

Geophysical Imaging of Sustainable Water Resources in Complex Geological Settings: Case Studies from USA and Africa

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Abstract: Groundwater accounts for approximately 30% of the world's total fresh water supply and a sole source of drinking water for millions of communities around the globe. For that reason, groundwater exploration has been developed as a prime research focus within the geoscience community. The well-based conventional techniques for groundwater exploration seemed to be limited to regional-scale aquifer systems. However, there exist subsurface settings where aquifers are laterally discontinuous, composed mainly of fine grained deposit, limited to basement fractures or have relatively high clay content. In these circumstances, integrated geophysical surveys can provide a more efficient groundwater exploration alternative compared to the conventional techniques. This research presents three case studies where integrated geophysical surveys in the form of seismic reflection and electrical resistivity have successfully imaged groundwater aquifers at complex subsurface settings in the US and Africa. The first case study presents imaging of a multiple-unit aquifer system based on compressional (P)-wave seismic survey aided by geophysical logs in Central Illinois US. The second case study presents the results of co-located electrical resistivity and shear (S)-wave seismic surveys acquired from Northern Illinois US to map a fine-grained aquifer system within complex glacial deposit. The third case study presents basement aquifer imaging based on integrated P-wave seismic and electrical resistivity surveys in Malawi Africa. Although the nature of the sediment in Illinois contrast sharply with the sediments in arid regions, the geophysical techniques implemented in the first two case studies will presumably have a remarkable potential for groundwater exploration in arid regions. The three case studies emphasize the role of integrated geophysical surveys in groundwater exploration especially when incorporating techniques that measure the chemical and mechanical properties of the aquifers such as electric and seismic methods.

Key words: Missing

INTRODUCTION

In recent years, fresh water resources have been increasingly stressed in many areas around the world due to the increase in population and the subsequent demand for clean water. There is an increasing need for finding new freshwater resources Worldwide, especially in arid regions. More than 1 billion people globally still lack safe drinking water, while more than 2.5 billion lack adequate sanitation. Although large lakes and rivers may exist in many of developing countries nevertheless the use of these water sources is geographically limited strictly by the economics of building pipeline infrastructure. Rural

communities in many countries have long called for a clean and reliable water supply. Finding new freshwater resources is even more pressing in arid regions. This has forced many communities in rural areas to investigate new water supplies particularly groundwater aquifers.

Exploring and characterizing groundwater aquifers based mainly on wells may not be efficient not only because of the cost of the well drilling but also because of the limited information provided by wells regarding the nature, extent and continuity of the aquifers. Geophysical methods can play a role in proper imaging and a more efficient characterization of groundwater aquifers when correctly applied. Geophysical methods such as electrical

and electromagnetic methods are typically used for mapping groundwater aquifers [1, 2, 3]. Seismic techniques have been shown to be effective for imaging and locating groundwater aquifers as well [4, 5, 6]. For example, Oldenborger *et al.* [7] have shown that the integration of seismic reflection, well log and airborne electromagnetic surveys resulted in providing quality data for aquifer mapping in southern Manitoba in Canada. Bradford *et al.*, (1998) used high-resolution seismic reflection profiles to image a shallow (<100 m) aquifer system in temperate glacial sediments at Puget Sound, Seattle. Giustiniani *et al.* [8] characterized an important multilayered aquifer located in the Friuli-Venezia Giulia plain northeast of Italy.

This article presents three case studies where exploring and characterizing groundwater aquifers based on integrated geophysical surveys were successful in identifying drill locations with the most potential for highest production rates. The first two case studies included imaging fine-grained discontinuous groundwater aquifers within complex glacial sediments in northern and central Illinois US respectively. In these studies, continuous high-resolution seismic profiling was integrated with electrical resistivity and well logs for effective imaging of the aquifers. The third case study was conducted in Malawi Africa, to image a fractured basement aquifer and integrated seismic and electrical resistivity surveys were applied.

Case Study I:

Overview: In central Illinois, the most prominent feature on the bedrock surface is a system of deeply incised valleys, known as the Mahomet Bedrock Valley System (Fig. 1). The bedrock valley formed part of an expansive preglacial bedrock drainage network, the Teays-Mahomet Bedrock Valley System, which contained a river with headwaters in the Appalachian Mountains [9]. Along the Mahomet Bedrock Valley, meltwater flowed in front of ice margins carrying enormous amounts of coarse-grained material sand and gravel, while in the tributary valleys, meltwater was ponded creating large glacial lakes [10, 11].

Data Acquisition and Processing: We acquired a number of high-resolution seismic profiles from central Illinois. The seismic data consisted of a series of high-resolution P-wave seismic reflection profiles over approximately 13 kilometers of survey (Fig. 2). The obtained seismic data were acquired using the P-wave land streamer technology developed by ISGS [7]. Fifty-pound weight drops were used as an energy source and 36 geophones mounted on

metal sleds spaced at 2 m intervals were the receivers. The land streamer data were acquired along rural paved roads and exhibited relatively good quality. The acquired data were processed using SeisSpaceProMax Processing Software and the processing workflow included frequency filtering, surface wave removal, refraction statics, deconvolution and stacking. The velocity field resulted from the velocity analysis was used to convert the seismic stacked data from time domain to depth domain.

Data Interpretation: The processed seismic lines of 13 Kilometers in total length were interpreted to characterize Aquifer system in the study area. The interpretation process started by building a geologic outline of the surveyed area based on available borehole lithological descriptions and well logs. This helped to understand the lateral and spatial variations in the area and enabled tracking of the continuity of depositional layers. This was followed by seismic to well log correlations in order to tie the major seismic horizons with corresponding lithological variations and assign the seismic reflections to corresponding lithology. This was used to interpret the seismic lines into different seismic units.

Seismic unit A includes glaciofluvial sediments directly overlying the bedrock surface (Fig. 3). These sediments contain weak reflectors compared to the overlying clayey deposits. This sediments, primarily sand and gravel are correlated to the Mahomet Sand Member (Banner Formation) and Grigg tongue (Pearl Formation) having a total thickness averaging 131 feet (40 m). Because these deposits of sand and gravel cannot be routinely differentiated by the seismic reflection surveys, therefore they have been collectively classified to the same seismic unit. The deposits are the primary source of groundwater in central Illinois. The top of seismic unit A is poorly defined because there lacks a significant contrast in seismic velocity between the water-saturated sand and gravel and the overlying clayey sediment. Within the Mahomet Sand Member, there appears to be a number of intra-unit delineated by a series of horizontal, discontinuous reflectors. The seismic unit was not subdivided because there is insufficient information about the features in the few boreholes in the area characterize the discontinuities.

Seismic unit B contains a series of horizontal, somewhat connected reflectors in sediment overlying deposits of sand and gravel correlated to Mahomet Sand Member (Banner Formation). The bottom of this unit is not well defined from the seismic data, but is better than in the underlying unit. The reflectors suggest these

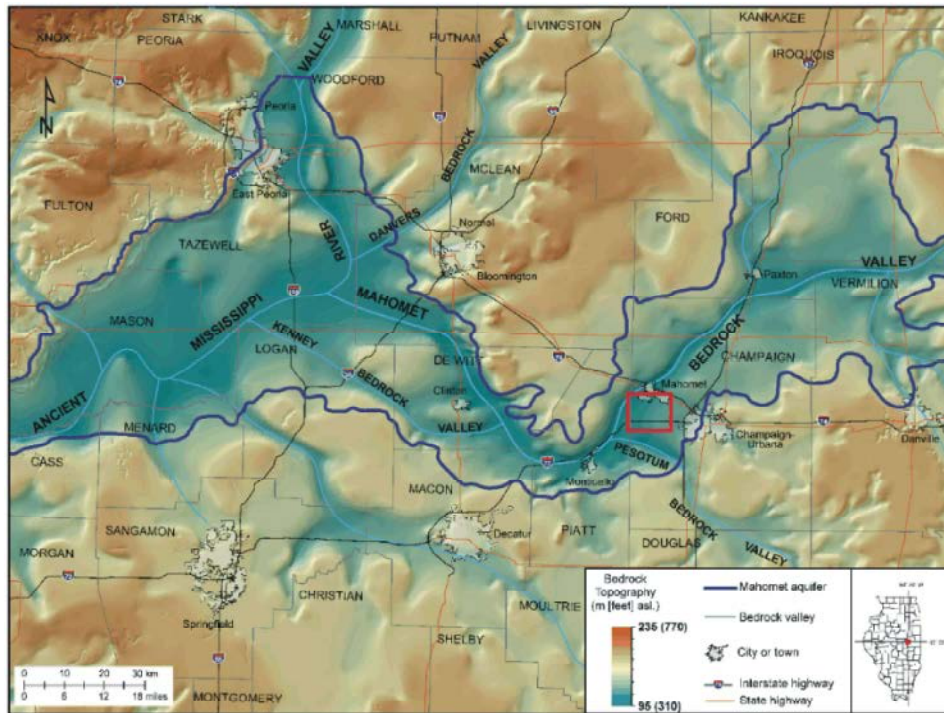


Fig. 1: Map of central Illinois showing the boundaries of the Mahomet aquifer and the study site (red box). Copyright © 2018 University of Illinois Board of Trustees. Used by permission of the Illinois State Geological Survey

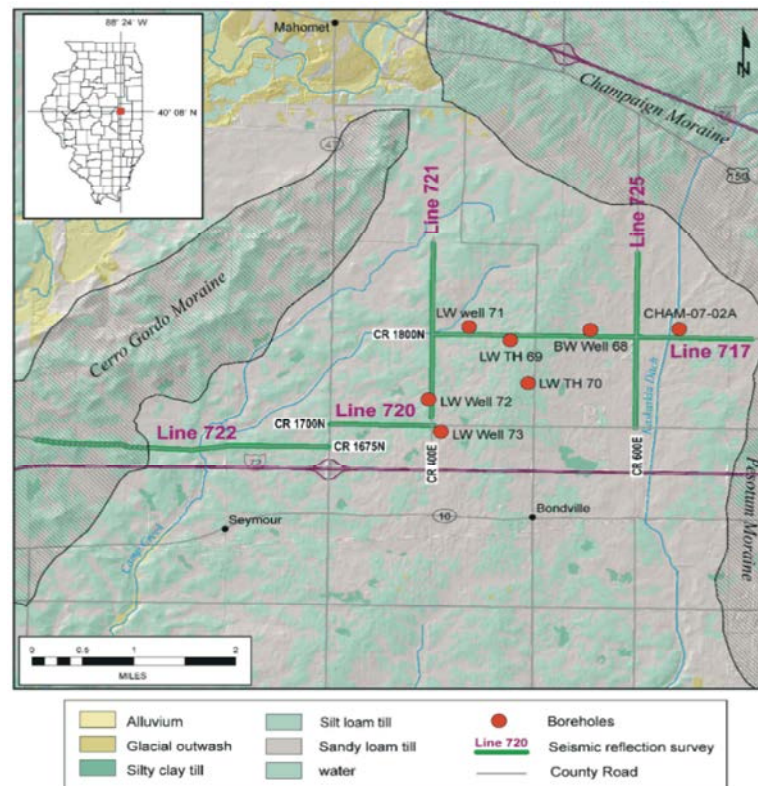


Fig. 2: Location of survey lines in the study area. Also shown is the surficial geology [12]. Copyright © 2018 University of Illinois Board of Trustees. Used by permission of the Illinois State Geological Survey

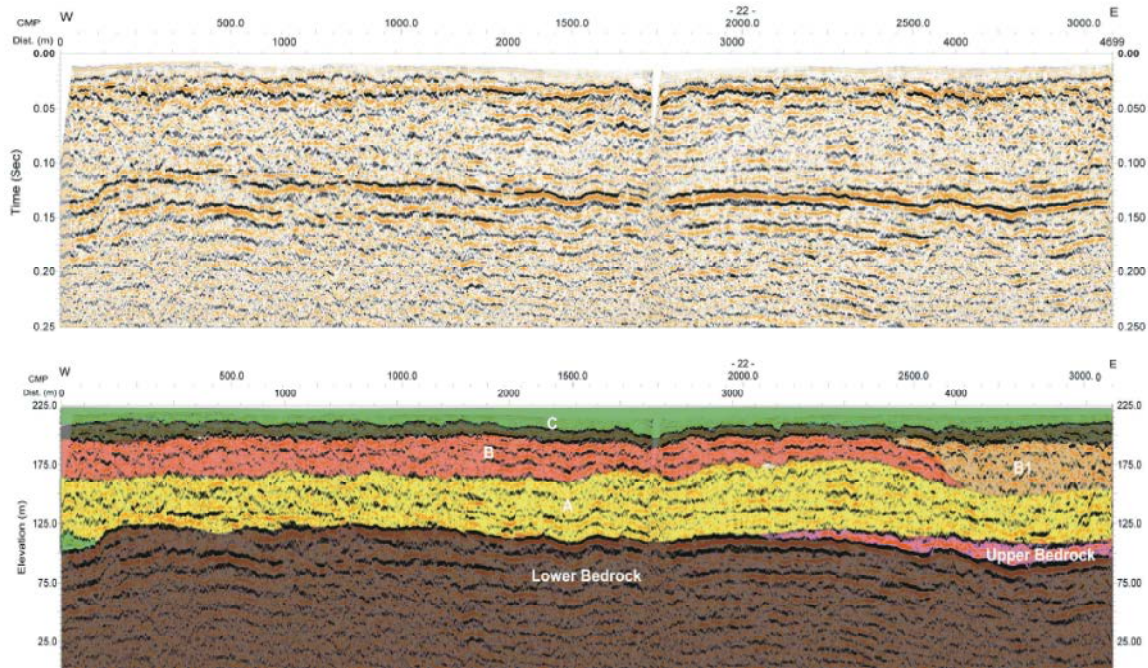


Fig. 3: P-wave seismic reflection line acquired along County Road 1675N in Champaign County in central Illinois. The location of the seismic line is shown in Figure 3. The top section is the relative amplitude time version and bottom section the depth-converted version with interpretation

deposits are either clayey till or bedded fine-grained sediment. The top of seismic unit B is delineated by a prominent and coherent reflector that lies at an elevation of 656–689 feet (200–210 m) asl. The uppermost reflector delineates the contact between the unit and fine-grained sediment and the bottom of clayey till deposited during the Wisconsin Episode.

Seismic unit B1 includes sediments that infill a glacial valley that was eroded into the underlying unconsolidated glacial sediments of seismic unit B. This part of the glacial valley ranges is 0.4–1.2 miles (645–1930 m) wide and up to 180 feet (55 m) deep (Fig. 3). A direct comparison of the geologic (lithology) and natural gamma radiation logs from the few boreholes that are drilled into this feature suggests that the valley-fill is composed of glacial diamicton (till), lacustrine and fluvial sediments. In places, this valley is incised into the Grigg tongue (Pearl Formation) and Mahomet Sand Member (Banner Formation), which may form hydraulic connection with the overlying aquifer units.

Seismic unit C is a well-defined unit recognized along all the seismic lines and includes tills deposited during the glaciations of the Wisconsin Episode (Figs. 4). The unit includes the surficial deposits and a strong and

coherent reflector delineate the bottom of this unit. The thickness of seismic unit C averages 95 feet (29 m). An internal reflector is present near the middle and most likely corresponds to the contact between tills correlated to the Tiskilwa Formation and Batestown Member (Lemont Formation).

Case Study II:

Overview: The study area is located in McHenry County in Illinois, approximately 80 kilometers northwest of Chicago (Fig. 4) and encompasses an area of approximately 315 square kilometers. The area lies within McHenry County, which is one of the fastest growing counties in the United States. The landscape of northern Illinois was shaped by at least three separate glacial cycles starting at about 730 [13] and ending at about 14 ka. Each glacial maximum was followed by a warming period causing meltwater that resulted in the deposition of more uniformly sized and well-sorted sediment than the glacial deposits. This allowed for the formation of sand and gravel aquifers between the deposits of each period of glacial advance [14]. These glacial and inter-glacial cycles resulted in the formation of complex glacial sediment interbedded with proglacial outwash sand and gravel aquifers.

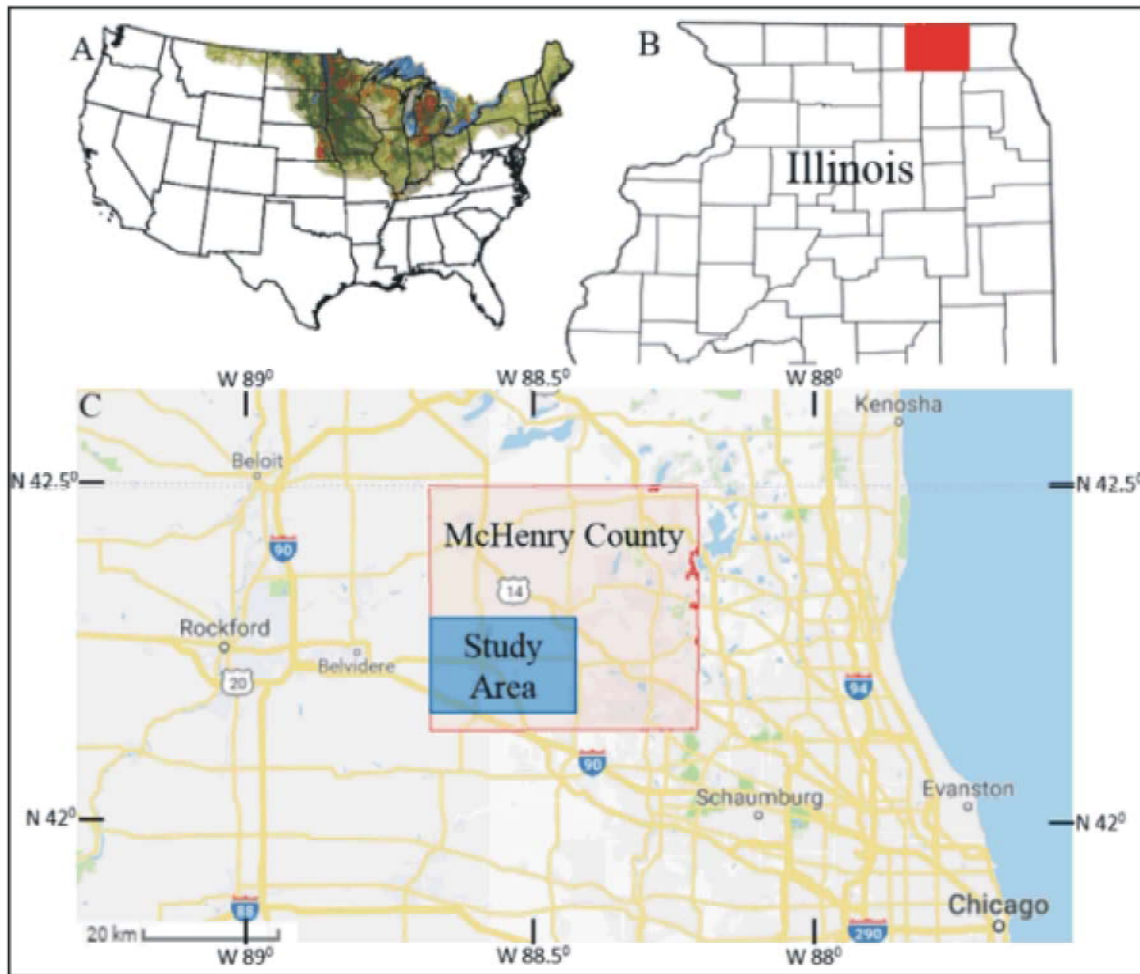


Fig. 4: Location map of the study area of case study II, in northern Illinois

Data Acquisition and Processing: An integrated electrical and seismic reflection surveys were used in this study to map potential groundwater aquifer in the area. Electrical resistivity data were acquired using 60 metal electrodes spaced at intervals of 5 m. The electrodes were connected through multi-core cable to a computer-controlled resistivity meter and switching system. During acquisition, a control program sequentially switched combinations of electrodes, operated the instrument and stored the data. The seismic data used in this study were horizontally polarized shear wave (SH) reflection data acquired using SH-wave land streamer technology. SH-wave data are obtained when the source orientation is perpendicular to the orientation of the receiver line. A 2-kg sledgehammer striking the horizontal axial of a ruling metal cylinder was used as the energy source. The land streamer method is a seismic data collection technique where a set of geophones are pulled behind a vehicle and

shots are taken at specific intervals, similar to how marine surveys are collected. For this data, 24 14-Hz horizontally polarized geophones were used at 0.75 meter spacing, with a shot spacing of 1.5 meters.

The 2-D resistivity models of the resistivity data were calculated using a finite-element inversion program [15]. For the seismic data, the Landmark's SeispacePromax software was used for processing. The processing workflow included frequency filtering, notch filter and surface wave removal. The surface wave removal module involved a two-step procedure where singular value decomposition (SVD) estimated the surface within a localized time-space window based on their estimated velocity and frequency then adaptively subtract them from the data in the second step. Deconvolution removes frequency-dependent responses of the source and receivers. Predictive deconvolution adopted in this study uses characteristics from earlier segments of a trace and

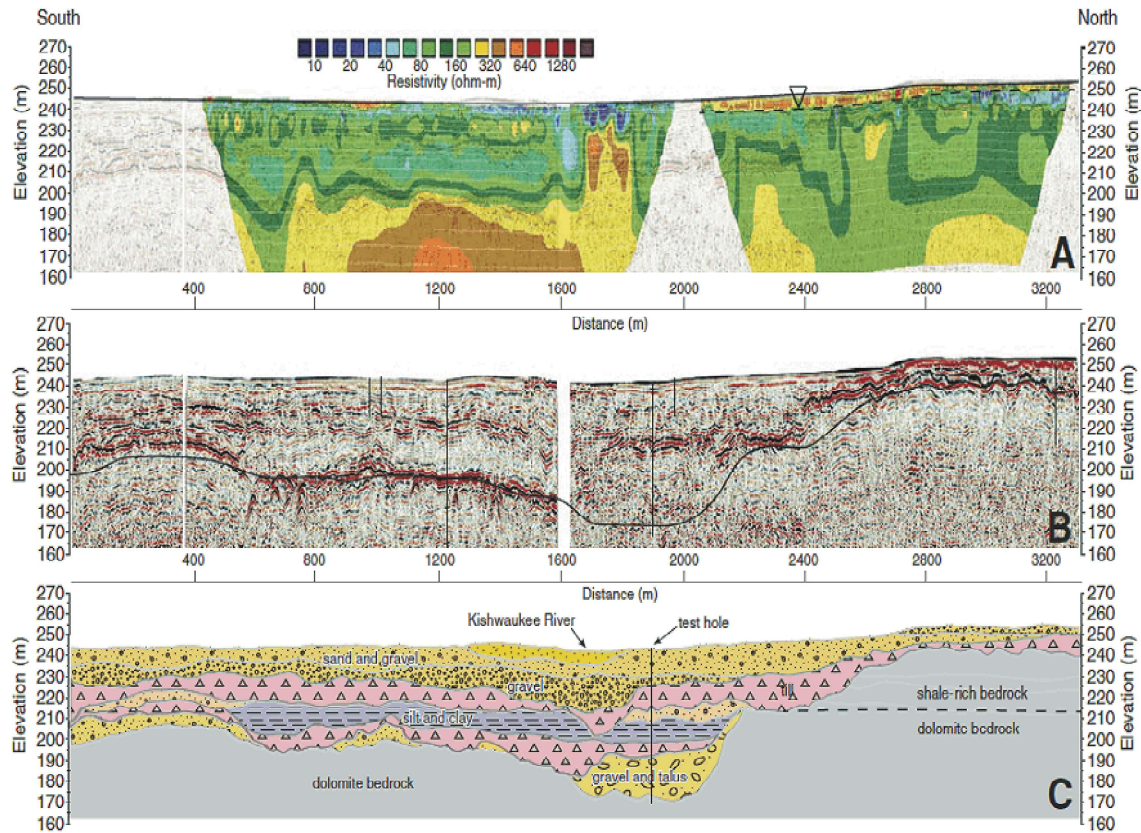


Fig. 5: Co-located S-wave and electrical resistivity profiles acquired from McHenry County in northern Illinois with the interpreted geologic profile

then uses that information to predict and deconvolve later segments of the trace, which aids in removing noise and multiples. Residual statics was then applied to clean the data using the Maximum Power Autostatics function. A normal move out (NMO) correction was applied with velocity values that were calculated from the velocity analysis step. The velocity fields derived from the velocity analysis of each SH-wave profile was later used to convert the profile from time to depth after relatively simple smoothing.

Data Interpretation: An example of collocated resistivity and S-wave seismic profiles is shown in Figure 5. The seismic and the resistivity profiles cross the location of a buried bedrock valley that carved over 60 m into the bedrock surface. One test hole was drilled along the center of the bedrock valley to be used for validating the geophysical results. The data from this test hole showed that the bedrock valley is filled with a complex sequence of glacial deposits. The geophysical interpretation (Fig. 5) shows reasonable correlation with the test hole data. The

electrical resistivity data show a variety of stratigraphic boundaries, changes in lithology and variability of sediment saturation (Fig. 5). Low-resistivity values (< 30 Ohm.m) near the center of the valley are likely associated with recent floodplain/wetland systems. More regionally, shallow sand and gravel outwash locally fills the young river valley to nearly 25 m depth. Within this outwash, shallow resistivity layers (0–10 m) show relatively high-resistivity values (320–380 Ohm.m) associated with unsaturated sand and gravel. The increased resistivity (140–200 Ohm.m) of the lower, saturated sand and gravel indicates coarser gravel of distal facies outwash.

The dolomite bedrock shows the highest-resistivity values (260–380 Ohm.m) at depths below ~50 m along the resistivity profile. The bedrock surface rises in the northern half of the profile, indicating a bedrock valley wall and paleo-valley uplands. Strong reflectors along the seismic profile (Fig. 5) indicate seismic velocity changes associated with lithologic boundaries and the bedrock surface. The bedrock surface exhibits the

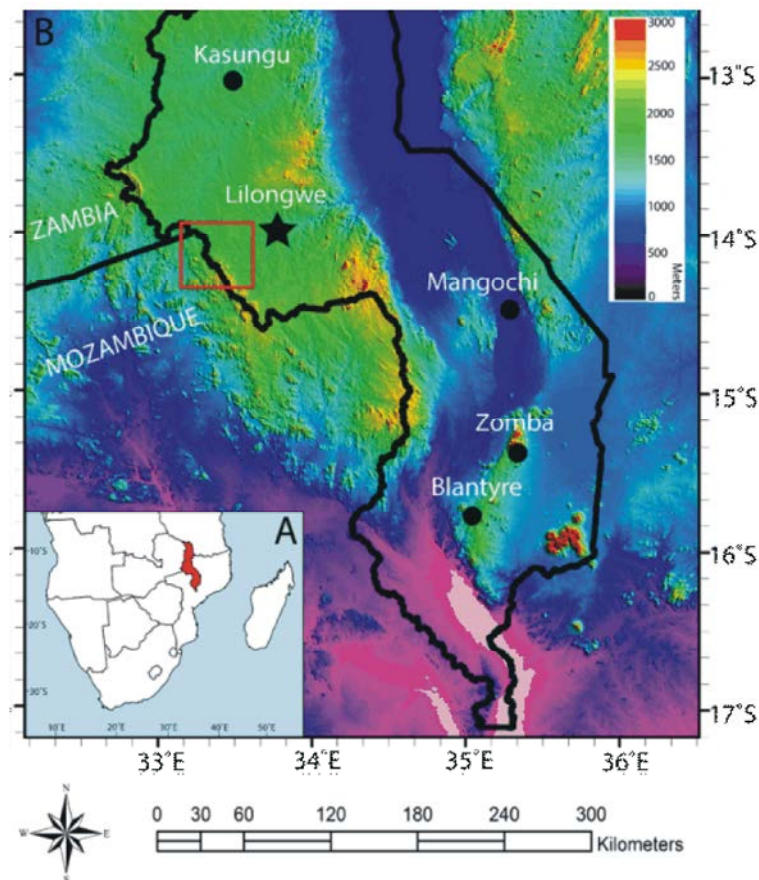


Fig. 5: A) Inset map of Southern Africa with the country of Malawi in red. B) Digital elevation model (DEM) of Southern Malawi from the Shuttle Radar Tomography Mission (SRTM) data. Highlights the major cities (black dots) and capital (star) of Malawi as well as surrounding countries

strongest reflector at ~40 m depth between distance marks of 0 to 1600 m along the seismic profile. That reflector amplitude degrades gradually until and completely fade out in the deepest part of the bedrock valley (1600–2200 m). The same reflector becomes apparent as a strong, shallow undulating reflector in the northern quarter of the profile (2400–3300 m). Using the available water-well record and test hole data to complement the interpretation of seismic data, the northern wall of the bedrock valley declines nearly 60 m in relief along 800 m laterally. The test hole along this profile indicates a thick, coarse talus deposit at the base of the bedrock valley, suggesting the influence of the nearby bedrock valley slope. At shallower depths, a relatively strong seismic reflector indicates the lower boundary of the uppermost sand and gravel.

Case Study III:

Overview: This study was conducted in rural Malawi Africa to map local basement aquifers for socioeconomic

use. High failure rates and the short lifespan of wells in Malawi exemplify the challenge of targeting reliable basement aquifer sources with a wildcat approach [16]. The Central Malawi plains consist of a deep weathering profile exposing lateritic soils at the surface that grade into the highly weathered clay-rich layer, or saprolite. The saprolite overlies the weathered bedrock, or saprock, which then grades into fresh basement [17, 18]. While the saprolite layer has the greatest groundwater storage potential, optimum permeability is found in the highly fractured and weather saprock layer. Therefore, the ideal aquifer target is at the brecciated contact between the saprolite and saprock [19, 17, 13]. To identify groundwater targets in this laterally discontinuous and fracture dominated environment we utilized electrical resistivity, seismic reflection and aeromagnetic data. Through combination of electrical and magnetic properties of the subsurface we infer chemical characteristics of the potential aquifer zones, while seismic reflection data provides us with the physical properties.



Fig. 6: Seismic P-wave data acquisition using land streamer in Malawi Africa

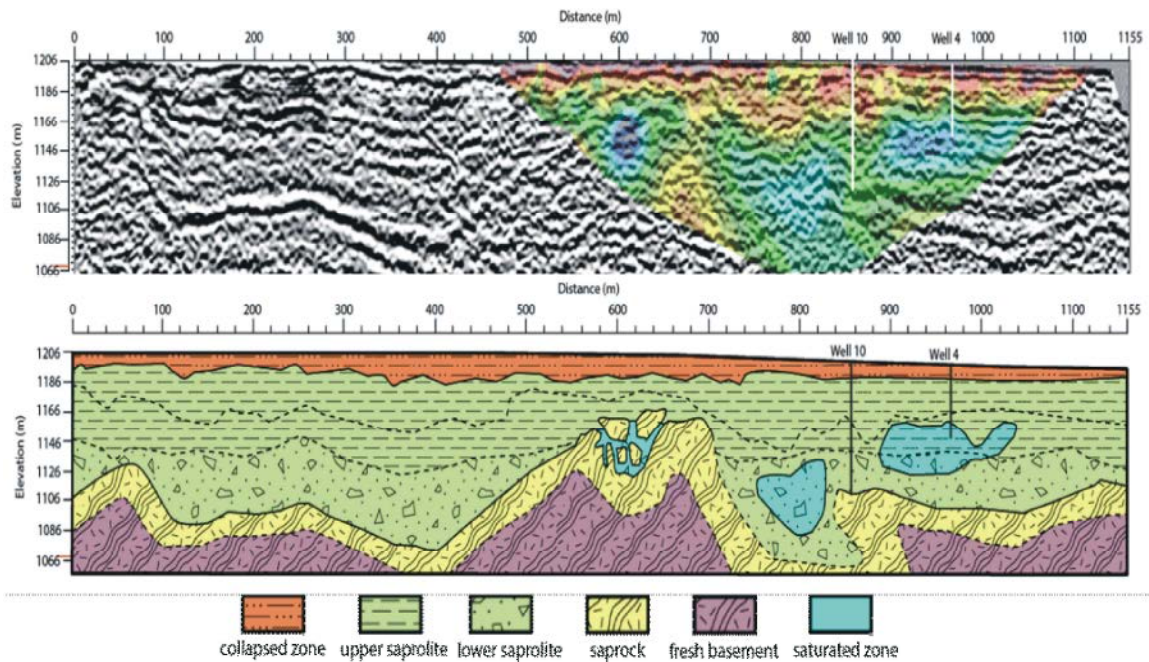


Fig. 7: Collocated seismic and electric resistivity profiles (upper panel) and their geological and hydrological interpretation (lower panel)

Data Acquisition and Processing: In this study, we collected collocated electrical resistivity and P-wave seismic profiles along a number of transects. We utilized a 10 channel Syscal Pro resistivity meter, 72 electrodes and the dipole-dipole and Werner-Schlumberger arrays. We then used a combined array to invert the data in RES2DINV. We deployed the first seismic reflection land-streamer survey; a rapid land based seismic acquisition system, in Malawi. Our system

consists of 24 channel geophones mounted on individual metal sleds that are gravity coupled to the ground surface. Connected by a cable, the sleds are towed by a common land vehicle. The survey utilized the common midpoint method, fifteen-kilogram sledgehammer source and two-meter geophone and shot interval (Fig. 6). Aeromagnetic data was purchased from the Malawi Geologic Survey and interpreted across each geophysical profile.

Data Interpretation: The seismic section shows three main reflectors (Fig. 7). The first is a shallow continuous reflector at 10 m depth. The second is at 30 m depth, is largely discontinuous across the profile and only easily identified at the small lateral distances. The strongest reflector is approximately at 100 m depth, becomes discontinuous along the profile between 710 – 810 m distance marks, but is otherwise easily identified. The electrical resistivity profile has a highly resistive (>1000 ohm.m) surficial layer that extends to 10 m. A second layer with resistivity ranging 178 – 1000 ohm.m underlies the surface resistor to a depth of roughly 40 m, where the underlying resistances are <178 ohm.m except for a resistive layer (56 – 578 ohm.m) from 50 – 80 m depths centered at 660 m profile distance. Three conductive (1 – 18 ohm.m) bodies can be found with centers at 600 m profile distance at 50 m depth, 780 m profile distance at 100 m depth and 940 m profile distance at 50 m depth. The combination of low resistivity and discontinuous reflections were found to mark places for potential groundwater aquifers.

DISCUSSION AND CONCLUSIONS

The three case studies presented in this article highlight conditions where groundwater aquifer occur in a complex subsurface settings that limit delineation and characterizations of these aquifer based solely on well drilling. The first case study showed thin sand and gravel aquifer imbedded within a complex outwash, fine grained and lake sediments. The aquifer has a limited spatial extension and exhibited obvious later heterogeneity. Imaging these type of aquifers with a single geophysical technique may not be feasible as it pertain a high level of uncertainty. Integrated a more than one geophysical technique in this will certainly be convenient especially if the two techniques respond to different physical parameters that complement each other.

The second case study presents a multiunit system aquifer composed of thin discontinuous units. Water quality and quantity are highly altered across the aquifer units that require a high-resolution imaging for the aquifer units and their connectivity. In this case, most of the conventionally used geophysical techniques including electrical and electromagnetic methods deemed not efficient due to the high clayey and moisture contents within the depositional system. Seismic reflection aided by geophysical logs measured in the water wells penetrating the aquifers seemed to be efficient to detect the aquifer units and their continuity and connectivity.

The third case study presents a very complex fractured basement aquifer system where storage relies on the saturation of the clay-rich saprolite layer and ideal permeability lies in the highly fractured basement. Geophysical results show laterally discontinuous zones of low resistivity that largely coincide with seismic discontinuities. This suggests that preferential weathering along zones of preexisting weakens such as faults or fractures 1) extend the weathering profile, 2) localize potential groundwater and 3) act as a structurally controlled basement aquifer with a preferred drilling target at the base of the electrically conductive anomaly (saprolite/saprock boundary).

The results of the three case studies indicate that geophysical surveys can play a role in proper imaging and a more efficient characterization of groundwater aquifers in complex geological settings where the data from the water wells are deemed insufficient. Integrated geophysical surveys can image the aquifer extent, continuity and homogeneity, which help in selecting the optimum locations for drilling new wells. The results also emphasized the feasibility of integrating the electrical resistivity and seismic reflection techniques in groundwater exploration and aquifer characterization as the two techniques complement each other.

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