GROUNDWATER EXPLORATION USING SHALLOW GEOPHYSICAL METHODS

FRANKLIN COUNTY, PENNSYLVANIA

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1. Abstract

Water quality issues related to high concentrations of manganese in a surface water reservoir have prompted a regional water authority to search for alternative water sources. Among the options, the development of a new groundwater source in the proximity of an existing water treatment plant in Gunter Valley situated in the Valley and Ridge Province in Franklin County, PA. Even though bedrock geology in the region suggests relatively low well yields, further review of geologic maps indicates the presence of a high angle fault that could enhance well yields. This project focused on studying the prospects of developing a productive water well using non-invasive geophysical methods to find the fault. A resistivity survey across the valley revealed the presence of an anomaly located between 20 and 50m on the survey transect. A secondary electromagnetic survey confirmed the presence of an anomaly at approximately the same location as in the resistivity survey. Since these methods are typically used as reconnaissance tools, further field research (e.g. drilling) will be needed to precisely identify the nature of the anomaly.

2. Introduction

Traditional methods including fracture trace analysis and borehole drilling have been used in groundwater exploration for decades. However, the introduction of innovative methods such as geophysics has improved efficiency and cost effectiveness in field surveys. It is not uncommon for investigators to employ more than one geophysical method to enhance accuracy in groundwater exploration. This study utilized electrical resistivity and electromagnetic methods to locate a documented existing fault in Gunter Valley, Franklin County (Appendix A, Figure 1A). The estimated water yields from existing private water wells in the surrounding areas were estimated to be in the range of 10-23 gal/min (Geyer and Wilshusen, 1972). Hence, secondary
porosity becomes important in such a low yield bedrock that predominantly consists of sandstone. A successful application of geophysical methods requires prior knowledge of the site under investigation. The challenges associated with electrical methods are reflected in result interpretations where surrounding natural and cultural environments can have a significant impact on the results.

3. Background/Literature Review

3.1 Fracture Traces

3.1.1 Fracture trace mapping

Fracture trace analysis is a method that has been used for decades across disciplines to aid in diverse environmental projects. This method was developed and applied based on the hypothesis that a correlation exists between fracture traces and the occurrence of groundwater (Lattman, 1958). A fracture trace refers to a surface expression of subsurface geologic features such as joints, faults, and related solution openings in both sedimentary and crystalline rocks. Fracture traces are manifested by diverse features including tonal variation in soils, vegetative alignment, surface sagging, straight stream segments, fault lines, etc (Fetter, 2001). Most features are readily seen on the ground except for variations in vegetation height and soil tone, which are mostly identified on aerial photos. In an attempt to eliminate inconsistencies in the definition of a fracture trace, Lattman (1958) described a fracture trace to be a natural linear feature (surface depression, soil tonal alignment, etc.) expressed continually for less than a mile. In contrast, a lineament is a fracture trace that is over a mile long (Fetter, 2001; and Tschirhart et al., 1984).
3.1.2 Fracture trace interpretation

The subjective nature of fracture trace mapping and interpretation has spurred the development of more reliable methodologies. In order to eliminate redundancy and enhance fracture trace accuracy, Mabee et al. (1994) established a three step methodology. Multiples observers were asked to map the same fracture traces on multiple trials creating a database of 6500 fracture traces. Fracture traces from participant observers were compared by overlay technique and only coincident fracture traces were retained for further field verification. A relatively small number, 217 fracture traces, were identified as having a physical existence in the field, relating the rest to errors in mapping and interpretation. This study demonstrates the importance of accurate interpretation of fracture traces and the benefit of field proofing to establish reliable data in groundwater exploration.

Separating natural features from man-made feature is a very common challenge for inexperienced geologists in the field (Tschirhart et al., 1984). Roads, railroads, fences, etc, are often confused with naturally occurring fracture traces on topographic maps because they tend to exhibit similar linear geometric patterns. Even though the fracture trace method was widely accepted and successfully applied as a prospecting tool in the past, the range of variation in its success rates requires an integrative approach to improve success rate in groundwater exploration. Thus geophysical methods are used in conjunction with fracture trace methods for more effective surveys (Golman and Neubauer, 1994; Mabee et al., 1994; Tschirhart et al., 1984; Mohammed-Aslam et al., 2010).
3.1.3 Fracture Trace and Groundwater

The productivity of a water well is typically measured by its specific capacity, which is often confused with specific yield by the non-technical community. Fetter.C.W. (2001) defines specific capacity as being the ratio of the well specific yield to drawdown; it is a function of an aquifer’s transmissivity (T) and storativity (S). The specific yield is defined as the ratio of the volume of water a rock or soil can deliver by gravity drainage to the volume of that rock or soil (Fetter, 2001).

The correlation between fracture traces and the occurrence of groundwater has been extensively studied in the past (Lattman and Parizek, 1964; Becher and Taylor, 1982). Lattman and Parizek (1964) studied the correlation between fracture traces and the specific capacities of 14 wells in the sedimentary bedrock of the Nittany Valley in Center County, Pennsylvania. The wells were drilled in three different structural settings which included interfracture areas, on or near a single fracture trace, and at the intersection of two fracture traces. The results of this study are shown in Appendix B, Figures 1B, 2B, and 3B. The calculated “unadjusted” specific capacity values for the wells drilled near a single fracture trace and at the intersection of two fracture traces were ten to a hundred times higher. The observed variations in specific capacity values are to some extent a function of geology. Figures 2B and 3B in Appendix B show a relatively lower specific capacity for wells drilled in dolomite than those drilled in limestone.

To further investigate the factors affecting well yields in this study, Lattman and Parizek (1964) looked at 8 borehole caliper survey log. Caliper surveys consist of measuring the vertical change in a borehole diameter. They found that wells drilled on fracture trace intersections showed numerous cavernous openings versus a relatively few in wells drilled in interfracture areas. A
similar study was carried out in the carbonate bedrock of Cumberland valley where specific capacities of 20 wells that were intentionally located on fracture traces were analyzed. Five of the wells have exceptional specific capacity values and 5 of them couldn’t even supply a domestic well and there were no further explanations for these observations (Becher and Taylor, 1982). These findings demonstrate the uncertainty associated with fracture traces as indicator of groundwater concentration zones. Even though the results from the Nittany Valley study were favorable, the authors (Lattman and Parizek, 1964) concluded the results to be inconclusive because of reasons that include the omission of transmissivity and storage coefficient values in the calculation of specific capacity values. In addition, other factors such as well depth, casing, and well screen can significantly have an impact on the specific capacity of a well.

4. Geophysical Methods

An alternative to fracture trace-based water bearing zone delineation is the application of geophysical methods. Following in the footsteps of petroleum and mining industries, hydrogeologists are increasingly integrating geophysical techniques in subsurface site characterization methods (Fetter, 2001). Geophysical methods describe the techniques used to collect subsurface information related to the physical properties of earth material (Technos, 2004). The application of geophysical methods significantly increase cost effectiveness by reducing the number of boreholes needed to “hit” a geologic target. Prior to fracture traces and geophysical methods, borehole siting was based on the “hit or miss” approach (Lattman and Parizek, 1964) which is described by an extensive campaign of borehole drilling. According to Technos Inc, (2004) a minimum of 10 boreholes are required to achieve a detection probability of 90% for a study site where the target surface area is 10 times smaller than the study site surface area.
It is important to note that not all geophysical methods are appropriate for groundwater exploration. The principal methods used in groundwater investigations include Electrical Resistivity (ER), Electromagnetics (EM), and Nuclear Magnetic resonance (NMR). The limitations associated with these methods have prompted hydrogeologists to use more than one method to collect accurate data in groundwater exploration (Abou Heleika, 2009; Baker et al., 2003; Golman et al., 1994; Ong et al., 2010; Oyedele et al., 2011, Revil et al., 2012; Bateyneh et al., 2011; Burazer et al., 2010; MacDonald et al., and Fetter, 2001). The most popular methods used in hydrogeological applications are ER and EM because of the close relationship between electrical conductivity and the physical properties of aquifers, i.e. conductance and resistance (Goldman et al., 1994). As previously mentioned, knowledge of the local geology, field observations and records from existing wells are required to successfully site a productive borehole (Zhu et al., 2001).

Accurate interpretations of resistivity values are as challenging as fracture trace interpretations because of existing resistivity value overlaps between different types of geologic features. For example, fresh water aquifer resistivity values tend to vary based on the degree of water saturation or content of dissolved ions in water bearing strata. However, Oyedele et al. (2011), and Batayneh (2011) reported locating fresh water in weathered bedrock with resistivity value ranging 88.6-251.1 and 50-200 ohm-m respectively. Thus Resistivity and Electromagnetic methods are usually coupled in groundwater investigations for optimum results.

In contrast to the fracture trace analysis methodology used by Lattman and Parizek (1964), this research project will primarily focus on finding a high angle fault, which would stand out as an anomaly against a solid bedrock in geophysical survey results.
5. Study area

The study area (Appendix A, Figure 1A) is located approximately a mile and half northwest of the village of Roxbury, Lurgan Township, and half a mile north of Letterkenny Reservoir. The local relief is described by a narrow valley bounded by two prominent ridges: Blue Mountain to the east, and the Kittatinny Mountain to the west. The surface elevation ranges from approximately 740 feet at the bottom of the valley, to 1,800 feet on the ridge tops as shown in Appendix C, Figure 1C. As part of the Tuscarora State Forest, the dominant land cover is forest with a small building footprint (Shippensburg Borough water treatment plant) that represents the only land development in the area.

5.1 Geology/hydrogeology

Cumberland valley and the contiguous valleys of Franklin County are formed on folded sequence of limestone to east and shale to the west. A series of small ridges mainly composed of more resistant material (sandstone, quartzite), run parallel to the regional orientation of the valley (Becher and Taylor, 1982). The complexity observed in this part of the Great Valley system pertains to folding, faulting and cross-faulting of the strata. In Gunter Valley, the local geology consists of Silurian Formations: the Clinton Group which underlies the floor of the valley and the Tuscarora Formation, which makes up the steep slopes of the ridges bounding the valley (Appendix D, Figure 1D). A major fault that runs along the valley axis was identified and mapped using a solid line to represent known location of the fault and a dashed line representing its unverified possible location (Appendix D, Figure 1D).

Beyond the geologic makeup of the valley, little is known about the hydrogeology of this area. Becher and Taylor (1982) reported an average annual rainfall of 43 inches of which 13 inches is available to recharge the groundwater. The valley is drained by a shallow stream, Trout Run,
which flows in the north-south direction to discharge in the head waters of the Conodoguinet Creek. The rock units of the valley are poor aquifers with estimated median yields of 23 and 12 gal/min for the Tuscarora and Clinton Group Formations respectively (Geyer and Wilshusen, 1982).

6. Methodology
Site physical characteristics and investigation goals help determine the appropriate method for a geophysical survey. This study employed two different geophysical electrical methods including Electrical Resistivity and Electromagnetism, to investigate the electrical properties of the study site.

6.1 Electrical resistivity method (ER)

The electrical resistivity method is based on the theory that when an electric current travels through a wire it experiences a resistance (R) that is proportional to the length of the wire (L) and inversely proportional to the cross sectional area (A) of the wire as expressed in the proportionality equation below:

\[ R \propto \frac{L}{A} \]

Resistance is calculated by using Ohm’s Law which is described as the ratio of the measured voltage to the input current.

\[ R = \frac{V}{I} \]

Where R is the resistance, V is the voltage, and I is the current.
Resistance is a variable that depends on the intrinsic property of solid and fluid bodies called resistivity. Figure 1 shows the resistivity values of different earth materials as measured in the lab. Resistivity is represented by the Greek symbol rho (ρ) and it is related to resistance by the following equation:

\[ R = \rho \frac{L}{A} \]

This equation can be re-arranged to derive resistivity as follows:

\[ \rho = R \frac{A}{L} \]

![Figure 1. Resistivity and conductivity values of common rocks and minerals (MoombarrigaGeoscience, 2009).](image-url)
Electrical resistivity surveys use several different electrode configurations to profile a cross section of a study site. These include, but are not limited to the Wenner Array, the Schlumberger Array and the Dipole-Dipole array. The Wenner and Schlumberger arrays use stakes that are pounded into the ground to ensure direct contact with the ground. Lateral and vertical changes in resistivity can be measured by incrementally moving the entire array across the field (profiling) or simply by keeping the potential electrodes fixed while the current electrodes are incrementally spread out (sounding). These methods are usually time consuming and not suitable for hard surfaces. In an attempt to resolve these challenges, a new geophysical system, the OhmMapper (Appendix E, Figure 1E) was developed to collect data faster and in all terrain conditions. Unlike the galvanic system (Wenner and Schlumberger Arrays), OhmMapper is a capacitively-coupled resistivity system that use the capacitance of an antenna to induce an alternating current into the ground, i.e. no direct contact with the ground is needed. The setup of the OhmMapper consists of an array of freely moving interconnected set of one to multiple receivers positioned in the center of the array and a single transmitter at one end of the array as depicted in Figure 2. This is described as the dipole-dipole electrode array.
The entire array is then towed along a transect using manpower or a motorized vehicle. Data are collected continuously at a constant depth of investigation which is determined by the ratio of the distance separating the receiver and the transmitter to the length of the transmitter dipole. This value is called the \( n \) factor and it controls both the resolution and the depth of investigation of a field survey to some extent. The relative resistivity of the ground is an important control factor as highly resistive layers can prevent the signal from reaching deeper layers—a phenomenon called signal attenuation (Technos Inc., 2004.). In contrast, in a low resistivity environment, large transmitter-receiver separations generate low voltage as theoretically predicted by Ohm’s law \( V = IR \). Hence, the smaller the transmitter-receiver separation the better the resolution, and the shallower the depth of investigation. These findings describe the OhmMapper system to be optimally suitable for shallow subsurface investigations.

Resistivity field surveys measure the apparent resistivity of the earth which assumes a homogeneous ground. It is represented by the Greek symbol \( \rho_a \) and calculated by multiplying the
resistance (R) by the geometric factor (k) where the latter determines the separation and the geometric arrangement of the electrodes. The measured apparent resistivity values are compared to computer-calculated apparent resistivity values to generate true resistivity values using the least square inversion method.

A 180m transect (Appendix A, Figure 1A) was run diagonally across the study area using the OhmMapper TRN equipment with 5m dipole. The raw data were post-processed using Mapmap2000 to create pseudosections of the subsurface. The latter represents a contour map of the apparent resistivity values. A pseudosection provides a rough picture of resistivity distribution across a profile. Even though a pseudosection presents a distorted image of the subsurface it allows the detection of bad resistivity measurements as they are represented by extreme low and high resistivity values. The data file resulting from the pseudosection is input into the 2-D inversion program (RES2DINV) for further processing. This program outputs 3 different resistivity models that are displayed in one set. The first model at the top represents the measured apparent resistivity followed by the calculated apparent resistivity model in the middle. The inverted model at the bottom of the set minimizes the differences between the measured apparent resistivity and the computer-generated resistivity values by using a least square inversion method (Loke, 1999).

6.2 Electromagnetic Method

Electromagnetic method is based on the principal of electromagnetic induction. The variations in an induced secondary electromagnetic field are correlated to the physical properties of the subsurface. Conductivity is represented by the Greek symbol sigma (σ) and measured in units of milliSiemens/meter (mS/m):
Where:

- \( H_s \): secondary magnetic field at the receiver coil.
- \( H_p \): primary magnetic field at the receiver coil.
- \( \sigma \): soil conductivity.
- \( \omega \): \( 2\pi f \)
- \( s \): intercoil spacing.
- \( \mu_0 \): permeability of free space.

Conductivity is related to the resistivity by the equation:

\[
\sigma (\text{mS/m}) = \frac{1000}{\rho (\text{ohm*m})}
\]

Two different techniques are used to measure electromagnetic induction response (conductivity), Frequency Domain Electromagnetic (FDEM) and Time Domain Electromagnetic (TDEM). In FDEM a continuous electromagnetic field is generated through a transmitter coil which creates a primary magnetic field. The primary field induces a secondary anomaly field in the earth and both the primary and secondary fields are measured at the receiver coil. The difference in strength of the magnetic fields can be attributed to the electrical property of the earth. This was the method used in this study. In the TDEM technique a time varying electromagnetic field is generated in a transmitter coil by switching an electric current on and off rapidly. This induces eddy currents which penetrate deeper into the earth as the time between pulses is increased. The eddies induce a secondary electrical field which in turn creates an electromotive force that reflects the electrical properties of the subsurface material (Fetter, C.W., 2001).

The electromagnetic survey was carried out by collecting data points every 5m using a 20m separation coil in the vertical mode along the same transect the resistivity survey was conducted.
The instrument used in this survey, EM 34-3 XL (Appendix D, Figure 1D), uses two separate coils (a transmitter and a receiver) along with their respective control units. Conductivity values were directly read from the receiver control unit display and recorded in a field book. The raw data were later transferred to an excel spreadsheet to plot a conductivity curve that showed conductivity variations at a constant exploration depth of 15m along the traverse.

7. **Results/Discussion**

The methodology used in this study provided a means of assessing the accuracy of the results by using more than one geophysical method as recommended for groundwater exploration by most studies. The survey results from the methods employed in this study revealed an anomaly characterized by resistivity values as low as 23.5ohm.m (Figure 3) and conductivity values greater than 100mS/m (Figure 4). This anomaly occurred on the horizontal distance halfway between the 13.5 and 53.5m tick marks along the resistivity survey line, and it is as shallow as 2m deep beneath the ground surface. The anomaly in the electromagnetic survey was located at the same location as described in the resistivity survey. These findings may suggest the location of the fault the study attempted to determine.
Resistivity and conductivity values by themselves are not diagnostic of a particular type of lithology; rather, the spatial variation of values is more important for result interpretations. In both profiles there were significant contrasts between the anomalies and their surrounding earth material. The resistivity model showed highly resistive rock (1229-2711 ohm.m) that surrounds the anomaly. These resistivity values are comparable to those describing the resistivity properties of sandstone in Figure 1.
**Figure 4.** Conductivity curve generated from the EM 34-3XL survey.

The sharp peak followed by an immediate reverse peak depicted in the conductivity curve in Figure 4 is indicative of the presence of a highly conductive body at that location. According to McNeil, (1980) dike-like targets such as water-boring fracture zones produce negative anomalies in the conductivity response. The instrument is programmed such that conductivity values that exceed 700 mS/m are assigned a zero value, and much greater values become negative. The observed low resistivity and high conductivity values in this survey may suggest some degree of mineralization of the water stored in this fracture as described in Figure 1.

The EM 34-3XL instrument operates by slicing the earth at a constant exploration depth, which is governed by the intercoil spacing. The insensitivity of this instrument to near-surface earth material in the horizontal dipole mode, and the exploration depth to which the survey was conducted (15m) minimized the possibility of detecting near-surface objects such as utility pipes.
that are typically placed four feet beneath the ground surface. Nonetheless, further investigations would help determine with certainty the physical nature of the anomaly observed in this study.

8. Conclusion

The application of geophysical methods has significantly enhanced the odds of siting productive water wells in various environmental settings across the globe. Because of the low yield characteristics of the geologic units in the study area, the application of geophysical methods may help locate a zone of enhanced secondary permeability such as a fault. Electrical resistivity and electromagnetic surveys have revealed an anomaly associated with low resistivity and high conductivity values, which is indicative a water-bearing fault. The challenges associated with the methodology employed in this study relate to result interpretations that require site knowledge and critical thinking skills. The successful detection of an anomaly should encourage further study that would focus on mapping the orientation and stretch of the anomaly to the extent possible.
9. References


Appendix A

Non-invasive Geophysical Survey
Gunter Valley, Franklin County PA

Figure 1A. Study area.
Appendix B

Figure 1B. Specific capacity of wells in interfracture area (Lattman and Parizek, 1964).

Figure 2B. Specific capacity of wells on or near a single fracture trace (Lattman and Parizek, 1964).

Figure 3B. Specific capacity of wells on the intersection of two fracture (Lattman and Parizek, 1964).
Appendix C

Figure 1C. Study area topography.
Appendix D

Figure 1D. Study area geology.
Figure 1E. The picture on the left shows the setup of the OhmMapper. Picture on the right shows the setup of the EM 3-3XL.