MARINE RESISTIVITY AS A TOOL FOR CHARACTERIZING
ZONES OF SEEPAGE AT LAKE LACAWAC, PA

Matthew J. Heaney, Temple University, Philadelphia, PA
Jonathan E. Nyquist, Temple University, Philadelphia, PA
Laura E. Toran, Temple University, Philadelphia, PA

Abstract

The groundwater-surface water exchange zones of lakes and streams are dynamic and difficult to characterize. The spatial variability of seepage zones makes them difficult to locate using traditional point sampling methods. The goal of this project is to use marine resistivity to identify potential zones of groundwater discharge and recharge, providing focus for point measurements. Multiple resistivity surveys were conducted at Lake Lacawac, a small, glacially formed lake in northeastern Pennsylvania. One target for these surveys was the resistivity contrast between groundwater and surface water. Another target was resistivity contrasts created by geologic heterogeneities that control groundwater discharge into the lake. Two types of surveys were conducted using a SuperSting® resistivity system. In a continuous resistivity profile, a multi-electrode cable was towed parallel to shore to look for spatial variability in resistivity around the lake. A second resistivity array was laid on the lake bottom perpendicular to the shoreline to examine how resistivity varied with distance from shore. The results of these surveys suggested several lithology changes both along the shoreline and with distance from shore. Seepage meters were used to provide ground truth about interpreted areas of seepage.

Introduction

The quantification of groundwater-surface water exchanges is an essential element in understanding mass fluxes and developing water budgets (e.g. Winter, 1976; Cherkauer, 1991). Numerous factors can control groundwater discharge, including topography, climate, sediment type, and hydrologic properties of different geologic materials (e.g. Sophocleous, 2002). These multiple factors can result in groundwater-surface water exchange patterns that vary on the scale of meters. A wide range of measurement techniques have been developed to search for groundwater discharge, including temperature sensors, conductivity meters, mini piezometers, and direct seepage measurements (e.g. Lee, 1977; Rosenberry et al., 2000; Anderson, 2005). These techniques are point measurements and are too expensive to monitor an entire shoreline on the scale dictated by geologic heterogeneity. An alternative to sampling a large area with a fine grid is to focus measurements on a smaller zone of interest. Geophysics may supply the means to guide seepage measurements and increase the effectiveness of point sampling techniques.
Electrical resistivity is a geophysical technique that has long been used to characterize saturated sediments (Archie, 1941). Resistivity surveys often focus on three potential targets; porosity, pore fluid conductivity, and clay content. An adaptation of Archie’s law that accounts for these three factors in the overall resistivity of a material was introduced by Rhoades et al. (1976).

\[
\frac{1}{\rho} = \frac{1}{\rho_w} (a \theta^2 + b \theta) + \frac{1}{\rho_s}
\]

Where \( \rho \) is the effective bulk resistivity, \( \rho_w \) is the pore fluid resistivity, \( \rho_s \) is the resistivity of the solid matrix, \( \theta \) is the volumetric fluid content, and \( a \) and \( b \) are constants characteristic of the solid and pore fluid. In saturated sediments, an increase in porosity results in an increase in the fluid content. Since bulk resistivity is inversely proportional to fluid content, an increase in porosity leads to a decrease in bulk resistivity. A change in pore fluid conductivity can also change the effective bulk resistivity. A more conductive pore fluid lowers the bulk resistivity. Groundwater is typically more conductive than surface water, a contrast that has been used with point measurements to identify zones of groundwater discharge (e.g. Rosenberry et al., 2000). An extreme example of pore fluid conductivity contrast is the difference between the resistivity of freshwater and salt water. Resistivity surveys targeting salt-freshwater contrasts have been used to examine submarine groundwater discharge, saltwater intrusions, groundwater recharge patterns and other groundwater-surface water interactions (Belavel et al., 2003; Manheim et al., 2004; Allen and Merrick, 2004; Day-Lewis et al., 2006).

Clay minerals can control the resistivity of a solid matrix (Samouelian et al., 2005). The presence of conductive clays has been a target for several resistivity surveys (Taylor and Cherkauer, 1984; Cherkauer, 1991; Synder and Wightman, 2002; Ball et al., 2006). The location of clay is important in understanding groundwater-surface water interactions because distribution of aquitards can focus where groundwater discharges. By mapping hydrologically transmissive layers, we hope to identify possible groundwater flowpaths.

The goal of our current research is to determine if resistivity surveys can guide the study of groundwater-surface water interactions by identifying possible groundwater discharge locations. Our targets are upwellings of conductive groundwater and geologic heterogeneities that control groundwater discharge. This project builds on the research of Freyer et al. (2006) who studied similar targets in a gaining stream.

**Background**

Lake Lacawac is a small (0.214 km\(^2\)), glacially formed lake in the Pocono Mountains of Northeast Pennsylvania. This mesotrophic lake is located in Wayne County, PA, shown in Figure 1. This lake has a mean water depth of 5.2 meters and a maximum depth of 13 meters. The catchment area for the basin is small, approximately 0.7 square kilometers (Moller et al. 1995 in Dalton, 1999). The underlying geology in the area is the undivided Packerton and Poplar Gap members of the Upper Devonian Catskill formation. The bedrock underlying the lake is primarily gray sandstone, visible in outcrop near the southern shore. The lake is part of the Lacawac Sanctuary and was designated a National Natural Landmark in 1968, so the watershed is largely unaltered by human activity. The Earth and Environmental Sciences Department at Lehigh University has conducted
research at Lacawac since 1988 and maintains a meteorological station in the lake year round. Data collected includes precipitation, relative humidity and water temperature at different depths.

Figure 1: Geographic Setting of Lake Lacawac. Photo from [www.lacawac.org](http://www.lacawac.org)

Dalton (1999) conducted a series of Ground Penetrating Radar (GPR) surveys at Lake Lacawac with the goal of reconstructing the depositional history of the basin. He also analyzed two cores, characterizing two major lithologic units, with highly organic silty-clay overlying a less organic silty-clay. Dalton’s work focused on benthic sediments in the deeper sections of Lake Lacawac and does not reveal much about the sediments closest to shore. Near-shore sediments have been shown to have a strong influence on groundwater discharge patterns (McBride and Pfannkuch, 1975) and were the primary targets for our survey.

**Field Methods**

**Towed Resistivity Surveys**

A Marine SuperSting® R8/IP (Advance Geosciences Inc.) was used to conduct all resistivity surveys. For towed resistivity surveys, we connected the SuperSting to a 20-meter cable to carry out a dipole-dipole survey. This cable had 11 electrodes spaced 2 meters apart, giving us a maximum depth of penetration of approximately 10 meters. Figure 2 shows a schematic of the array set-up. We towed the streamer behind a 14-foot boat propelled by a trolling motor. A Lowrance 332C GPS/Sonar unit connected to the SuperSting logged position, water temperature, and water depth during the surveys. The first two graphite electrodes injected current into the water while the remaining 9 stainless steel electrodes recorded voltage drops across 8 dipoles. These measurements were recorded every 4 seconds along each of the SuperSting’s 8 channels and used to calculate apparent resistivities for different sections of earth. These values were assigned different depths and locations based on the positions of the electrodes used in their measurements. This survey remained in constant motion, allowing for the collection of up to 3 km of data in a single hour. We towed the streamer roughly parallel to shore in water 0.5 to 3 meters deep, approximately 5 to 10 meters from shore. Figure 3a shows the general path of the surveys. We inverted the measurements using EarthImager2D®,
creating a continuous resistivity profile. We used the results of these towed surveys to
guide follow-up measurements in the northeast corner of the lake (Figure 3b).

Figure 2. Schematic of towed dipole dipole survey. Current is injected by A and B
electrodes, potential is measured by P1–P9. Apparent resistivity is calculated based on
voltage drop and the electrode position. The boat remains in constant motion, creating a
grid of points by moving the array.

Figure 3. Measurement locations. Yellow dots represents the path of towed resistivity
surveys. The blue line shows locations of extracted lines that are shown in Figure 5. Red
lines show lake bottom surveys, those shown in Figure 6 are labeled above. Green dots
represent seepage meters. a) Overview of entire lake. b) Close up of dashed box.

Lake Bottom Surveys
We also used the SuperSting to carry out dipole–dipole surveys near the shore of
the lake. In these lake bottom surveys, we attached the SuperSting to a 27-meter cable
that rested on the bottom of the lake, extending perpendicular to shore. This cable had 28
stainless steel electrodes spaced 1 meter apart. The maximum depth of penetration for
these surveys was roughly 6 meters. We placed the electrodes directly on the benthic
sediments, so unlike the towed resistivity surveys the lake bottom surveys did not need to
penetrate through the water column before reaching the sediment layer. We measured
water depth at each electrode in order to constrain the thickness of the water layer during the inversion process. The shorter electrode spacing gave the lake bottom surveys greater resolution than the towed array, but the set up and measurement time makes the data collection slower. For this reason we used the lake bottom array as a follow-up tool. We conducted 11 unique surveys around the lake. Figure 3 shows their locations.

**Seepage Meters**

Seepage meters for this project were constructed out of 55 gallon drums attached to plastic bags. This design was adapted from Lee (1977), an example of which can be seen in Figure 4. We cut the drums to create an open-ended cylinder. The open end of the barrel was pushed into the sediment, creating a trap for all seepage through the area encompassed by the drum. We attached a partially filled 3 liter plastic bag to a hole in the barrel to capture any in-seepage or record any out-seepage. We weighed the bag before and after measurement periods to observe any change in volume. The bag was attached to the drum with a 2 meter section of hose so that we could detach and measure the bag without compressing sediment near the drum. We installed 8 seepage meters 25 meters apart along the northeast shoreline. Each meter was placed approximately 2 to 6 meters from shore. We installed two more seepage meters 5 and 10 meters from shore along a perpendicular, lake bottom line (LAC19P).

![Figure 4. Seepage Meter.](image-url) The blue drum in the background is pressed into the benthic sediment, forcing seepage through the green hose to a plastic bag protected by the white case shown in the foreground.
Results and Discussion

**Towed Resistivity Surveys**

Figure 5 shows the result of two different towed resistivity surveys. The approximate path of these surveys is shown in Figure 3a. The first towed survey (5a) was conducted in July, 2006. This is an extraction covering approximately 200m along the southern shore. Vertical exaggeration in this image is 10:1. The tomograph is a cross-section running parallel to shore from west to east. The yellow layer represents the lake water, fixed at a resistivity of 500 ohm-m (20 micro-siemens/cm). The black line denotes the lake bottom. The red, resistive area is interpreted to be the sandstone bedrock visible in outcrop near the shore. The blue, conductive area is interpreted to be the silty clay described by Dalton (1999). Some of the green, intermediate layers may be artifacts of the smoothing of the inversion process, but there is a sandy sediment layer overlying some of the shallow bedrock along this shore. This sandy layer is more resistive than the clay, less resistive than the sandstone, and would appear as green in this tomograph. Unless the bedrock is highly fractured, both the clay layer and the bedrock are likely less permeable than the sandy layer. In terms of groundwater discharge, the sandy layer is a more likely flowpath than the clay or the bedrock.

The second towed survey (5b) was conducted in October, 2006. This cross-section covers approximately 200m near the northeastern shore, running from south to north. Vertical exaggeration is again 10:1. The color scale is the same as 5a, with red being the most resistive (1000 ohm-m) and blue the most conductive (100 ohm-m). The dominant feature in this tomograph, and in most of the lake, is the interpreted clay layer, shown in blue. In the first half of the profile, the clay layer appears to deepen or thin out. The yellow and orange layer overlying the clay is interpreted to be a sandy sediment layer. This layer is likely more permeable than the clay and presents a possible flowpath for groundwater discharge. An area with no sandy sediment layer, such as the right third of 5b, is less likely to have groundwater discharge because the only flowpath would be through the thick clay layer. Since the northeast corner showed evidence of a greater depth to clay with more resistive sediments on top of the clay layer, we focused our follow-up surveys in this region.

**Lake Bottom Resistivity Surveys**

Figure 6 shows the results of several simulated and actual lake bottom surveys. In all of these figures, the shore is on the left and the profile is a cross section perpendicular to shore. There is no vertical exaggeration in these images. Figure 6a is a model of a 3 layer earth. The red layer represents resistive bedrock, the blue layer represents conductive clay and the green layer represents a thin, (~1m thick) hydrologically transmissive sandy layer. Approximately 5 meters from the start of the line, this sandy layer pinches out into a clay blockage. Figure 6b shows the result of a computer simulated survey and inversion of this synthetic model. The 3 layers are still visible, as is the clay blockage. This suggests that the lake bottom surveys can determine if layers are continuous. Figure 6c shows the result from an actual survey (LAC7P). The layering mirrors the synthetic model, with conductive clay overlying resistive bedrock and a thin (~1m thick) sandy sediment layer on top of the clay. This sandy sediment layer, shown
Figure 5. Results of towed resistivity surveys. Each section is approximately 200 m long, with a vertical exaggeration of 10:1. The black line represents the lake bottom, with the yellow section above this line showing the water layer, resistivity constrained to 500 ohm-m. The red sections are interpreted to be resistive bedrock and the blue layers are interpreted to be conductive clay. The green layers of intermediate resistivity are interpreted to be permeable sandy sediments.

a) Cross section running parallel to the southeastern shore (location shown in Figure 3). Sandy sediment areas are interpreted to be more likely flow paths than the bedrock or clay.

b) Cross section running parallel to the northeastern shore (location shown in Figure 3). Clay layer thins in the first half of the section, suggesting possible flow paths above the clay layer.
Figure 6. Lake bottom Resistivity Results. Horizontal axis is distance from shore, vertical axis is depth. No vertical exaggeration. a) Synthetic model of a 3 layer earth showing the permeable sandy sediment layer pinching out. b) Simulated inversion of the synthetic model shown in part a. The 3 layers are all resolvable, as well as the sandy sediment pinchout. c) Inverted 2D cross section of LAC7P. The layering mirrors the synthetic model, including the pinching out of the interpreted sandy sediment layer. d) Inverted 2D cross section of LAC18P. The interpreted sandy sediment layer is not connected to shore. A seepage meter placed 5 m from shore showed surface water discharge of 0.19 cm/day. e) Inverted 2D cross section of LAC19P. The interpreted sandy sediment layer is continuous from shore. Seepage meters placed 5 and 10 m from shore showed groundwater discharge of 0.05 and 0.02 cm/day respectively.
in green, yellow, and red is still the most likely path for groundwater discharge. In Figure 6c, this layer pinches out approximately 2 meters from shore, suggesting that groundwater discharge along this path is less likely further than 2 meters from shore. Figures 6d and 6e show two profiles from the northeast corner of the lake. LAC18P (Figure 6d) is located approximately 20 meters south of LAC19P (Figure 6e). Like Figure 5b, the bedrock in this area is too deep to be seen in this profile. Both 6d and 6e show a thick, conductive layer interpreted to be clay overlain by a thin, more resistive layer interpreted to be sandy sediment. The primary distinction between the two profiles is the continuity of the more resistive layer. In Figure 6e the more resistive layer is clearly continuous for the first 10 meters from shore, while in 6d the layer pinches out without connecting to shore. This suggests that if groundwater flow is coming from the shore, discharge is less likely to be found along LAC18P (Figure 6d). For ground truth, seepage meters were installed along both LAC18P and LAC19P.

**Seepage Meters**

The results of seepage meters along LAC18P and LAC19P are shown in Figure 6d and 6e. Seepage meters were placed 5 and 10 meters from shore along LAC19P and 5 meters from shore along LAC18P. Both meters along LAC19P showed slight discharge from groundwater to surface water, with a decrease in rate further from shore. The meter along LAC18P showed the largest out-seepage (0.19 cm/day) of any seepage meter in the study, suggesting surface water discharge to groundwater. Both seepage meters along LAC19P showed in-seepage, suggesting groundwater discharge into surface water. These results are quite low, possibly because actual seepage rates at this lake are too low to measure with our approach. Seepage results do correlate with the interpretation that groundwater discharge is more likely along a continuous flow path.

**Conclusions**

Towed resistivity surveys demonstrated clear lithology changes around the perimeter of the lake. Changes in clay content provided a strong signal that overwhelmed contrasts in pore fluid conductivity. Identifying transitions between zones of benthic sediments can prove useful when characterizing likely groundwater discharge areas.

Results of lake bottom resistivity surveys show contrasts in the continuity of transmissive sediments in different locations around the lake. Forward models suggest that lake bottom resistivity surveys can characterize the continuity of potential flowpaths. Transmissive sediments alone are not conclusive evidence of groundwater discharge, but their presence makes seepage more likely. The observed seepage data suggests that the absence of flowpaths connected to the shore makes groundwater discharge less likely, but the small response limited the seepage meter studies. Future work will target lakes known to have higher seepage rates. Even with the low seepage rates observed at Lacawac, geophysical data provides insights into the variability of lake bottom sediments.
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