COMPILATION GEOLOGIC MODEL FOR MISSOURI 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

Minnesota Geological Survey Open File Report OFR-22-06

University of Minnesota

Minnesota Geological Survey
Harvey Thorleifson, Director

Funded through Minnesota Department of Health

July 2022

Table of Contents

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 Missouri 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, Cannon 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 Missouri River Watershed ("Missouri River Basin Watersheds of Minnesota Groundwater Restoration and Protection Strategies Report", 2018). 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 Missouri River Watershed are based on previously published and 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/1iimH50) 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 Missouri River Watershed in southwest Minnesota (Fig. 1). Separate reports describe the results for the Zumbro, St. Louis, Redeye, and Cannon River Watersheds (Steenberg and others, 2021a,b; Steenberg and others, 2022b,a). This report documents the steps taken to compile MGS mapping in the Missouri 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 Missouri 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 Geographic Information Systems (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 Missouri River Watershed spans six southwest Minnesota counties (Rock, Nobles, Lincoln, Pipestone, Murray, and Jackson) and covers an area approximately 2187 square miles (5665 square kilometers). Rock and Nobles Counties have been mapped as part of the CGA program recently and contain completed bedrock and Quaternary subsurface information (Bauer and others, 2020ab). Lincoln and Pipestone Counties are in progress and interim products were used for this project for the bedrock geology and bedrock topography datasets. CGA mapping is yet to commence in Jackson and Murray Counties, and therefore this project included geologic information from regional studies, statewide compilations, and interpolated datasets in those areas (Lusardi and others, 2019; Jirsa and others, 2011).

Geologic Setting

Beneath the land surface, the Missouri River Watershed is composed of unconsolidated Quaternary deposits (<2.6 Ma), various shale and sand layers deposited during the Cretaceous Period (~101 to 80 Ma) and various rocks of Precambrian age. Unconsolidated Quaternary sediments range in thickness, generally between 0-900 feet (274 meters). They are thickest in the northern part of the watershed in Lincoln County and in the central part of Nobles County. Sediments are thin in Pipestone and northern Rock County where bedrock is near the land surface (Fig. 2). Areas with the thickest sediments overlie deeply buried bedrock valleys. 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 alluvium is also present and composed of various textures.

Groundwater is a limited resource in the Missouri River Watershed due to the underlying geology. Most of the area has clayey till or hard bedrock at the land surface. 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 and can influence groundwater chemistry during infiltration. Alternatively, glaciogenic sand and gravel deposits tend to be highly transmissive and are typically regarded as potential aquifers capable of storing groundwater and yielding adequate flow to a well. However, these sand deposits are discontinuous and vary in thickness, elevation, and extent over relatively short distances, and are not available everywhere. Cretaceous sandstone aquifers provide groundwater in some areas, especially the more permeable units rich in quartz sandstone, including the Dakota Formation and the undifferentiated Cretaceous rocks. The Dakota Formation occurs lowest in the Cretaceous stratigraphic sequence, while the undifferentiated Cretaceous rocks generally occur around Precambrian bedrock highs. The Precambrian Sioux Quartzite is also used for water supplies in the watershed through an interconnected network of fractures in the rock.

The various unconsolidated deposits described above that occur within roughly 10 feet (3 meters) of the lowermost soil horizon are depicted as mapped in Fig. 3A. These units were simplified for visualization purposes 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 25 units were differentiated within the Missouri River Watershed, including 13 surficial and 18 subsurface units (Table 1) with some units occurring in both.

Individual bedrock units are mapped and differentiated for 6 bedrock layers in the Missouri River Watershed beneath the Quaternary sediment (Fig. 4). The Carlile Shale, Greenhorn Limestone, Graneros Shale, Dakota Formation, undifferentiated Cretaceous bedrock and undifferentiated Precambrian Bedrock. Properties within the bedrock formations control the direction and speed of groundwater flow. More permeable units such as sandstone are aquifers and easily transmit water. Layers with more shale and fine-grained material are less permeable and commonly do not transmit 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.

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 across the watershed. Compiled products for the Missouri 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 Rock and Nobles CGAs (Bauer and others, 2020ab) and the in progress bedrock topography from the Lincoln and Pipestone CGAs (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 undifferentiated Precambrian bedrock (Table 2). 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. For each Cretaceous bedrock unit, existing unit surfaces from previous maps were merged into one surface across the watershed (Table 2). Unit surfaces in Lincoln and Pipestone Counties were derived using the unit surface of the top of the Carlile Shale as a reference. In Rock and Nobles Counties, unit surfaces were derived using the unit surface of the top of the Dakota Formation 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 Missouri River Watershed. 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 Rock and Nobles Counties (Bauer and others, 2020a,b). 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 Rock and Nobles CGAs 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. Rock and Nobles are the only counties in the watershed with Quaternary subsurface mapping that defines the Quaternary formations and textures. No new Quaternary subsurface mapping was completed for this project.

To define the texture of the subsurface Quaternary materials in the watershed outside of Rock and Nobles Counties, interpolation models were run that incorporate drillers descriptions from water-well information and a geologists interpretation of that information. Information outside of Rock and Nobles Counties only defines texture in a general sense and does not assign the texture to a particular unit. This method is described below.

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 description, as this is an important property 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/1iimH50). 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 250-meter (820-foot) regularly-spaced intervals 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 3.3 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 assign the uppermost points in the matrix, at ground elevation, with the respective map unit and texture by intersecting the surficial geology polygons in GIS. The subsurface model points were intersected with the 18 subsurface rasters within Rock and Nobles Counties. Points were assigned the respective map unit 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 ArcGIS Pro 2.8 software and 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 were 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 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 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 = 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. 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 Missouri 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 20 (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 Missouri 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 separate 2D polygon layers. To 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 Rock and Nobles Counties were the only data in the Missouri River Watershed based on more detailed Quaternary 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] 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/1iimH50) 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 Rock and Nobles Counties 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 Cretaceous and the top of the Precambrian bedrock in the Missouri 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.

References

Bauer, E.J., Retzler, A.J., Jirsa, M.A., Chandler, V.W., Pettus, M.C., Gowan, A.S., Hamilton, J. D., 2020a, Geologic Atlas of Rock County, Minnesota. Minnesota Geological Survey County Geologic Atlas C-47. Retrieved from the University of Minnesota Digital Conservancy, https://hdl.handle.net/11299/218637.

Bauer, E.J., Retzler, A.J., Jirsa, M.A., Chandler, V.W., Pettus, M.C., Gowan, A.S., Hamilton, J. D., 2020b, Geologic Atlas of Nobels County, Minnesota. Minnesota Geological Survey County Geologic Atlas C-48. Retrieved from the University of Minnesota Digital Conservancy, https://conservancy.umn.edu/handle/11299/219159.

"County Atlas Series." *University of Minnesota Libraries Digital Conservancy,* University of Minnesota, https://conservancy.umn.edu/handle/11299/57196

"County Geologic Atlas" *Minnesota Geological Survey,* University of Minnesota, https://cse.umn.edu/mgs/county-geologic-atlas

"D-1 Surficial Geology of Minnesota." *Minnesota Geological Survey,* University of Minnesota, https://mngs-umn.opendata.arcgis.com

"Groundwater Restoration and Protection Strategies (GRAPS)." *Clean Water Fund,* Minnesota Department of Health, 2018, https://www.health.state.mn.us/communities/environment/water/cwf/localimplem.html

Jirsa, M.A., Boerboom, T.J., Chandler, V.W., Mossler, J.H., Runkel, A.C., Setterholm, D.R., 2011, S-21 Geologic Map of Minnesota-Bedrock Geology. Minnesota Geological Survey. Retrieved from the University of Minnesota Digital Conservancy, https://hdl.handle.net/11299/101466.

Johnson, M.D., Adams, R.S., Gowan, A.S., Harris, K.L., Hobbs, H.C., Jennings, C.E., Knaeble, A.R., Lusardi, B.A., and Meyer, G.N., 2016, Quaternary lithostratigraphic units of Minnesota: Minnesota Geological Survey Report of Investigations RI-68, 262 p. Retrieved from University of Minnesota Digital Conservancy, https://hdl.handle.net/11299/177675.

Lusardi, B. A., Gowan, A. S., McDonald, J. M, Marshall, K. J., Meyer, G. N, Wagner, K. G., 2019, Geologic Map of Minnesota, Quaternary Geology: Minnesota Geological Survey State Map S-23, scale 1:500,000. Retrieved from the University of Minnesota Digital Conservancy, https://hdl.handle.net/11299/208552.

"Missouri River Basin Watersheds of Minnesota Groundwater Restoration and Protection Strategies Report", 2018, Minnesota Department of Health, https://www.health.state.mn.us/communities/environment/water/docs/cwf/grapsmrb.pdf

Natural Resources Conservation Service, 2014, Gridded soil survey geographic (gSSURGO) database for Minnesota: U.S. Department of Agriculture. http://datagateway.nrcs.usda.gov.

Retzler, A.J., in press, Geologic Atlas of Pipestone County, Minnesota. Minnesota Geological Survey County Geologic Atlas C-59.

Retzler, A.J., in press, Geologic Atlas of Lincoln County, Minnesota. Minnesota Geological Survey County Geologic Atlas C-58.

Soil Science Division Staff, 2017, Soil survey manual. C. Ditzler, K. Scheffe, and H.C. Monger (eds.). USDA Handbook 18. Government Printing Office, Washington, D.C. Retrieved from Natural Resources Conservation Service, https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs142p2_054261.

Steenberg, J.R., Retzler, A.J., McDonald, J.M., and Hamilton, J.D., 2021a, Compilation geologic model for Zumbro River Watershed: a pilot project: Minnesota Geological Survey Open File Report 21-03. Retrieved from the University of Minnesota Digital Conservancy, https://hdl.handle.net/11299/220567

Steenberg, J.R., Retzler, A.J., Wagner, K.G., and Hamilton, J.D., 2021b, Compilation geologic model for St. Louis River Watershed: a pilot project: Minnesota Geological Survey Open File Report 21-04. Retrieved from the University of Minnesota Digital Conservancy, https://hdl.handle.net/11299/223234

Steenberg, J.R., Retzler, A.J., Hamilton, J.D., and Francis, S.W., 2022a, Compilation geologic model for Cannon River Watershed: a pilot project: Minnesota Geological Survey Open File Report 22-05. Retrieved from the University of Minnesota Digital Conservancy

Steenberg, J.R., Retzler, A.J., Hamilton, J.D., and Francis, S.W., 2022b, Compilation geologic model for Redeye River Watershed: a pilot project: Minnesota Geological Survey Open File Report 22-07. Retrieved from the University of Minnesota Digital Conservancy

Tipping, R. G., 2019, Pilot multi-county modeling Synthesis for Bonanza Valley Groundwater Management Area: Minnesota Geological Survey Open File Report 21-02. Retrieved from the University of Minnesota Digital Conservancy, https://conservancy.umn.edu/handle/11299/219591.

Figure and Table Captions

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

Figure 2. Depth to bedrock or thickness of the unconsolidated (Quaternary) sediments in the Missouri River Watershed generated from subtracting the bedrock topography grid from the land surface grid. Thickness of unconsolidated deposits are depicted in the legend in 50-foot intervals. Thicker sediments are represented by orange and red colors and areas of thin sediments are green and light green.

Figure 3. A) Surficial geology map of the Missouri 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 Missouri 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/1iimH50).

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

Figure 5. Screen capture of the entire 3D geologic model for the Missouri River Watershed. This image shows the texture-based point model for the Quaternary sediments in four generalized texture categories (clay, mixed, sand, and unknown) 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 Rock and Nobles CGAs 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

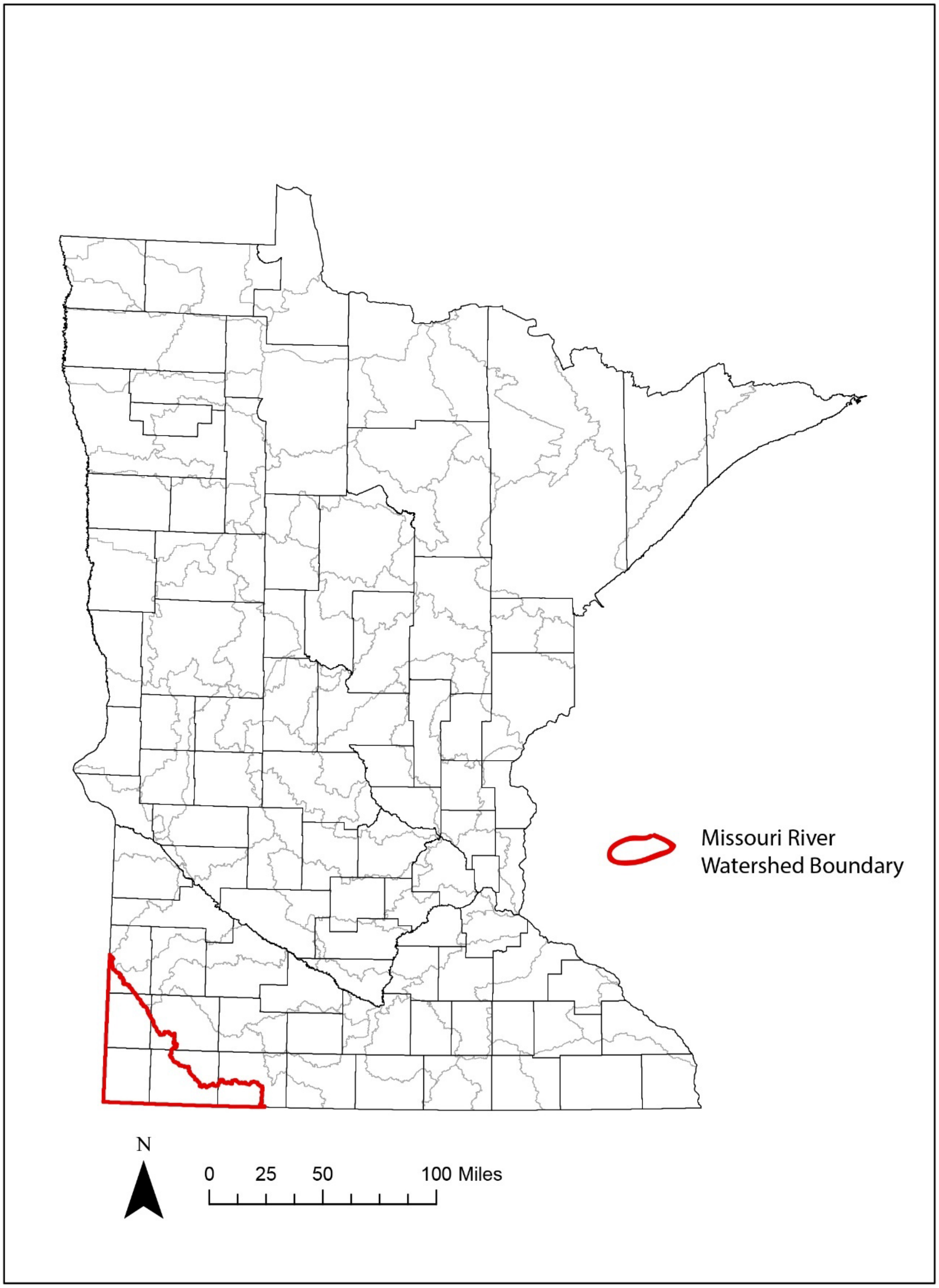


Figure 2

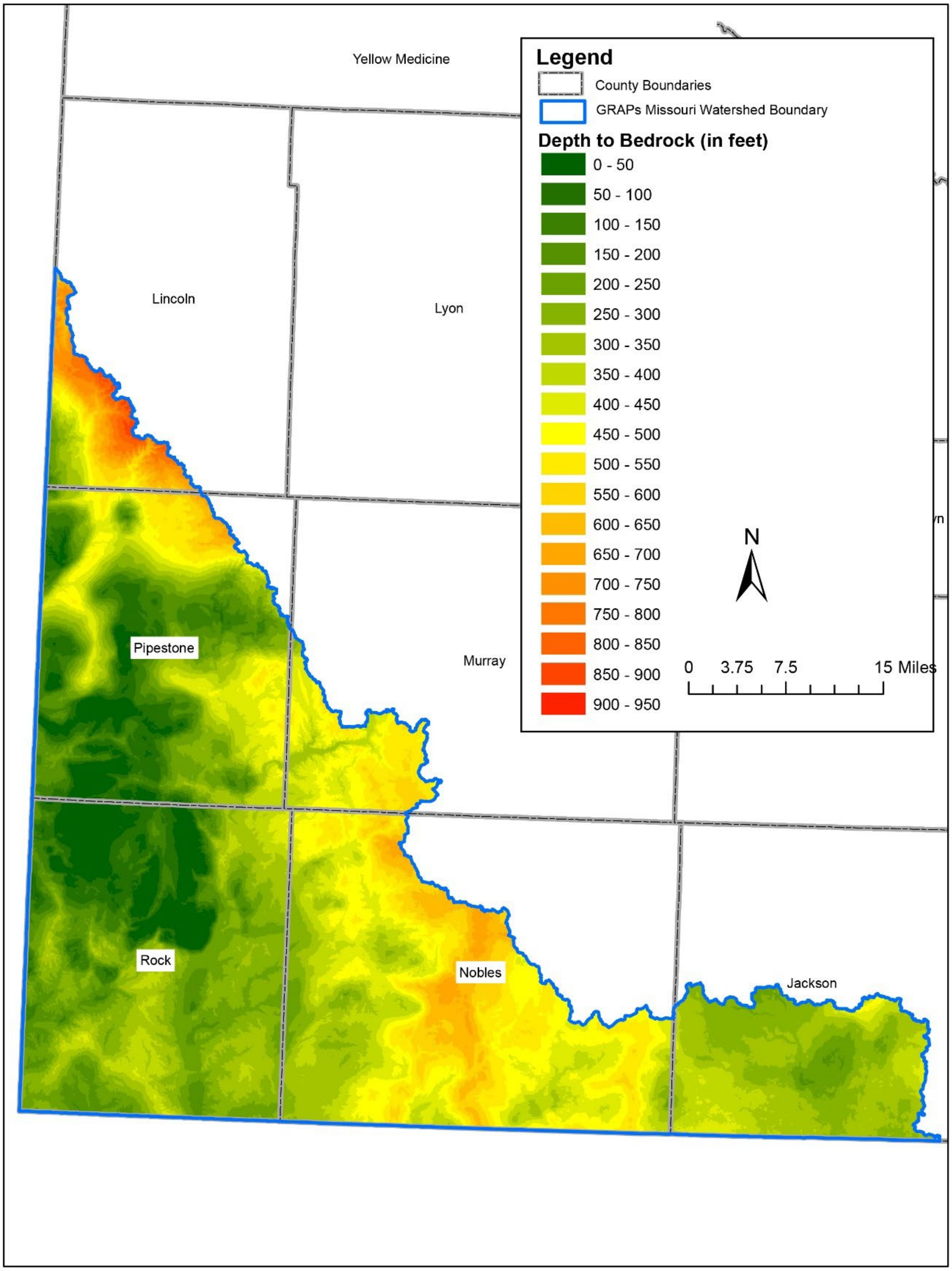

Legend
County Boundaries
GRAPs Missouri Watershed Boundary
Depth to Bedrock (in feet)
0 - 50
50 - 100
100 - 150
150 - 200
200 - 250
250 - 300
300 - 350
350 - 400
400 - 450
450 - 500
500 - 550
550 - 600
600 - 650
650 - 700
700 - 750
750 - 800
800 - 850
850 - 900
900 - 950
N
0 3.75 7.5 15 Miles
Yellow Medicine
Lincoln
Lyon
Pipestone
Murray
Rock
Nobles
Jackson

Figure 3A

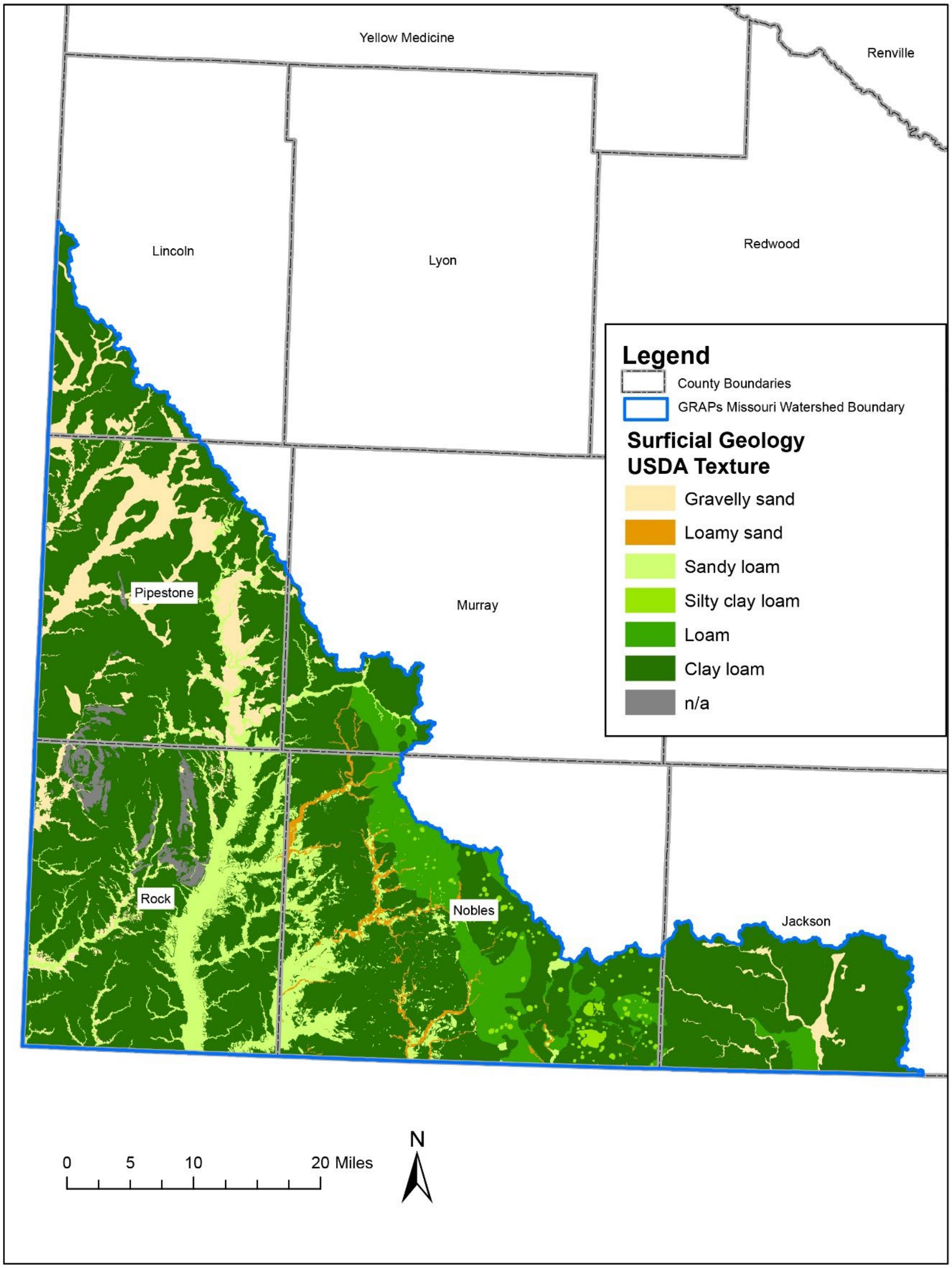
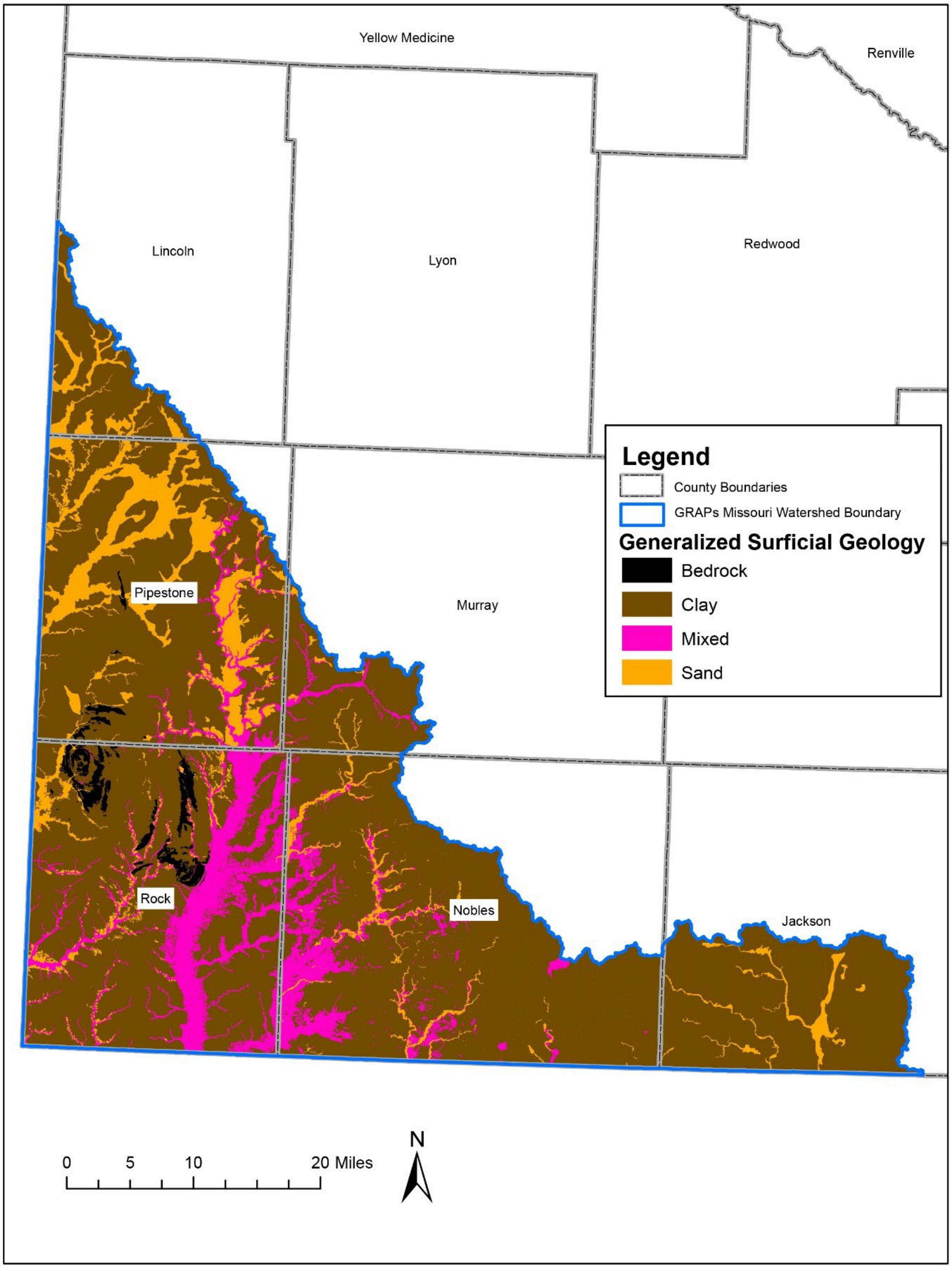
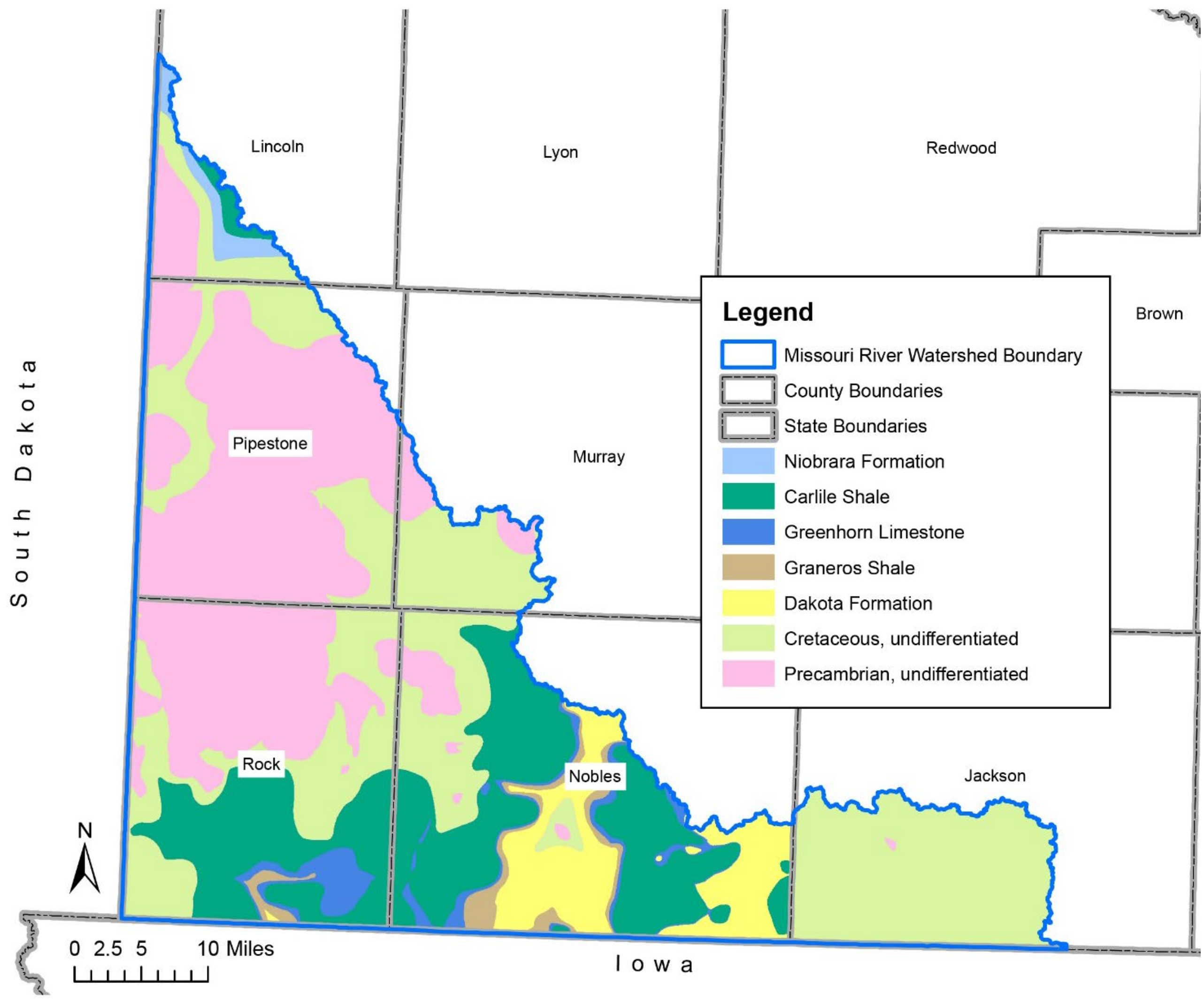

Yellow Medicine
Renville
Lincoln
Lyon
Redwood
Pipestone
Murray
Rock
Nobles
Jackson
Legend
County Boundaries
GRAPs Missouri Watershed Boundary
Surficial Geology
USDA Texture
Gravelly sand
Loamy sand
Sandy loam
Silty clay loam
Loam
Clay loam
n/a
0 5 10 20 Miles
N

Figure 3B



Yellow Medicine
Renville
Lincoln
Lyon
Redwood
Pipestone
Murray
Rock
Nobles
Jackson
Legend
County Boundaries
GRAPs Missouri Watershed Boundary
Generalized Surficial Geology
Bedrock
Clay
Mixed
Sand
0 5 10 20 Miles
N

Figure 4



Lincoln
Lyon
Redwood
Brown
Pipestone
Murray
Rock
Nobles
Jackson
South Dakota
Iowa
N
0 2.5 5 10 Miles
Legend
Missouri River Watershed Boundary
County Boundaries
State Boundaries
Niobrara Formation
Carlile Shale
Greenhorn Limestone
Graneros Shale
Dakota Formation
Cretaceous, undifferentiated
Precambrian, undifferentiated

Figure 5

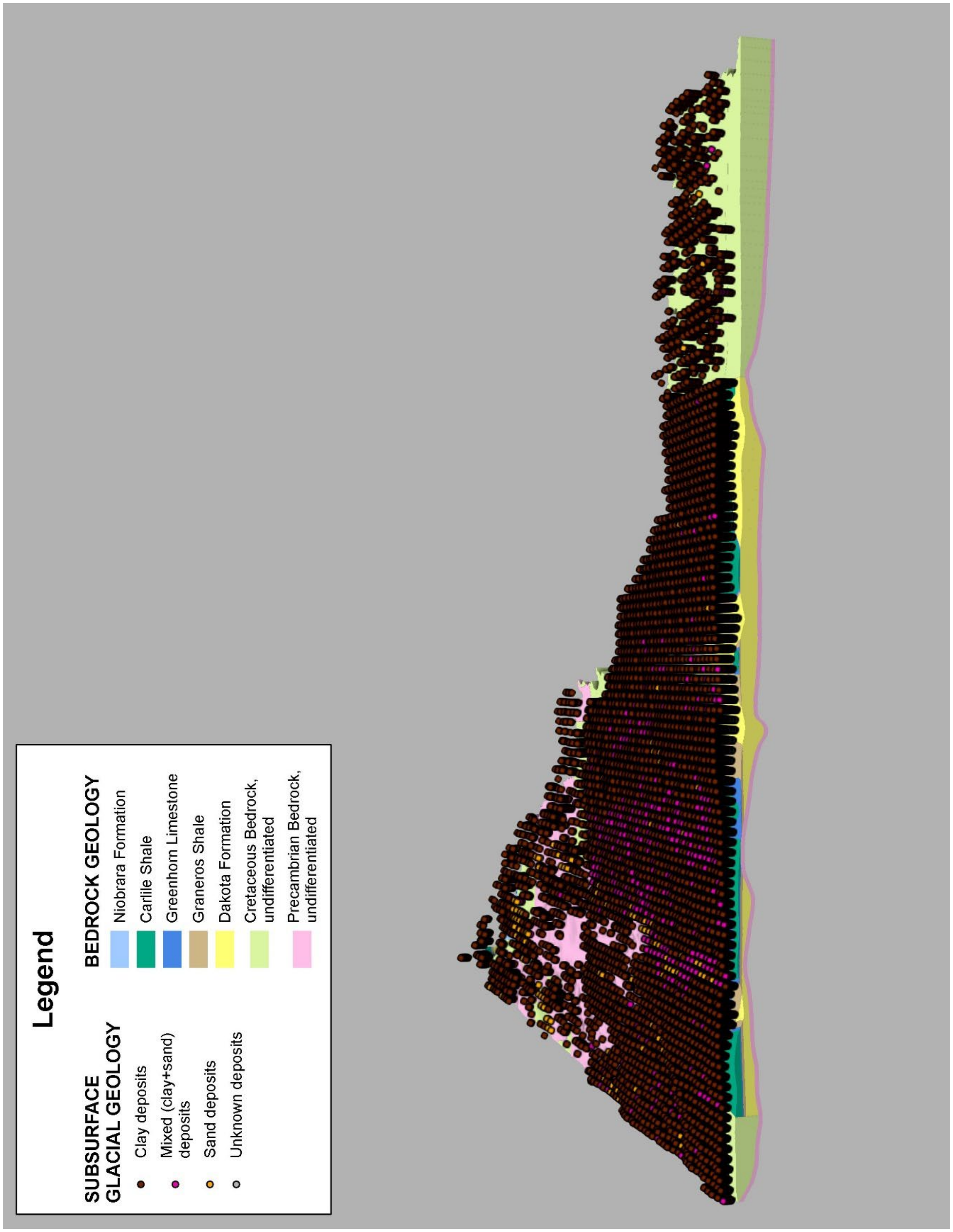

Legend
SUBSURFACE GLACIAL GEOLOGY
Clay deposits
Mixed (clay+sand) deposits
Sand deposits
Unknown deposits
BEDROCK GEOLOGY
Niobrara Formation
Carlile Shale
Greenhorn Limestone
Graneros Shale
Dakota Formation
Cretaceous Bedrock, undifferentiated
Precambrian Bedrock, undifferentiated

Table 1

Map type		Unit code	Lithostratigraphic Formation/Member	Unit type	USDA texture	Generalized online 3D model texture	CGA Unit
Subsurface	*Surficial*	al	Post-glacial	Alluvium	Sandy loam, gravelly sand, loamy sand	Mixed, sand	Qa
	Surficial	glc	New Ulm Formation, Ivanhoe Member	Glaciolacustrine	Clay loam, silty clay loam	Clay	Qil
	Surficial	glf	New Ulm Formation, Ivanhoe Member	Glaciolacustrine	Silty clay loam	Clay	--
Subsurface	*Surficial*	nuo	New Ulm Formation, Ivanhoe and Verdi Members	Outwash	Sandy loam, gravelly sand	Mixed, sand	Qno
	Surficial	ni	New Ulm Formation, Ivanhoe Member	Washed Till	Clay loam, loam	Clay	Qwi
	Surficial	nih	New Ulm Formation, Ivanhoe Member,	Hummocky Till	Clay loam, loam	Clay	Qhi
	Surficial	nim	New Ulm Formation, Ivanhoe Member	Moraine Till	Clay loam, loam	Clay	Qmi
Subsurface		ni	New Ulm Formation, Ivanhoe Member	Till	Loam	Clay	Qni
Subsurface	*Surficial*	nv	New Ulm Formation, Verdi Member	Till	Clay loam	Clay	Qnv
Subsurface		lm	Lake Henry Formation, Meyer Lake Member	Till	Clay loam	Clay	Qlm
Subsurface	*Surficial*	uw1	Pre-Wisconsinan unnamed Winnipeg provenance till	Till	Clay loam	Clay	Qd1
Subsurface	*Surficial*	uno	Pre-Wisconsinan undifferentiated outwash	Outwash	Sandy gravel, gravelly sand	Sand	Qoo
	Surficial	ot	Pre-Wisconsinan old till	Till	Clay loam	Clay	--
Subsurface	*Surficial*	ur1	Pre-Wisconsinan Casenovia till	Till	Clay loam	Clay	Qct
Subsurface		us1	Pre-Wisconsinan unnamed Superior provenance till	Till	Clay loam	Clay	Qos
Subsurface		urm1	Pre-Wisconsinan unnamed Riding Mountain provenance till	Till	Clay loam	Clay	Qom
Subsurface		urm2	Pre-Wisconsinan Magnolia till	Till	Clay, Clay loam	Clay	Qm
Subsurface		ur2	Pre-Wisconsinan unnamed Rainy provenance till	Till	Silty clay loam, clay loam	Clay	Qd4
Subsurface		us2	Pre-Wisconsinan unnamed Superior provenance till	Till	Loam	Clay	Qos2
Subsurface		ur3	Pre-Wisconsinan unnamed Rainy provenance till	Till	Silt loam	Clay	Qor
Subsurface		urm3	Pre-Wisconsinan unnamed Riding Mountain provenance till	Till	Silty clay loam	Clay	Qd6
Subsurface		uw2	Pre-Wisconsinan unnamed Winnipeg provenance till	Till	Silty clay loam	Clay	Qow

Subsurface		un	Pre-Wisconsinan unnamed unknown provenance	Till	Loam	Clay	Qtu
Subsurface		und	Undifferentiated Quaternary Sediment	Unknown	n/a	Unknown	Qu
	Surficial	b	Bedrock	Bedrock	n/a	Bedrock	b

Table 2

Dataset	Sources	Areas
Bedrock Topography	S-21 Bedrock Geology of Minnesota (Jirsa and others, 2011)	Jackson and Murray Counties
	Rock County Bedrock Topography (Bauer and others, 2020a)	Rock County
	Nobels County Bedrock Topography (Bauer and others, 2020b)	Nobles County
	Pipestone County Bedrock Topography (Retzler and others, in progress)	Pipestone County
	Lincoln County Bedrock Topography (Retzler and others, in progress)	Lincoln County
Bedrock Geology	Rock Bedrock Geology (Bauer and others, 2020a)	Rock County
	Nobels Bedrock Geology (Bauer and others, 2020b)	Nobles County
	Lincoln Bedrock Geology (Retzler and others, in progress)	Pipestone County
	Pipestone Bedrock Geology (Retzler and others, in progress)	Lincoln County
	S-21 Bedrock Geology of Minnesota (Jirsa and others, 2011)	Jackson and Murray Counties
Surficial Geology	D-1 Surficial Geology of Minnesota (2021)	Murray, Jackson, Pipestone, Lincoln, Rock and Nobles Counties
Quaternary Subsurface	Rock Quaternary Stratigraphy (Bauer and others, 2020a)	Rock County
	Nobels Quaternary Stratigraphy (Bauer and others, 2020b)	Nobles 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

	strat	COUNT_strat	kclass
1	bedrock	6937	0
2	boulder	502	0
3	clay	1739	1
4	clay, black	175	1
5	clay, blue	4768	1
6	clay, brown	1318	1
7	clay, gravel	317	1
8	clay, gravel, black	9	1
9	clay, gravel, blue	317	1
10	clay, gravel, brown	149	1
11	clay, gravel, gray	371	1
12	clay, gravel, green	9	1
13	clay, gravel, red	2	1
14	clay, gravel, yellow	237	1
15	clay, gray	3674	1
16	clay, green	132	1
17	clay, organic	49	1
18	clay, red	8	1
19	clay, sand	650	2
20	clay, sand, black	19	2
21	clay, sand, blue	1156	2
22	clay, sand, brown	627	2
23	clay, sand, gray	1176	2
24	clay, sand, green	37	2
25	clay, sand, organic	1	2
26	clay, sand, red	2	2
27	clay, sand, white	8	2
28	clay, sand, yellow	577	2
29	clay, silt	275	1
30	clay, silt, black	50	1
31	clay, silt, blue	28	1
32	clay, silt, brown	114	1
33	clay, silt, gray	151	1
34	clay, silt, green	4	1
35	clay, silt, yellow	19	1
36	clay, white	16	1
37	clay, yellow	4664	1
38	coal	17	0
39	drift	196	0

40	fill	617	0
41	gravel	1626	3
42	gravel, clay	141	2
43	gravel, clay, black	1	2
44	gravel, clay, blue	36	2
45	gravel, clay, brown	53	2
46	gravel, clay, gray	54	2
47	gravel, clay, red	2	2
48	gravel, clay, yellow	39	2
49	gravel, organic	2	0
50	gravel, silt	17	2
51	gravel, silt, blue	2	2
52	gravel, silt, brown	10	2
53	gravel, silt, gray	8	2
54	irrelevant	353	0
55	marl	2	0
56	nrcd	4	0
57	organic	63	0
58	pit	9	0
59	sand	2522	3
60	sand, black	24	3
61	sand, blue	216	3
62	sand, brown	765	3
63	sand, clay	259	2
64	sand, clay, black	3	2
65	sand, clay, blue	96	2
66	sand, clay, brown	71	2
67	sand, clay, gray	168	2
68	sand, clay, white	3	2
69	sand, clay, yellow	37	2
70	sand, gravel	2238	3
71	sand, gray	1378	3
72	sand, green	12	3
73	sand, organic	18	3
74	sand, red	31	3
75	sand, silt	252	3
76	sand, silt, black	15	3
77	sand, silt, blue	39	3
78	sand, silt, brown	153	3
79	sand, silt, gray	123	3
80	sand, silt, green	2	3
81	sand, silt, white	2	3

82	sand, silt, yellow	20	3
83	sand, white	33	3
84	sand, yellow	592	3
85	saprolith	15	0
86	silt	79	2
87	silt, black	88	2
88	silt, blue	3	2
89	silt, brown	21	2
90	silt, clay	93	1
91	silt, clay, black	7	1
92	silt, clay, blue	2	1
93	silt, clay, brown	9	1
94	silt, clay, gray	10	1
95	silt, clay, yellow	3	1
96	silt, gravel	30	2
97	silt, gravel, black	3	2
98	silt, gravel, brown	9	2
99	silt, gravel, gray	7	2
100	silt, gravel, yellow	2	2
101	silt, gray	24	2
102	silt, green	2	2
103	silt, organic	8	2
104	silt, sand	113	3
105	silt, sand, black	10	3
106	silt, sand, blue	3	3
107	silt, sand, brown	33	3
108	silt, sand, gray	38	3
109	silt, sand, green	2	3
110	silt, yellow	3	2
111	soil	4486	2
112	till	292	1
113	till, black	2	1
114	till, blue	61	1
115	till, brown	32	1
116	till, gray	86	1
117	till, green	8	1
118	till, red	1	1
119	till, sand	7	1
120	till, yellow	61	1
121	unknown	4	0
122	wood	2	0