Characterization of water movement in a reconstructed slope in Keokuk, Iowa, using advanced geophysical techniques

Megan Elizabeth Schettler

University of Iowa

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CHARACTERIZATION OF WATER MOVEMENT IN A
RECONSTRUCTED SLOPE IN KEOKUK, IOWA, USING ADVANCED
GEOPHYSICAL TECHNIQUES

by

Megan Elizabeth Schettler

A thesis submitted in partial fulfillment
of the requirements for the
Master of Science degree in Geoscience
in the Graduate College of
The University of Iowa

May 2013

Thesis Supervisor: Associate Professor Frank Weirich
This is to certify that the Master’s thesis of

Megan Elizabeth Schettler

has been approved by the Examining Committee for the thesis requirement for the Master of Science degree in Geoscience at the May 2013 graduation.

Thesis Committee:

Frank Weirich, Thesis Supervisor

E. Arthur Bettis III

David Campbell
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ABSTRACT

This project addresses the topic of evaluating water movement inside a hillslope using a combination of conventional and advanced geophysical techniques. While slope dynamics have been widely studied, ground water movement in hills is still poorly understood. A combination of piezometers, ground-penetrating radar (GPR), and electrical resistivity (ER) surveys were used in an effort to monitor fluctuations in the subsurface water level in a reengineered slope near Keokuk, Iowa. This information, integrated with rainfall data, formed a picture of rainfall-groundwater response dynamics. There were two hypotheses: 1) that the depth and fluctuation of the water table could be accurately sensed using a combination of monitoring wells, ground-penetrating radar and resistivity surveys; and 2) that the integration of data from the instrumentation array and the geophysical surveys would enable the characterization of water movement in the slope in response to rainfall events. This project also sought to evaluate the utility and limitations of using these techniques in landslide and hydrology studies, advance our understanding of hillslope hydrology, and improve our capacity to better determine when slope failure may occur. Results from monitoring wells, stratigraphy, and resistivity surveys at the study site indicated the presence of a buried swale, channelizing
subsurface storm flow and creating variations in groundwater. Although there was some success in defining hydrologic characteristics and response of the slope using this integrated approach, it was determined that GPR was ultimately not well suited to this site. However, the use of GPR as part of an integrated approach to study hillslope hydrology still appears to hold potential, and future work to further evaluate the applicability and potential of this approach would be warranted.
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### LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>ER</td>
<td>Electrical Resistivity</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GPR</td>
<td>Ground-Penetrating Radar</td>
</tr>
<tr>
<td>NCDC</td>
<td>National Climatic Data Center</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>NRCS</td>
<td>Natural Resources Conservation Service</td>
</tr>
<tr>
<td>NWX</td>
<td>National Weather Service</td>
</tr>
<tr>
<td>PPM</td>
<td>Part Per Million</td>
</tr>
<tr>
<td>PSA</td>
<td>Particle Size Analysis</td>
</tr>
<tr>
<td>PSI</td>
<td>Pound per Square Inch</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>RTK</td>
<td>Real Time Kinematic</td>
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<td>USGS</td>
<td>United States Geological Survey</td>
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CHAPTER I. INTRODUCTION

Despite numerous studies, it remains difficult to understand hillslope hydrology. Instrumenting a hill with an array of monitoring wells can provide good quality results but often a minimal density of wells is chosen in an effort to reduce the expense and time associated with the deployment of a more extensive network of instruments. It may be more efficient to deploy a small array of piezometers, and evaluate the remainder of a slope using geophysical methods such as ground-penetrating radar. Such an approach may provide more accurate and complete information regarding local fluctuations in water level and subsurface topography with much less effort and expense. This thesis seeks to evaluate if the method works, and what operating constraints may apply.

Similar studies have, of course, been performed with integrated instrumentation networks and geophysical surveys (Barla et al., 2010; Méric et al., 2007; Fu and Ding, 1990). However, considerable room for refinement of techniques and applications exists. In order to advance our understanding of slope processes and, in particular, in an effort to better evaluate and characterize the rainfall-groundwater response characteristics of hillslopes, an integrated surface/subsurface hydrologic study was undertaken in a recently failed and reconstructed slope with well-documented structural characteristics and material composition. Specifically, the study evaluated the relative utility of GPR and ER
surveys in locating and characterizing subsurface water flow by using a combination of: a) rainfall monitoring; b) an array of in-situ piezometer wells to continuously monitor local water level changes; and c) several GPR and ER studies, which were calibrated using the piezometer data to develop a reliable slope wide three dimensional mapping of water level fluxes in response to input changes.

The results and methodology used at this site may potentially be applicable on a broader scale to allow us to better understand and study those factors in hillslopes that contribute to slope failures. This will ultimately contribute to advancing the ability to prevent, predict, or mitigate slope failures. If the water table and water table fluctuations can be reliably imaged with the GPR, with limited borehole calibration, this method could potentially substitute for the extensive instrumentation of slopes in a watershed or slide prone area.
CHAPTER II. LITERATURE REVIEW

Understanding the hydrogeology of an area is important to source wells, predict potential contamination paths, and given that water is a major trigger for mass movement (Van Asch et al., 1999), the assessment of slope stability to determine suitability for construction and the prediction of any future motion. In the following discussion the difficulties with hillslope studies, slope stability, common instruments used in hillslope studies, basic types of geophysical studies, and an overview of efforts to integrate these techniques will be reviewed.

2.1. Subsurface Flow

The movement of groundwater through a slope is difficult to predict because it cannot be seen, and because heterogeneities in the subsurface create unseen obstacles which affect flow. Shallow groundwater flow is influenced by topography, slope position, and sediment and bedrock characteristics (Öhrström et al., 2002). Different hillslopes within the same basin will generate runoff at different times, and in different amounts, depending on rainfall amount, intensity, antecedent moisture conditions, and sediment characteristics (Hardie et al., 2011). Additionally, heterogeneities and preferential flow paths can slow, speed, or redirect flow locally (McCaig, 1983; Kung 1990; Weiler and Naef, 2003; Tromp-van Meerveld and McDonnell, 2006). Subsurface water can also percolate
until reaching a relatively impermeable subsurface boundary and flow preferentially along the interface (Graham et al., 2010) and potentially reduce friction along potential slip planes. Despite these heterogeneities, in the interest of simplicity, an area is often assumed to adhere to Darcian flow laws (Knapp, 1974).

In rainfall-surface-subsurface flow studies, it is generally observed that the water table responds more markedly to low intensity, long lasting storms; when the water table is initially shallow; and when the material has a high hydraulic conductivity or is already moist from previous storms (Dunne, 1978).

2.2. Slope Stability

Water, although an important contributor to hillslope failure, is only one of many factors influencing hill stability. Engineers generally examine the balance of forces using the “Factor of Safety” (FoS). This is the ratio of the total shear stress (driving forces) acting on a hill and the total shear strength (resisting forces) of the hill, which produces a numerical value representing the stability or strength of the slope. Hill systems with values near or below one are considered unsafe, while those with values greater than one are considered stable; engineering standards generally require values at or exceeding 1.5.

The Factor of Safety considers any components that either detract from stability or enhance it; for example, it considers pore water pressure, loading,
and slope angle. Failures occur when shear stress overwhelms shear strength. This can happen as a result of natural processes, such as disparate bed permeability; weathering; earthquake shaking; erosion of the toe slope; deposition on the head of the slope causing overloading; or loss of cohesion through vegetation removal (Highland, 2004). Stability can also be influenced by anthropogenic activities, such as overpumping groundwater; removal of vegetation; excavation of the toe slope for various reasons; or the creation of vibrations which can liquefy a slope. Extra stresses on the hillslope are also introduced by loading the top with buildings or introducing water into the soil through broken pipes, leaking swimming pools, etc., which adds weight and decreases cohesion.

Although forces acting upon any one area are constantly changing and are often difficult to quantify, the Factor of Safety is a useful calculation as it forces the consideration and weighing of potential issues in an area. A good overview on slope stability and Factor of Safety is done by the U.S. Army Corps of Engineers (2003) manual on the topic.

### 2.3. Methods of Study

Hillslope subsurface processes can be fairly well monitored by three basic approaches: 1) traditional instrumentation; 2) geophysical methods; and 3) integrated methods. The first two subsections in this section of the review will
cover the most common methods used in hydrogeological and geomorphological studies, while the third is comprised largely of a discussion of case studies.

2.3.1. Traditional Instrumentation Methods

Traditional instrumentation of hillslopes, for the purpose of studying hydrology and stability, typically involves inclinometers, piezometers, tensometers, and rain gauges, each of which will be addressed in turn. These instruments are installed in the ground where they directly measure physical properties of the slope, such as movement, groundwater level, pore pressure, and amount of rain received during storms.

2.3.1.1. Inclinometers

Inclinometers are referred to by many different names, including tilt meter, tilt sensor, slope meter, and clinometer. Inclinometers measure lateral movements in a hillslope, and can also be used to determine the depth to the failure plain (Stark and Choi, 2008). The three general types of inclinometer include probe-type, platform, and in-place or borehole inclinometers. Probe type, or “traversing” inclinometers are small instruments that are inserted into a specially cased borehole. The borehole casing is flexible and will deform in response to hillslope movement, and the inclinometer will read the deformation as angular tilt relative to vertical (gravitational acceleration). Grooves in the casing and guide wheels extending from the probe keep the inclinometer
position steady and consistent relative to the borehole sides through multiple readings (Dunnicliff, 1993). Data for probe-type inclinometers is recorded with a data logger system and collected from the device; when data is taken over time, all of the tilt readings can be converted into horizontal movement and plotted together to produce a displacement profile (Stark and Choi, 2008). The shape of the displacement profile provides insight into the direction, magnitude, and rate of motion of a hillslope, as well as type of failure and depth to the failure plane.

In-place or borehole inclinometers function on the same principles as probes, but are installed permanently in the ground. A borehole is drilled and cased with PVC pipe, and the instrument is inserted and stabilized with sand and cement (García et al., 2010), or wheels extending from the rod to the casing. The instrument itself is a rod-shaped string of inclinometer sensors, which provide signals via cables connected to a data logger (Durham Geo Slope Indicators (DGSI), 2011). Platform inclinometers are also left in-place, and read and transmit data like other in-place inclinometers. They are installed mostly underground on a level concrete platform, and are protected with a hard iron casing (García et al., 2010). Platform inclinometers measure any change in the tilt of the concrete platform they rest on, much like a bubble level. Data can be read automatically by data loggers and transmitted wirelessly via internet or satellite. One data logging system can be used to simultaneously collect data from both
the platform and borehole inclinometers. This can make them more attractive than probe-type inclinometers, as a continuous data stream is provided without a site visit. Resolution can be as high as 0.04 millimeters/meter (DGSI, 2011).

There are comparatively few issues associated with inclinometer function, although the necessary manual handling of probe-type inclinometers can be inconvenient and impractical for more remote sites. In-place inclinometers have the ability to send data remotely, which eliminates much of the issue. However, these inclinometers can only monitor one area on site at a time, so for a larger area, it is less expensive to case several holes and monitor them with all with a single probe-type inclinometer. Stark and Choi (2008) estimate that the horizontal accuracy of most inclinometers is generally plus or minus 7.8 millimeters for every thirty meters of casing, but note that the accuracy can vary depending on sensitivity of the probe and components, the depth of the borehole, and on the amount of readings taken. Many issues with inclinometers have to do with improper use or handling. Boreholes must be drilled to sufficient depth; those that are too shallow will not see the shear zone (Garcia, 2010) and may fail to represent the motion of the entire landslide mass and can lead to misinterpretation about landslide characteristics (Stark and Choi, 2008). Additionally, boreholes that become very deformed by slide motion may no longer be usable for probe-type inclinometers.
2.3.1.2. Piezometers

Piezometers measure the hydraulic gradient at a location, or the height of the water table (total head). Boreholes are drilled and cased with open-ended PVC pipe, forming a well station where the local ground water level can be read by one of several methods. Simple open well piezometers, which are called standpipes or Casagrandes, have a cap or cover that is removed at the time of reading (Dunnicliff, 1993). Depth to water can be measured by a standard or chalked survey tape, an electric dipmeter, or electric water level tape (Dunnicliff, 1993).

Chalked or standard tape or rod measures are fed into the well until the end is below the expected water surface; the foot mark of the tape at the top of the well casing is noted and the tape or rod is pulled up. The wet or chalk-less length of the tape or rod is the amount that was below water, and depth to surface can be found by subtracting this from the total length fed into the well. Electric dipmeters or sounders can also be used. These devices are lowered into the borehole, and an electrical circuit is closed when the dipmeter reaches the surface of the water, allowing a current to move through and signal that the water table has been reached (Trimmer, 2000). Depth is then read from the marked wire. These are also sometimes referred to as electric water level tapes, e-lines, or water level meters. Some of the issues with electric dipmeters mentioned
by Trimmer (2000) are that boreholes will occasionally be drilled crooked or become deformed, which could cause the dipmeter to become stuck or prevent it from reaching the water table.

Another way to find the elevation of the water table is through the use of a pressure gauge or pressure transducer. This device is similar in appearance to the electric dipmeter, but its process is slightly different as it measures the weight (pressure) of overlying water as a proxy for the head. These instruments can be removable or grouted permanently in the well and sealed at the top, and can be installed as a single pressure gauge or with several in the same borehole at different height, called multi-level or multipoint piezometers (Dunnicliff, 1993).

Some of the issues with all piezometer types are that they only collect data on the height of water table at a specific point. It is not guaranteed that this is representative of the water table in the surrounding area. To obtain better results, a dense array of piezometers should be installed on a slope. In some cases, it can also take a long time for the water in the borehole to match the water level in the ground, especially if the material has a low permeability. The first reading should not be taken until the water table has had time to adjust in the piezometer. Benefits of piezometers are they are relatively simple and easy to use.
2.3.1.3. Tensiometers

Tensiometers or tensometers measure pore water pressures in a slope, or how tightly the soil holds onto water (WMO, 2008). The instrument essentially has a ceramic and permeable cup installed in the ground, which allows water to travel back and forth from the soil matrix as water potential increases or decreases (WMO, 2008). Several tensiometers, or even several rows, can be installed around the slope representing different areas, and can be used to measure the pressure at different depths. One study done by Tsaparas et al. (2003) in Singapore used six rows of five tensiometers installed in side-to-side rows covering the slope face. Each measured at a different depth so researchers could compare variation in pore water pressure with depth. Although these instruments can be valuable in hydrology studies, they are more useful for understanding pore pressures, soil properties, and infiltration than they are for groundwater flow.

2.3.1.4. Rain Gauges

Rain gauges, which measure the amount of rain falling in an area during a storm, are fairly common in every-day life. However, when measuring rainfall aspects for research applications, accuracy becomes a concern. There are many considerations to take into account, such as possible evaporation and splashback, the effects of wind on the gauge collection, and measurement of the intensity of
storms in addition to total amount of precipitation (WMO, 2008). The conical funnel on most standard rain gauges, which narrows into the collection tube, reduces evaporation, while a beveled edge around the top removes raindrops that fall outside of the collection area. To reduce the impact of wind on rainfall collection and prevent “under-catch”, some gauges have Nipher shields, which are solid cone shapes situated on the rain funnel, or Alter shields, which are rings of thin vertical strips of metal hanging vertically and deflect the wind (WMO, 2008).

Another important factor in rainfall correlation studies is the storm intensity over time. This is commonly tracked with a tipping bucket rain gauge. This type of gauge contains two small calibrated dippers or “buckets” on either end of a lever which is mounted on a fulcrum. Rain falling into the gauge is funneled to the upper bucket, which, when it reaches the calibrated amount, will dip down in a see-saw motion and empty while the other one fills (WMO, 2008). Each time a bucket fills and tilts, the motion is recorded electronically, with the number of times the bucket tips in a time period indicating the intensity of the rainfall. The weighing rain gauge, which electronically records the change in weight of the rain water over time, also indicates rainfall intensity, although the error increases during heavy rainfalls due to the time it takes for the bucket to tip (WMO, 2008). To reduce this error, a weighing bucket gauge is often used, which
records the weight of the container continuously. This can also provide intensity measurements (WMO, 2008).

The height of the gauge and the proximity to tall objects such as buildings and trees can also affect measurements. The recommended height of the rain gauge affects measurement error and varies by country, but is usually between 0.5 and 1.5 meters (WMO, 2008). Generally, gauges should be placed at a distance from tall objects equal to at least twice the height of that object, but not in the open where wind effects would be greater (Plummer et al., 2003).

2.3.2. Geophysical Methods

With increasing frequency over the last thirty years, researchers and geotechnical engineers have been incorporating geophysical methods such as: seismic reflection and refraction; electrical resistivity; electromagnetic surveys; and GPR surveys into hillslope studies. This has been prompted by an increase in computer power and a refinement in instrumentation, allowing lighter, more easily operable field equipment (Schrott and Sass, 2008). These methods measure physical properties of earth materials such as dielectric constant, density, or conductivity which when interpreted provide information on the depth to subsurface features, changes in material composition, water chemistry, or water content.
Geophysical methods have long been employed in industry to locate gas and minerals (Milson and Eriksen, 2011). They are becoming more frequently used in geomorphology to study landslide geometry and structure, talus slopes, karst landscapes, permafrost and glacial regions, and valley fill, among other things (Götküker et al., 2008; Schrott and Sass, 2008), and are gaining ground as a tool in hydrogeology where they can be used to locate and map aquifers, determine hydrologic properties, sense saltwater intrusion, and in some instances monitor the amount and rate of movement of groundwater and contaminants in an area (Karous et al., 1993).

Geophysical techniques fall into several basic categories, such as seismic reflection and refraction, gravity, magnetic, electrical resistivity, electromagnetics, and ground-penetrating radar (Milson and Eriksen, 2011). Radiometrics, Time Domain Electromagnetics, and wireline logging are also common methods. Gravity and magnetism have an important function in many geophysical surveys, but are more useful for location of large masses than studying small scale hydrology, and will not be discussed here. Likewise radiometrics, which involves reading natural or artificial radiation levels, is less common and will not be covered here.
2.3.2.1. Seismic Surveys

Near-surface seismic surveys function by measuring the amount of time it takes for seismic waves to propagate through subsurface material. A wave is produced using shots from a hammer hit or explosives, or, commonly with large oil companies, a portable crane dropping a heavy weight (Milsom and Eriksen, 2011). The waves move through the subsurface, and either reflect or refract at any interface encountered. The reflecting or refracting waves are picked up by a line of geophones (motion sensors) fixed in the ground at even intervals, and recorded by a seismic recorder or a computer program (Milsom and Eriksen, 2011). The basic principle is that different rock types allow propagation at different speeds, and waves that refract along interfaces will arrive before those that reflect from the interfaces. Surveys are used to find depth, thickness, and tilt of bedrock layers, and they can also provide a very general idea of the sediment or rock type based on velocity.

Seismic reflection surveys record reflected seismic energy. A wave traveling through the subsurface will be partially reflected when it encounters an interface with different wave transmission properties. Huygens’ and Fermat’s principles demonstrate that it will reflect at an angle equal to the angle at which the surface was encountered, called the angle of incidence, if it encounters a planar surface (Burger et al., 2006). This principle is complicated by the imperfect
nature of bedding planes in real life, and data requires intensive processing. Seismic reflection is primarily used to determine the location of a subsurface boundary or interface at depth, particularly in the oil industry (Milsom and Eriksen, 2011)

In seismic refraction surveys, the travel time of the refracted seismic ray is measured. When a wave refracts, it will bend and travel at an adjusted angle; a “critically refracted” wave will travel along the bedding interface. Waves generated by this critically-refracted wave are the first to arrive at geophones located beyond a critical distance from the seismic source. The path and velocity of the energy can be determined by the arrival time and the geophone distance, and the velocity by extension can indicate what material type is present (Haines et al., 2008). These surveys are ideally used to study shallow, gently dipping layers (Milsom and Eriksen, 2011).

Seismic energy propagates as two main types of waves. Longitudinal waves have particle motion in the direction of propagation, while transverse waves have particle motion perpendicular to the direction of propagation. Longitudinal waves move through a material the fastest, and are called primary waves or P-waves (Burger et al., 2006). They are also often called compressional waves based on the type of stress propagated (Haines et al., 2008), which depends on incompressibility and rigiditiy constants for the medium. Transverse
waves move more slowly and are thus termed secondary or S-waves, and are also referred to as shear waves because they respond to the rigidity constant of the material. Other waves occur but are generally treated as ground roll or noise. Surface waves travel only through the surface of the substrate, and because they travel a direct path to the geophones, they are easily distinguished from other types of waves based on their velocity (Burger et al., 2006). Air waves are compressional waves that travel through the air, and are generally the result of the hammer strike or explosion that produced the seismic waves. The acoustic signature of the air wave can show up on geophone data.

Seismic methods measure reflected waves or refracted waves, but they can be further divided into P-wave and S-wave surveys and surface wave analysis. P-waves are generally used for refraction surveys. S-waves can be used as well, although are less commonly used because of their tendency to arrive at a geophone at the same time as the surface waves, making them hard to separate (Steeples, 2001). Techniques are chosen based on site conditions and project goals.

Seismic surveys are one of the most commonly used geophysical techniques. Equipment is easy to use and relatively cheap, and results can be highly accurate. However, the resulting data needs interpretation that requires extensive experience. Moreover, depth of penetration may be low in certain
deposit types, and occasionally the method chosen isn’t appropriate for the particular stratigraphy of the site. Seismic surveys of both types also have the disadvantage of creating physical waves that travel through potentially loose landslide material, so may be unsuitable for use in potentially unstable slopes.

2.3.2.2. Electrical Resistivity

Electrical resistivity or direct current (DC) resistivity surveys measure the collective electrical resistance of the ground, or how much the material resists the flow of electrical currents. A simplified survey apparatus consists of four electrodes, a current source, and a volt reader. Two electrodes inject an electrical current into the ground, which passes through the ground to two spatially separate electrodes, which measure the resulting difference in potential (voltage) (Steeples, 2001). Ohms law, which when rearranged states that the resistance of a conductor (measured in ohms) is equal to the potential difference measured by the electrodes (volts) divided by the value of the current through the conductor (ground; amperes), is then used to find the resistance of the ground (Burger et al., 2006). Since resistance depends on the dimensions of the measured area as well as the material properties, resistance is converted to resistivity (ohm-meters). This is done using a relationship which considers the cross sectional area and the length, which is related to the electrode spacing, and the resistance of the ground (Burger et al., 2006). The resistivity of a material is related to water content,
porosity and chemistry of pore fluids (total dissolved solids), and mineral type. Values vary widely depending on rock or sediment type, which makes them more easily distinguished (Dobecki and Romig, 1985; Haines et al., 2008).

DC resistivity surveys can produce data in two or three dimensions. Two-dimensional surveys are set up as lines with evenly spaced electrodes, and only provide information on what is directly beneath that transect. In three-dimensional surveys, however, electrodes are placed as an array and can measure currents more fully. Typically, the electrodes reading difference in potential are left in place and the electrodes producing the charge are moved around to survey the area.

Resistivity soundings are a variation on this, and can give estimates of the thickness of beds, depth to bedrock, and type of sediment (by resistivity values) in addition to shapes of features (Bevan, 1998). In soundings, electrodes reading difference in potential are fixed and the electrodes producing the charge are moved farther and farther apart. This will produce deeper readings. Alternately, the entire array can be moved repeatedly, either retaining the original spacing and moving all four electrodes some distance away, or by “leapfrogging” the outer electrodes, to survey large areas at the same depth (Bevan, 1998). A newer technique, known as multi-electrode resistivity, resistivity imaging, or electrical resistivity tomography (ERT), allows the operator to plug multiple electrodes-
generally 24, 48, or 72- into the ground at fixed distances. The survey is computer controlled, and the resistivity meter is programmed to automatically switch electrodes in a variety of combinations of transmitters and receiving pairs. This allows for the maximum depth and accuracy (Owen et al., 2006).

There are two common variations on the DC electrical resistivity surveys: induced potential (IP) and streaming (or spontaneous) potential (SP). The IP method essentially measures the subsurface abilities as a capacitor. A charge is applied, then removed, and the “persistence” of the electrical current, called chargeability, is continually measured (Steeples, 2001). The rate of decay is related to material type. The SP method does not require a current to be injected into the ground; it just measures the background electrical signatures created by water movement and biogeochemical factors (collectively called electrochemical activity), as well as noise created from other sources. These surveys largely focus on finding geochemical anomalies, such as contamination plumes (Subsurface Surveys, 2007).

Resistivity is generally used to measure sediment composition, rock type and water content. Materials like clay, silt, shale, and loam tend to have the lowest resistivities, while dry sediment, sand, gravel, limestone and massive igneous or metamorphic rocks tend to have high resistivities (Apex Geoservices
Additionally, water content and salinity can significantly decrease the resistivity of the subsurface.

The advantage of resistivity surveys is that they are the simplest to perform of all geophysical techniques, as the equipment is simple and data may be interpreted using free computer programs. Resistivity is also cheaper to use than other techniques and can be used at most sites, although depending on electrode spacing, can be less precise than methods like seismic reflection (Steeples, 2001).

2.3.2.3. Electromagnetic Surveys

Electromagnetic survey techniques measure the conductivity of the material, which is the reciprocal of resistivity. These are two-loop systems: a transmitter loop produces a current, which generates a secondary magnetic current in the conducting body (subsurface), which is then picked up with a receiver. Some of the most common techniques that utilize waves on the electromagnetic spectrum are GPR, SAR, and TDR.

Benefits of EM surveys are that no contact with the ground is necessary to complete them, meaning that data can be collected on the ground or from the air. Steeples (2001) notes that EM is replacing resistivity in popularity because EM can produce the same data from the air much more quickly, and is relatively cheap. A drawback of these methods is that depth of penetration and resolution
of the data will vary depending on equipment, wave frequency, and conductivity of the ground.

Ground-penetrating radar (GPR) also uses the velocity of electromagnetic waves to make inferences about the subsurface. However, this technique can be distinguished from electromagnetic techniques because it tends to use higher frequency waves; it doesn’t rely on a two-loop system; and it depends on the dielectric constant rather than the conductivity of the subsurface materials. In practice, GPR is similar to the seismic reflection technique, except that it uses electromagnetic waves rather than acoustic waves. A transmitter at the surface produces centimeter- to meter-wavelength pulses, the waves bounce off of structures in the subsurface with different dielectric constants, and the receiver picks up the reflected signals. The travel times can be converted to depth to bedding interfaces.

GPR is especially useful in finding the level of water in the subsurface. It is also commonly used for finding gaps or holes in the subsurface created by pipes or caves, since air and water have very different dielectric constants. However, it is somewhat shallow-penetrating, and its effectiveness is dependent on material type and condition; in dry, sandy material the depth of penetration can reach fifteen meters, but in wet clay-rich deposits it can only see about 1.2 meters, as the waves do not easily penetrate materials with high electrical
conductivities. It is best used in dry deposits that lack clays or other conductors (Steeples, 2001). This limited suitability has prompted the production of maps which distinguish areas that are generally good candidates for GPR survey from those that are generally not (Doolittle et al., 2007). Also, a compromise must often be made between higher resolution and greater depth; a longer wavelength will penetrate farther but will have poorer resolution, while a shorter wavelength will have better resolution but will not see as deeply (Bichler et al., 2004).

Radar surveys can also be performed from the air with Synthetic Aperture Radar (SAR). SAR uses a radar and antenna attached to an aircraft to produce a two dimensional map of the ground surface. It works in essentially the same way as GPR, by measuring the amount of time it takes a transmitted pulse to return. These measurements provide information on the height of the ground surface at multiple points, which produces a picture of the topography. As with GPR, researchers must often choose between resolution and area covered. Newer variations on SAR, called SAR interferometry (InSAR), can produce three-dimensional maps (Machan & Bennett, 2008). Interferometry is essentially the combination of two sources of the same wave type. If ground surface is the same in successive readings, the wave velocity (distance) readings should be the same. Any change in the ground surface will cause the radar waves to go out of phase and interfere with each other. InSAR combines two SAR readings taken over the
same area to look at any changes in topography. A much more exhaustive
discussion of SAR and InSAR techniques is given by Ferretti et al. (2007) of the
European Space Agency.

2.3.2.4. Other

The line between traditional instrumentation techniques and geophysics
can be somewhat subjective, as technology is advancing and more complex
physics are being incorporated into what were once rudimentary instruments.
There is also some debate about where Time Domain Reflectometry (TDR) fits.
For the purposes of this discussion, it will be classified as a type of
electromagnetic survey, and thus a geophysical technique, although it has a
function similar to an inclinometer and is the only necessarily invasive technique
(although several other methods can be modified to work down-borehole).

TDR’s are essentially coaxial cables (insulated conductors) that are
attached to a TDR cable tester at one end. A pulse or current is sent through, and
the waveform is reflected when it encounters a break or bend in the cable. They
were originally designed to locate breaks in electrical cables, but they can also be
used to find the depth of landslide motion when encased in a borehole. If the
hillslope moves, the cable will bend and it will show up as a spike in the data
proportional to the magnitude of the deformation. TDR is often used when
borehole casing is bent by landslide motion and inclinometer probes can no
longer take measurements (Machan & Bennett, 2008), or as a backup in case the inclinometer fails (Eberhardt, 2008). This technology provides accurate information with relatively little effort, although readings are taken on a handheld tester and must be done in the field rather than remotely.

2.3.3. Integrated Data and Examples in the Field

Traditional instrumentation networks and geophysical methods each individually have limitations in the extent or accuracy of the data they provide; the most accurate data can be gained by using a combination of methods on the same slope. The primary advantage of traditional methods is their ability to provide tangible data from inside the hill. In addition, many of these instruments can now read continuously and send data remotely, reducing the amount of field-work necessary. However, the data they provide is only representative of a specific point on the landslide, and does not provide extensive, three-dimensional data. They also must be carefully placed in geologically meaningful areas so they can accurately represent the conditions in the area as well as possible (Angeli et al., 2000).

Geophysical methods may have several advantages. Almost all geophysical methods are or can be noninvasive, and they can map the subsurface in three-dimensions, and can often be adjusted to provide data at higher resolution or more depth. Setup is generally much easier than installing
instrumentation, as in most cases there is no drilling; setup is simply placing geophones or electrodes, or unpacking the machine. More ground can be explored for a lower cost (Bichler et al., 2004). These methods do not have to disturb subsurface materials to gain information about their properties. However, the noninvasive nature of most geophysical techniques means that all data are inferred from measured physical properties of the substrate, and solutions tend to be non-unique. Experience can be a factor in the result. Data can be easily misinterpreted, and second-hand results should be avoided or taken from reliable sources.

The pairing of near-surface geophysics and traditional techniques, or the use of multiple geophysical techniques, seems to offer some distinct advantages. Borehole sediment and rock samples can confirm seismic survey data and piezometer readings can support GPR or electrical resistivity results and vice versa. Geophysical methods increase in accuracy when combined with other monitoring techniques. Also, geophysical methods used together could avoid the common compromise between depth of penetration and high resolution by providing complementary data. This operating style has been proven effective in several cases. Finally, geophysical techniques, when calibrated by actual borehole data, can be used to interpolate between the boreholes.
Barla et al. (2010) used a combination of conventional and geophysical techniques to monitor the Beauregard landslide in Italy. This landslide has a very deep shear plane and has been moving very slowly (millimeters/year) for a long period of time. After the construction of a dam upstream in the 1950’s, it has been investigated and monitored with various instruments including extensometers, inclinometers, and piezometers, simple plumb lines and GPS topographic measurements. These instruments monitored the lower, thinner portion of the mass, and provided an accurate annual displacement profile. However, traditional instrumentation did not provide sufficient information on the conditions at and the head of the slide or near the shear plane.

In 2008, Barla et al. (2010) used a variation of the SAR interferometry, called Ground-Based Interferometric Synthetic Aperture Radar (GBInSAR), on the upper portion of the slide. This technique is an adaptation of the InSAR that is used on the ground, and it can detect very small displacements in vertical or horizontal planes, and provides much more detailed data than a regular GPR survey. By running the GBInSAR frequently for four months, they were able to produce a displacement map of the upper portion of the landslide, which allowed them to infer the landslide mechanism on both portions. GBInSAR monitoring also led to the discovery of a higher-velocity section on the mass.
Méric et al. (2007) also compared geophysical techniques with geotechnical data on the Super Sauze mudslide and the Saint Guillaume rotational slide in France. They applied two-dimensional electrical resistivity and two- and three-dimensional seismic surveys to both. Though the geometry and characteristics of the failure mass differed greatly because they were different types of landslides, they found that they were able to get valuable information about both using these methods. The electrical resistivity produced a good map of the geometry of the mudslide, while a seismic method characterized the failure planes of both the mudslide and landslide. The three-dimensional seismic array data were compared to results of traditional instrumentation including inclinometers and seismic stations, and was found be fairly accurate on the rotational slide, but inefficient on the mudslide.

Bichler et al. (2004) used multiple geophysical techniques to map the Quesnel Forks landslide in British Columbia, Canada. They tested GPR, DC resistivity, and seismic reflection and refraction in the same area. They found that GPR could provide high-resolution data on the upper layers (to about 25 meters or 82 feet) and locate failure planes, while seismic surveys could reach deeper (up to eighty meters, or 262 feet). They found electrical resistivity to be useful for confirming the depth of bed interfaces and failure lines up to forty meters (131 feet). Combined resistivity and seismic velocities through layers
allowed a more accurate interpretation of type of material. The data produced by these methods were tested against stratigraphic and surface maps, as well as digital terrain models to produce a very through, three-dimensional picture of the landslide. They note that none of the methods individually were ideal for that particular area, but using three together provided more detail and less ambiguity in the results.

Fu and Ding (1990) used combined borehole data and electrical resistivity soundings to locate Quaternary aquifers in the Huang-Huai-Hai plains in East China. Evaporation in this area exceeds precipitations, so there is a water shortage and the people who live there therefore rely on groundwater. Over time, the plains have been extensively explored using Shlumberger ER soundings and wells to find promising drill spots, locate the freshwater-saline boundary and determine the amount of freshwater available. Unsaturated rock has a much higher resistivity than freshwater saturated rock, while salinity further decreases resistivity. The authors were able to locate fresh groundwater and delineate saline aquifers, as well as look at the distribution of saline soils. The authors note that using geophysical techniques, they were able to cover much more ground than even the high density well network long in existence in the area (Fu and Ding, 1990).
Though many of these studies employed only one geophysical method, Schrott and Sass (2008) urge researchers to use additional techniques in a study to make solutions more unique and decrease the probability and magnitude of interpretation errors. Surveys which depend on different physical properties, especially, can be an important check. A study conducted by Van Overmeeren (1981) underscores the importance of integrating several geophysical techniques. Van Overmeeren used electrical resistivity profiles to study an area in Sudan, which alone suggested the presence of fresh water in the subsurface. However, once this was supplemented with seismic refraction and borehole measurements, he was able to identify depth to bedrock. From this, he was able to produce a unique solution for both geophysical methods, which showed that the water was in fact saline.

2.3.4. Summary

There is still work to do in understanding the extent of applicability for different geophysical techniques. Although geotechnical instrumentation has been the norm, and allows a good understanding of the hillslope, there are potentially cheaper, faster, and more spatially extensive geophysical techniques that can replace some of the necessity for instrumentation without sacrificing accuracy.
GPR is a relatively fast, simple method to image the subsurface, but it can have calibration issues. Knowing the thickness, geometry, orientation and material properties of subsurface units can go a long way towards the calibration of the GPR data and better prediction of potential flow patterns. If the water table and water table fluctuations can be reliably imaged with the GPR, with limited borehole calibration this method could potentially substitute for extensive instrumentation of slopes in a watershed or slide prone area.
CHAPTER III. METHODOLOGY

This chapter outlines selection and description of the field site and the methods used during the study. This includes the collection and analysis of sediment samples, installation and collection of data from piezometers, the surface elevation survey, the type and use of ground-penetrating radar, and type and use of electrical resistivity.

3.1. Site Selection

The site selected for this study is located on a property in Keokuk, Iowa, on a bluff overlooking the Mississippi River Valley. This particular area is unusual in that it was subject to a large slope failure (1,700 m³ or ~60,000 ft³ area) located in a state not known for significant mass movements. The bedrock in the region is Mississippian-age sandstones and carbonates, with dolomitic limestone lying beneath the site area. Keokuk lies in the extreme southeast corner of the state. In this area, a sequence of loess-mantled weathered pre-Illinoian till and interbedded fluvial deposits buries the bedrock surface.

The majority of the building site itself is flat, but the bluff to the back of the property drops 26 meters (86 feet) over the 70 meters (230 feet) to the river at a slope of 37.5 degrees (76% grade). The home at the site was built on or slightly above a bedrock outcrop, partially on the foundations of a previous building built in 1888 and leveled in 1918 (Weirich, 2011). The steep slope was originally
stabilized (in 1919) with a limestone block retaining wall, which was modified in 1993 with the addition of concrete “buttresses” at the base of the wall, and the addition of several small drain pipes. NRCS-mapped units on the site include the Clinton and the Nordness rock outcrop complex (Figure 1; Web Soil Survey, 2012). The Clinton unit is primarily in the front (southwest) side of the house. It is a moderately well drained silt loam and silty clay loam. The Nordness rock outcrop complex making up the bluff is a well-drained silt loam and silt clay loam with a low water-holding capacity (Web Soil Survey, 2012).

According to an initial survey, there was a somewhat coarser fill material between the house and retaining wall, which was likely added by previous owners to level and extend the back yard (Weirich, 2011). In a GPR profile from the same survey, the bedrock beneath the house dips inward in what appears to be a shallow buried valley or swale (Figure 2), about 7.6 to 9.1 meters (25 to 30 feet) below the surface, which was filled with sediment and alluvium. These data are not corrected for topography, but the transect runs transverse across the hill and the topography does not vary significantly. The exact location of bedrock past the bedrock ledge remains to be determined, but it likely drops off and creates a natural swale which dips downward to the river.

In June 2010, significant overnight subsidence (38 cm in some areas) behind the limestone retaining wall was observed, and in June 2011, despite
efforts to protect the gap from further precipitation, the entire side of the bluff failed (Figure 3; Weirich, 2011), beginning as a rotational slump and turning to a flow downhill. Concurrent with the slump was the catastrophic failure of the retaining wall and the destruction of the patio and part of the residence on the property. Preliminary investigation by Weirich (2011) suggests that failure was due to a combination of: record rainfall in 2010 and 2011; the lack of adequate drainage in the retaining wall coupled with differences in material properties that caused water to be held behind the wall; and the injection of additional water into the hillslope from broken subsurface drains.

An initial hypothesis for the collapse was that there had been ground settlement and infilling of a sinkhole behind the wall. The bedrock underlying the site is dolomitic limestone, which can form karst features, and as a result the possibility of the presence of a sinkhole as a cause of the initial subsidence behind the retaining wall was suggested. However, sinkholes are not common in the area, and the linear scarp produced along the retaining wall in June 2011 was not characteristic of a sinkhole. A GPR survey also did not support the presence of karst sinkholes in the bedrock (Weirich, 2011). After the catastrophic failure, the area was somewhat stabilized by: a) a slight decrease in slope angle; b) by addition of material to the toe slope; and c) by the addition of a terrace and rip-rap on the upper portion of the hill. Despite these measures, the surface shows
the development of new cracks and deep holes, and is prone to rill erosion despite lush vegetation growth (Figure 4).

This site was chosen to study hillslope rainfall-response interactions, to test the utility of GPR, and to provide information on the interactions that may have led to the collapse of the bluff. This site’s location and history also makes it useful for the broader study of hillslope hydrology and the evaluation of the utility of various geophysical techniques. It also is of interest as a case study.

3.2. General Methodology

The methodology chosen for this study was based in part on a review of existing literature and in part on availability of equipment. It was decided to conduct several surveys using GPR, which is particularly suitable for distinguishing changes in material saturation (Karous et al., 1993). It was decided to undertake a resistivity survey both to complement and supplement the GPR data since unlike the GPR approach, the resistivity survey would be functional in highly conductive materials. Traditional instrumentation at the site consists of a network of piezometers, a barometer, and a rain gauge.

3.2.1. Piezometer Installation

An array of ten piezometers was installed on the hill in a field-adaptive grid. Seven of these wells were hand-drilled with a 7.62 centimeter (three inch) diameter auger (Figure 5), while three on a more stable and relatively flat upper
portion of the site were bored by a drill rig. Depths range from one to about 7.4 meters (3.3 to 24 feet), and were limited by encountering bedrock or a subsurface obstruction (Table 1). The wells were cased with five centimeter (two inch) diameter plastic PVC piping, the lower 1.5 meter (five foot) section of which was slotted. This section was wrapped in permeable commercial-grade landscape fabric to prevent silting. The lower portion of the well was threaded with a cone-shaped extension which was driven into the bottom of the borehole. The outside was then packed with sand and bentonite, and then fitted with pressure transducers.

The pressure transducers were suspended by a thin coated stainless steel cable into the well (Figure 5), and collected data in 15-minute intervals. Initially, two different transducer types were used on site. A Solinst Levelogger LT F15/M4, model 3001, (by Schlumberger) recorded time, pressure, and water temperature. These loggers automatically compensate for pressure differences due to variations in water temperature, and according to the Solinst Website (2013), are accurate between zero and forty degrees C and 0.1% FS (full scale). This specific model has a full scale pressure range of five meters or less. The second type of transducer deployed was the Rugged TROLL 100 by In-Situ Inc. The Rugged TROLL 100 is accurate between zero to fifty degrees C and to 0.3% FS. This transducer was chosen because it records temperature in addition to
pressure, and has a range of 0 to 9.1 meters (In-Situ Inc, 2013). Both models connect and download to a laptop via a USB docking station. Eventually, all of the Solinst transducers were replaced by the Rugged TROLL 100 units due to unreliability of several of the Solinst units. This switch to a single type and model provided the additional benefit of increased ease of analysis and increased reliability.

As both of these transducer models need to be manually corrected for barometric pressure, a Rugged BaroTROLL was also installed at the site. It collected barometric information at fifteen minute intervals. Atmospheric and borehole pressures were recorded in pounds per square inch (psi). Readings were automatically adjusted for pressure changes due to water temperature, and atmospheric pressure was subtracted from the remaining value. This pressure was converted to feet of overlying water by the relationship 1 psi pressure is equal to 0.7043 meters (2.3106 feet) of head at 68\(^{\circ}\) F; pressure increases by about 0.42197 psi per 0.3 meters (1 foot) in fresh water. To get water table elevation, depth below surface was calculated by subtracting the depth of overlying water from the total measured depth of the well (discounting any “stickup”, or piping protruding above the ground surface), and then this value was subtracted from the elevation of that well at the surface.
3.2.2. Precipitation data

Precipitation data were retrieved from Weather Source, LLC (2013), which compiles historical precipitation data from government sources including the NOAA, NCDC, and NWS (National Weather Service). Data were recorded at Keokuk Lock and Dam 19, which is located on the river about 1.2 km from the field site, and has daily recorded precipitation values. Integration of pressure transducer data and rainfall records showed areas of the subsurface with heavy response to rainfall events.

3.2.3. Sediment Tests

Results from the Web Soil Survey are not meant to be accurate on smaller scales, and do not cover any underlying stratigraphy. Three 7.6-centimeter (three-inch) diameter core samples were taken via drill rig from boreholes 1, 2, and 3 (refer to Figure 6) to get a basic idea of sediment composition, and monitor for any dramatic changes. The steepness of the hill created issues with obtaining additional samples from other locations on the hill. Such additional samples would have otherwise been helpful given the complex history of the hillslope and the obvious heterogeneity.

A particle size analysis (PSA) was performed in the Department of Geoscience Quaternary Materials Laboratory on each distinct material retrieved
from the cores using the pipette method to determine the relative proportions of clay, silt, and sand textures, as outlined in the unpublished Quaternary Materials lab procedures on the University of Iowa Campus. Samples from each of the well cores were dried and ground, and the fine earth fraction (sand size or less) were separated from any pebbles with a two millimeter sieve. Organics were chemically removed with H$_2$O$_2$, and a dispersant (sodium hexametaphosphate) was added to deflocculate the clays and separate them from the silts and sands (using hydrogen peroxide), and finally acetic acid was added to remove carbonates. Samples were then boiled, refilled to the initial volume and shaken overnight on a reciprocating shaker to disperse the sample.

Dispersed samples were then added to a large (1000 mL) graduated cylinder and diluted with RO water, and agitated. Aliquots were pipetted from each cylinder (Figure 7) at intervals determined by a settling velocity chart and placed in beakers. The mixture remaining after silt and clay samples were obtained was poured through a 63 micron sieve to isolate the portion of the sample which was sand. The liquid was then evaporated and weighed, and the relative proportions of sand, silt, and clay were determined using by comparing net sample weights with the total net weight.

To ensure lab accuracy and consistency, samples were run with a loess standard. Wait times after stirring were based on Stokes’ law, which can be
solved to find the settling velocity of a particle based on their radii. This law is in part a function of fluid viscosity, which changes in response to the ambient temperature, so settling times were recalculated during each session based on a room thermometer.

3.2.4. Ground-Penetrating Radar

Instrument data were integrated with the information gained from several GPR and electrical resistivity surveys conducted through the field season. These particular geophysical techniques detect differences in the electrical properties of saturated and unsaturated sediments (Jongmans & Garambois, 2007; Dobecki & Romig, 1985), and one of the interfaces between them represents the water table. GPR surveys were undertaken on July 8th, September 10th, and October 12th.

A MALÅ Professional Explorer multichannel GPR system was used to collect high resolution data. The available system had antenna frequencies of 250, 500, 800 MHz, and 2.3 GHz, which are well suited for shallow surveys. In this study, four multi-line surveys were done; three using the 250 MHz antenna and one using the 500 MHz antenna. A mobile set-up was constructed on a sled consisting of the antenna, battery unit, and a laptop (Figure 8). This unit was dragged vertically and horizontally over the hillslope in a field adaptive grid (Figure 9); survey lines ranged between 7.6 and 39.9 meters in length. Grid transects closely followed piezometer lines when possible to allow for accurate
calibration via transducer data collection data. The computer was reset at the end of each line, to produce eight to twelve discrete radargrams. End points were marked for a later elevation survey.

Field accuracy was ensured by stacking eight readings per measurement. Antenna separation (between transmitter and receiver) was 0.36 meters for the 250 MHz antenna and 0.18 meters for the 500 MHz. Sampling frequency was 3,686.08 MHz. Transect length and location was measured using a 273 millimeter diameter master wheel.

Data collected by the GPR were then transferred to a software program to produce the subsurface maps. This project used GroundVision™ software, which deals with acquisition, filtering, and printing images of the two-dimensional transect lines, and RadExplorer Software produced by MALÅ, which is used to process 2-D GPR data and produce subsurface models.

Processing involves applying several different filters to the radargram to clarify and enhance reflections. The filters used on this data were: DC Removal; Time Zero Adjustment; Background Removal; Amplitude Correction (with Spherical Divergence Correction or Trace Equalization), and Bandpass Filtering. DC Removal removes the average value of each sample or “trace”. Time Adjustment adjusts the top of the radargram to the time when the wave has actually left the antenna, cutting out any empty space visible on the top of the
radargram, and corrects for the distance between the receiver and transmitter. Background removal is intended to remove excess noise from the radargram by subtracting a constant portion of each trace. However, this can be a problematic filter, because it can also remove actual boundary reflections. Amplitude correction allows for “gain correction”, the manipulation of the magnitude of the trace in certain areas down its length; Spherical Divergence Correction and Trace Equalization are two versions of this filter, the first of which enhances the amplitude of the wave front, and the second of which minimizes variations in amplitude between traces. Finally, Bandpass Filtering increases the signal-to-noise ratio by removing high or low frequencies as dictated, which may be noise. After filtering the data, “picks”, or reflections interpreted to indicate a boundary, are made based on the processed data.

3.2.5. Electrical Resistivity

Several electrical resistivity (ER) surveys were conducted to supplement GPR survey results. Measurements were made using the IRIS SYSCAL Pro Switch 96 DC electrical resistivity system (IRIS Instruments, Orleans, France) between September 28th and October 15th. Four 2-D electrical resistivity profiles were collected perpendicular to the slope using a line of 48 stainless steel electrodes with a diameter of 1.3 centimeters. The electrodes were driven approximately thirty centimeters into the ground, oriented normal to the slope.
surface, and spaced at even intervals based on the length of the survey line (spacing of 35.6 centimeters for line 1, 30.5 centimeters for lines 2 and 3, and 30.5 centimeters for line 4). The electrodes were then connected to each other and the Syscal unit via multi-core cables and alligator clips (Figure 10). The locations of electrodes were flagged during collection and later surveyed.

Data were collected using a mixed array method, in which electrodes were combined into a variety of geometric configurations to make observations of voltage field potential given a fixed current injected into the subsurface. 1,559 data points were collected for each of the four lines, which were downloaded from the IRIS box to laptop via a USB connection and imported to Prosys II collection software.

Data quality were assessed based on the standard deviation of each reading, the voltage of current introduced to the charge, and a positive voltage potential reading. Each voltage potential observation was stacked, or averaged, with at least one additional measurement, and up to four total if the standard deviation of their average was greater than two percent. Any data points with standard deviations exceeding this percentage following three stacks were repeated.

Data were processed using resistivity inversion freeware, available at the Lancaster University Environment Centre webpage (Binley, 2013). This “Occam’s
type” inversion code statistically regularizes data using an objective function which indicates how much each variable contributes to the solution, and uses a weighted least squares regression to assign values more or less weight based on their precision. This collectively “smooths” errors arising from ill-conditioning (where small data errors create large errors in the model) and non-unique solutions as long as the dampening factor applied is large enough (Loke and Barker, 1995). Initially, all data were assigned equal weight, and were then reduced accordingly in individual datum for further processing.

The solution used an inversion mesh for 2-D current flow of ten centimeters by ten centimeters for the area encompassed by each transect, which was extended beyond the transect borders and below the surface to show boundary conditions.

Absolute model error in the field data was assumed to be 0.001 Ohm, and relative error was assumed to be two percent of the resistance value. All datum had resistivities with a magnitude of less than 10,000 Ohm-meters, an arbitrary value above which values are considered noise, and were included in the inversion.

Sensitivity matrices were also calculated based on inversion data, which measures how well the instrument detected changes in subsurface properties.
Higher values indicate that the electrodes were more sensitive to changes, while lower values indicate the electrodes were less sensitive to change.

3.2.6. RTK Survey

An elevation survey of the hillslope was also completed using a Trimble R8 Global Navigation Satellite System (GNSS). This was necessary to correct GPR and ER data for topography, since both measure subsurface depths with reference to surface, and for the purpose of making an accurate site map. This is a 440 channel system comprised of a base and a rover (Figure 11). The base was set up using a survey pin at the corner of the property. The rover was on a bubble-leveled tripod and sent results to a Trimble TSC2 data collector, which exported to laptop via a USB connection at the conclusion of the survey. Elevation data points were taken at each well and along ER and GPR survey lines.

According to the Trimble R8 data page on the Trimble company website (Trimble, 2013), when conducting real time kinematic surveys the base receiver is accurate to eight millimeters plus one ppm RMS horizontally and fifteen millimeters plus one ppm RMS vertically, with a measurement precision of less than one millimeter.
Figure 1: Results of the NRCS Web Soil Survey (2012) at the site. The property is outlined in yellow; the soil mapping units are separated by an orange line and include the Nordness rock outcrop complex (478G) to the right and Clinton silt loam (80B) to the left.

Figure 2: Raw GPR data taken along a transect going from NW (beginning at left) to SE (right). Not corrected for topography. After Weirich (2011).
Figure 3: Pictures of the portion of the property near the bluff after modest subsidence in July 2010 (left), and after failure in July 2011 (right). The red arrow marks the same location in each picture.

Figure 4: Picture of the site in the late summer 2012, after reconstruction and the emplacement of instrumentation.
Figure 5: Manual installation of well 7 (left) and one of the Rugged TROLL 100 pressure transducers that were installed in the wells (right). Transducers were suspended using insulated stainless steel cable.

<table>
<thead>
<tr>
<th>Location</th>
<th>Well Depth (m)</th>
<th>Well Depth (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well 1</td>
<td>6.3</td>
<td>20.5</td>
</tr>
<tr>
<td>Well 2</td>
<td>7.1</td>
<td>23.2</td>
</tr>
<tr>
<td>Well 3</td>
<td>7.4</td>
<td>24.3</td>
</tr>
<tr>
<td>Well 4</td>
<td>2.0</td>
<td>6.6</td>
</tr>
<tr>
<td>Well 5</td>
<td>4.2</td>
<td>13.8</td>
</tr>
<tr>
<td>Well 6</td>
<td>1.6</td>
<td>5.1</td>
</tr>
<tr>
<td>Well 7</td>
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<td>21.8</td>
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<tr>
<td>Well 8</td>
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<td>8.0</td>
</tr>
<tr>
<td>Well 9</td>
<td>1.6</td>
<td>5.3</td>
</tr>
<tr>
<td>Well 10</td>
<td>1.0</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Table 1: Total well depth from surface.
Figure 6: Map of the site indicating the location of wells (red dots) and resistivity profile lines (in yellow). Coordinates were taken from an RTK elevation survey and overlaid on a Google Earth™ image. Wells are labeled from well 1 to well 10 and named consistently throughout the text, and ER profiles are line 1 to line 4, and are also named consistently. The approximate location of the GPR line from Figure 2 is shown by a red dashed line.
Figure 7: Particle Size Analysis using the pipette method. As part of the procedure, samples were boiled for several hours to remove organics and excess liquid (left) before being transferred to a 1000 mL graduated cylinder for pipetting.

Figure 8: GPR field equipment set up. To adapt to the steep terrain and rough ground surface, the antenna, receiver, and laptop were secured to a sled which was pulled and stabilized using ropes.
Figure 9: General GPR survey lines followed during July 8th, September 10th, and October 12th surveys. Well locations relative to the GPR survey lines are numbered and indicated by the red dots (see Figure 6).
Figure 10: Resistivity profiling equipment and setup. At left is a down-line view of line 4, which is oriented lateral to the slope (see Figure 6), with excess cable looped; electrodes were connected to the multi-core cable with alligator clips (top right); and then to the Syscal unit (bottom right).

Figure 11: RTK base station setup (left) and rover equipment (right).
CHAPTER IV. RESULTS AND DISCUSSION

This chapter outlines and discusses the results of the study. Specifically: rainfall vs. well data; sediment characteristics; GPR findings; and results of the ER survey.

4.1. Integrated Transducer & Rainfall Data

Several significant storms occurred throughout the monitoring period (Figure 12). The response of the water table in the wells are shown in Figures 13-22; gaps indicate bad data points or nonworking transducers, and anomalously low data points represent periods where the transducers were pulled for reading. Wells 1 and 2 (Figures 13 and 14) responded dramatically to rainfall events, with water elevation increasing as much as 1.8 to 2.4 meters (six or eight feet) over a three day period at times. Wells 6, 7, and 9 (Figures 18, 19, and 21) responded markedly as well, increasing 0.9 to 1.2 meters (three to four feet) in elevation. In contrast, wells 3 and 4 (Figures 15 and 16) showed no response to precipitation events, and remained at a relatively constant elevation throughout the monitoring period even after a relatively large rainfall. The remainder of the wells (5, 8, and 10; Figures 17, 20, and 22) showed small storm responses to precipitation events of about 0.3 meters (one foot).

Variation in response can be summarized statistically using the standard deviation from the average individual well elevation, or the range of the well.
Wells 1 and 2 had ranges of 0.29 and 0.52 meters, respectively. Wells 6, 7, and 9 had values of 0.24, 0.18 and 0.47 meters. Wells 3 and 4 had ranges of 0.08 and 0.13 meters, respectively, while wells 5, 8, and 10 had ranges of 0.17, 0.23, and 0.16 meters.

It should be noted that some early season data from certain wells were not considered, as the Solinst instruments experienced technical failure and were replaced eventually by In-Situ transducers, which had the additional benefit of allowing more uniform data collection and processing.

4.2. Sediment Tests

The results of the PSA (Table 2 and Figure 23) showed a texture ranging from silt loam to sandy clay loam at the site. On a transverse plane across the hillslope, the boreholes showed a consistent sequence but varied in thickness (Figure 24). The core from well 1, to the south, was comprised of 2.4 meters (eight feet) of rubbly silty clay loam fill with mixed limestone debris; 2.1 meters (seven feet) of loess with a loam texture, overlying a loamy glacial till to the base of the hole at seven meters (23 feet). The second core, from well 2, had the same layer of rubbly fill (1.8 meters) burying a truncated silt loam loess unit on top (1.2 meters) over a silty clay loam Farmland soil (0.8 meters) and silty clay Sangamon (0.8 meters) Geosol, developed in till loam with intermittent sand layers to the base of the well at 8.2 meters (27 feet). The third core, from well 3, showed about 0.6
meters (two feet) of fill, 0.9 meters of truncated loess (three feet; silty clay loam),
the silty clay Farmdale soil (0.46 meters) and the clay loam Sangamon Geosol
(0.6 meters), developed in sandy clay loam till with intermittent sand lenses until
reaching a hard layer at 7.6 meters (25 feet) which is potentially the dolomitic
limestone bedrock, although no chips were brought up. The elevation of each of
these drill sites is roughly the same at about 196 meters (645 feet). This
stratigraphy shows a slight subsurface rise in the units to the north of the
property.

The high electrical conductivity values of silts and clays can be expected to
cause rapid signal attenuation for the ground-penetrating radar, causing
somewhat shallow depth of penetration, but should still allow sufficient depth to
locate the water table. The high conductivity, by contrast, should increase the
effectiveness and accuracy of electrical resistivity surveys.

4.3. Ground-Penetrating Radar

The characterization of the sediment allowed estimation of the probable
dielectric constant of the average material type, which was used to calibrate GPR
data. Loamy sediment, on average, will have a dielectric constant of four to six if
dry, and ten to twenty if wet (Table 3; Cassidy, 2009). Given the relative
similarity in the dielectric constant of the units, the largest reflection on the
radargram was assumed to be the boundary between the saturated and
unsaturated zones. The dielectric constant value was used to calculate the wave velocity from the 250 and 500 MHz antenna through the subsurface, and converted to a depth over time graph. Head measurements gained from the piezometers were substituted in for depth to determine what “time” (Y axis value) on the radargram the water table should be reached. Due to the rapid attenuation of the signal from the 500 MHz antenna, depth of penetration was found to be not sufficient to be useful and in the end, this survey data was not used. Resolution with a dielectric constant of five, using an antenna frequency of 250 MHz, is about 13.4 centimeters. Resolution below the water table improves to about 7.8 centimeters.

Some issues that came up during the data processing phase were the presence of “noise” near the surface and at around 115 nanoseconds depth. The level of noise at the surface, in part, is related to the smoothness of the surfaces the GPR is traversing. The large amount of noise in this case is likely due to the rough surface terrain at the site. It was noted that this caused the GPR to rock back and forth and side to side, causing crossed signals near the surface. The noise at 115 nanoseconds appears to be an error in the GPR collection software or an issue with the 250 MHz antenna, and is present at the same spot when used in different geographic locations. Given its depth compared to the expected depth of the reflections in this study, it was not considered to impact the results.
Selected radargrams from the July survey are presented in Figures 25 and 26. Figures 27 and 28 show September surveys, and Figures 29 and 30 are from the October survey. These were chosen based on the proximity of the survey line to wells which would allow accuracy checks. Despite multiple processing angles, the radargrams from the GPR survey did not lend themselves to simple corroboration with piezometer records.

Extrapolating signal arrival time at the water table using normal dielectric constant values or velocity estimates for the material, a method discussed by Vasudeo et al. (2009), disagreed with the picks which were selected as representing a subsurface boundary; in this case, the water table. Since the material at the site was generally loamy with a clay and silt component, the dielectric constant of the material should be between four and sixteen (Table 3). Groundwater depth below surface was taken from the wells at either end of the GPR line and used to calculate the two way travel time of the signal. Since

\[ \text{velocity} = \frac{c}{\sqrt{\varepsilon}}, \]  

with C being the speed of light in a vacuum, and \[ \text{distance} = \frac{tv}{2}, \]  

two-way travel = \[ \frac{2d\sqrt{\varepsilon}}{c} \]. Travel time was calculated with the upper, lower, and middle potential dielectric constant values, and these were then compared to the radargram for a reflection at this depth. No reflections were found for the calculated depths for any of the radargrams, and the picks were well above the value calculated for even the lowest dielectric constant.
Likewise, adjusting the dielectric constant to match the travel time displayed by picks produced values far outside of the normal, or even reasonable, range (Vasudeo et al., 2009). This method was used on the assumption that subsurface properties were variable (i.e. the dielectric constant changes in different areas) due to the slope failure. The equations were rearranged to solve for $\varepsilon$, with the two way travel time (from picks) and the depth (from the wells at either end of the line) known. Values ranged from 95 to less than one. This suggests that the GPR is not reliably locating the water table at this site.

The lack of agreement between the GPR based picks and the measured water table level could be a combination of variable subsurface properties due to the landslide and variations in water content. Likewise, clay content could be causing severe signal attenuation, although a significant impact would have been recognized during the well calibration procedure. The more likely possibility is that the clay component created a thick capillary fringe such that the change between the saturated and unsaturated zones was too gradual to cause a clear reflection. For two interfaces to be clearly distinguished, the boundary has to be about $\frac{1}{4}\lambda$ in thickness or less, according to the Rayleigh Criterion. Since $\lambda = \frac{V}{f} = \frac{12.23 \text{ cm/ns}}{250 \text{ MHz}}$, and assuming a dielectric constant of six, $velocity = \frac{C}{\sqrt{\varepsilon}} = \frac{30 \text{ cm/ns}}{\sqrt{6}} = 12.23$. 
centimeters/nanosecond, and \( \lambda = \frac{V}{f} = \frac{1.223 \, cm/ns}{250 \, MHz} = 0.49 \) meters, or 49 centimeters.

The theoretical resolution of the 250 MHz antenna is then about twelve centimeters, a value which decreases with an increasing dielectric constant. In clayey materials, however, the capillary fringe can be between 25 and 60 centimeters thick (Mausbach, 1992), exceeding this calculated antenna resolution. That this may be the case in this area is supported by the presence of redoximorphic features in the materials near the surface, which suggest that even the materials well above the water table are saturated for significant periods of time during the year. In this case, the picks are likely false reflections or enhanced noise introduced in processing.

Reflections from the bedrock were not seen, either, possibly because of rapid attenuation of the radar signal, or because of the similarity in the dielectric constant range for both saturated bedrock (limestone) and saturated sediment (loam) at the site (Table 3), which would not create a clear reflection. The reflection was seen while the retaining wall was still up likely because an aquitard separated the bedrock and the thick fill behind the wall, causing an abrupt change in physical properties and producing a clear reflection.

4.4. Electrical Resistivity

Results of data inversion are subsurface maps showing areas of high and low electrical resistivity, based on the best-fit solution (Figure 31). It was found
that average stacking error, which is an indication of the repeatability of measurement on subsequent stacks, was 0.13 percent for lines 1 and 3, 0.10 percent for line 2, and 0.18 percent for line 4. The final root mean square error value, which is a measure of how well the model fit the data, was 1.00 (1 percent) for lines 1 and 3, 1.13 percent for line 2, and 1.03 percent for line 4.

Line 1 ran from well 3 to well 1 at the top of the slope, covering a horizontal distance of about 22 meters and reaching three meters depth. Results of the data inversion reveals relatively minor but spatially frequent variations in resistivity throughout the subsurface. This variation of about 3.16 Ohm-meters could be caused by differences in lithology or areas that are retaining more moisture; the complex history and heterogeneity of the upper slope prevents further accurate interpretation.

Line 2 ran about 15 meters from well 4 to well 6, on the upper mid-slope. This area of the slope showed larger variations in resistivity, with values of around 31.6 Ohm-meters around the edges, and a low resistivity (3.16 Ohm-meters) pocket in the center.

Line 3 and 4 were completed on a different field day, soon after a rainfall event, which was an ideal condition for this type of survey. Line 3 was set up over about fifteen meters, from a point south of well 7 to well 8 on the lower-mid
slope. The subsurface, similar to line 2, has a generally lower-resistivity center (~5.62 Ohm-meters) with higher-resistivity edges (~31.62 Ohm-meters).

Line 4 was set up from well 9 to a point on the north side of the hill, and covered about eighteen meters. The resistivity image shows more variable subsurface properties; much of the line has moderate resistivity values of around 31.62 Ohm-meters, while the area near well 9 and in the center of the hill has very high resistivity values. Sensitivity of all four lines was highest near the surface and center of the data collection area, and decreased with depth and towards the edges (Figure 32).

Electrical resistivity readings can be affected by material type, degree of compaction, total fluid content, temperature, and fluid chemistry. Information gained from borehole samples and piezometer data suggest that areas of low resistivity at this site are the result of a higher clay or water content. It should be noted that these survey lines are two-dimensional, and it cannot be inferred whether areas of low or high resistivity extend continuously through the hillslope as a feature, or whether they just represent conditions in the immediate subsurface.
Figure 12: Daily precipitation values for the study period (between July 2nd, 2012 and February 12, 2013), from the weather station at Keokuk Lock and Dam 19. Data was retrieved through Weather Source, Co. (2013). For reference, GPR surveys were taken on July 8th, September 10th, and October 12th, and resistivity surveys were completed on September 28th and October 15th.
Figure 13. Well 1 seasonal water table fluctuations (black line), shown with precipitation (grey line) and the total well depth (dotted line).

Figure 14. Well 2 seasonal water table fluctuations (black line), shown with precipitation (grey line) and the total well depth (dotted line).
Figure 15. Well 3 seasonal water table fluctuations (black line), shown with precipitation (grey line) and the total well depth (dotted line).

Figure 16. Well 4 seasonal water table fluctuations (black line), shown with precipitation (grey line) and the total well depth (dotted line).
Figure 17. Well 5 seasonal water table fluctuations (black line), shown with precipitation (grey line) and the total well depth (dotted line).

Figure 18. Well 6 seasonal water table fluctuations (black line), shown with precipitation (grey line) and the total well depth (dotted line).
Figure 19. Well 7 seasonal water table fluctuations (black line), shown with precipitation (grey line) and the total well depth (dotted line).

Figure 20. Well 8 seasonal water table fluctuations (black line), shown with precipitation (grey line) and the total well depth (dotted line).
Figure 21. Well 9 seasonal water table fluctuations (black line), shown with precipitation (grey line) and the total well depth (dotted line).

Figure 22. Well 10 seasonal water table fluctuations (black line), shown with precipitation (grey line) and the total well depth (dotted line).
<table>
<thead>
<tr>
<th>Origin</th>
<th>Sample</th>
<th>Sand %</th>
<th>Silt %</th>
<th>Clay %</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well 1</td>
<td>Fill</td>
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<td>68.0</td>
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<tr>
<td></td>
<td>Loess</td>
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<td>21.9</td>
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</tr>
<tr>
<td></td>
<td>Till</td>
<td>48.1</td>
<td>40.9</td>
<td>11.1</td>
<td>Loam</td>
</tr>
<tr>
<td>Well 2</td>
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<td>Farmdale</td>
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<td>44.6</td>
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</tr>
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<td>3.5</td>
<td>79.5</td>
<td>17.0</td>
<td>Silt loam</td>
</tr>
</tbody>
</table>

Table 2. Sediment textures were analyzed using the PSA pipette method.
Figure 23. Sediment textures were classified using a U.S. Soil Texture Triangle at the U.S. Department of Agriculture NRCS site. Sample textures from well 1 are represented by green dots; those from well 2 are red; well 3 samples are yellow; and the loess standard is in black. After USDA (2013).
Figure 24. Simple stratigraphic column showing the approximate depth and location of each unit.
<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric Constant ($\varepsilon$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
</tr>
<tr>
<td>Clay – dry</td>
<td>2–20</td>
</tr>
<tr>
<td>Clay – wet</td>
<td>15–40</td>
</tr>
<tr>
<td>Concrete – dry</td>
<td>4–10</td>
</tr>
<tr>
<td>Concrete – wet</td>
<td>10–20</td>
</tr>
<tr>
<td>Freshwater</td>
<td>78 (25 °C)–88</td>
</tr>
<tr>
<td>Freshwater ice</td>
<td>3</td>
</tr>
<tr>
<td>Seawater</td>
<td>81–88</td>
</tr>
<tr>
<td>Seawater ice</td>
<td>4–8</td>
</tr>
<tr>
<td>Permafrost</td>
<td>2–8</td>
</tr>
<tr>
<td>Granite – dry</td>
<td>5–8</td>
</tr>
<tr>
<td>Granite – fractured and wet</td>
<td>5–15</td>
</tr>
<tr>
<td>Limestone – dry</td>
<td>4–8</td>
</tr>
<tr>
<td>Limestone – wet</td>
<td>6–15</td>
</tr>
<tr>
<td>Sandstone – dry</td>
<td>4–7</td>
</tr>
<tr>
<td>Sandstone – wet</td>
<td>5–15</td>
</tr>
<tr>
<td>Shale – saturated</td>
<td>6–9</td>
</tr>
<tr>
<td>Sand – dry</td>
<td>3–6</td>
</tr>
<tr>
<td>Sand – wet</td>
<td>10–30</td>
</tr>
<tr>
<td>Sand – coastal, dry</td>
<td>5–10</td>
</tr>
<tr>
<td>Soil – sandy, dry</td>
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<td>Soil – loamy, dry</td>
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<td>Soil – loamy, wet</td>
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<td>Soil – clayey, dry</td>
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<td>Soil – clayey, wet</td>
<td>10–15</td>
</tr>
<tr>
<td>Soil – average</td>
<td>16</td>
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</tbody>
</table>

Table 3: Dielectric constant ranges of common earth materials. After Cassidy (2009).
Figure 25: Processed radargram from the July 8th survey. This was taken downslope, passing by wells 1 and 7. Well locations are indicated.

Figure 26: Processed radargram from the July 8th survey. This was a cross-slope survey line, passing by wells 3 and 1. Well locations are indicated.
Figure 27: Processed radargram from the September 10\textsuperscript{th} survey. This was taken upslope, passing by wells 7 and 1. Well locations are indicated.

Figure 28: Processed radargram from the September 10\textsuperscript{th} survey. This survey line was cross-slope, passing by wells 3 and 1. Well locations are indicated.
Figure 29: Processed radargram from the October 12\textsuperscript{th} survey. This was taken upslope, passing by wells 7 and 1. Well locations are indicated.

Figure 30: Processed radargram from the October 12\textsuperscript{th} survey. This was taken cross-slope, passing by wells 4 and 6. Well locations are indicated.
Figure 31: Results of the resistivity survey, expressed as the log of the resistivity value, for lines 1, 2, 3, and 4 respectively. The Y axis to the left indicates elevation, and the right axis displays the log resistivity scale bar (where resistivity = $10^8$) alongside actual resistivity values. Red represents areas with higher resistivity values, while green and blue values represent areas with relatively low resistivity values. Approximate well locations along the line are indicated; note that lines 3 and 4 are oriented backwards compared to their actual hillslope position, due to the location of the resistivity meter.
Figure 32: Sensitivity measurements from the resistivity survey for lines 1, 2, 3, and 4 respectively. Sensitivity is a qualitative assessment of measurement quality in different areas of the subsurface. It is represented numerically by unitless log 10 values on the right, alongside the equivalent sensitivity value. Red represents areas with higher sensitivity, while blues and greens represent areas of lower instrument sensitivity.
CHAPTER V. CONCLUSIONS

The use of an array of continuous monitoring pressure transducers in a network of monitoring wells on the slope proved to be a valuable source of information during the study. Variations in hydraulic head in different wells suggest that subsurface storm flow is being concentrated through the center left of the slope, largely through the area of piezometers 1, 2, and on through the area of wells 6, 7, and 9.

The stratigraphic columns assembled from borehole information at the top of the slope, though not representative of a large area, also suggested the presence of a buried swale leading to the river as a mechanism for channeling the subsurface water, and potentially affecting the distribution of groundwater in the area. The columns are also in agreement with the results of the 2011 GPR survey (Figure 2).

The resistivity data, in broad terms, supported the transducer data and provided additional data that suggested that the shallow subsurface valley indicated by boreholes at the top of the slope potentially continued downward as a swale through the buried face of the bluff. In addition, ER lines 2 and 3 show areas of lower resistivity through the center of the line, which can be interpreted as representing higher soil moisture content. Line 4, which was positioned at the footslope, showed a generally low-resistivity subsurface, which is supported by
the observed wetness of the area due to return flow. No conclusions were drawn from line 1 given the heterogeneity of the subsurface and the consequent complexity of the ER results for that line. However, the ER survey was not able to reach bedrock and as a result comparison with the initial 2011 GPR mapping of the soil and bedrock interface was not possible. Later surveys did not reach bedrock because conditions changed.

While the GPR, based on an analysis of the data using both the Ground Vision Software and the Rad Explorer software, was not able to clearly and consistently delineate the groundwater table, it was successful at delineating the soil or bedrock interface and documenting the presence of the swale. The lack of consistent agreement between the patterns noted in the radargrams and the records provided by the piezometer system proved critical in ensuring that incorrect interpretation of the patterns noted in the radargrams did not occur. While the radargrams in fact did show a false pattern, this pattern was not corroborated by piezometer records. Applying normal dielectric constant ranges and velocity estimates based on sediment texture and moisture content did not match radargram picks, and assuming variable material properties and adjusting dielectric constant to match the picks did not produce reasonable values.

Although the use of the GPR was able to define the subsurface topography and general subsurface flow path for drainage over and down the
slope, it was not able to clearly define the subsurface water table. The complex arrangement of materials in the subsurface due to the slope failure may have introduced limitations in our capacity to effectively evaluate the GPR survey data which, in turn, ultimately reduced the effectiveness of the GPR in effectively and reliably delineating the water table.

The use of the integrated approach however appears to have been quite successful at providing an overview of the nature of the slope and response of the subsurface hydrology to rainfall events. The use of the continuous monitoring well sensor array in conjunction with the boreholes, the GPR and ER surveys was also useful in ensuring that potentially incorrect subsurface water level interpretations did not occur, and confirmed the need for calibration support when such geophysical methods are utilized.

5.1. Future Work

It would appear that while the overall integrated methodology employed in this study was successful, the use of GPR to document subsurface water levels does face limitations and that its use for this specific purpose might be more successful in slopes with a relatively uniform composition, regular stratigraphy, or more suitable conductivity ranges. Moisture, as has been noted in previous work, is a major factor in determining of the success of a survey, and the same type of GPR survey may be more successful during a dry period. The method
still holds potential and work on the use of GPR for this purpose should continue on less complex sites.
REFERENCES


