University of Wisconsin-Extension

WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY

3817 Mineral Point Road
Madison, WI 53705-5100
Tel • 608.262.1705
Fax • 608.262.8086
Wisconsin Relay • 711
WisconsinGeologicalSurvey.org

KENNETH R. BRADBURY
DIRECTOR AND STATE GEOLOGIST

Hydrogeological characterization of the Town of Lincoln, Kewaunee County, Wisconsin

Michael J. Parsen
Stephen W. Mauel
Carolyn M. Streiff

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Contents:

- report (33 p.)
- 8 maps (scale 1:50,000, 11 in x 17 in)
- 1 appendix (15 p.)

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Michael J. Parsen, Stephen W. Mauel, Carolyn M. Streiff
Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension, Madison, WI

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Contents

Abstract

This report and accompanying maps provide residents and local officials with basic information about groundwater and hydrogeologic conditions in the Town of Lincoln, Kewaunee County, Wisconsin. This information is intended to be both educational and a basic reference for discussing and making land-use decisions. The primary motivation for this cooperative project between the Town of Lincoln and the Wisconsin Geological and Natural History Survey (WGNHS) was concern over the susceptibility of groundwater in the town to contamination, and the quality and safety of drinking water from local wells. The Town of Lincoln is located in an area of northeastern Wisconsin where natural groundwater conditions and shallow, fractured, dolomite bedrock create the conditions for groundwater to be susceptible to contamination, including increased incidences of elevated nitrate concentrations and the presence of bacteria in rural drinking-water wells.

This study produced a series of resource maps depicting geologic and hydrogeologic conditions in the town. The resource maps include:

1. **Site map**, shows place names;
2. **Depth to bedrock**, an important tool in determining groundwater susceptibility;
3. **Input datasets for depth-to-bedrock map**, which documents data used in the depth-to-bedrock interpretation;
4. **Water-table elevation** indicates the direction of groundwater movement and the elevation of the water table above mean sea level;
5. **Depth to water table**, an important tool in determining groundwater susceptibility, complements the water-table-elevation map;
6. **Groundwater recharge**, an important tool in determining groundwater susceptibility;
7. **Groundwater contaminant susceptibility**, shows relative susceptibility to groundwater contamination, the result of combining maps showing depth to bedrock, depth to water, and groundwater recharge;
8. **Catchments and closed depressions**, shows areas of internal drainage on the landscape, it identifies areas where water may pond and its maximum potential depth.

Land in the Town of Lincoln ranges from moderately to highly susceptible to groundwater contamination from surface sources. The groundwater contaminant susceptibility map was constructed by combining four environmental or geologic factors known to influence the movement of contaminants in groundwater, notably the type of bedrock, depth to bedrock, groundwater recharge rate, and depth to water table. Applying the terminology of “moderate”, “high”, and “highest”, in order of increasing susceptibility, the areas of *highest* susceptibility occur mainly in the north-central part of the town and in several areas near the lower flanks of isolated hills. These areas are generally underlain by very shallow bedrock, exhibit shallow depth to groundwater, and elevated rates of groundwater recharge. Areas with *high* susceptibility occur throughout much of the town and are dominant in the central and western parts of the town where bedrock and groundwater occurs at relatively shallow depths but groundwater recharge is generally lower. *Moderate* groundwater contaminant susceptibility areas are located primarily along the eastern and southwestern portions of the town in areas with lower recharge and greater depth to bedrock. No ranking was assigned below “moderate” because all parts of the town are underlain by fractured dolomite bedrock.

Introduction

This study improves upon our understanding of the hydrogeology of the Town of Lincoln (Kewaunee County) and provides residents and local officials with basic information about groundwater and hydrogeologic conditions in the town. (The site map, map 1, identifies place names within the town.) This information is intended to provide a framework for better understanding the hydrogeological system as well as a tool for making informed land-use decisions. The study was commissioned by the Town of Lincoln in 2015 and the Wisconsin Geological and Natural History Survey (WGNHS) completed the project in 2017. The study incorporated both existing and newly obtained data sets and employed a number of techniques to estimate and map depth to bedrock, water-table elevation, depth to groundwater, groundwater recharge, groundwater contaminant susceptibility, catchment basins, and closed topographic depressions.

Due to its fractured nature and generally thin soil cover in many areas, the Silurian dolomite of northeastern Wisconsin is very susceptible to groundwater contamination from surface contaminants, and there have been numerous reports of impaired water quality in local wells, with elevated nitrate and bacteria levels being the most common problem (M.A. Borchardt, M.A. Muldoon, and R.J. Hunt, written commun., 2017; D. Bonness and K.C. Masarik, written commun., 2014). The presence of these naturally susceptible geologic conditions has been well documented (Erb and Stieglitz, 2007). In 2017, there were three large confined animal feeding operations (CAFOs) active in the town as well as dozens of smaller farms, and hundreds of rural homeowners with septic systems. Due to the combination of naturally susceptible geologic conditions and nutrient-intensive land-use practices, local decision-makers need improved maps and tools to help make land-use decisions.

Objectives

This project was commissioned by the Town of Lincoln during the summer of 2015 and the project design based on previous groundwater susceptibility mapping by the WGNHS in the Town of Byron in Fond du Lac County, Wisconsin (Bradbury and Batten, 2010). The WGNHS designed the project to provide baseline hydrogeologic information about the local hydrogeology, susceptibility of groundwater contamination, and the geometry of drainage areas and closed depressions for the town. The WGNHS compiled these maps at a scale of 1:50,000, or about 1.27 inches per mile, and are more accurate than previously-available maps for the town. These maps include the following:

- Depth to bedrock,
- Input datasets for depth-to-bedrock map,
- Water-table elevation,
- Depth to water table,
- Groundwater recharge,
- Groundwater contaminant susceptibility, and
- Catchments and closed depressions.

For ease of use, each of these maps and diagrams are presented on individual pages (maps 2 to 8). All maps and datasets, with accompanying metadata, are available in digital form for use in geographic information system (GIS) applications. The maps are intended to be used at the 1:50,000 scale and are not considered accurate for site-specific applications. The maps should not be used as the sole criterion for making siting or land-use decisions. Site-specific decisions should always be made using site-specific information. This report contains descriptions of the maps and diagrams, details of map construction, and references to other materials.

Primary data sources

Datasets utilized for this study included well records and maps, previously unpublished information, and new field data. These were combined in a GIS database compilation that included mapping and computer modeling. The boundary of the study area is the 36-square-mile legal township, but most mapping extended 1 to 2 miles outside the town boundaries to account for conditions along the boundaries. Data collection efforts, such as for well construction records, extended 3 miles beyond the town border, covering a total area of 144 square miles.

A diverse array of datasets were incorporated, including 289 well construction records for the Town of Lincoln and existing depth-to-bedrock mapping by the WGNHS (Clayton, 2013), U.S. Geological Survey (USGS) and Wisconsin Department of Natural Resources (DNR) (Sherrill, 1978, 1979), and Kewaunee County (T. Engels, written commun., 2017). This project included soils data from the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS), karst landform mapping of sinkholes and fracture traces from the Kewaunee County Land Conservation Department, high-resolution lidar (*li*ght + ra*dar*) land elevation mapping from Kewaunee and Door County land information offices, field-scale shallow-depth-to-bedrock mapping from El-Na Farms LLC and Dairy Dreams LLC, shallow-depth-to-bedrock mapping from Wisconsin Public Service gas-line trenching, and borings data from Madison Gas and Electric's wind turbine installations. These methods are discussed in more detail below in each respective mapping chapter.

The investigators also made several field visits to collect geophysical data, confirm well construction locations, measure base flow in local streams, and drill additional borings to the top of the bedrock. A detailed description of geophysical methods is included in Appendix A.

Geologic setting

The town is completely underlain by dolomite of Silurian age, and contains several scarps (steep faces of exposed rock which separate two relatively level surfaces) of Silurian dolomite along its western border with the Town of Red River (Kewaunee County) (Clayton, 2013). The Niagara Escarpment lies roughly 4 miles to the west of the Town of Lincoln, running parallel to the shoreline of Green Bay (Clayton, 2013); and does not enter the Town of Lincoln. Several hills, ranging in height from 20 to 60 feet, are present throughout the town and are typically underlain by shallow Silurian dolomite. Depth to bedrock increases between these small hills and along the southwestern and eastern portions of the town where erosion has carved deeper into the bedrock surface. The dolomite forms an important local aquifer, or water-bearing unit, that provides water for domestic wells in the town.

Based on well construction records, the total thickness of Silurian dolomite beneath the town estimated to be on the order of 400 feet and underlain by another 400 feet of Maquoketa Shale of late-Ordovician age (Luczaj, 2013).

Acknowledgments

The Town of Lincoln commissioned and funded this study through a contractual arrangement with the Wisconsin Geological and Natural History Survey (WGNHS), a unit of the University of Wisconsin–Extension. The WGNHS contributed in-kind services, including staff time, to this project. The time and effort of Cory Cochart, Town Board Chair, and Mick Sagrillo, Town Plan Commission Chair, were essential to facilitating and completing this project. The WGNHS thanks Davina Bonness and staff at Kewaunee County Land Conservation Department, as well as Steve Hanson and staff at the Kewaunee County Land Information Office for their assistance. We also thank several landowners, including Lonnie Fenendael, Barry Fenendael, Ken Jeanquart, Mark Mandich, Jodi Parins, Mick Sagrillo, Jim Strnad, Tim Strnad, and Paul Wallace who provided access to their property for the collection of field data. Ken Bradbury, Linda Deith, Madeline Gotkowitz, Elmo Rawling, Caroline Rose, and Peter Schoephoester of the WGNHS made important contributions to project design, groundwater modeling, data management, manuscript review, graphics, and editing.

Map 2. Depth to bedrock
Map 3. Input datasets

What is a depth-to-bedrock map?

Map 2 shows the depth to the top of the bedrock in the Town of Lincoln. Contour lines and shading indicate the depth to competent bedrock in feet below land surface. This map can also be thought of as showing the thickness of unconsolidated soil and glacial deposits overlying bedrock (i.e., a depth to bedrock of 20 feet is the same as an unconsolidated thickness of 20 feet). Shallow bedrock is a key factor in determining land surface areas where groundwater is most susceptible to contamination. The thinner the overlying soils and unlithified sediment, the faster the downward seepage of contaminants, resulting in less time for natural biological and chemical processes to attenuate the contamination (Gotkowitz and Mauel, 2012). This is particularly the case in areas where the uppermost bedrock unit is dolomite, which contains ubiquitous interconnected fracture networks that can rapidly transport contaminants. Map 3 depicts all datasets that were incorporated into the depth-to-bedrock interpretation. A description of these datasets is included below in the section “How was this map constructed?”

What does this map show?

Map 2 shows the depth from land surface to the top of bedrock using contour intervals of 10, 20, 50, and 100 feet. Depth to bedrock ranges from 0 to 10 feet on hilltops and ridges, defined by scarps of Silurian-age dolomite, which extend along much of the northern and western edge of the town (Clayton, 2013). In the south central and southeastern parts of the town, there are four other hills or higher-elevation areas containing bedrock within 10 feet of land surface. Although these are not considered scarps, due to the absence of steep exposed bedrock faces, they are upland features on the landscape which are clearly distinguishable in the depth-to-bedrock data as well as with lidar land-surface elevation data.

In valleys and other lower-lying areas the depth to bedrock approaches 100 feet in the very southeastern-most corner of the town. The 50-foot depth-to-bedrock contour illustrates the two major erosional valleys present within the town; one to the east along a north-south axis through the Black Ash Swamp, and another to the southwest where Casco Creek moves south before joining the Kewaunee River in Town of Casco south of the study area.

This updated depth-to-bedrock interpretation is similar to previous interpretations by Clayton (2013) and Sherrill (1978, 1979); however, new data within valleys, including borings and well construction records, provided justification for updating the depth-to-bedrock interpretation. In many shallow depth-to-bedrock areas near hills, the total depth to bedrock has been interpreted to extend deeper, between the 20 and 50-foot contours rather than within the 10 to 20-foot contour.

How was this map constructed?

The depth-to-bedrock map was constructed by incorporating multiple datasets containing depth-to-bedrock information. Primary datasets included drillers' well construction records, borings completed as part of wind turbine installations by Madison Gas and Electric, Geoprobe borings completed by OnSite Environmental under the direction of the WGNHS, manual push probe and hand augering performed by the WGNHS, as well as field observations of bedrock outcrops at land surface. Previous depth-to-bedrock interpretations generated by the WGNHS (Clayton, 2013), USGS and DNR (Sherrill, 1978, 1979), and Kewaunee County were utilized to inform the updated interpretation. In areas of the town where data was sparse or unconfirmed, the WGNHS conducted geophysical surveys to verify bedrock depth. In addition, interpretations were confirmed by including shallow depth-to-bedrock soils data from the U.S. Department of Agriculture Natural Resources Conservation Service (USDA NRCS), karst landform data of sinkholes and fracture traces by the Kewaunee County Land Conservation Department, high-resolution lidar land elevation data from Kewaunee and Door County land information offices, field-scale shallow-depth-to-bedrock data from El-Na Farms LLC and Dairy Dreams LLC, and shallow-depth-to-bedrock data from Wisconsin Public Service based on gas-line trenching. The final set of field data collected by or under the direction of WGNHS staff is available in electronic format.

Water well construction records were incorporated into the study for an area extending 3 miles outside of the Town of Lincoln into neighboring towns, in Kewaunee and Door counties. In the Town of Lincoln, a total of 289 water well construction records were available. Local well drillers usually record well locations to the nearest quarter section and record a depth to bedrock (if the well reached bedrock) on each well construction report. Reported well locations were improved wherever possible, using available plat maps, aerial photos, and parcel-address records to georeference each well to the probable location indicated in the well construction report. This often involved moving the reported well location, originally geocoded to the center of the section (5,280 x 5,280 feet, 640 acre square), quarter-section (2,640 x 2,640 feet, 160 acre square), or quarter-quarter section (1,320 x 1,320 feet, 40 acre square), to a house, barn or other structure described by the driller on the well construction report. A location confidence was assigned to each well record point during this location checking and improvement process. When creating a preliminary depth-to-bedrock model, wells with a location confidence better than 500 feet are typically considered acceptable, and were incorporated into the depth-to-bedrock interpretation. Of the 289 wells in the Town of Lincoln, 266 wells have a location confidence better than 500 feet. These refined water well points were incorporated, along all other data sources, in a digital mapping software environment to construct contour lines depicting depth to bedrock.

Prior to the work reported here, WGNHS geologist Lee Clayton made significant efforts to locate well construction records and map depth to bedrock throughout Kewaunee County as part of a study of the county's glacial history. While portions of this work are included in the Pleistocene Geology for Kewaunee County bulletin (Clayton, 2013), much of it existed as unpublished data and maps until it was digitized by WGNHS staff during the summer of 2017 as part of a county-funded project to locate well construction records for all of Kewaunee County. Clayton's mapping and well locations were verified within the Town of Lincoln to ensure consistency with the well construction database being prepared for the county. The final set of well construction records, available in electronic format, includes wells located within one half-mile beyond the town border. This dataset consists of 371 wells, 339 of which have a location confidence better than 500 feet.

While the depth-to-bedrock interpretation was made by incorporating each of the above referenced datasets, it is important to understand that the process is ultimately subjective, as interpretations need to be made in situations where datasets may be contradictory, or simply very few data exist. Examples of this include situations where lithological descriptions for closely neighboring wells conflict, or a driller's description as "gravel and stones" could in fact be competent bedrock that is simply broken up during drilling. In other instances, when little to no depth-to-bedrock point data are available, interpretations are based on a combination of land elevation data, soil maps, geologic maps, or simply the geometry of stream channels. A good example of this is in an area immediately west of Black Ash Swamp, where Silver Creek flows around an area of higher relief on the landscape. Although no well construction records are available, this area is mapped by the NRCS as containing shallow depth-to-bedrock soils and by Clayton (2013) as an area with less than 10 feet to bedrock. The geometry of the stream channel, which bends around this elevated feature, suggests the underlying material is more resistant to weathering and erosion and may in fact be underlain by bedrock. Despite the lack of point data, this area was mapped as having shallow depth to bedrock (less than 20 feet to bedrock) due to these multiple lines of evidence.

Another important consideration with this depth-to-bedrock map concerns the density of input data that was used to inform the interpolation. As discussed above, the interpretation is ultimately subjective and incorporated a variety of datasets in different ways. Rather than attempting to communicate the degree of uncertainty associated with depth-to-bedrock contours (e.g., 10, 20, 50 feet) using solid and dashed lines, we decided to solely use solid lines yet provide the location of primary input datasets in a companion map (map 3). The only input data not shown on this map include geologic mapping by Sherrill (1987, 1988) and Clayton (2013), and the lidar land elevation data. Areas on the map containing a greater density of input data are generally considered to be mapped with greater confidence while areas with less data are less certain. As expected, the highest concentration of input data is often located in shallow depth-to-bedrock areas where bedrock is commonly encountered during shallow subsurface investigations. The data inputs depicted in map 3 are also intended to serve as a starting point for future depth-to-bedrock investigations and mapping work.

Why is this map important?

The depth to bedrock and the type of bedrock are very important in evaluating groundwater susceptibility. As discussed earlier, Silurian dolomite is the uppermost bedrock unit across the entire town. This dolomite tends to be extensively fractured, both horizontally and vertically. Rain water, which is slightly acidic, infiltrates the soil and glacial deposits, and further widens these fractures by dissolving dolomite rock along these conduits, and also along the bedding-plane openings of the dolomite. Examples of these fractures and bedding-plane openings are readily visible along the faces of quarry walls and road cuts in northeastern Wisconsin. These openings act as open conduits for water infiltrating the land surface to move rapidly into and through the bedrock. The incorporation of depth to bedrock into the overall groundwater contamination ranking will be discussed below in the groundwater contaminant susceptibility chapter.

Limitations of this map

The availability of future well construction records or field-based investigations, will undoubtedly provide new insights into the geometry of the bedrock surface. As with all geological maps, new information may contradict the current interpretation and represents the natural evolution in our understanding of the subsurface. For this reason, all depth-to-bedrock data collected by or under the direction of WGNHS staff is available in electronic format. Data that the WGNHS obtained directly from other sources, such as wind turbine borings from Madison Gas and Electric or shallow-depth-to-bedrock soil mapping by the USDA NRCS, can be obtained directly from those data providers.

Map 4. Water-table elevation
Map 5. Depth to water table

What is a water-table map?

The water-table surface is represented in this report as two distinct maps, a water-table-elevation map (map 4) and a companion depth-to-water-table map (map 5). Together, these maps show the approximate location of the same surface, the water table, relative to mean sea level and land surface in the Town of Lincoln. The water-table-elevation map, which was developed first, is described in detail in this chapter; the companion depth-to-water-table map was developed by subtracting water-table elevation from land-surface elevation.

The water table represents the top of the saturated zone. Below the water table, all pores, cracks, fissures, and other voids in the subsurface are filled with water. Above the water table, these voids are filled mostly with air. The water table is the elevation (or depth) below which water will freely fill a hole or well. Streams, lakes, and wetlands in the town are places where the water table intersects the land surface.

The water table fluctuates seasonally in response to periods of precipitation, snowmelt, and drought. These fluctuations are greatest where the water table is highest and far from surface water features. Monitoring well 31000183 (aka: KW-183), which is part of the Wisconsin Groundwater-Level Monitoring Network and operated by the USGS Wisconsin Water Science Center, WGNHS, and the DNR, illustrates the water-level response throughout the year (fig. 1). Although the water-level trends vary from year to year, the past two years of data for monitoring well KW-183, demonstrate that water levels tend to rise during a 6- to 7-month period from September/October to March/April and then rapidly drop during the late spring and summer months. Smaller periodic rises and falls in the hydrograph correspond to rainfall or snowmelt events. Although, the past two years may be uncharacteristic due to shortened winter frozen-ground intervals, leading to increased winter recharge, the magnitude of annual water-level fluctuation, on the order of 10 feet, is consistent for this type of aquifer system.

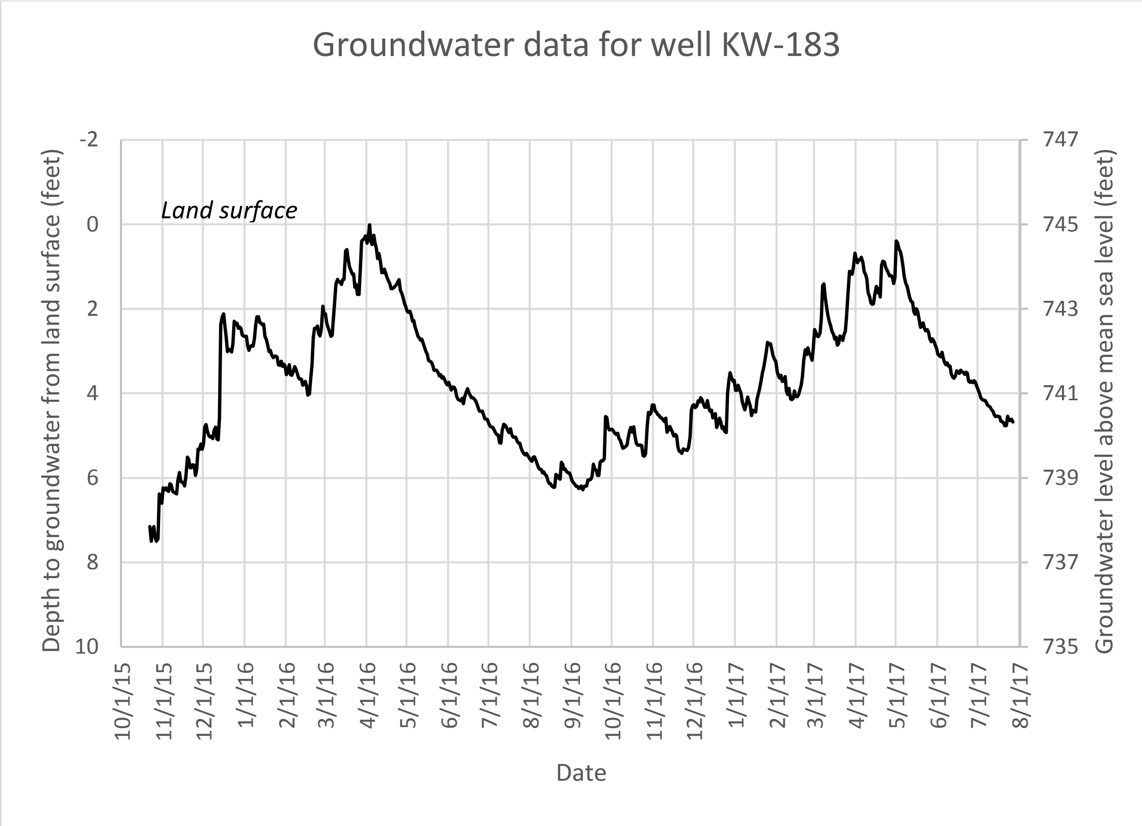


Figure 1. Water-level record for Wisconsin Groundwater-Level Monitoring Network well 31000183 (KW-183) in southern Town of Lincoln, illustrating annual and seasonal fluctuations in groundwater levels. Data obtained directly from U.S. Geological Survey's Groundwater Watch website for USGS Site Number: 443535087345O1 – KW-25/24E/34-0183. Sea level datum is NAVD 88.

Other studies by Sherrill (1978) in Door County and water levels documented by Bradbury and others (1998) demonstrate that water levels in the Silurian dolomite aquifer system can fluctuate on the order of 30 to 100 feet over the course of one year. These large fluctuations are due both to rapid recharge and to low effective porosity in the fractured dolomite.

What do these maps show?

The contour lines on the water-table-elevation map (map 4) represent lines of uniform elevation of the water table, in feet above mean sea level. For instance, at every point along the 700-foot contour, the water table occurs at 700 feet above sea level.

Water-table elevations are lowest (about 660–680 feet above sea level) within the Black Ash Swamp area in the eastern part of the town, and are highest (about 790–800 feet above sea level) in the western and northwestern parts of the town. Groundwater moves from higher to lower water-table elevations, running perpendicular to the water-table contours. Over most of the town, groundwater moves to the east or southeast, discharging to Rio Creek or Silver Creek, both tributaries of the Ahnapee River. In the southwestern part of the town groundwater moves to the south and east, towards Casco Creek, a tributary of the Kewaunee River. A major groundwater divide, along which flow diverges, is present along the west and northwestern part of the town where water flows either towards Green Bay via the Red River and its tributaries, or towards Lake Michigan via Casco Creek, Rio Creek, and Silver Creek. Another minor groundwater divide is also present in the west and southwestern part of the town which divides tributaries of the Kewaunee River.

The arrows shown on the map run perpendicular to the contour lines, at 90 degree angles, and illustrate the general direction of groundwater flow. The surface water features on this map also serve as a guide to understanding the general groundwater flow, since groundwater discharges locally to feed streams, lakes, wetlands as well as many backyard ponds that have been dug out below the water table. During wetter periods of the year, ditches and ephemeral streams begin to support stream flow as runoff from snow melt and rainfall is routed to these features. As the water-table rises and intersects the land surface, groundwater provides an additional contribution of flow to these intermittent surface water features. During drier parts of the year, runoff is reduced, groundwater levels fall, and ephemeral streams go dry, and perennial streams, which sustain flow throughout the year, return to baseflow conditions. During this time, streamflow is largely supported by groundwater discharge.

The depth-to-water-table map (map 5) approximates the depth to groundwater using colors ranging from light green (shallow) to dark green (deep). The water table in the Town of Lincoln ranges from zero depth (water at land surface) to greater than 100 feet deep. The shallowest depths to the water table occur in areas that are close to surface water features, such as streams and wetlands. In contrast, the greatest depths to the water table typically occur in upland areas, such as below Dhuey Hill or other hills within the town (map 1).

How were these maps constructed?

The water-table-elevation map was constructed using a computerized groundwater flow model called GFLOW which is based on the analytic element method (Haitjema, 1995). This model accounts for groundwater recharge, variations in aquifer properties and thickness, and the connections between groundwater and lakes, streams, and other surface water features such as wetlands or springs. The model was adjusted to best match the water-level measurements available and to be consistent with local streamflow measurements collected for this study. Often, a water-table map is constructed by measuring water levels in many shallow wells and then contouring these data points. Drillers' well construction reports can aid in this interpretation because water levels recorded during well installation are an additional source of water-level data. However, challenges arise when wells are installed over different decades and during periods of high and low water levels, leading to discrepancies in measured water levels. Furthermore, wells are sometimes drilled and cased many feet below the water table, and water levels in such wells may not represent the water table. For these reasons a groundwater flow model was used to estimate water-table elevations for the town. Installation of dedicated wells for water-table measurement would be very expensive and was beyond the scope of the current project. Water levels recorded in well construction reports were used as a set of calibration targets to ensure that modeled water levels remained within a reasonable range. Stream flow measurements gathered for this study were also used as calibration targets to ensure that modeled stream flows approximated real-world stream flows during observed baseflow conditions. As an additional check, water-table elevations were compared to land-surface elevation to ensure that groundwater flooding was limited and only occurred in wetland areas that already experience regular flooding and ponding of water at the land surface.

The companion depth-to-water-table map (map 5) was constructed by performing a raster-math operation in ArcGIS that subtracts the water-table digital elevation model (DEM) from the land-surface DEM. The resulting DEM, depicts depth to the water table in feet for every 98.4 foot (30 meter) cell.

Why are these maps important?

The water-table-elevation map (map 4) has many uses. As discussed above, this map can be used to indicate the directions of shallow groundwater flow, because groundwater generally moves perpendicular to the contour lines on the map. The companion depth-to-water-table map (map 5) is also informative as it is one component of groundwater susceptibility; shallow groundwater is generally more susceptible to contamination than deep groundwater. In addition, knowing the depth to the saturated zone can be useful in construction activities such as excavations, foundation design, and highway planning.

Limitations of these maps

The water-table-elevation map (map 4) is based on the analytic element GFLOW model and there are areas where water levels recorded in drillers' well construction reports disagree with modeled water-table elevations. One of the key assumptions in the GFLOW model is that groundwater is well connected to the surface water system; however, in areas with thick clays or highly compacted glacial deposits groundwater levels and surface-water levels can differ. One interesting observation during model calibration was that observed groundwater levels in some wells were consistently lower than modeled groundwater levels in areas immediately west of Casco Creek and over an extensive area north of Silver Creek. Furthermore, some observed groundwater levels in these areas were also below the elevation of the perennial stream systems. These elevation differences suggest that there may be downward hydraulic gradients in some areas close to streams and that some of these wells may in fact be connected to a deeper groundwater system that has a lower hydraulic head than the adjacent stream. Studying these vertical flow dynamics were not within the scope of this project, and are not reflected in the water-table-elevation map. However, this is an indication of the hydrogeological complexity inherent to fractured carbonate bedrock systems and should be taken into account in future efforts to evaluate groundwater flow.

Areas that were simulated as flooded were not identified in the depth-to-water-table map (map 5) but rather included in the range of <10 feet below land surface. Flooded areas occur due to two main factors: (1) the averaging that occurs over the size of a DEM cell when raster math is performed to subtract water-table elevation from land-surface elevation and (2) the GFLOW model result which represents a relatively smooth water-table elevation and does not account for topographic features. Flooded areas are consistent with parts of the town where the water table is at or near land surface.

The water-table maps were developed for the town under base-flow conditions which represent background groundwater levels during drier periods of the year when streamflow is dominated by groundwater discharge to streams. During wetter periods, water-levels could rise significantly and present conditions that are not reflected on this map.

Map 6. Groundwater recharge

What is a recharge map?

The recharge map (map 6) shows the locations and rates of average groundwater recharge in the Town of Lincoln. Groundwater recharge is water that has moved from the land surface to the groundwater system; recharge is thus the ultimate source of all groundwater. Understanding recharge and its distribution is important in making informed land-use decisions so that the groundwater needs of people and the environment can be met. The rate of groundwater recharge that occurs varies depending on the physical location and the time of year. Locational variation is due primarily to differences in land use, soils, and topography. Seasonal variation occurs due to variations in climate and precipitation.

What does this map show?

The map shows recharge rates for an average year. Actual recharge rates vary from year to year in response to variations in precipitation, temperature, the timing of snowmelt, and other factors. The map indicates recharge rates using colors ranging from dark green (low recharge) to light green (high recharge). Recharge in the Town of Lincoln varies from none at all per year up to 10 inches per year with an average recharge of about 1.2 inches per year across the town. In general, the highest recharge rates (greater than 4 or 5 inches per year) occur along a narrow corridor of collapsed outwash sand and gravel that crosses the town from northwest to southwest. The middle tier of recharge rates (2–4 inches per year) occur in the higher-elevation parts of the town where soils are thin and bedrock is close to the surface. Such areas are generally located in the western and northern parts of the town with other isolated areas of higher recharge in the south-central part of the town. Lowest recharge rates (0–2 inches per year) occur across large parts of the town and include areas that are actively farmed, large wetland areas, such as within the Black Ash Swamp, as well as isolated pockets of wetlands located throughout the town in lower-lying areas. Low recharge rate areas are characterized by clay-rich soils that have a low available water-storage capacity and are typically saturated.

Although this map shows recharge for an average year, the pattern of recharge in wetter or dryer years remains similar even though the absolute rates differ.

How was this map constructed?

The map is based on a soil-water balance model developed in Wisconsin (Dripps and Bradbury, 2007; Westenbroek and others, 2010). The model uses soil-water balance (SWB) accounting to determine the fate of precipitation on the land surface and within the soil zone. This method accounts for the various processes that divert precipitation from becoming recharge to the groundwater system. The difference between processes that divert water (indicated by negative signs in the following equation) and precipitation represents estimated recharge.

RECHARGE = precipitation – interception – runoff – evapotranspiration – (total soil moisture storage capacity of the root zone – antecedent soil moisture)

The terms of the equation are defined below and expressed using units of amount per time period (e.g., inches per year).

Recharge – The volumetric rate of water entering the groundwater flow system over some area.

Precipitation – The amount of water that falls to the earth as rain, sleet, snow, or hail.

Interception – The amount of water that falls on the plant canopy that does not reach the ground surface.

Runoff – The amount of water that flows across the land surface.

Evapotranspiration – The amount of water that is either evaporated or taken up by plants and transpired through their leaves.

Total soil moisture storage capacity of the root zone – The amount of water that the soil type can hold.

Antecedent soil moisture – The amount of water already stored in the soil.

Input to the SWB recharge model consisted of daily climate records for the model period and four map data layers for the model extent: topography, soil hydrologic group, soil available water storage, and land use. The model centered on the Town of Lincoln and included portions of surrounding towns. The spatial resolution of the model grid was 98.4 feet (30 meters), corresponding to the resolution of the land-surface elevation input data. Daily temperature and precipitation observations recorded at the Green Bay-Austin Straubel airport weather station were tabulated for model input. Although these climate parameters are from a neighboring county, this dataset is representative of the average regional trends.

The recharge model uses topographic data, in the form of surface water flow direction, to route runoff. A standard flow direction calculation was applied to a 5-foot DEM based on lidar data from Kewaunee County and Door County. Digital soil data from the Natural Resources Conservation Service Soil Survey Geographic (SSURGO) Database were used for two input datasets to the model—the hydrologic group and available water storage. The hydrologic group is a classification of the infiltration potential of a soil map unit, and is used in the recharge model input to calculate runoff. The primary categories range from A to D, representing low runoff potential to high runoff potential. Several map units in the model domain were classified with dual designations, such as “A/D,” where the lower-runoff designation typically indicates artificially drained land. Since any infiltration occurring in this situation would not contribute to groundwater recharge, all dual-designation soil map units were reassigned to the higher-runoff category for input to the recharge model. Available water storage, a measure of the amount of water held in a specified soil thickness, is used by the model for root zone moisture accounting. Land-use data are used in calculations of interception, runoff, evapotranspiration, and for determination of root zone depth. Land-use data were obtained from the National Land Cover Database (NLCD) 2011 data set.

Data grids for the four map inputs were generated from these source datasets for input to the model. Long-term climate trends for temperature and precipitation, as measured at the Green Bay Airport, were analyzed for the period from 1970 to 2015. Based on this analysis, the year 1995 was selected as a “typical” weather year for inclusion in the soil-water balance model. In

1995, annual precipitation totaled 30 inches and lies along the long-term trend in precipitation. The use of a typical weather year is important for generating reasonable precipitation levels and avoiding years which experienced anomalously high or low precipitation. Prior the performing the SWB model run for 1995 climate conditions, the model was run using 1994 climate data to ensure that antecedent moisture levels were representative of conditions immediately preceding the 1995 model year.

As an additional check on groundwater recharge rates, estimates from SWB were compared to published recharge rates by the USGS for surface watersheds (Gebert and others, 2009). Although the methodology employed by the USGS utilizes a different approach than SWB, and estimates recharge based on historical stream base flow measurements recorded at stream-gaging stations, the two methods compare favorably within the Town of Lincoln and neighboring areas. The SWB model estimated average annual recharge rates of 0 to 10 inches per year across the town, while the recharge rates estimated by Gebert and others (2009) range from 0.8 to 10.8 inches per year. It is encouraging to see such similarity between these two recharge estimation methods and should provide more confidence in the results obtained using the SWB model.

Why is this map important?

Recharge is the ultimate source of all groundwater in the town and is the source of baseflow to streams. Understanding the amount and distribution of groundwater recharge is important in land-use planning. Areas of high recharge tend to be more susceptible to groundwater contamination than areas of lower recharge.

Limitations of this map

The modeling method used assumes that deep infiltration equals recharge. However, it is possible that in some areas of the town this assumption is violated, and deep infiltration does not reach the groundwater system. For example, water that leaves the soil zone might flow laterally along bedrock fractures to discharge at a cliff face far above the water table; such water would not be considered recharge.

Areas mapped as gravel pits or gravelly outwash (classified by NRCS as soil type “Pg”) were not included in the recharge calculation but are considered to represent areas of elevated recharge. These areas are of limited extent within the Town of Lincoln and shown as black in map 6.

Map 7. Groundwater contaminant susceptibility

What is a groundwater contaminant susceptibility map?

Map 7 shows the relative susceptibility of different areas of the Town of Lincoln to groundwater contamination originating from surface or near-surface sources. The map is constructed by combining four environmental or geologic factors known to influence the movement of contaminants in groundwater: (1) depth to bedrock, (2) type of bedrock, (3) groundwater recharge rate, and (4) depth to water table. Such potential sources of contamination include waste disposal, chemical spills, septage or manure spreading, septic systems, leaking underground storage tanks, leaking sewers, and fertilizer and pesticide application. The map is simply a depiction of relative risk of contamination, and does not indicate that contamination either has occurred or will occur.

The map indicates relative contamination susceptibility using a three-color system. In areas shaded red, susceptibility to contamination is highest; in areas shaded orange, susceptibility is high; and in areas shaded yellow, susceptibility is moderate. This terminology has been consistently used by WGNHS researchers for contaminant susceptibility maps developed for Columbia County (Gotkowitz and Mauel, 2012) and Calumet County (Gotkowitz and Gaffield, 2006).

What does this map show?

The Town of Lincoln ranges from moderately to highly susceptible to groundwater contamination from surface sources. Areas identified with a susceptibility ranking of highest occur primarily in the north of the town as well as several areas along the lower flanks of isolated hills in the western and southern portion of the town which are underlain by shallow bedrock and the water table is high. Areas identified with a susceptibility ranking of high occur throughout many areas of the town but are concentrated along a wide north-south trending swath of the town including areas to the west where bedrock and groundwater is at relatively shallow depth. Areas identified with a susceptibility ranking of moderate occur primarily along the eastern and southwestern portions of the town in areas exhibiting lower recharge rates and deeper depth to bedrock. It should be noted that no ranking was assigned below moderate since all parts of the town are underlain by fractured dolomite bedrock and contain areas with either shallow depth to bedrock and/or shallow depth to groundwater. In other words, all areas of the town are considered to exhibit a minimum level of groundwater contaminant susceptibility which are designated as moderate.

How was this map constructed?

The susceptibility map represents a combination of four environmental or geologic factors known to influence the movement of contaminants to groundwater. These four factors are (1) depth to bedrock, (2) type of bedrock, (3) depth to water table, and (4) groundwater recharge rate. As part of this project, all of these factors have been mapped except for bedrock type. Bedrock underlying the town consists entirely of Silurian dolomite which is highly fractured and effectively increases the groundwater contaminant susceptibility ranking by a uniform amount across the entire town.

Once mapped, various categories within each factor were assigned a value of 1 to 5, with 1 being least susceptible to 5 being most susceptible, as shown in the following tables.

Depth to bedrock

The amount of soil, sand, gravel, and clay overlying bedrock helps slow the downward movement of contaminants and increases the time for contaminant attenuation and breakdown. Areas where bedrock is near the surface are more susceptible than areas where it is deeply buried (table 1). Depth to bedrock in the Town of Lincoln ranges from zero, where bedrock outcrops at the land surface, to over 100 feet in the very southeastern most part of the town.

Table 1. Depth to bedrock

Depth range, feet	Ranking
0–10	5
10–20	4
20–50	3
50–100	2
>100	1

Type of bedrock

Only one type of bedrock occurs in the Town of Lincoln – Silurian dolomite (table 2). The Silurian dolomite is the gray, fractured limestone that forms many of the scarps in the west of the town as well as other isolated hills and elevated areas in the northcentral and southcentral parts of the town. Outcrops are present in the western part of the town along the western flanks of Dhuey Hill, north and south of Martin Road, as well as in road ditches at culverts along Cardinal Road, just east of County Road C (Maple Road), and along Fir Road, just south of County Road X. This dolomite contains numerous voids, fractures, and solution cavities through which water (and contaminants) can move very rapidly. This rock is very susceptible to contamination. The Silurian dolomite is underlain, 300 to 400 feet deeper, by the less permeable and less fractured Maquoketa shale; however, this bedrock unit does not factor into the groundwater contaminant susceptibility mapping.

Table 2. Type of bedrock

Bedrock type	Ranking
Silurian dolomite	5
-	4
-	3
-	2
-	1

Depth to water table

Depth to water table indicates the thickness of the unsaturated zone, where the pores in rock and soil are partially filled with air. Within this unsaturated zone, biological processes can break down and attenuate contaminants, and thicker unsaturated zones allow more time to pass before contaminants can enter the groundwater system. Accordingly, areas with shallow depths to groundwater are considered more vulnerable than areas with greater depths to groundwater (table 3). The depth-to-bedrock map was calculated by subtracting the water-table-elevation surface from land surface. It is important to note that the water-table map developed for the town represents base-flow conditions which correspond to background groundwater level during drier periods of the year when streamflow is dominated by groundwater discharge to streams. Depending on the time of year, water-levels could be significantly higher within low-lying areas and fields, becoming flooded and presenting an elevated risk of groundwater contaminant susceptibility. This water table map, and therefore the groundwater contaminant susceptibility map, does not account for these potential seasonal water-table fluctuations.

Table 3. Depth to water table

Depth range, feet	Ranking
0–10	5
10–20	4
20–50	3
50–100	2
>100	1

Groundwater recharge estimate

The groundwater recharge rate is the annual rate, expressed as inches per year, of water entering the groundwater system from the surface. Recharge varies from place to place across a landscape, and is controlled by topography, soil type, vegetation, and land use. In general, areas where more recharge occurs are more susceptible than areas where less recharge occurs (table 4).

Table 4. Recharge rate

Recharge, in/yr	Ranking
>4	5
3–4	4
2–3	3
1–2	2
<1	1

Overall ranking

The overall ranking is based on a simple addition of ranking scores from each of the four categories. These numerical scores were then grouped into three categories of moderate, high, and highest susceptibility to contamination (table 5). No areas on the map are depicted as low-susceptibility since fractured carbonate bedrock is present everywhere at depth across the town. A similar susceptibility ranking system has been applied for Calumet County (Gotkowitz and Gaffield, 2006) and Columbia County (Gotkowitz and Mauel, 2012) where it was determined that the minimum groundwater susceptibility ranking is moderate.

Table 5. Overall ranking

Numerical score total	Susceptibility ranking
17–20	Highest
14–16	High
10–13	Moderate

How should this map be used?

This map is primarily an informational and educational tool to indicate which parts of the Town of Lincoln are more or less susceptible to groundwater contamination. Decision makers and private land owners can use this map as a guide to the relative risk of locating facilities and for making land-use decisions in various parts of the town. Likewise, the map can be used to help assess the relative risk of contamination from spills or other accidents in different parts of the town. For example, a spill of petroleum products in the red areas of the map is more likely to contaminate groundwater than a spill occurring in the yellow areas of the map.

Limitations of this map

Not all factors that influence the transport of contaminants were considered in this evaluation. Factors such as the type of contaminant present and the location of contamination relative to groundwater flow direction are independent of the natural groundwater system and can change over time. Just as the sources of contaminants can vary over time due to land-use changes, groundwater pumping can influence the direction and rate of contaminant transport, as groundwater flow paths become altered. Regardless of factors considered in this susceptibility evaluation, areas on the landscape where agricultural or industrial waste is land-spread are more likely to experience groundwater contamination than areas that do not. Furthermore, because contaminant susceptibility cannot be directly measured and is rather estimated based on multiple hydrogeologic factors, as discussed previously, the map should be used with caution.

Areas mapped as gravel pits or gravelly outwash (classified by NRCS as soil type “Pg”) that were not included in the SWB analysis were also excluded from the final groundwater contaminant susceptibility analysis; however, these areas should be considered to represent areas of elevated contaminant susceptibility. These areas are of limited extent within the Town of Lincoln and shown as black in map 7.

As stated above, it important to emphasize that the water-table map developed for the town represents base-flow conditions which correspond to background groundwater level during drier periods of the year when streamflow is dominated by groundwater discharge to streams. Depending on the time of year, water-levels could be significantly higher within low-lying areas and fields, becoming flooded and presenting an elevated risk of groundwater contaminant susceptibility. The water table map, and therefore this groundwater contaminant susceptibility map, does not account for these potential seasonal water-table fluctuations.

Map 8. Catchments and closed depressions

What is a catchments and closed-depressions map?

Map 8 delineates surface-water catchment basins, identifies catchment basins which serve as closed depressions, and depicts the maximum spatial extent and water-accumulation depth for each closed depression in the Town of Lincoln. A catchment basin is the extent of land over which all precipitation (rain and melting snow) converges to a single point at a lower elevation. This accumulation point is typically the exit or outlet of the basin where water joins another surface water body. In instances where the outlet is located at a higher elevation, the accumulation point represents a closed depression, or internally drained feature, where water either infiltrates or evaporates. While all areas at the land surface are contained within a specific surface water catchment basin, only a few basins contain closed depressions which are internally drained. The maximum water-accumulation depth calculation provides an indication of the spatial extent and depth to which standing surface water can accumulate in a closed depression before flowing out via a ditch, channel, or some other drainage feature. This maximum depth to which water can accumulate in a closed depression is limited by the height of the outlet, or “pour point”, above which water flows overland and out of the catchment basin.

If overland flow occurs during frozen-ground conditions, such as a during brief winter warm-up accompanied by rainfall or snow-melt event, or before the ground thaws in early spring, water can run off and accumulate in these closed depressions. Another common scenario resulting in water accumulation within closed depressions occurs during very wet periods of the year when the ground is saturated and additional precipitation tends to run off instead of infiltrating into the ground.

What does this map show?

The map shows surface water catchment basins, closed depressions, and the maximum depth to which water can accumulate at the land surface before flowing out of an individual closed depression. By delineating these features, the map serves as a tool for identifying the lateral boundaries for overland flow and the locations where water may accumulate or pond at land surface during frozen-ground or saturated-ground conditions. Each polygon on the map delineates an individual catchment basin. Light blue colored polygons identify catchment basins that contain a closed depression, and would contribute water to the closed depression during frozen or saturated-ground conditions as calculated by the numerical model. The spatial extent and depth of closed depressions, where at least 1 foot of water accumulates, are highlighted using yellow for shallow areas (1–2 feet), orange for moderately deep areas (2–4 feet), and red for deep areas (4–16 feet).

How was this map constructed?

The surface-water catchment/closed-depression map is derived from detailed lidar data (described above) representing land surface topography. Using the lidar data, we generated the features of this map in a GIS environment using ESRI ArcGIS 10.4. First, impediments to overland flow, such as road, highway, railroad, and driveway grades, which represent “digital dams” in the land-surface DEM were removed. Second, the resulting DEM was then “filled” to determine the pour point (i.e., the elevation above which surface water flows out of a closed depression) for each closed depression across the land surface. Third, the unfilled DEM was subtracted from the filled DEM in ArcGIS to generate the areal extent and depth of water accumulation for each closed depression. Historical satellite imagery available for particularly wet years was routinely used to help confirm the presence of water-accumulation points.

In order to determine the land surface area contributing to each closed depression, the ArcGIS “Watersheds” tool was then used to delineate the catchment basin (i.e., polygon feature on the map) corresponding to each water-accumulation point. Each catchment basin corresponding to a closed depression, as identified by the Watersheds tool, was visually inspected for evidence of manmade drainage or ditching structures (such as culverts and bridges). Only those catchment basins lacking evidence of manmade drainage or ditching structures retained their designation as catchment basins contributing to closed depression features.

Why is this map important?

Understanding the location and extent of surface-water catchment basins, closed depressions, and the maximum water-accumulation depth can aid in making informed land-use decisions. Human activities on the land surface can affect the chemical and biological composition of surface water. Water flowing to, and accumulating in, closed depressions (areas of internal drainage) has the potential to influence groundwater quality. Closed depressions that are located in areas of elevated groundwater contaminant susceptibility pose the greatest risk for surface-water induced groundwater contamination.

Limitations of this map

This map was generated using ArcGIS 10.4, lidar-derived digital elevation from 2015, and aerial photography data (multiple years) available at the time of map making and did not incorporate field confirmation of manmade drainage or ditching structures. It is therefore possible that culverts or ditches may exist in areas mapped as closed depressions, in which case these areas would not serve as closed depressions. Similarly, any efforts to ditch, drain, or even dam surface water which post-date the digital elevation datasets and aerial photography used to construct this map may modify features depicted in this map.

References

Bradbury, K.R., and Batten, W.G., 2010, Groundwater susceptibility of the Town of Byron, Fond du Lac County, Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 2010-02, 16 p., 7 plates.

Bradbury, K.R., Rayne, T.W., Muldoon, M.A., and Roffers, P.D., 1998, Application of a discrete fracture flow model for wellhead protection at Sturgeon Bay, Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 1998-04, 62 p.

Clayton, L., 2013, Pleistocene geology of Kewaunee County, Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 104, 44 p., 1 plate.

Dripps, W.R., and Bradbury, K.R., 2007, A simple daily soil-water balance model for estimating the spatial and temporal distribution of groundwater recharge in temperate humid areas: *Hydrogeology Journal*, vol. 15, no. 3, p. 433–444.

Erb, K., and Stieglitz, R., 2007, Final report of the Northeast Wisconsin Karst Task Force: UW-Extension publication G3836, 22 p. plus appendices.

Gebert, W.A., Walker, J.F., and Kennedy, J.L., 2009, Estimating 1970-99 average annual groundwater recharge in Wisconsin using streamflow data: U.S. Geological Survey Open-File Report 2009-1210, 14 p. plus appendices.

Gotkowitz, M.B., and Gaffield, S.J., 2006, Water-table and aquifer susceptibility maps of Calumet County, Wisconsin: Wisconsin Geological and Natural History Survey Map 147, 1 plate.

Gotkowitz, M.B, and Mauel, S.W., 2012, Groundwater susceptibility map of Columbia County, Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 2012-03, 1 plate.

Haitjema, H.M., 1995, Analytic element modeling of groundwater flow: San Diego, Academic Press, 394 p.

Luczaj, J.A., 2013, Geology of the Niagara Escarpment in Wisconsin: *Geoscience Wisconsin*, vol. 22, no. 1, p. 1–34.

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 plates.

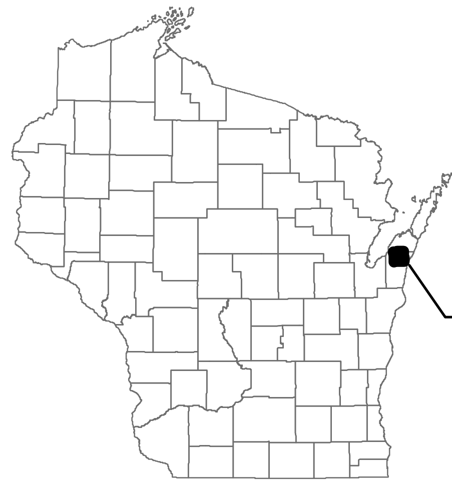
Sherrill, M.G., 1979, Contamination potential in the Silurian Dolomite aquifer, eastern Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 78-108, 2 plates.

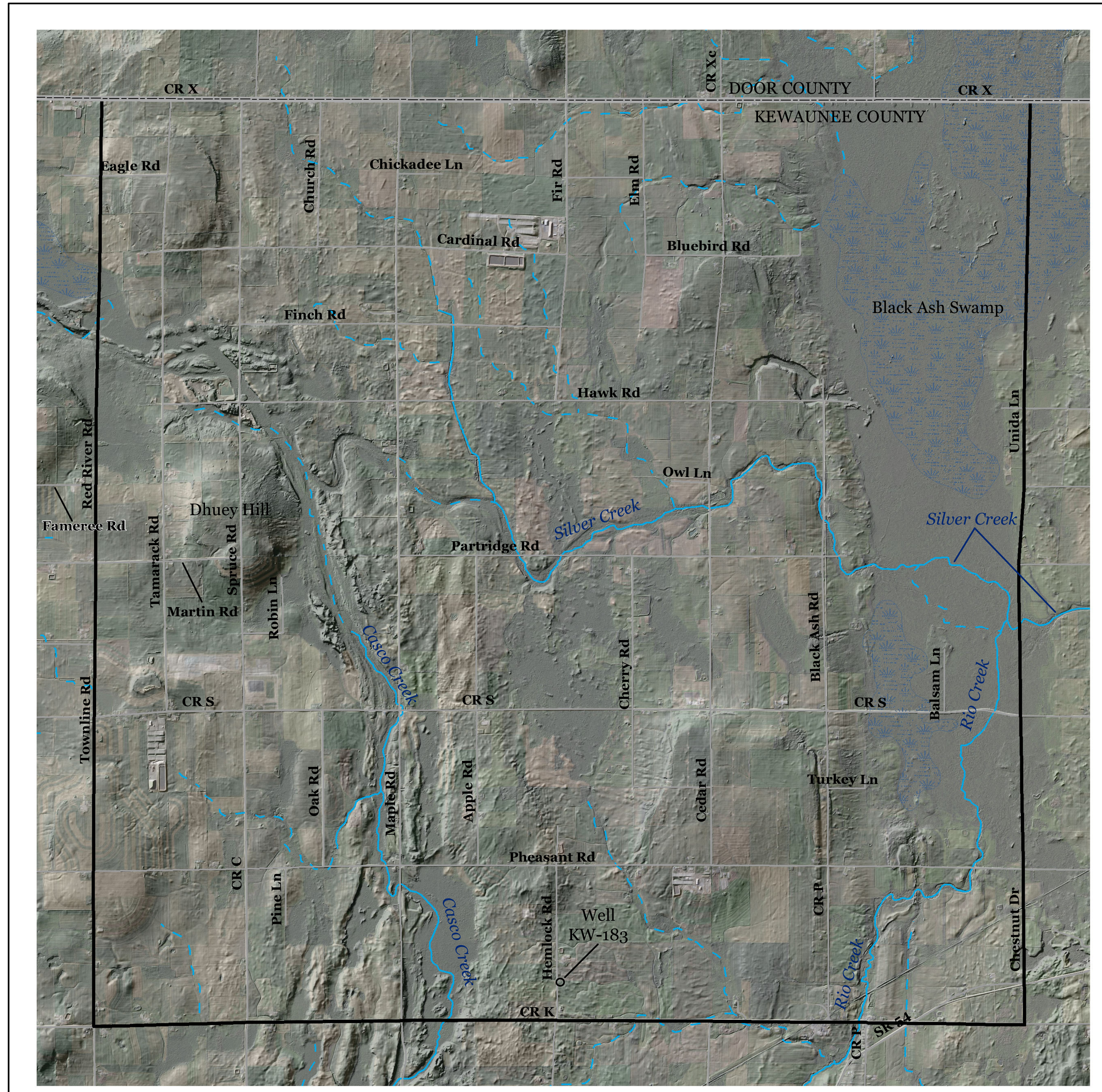
Westenbroek, S.M., Kelson, V.A., Dripps, W.R., Hunt, R.J., and Bradbury, K.R., 2010, SWB—A modified Thornthwaite soil-water-balance code for estimating groundwater recharge: U.S. Geological Survey Techniques and Methods 6-A31, 60p.

Map 1. Site map

Legend

- County Boundary
- Town Boundary
- Roads
- Wetland areas
- Perennial streams
- Intermittent streams





0 0.5 1 Miles

1:50,000

Satellite imagery Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Map 2. Depth to bedock

Legend

- County Boundary
- Town Boundary
- Roads
- Wetland areas
- Perennial streams
- Intermittent streams

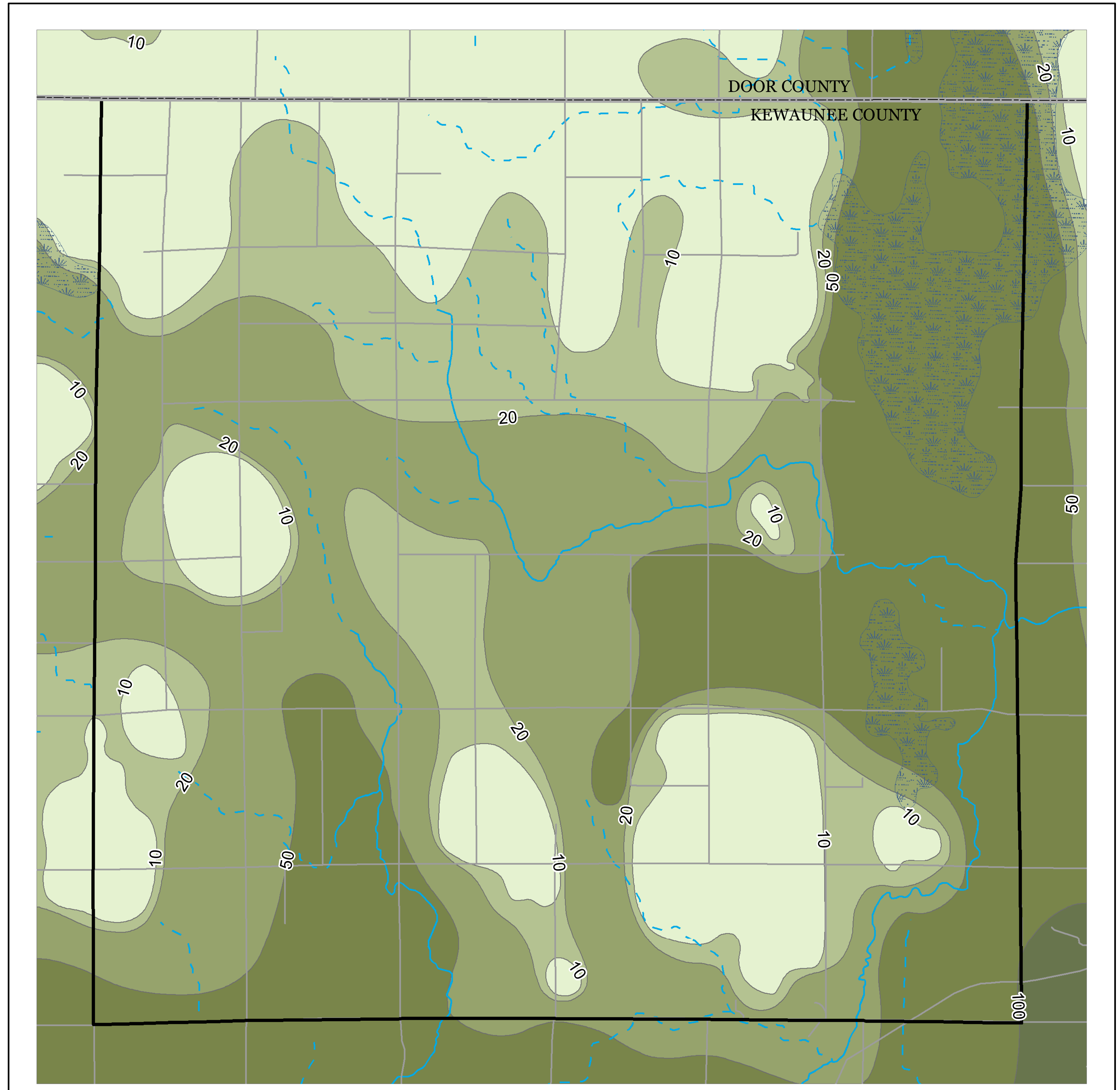
Depth to bedrock (feet)

- < 10 (most susceptible)
- 10 - 20
- 20 - 50
- 50 - 100
- > 100 (least susceptible)

0 0.5 1 Miles

N

1:50,000



Map 3. Input datasets for depth-to-bedrock map

Legend

County Boundary
Town Boundary
Roads
Wetland areas
Perennial streams
Intermittent streams
Well construction reports
Fracture traces
Sinkholes
Geologic log
Borings (WGNHS)
Borings (wind turbine)
Hand auger and push-probe points
Surface geophysics measurements
Bedrock outcrop observations
Utility trenches
0 - 24 inches to bedrock (mapped by farmers)

NRCS soil thickness, depth to bedrock (inches)

0 - 20
20 - 40

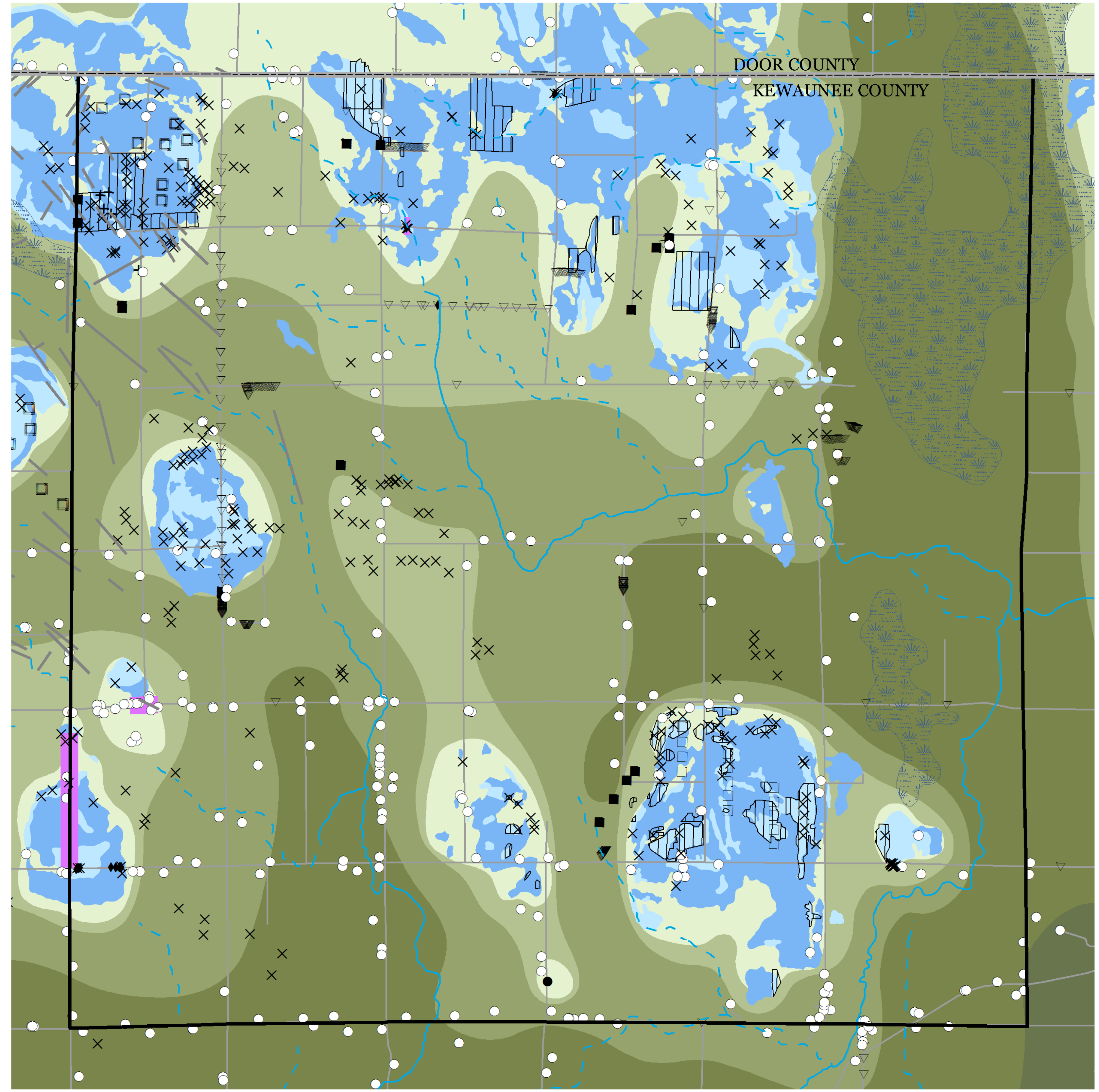
Depth to bedrock (feet)

< 10
10 - 20
20 - 50
50 - 100
> 100

0 0.5 1 Miles

N

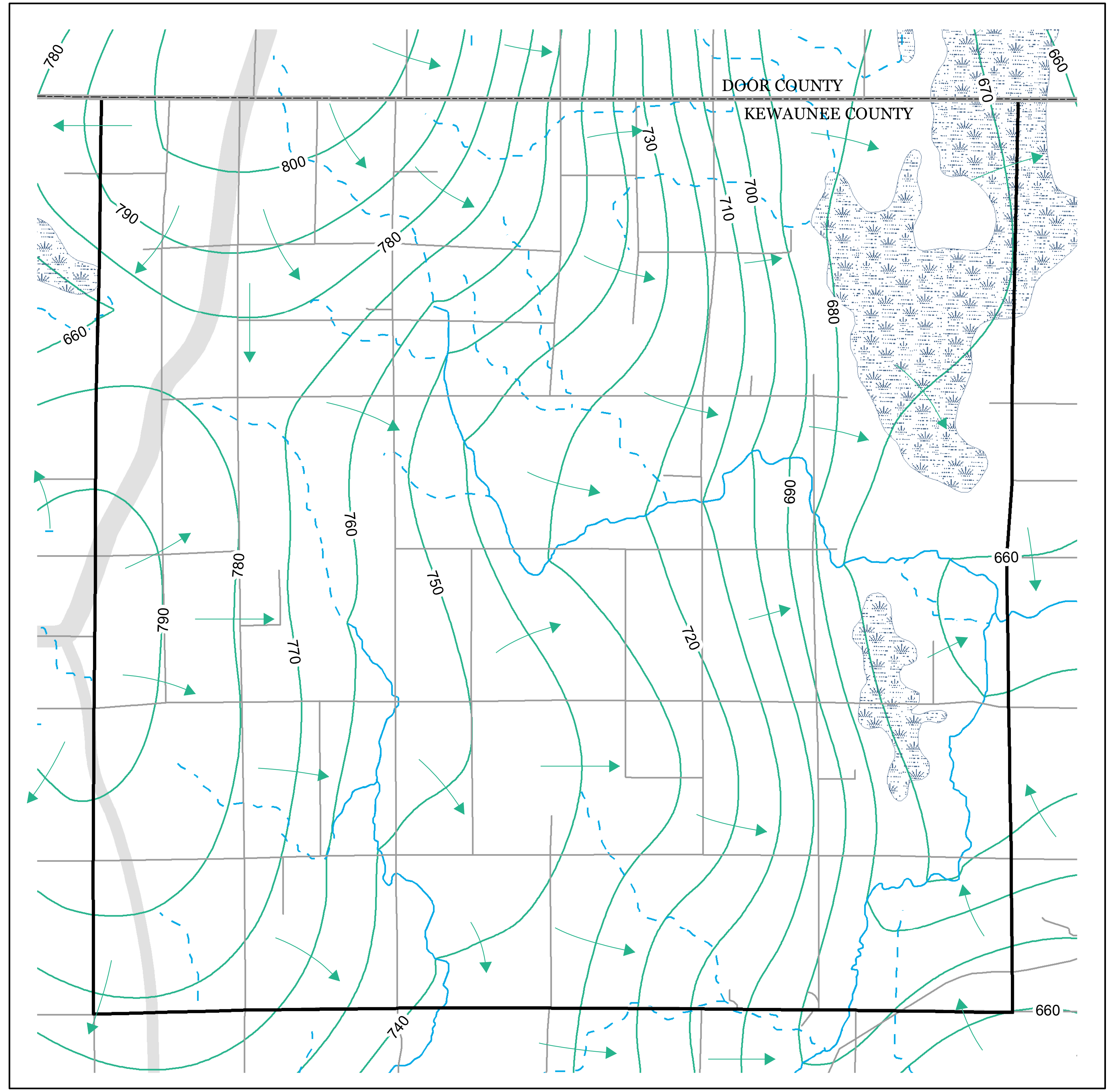
1:50,000



Map 4. Water-table elevation

Legend

- County Boundary
- Town Boundary
- Roads
- Wetland areas
- Perennial streams
- Intermittent streams
- Major groundwater divide
- Minor groundwater divide
- Water-table elevation, contour interval = 10 feet (datum is sea level)
- Generalized groundwater flow direction (estimated from contour lines)



0 0.5 1 Miles

1:50,000

Map 5. Depth to water table

Legend

- County Boundary
- Town Boundary
- Roads
- Wetland areas
- Perennial streams
- Intermittent streams

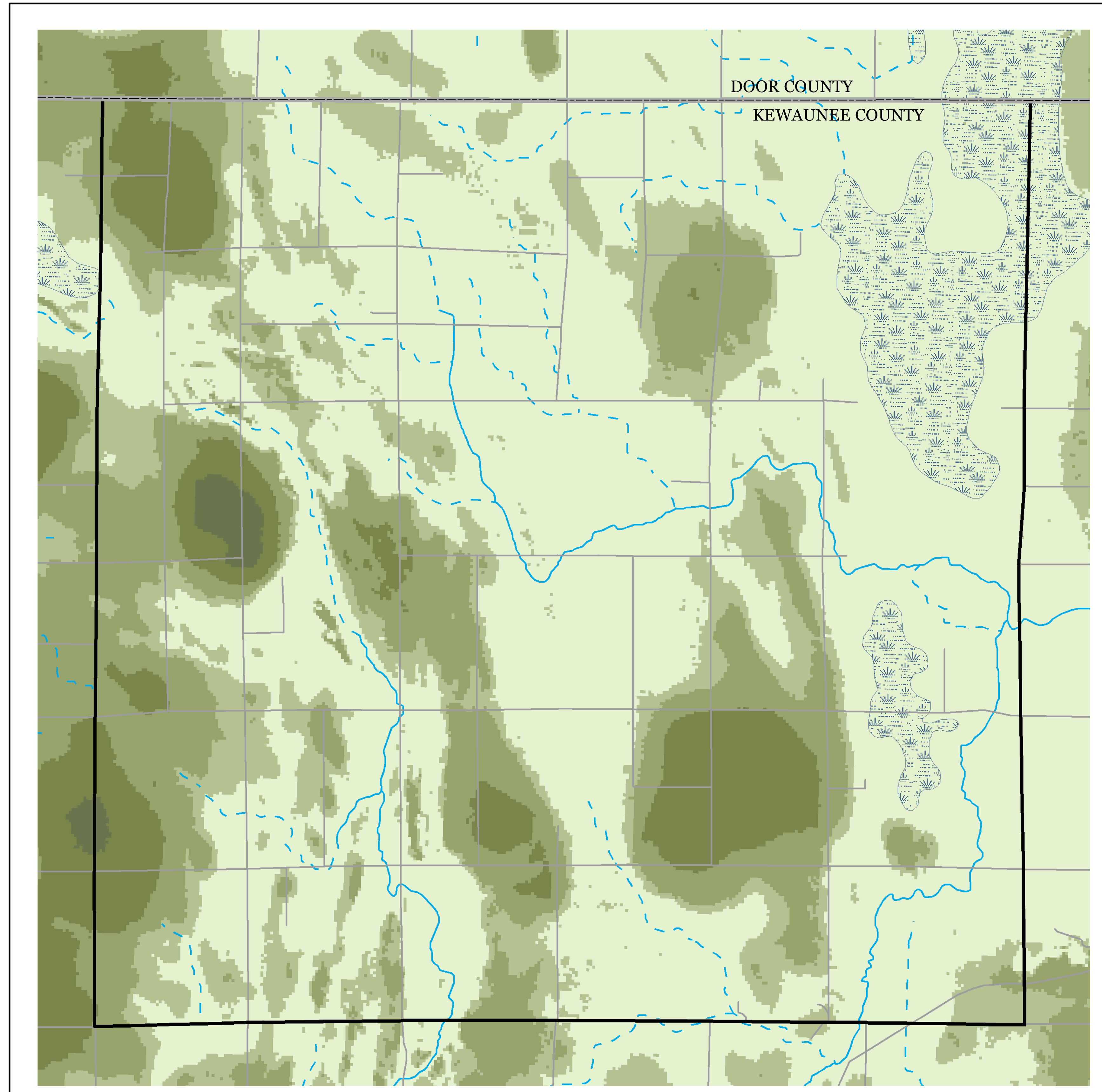
Depth to water table (feet)

- < 10 (most susceptible)
- 10 - 20
- 20 - 50
- 50 - 100
- > 100 (least susceptible)

0 0.5 1 Miles

N

1:50,000



Map 6. Groundwater recharge

Legend

- County Boundary
- Town Boundary
- Roads
- Wetland areas
- Perennial streams
- Intermittent streams

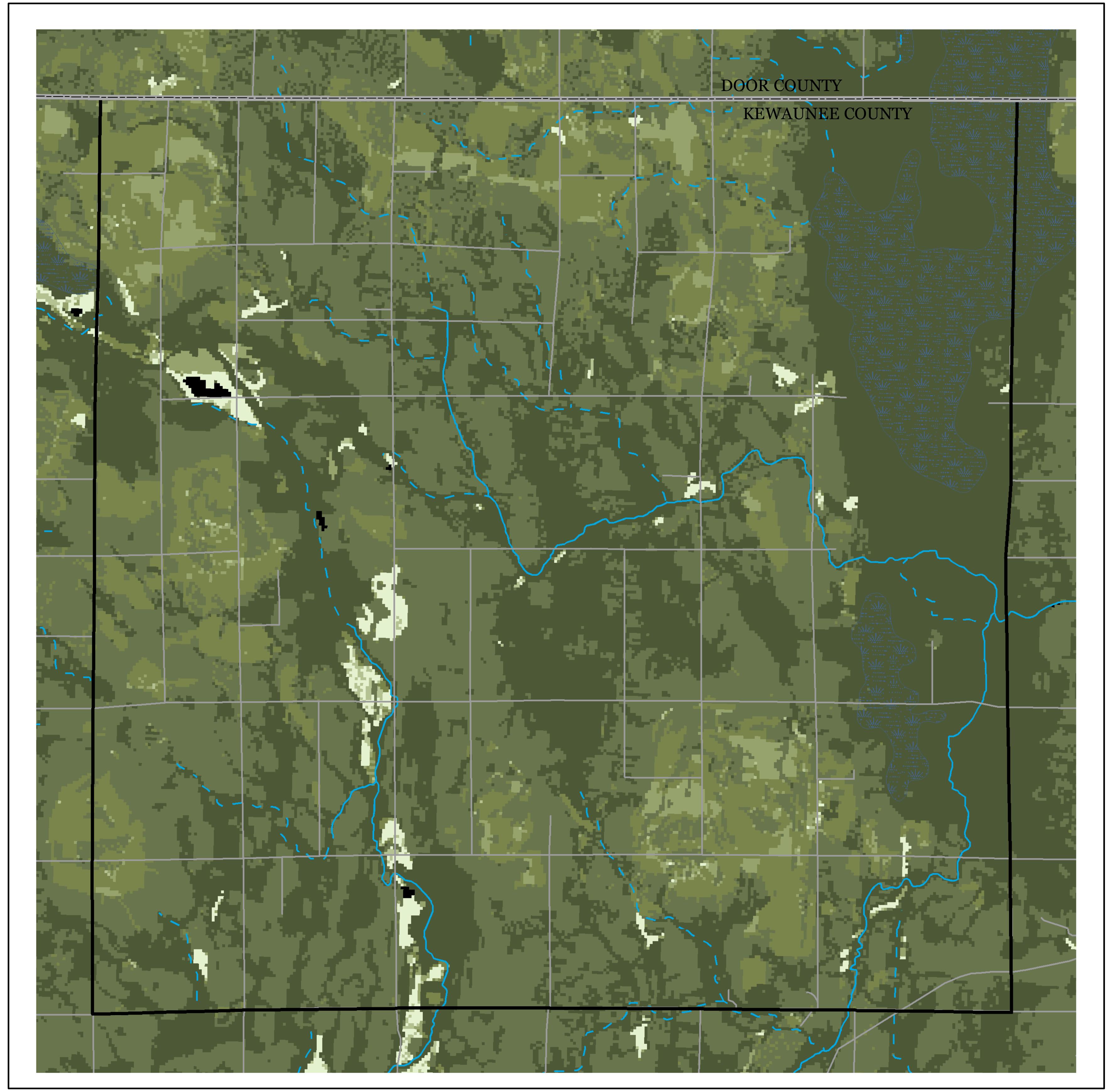
Estimated recharge (inches per year)

- 0 - 1 (least susceptible)
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- > 5 (most susceptible)
- Area mapped as gravel pits or gravelly outwash (NRCS soil type "Pg"). Excluded from recharge calculation based on soil classification; however, considered to be an area of elevated recharge (> 5 inches per year).

0 0.5 1 Miles

N

1:50,000



Map 7. Groundwater contaminant susceptibility

Legend

County Boundary

Town Boundary

Roads

Wetland areas

Perennial streams

Intermittent streams

Groundwater contaminant susceptibility (relative ranking)

Moderate

High

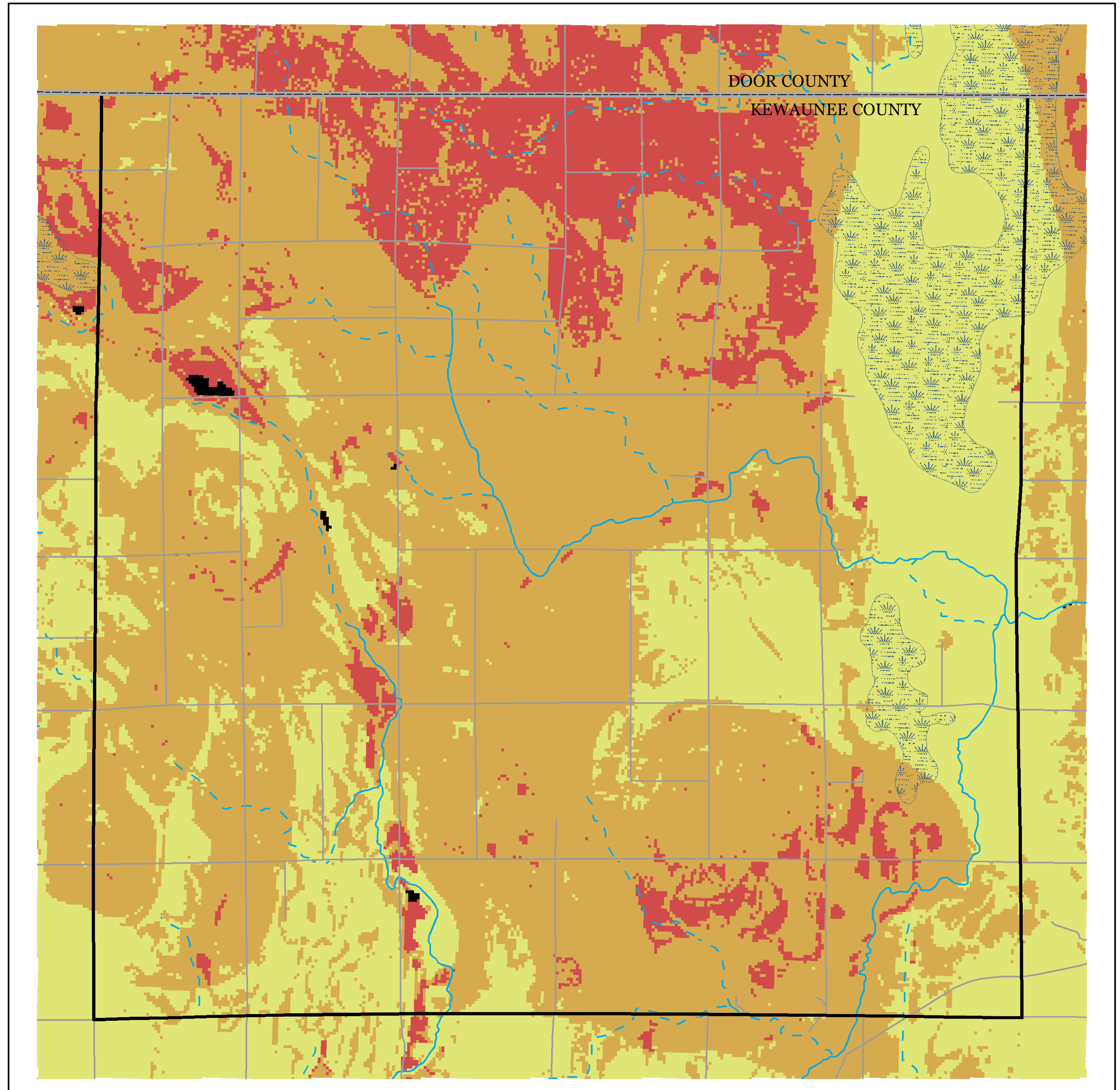
Highest

Area mapped as gravel pits or gravelly outwash (NRCS soil type "Pg"). Excluded from groundwater contaminant susceptibility calculation based on soil classification; however, considered to be an area of "highest" susceptibility.

0 0.5 1 Miles

N

1:50,000



Map 8. Catchments and closed depressions

Legend

County Boundary

Town Boundary

Roads

Wetland areas

Perennial streams

Intermittent streams

Catchment basin

Catchment basin containing closed depression

Maximum water-accumulation depth (feet)

1 - 2

2 - 4

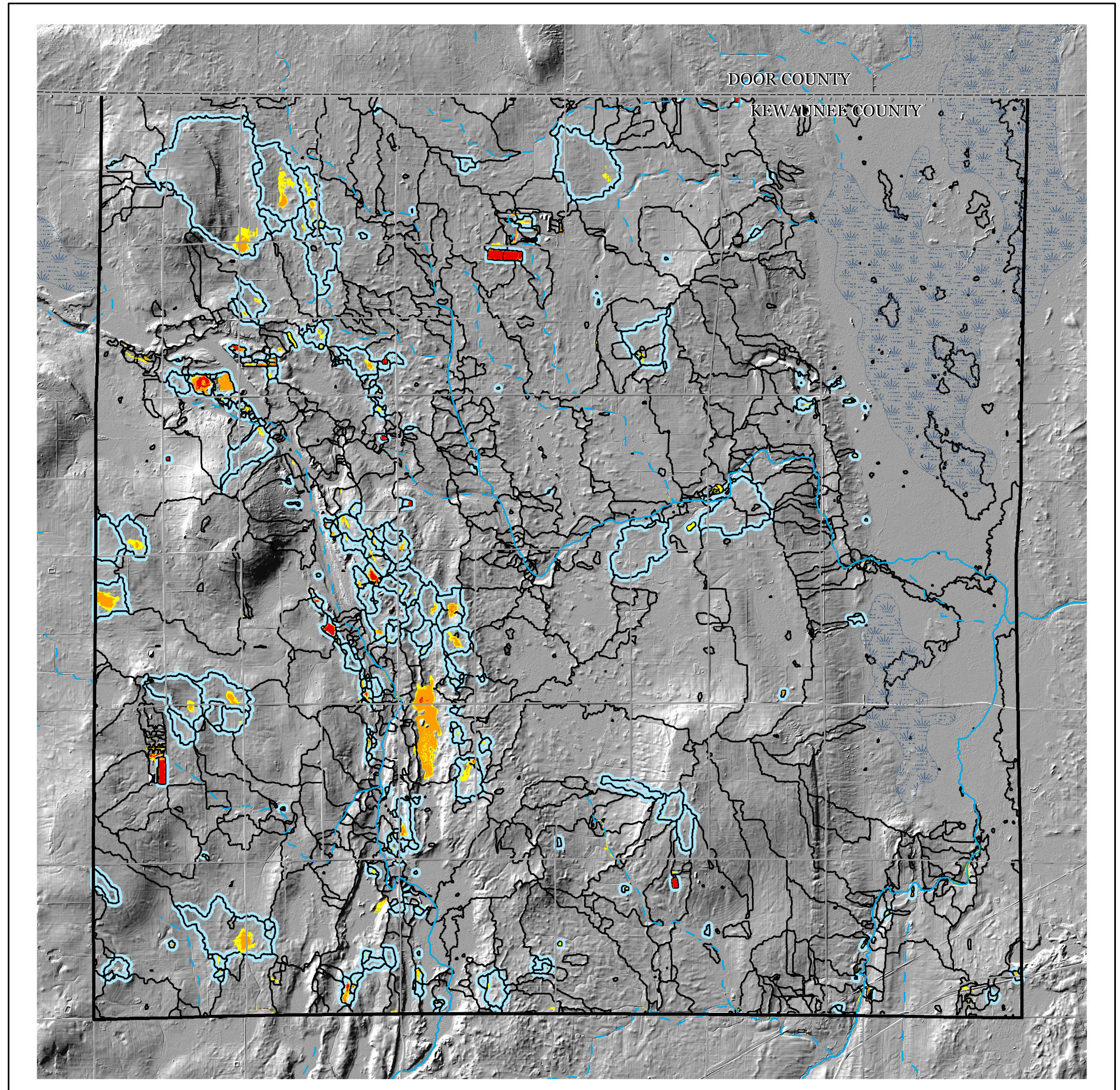
4 - 16

Land-elevation hillshade (lidar derived)

0 0.5 1 Miles

N

1:50,000



APPENDIX A. GEOPHYSICAL TECHNIQUES USED IN THE TOWN OF LINCOLN STUDY

Several different geophysical data acquisition methods were used to acquire depth-to-bedrock estimates in the Town of Lincoln. Initially, the geophysical data collection focused on using the Horizontal-to-Vertical Ratio Passive Seismic (HVSR) method. As the project progressed, Electrical Resistivity Imaging (ERI), Electromagnetic Terrain Conductivity (EM-31), and Ground Penetrating Radar (GPR) were also used to acquire supplemental bedrock depth information. While these methods provided useful subsurface information for incorporation into this study, many of them also encountered difficulties due to the unique subsurface expression in this region.

The dataset of depth-to-bedrock estimates, acquired using geophysical methods, include metadata and are available in digital form for use in geographic information system (GIS) applications.

The following sections provide an overview of each geophysical method employed in the Town of Lincoln, including the methodology and a discussion of the strengths and limitations of each method.

Horizontal-to-vertical Spectral Ratio (HVSR) Passive Seismic

Horizontal-to-vertical Spectral Ratio (HVSR) Passive Seismic is a fast, non-destructive geophysical method for acquiring depth-to-bedrock estimates. The instrument is a small seismometer that collects ground vibrations that are already present in the ground, like ocean waves and distant traffic (fig. 1). After data collection, seismic waveform processing software is used on the acquired waveforms to obtain a frequency that corresponds to the sediment/bedrock contact. A short calculation is performed to determine a reliable depth-to-bedrock estimate from this frequency.

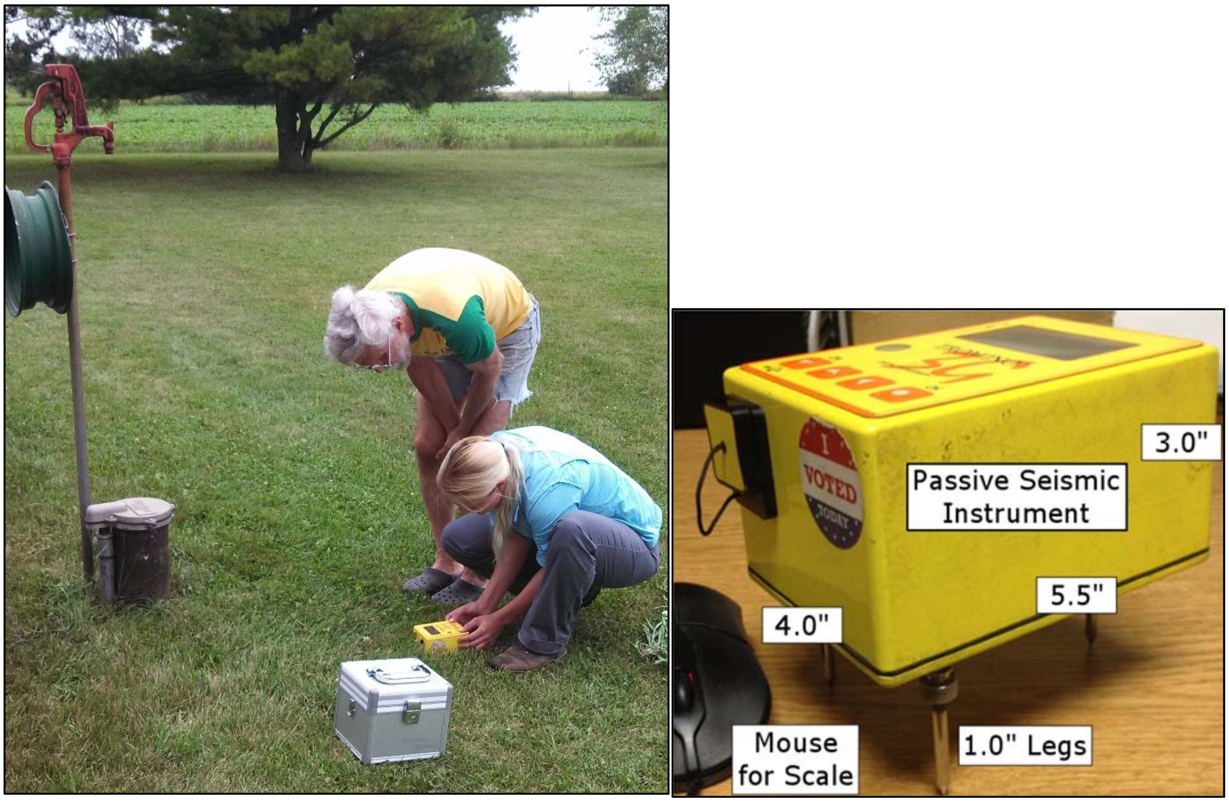


Figure 1: The Horizontal-to-Vertical Spectral Ratio Passive Seismic instrument. The Passive Seismic instrument shown in the field (left) and up close (right). The three 1-inch metal legs are inserted into the ground to record ambient ground vibrations for bedrock depth data collection. A computer mouse is shown for scale in the photo on the right. Ambient ground vibrations occur due to movement of objects at the ground surface penetrating down into the earth, such as the roots of a tree vibrating as the tree blows in the wind.

Methodology

To acquire the data, we used a Tromino 3G Digital Seismometer. This unit includes three highly sensitive accelerometers that provide continuous collection of inherent horizontal and vertical ground motion. This new technology allows depth-to-bedrock information to be collected faster and easier than previous bedrock mapping techniques.

For each data acquisition location, the passive seismic instrument collects north-south and east-west horizontal ground motions, as well as up-down vertical ground motions. During processing, a Fourier transform is performed on the waveforms. A Fourier transform displays the different frequencies that created the acquired ground motion waveforms. They are displayed as north-south, east-west, and up-down components. These plots are referred to as the “spectral output”. The frequency where the movement of the horizontal components are the largest compared to the vertical component, is the frequency that specifies the sediment/bedrock contact. This is the resonant frequency of the sediment, and corresponds to the peak in spectral output when frequency is plotted against the horizontal-to-vertical ratio. This observed HVSR Passive Seismic peak frequency is inversely proportional to the sediment thickness (depth-to-bedrock) using an empirical power-law relationship (Ibs-von Seht and Wohlenberg, 1999)[1]. This frequency is entered into the empirical formula for the depth-to-bedrock estimate calculation. Two coefficients within this equation were determined from previous studies where acquired HVSR peak frequencies were plotted vs known bedrock depths, and line fitting was done. Since different coefficients have been developed for different landscapes and geologic substrates, a basic understanding of the subsurface material needs to be known in order to apply the proper coefficients.

Strengths and Limitations

Location conditions and subsurface characteristics strongly impact data acquisition. While some locations and subsurface conditions create clear and reliable data, other locations and subsurface conditions can negatively impact data acquisition and spectral output. In the Town of Lincoln, several locations produced strong, reliable peaks in the spectral output; however, the quality of many data points suffered from unique subsurface characteristics that complicated the spectral output clarity. The spectral output quality and corresponding subsurface character encountered in the Town of Lincoln is described below.

A horizontal, unweathered bedrock contact with overlying homogeneous sand or clay sediment produces the best spectral output (Figure 2). If the instrument is coupled to the ground correctly and vibrational noise is minimal, this subsurface will produce a sharp HVSR Passive Seismic peak in the spectral output that corresponds to the sediment/bedrock contact. In Lincoln, the sharpest, highest-quality, peaks were acquired within swamp areas, such as Black Ash Swamp.

[1] Ibs-von Seht, M., and Wohlenberg, J., 1999, Microtremor measurements used to map thickness of soft sediments: *Bulletin of the Seismological Society of America*, vol. 89, no. 1, p. 250–259.

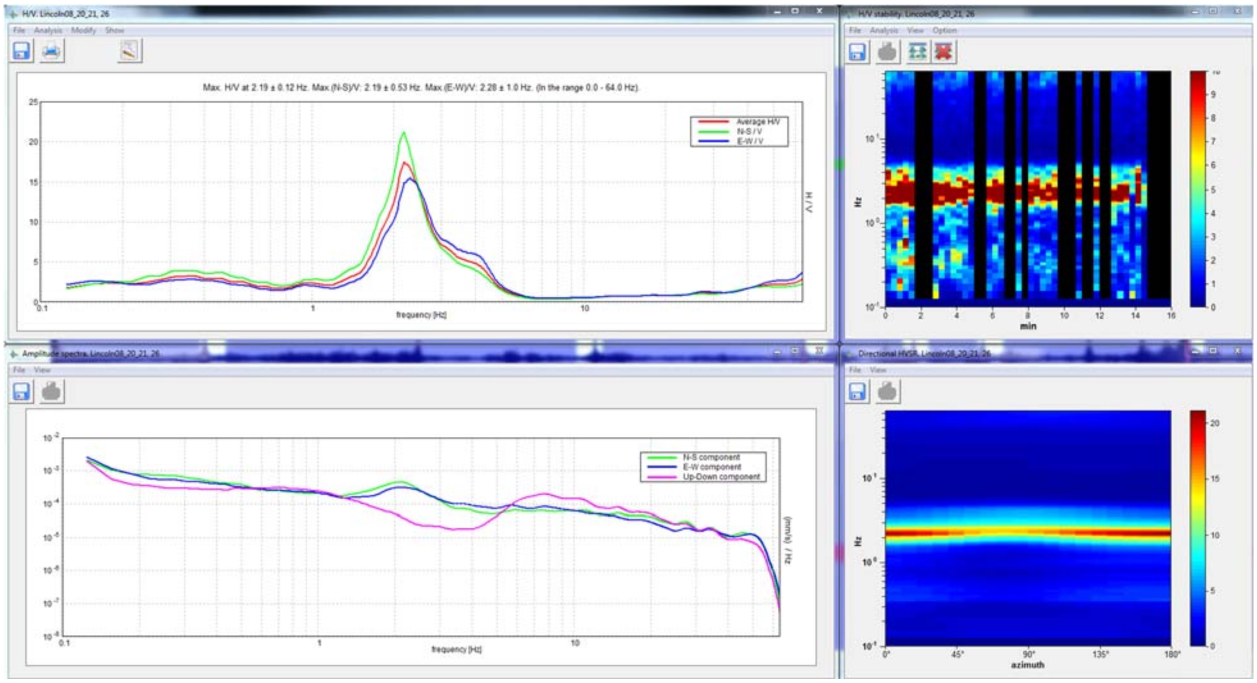


Figure 2: Spectral output of the passive seismic data acquired at Black Ash Swamp. (Upper Left): HVSR Passive Seismic peak (Lower Left): Frequency vs amplitude for the two horizontal components of the instrument and the vertical component. (Upper Right): Time vs. Frequency. (Bottom Right): Azimuth vs. Frequency.

In several locations, bedrock depth was much shallower than anticipated. If bedrock is within a few feet of ground surface, the instrument might not create a distinct peak at the resonant frequency corresponding to depth-to-bedrock (Figure 3).

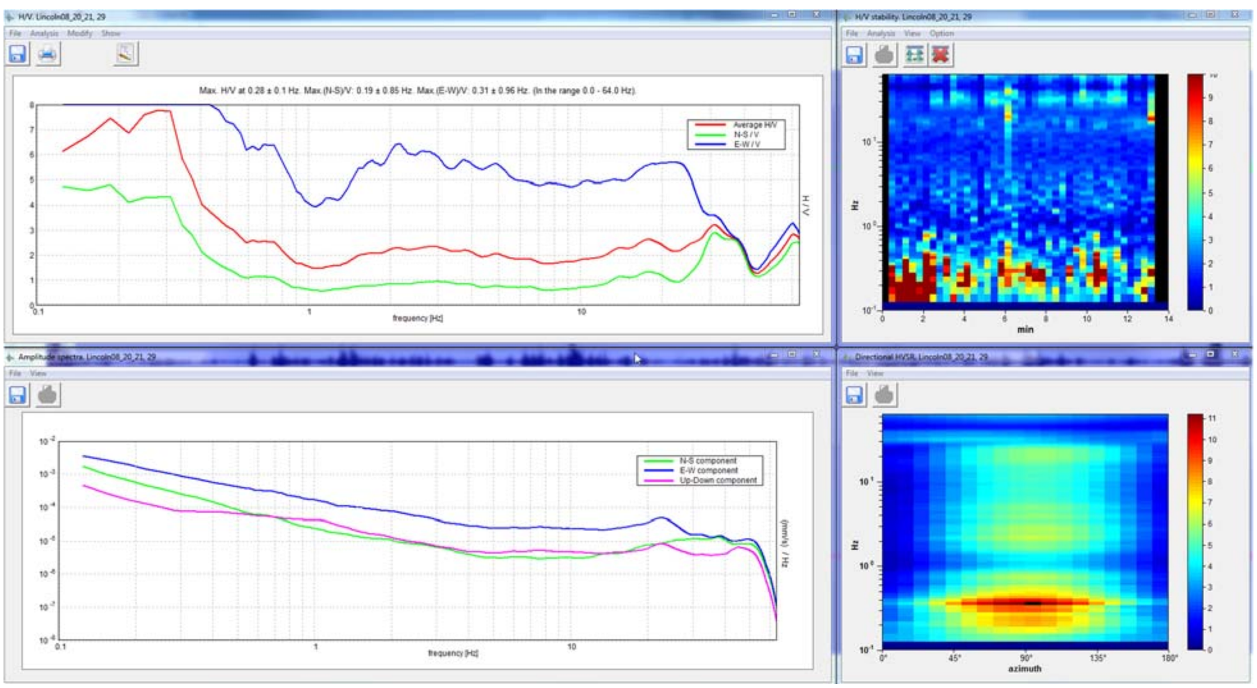


Figure 3: Spectral output of the passive seismic data acquired on Hawk Rd where bedrock was much shallower than anticipated. This creates no reliable HVSR peak for depth-to-bedrock estimation.

In some locations, gravel layers created broad peaks in the data (figs. 4–5). In areas where gravel is present, no reliable peak, corresponding to the sediment/bedrock contact, was present in the spectral output. Current research into HVSR Passive Seismic methods suggests that if a peak is present in the spectral output at a frequency lower than the spectral gravel signature, the sediment/bedrock contact frequency is shifted by an unknown amount. In the Town of Lincoln, gravel layers are present adjacent to the swamps and heavily forested areas. Based on well construction records, bedrock depths are likely to be 5 to 20 meters (16.4 - 65.6 feet) in these areas.

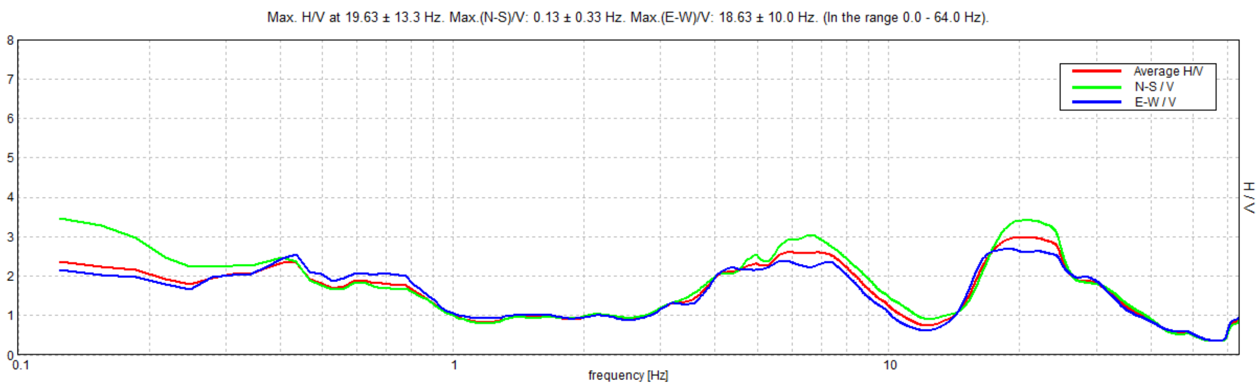


Figure 4: Passive seismic HVSR spectral output at a location east of Black Ash Rd. along the western edge of Black Ash Swamp. Gravel is seen in well records from nearby properties.

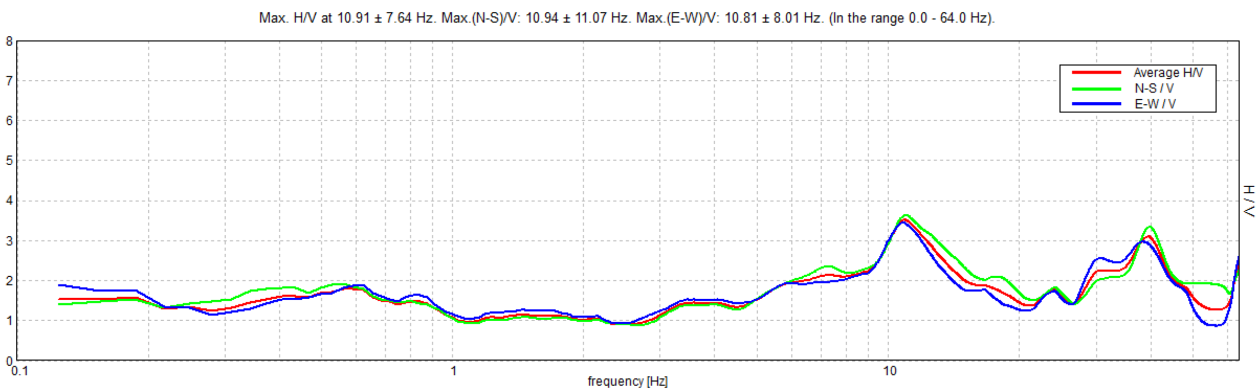


Figure 5: Passive seismic HVSR spectral output at a location east of Black Ash Rd. along the western edge of Black Ash Swamp at the locatin of a well. The well record for this well indicates clay and gravel at 0-64 feet and limestone/dolomite at 64-262 feet deep.

Within the central part of the Town of Lincoln, there is a compact gravel layer within the first 5 meters (16.4 feet) of the surface that is extremely hard and relatively thick. In the Town of Lincoln, this compact gravel layer created difficulties for several geophysical survey methods. The highest HVSR Passive Seismic peak frequency at a location east of County Rd. P and just west of Black Ash Swamp could be a result of this layer (Figure 6). The lower frequency, strong peak is likely bedrock at this location.

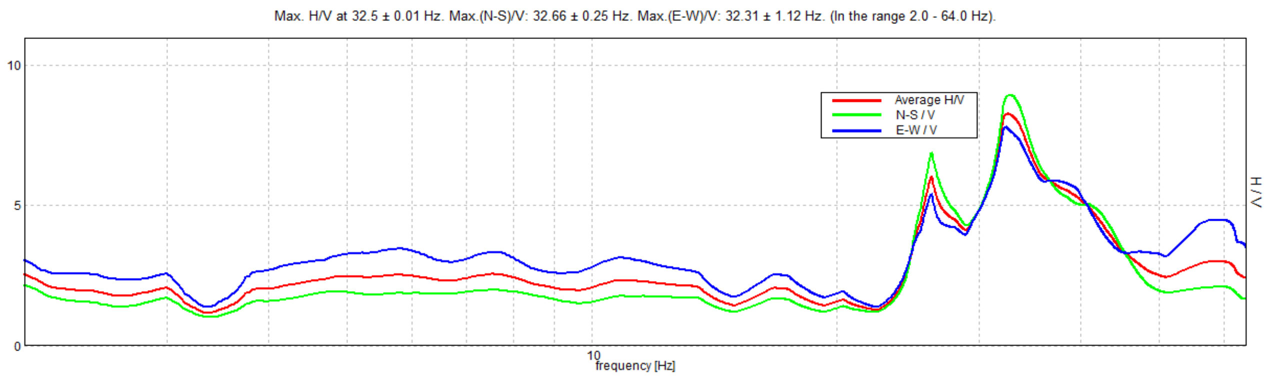


Figure 6: Passive seismic HVSR spectral output at a location east of County Rd. P, just west of Black Ash Swamp where a compacted gravel layer could be causing anomalous an anomalous trough and peak in the spectral output.

Anomalous frequencies in the HVSR spectral output were also seen at a few locations. These locations happened to be near wind turbines, although a direct connection to these ground frequencies and the wind turbines could not be determined during this project. The data point taken just southwest of the intersection of Red River Lincoln Town Line Rd and Fameree Rd has anomalous frequencies and is located near wind turbines (Figure 7). Due to these anomalous frequencies, a peak for depth-to-bedrock estimation could not be determined at this location. The anomalous peaks below 1 Hz are most likely from wind, but the peaks above 1 Hz could be from the turbines or other industrial noise.

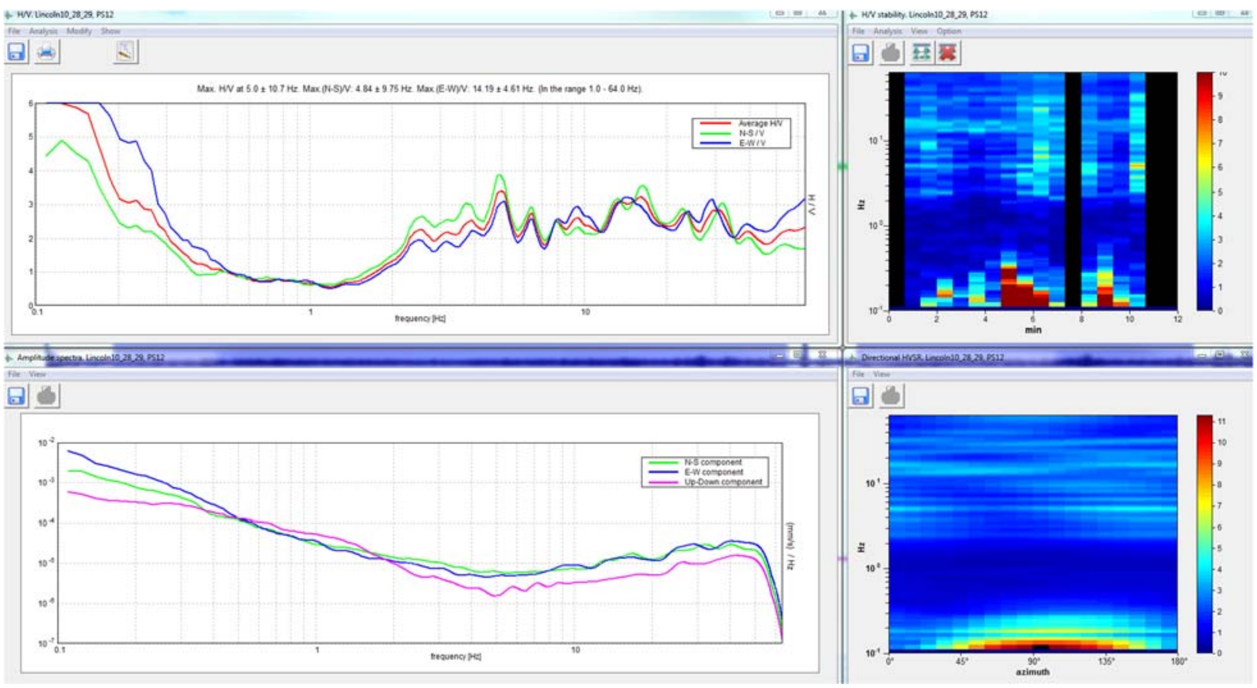


Figure 7: The data point taken just southwest of the intersection of Red River Lincoln Town Line Rd and Fameree Rd has anomalous frequencies and is located near wind turbines. A direct connection between the wind turbines and these frequencies was not determined. This occurred at a few locations near wind turbines during the Town of Lincoln project.

Electrical Resistivity Imaging (ERI)

Electrical Resistivity Imaging (ERI) is a fast, nondestructive technique used to generate two-dimensional resistivity images of the depth to underground objects and geologic structures. First, a small current is injected into the ground along a survey transect line (fFigure 8). As the current travels through the earth, it is affected by the ambient resistivity levels of different sediments and rock units and the resulting current is then collected at the surface. These voltage changes are used to build an apparent resistivity profile of the subsurface. After apparent resistivity values are collected in the field, the data file is processed using inversion software to create a two-dimensional resistivity profile with depth of the subsurface. Subsurface sediment and rock type can be inferred from the resistivity values in the image. More competent units, like bedrock, consistently have higher resistivity values than less competent units in the overlying sediment. Dryer and/or harder subsurface units almost always have a higher resistivity than wetter and/or less competent subsurface units. By using accepted ranges of resistivity values for sediment (<~750 ohm-m) and bedrock (>~750 ohm-m for weathered bedrock, >~1000 ohm-m for competent bedrock), estimates of depth-to-bedrock can be determined from the two-dimensional resistivity profile.

Figure 8: Electrical Resistivity Imaging survey line set-up. A) The survey line is a straight transect. B) The Syscal Kid Switch-24 instrument sends a current into the ground through electrodes. C) Electrodes are spaced evenly along the survey line. Two electrodes send the current into the ground, and two electrodes receive the current after it has gone through the subsurface.

Methodology

To acquire the data, IRIS Instruments' Syscal Kid Switch-24 compact resistivity meter was used. This unit provides a multi-electrode switching system for quicker acquisition over larger survey areas than previous ERI systems allowed.

For the Town of Lincoln project, two different electrode configurations were used, the Dipole-Dipole and Wenner array configurations. Varying the electrode configuration changes the level of detail in the data and the penetration depth of the survey line. The Dipole-Dipole method images the resistivity of near surface features with greater detail than the Wenner array, but has a shallower penetration depth. The Wenner array images deeper, but provides less detail of smaller subsurface features. These two methods are described in greater detail and are included in figures 9–10.

Both the Dipole-Dipole and Werner current injection electrode configurations can be used to reach a maximum survey line length of 115 meters (377.3 feet) with 24 electrodes spaced 5 meters apart. Tighter electrode spacing creates shorter survey line lengths, shallower penetration depths, and greater detail near the ground surface. Conversely, wider electrode spacing creates longer survey line lengths, greater penetration depths, and less resolution. For each method, electrodes are driven into the ground and survey parameters are entered into the Syscal Kid resistivity meter prior to the resistivity survey.

Shallow survey lines were collected primarily for the purpose of obtaining reliable estimates of subsurface conductivity for later use in EM-31 bedrock-depth calculations. Use of the EM-31 and the incorporation of ERI values into the EM-31 calculations are described below in the EM-31 section.

Dipole-Dipole Array

Once the electrodes are equally spaced in the ground, survey parameters are entered into the Syscal Kid box. In this array configuration, both potential electrodes (receiving voltage after subsurface travel) are to one side of the current electrodes (injecting current). The distance between the two potential electrodes is the same as the distance between the two current electrodes. These electrode pairs are called dipoles. The distance between dipoles can be varied to obtain shallower or deeper resistivity penetration depths and therefore image shallower or deeper subsurface features.

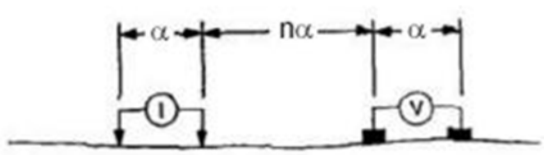


Figure 9: Dipole-Dipole Array Method

This array configuration is useful for measuring lateral changes in resistivity. A higher resolution image of the subsurface can be acquired with this method, but the penetration depth is shallower than the Wenner method. A standard 24 electrode line with electrodes spaced 5 meters (16.4 feet) apart is 115 meters (377.3 feet) long has a maximum penetration depth of approximately 13 meters (42.6 feet).

Wenner Array
This array configuration places the two potential electrodes between the current electrodes. The distance between the electrodes needs to remain equal and as current electrodes are spaced farther apart, the potential electrodes are also moved farther apart. The current electrode located at the beginning of the survey line stays in place until the first increase in electrode spacing is complete. Then that current electrode moves over, and the process repeats. As the spacing between electrodes increases, the penetration depth of the survey increases.

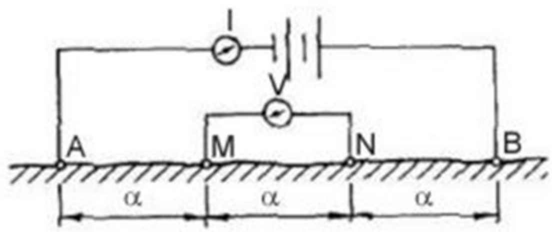


Figure 10: Wenner Array Method

The Wenner array configuration is useful for seeing vertical changes in resistivity. The subsurface inversion results provide less detail with this method but the maximum penetration depth, approximately 19 meters (62.3 feet), is greater than the Dipole-Dipole method.

Strengths and Limitations
The ERI method works best where the subsurface has relatively low resistivity, especially if deeper subsurface features need to be imaged. High resistivity units, like hard competent bedrock, can be reliably imaged beneath lower-resistivity sediment units, like sediment and soil. If higher-resistivity features are present near the ground surface, Ground Penetrating Radar (GPR) might be an alternative method (discussed in GPR section below).

In the Town of Lincoln, ERI was successfully deployed in several areas where a sharp sediment/bedrock contact was present and a distinct resistivity profile was measured at depth. One example of this was to the west of Spruce Rd, north of Robin Ln, in the Town of Lincoln. Where resistivity values in this area are more than 1,000 ohm-m, purple zone in Figure 111, competent bedrock is inferred. Using the elevation information on the y-axis, depth-to-bedrock can be determined.

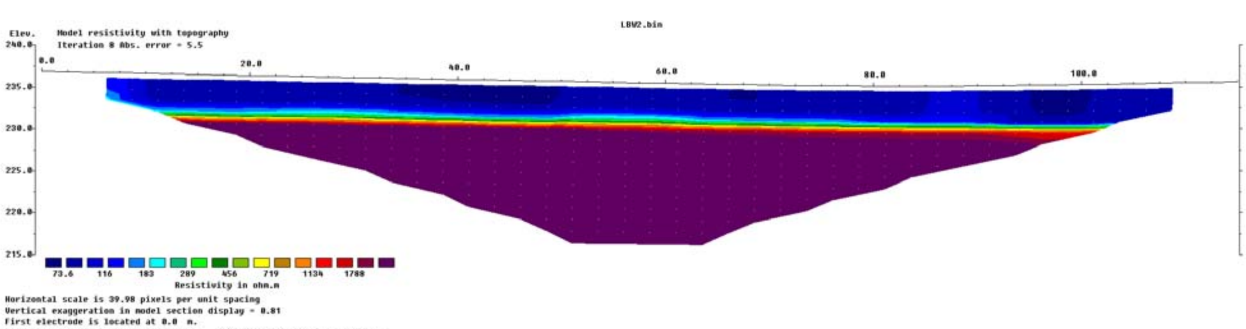


Figure 11: An ERI line was acquired from south to north just west of Spruce Rd and north of Robin Ln. Bedrock is inferred in this inversion image where bedrock values are higher than 1000 ohm-m (purple).

When using ERI, the maximum penetration depth of each method, 13 meters (42.6 feet) for Dipole-Dipole and 19 meters (62.3 feet) for Wenner, can become a limitation. If bedrock is greater than 19 meters (62.3 feet), the measurement is still valuable as it provides a minimum bedrock depth which can serve as a constraint on depth to bedrock. As an example, the ERI line shown in Figure 12 provided bedrock depth minimum values instead of specific bedrock depth estimates, because the resistivity values in the image are not high enough to indicate bedrock. The geophysical transect in figure 12 was acquired on the west edge of Black Ash Swamp and east of Black Ash Rd.

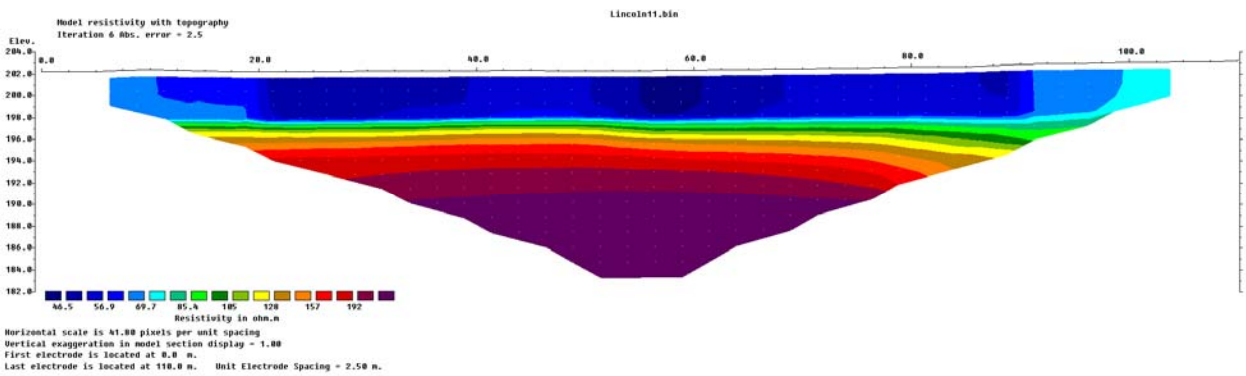


Figure 12: This ERI line was acquired on the west edge of Black Ash Swamp and east of Black Ash Rd. Resistivity values are not high enough to indicate bedrock here, but that still provides a minimum bedrock depth for bedrock mapping.

In the Town of Lincoln, some locations had bedrock, tightly compacted gravel layers, or other hard barriers such as boulders and cobbles within several inches of the subsurface. At these locations, ERI survey lines were not successful since electrodes could not be driven into the ground. This occurred in several locations along Hawk Rd.

Electromagnetic Terrain Conductivity Method (EM-31)

The Electromagnetic terrain conductivity method (EM-31) is often used in conjunction with the Electrical Resistivity Imaging (ERI) acquisition method. To use the EM-31 efficiently, it is best to have a basic knowledge of the subsurface layering and some estimates of these layer's conductivities (inverse of resistivity).

The EM-31 is a portable ground-conductivity instrument with the ability to collect point data over large areas more quickly than the ERI (fig. 13). An analog conductivity value is read from a scale on the instrument and recorded by hand. This instrument effectively scans to a depth of six meters in the ground.

Figure 13: The Electromagnetic Terrain Conductivity instrument (EM-31). One end of the pole is a transmitter that sends a magnetic field into the ground. The other end of the pole is a receiver that acquires a secondary magnetic field after interaction with subsurface units.

Methodology

The EM-31 has a transmitter and a receiver coil separated by 1.7 meters (5.6 feet). A current is applied to the transmitter coil that produces a time-varying magnetic field. These time-varying magnetic fields induce very small currents in the subsurface. From those small currents, a secondary magnetic field is produced out of phase with the primary field. Both fields are picked up by the receiver coil.

Conductivity data points are collected individually at specific point locations. This acquisition method works best with two people, but one person can also use this technique effectively in the field. After the instrument is assembled, it is carried with the aid of a shoulder strap for support while walking. Transects are then made with the EM-31 over specific areas of interest and the technician records the point conductivity values, instrument sensitivity settings, and latitude and longitude for each conductivity measurement. If two people are available, one person carries the instrument while the other records measurements. The latitude and longitude of each location are recorded in the field using hand-held GPS units. Elevations are later determined back in the office by using these X-Y locations to extract point elevations from GIS raster elevation datasets.

After collecting conductivity point data, each measurement is used in calculations to estimate depth-to-bedrock at each location. Each conductivity data point acquired by the EM-31 (σ_v) is inserted into an equation with estimated subsurface layer conductivities (σ_1 and σ_2) to calculate a relative contribution to the secondary magnetic field at the receiver coil (R_{vz}). This is an apparent conductivity from all material below the instrument within ~ 6 m of the surface. Using the value from Equation 1, a depth-to-bedrock estimate is calculated in Equation 2.

Equation 1:

$$R_{vz} = \frac{(\sigma_v - \sigma_1 * .91)}{(\sigma_2 - \sigma_1)}$$

Equation 2:

$$Z_{contact} = \sqrt{.25\left(\frac{1}{{R_{vz}}^2} - 1\right)} * 3.7m - 1m$$

These equations rely on subsurface layer-conductivity estimates that would have previously been calculated from the ERI survey lines. This is possible since resistivity is simply the mathematical inverse of conductivity.

Strengths and Limitations

With a basic understanding of the subsurface materials and layers, an estimate of the overall conductivity of these layers can be determined using EM-31. EM-31 works well for estimating depth-to-bedrock within approximately 6 meters (19.7 feet) of the subsurface.

In the town of Lincoln, some locations had small lateral changes in bedrock depth within 6 m of the surface. The EM-31 instrument worked well in these areas. Because some of this data was collected on elevated roads, the road height has to be corrected for in order to estimate a more reliable bedrock depth.

In some areas, an estimated depth-to-bedrock was calculated to be over 6 meters (19.7 feet) deep. At these locations, a depth-to-bedrock constraint was used instead of an estimated depth-to-bedrock.

Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) provides a two-dimensional profile image with depth of the subsurface, rather than point data. The GPR instrument is an antenna that sends radio waves into the ground through a transmitter and then receives the reflected radio waves through a receiver (Figure 14). This antenna is typically towed very slowly behind a truck (about 5 mph) or dragged overland by foot. Radio waves emitted from the antenna's transmitter reflect off subsurface materials, such as sediments or rock and then return to the receiver. The round-trip travel time of the radio waves, from the transmitter back to the receiver, provides an estimate of depth to specific subsurface features, such as the top of bedrock.

Figure 14: Photos of the 80 MHz Ground Penetrating Radar (GPR) equipment during set-up (above) and in action on the roads in the Town of Lincoln (below). This unit is typically pulled behind a pickup truck along roads or open fields at slow speeds (about 5 mph).

Methodology
The frequency of the radio wave transmitted and received by the GPR antenna effects the resolution and penetration depth of the GPR survey. Smaller frequncy waves have longer wavelengths which can penetrate to greater depth before being attenuated; however, they result in reduced resolution images of subsurface features. By contrast, the higher freqency radio waves, with shorter wavelengths, do not penetrate as deep but generate higher resolution images of subsurface features. The larger 80 MHz antenna can be towed by truck or pulled by foot on lightly travelled public roads, dirt roads, open fields, or grasslands. The smaller 500 MHz antenna can only pulled along a transect by foot but for data collection in harder to access areas where the larger, heavier 80 MHz antenna cannot go.

Prior to performing a new GPR transect, it is important to have a basic understanding of subsurface materials at depth in the area. A dielectric constant needs to be established for data processing after acquisition and is often estimated based on existing knowledge of the subsurface materials. When appropriate, a metal plate can be buried at depth and a GPR transect can be acquired over this plate. This operation serves as a calibration step and provides radio wave velocity corrections for processing, ensuring that subsurface features line up in the correct lateral and vertical location. This calibration technique was not performed in the Town of Lincoln since GPR transects were either not performed deep enough or directly on roads where a plate could not be deployed.

Most GPR data for the Town of Lincoln was acquired by towing the 80 MHz antenna over paved roads. After the transmitter sends out the radio wave, this wave will encounter changes in the density and conductivity of subsurface layers. When the wave hits one of these layer contacts, the wave will reflect back up towards the antenna and be collected by the receiver. This travel time can be converted to a depth estimate of the layer in the ground that created the reflection. These reflectors can be tracked as the same subsurface contact over large distances. The brightest reflector is usually the sediment-to-bedrock contact.

Strengths and Limitations
GPR can be used to obtain two-dimensional subsurface profiles in areas where subsurface features of interest, such as the sediment-bedrock contact, are too deep for using ERI or too shallow for HVSR passive seismic. Along Hawk Rd, between Fir Rd and Hwy P, the GPR method imaged bright sediment/soil layers above a bedrock layer with no reflections (Figure 15). This provides a clear depth-to-bedrock in an area that was too shallow for the HVSR passive seismic method.

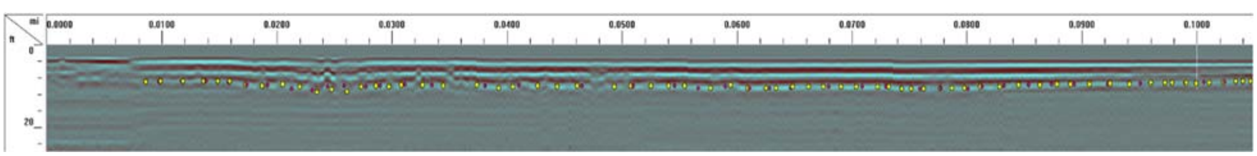


Figure 15: Ground Penetrating Radar subsurface image of sediment/soil layers above bedrock on Hawk Rd.

One significant limitation with GPR is that it does not work well when the ground has a relatively high conductivity, such as when the ground is saturated. GPR is of little use in these instances because the highly conductive material attenuates the radio wave quicker than the resistive material. Within the Black Ash Swamp, where ground is commonly saturated and bedrock is at significant depths (> 50 ft), ERI could not penetrate deep enough but the GPR radio waves could not penetrate the highly conductive, saturated ground materials. In these saturated ground areas, HVSR Passive Seismic was the only geophysical technique which was capable of estimating depth to bedrock.

The GPR is a quick method to acquire long survey lines, because it can be conveniently towed behind a truck to collect several miles of subsurface data in an hour. Unfortunately, in the Town of Lincoln, roads are commonly constructed on road-base materials which quickly attenuate radio waves; preventing this technique from providing data in many areas.

Another limitation is that while a strong reflector can be seen in many GPR transects there is a potential for this reflector to be a compacted gravel layer instead of bedrock. If it was known that the subsurface material was indeed compacted gravel, the GPR values could serve as a minimum depth constraint for depth to bedrock.