)	Steele County

Table 3.

USDA Texture	Generalized Web Model Texture
Clay	Clay
Silty Clay	Clay
Clay Loam	Clay
Silty Clay Loam	Clay
Loam	Clay
Silty Loam	Clay
Silt	Mixed
Sandy Clay	Mixed
Sandy Clay Loam	Mixed
Sandy Loam	Mixed
Loamy Sand	Sand
Sand	Sand
Gravelly Sand	Sand

Table 4.

OBJECTID	strat	FREQUENCY	kclass
1		56	
2	bedrock	18269	
3	boulder	178	
4	clay	811	1
5	clay, black	40	1
6	clay, blue	2492	1
7	clay, brown	1308	1
8	clay, gravel	183	1
9	clay, gravel, black	8	1
10	clay, gravel, blue	212	1
11	clay, gravel, brown	259	1
12	clay, gravel, gray	311	1
13	clay, gravel, green	4	1
14	clay, gravel, red	3	1
15	clay, gravel, white	4	1
16	clay, gravel, yellow	73	2
17	clay, gray	730	1
18	clay, green	43	1
19	clay, organic	11	1
20	clay, red	41	1
21	clay, sand	290	2
22	clay, sand, black	18	2
23	clay, sand, blue	532	2
24	clay, sand, brown	412	2
25	clay, sand, gray	346	2
26	clay, sand, green	10	2
27	clay, sand, organic	1	2
28	clay, sand, red	9	2
29	clay, sand, white	5	2
30	clay, sand, yellow	182	2
31	clay, silt	40	1
32	clay, silt, black	19	1
33	clay, silt, brown	27	1
34	clay, silt, gray	17	1
35	clay, silt, yellow	3	1
36	clay, white	32	1
37	clay, yellow	1743	1
38	coal	2	
39	drift	933	1
40	fill	203	1
41	gravel	1167	3
42	gravel, clay	65	1
43	gravel, clay, black	3	1
44	gravel, clay, blue	28	1
45	gravel, clay, brown	87	1
46	gravel, clay, gray	51	1
47	gravel, clay, green	1	1

48	gravel, clay, red	1	1
49	gravel, clay, white	4	1
50	gravel, clay, yellow	7	1
51	gravel, organic	1	
52	gravel, silt	17	3
53	gravel, silt, black	1	2
54	gravel, silt, brown	3	2
55	gravel, silt, gray	1	2
56	gravel, silt, green	1	2
57	irrelevant	297	
58	lake_sed	1	2
59	nrcd	5	
60	organic	20	
61	pit	1	
62	sand	820	3
63	sand, black	14	3
64	sand, blue	4	3
65	sand, brown	1309	3
66	sand, clay	112	2
67	sand, clay, black	7	2
68	sand, clay, blue	64	2
69	sand, clay, brown	166	2
70	sand, clay, gray	85	2
71	sand, clay, green	3	2
72	sand, clay, red	1	2
73	sand, clay, white	2	2
74	sand, clay, yellow	28	2
75	sand, gravel	1501	3
76	sand, gray	343	3
77	sand, green	2	3
78	sand, organic	7	3
79	sand, red	17	3
80	sand, silt	57	3
81	sand, silt, black	14	3
82	sand, silt, blue	2	3
83	sand, silt, brown	72	3
84	sand, silt, gray	30	3
85	sand, silt, yellow	1	3
86	sand, white	17	3
87	sand, yellow	115	3
88	silt	18	1
89	silt, black	40	2
90	silt, brown	19	1
91	silt, clay	12	1
92	silt, clay, black	2	1
93	silt, clay, brown	5	1
94	silt, clay, gray	3	1
95	silt, clay, green	1	1
96	silt, gravel	8	1
97	silt, gravel, black	2	1

98	silt, gravel, brown	8	1
99	silt, gray	13	1
100	silt, organic	3	1
101	silt, red	1	1
102	silt, sand	15	3
103	silt, sand, black	1	3
104	silt, sand, blue	1	3
105	silt, sand, brown	6	3
106	silt, sand, gray	39	2
107	silt, sand, red	1	3
108	soil	1340	2
109	till	36	1
110	till, brown	12	1
111	till, gray	25	1
112	till, green	1	1
113	till, sand	2	1
114	till, yellow	1	1
115	unknown	1	
116	wood	1	