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Using airborne electromagnetics to improve depth to bedrock estimates in Wisconsin

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SUMMARY

Depth to bedrock is often an important factor in hydrologic systems because hydraulic properties of bedrock and overlying sediments are typically appreciably different. For example, the thickness of glacial sediments overlying bedrock in Wisconsin controls the routing of groundwater in surficial aquifers and its connection with surface water bodies such as lakes and wetlands. In fractured bedrock environments, shallow bedrock can be vulnerable to degraded water quality when contaminants at the surface infiltrate quickly through permeable formations. Here, airborne electromagnetic surveys were acquired in three different parts of Wisconsin, totalling more than 5,700 flight line-kilometers, to improve understanding of depth to bedrock, the lithologic composition of overlying sediments, and as input structure for groundwater model development.

Key words: airborne electromagnetic, bedrock, groundwater resources, Wisconsin

INTRODUCTION

Improved estimates of the depth to sedimentary bedrock units and the composition of overlying materials are needed to characterize groundwater systems and support their protection in Wisconsin. Glacial sediments overly Ordovician to Silurian-age bedrock units in southwest, southeast, and northeast parts of the state where airborne electromagnetic (AEM) surveys were conducted in 2021 and 2022 in support of shallow geologic mapping studies (Figure 1). Electrical resistivity models derived from the AEM data are used to distinguish the top of bedrock, spatial variability of glacial sediment and bedrock lithology, and deeper shale units beneath the shallow bedrock. This work involved collaboration across several USGS projects along with the Wisconsin Geological and Natural History Survey (WGNHS), the Wisconsin Department of Agriculture, Trade, and Consumer Protection (DATCP), and the Wisconsin Department of Natural Resources (WDNR).

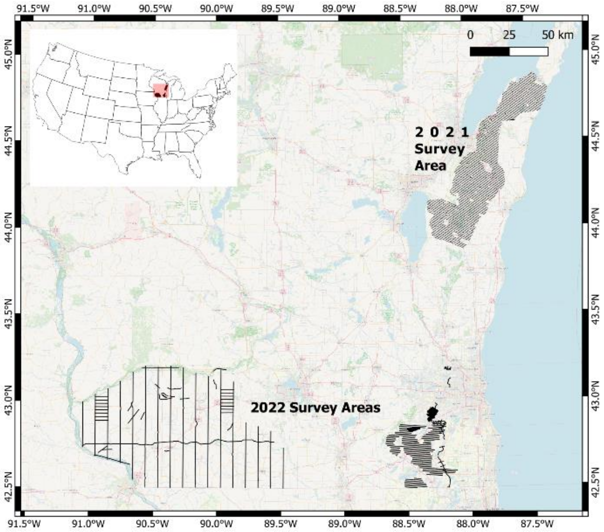

Figure 1. Airborne electromagnetic survey flight lines acquired in Wisconsin from 2021 to 2022.

Depth to Silurian bedrock is the metric used in the state of Wisconsin to control mechanical application of manure to cropland and pasture areas. Because the dolomite bedrock is fractured and highly permeable, technical standards on verification of depth to bedrock are implemented to help prevent pathogens from reaching groundwater. Manure application is prohibited where depth to bedrock is less than two feet, and application restrictions apply where depths are 20 feet or less. In the northeast 2021 study area, an AEM survey was conducted over an area of about 2,600 square kilometers to provide a systematic approach for mapping bedrock depth beneath glacial sediments. Semi-automated picks of the top-bedrock elevation were made at over 80,000 AEM model locations, and picks were used to generate a gridded depth to bedrock map over the survey area (Figure 2).

The 2022 southeast Wisconsin survey covered an area along the Fox River, in the uppermost part of the Illinois River Basin where additional AEM surveys extended in early 2023. This study area partly overlaps an existing inset groundwater model of the Mukwonago Basin that focused on characterization of the glacial aquifer system and its importance to surface water and wetlands (Feinstein et al. 2020). Here, AEM-derived interpretations of the depth to bedrock were used to refine the thickness and geometry of the overlying glacial aquifer system in the groundwater model. The existing model allows comparison of model outputs with and without the refined bedrock geometry to test the value of new AEM information in groundwater model performance.

METHOD AND RESULTS

AEM data were acquired in northeast Wisconsin (3,170 line-kilometers) during January and February 2021, and in southwest (1,381 line-kilometers) and southeast (1,171 line-kilometers) Wisconsin during February and March 2022 (Figure 1). Both surveys used the SkyTEM 304 system, with a modified system configuration where an increased high-moment base frequency was implemented to improve early-time responses given the particular focus on resolving shallow bedrock. The higher base frequency resulted in some compromise with reduced depth of investigation, given the last time gate around 3 ms as opposed to 9 ms for the standard SkyTEM 304 configuration. One-dimensional electrical resistivity models were recovered for using Aarhus Workbench laterally constrained inversions (Auken et al. 2015).

Northeast Wisconsin depth to Silurian bedrock

Inverted resistivity models for northeast Wisconsin (Minsley et al. 2022) were imported into Geoscene3D (I-GIS, Denmark) where semi-automated picks of the top-bedrock elevation were made by evaluating the shallow transition to high resistivity at over 80,000 locations along AEM flight lines (Figure 2A). Picks were interpolated into maps of bedrock elevation (Figure 2B) and bedrock thickness (Figure 2C) by differencing the elevation from a Lidar digital elevation model. Bedrock thicknesses are displayed within several classes that are relevant to the state technical standards.

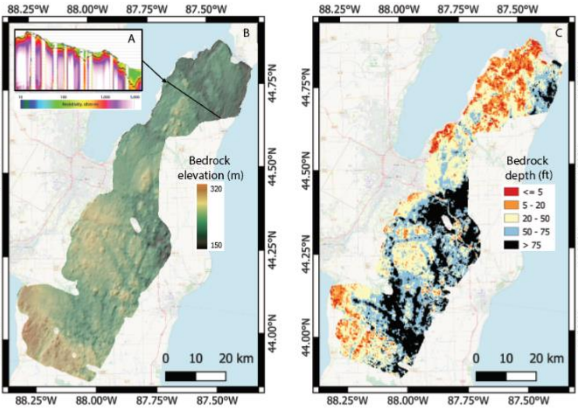

Figure 2. AEM interpretations of shallow bedrock. (A) Bedrock elevation was interpreted at over 80,000 locations along AEM flight lines, where were interpolated into a bedrock elevation surface (B). (C) Map of depth to bedrock classes relevant to state technical standards produced by subtracting the bedrock elevation from a lidar DEM.

Although AEM is effective in identifying bedrock depth using a systematic approach, small-scale details can be missed between flight lines separated by 800 m and regions outside the AEM footprint are not included. For this reason, we augmented the AEM-only maps using a statistical approach that incorporated both AEM picks along with other ground-based datasets of bedrock depth (over 170,000 points). Empirical Bayesian kriging with regression prediction was implemented using Esri ArcGIS Pro 2.9.1 (Esri, Redlands, California) to assimilate all available AEM and ground-based data into a map of bedrock elevation over a larger area in eastern Wisconsin (Hart et al. 2022). Updated bedrock maps will be incorporated in publicly available maps used to apply state technical standards.

At one location where AEM interpretations of bedrock depth were significantly greater than previous maps derived from manual probing, detailed ground-truthing was undertaken to understand this difference. Digging of a shallow trench with an excavator confirmed that bedrock depth was greater than indicated by manual probing, which was likely misinterpreted when shallow cobbles were hit in coarse grained glacial layers.

Groundwater model improvements with refined aquifer thickness

We followed a similar process in southeast Wisconsin to refine interpretations of depth to bedrock, corresponding here to the thickness of a glacial aquifer system, by using Geoscene3D to make bedrock picks guided by resistivity transitions along AEM flights (Crosbie et al. 2023). Refining the geometry of the glacial aquifer provided an opportunity to evaluate the value of this information in performance of an existing groundwater model in the Mukwonago Basin (Figure 3A; Feinstein et al. 2020).

Although AEM survey lines do not cover the entire model domain because of populated areas, new interpretations most notably enhanced representation of a bedrock valley that intersects the southern part of the model domain (Figure 3B-C). The bedrock valley is apparent as a transition to a resistive layer at depth that can be tracked in cross-section view (Figure 3D). Although its general location and pattern remain similar, interpreted depths can vary by more than 25 m, with the updated bedrock surface being narrower than in the original version.

Analysis compared groundwater model fit and performance between the original groundwater model (Feinstein et al. 2020) and a re-run with refined estimates of depth to bedrock, both calibrated with the parameter estimation code PEST (Doherty 2022). Addition of the AEM data improved overall model fit by 17%. More importantly, however, significant improvements were observed in simulation of wetland fens (114% improvement in fen count) and distribution of groundwater discharge to non-fen surface water features (72% improvement). Estimates of total basin discharge worsened somewhat (-26%).

Better assessment of groundwater interaction with fens and other surface water features is achieved through including more realistic aquifer geometry and associated distribution of groundwater flow between the bedrock and overlying unconsolidated sediments. This insight, in turn, improves the ability to inform decisions about water resource management in this basin. Future efforts will aim to further improve model performance and predictions by incorporating additional details interpreted from the AEM data beyond just bedrock depth estimates: (1) refine the geometry of different subcropping bedrock units beneath the glacial aquifer, which have different hydrologic properties; and (2) inform lithologic changes within the model's glacial aquifer that are likely important for local groundwater flow.

CONCLUSIONS

AEM surveys can contribute in various ways to support decision making, land use management, and understanding of groundwater resources. Model-independent information such as depth to bedrock is directly useful in informing land management practices in agricultural areas where shallow fractured bedrock is vulnerable to contamination. In other areas, basic interpretations of depth to bedrock are shown to improve groundwater model predictions when more representative aquifer geometry is assigned from AEM interpretations.

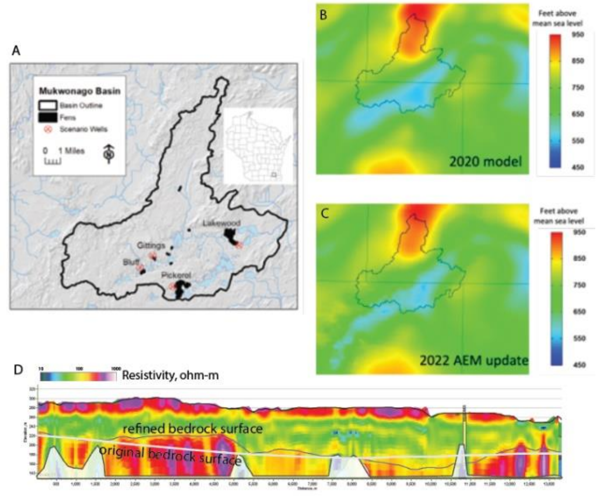

Figure 3. Groundwater model area bedrock surface interpretations. (A) Mukwonago Basin model domain and area of mapped fens. (B) Bedrock elevation for the original 2020 model (Feinstein et al. 2020) and (C) and revised 2022 update based on AEM interpretations. (D) Example resistivity cross-section along an AEM flight line shows interpretation of the bedrock surface and difference compared to the original model

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