Wisconsin Geological
and Natural History Survey
DIVISION OF EXTENSION
UNIVERSITY OF WISCONSIN–MADISON

Supplemental report on depth to Silurian bedrock in eastern Wisconsin

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Contents

Abstract

Silurian-aged bedrock in eastern Wisconsin is shallow, fractured, and contains groundwater that is susceptible to surface water contamination. Revisions to Wisconsin state rules ATCP50 and NR151 to regulate manure spreading over this Silurian-aged bedrock create the need for a depth-to-bedrock (DTB) map of eastern WI. The Wisconsin Geological and Natural History Survey, supported by the Wisconsin Department of Agriculture, Trade and Consumer Protection (DATCP)–Soil and Water Resource Management (SWRM) program, created an updated depth-to-bedrock raster surface with 5-foot and 20-foot contours over the 4,750 square-mile study area.

The raster surface was created using the Empirical Bayesian Kriging with Regression Prediction (EBKRP) in Esri ArcGIS Pro 2.9.1. We first modeled the bedrock elevation and then estimated DTB by subtracting the bedrock elevation surface from land surface. We tested various EBKRP input model parameters and data methods, and ultimately used 186,054 points to create the map. The data include airborne electromagnetics (AEM) collected by helicopter flight via SkyTEM Canada Inc. in collaboration with the United States Geological Survey (USGS) in 2021. Geostatistical techniques with novel subsurface data have allowed the WGNHS project team to generate a DTB map for the Silurian dolomite in Wisconsin with higher resolution and more accuracy than previous efforts.

Introduction

The Silurian dolomite aquifer in eastern Wisconsin (fig. 1) is vulnerable to contamination (Muldoon and others, 2018). In recognition of this issue, the Wisconsin Administrative Code (rules ATCP50 and NR151) has been revised to regulate manure spreading. The revised regulations are supported by an updated map of the depth to bedrock (DTB) over the Silurian aquifer. The map has several requirements:

1. higher resolution and accuracy than previously published maps;
2. able to be readily modified as new data became available;
3. able to communicate areas where DTB is well known and areas where it is less well known.

Requirements 2 and 3 are due to provisions in the rules that allow growers and landowners to contest DTB maps used by the Wisconsin Department of Natural Resources (WDNR) and by counties, including this one, and provide updated data. Knowing where a map is likely to be less accurate gives a sense of areas where contesting a map might make more sense for growers.

The issue of groundwater contamination in the Silurian dolomite aquifer is not new. Land use planning maps by Sherrill (1978; 1979) are still widely used. These maps were generated using National Resources Conservation Service (NRCS) shallow soils data, well construction report (WCR) points, and geologic interpretation. DTB contours varied between Door County (16 ft) and the rest of the region (20 ft), creating a discontinuity in either application of rules or interpreted depths at the county border. To assist with compliance to the NR151 standards, Baeten (2022), updated the Sherrill maps and incorporated additional WCR and county push probe data. A statewide DTB map by Trotta and Cotter (1973) is also frequently used to estimate DTB in eastern Wisconsin. However, this map has 50-ft contours and lacks the depth resolution needed to apply the rules.

More recent DTB maps were generated for Kewaunee, Brown, and Door counties (Luczaj, 2011; Clayton, 2013; Luczaj and others, 2019; Brodhagen, 2023). The Clayton (2013) map was not intended for regulatory use but to illustrate how glacial sediments were deposited. The Luczaj (2011), Luczaj and others (2019), and Brodhagen (2023) maps use geolocated and up-to-date WCRs and push probe data as well as inverse distance weighting mapping methodologies. The Wisconsin Geological and Natural History Survey (WGNHS) has published county-scale (1:100,000 map scale) DTB maps for Fond du Lac County (Batten, 2018) and Dodge County (Stewart, 2021). In southeastern Wisconsin, a DTB map (1:100,000 map scale) was drawn for Washington, Ozaukee, Waukesha, Milwaukee, Walworth, Racine, and Kenosha counties (Evans and others, 2004). Two township-scale maps were created for the Town of Lincoln in Kewaunee County (1:50,000 map scale; Parsen and others, 2017) and the Town of Byron in Fond du Lac County (1:24:000 map scale; Bradbury and Batten, 2010).

This report summarizes the effort to provide an updated DTB map of the Silurian dolomite in eastern Wisconsin. The raster and polygons described in this report are available as dataset 1, an accompanying resource to this report. The map has undergone internal review (WGNHS) and external review by the WDNR, DATCP, and County Land and Water Conservation Departments of Door, Kewaunee, Calumet, Manitowoc, Sheboygan, Fond du Lac, and Dodge counties, and was presented to state and national scientific and Geographic Information System (GIS) communities.

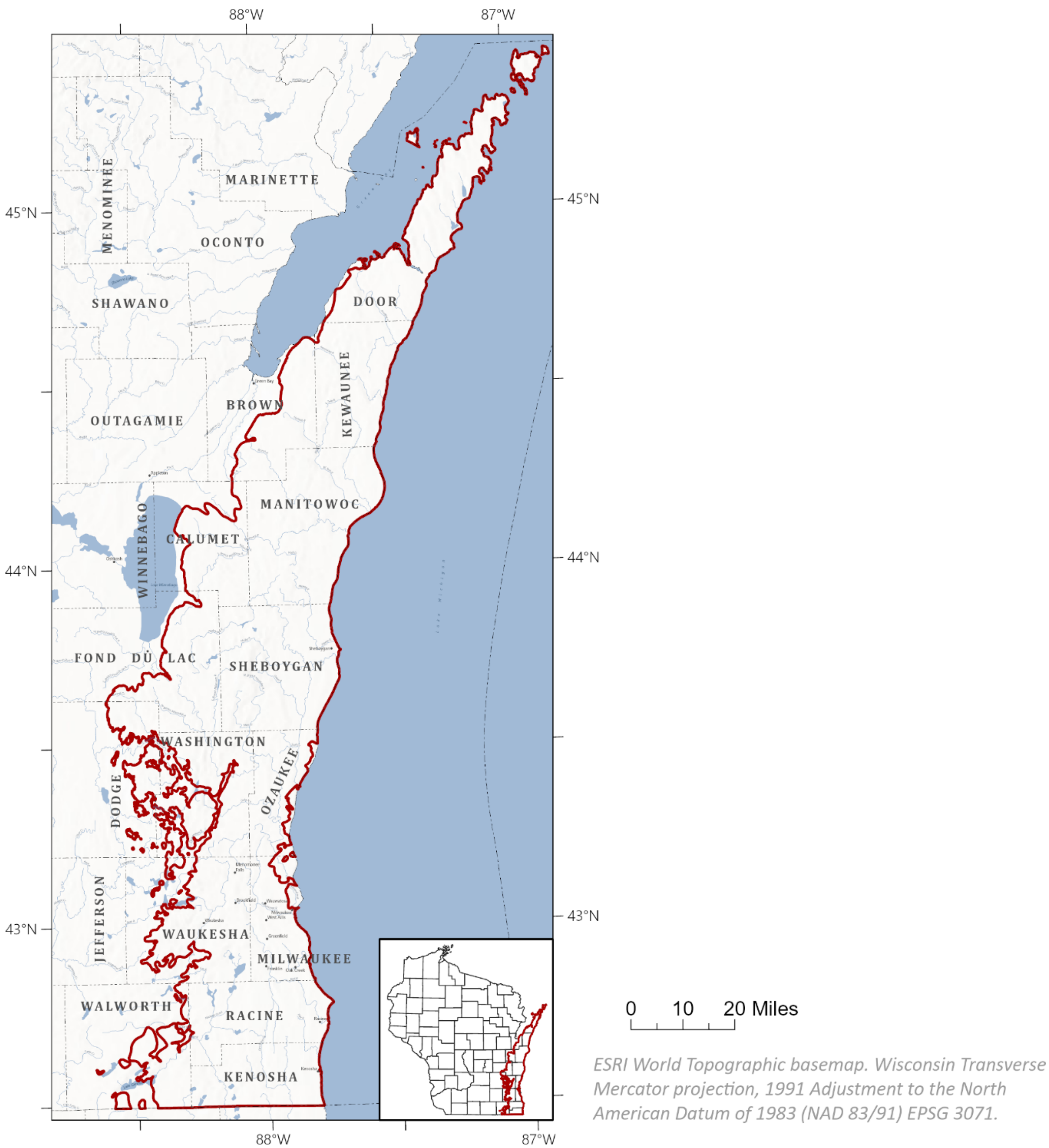


Figure 1. *Map showing the extent of Silurian dolomite in eastern Wisconsin, shown as a dark red outline.*

Methods

We compiled DTB point data from nineteen sources, including well construction reports and airborne electromagnetics (AEM) data. For each data point, the land surface elevation was first determined by extracting the elevation from an elevation raster (USGS, 2023). Next, the DTB point data were subtracted from the land surface elevation to provide top-of-bedrock elevation. Those bedrock elevation point data were then interpolated to generate a bedrock elevation raster. Finally, that generated bedrock elevation raster was subsequently subtracted from the land surface to provide a continuous estimate of the DTB across the Silurian dolomite in eastern Wisconsin. By creating a bedrock elevation raster as an intermediary step, we can assess inconsistencies in the data that would be present if we had just used the DTB point data.

Silurian Boundary

The outline of the Silurian-aged bedrock is a compilation of county-scale (1:100,000) and regional-scale (1:250,000) mapping merged using Esri ArcGIS Pro. The Sherrill (1978; 1979) Silurian outline was clipped and merged with Silurian extents from four county-scale studies: Brown County (Luczaj, 2011), Dodge County (Stewart, 2021), Fond du Lac County (Batten, 2018), and the southeastern Wisconsin region including Walworth, Racine, Kenosha, Milwaukee, Waukesha, Ozaukee, and Washington counties (Evans and others, 2004). WCR records and county-specific high-resolution lidar (available from https://geodata.wisc.edu/) were used to delineate the boundary of the Silurian where disagreement occurred between boundaries from the different maps.

Data Inputs

DTB point data (n=186,054) from nineteen datasets were compiled, checked for errors, and merged into a single dataset for Empirical Bayesian Kriging with Regression Prediction (EBKRP) analysis and DTB raster creation. These datasets include AEM flights, WCRs and geologic logs from the WGNHS and the WDNR, engineering borings from the Department of Transportation (DOT), observations of exposed rock from the NRCS and county conservation departments, mapped shallow soils from the NRCS, hand push probe measurements from counties, and estimates from passive seismic measurements.

The DTB data points are not distributed equally in the study area, with more push probe data in the north and along the escarpment, AEM data along the west and north, and well and test boring data spread across the region with a greater density to the south (fig. 2). Increased data density will result in a more accurate map. Each of the nineteen datasets, including source and number of points, is described below. Table 1 lists error estimates for each dataset.

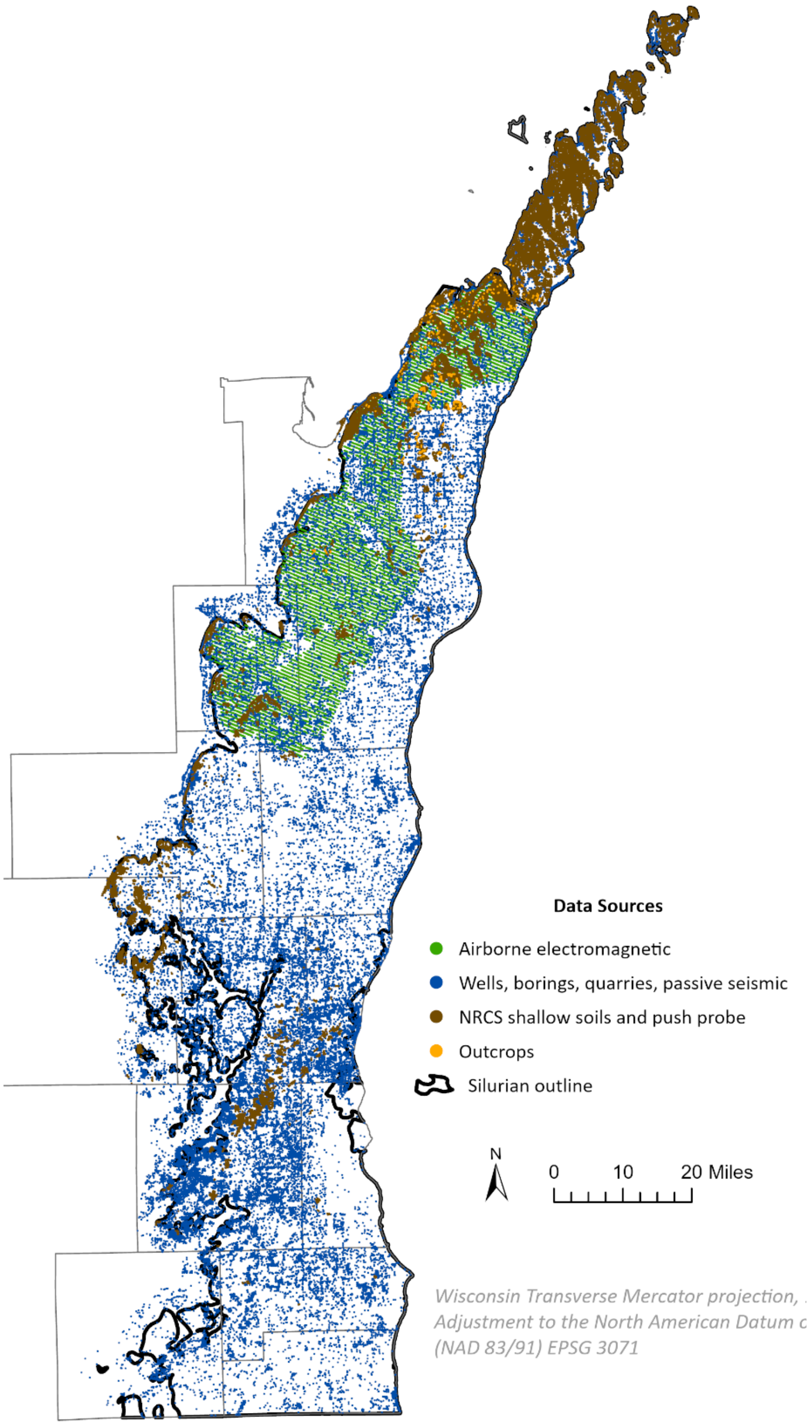


***Figure 2**. Data sources used for the bedrock elevation surface.*

Land surface elevation

A digital elevation model (DEM) with 10- by 10-m (32.8 by 32.8 ft) cell size from the National Elevation Dataset (NED) was used to represent the land surface (USGS, 2023). This specific DEM was chosen as the cell size matches the output bedrock elevation raster. Using the same resolution when subtracting rasters reduces aliasing and artifacts that occur when the rasters are at different resolutions.

Airborne electromagnetics (AEM) (n=79,781)

AEM surveys were carried out by the United States Geological Survey (USGS) and the WGNHS with support from DATCP in northeastern Wisconsin (Minsley and others, 2022). SkyTEM Canada Inc. acquired the AEM data via helicopter in January and February of 2021. The flight lines were flown along a northwest to southeast trend, separated by ½ mile between flight lines (fig. 3). Resistivity depth sounding points were captured every 100 ft and geolocated with a Global Positioning System (GPS). The measurements were inverted to produce electrical resistivity data to depths of approximately 1000 ft with 3 ft near-surface vertical resolution. Transitions in resistivity values in the shallow subsurface are used to estimate DTB. Where it was possible, the AEM data were correlated to borings to improve depth estimates. Figure 4 shows a profile along a flight line of multiple data points with the overlying sediment and bedrock indicated. The bedrock elevation for these points was calculated by subtracting the DTB from AEM points from the 10-m (32.8-ft) DEM. Measurement error for the AEM data was assigned 6 ft to account for uncertainty in location and depth estimates. Of the 79,781 points, 20 entries had no associated DTB and were removed from the dataset. Another 161 entries had negative DTB values with maximum value of -17.7 ft and median of -0.73 ft. Those data were either next to AEM data with depths of 1 ft or were within NRCS shallow soils polygons. They were assigned a DTB value of 0 ft.

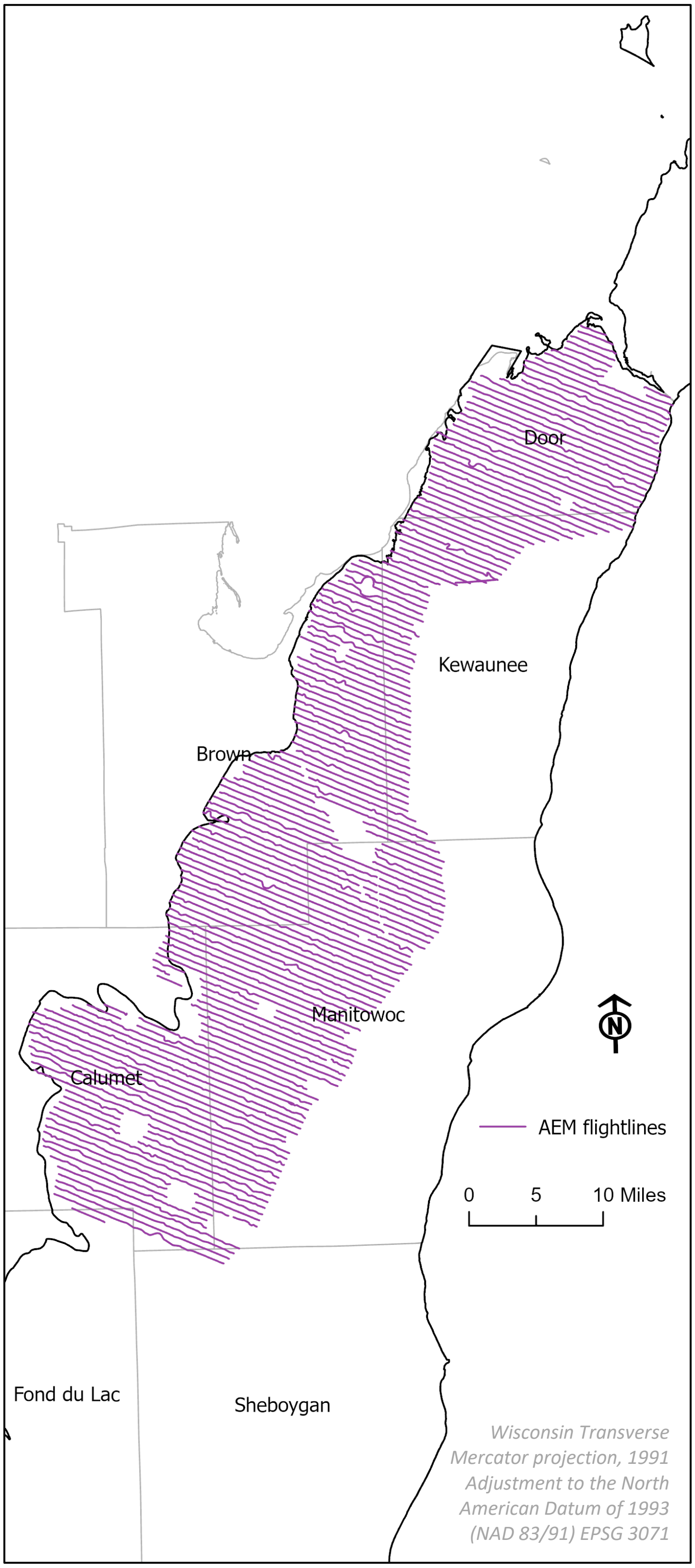


Figure 3. *Locations of AEM flight lines and data. Counties are labeled.*

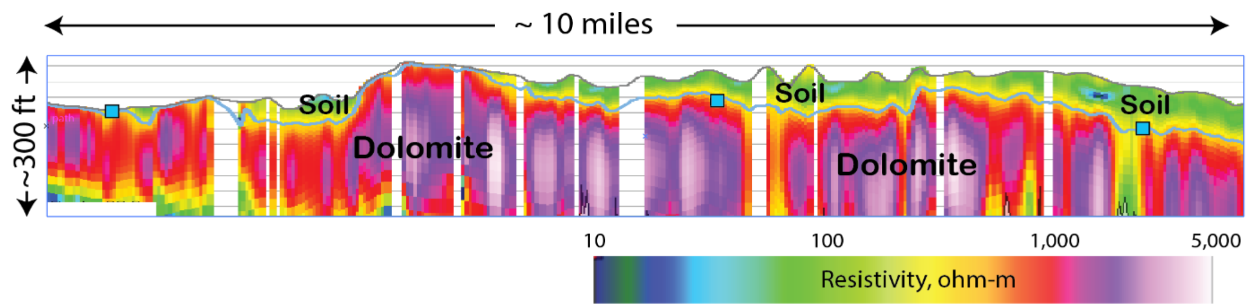


Figure 4. *Resistivity profile showing soil and bedrock. Soil is less resistive (yellow to green) and dolomite is more resistive (orange to purple). The blue squares indicate DTB determined from WCRs located within 100 m of the AEM line.*

Well Construction Reports and geologic logs (n=65,660)

During well drilling and construction, the transition from sediment to bedrock is documented on a WCR, providing an estimate of DTB. WCRs are available in a GIS format or as scanned paper copies. Many of the scanned WCRs were used in geologic studies and converted to a digital format and so were available as data. In addition to WCRs, geologic logs were created by WGNHS geologists for selected, mostly high-capacity wells. The logs are based on well cuttings collected during drilling. Bedrock elevation at each WCR and geologic log point was determined by subtracting DTB from the land surface elevation.

Well Construction Reports (WCRs) Post-1988 (n=55,224)

The DNR has managed and documented approximate digital WCR well geolocations statewide since 1988. These data are provided to the WGNHS, which houses an internal WCR database of these WCRs and more precisely geolocates these wells on a project-by-project basis. Those wells are then routinely shared back to the DNR. The dataset used here was exported from the DNR database on June 1, 2022, and updated on May 30, 2023. This dataset has a statewide extent and so was clipped to within 5 km from the Silurian boundary for this project. Within this clipped dataset, wells were removed if they contained no DTB value, were reconstructed, not locatable, or were deemed erroneous by human judgment. The WCRs all have location confidence ranging from 1350 ft (approximate quarter-quarter section geolocation resolution) to 3 ft using GPS or visual identification.

Door County dataset—Mickelson (n=644)

A dataset of geolocated wells in Door County is in the WGNHS in-house GIS Library (D. Mickelson, unpub. data, 2010). These WCRs had been assigned a location confidence of 300 ft.

SEWRPC area WCRs (n=8,175)

These WCRs are from two project datasets associated with mapping efforts for the Southeastern Wisconsin Regional Planning Commission (SEWRPC) counties. The individual datasets are from Evans and others (2004) and Eaton and others (1999). These datasets were queried against the WCR Post-1988 dataset to remove duplicates and retain geolocated DTB well data from scanned WCRs. These data cover Walworth, Racine, Kenosha, Milwaukee, Waukesha, Washington, and Ozaukee counties.

GeotechIndexPnt_WisDOT2013 (n=9)

These data are from borings supplied by the Wisconsin DOT in 2013. These borings are from DOT site investigations for road construction (Reid, unpub. data, 2013).

Geologic logs (n=1,608)

The logs were generated from cuttings submitted to the WGNHS upon completion of high-capacity wells. They are high quality and more accurately located since the location was determined by a WGNHS geologist. While the geology may be more accurate and the DTB is often reported to the nearest foot, the vertical resolution is more often only known within ± 2.5 ft because cuttings and the DTB estimate are classified in 5 ft intervals.

Soils data (n=33,475)

NRCS rock points (n=1,229)

The NRCS Soil Survey Geographic Database (SSURGO) (Soil Survey Staff, 2012) contains locations of exposed rock as recorded by NRCS during soil surveys. Only points located within 5 km (3.1 miles) of the study area were used in the analysis. These points were assigned DTB of 0 ft below land surface, so the bedrock elevation was set to the land surface.

NRCS shallow soils (n=32,246)

The NRCS SSURGO database also contains mapped polygons of shallow soil units. Because the bedrock surface contouring algorithm used in this analysis uses only point data, the NRCS polygon boundaries were converted to points. The dataset was clipped to within 5 km (3.1 miles) of the Silurian boundary. The DTB at each point was set to the polygon’s minimum DTB. These values are 3.18 ft or shallower.

Push probe (n=3,780)

Push probe data are an efficient low-cost method to determine shallow DTB. A tile probe is pushed into the soil until refusal, the depth is measured, and the location of the measurement is recorded by GPS. This method requires some expertise and training to eliminate false refusal measurements such as those that might be encountered if the tile probe hits a cobble or indurated till.

Kewaunee County—Engles (n=3,663)

Geolocations of exposed rock in Kewaunee County were provided by the Kewaunee County Land & Water Conservation Department. These data only included push probe with DTB values of less than 48 inches (T. Engles, unpub. data, 2023).

Brown County—Peltier (n=36)

Unpublished DTB measurements in Brown County that were collected with push probe by research conducted by UW–Madison Russell Laboratories. The data only included push probe with DTB less than 3.35 ft (T. Peltier, unpub. data., 2023).

Kewaunee and southern Door—Luczaj (n=81)

Unpublished DTB measurements in Kewaunee and southern Door Counties (J.A. Luczaj, unpub. data, 2023).

Mines, pits, quarries (n=67)

The mines, pits, and quarries dataset was assembled by combining previous mining inventories with county-level data collected from local and regional planners (B. Brown, unpub. data, 2011). Using air photos and lidar-derived hillshade rasters, the DTB point was located on the uppermost bare rock of the quarry in areas where the overlying sediment had been removed but where bedrock was not quarried. The DTB at the quarries was set to 0 ft, so bedrock elevation was set to the land surface.

Exposed bedrock and outcrops (n=3,092)

Exposed bedrock provides a low cost and certain indication of DTB. These data are used by counties and geoscientists to create bedrock maps and implement regulation. Bedrock elevation at each point was set to the land surface elevation.

Brown County exposed bedrock (n=41)

These data were collected as part of a county bedrock mapping study (Luczaj, 2011).

Dodge outcrops (n=8)

These data were collected as part of a county bedrock mapping study (Stewart, 2021).

Kewaunee County exposed bedrock (n=2,502)

These are locations of exposed bedrock recorded by the Kewaunee County Land & Water Conservation Department (T. Engles,, unpub. data, 2023).

SEWRPC outcrops (n=277)

These data were compiled by during bedrock mapping of the SEWRPC counties (Evans and others, 2004).

Door County exposed bedrock (n=247)

These are exposed rock points within the Red River watershed from the Door County Soil and Water Conservation Department (Steiglitz and Dueppen, 1994).

Silurian outcrops (n=17)

Exposed outcrops recorded by Haas in 2023 to support this DTB mapping effort.

Passive seismic (n=199)

We used a Tromino three-component seismometer to estimate DTB in the study area. The depths were estimated using the horizontal-to-vertical-spectral-ratio method (Chandler and Lively, 2014). These data locations were chosen to infill areas where no data existed or to provide another data point at locations where two other separate data sources disagreed.

Data measurement error and accuracy

The DTB measurement from each of the datasets listed above have an associated error. To estimate that measurement error we took two different sources into consideration. The first was an absolute estimate of how well the DTB was measured by the method. For example, push probe measurements are likely precise to within two inches while geologic logs are precise to within five feet. The second source of error was due to how well the data were located. A data point with poor locational accuracy is more likely to have a bedrock elevation error associated with it even if the recorded depth is well known. Since it is mislocated, it does not represent the actual bedrock surface. For example, a point might be recorded as being in a valley while it should be at the top of a hill (fig. 5). We estimate that error in the bedrock surface elevation by assuming an average slope of 2 percent in bedrock elevation. That slope was used that as a multiplier of the horizontal locational confidence to give the measurement error in bedrock elevation point data. For example, a point with a horizontal locational confidence of 1000 ft would have an associated bedrock elevation vertical measurement error of 20 ft. The horizontal locational confidence and estimated vertical measurement error for the different data are shown in Table 1 below.

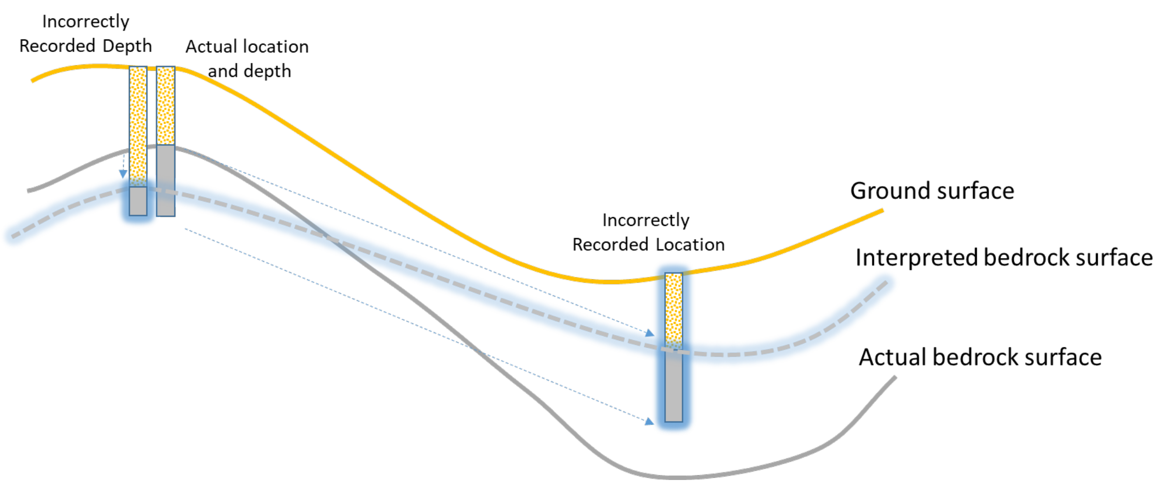


Figure 5. *Diagram showing how depth and location errors might create bedrock elevation errors.*

Table 1. Data sources and associated ranges of error.

Data Source	Number of Points	Horizontal Location Confidence Range (ft)	Estimated Vertical Measurement Error (ft)
Airborne electromagnetics	79,781	300	6
Well Construction Report and Geologic Logs			
Well Construction Reports Post 1989	55,224	100–1,350	3–27
Door County Dataset – Mickelson	644	300	6
SEWRPC Area WCRs	8,175	1–1,350	3–27
GeotechIndexPnt_WisDOT2013	9	300	6
Geologic Logs	1,608	300–1,350	6–27
Soils Data			
NRCS Rock Points	1,229	300–1,000	6–20
NRCS Shallow Soils	32,246	300–1,000	6–20
Push Probe			
Kewaunee County	3,663	300	6
Brown County	36	300	6
Kewaunee and Southern Door	81	300	6
Mines, Pits, and Quarries	67	300	6
Exposed Bedrock and Outcrop			
Brown County Exposed Bedrock	41	2–30	3
Dodge County Outcrops	8	100	3
Kewaunee County Exposed Bedrock	2,502	300	6
SEWRPC Outcrops	277	50	3
Door County Exposed Bedrock	247	300	6
Silurian Outcrops	17	100	3
Passive Seismic	199	100–1,350	3–27

Modeling methods

Since it is not possible to collect data for DTB at the resolution of a point in every acre or tens of square meters, we must rely on interpolation. Interpolation applies what is known at specific locations to predict values in areas where information is unknown. In this study, we interpolated bedrock elevation and then subtracted that from the land surface elevations to estimate DTB. The bedrock elevation surface was chosen to be interpolated rather than DTB because the bedrock surface varies in a more predictable manner than DTB, thus making it the better choice for interpolation. That is, we are only mapping the surface that resulted from bedrock erosion and deposition. However, if we used DTB, uncertainty created by the erosional and depositional processes of overlying sediments would be added to the bedrock surface uncertainty, making the interpolation results less accurate.

We chose EBKRP to create the bedrock elevation raster (Pilz and Spock, 2008; Krivoruchko, 2012; Krivoruchko and Gribov, 2014; Njoku and others, 2023). This method allowed us to meet the three requirements listed on page 3 of this report. Using similar datasets, we found EBKRP provided similar results for Kewaunee County as the Luczaj (2019) and the Brodhagen (2023) maps. These maps were all based on more densely spaced and newer data, an improvement from the Sherrill (1978; 1979) maps, thus meeting the first requirement for this map. Using the vertical measurement error shown in Table 1 and geostatistics, EBKRP provides an estimate of map error, meeting a second requirement for the map.

Uncertainty is needed for this dataset since it provides users with guidance about areas where the map is more accurate and where the map is less accurate. An individual grower or county government might use that information to decide whether to challenge the map. In addition, the EBKRP method also allows for incorporation of additional data using the same interpretation method and with minimal effort, eliminating issues that might arise with different users having different interpretations of the same data, meeting a third requirement for the map. The EBKRP method also splits the area to be mapped into smaller subsets. This allows the interpolation to match the smaller areas better than trying to fit the entire area at once. This is needed since there are areas of the bedrock surface where it changes quickly and others where it varies much less.

We applied EBKRP in the Geostatistical Analyst Toolset in Esri ArcGIS Pro 2.9.1 to first generate a bedrock elevation raster at 10 by 10 m (32.8 ft by 32.8 ft) cell resolution. We then derived DTB surface by subtracting the bedrock elevation raster from a land surface raster with the same 10 by 10 m (32.8 ft by 32.8 ft) cell resolution. Data types loaded into the EBKRP tool to generate the bedrock elevation raster included the bedrock elevations calculated from the DTB point dataset (n=186,054) compiled from the 19 different datasets listed above, and the land surface represented by a 10 m DEM (32.8 ft) (USGS, 2023). Each data point was assigned a vertical measurement error as shown in Table 1. EBKRP assigned less weight to those data with larger measurement error than data with less measurement error.

EBKRP parameters

Specific inputs and parameters used in the EBKRP model included (also listed in Table 2): 1) point dataset with bedrock elevation values as the dependent variable, 2) the DEM land surface as the explanatory raster, 3) specified measurement error for each bedrock elevation point, and

4) interpolation parameters. The point dataset and error were described above. The explanatory raster and interpolation parameters are discussed below.

Explanatory raster

An explanatory raster is an input in Esri's EBKRP tool to help guide the interpolation analysis. A good explanatory raster has low error and is correlated to the interpolation surface, which here is the bedrock elevation. For example, a land surface elevation raster in a mountainous region can be used as a guide for modeling precipitation (Njoku and others, 2023). We noted that higher elevation land surface is generally correlated to higher elevation bedrock. We used the National Elevation Database DEM at 10-m (32.8-ft) resolution (USGS, 2023) clipped to the study area as the explanatory raster.

To test the impact of the explanatory raster, we looked at the resulting interpolated bedrock elevation using empirical Bayesian kriging with and without the explanatory raster. Figure 6 shows the land surface hillshade raster, the interpolated bedrock elevation created without an explanatory raster, and the interpolated bedrock elevation with an explanatory raster (10 m land surface DEM). The land surface hillshade raster shows three bedrock wedge-shaped scarps labeled 1, 2, and 3 (fig. 6A). The two largest, 1 and 2, are located on the west and east sides of the image, respectively, and point north. The smaller scarp, labeled 3, also points north and is located to the southeast. The two plots of modeled bedrock elevation (fig. 6B and 6C) are similar and both show elevated bedrock elevations at the locations of the scarps, as would be expected. The bedrock is nearly coincident with the land surface at the scarps in both models. The EBKRP surface, Figure 6C, has a slightly sharper slope at the scarp than the EBK alone surface, Figure 6B. While this is a minor difference, the shallow bedrock depths are of most interest for the intended users of this raster and the slight improvement from using the land surface as the explanatory raster is warranted.

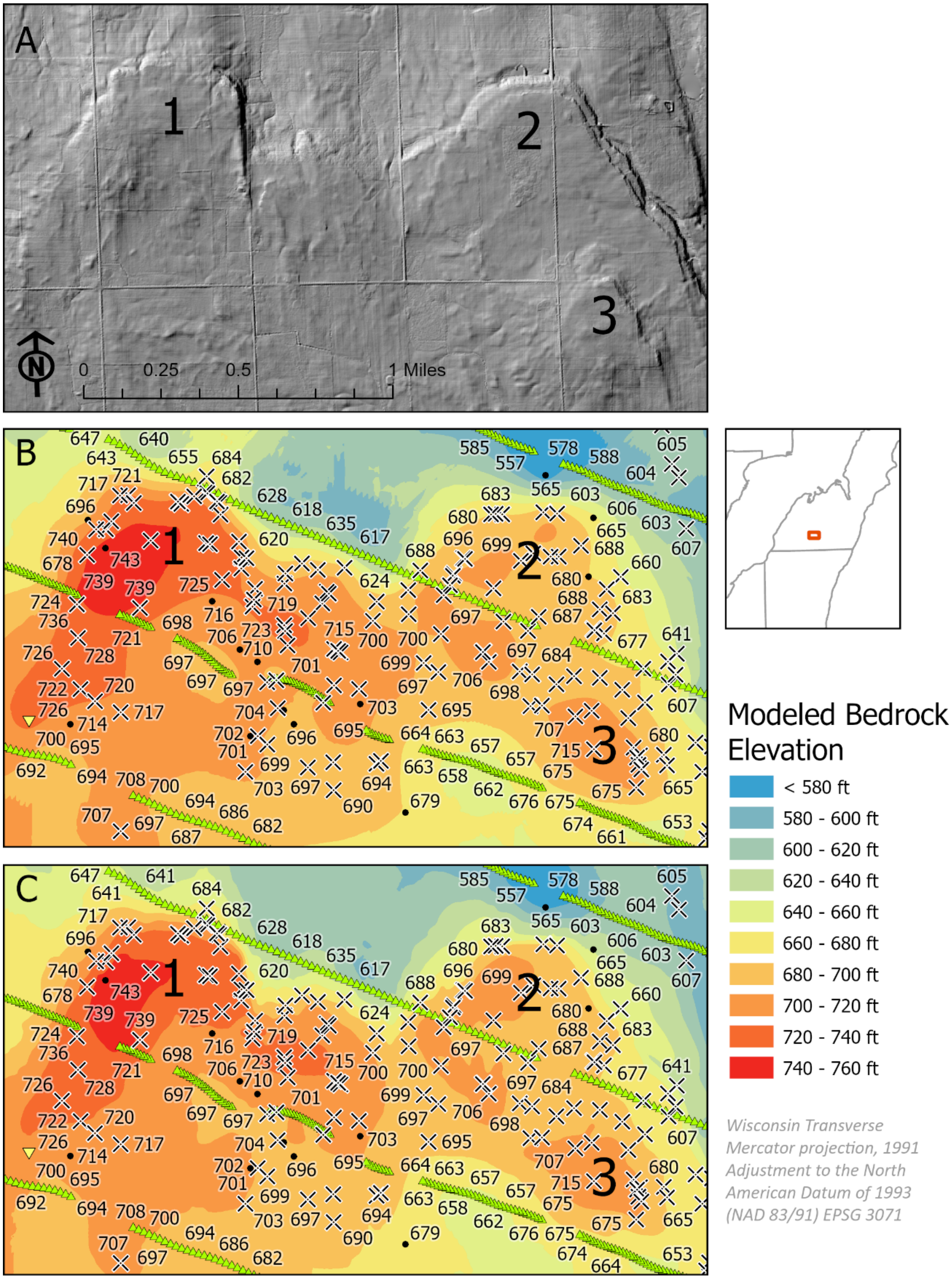


Figure 6. *Maps of a part of southern Door County showing (A) land surface hillshade; (B) bedrock elevation with no explanatory raster, EBK; and (C) bedrock elevation with land surface as explanatory raster, EBKRP. The scale and extent are the same for the three maps. Contours of the modeled bedrock elevation are the same hue and interval for maps B and C.*

EBKRP interpolation parameters

The EBKRP parameters control aspects of the interpolation process. While we found varying the values below does have some affect, the interpolated bedrock elevation results with the different parameters are similar. The values we used are either the default or were selected to better match the expected bedrock elevation surface. Table 2 shows the parameters used in the final interpolation with explanations of each parameter provided below.

Table 2. EBKRP Interpolation input parameters

Parameter	Setting
Cumulative Variance	95%
Transformation Type	None
Semivariogram Model Type	Exponential
Subset Size	100 points
Overlap Factor	1
Number of Simulations	100
Searching Neighborhood	Standard Circular
Neighbors to Include	8
Include at least	8
Sector Type	8
Radius	104 m (341.2 ft)

Cumulative variance

The cumulative variance parameter controls how the explanatory rasters are weighted after a principal component analysis. Since we supply only one explanatory raster, this condition is always met. We looked at using additional rasters such as land cover but found no noticeable improvement in the resulting raster. If we had used multiple rasters, then this parameter would have been relevant. It is set at the default of 95 percent.

Transformation type

This parameter is used for data that are known to be highly skewed and always positive. For example, hydraulic conductivity would be this type of data and would need to be transformed. There was no need to transform the bedrock elevation data.

Semivariogram model type

There are choices for semivariogram models. Some models represent smoothly varying data better while others work better with discontinuous data. Since the bedrock elevation can change rapidly over small distances, we selected the exponential semivariogram so that the closest neighbors have greater influence on the predicted value. As a result, this variogram changes more rapidly near the origin than the other commonly used semivariograms such as spherical or Gaussian.

Subset size
This is the maximum number of points within each subset area. Setting this value too high risks attempting to correlate data well beyond the correlation length or range and is wasted computation effort. Setting it too small might cut off the analysis before the range has been reached and can be determined. It was left as the default value of 100 points.

Overlap factor
This controls how many times data points are used in all the subset areas. A high number will mean that a point can be used in several subset areas. That will result in a smoother interpolation surface but with increased computation time. We used the default value of one, so each point is used only once in each subset area. Increasing the number of times the data points are used creates smoother output.

Number of simulations
This is the number of simulated semivariograms per subset area. We used the default value of 100. This set of variograms is used to estimate the prior kriging parameters for each subset area.

Search neighborhood
A standard circular search neighborhood with a maximum and minimum number of eight neighbors in eight sectors within a radius of 104 m (~341 ft) was used. This means that for each interpolated point, a circle of 104 m (~341 ft) was split into eight sectors, and eight neighbors, or points, within each of the eight sectors were used to generate the interpolated bedrock elevation at the interpolated point. If eight points were not within the sector at the search radius, then the search automatically expanded outward until eight points were encountered. This means that the number of points used to estimate the value is always 64, eight points in eight sectors. This option tends to include more subset areas and their corresponding regression coefficients than does a use of a single sector. The subsets and their regression coefficients are weighted by the number of data points within each subset to estimate the interpolated value.

Results

Depth-to-bedrock raster

After completion of the EBKRP interpolation, the bedrock elevation model results were first exported to a raster with 10 by 10 m (32.8 ft by 32.8 ft) cell size resolution. Next, this bedrock elevation raster was subtracted from the land surface elevation raster (USGS, 2023). We observed that using different cell sizes when subtracting rasters produced stepped offsets in the resulting raster but found that using the same raster resolution eliminated those stepped offsets. The resulting raster had some values less than zero where the bedrock elevation interpolation was calculated to be above than the land surface. These values were identified and set to zero depth. Lastly, the DTB raster was clipped to the Silurian bedrock extent (fig. 7). Most shallow bedrock is found in the north and to the west along the Niagara escarpment. Some smaller-scale scarps are also apparent along the same northeast-southwest orientation as the western extent of the Silurian dolomite. These likely correspond to different geologic members within the Silurian dolomite.

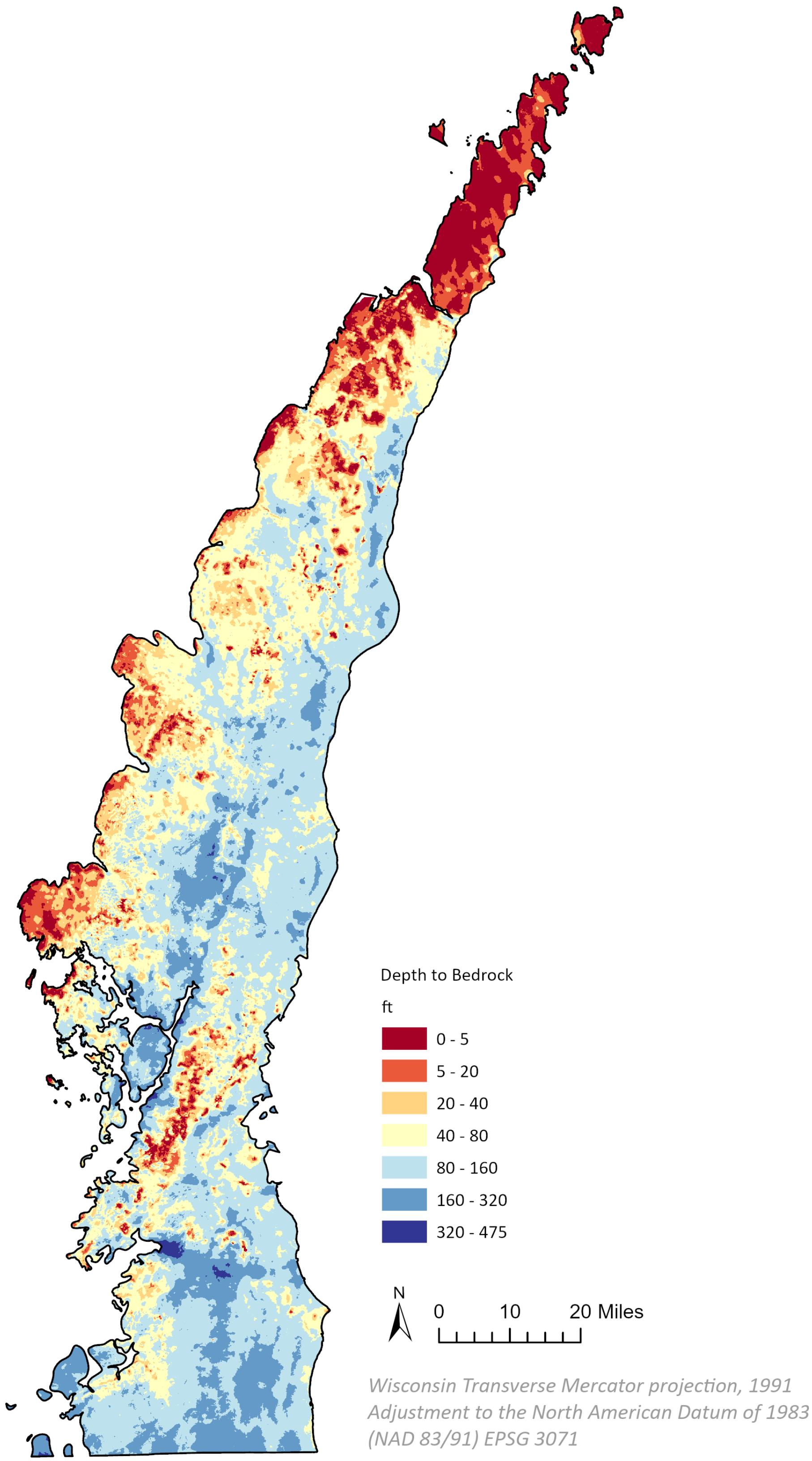


Figure 7. *Depth to bedrock over the Silurian dolomite. Raster DEM has a 10-m (32.8 ft) cell size.*

5-ft and 20-ft contour polygons

DTB of five and twenty feet are specified in the land spreading rules (NR151 and ATCP50). To aid users in identifying these areas, we generated feature polygons of the five-feet-and-under and twenty-feet-and-under areas from the DTB raster (fig. 8). Small, isolated features with areas of less than 0.5 acres (2000 m^2) were removed. The feature boundaries were then smoothed.

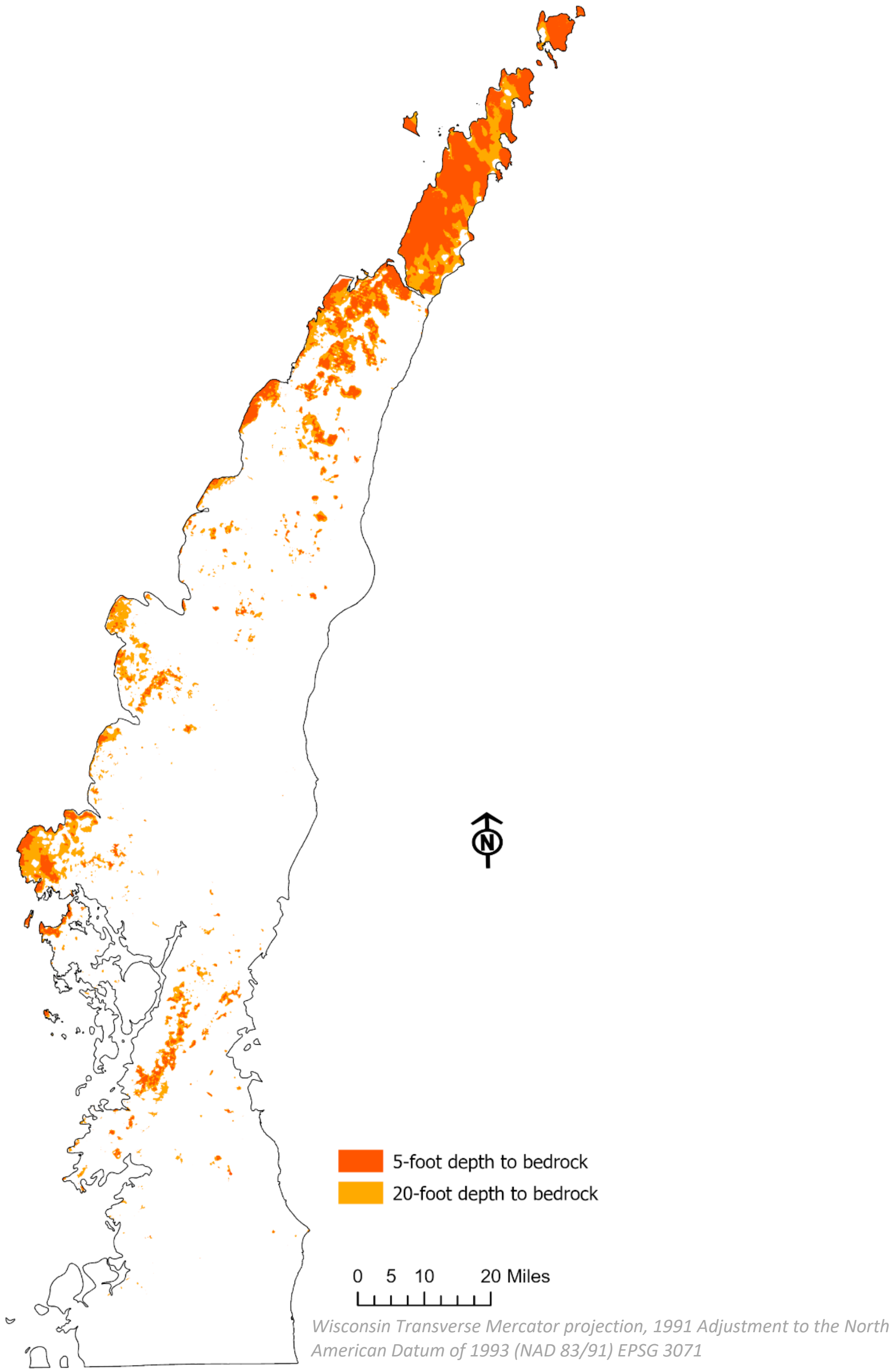


Figure 8. Five- and twenty-foot depths-to-bedrock.

Guide to data use and limitations

This dataset consists of a raster and polygons, which are interpretations of available data. As additional data and better interpretations are available, the resulting maps can be improved. This dataset was developed to provide guidance on the DTB over the Silurian dolomite for application of NR151 and ATCP50 rules. It can also serve as a resource for other purposes such as manure pit, pipeline, foundation, and highway construction. The dataset is constructed so that it can be updated and improved with relative ease as additional data become available. The ability to challenge DTB maps used by the counties, DNR, and DATCP, and collect additional data for a field determination of bedrock depth is provided in NR151 and ATCP50. We expect this additional data to be collected. The additional data, once vetted, would take precedence over the existing dataset, and subsequently be incorporated and the dataset would be released in updated versions.

We address this issue of contesting and updating the map produced by this dataset by providing guidance on identifying areas where the map accuracy is lower and additional data are needed. These areas are identified two ways. The first is to use the error determined by the EBKRP process. Each data point had a measurement error associated with it. That error was incorporated into the analysis and used to determine the accuracy of the interpolated bedrock elevations (fig. 9). The units of the error are in feet and represent the standard error of the interpolated bedrock elevation estimate. As might be expected, the error is largest in areas with little data. Also evident is that the error increases with depth. This is likely the result of greater variation in the DTB data used to determine the bedrock elevation. In areas with shallow DTB and with a higher data density, the standard error is around 5 ft or less. In areas with little data and greater DTB the standard error is 50 ft or more.

The second method of assessing map accuracy is to look at areas where the data disagree. In most maps, a judgement is made by the author to remove data or completely discount data that disagree with other data. However, given that we expect this map to be updated with additional data, we chose to leave all reasonable data in the interpolation and not remove it even in areas where the data disagree. During the creation of this map, we did not know for certain which data are most likely to be in error. By using all the data, it was our intent to remove some degree of subjective judgement from the final map.

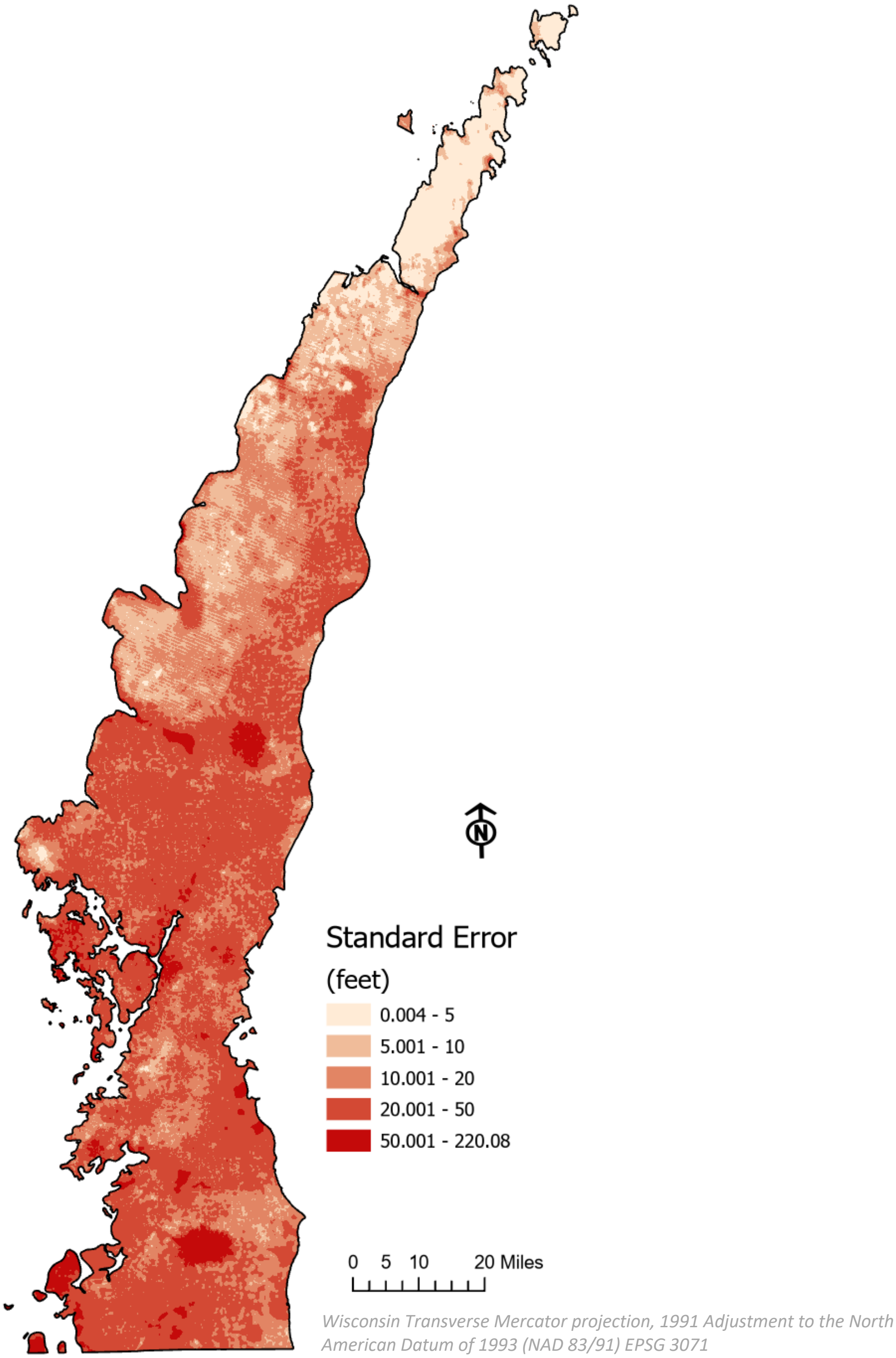
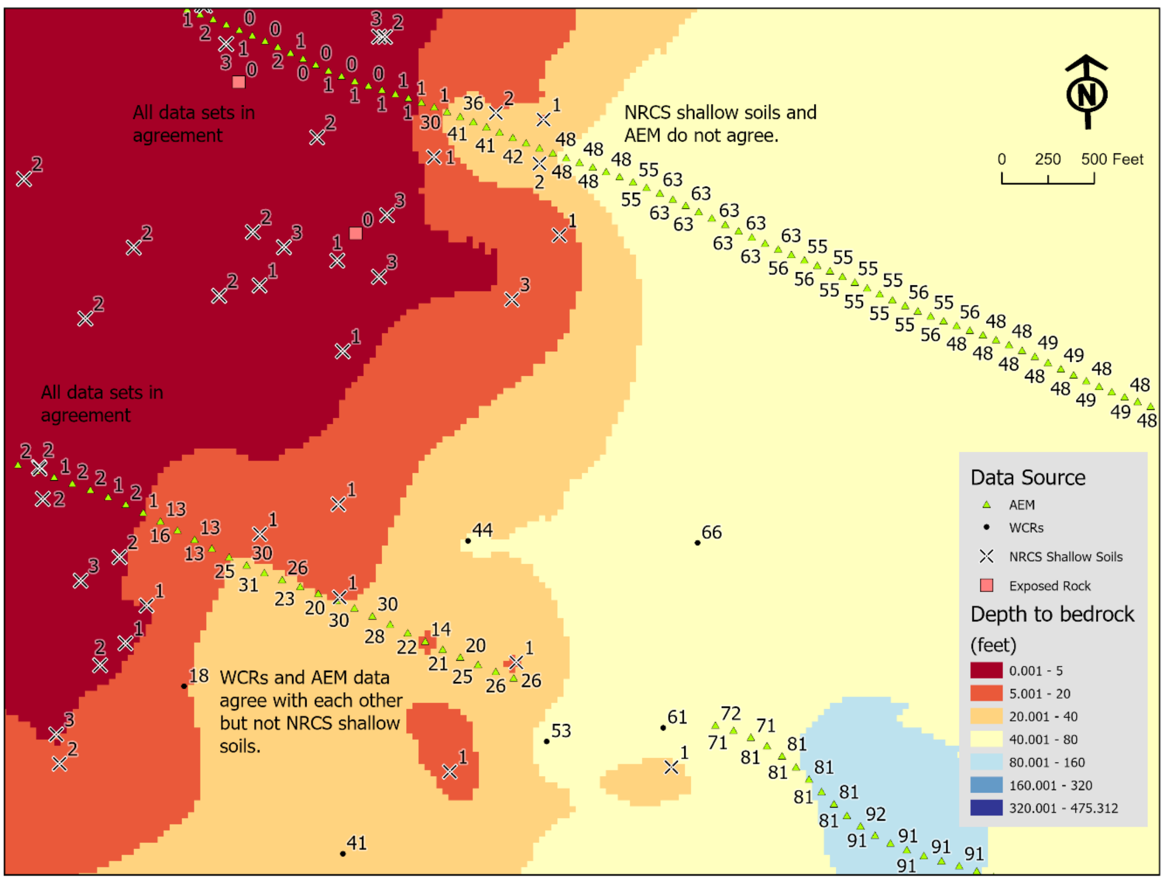


Figure 9. *Estimated standard error determined during EBKRP processing.*

An example of an area where data disagree is shown in Figure 10. In this portion of the study area, bedrock is deep in the east and shallow in the west as shown by the raster color flood. The map shows AEM data (green triangles), WCR data (black dots), NRCS shallow soils (Xs), and exposed rock (red squares). There are two lines of AEM data running northwest to southeast. In the western part of the map, all the data agree, and we would expect bedrock depths to be shallow. The areas of disagreement are at the transition from deep to shallow. The DTB from the AEM data and the WCRs are generally greater than the NRCS soils at the transition. This is evident in the DTB raster as U-shaped indentations of greater depths associated with the AEM data points into more shallow depths north and south of the AEM data as indicated by the NRCS soils data. It seems likely that either the NRCS or the AEM data are incorrect. This area would be one where the depth is uncertain and additional measurements would be needed to resolve the difference. Similar areas where the raster shows this U-shaped pattern are common in western Door and Kewaunee counties. These are areas where additional measurements would improve the map and where contesting the map would be more likely to change the map.



Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1993 (NAD 83/91) EPSG 3071

Figure 10. *Example where data are not in agreement.*

Conclusions and recommendations

DTB raster and polygons were created using available data from multiple sources and EBKRP. This map is meant to provide guidance for application of rules governing manure application over the Silurian dolomite in eastern Wisconsin. The map can be updated and improved as new data become available. As in previous maps, most areas of shallow DTB over the Wisconsin Silurian dolomite occur near the Niagara escarpment along the western edge of the study area and to the north in Kewaunee and Door counties.

Towards the goal of improving the map, we recommend that the raster and polygons be routinely updated as additional data become available. These data might be from newly drilled wells, county surveys and investigations, and contested depth fields. We also recommend that areas where the data disagree, should be investigated as time and effort allow. Those investigations could use a variety of methods including soil probes, passive seismic, and drilling.

Data contents

The data and accompanying materials for this publication are available for download from the WGNHS Publications Catalog at https://doi.org/10.48358/ihyi3520.

Dataset 1: Eastern Wisconsin Silurian depth-to-bedrock database

A file geodatabase (.gdb format) that includes the DTB raster, polygon feature classes of the five-feet-and-under and twenty-feet-and-under areas, and a point feature class (n=186,054) of DTB and bedrock elevation values.

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References

Baeten, Joe, 2022, Silurian Thickness of Unconsolidated Materials: WI Department of Natural Resources Data Open Data, accessed May 2023, at https://data-wi-dnr.opendata.arcgis.com/datasets/wi-dnr::silurian-thickness-of-unconsolidated-materials/about.

Batten, W.G., 2018, Depth to bedrock map of Fond du Lac County, Wisconsin *in* Batten, W.G., Bedrock geology of Fond du Lac County, Wisconsin: Wisconsin Geological and Natural History Survey Map 505, scale 1:100,000, https://wgnhs.wisc.edu/catalog/publication/000963/resource/m505plate02.

Bradbury, K.R, Batten, W.G., 2010, Groundwater susceptibility maps and diagrams for the Town of Byron, Fond du Lac County, Wisconsin: Wisconsin Geological and Natural History Survey Map Open-File Report 2010–02, 16 p., 7 pls., https://wgnhs.wisc.edu/pubs/000892.

Brodhagen, P.A., 2023, Depth-to-bedrock evaluation, bedrock stratigraphic analysis, and groundwater assessment for southern Door County, Wisconsin: Green Bay, University of Wisconsin–Green Bay, M.S. Thesis, 119 p., https://diglib.uwgb.edu/digital/collection/p17003coll1/id/99/rec/1.

Chandler, V.W. and Lively, R.S., 2014, Evaluation of the horizontal-to-vertical spectral ratio (HVSR) passive seismic method for estimating the thickness of Quaternary deposits in Minnesota and adjacent parts of Wisconsin: Minnesota Geological Survey Open-File Report 14-01, 54 p., https://hdl.handle.net/11299/162792.

Clayton, Lee, 2013, Pleistocene geology of Kewaunee County, Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 104, 44 p., scale 1:100,000, https://wgnhs.wisc.edu/pubs/000150.

Eaton, T.T., Bradbury, K.R., and Evans, T.J., 1999, Characterization of the hydrostratigraphy of the deep sandstone aquifer in southeastern Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 1999–02, 30 p.

Evans, T.J., Massie-Ferch, K.M., Peters, R.M., 2004, Preliminary depth to bedrock map of Walworth, Racine, Kenosha, Milwaukee, Waukesha, Ozaukee, and Washington Counties: Wisconsin Geological and Natural History Survey Map Open-File Report 2004–20, scale 1:100,000, https://wgnhs.wisc.edu/pubs/000853.

Krivoruchko, K., 2012, Empirical bayesian kriging: ArcUser Fall 2012, p. 6–10, https://www.esri.com/news/arcuser/1012/empirical-byesian-kriging.html.

Krivoruchko, K. and Gribov, A., 2014, Pragmatic Bayesian kriging for non-stationary and moderately non-Gaussian data *in* Pardo-Iguzquiza, E., and others, eds, Mathematics of Planet earth—Proceedings of the 15th Annual Conference of the International Association for Mathematical geosciences: Berlin, Springer, p. 61–64, https://doi.org/10.1007/978-3-642-32408-6_15.

Luczaj, J.A., 2011, Preliminary geologic map of the buried bedrock surface, Brown County, Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 2011–02, scale 1;100,000, https://wgnhs.wisc.edu/pubs/000896.

Luczaj, J.A., Houghton, C.J., Shea, A.W., 2019, A Depth-to-Bedrock Map and Deep Aquifer Characterization for Kewaunee County, Wisconsin: Final report to the WI Department of Natural Resources, scale 1:100,000.

Minsley, B.J, Bloss, B.R., Hart, D.J., Fitzpatrick, W., Muldoon, M.A., Stewart, E.K., Hunt, R.J., James, S.R., Foks, N.L., and Komiskey, M.J., 2022, Airborne electromagnetic and magnetic survey data, northeast Wisconsin (ver. 1.1, June 2022): U.S. Geological Survey data release, https://doi.org/10.5066/P93SY9LI.

Muldoon, M.A., Borchardt, M.A., Spencer, S.K., Hunt, R.J., Ownes, D., 2018, Using enteric pathogens to assess sources of fecal contamination in the Silurian Dolomite Aquifer—preliminary results, *in* White, W., and others, eds, Karst Groundwater Contamination and Public Health: Springer, Karst Waters Institute, San Juan, 2016 [Proceedings], p. 209–213, https://doi.org/10.1007/978-3-319-51070-5_23.

Njoku, E.A., Akpan, P.E., Effiong, A.E. and Babatunde, I.O., 2023, The effects of station density in geostatistical prediction of air temperatures in Sweden: A comparison of two interpolation techniques: Resources, Environment and Sustainability, v. 11, p. 100092, https://doi.org/10.1016/j.resenv.2022.100092.

Soil Survey Staff, 2012, Gridded Soil Survey Geographic (gSSURGO) Database for Wisconsin, United States Department of Agriculture, National Resources Conservation Service, accessed at https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/home/?cid=nrcs142p2_053628.

Parsen, M.J., Mauel, S.W., and Streiff, C.M., 2017, Hydrogeological characterization of the Town of Lincoln, Kewaunee County, Wisconsin: Wisconsin Geological and Natural History Survey Map Open-File Report 2017–05, 33 p., 8 pls., scale 1:50,000, https://wgnhs.wisc.edu/pubs/000952.

Pilz, J. and Spöck, G., 2008, Why do we need and how should we implement Bayesian kriging methods: Stochastic Environmental Research and Risk Assessment, v. 22, p. 621-632, https://doi.org/10.1007/s00477-007-0165-7.

Sherrill, M.G., 1978, Geology and ground water in Door County, Wisconsin, with emphasis on contamination potential in the Silurian dolomite: U.S. Geological Survey Water Supply Paper 2047, 38 p., 5 pls., scale 1:125,000, https://doi.org/10.3133/wsp2047.

Sherrill, M.G., 1979, Contamination potential in the Silurian Dolomite aquifer, eastern Wisconsin: U.S. Geological Survey Water Supply Paper 78–108, 2 pls., https://doi.org/10.3133/wri78108.

Stieglitz, R.D. and T.J. Dueppen, 1994, Mapping and inventorying of geologic features in the Sturgeon Bay–Red River Priority Watershed: University of Wisconsin–Green Bay Technical Report to Door, Brown and Kewaunee Counties, 85 p.

Stewart, E.K. 2021, Depth-to-bedrock map of Dodge County, Wisconsin: Wisconsin Geological and Natural History Survey Map Open-File Report 2021–03, 13 p., scale 1:100,000, https://wgnhs.wisc.edu/pubs/000981.

Trotta, L.C., and Cotter, R.D., 1973, Depth to bedrock in Wisconsin: Wisconsin Geological and Natural History Survey Map 51, scale 1:1,000,000, https://wgnhs.wisc.edu/catalog/publication/000376/resource/m051.

U.S. Geological Survey, 2023, 1/3rd arc-second Digital Elevation Model - USGS National Map 3DEP Downloadable Data Collection, accessed at https://data.usgs.gov/datacatalog/data/USGS:3a81321b-c153-416f-98b7-cc8e5f0e17c3.