# COMPILATION GEOLOGIC MODEL FOR ZUMBRO RIVER WATERSHED: A PILOT PROJECT

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**Executive Summary**

This report is a summary of year one of a two-year pilot project between the Minnesota Geological Survey (MGS) and the Minnesota Department of Health (MDH) Groundwater Restoration and Protection Strategies (GRAPS) program designed to support watershed planning efforts. Our goal 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 Zumbro River Watershed. Geologic data for the St. Louis River Watershed was also compiled in year one and is presented in a separate report.

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). A 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. Many state agencies (Minnesota 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. General geologic information exists in these reports, but it does not contain 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 rocks 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 GIS environment. This pilot project was set up to address this need for the GRAPS program.

Seamless geologic products across a watershed are based on a compilation of previously published MGS maps along with new mapping where necessary. Revisions were made to the published maps where needed to achieve consistency across the watershed. Compilation methods and errors

associated with the subsurface modeling processes are described. These products were transferred into web-based 3D models 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. All 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.

**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 Zumbro River Watershed in southeast Minnesota (Fig. 1). A separate report describes the results for the St. Louis Watershed in northern Minnesota. Additional watersheds will be compiled in year two to complete this pilot project in 2022.

This report documents the steps taken to compile MGS mapping in the Zumbro River Watershed for both the unconsolidated sediments and the underlying bedrock layers. It is a summary of the compilation process and should not be used as a guide to explain the geology. The County Geologic Atlas (CGA) program run collaboratively by the MGS and MNDNR provides information essential to sustainable management of groundwater resources through a more comprehensive set of maps. This includes greater detail on the sediments and bedrock at the land surface and in the subsurface. CGA maps across the watershed are referenced and should be consulted for specific geologic information including the geologic setting, geologic data utilized, detailed map unit descriptions, and hydrogeologic properties.

The Zumbro River Watershed spans six southeast Minnesota counties (Wabasha, Rice, Goodhue, Olmsted, Dodge, and Steele) and covers an area over 1400 square miles. Each of these counties has been mapped as part of the CGA program; however, they have been individually published over several decades, ranging from 1995 to present day, and vary in GIS data availability. Data produced for Rice, Goodhue and Wabasha CGAs are older (1995-2001) while the Steele, Dodge and Olmsted CGAs are more recent (2019 to in press). As with any geologic mapping program, our methods improve alongside advances in science and technology, and as new data are continuously incorporated into our maps. Therefore, our old and new products differ in GIS content and the degree to which mapping datasets align across county boundaries.

A modern CGA contains two major components, designated as “Part A” and “Part B”. Part A is completed by MGS and includes a package of six maps or plates. These large format documents are available in print or as pdfs. They contain all the information associated with the geology of the county and the data used in the creation of the maps. Figures, tables and all other associated geologic information are presented on the map or in associated appendices. A map package contains 1) Database Plate, 2) Bedrock Geology Plate, 3) Surficial Geology Plate, 4) Quaternary Stratigraphy Plate, 5) Sand-Distribution Model Plate, and 6) Bedrock Topography and Depth to Bedrock Plate. 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 of the aquifers within the county. Together, this information can be used to make land-use decisions that consider aquifer sensitivity, water quality, and sustainability.

CGAs published prior to the late 2000s, generally contain limited GIS data available for download. Furthermore, they do not include unit surfaces for the individual bedrock and glacial map units. A unit surface is a GIS raster representative of the elevation of the tops and bottoms of the mapped units for use in GIS software. A raster is a spatial data model that defines space as an array of equally sized cells arranged in rows and columns. Each cell contains an attribute values 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 or groundwater flow.

*Geologic Setting*

The regional geologic framework within the Zumbro River Watershed is referred to as a bedrock-dominated landscape. Unconsolidated sedimentary cover is thin, and the land surface largely reflects the topography of the bedrock. The bedrock formations are Paleozoic in age and made up of sandstone, shale and carbonate rock. Seventeen individual bedrock formations are mapped and differentiated in the Zumbro River Watershed (Fig. 2). The uppermost layers are dominated by carbonate bedrock and the deepest layers are dominated by sandstone. Paleozoic bedrock formations contain significant sources of groundwater that provide 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 are more difficult to transmit water through. These layers act as aquitards (confining units) 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 Zumbro River Watershed, but were not considered here as they do not play a significant role in the groundwater system.

The thickness of unconsolidated sediments generally increases to the west across the watershed, ranging from absent to 275 feet (167 meters). Areas with the thickest sediments overlie deeply incised bedrock valley systems. Various layers of till, sand, loess and colluvium are mapped at the surface just below the soil (Fig. 3A). We simplified these units for visualization purposes into three categories that represent sand, mixed (meaning the material contains variable amounts of both sand and clay) and clay (Fig. 3B). Clay-rich tills are present mainly in the western part of the watershed and sand is mostly restricted to bedrock valleys. Most clay in the Zumbro River Watershed is interpreted to be till, which can be considered an aquitard. Till is sediment directly deposited by glacial ice and is composed of a mixture of clay to boulder-sized fragments. Sandy-textured tills commonly contain a higher proportion of sand grains in the matrix, and more cobbles and boulders than clayey-textured tills. Below the surficial sediments, only layers of till, loess, and colluvium were mapped in the subsurface. Sand and gravel units are depicted through an interpolation process described below. Glacial units are thin and more complex than the bedrock units due to their depositional environment and repeated episodes of erosion. Units tend to be discontinuous and variable in both thickness and elevation over relatively short distances. The unconsolidated sediments in the Zumbro River Watershed were differentiated into 19 different Quaternary units, including seven distinct till units (Table 1).

**Methods**

Several methods were used to compile seamless geologic data within the Zumbro River Watershed, an area which includes data from six different CGAs. New mapping was completed for both the unconsolidated sediment and bedrock datasets in areas along county edges where Atlas products were inconsistent, where new data had significantly changed the geologic interpretation of an area, and in areas previously mapped prior to the inclusion of unit surfaces in CGA products. No new fieldwork was done for this project. Compiled products for the Zumbro River Watershed were developed into an ArcGIS Online 3D map 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 map. Explanatory text in the CGAs should be consulted for more detailed MGS mapping methodology.

*Bedrock Compilation*

To create bedrock unit surfaces, existing GIS data from the bedrock geology and bedrock topography maps of the six counties in the watershed were compiled (Hobbs and others, 1995; Setterholm and others, 1998; Runkel and others, 2001; Steenberg and others, 2019; Steenberg and others, 2020; Retzler and others, in press). Bedrock topography represents the elevation of the bedrock surface and the bottom of the unconsolidated sediments. Bedrock topography contours were merged into a new set of bedrock topography contour lines with 25-foot (7.6-meter) intervals. Linework was edited along county edges and where new geologic data warranted changes. These contours were transformed into a raster surface using the "Topo to Raster" tool in ArcMap.

A similar approach was used for the creation of unit surfaces that depict the individual bedrock units. Existing contour lines from previous maps were compiled into one shapefile for the elevation of the top of the Jordan Sandstone. Contours were edited to match along county edges. Revised contour mapping focused on the faulted area within Wabasha County 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. Using the unit surface of the top of the Jordan Sandstone as a reference, unit surfaces for all other bedrock unit surfaces 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 Zumbro River Watershed. These units include the Mt. Simon Sandstone, Wonewoc Sandstone, St. Lawrence Formation, Oneota Dolomite, Shakopee Formation 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 map. Figure 4 shows a generalized cross section across the watershed to add the dimension of depth and illustrate the stratigraphic, structural, and topographic relationships of the bedrock units, as well as the variable thickness of the overlying unconsolidated sediments.

*Quaternary (Unconsolidated) Sediments Compilation*

CGA surficial geology maps of the Quaternary depict the unconsolidated sediments encountered within a few meters of the land surface, which is referred to as the surficial geology. In an effort to make a seamless surficial geology map across the watershed, the 1:100,000 scale GIS files of the statewide digital database D-1 (https://mngs-umn.opendata.arcgis.com) were combined with the GIS files of more recent maps completed in Dodge and Olmsted Counties (Steenberg and others, 2019; Steenberg and others, 2020). 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 S-23; the Geologic Map of Minnesota-Quaternary Geology (Lusardi and others, 2019). 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), the MNDNR Aggregate Resources map (Anderson, 2002), 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. The Quaternary deposits are assigned to lithostratigraphic units defined in Johnson and others (2016). A total of 18 surficial geologic units are established for this watershed (Fig. 3A, Table 1). Refer to the referenced source material to learn more about the glacial history of the Zumbro River Watershed.

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. For this compilation mapping project 12 cross sections were constructed at regular (5-kilometer (3.1-mile)) intervals across the watershed. From these cross sections, unit surfaces were constructed for 11 of the glacial units (Table 1).

*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). These include sand, loamy sand, sandy loam, sandy clay loam, loam, silt loam, silt, silty clay loam, clay, clay loam, sandy clay, and silty clay. We have also included gravel, sandy gravel, and rock in our descriptions, as these are important properties for modeling groundwater flow in the subsurface, despite not being recognized as official USDA textures. The texture-based point model can be viewed 2-dimensionally or 3-dimensionally in a GIS environment or through our online 3D map (Fig. 5, https://arcg.is/fevGS). The texture-based point model for our online 3D map generalized these textures further into sand and gravel, mixed (variable amounts of clay and sand), and clay. Table 1 depicts the generalized texture for each unit.

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 intervals with 5-foot (1.5-meter) vertical spacing for the watershed. There are nearly 1.3 million points in the model. The model was produced in three different modeling stages that were subsequently combined. The three modeling processes are referred to as the surficial model, subsurface model, and the interpolated model. All modeling processes used the same matrix spacing.

The surficial model used the surficial map created for this project. The map was intersected with the uppermost point in the matrix and assigned the map unit label and its associated texture in the attribute table. The subsurface model was created using a two-part process. The point matrix was first intersected with the 11 subsurface Quaternary unit surfaces. Points were selected if their elevation was within the elevation range of the top and bottom of a particular Quaternary unit surface and assigned the texture of that unit. An additional method was developed using the "near 3D" tool in ArcPro to fill voids of no data in the point matrix. This tool assigned CWI well stratigraphy data from the closest x, y, and z well locations to the null matrix point. Texture data is from driller's description on water well records. Descriptions such as sand, clay, till, gravel or loess were assigned equivalent USDA textures by MGS; other descriptions were not assigned a texture.

The interpolated model was constructed 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). Data was 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 second 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 = mix. 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. Remaining points are assigned their likelihood of occurrence in the field 'spot' in the point model attribute tables. In the case of overlapping values, 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. We've included results from all three processes for this watershed. In the case of overlapping points, we recommend the following hierarchy of use: the surficial model, interpolated model's sand values, subsurface model, and the interpolated model's mixed and clay values for any remaining points. All points are uniquely identified with a 'loc_code' attribute that includes the points UTM coordinates and elevation so users can query the datasets individually.

*3D Visualization Methods*

A 3D geologic model for the Zumbro River Watershed was built using ArcPro and the data described above (Fig. 5). For the bedrock, each of the top and bottom unit surfaces were converted into triangulated irregular network (TIN) datasets using the "Raster to TIN" tool. Each TIN was configured with a Z Tolerance value of 5 (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 Zumbro River Watershed, were then used to create 3D multipatches of each bedrock unit using the "Extrude Between" tool. Prior to this, the Zumbro River Watershed polygon was split into multiple polygon subdivisions using the "Subdivide Polygon" tool to minimize 3D data outliers that can occur during the extrusion process.

For the Quaternary, the surficial geology polygons were reclassified based on the USDA texture defined for each unit into three generalized textural categories (clay, mixed, or sand) (Fig. 3B, Table 1). Each of the three textural categories were then exported as 2D polygon layers. To visualize the subsurface data, a subset of the texture-based point model (500 x 500 meters and 20 feet in the vertical) was created and their vertical z-axis values converted to meters and exaggerated 20 times. Each of the three textural categories (clay, mixed, and sand) were then exported as 3D point layers.

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 land surface DEM of the Zumbro River Watershed. 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.

*Using the Web-based 3D Model*

The web-based 3D model (https://arcg.is/fevGS) is meant to be a visualization tool for water planners, other state agencies involved in the GRAPS process, and the general public, and is made readily accessible in a browser, requiring no GIS software. The model is separated into three parts: surficial geology, subsurface geology, and bedrock geology. The surficial and subsurface geology has been simplified into three textural categories of clay, mixed, or sand. 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. The polygons are shown with slight transparency to allow users to peer through them at underlying data. Below these polygons are the regularly spaced, 3D point data representative of the subsurface geology from the base of the surficial deposits down to the top of bedrock. Below the regularly spaced point data lie the 3D bedrock layers representing the mappable Paleozoic units in the Zumbro River Watershed. Each bedrock unit is a separate layer in the model that can be turned 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 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 three 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.

**Discussion and Future Work**

The modeling process we use to create unit surfaces of the Quaternary units from 5-kilometer (3.1-mile) spaced cross sections (as opposed to manually mapping these surfaces in plan-view) has some unintended model artifacts. These include linearity along cross section lines in both elevation and map unit extent, unintended gaps in map units between cross sections and oversimplification of unit distribution between cross sections. Tipping (2019) evaluated these methods and offered solutions for improvement. We incorporated some of these solutions by creating unit surfaces of the Quaternary unit tops and bottoms of only till and fine-grained materials and superimposing the interpolated model to capture the most recent sand deposits. Although this improved the model output, some unintended modeling artifacts remained. These included oversimplifications of map unit distribution between cross sections, and gaps in the model with no assignment of map unit or texture. These gaps occurred locally across some units in plan-view, and between the bedrock surface and base of the Quaternary. To correct for gaps in the model near the base of the Quaternary, unit bases directly above the bedrock were set equal to the bedrock topography locally between 5-kilometer (3.1-mile) cross section lines. These adjusted unit bases were used to populate the map units and textures in the subsurface texture-based point model. To account for the smaller gaps in the dataset, we developed an additional stratigraphy method, described above, to fill available texture values from the CWI dataset. Next year, we intend to develop improved methods to map the Quaternary fine-grained sediments in plan-view by manually contouring till unit bases in a similar manner to the way in which flat-lying bedrock geologic units are mapped. This will be a challenge due to the complexity of these deposits but is needed to correct for the oversimplification of map unit distribution between 5-kilometer (3.1-mile) cross section lines. Working in watershed areas that already have CGA Quaternary cross sections completed at 1-kilometer (0.6-mile) spacing should aid in developing this process.

The Zumbro River Watershed model is based on the USGS HUC-8 boundaries that differs slightly from BSWR 1W1P boundary. A small section of the Cannon watershed extending north to Red Wing is not part of this model. This was done to limit quantification of water budget, both surface water and groundwater, to the watershed boundary itself. The Cannon extension will be included in a future watershed model. Future efforts with the GRAPS program will also include putting together more supporting text from a hydrogeologic perspective to be presented along with the model for the general user to make sense of the information and how to apply to their resources conservation work.

**List of Figures and Tables**

**Figure 1.** Watershed map of Minnesota highlighting the location of the Zumbro River Watershed in southeast Minnesota. Gray lines show watersheds in Minnesota and red line depicts the Zumbro River Watershed.

**Figure 2.** Bedrock geology map of the Zumbro River Watershed compiled for this project. Bedrock faults are shown in black. Bedrock layers are differentiated by colors shown in the legend.

**Figure 3.** A) Surficial geology map of the Zumbro River Watershed compiled for this project. Quaternary units are differentiated by colors shown in the legend. Map units listed as formation names are tills. B) Surficial geology map of the Zumbro River Watershed simplified into three texture classes of clay, mixed (variable amounts of clay and sand) and sand as shown in the online 3D model.

**Figure 4.** Generalized cross section of the Zumbro River Watershed depicting Quaternary and bedrock geology. Inset map shows cross section location (A-A'), bedrock topography (dark is lower elevation and light is higher elevation), and population centers. Black vertical lines are wells.

**Figure 5.** Screen capture of the entire 3D geologic model for the Zumbro River Watershed. This image shows the texture-based point model for the Quaternary sediments in three generalized texture categories (clay, mixed and sand) as well as the underlying bedrock geologic units.

**Table 1.** Quaternary map units showing map unit type, name, code, texture, and generalized texture.

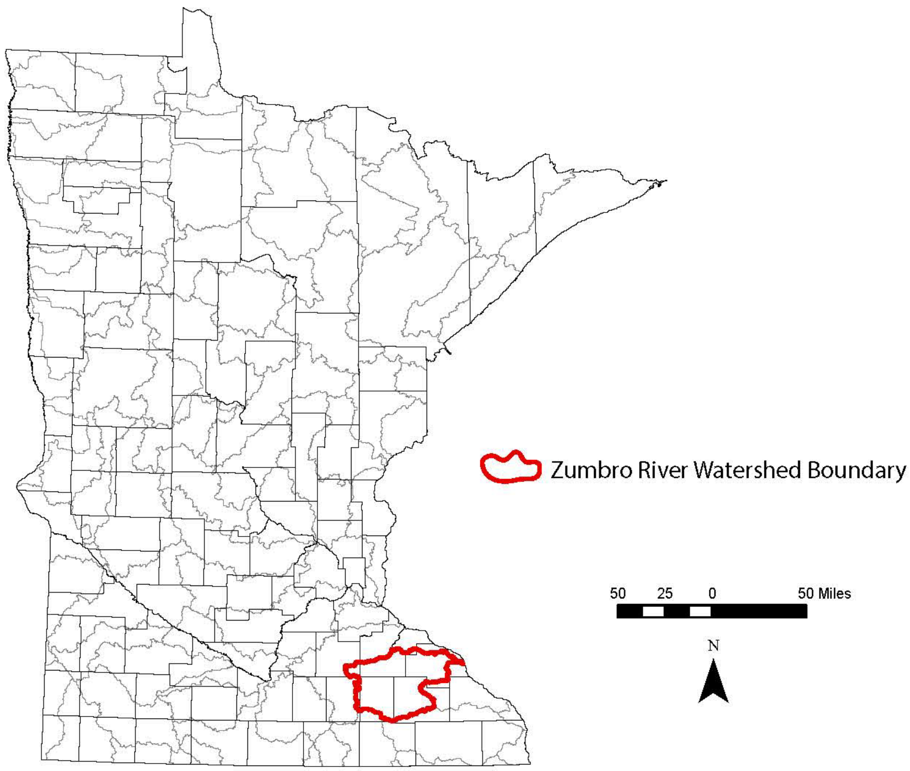


Figure 1

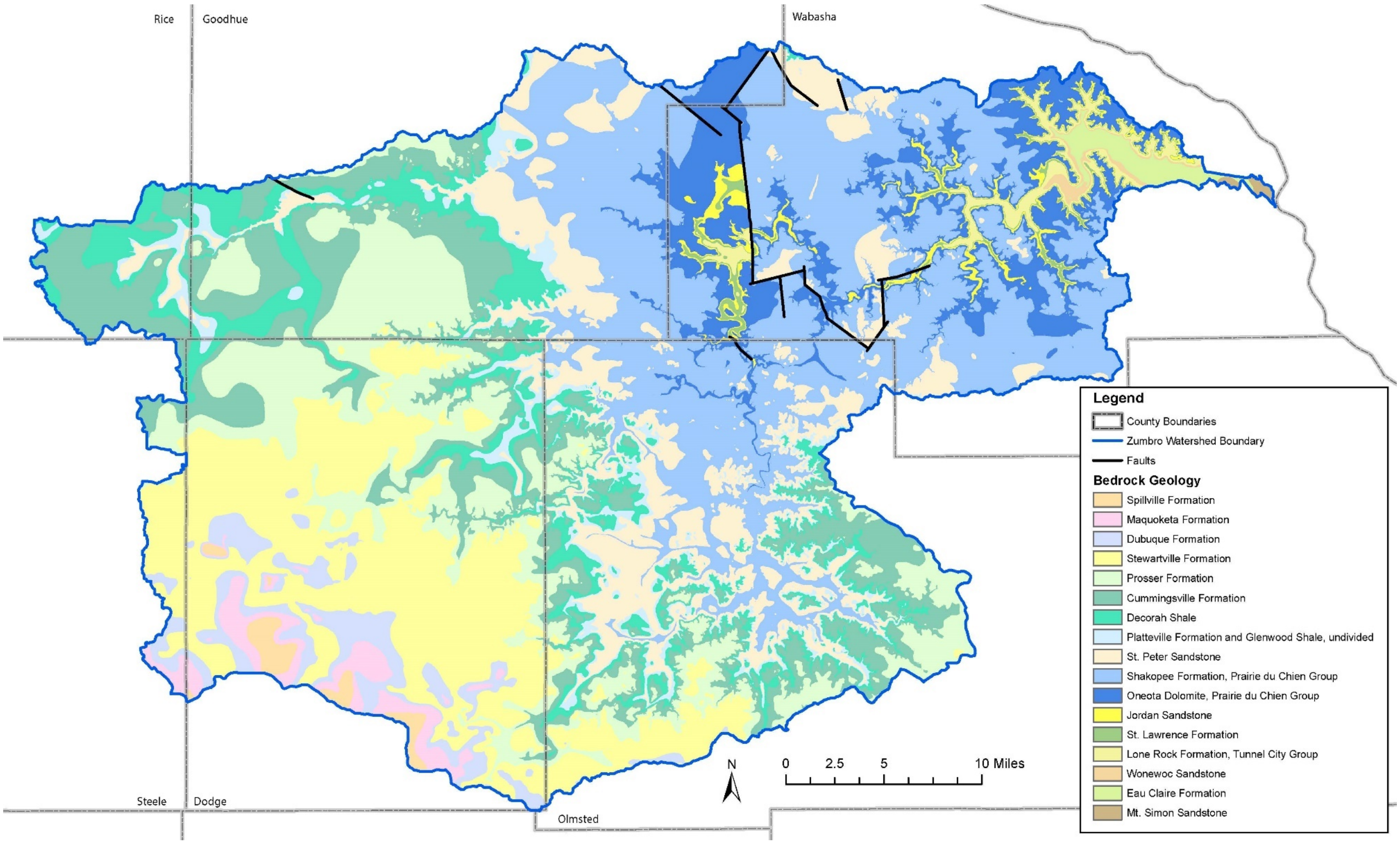
Rice
Goodhue
Wabasha
Steele
Dodge
Olmsted
N
0 2.5 5 10 Miles
Legend
County Boundaries
Zumbro Watershed Boundary
Faults
Bedrock Geology
Spillville Formation
Maquoketa Formation
Dubuque Formation
Stewartville Formation
Prosser Formation
Cummingsville Formation
Decorah Shale
Platteville Formation and Glenwood 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

Figure 2

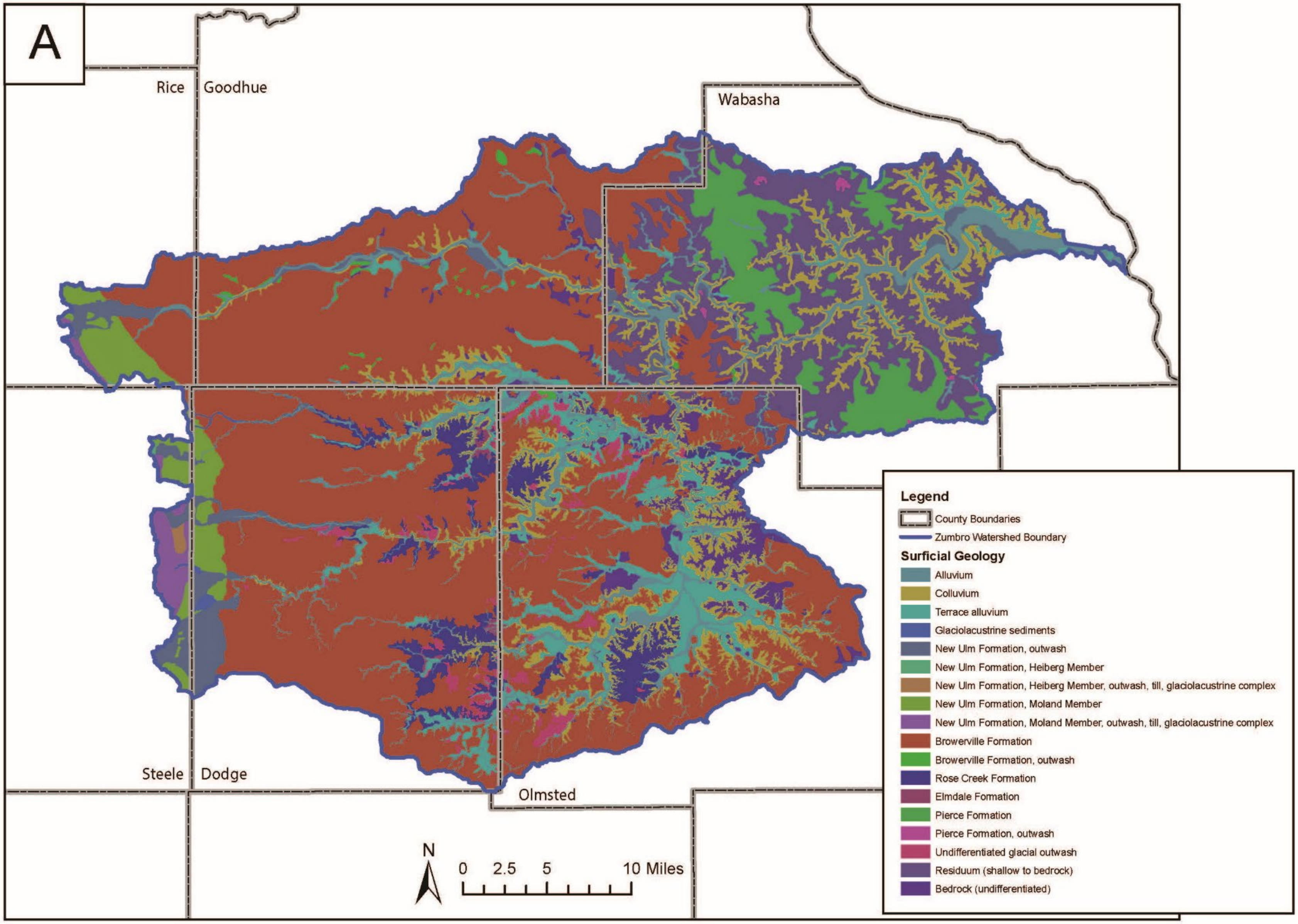
A
Rice
Goodhue
Wabasha
Steele
Dodge
Olmsted
N
0 2.5 5 10 Miles
Legend
County Boundaries
Zumbro Watershed Boundary
Surficial Geology
Alluvium
Colluvium
Terrace alluvium
Glaciolacustrine sediments
New Ulm Formation, outwash
New Ulm Formation, Heiberg Member
New Ulm Formation, Heiberg Member, outwash, till, glaciolacustrine complex
New Ulm Formation, Moland Member
New Ulm Formation, Moland Member, outwash, till, glaciolacustrine complex
Browerville Formation
Browerville Formation, outwash
Rose Creek Formation
Elmdale Formation
Pierce Formation
Pierce Formation, outwash
Undifferentiated glacial outwash
Residuum (shallow to bedrock)
Bedrock (undifferentiated)

Figure 3A

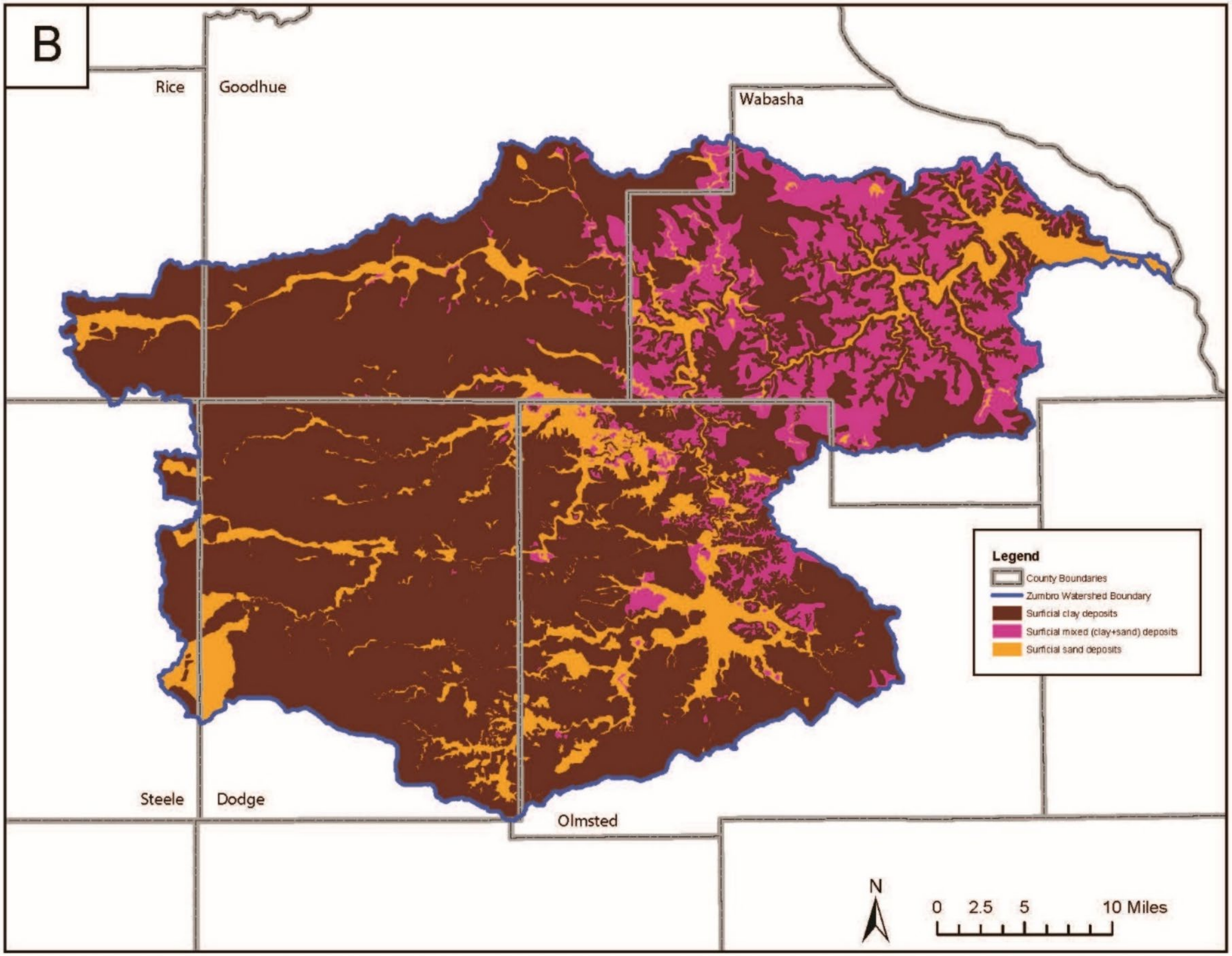
B
Rice
Goodhue
Wabasha
Steele
Dodge
Olmsted
Legend
County Boundaries
Zumbro Watershed Boundary
Surficial clay deposits
Surficial mixed (clay+sand) deposits
Surficial sand deposits
N
0 2.5 5 10 Miles

Figure 3B

Generalized Geologic Cross Section for the Zumbro River Watershed

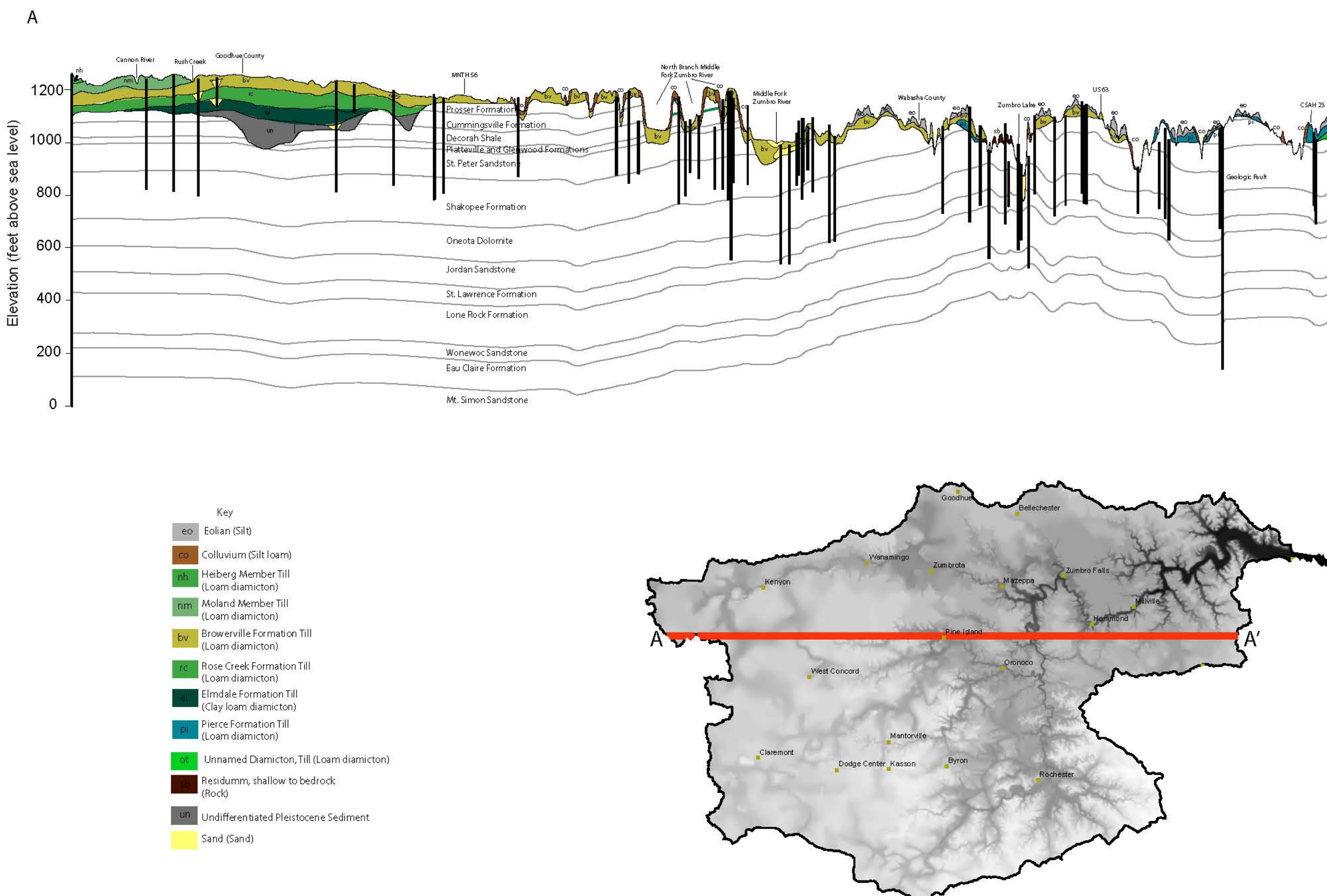


Figure 4

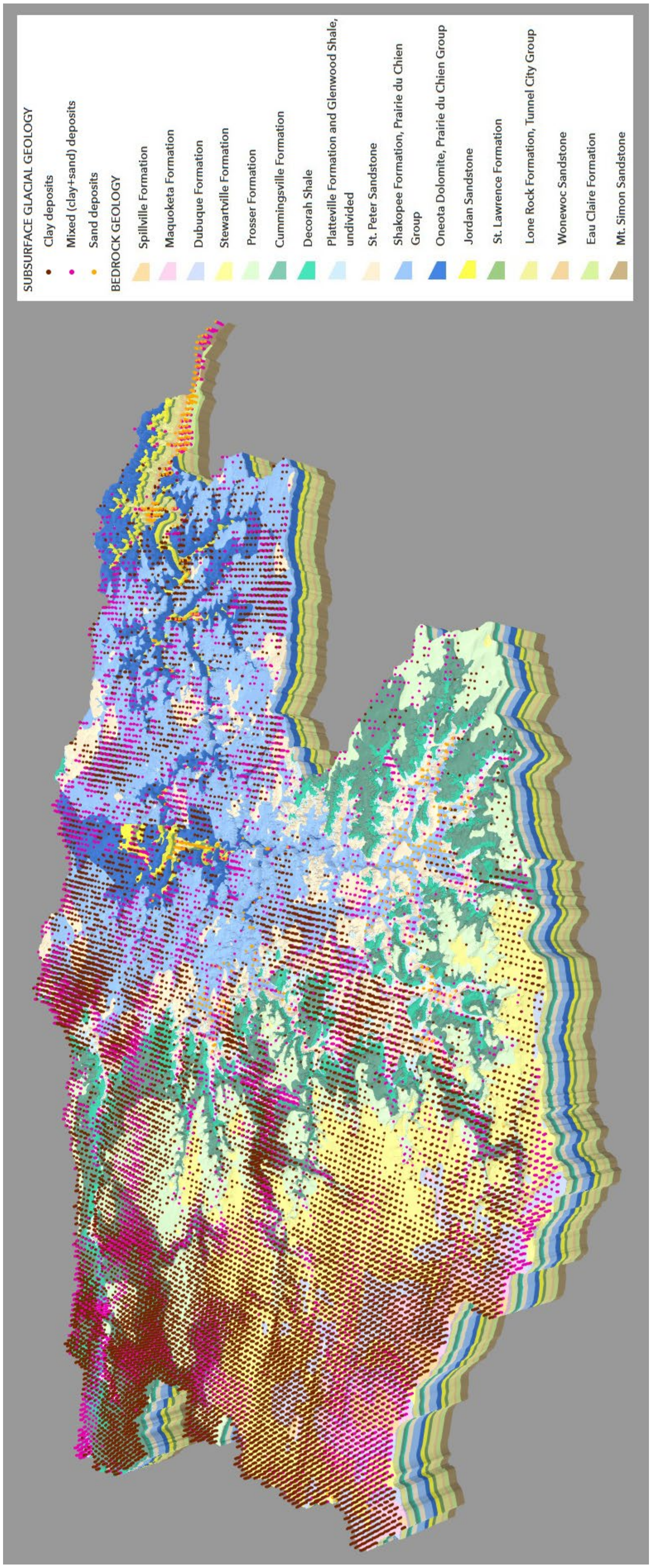
SUBSURFACE GLACIAL GEOLOGY
Clay deposits
Mixed (clay+sand) deposits
Sand deposits
BEDROCK GEOLOGY
Spillville Formation
Maquoketa Formation
Dubuque Formation
Stewartville Formation
Prosser Formation
Cummingsville Formation
Decorah Shale
Platteville Formation and Glenwood Shale, undivided
St. Peter Sandstone
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

Figure 5

**Table 1.** Quaternary Map Units

| Unit type | | Unit code | Unit Name | USDA Texture | Generalized Online 3D Model Texture |
|---|---|---|---|---|---|
| | *surficial* | al | Alluvium | gravelly sand | sand and gravel |
| *subsurface* | *surficial* | co | Colluvium | silt loam | clay |
| | *surficial* | te | Terrace alluvium | gravelly sand | sand and gravel |
| *subsurface* | | eo | Eolian | silt | mixed |
| | *surficial* | gld | Glaciolacustrine sediments | silt loam | clay |
| | *surficial* | nuo | New Ulm Fomation outwash | gravelly sand | sand and gravel |
| *subsurface* | *surficial* | nh | New Ulm Formation, Heiberg Member | loam | clay |
| | *surficial* | nhh | New Ulm Formation, Heiberg Member, outwash, till, glaciolacustrine complex | loam | clay |
| *subsurface* | *surficial* | nm | New Ulm Formation, Moland Member | loam | clay |
| | *surficial* | nhm | outwash, till, glaciolacustrine complex | loam | clay |
| *subsurface* | *surficial* | bv | Browerville Formation | loam | clay |
| | *surficial* | bvo | Browerville Formation outwash | gravelly sand | sand and gravel |
| *subsurface* | *surficial* | rc | Rose Creek Formation | loam | clay |
| *subsurface* | *surficial* | el | Elmdale Formation | clay loam | clay |
| *subsurface* | *surficial* | pi | Pierce Formation | loam | clay |
| | *surficial* | pio | Pierce Formation outwash | gravelly sand | sand and gravel |
| *subsurface* | | ot | Old tills (undifferentiated) | loam | clay |
| *subsurface* | | un | Undifferentiated Pleistocene sediments | null | mixed |
| | *surficial* | uno | Undifferentiated glacial outwash | gravelly sand | sand and gravel |
| *subsurface* | *surficial* | sb | Residuum (shallow to bedrock) | rock | mixed |
| | *surficial* | b | Bedrock, undifferentiated | rock | mixed |

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