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SEEPAGE PHENOMENON CONTROL BASED ON ELECTRICAL RESISTIVITY METHOD CASE STUDY: THE MIRROR LAKE, NH

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ABSTRACT

The results of electrical resistivity surveys using cables both surface-towed and stationary (lake bottom)at Mirror Lake, NH suggest that resistivity surveying can be useful for characterizing geologic heterogeneities that control groundwater-surface water interaction, as well as for imaging road-salt contamination. In-situ measurements of seepage coincident with resistivity surveys suggested relationship between resistivity values and seepage rates. Specifically, we observed that seepage rates were low (averaging -22 cm/day) at Mirror Lake where resistivity values were greater than or equal 3000 Ω-m and where they were less than or equal to 100 Ω- m. Low (100 Ω- m) resistivity values were indicative of organic matter deposits. High (3000 Ω-m) resistivity values were indicative of low porosity, poorly sorted till. Intermediate (~ 1500 Ω-m) resistivity values were observed in the regions where seepage rates were highest (averaging -92 cm/day). Core, modeling, and slug test data suggest that these intermediate resistivity values reflect more well-sorted, higher-porosity drift. Resistivity surveys of the suspected region of salt contamination revealed a plume-shaped feature of low resistivity. Low resistivity and high chloride content were confirmed by laboratory analysis of pore fluid. We conclude that the rapidly acquired towed-cable survey can guide placement of higher-resolution, more time-consuming stationary cable surveys. The use of stationary cable resistivity surveys in the very near shore environments (<2 m from shore), which are generally inaccessible with a towed-cable survey, can guide seepage meter placement.

KEYWORDS: Electrical Resistivity, Marine Resistivity, Seepage Flux in Lakes

INTRODUCTION

The exchange of water between groundwater and surface-flow regimes is an important feature of hydrologic systems. Temperature, solute content, and water-flow conditions of such transition zones make them crucially important to many aquatic species (Reinstorf and Schirmer, 2006; Hayashi and Rosenberry, 2002; Brunke and Gonser, 1997; Asbury, 1990). Groundwater exchange can also serve as a significant source or sink of water to lakes and streams (Rosenberry, 2005; Lee, 1977; McBride and Pfannkuch, 1975). Tools that can characterize and quantify the interaction between groundwater and surface water are therefore essential to watershed management strategies. The spatial and temporal variability of seepage makes characterizing and quantifying it difficult in any setting. Underwater seepage is all the more challenging to characterize because it occurs beneath a body of water. Seepage can occur from groundwater to a lake (in-seepage) or from a lake to groundwater (out-seepage, expressed as negative rates). Commonly used methods for analyzing underwater seepage include direct measurements using seepage meters (Warnick, 1951; Robinson and Rohwer, 1959; Lee, 1977; Fellows and Brezonik, 1980; Kelly and Murdoch, 2003; Rosenberry, 2005), and methods that calculate seepage based upon proxies such as measured hydraulic and temperature gradients, hydraulic transmissivity of lake bottom sediment, and flow analysis via dye or isotope tracing (summarized by Reinstorf and Schirmer, 2006). Beginning in the 1980.s, electrical resistivity profiling, with which one can rapidly characterize a large area, was used as an adjunct to these point measurement techniques (Taylor, 1982; Taylor and Cherkauer, 1984; Cherkauer, 1991; Cherkauer and Carlson, 1997). Electrical resistivity profiling is sensitive to changes in pore fluid resistivity (ρw), porosity (φ), saturation (s), and changes in mineralogic and cementing factors (constants a, m and n), as quantified by Archie’s law:

$$\rho = a\varphi^{m} s^{n} \rho_w$$

where ρ is the bulk resistivity (Archie, 1942). Because geologic heterogeneity may cause changes in the values of any of the factors, electrical resistivity profiling has the potential to image the geologic variations that control seepage. Building upon the work of Heaney et al. (2006), we sought to develop the use of electrical resistivity profiling as a tool for characterizing variability in underwater seepage.

Case Study

The study site for this project was Mirror Lake, a small (15 hectare), glacially formed lake in the White Mountains of central New Hampshire (**Figure 1**). The lake has been a National Science Foundation-designated Long Term Ecological Research site (LTER) since the 1980.s and is part of the Hubbard Brook Experimental Forest (United States Department of Agriculture Forest Service) with considerable topographic, geologic and hydrologic data available (Winter, 1985; Winter, 1989; Harte,1997; Tiedeman et al., 1997; Johnson, 1999; Ellefsen et al., 2002). Mirror Lake is a flow-through lake, with three inlet streams and one outlet. Bedrock beneath Mirror Lake is fractured quartz monzonite, schist, and a variety of igneous intrusives (Winter, 1985; Johnson, 1999).

Fracture flow dominates the groundwater system (Ellefsen et al., 2002; Johnson, 1999; Tiedeman et al. 1997; Paillet, 1988). Bedrock is immediately overlain by a layer of glacial drift, which ranges in thickness from nearly non-existent at its minimum (the center of the lake) to over 50 meters at its maximum (lake.s edge).

The drift is clay-poor and ranges in composition from silt to silty sand, with cobbles and boulders in many places (Winter, 1985; Winter, 2000). Previous work (Rosenberry and Winter, 1993; Asbury, 1990) has shown the southwest shore to be a region of very high seepage.

Though the drift is generally poorly sorted and of very low hydraulic conductivity (K = 10-6 m/sec), data from core samples, slug tests, and modeling studies suggest a deposit of relatively well-sorted sand and gravel occurs there (Figure 1).

The hydraulic conductivity of this sand and gravel deposit (K = 10-3 m/sec) is approximately 1000 times that of the surrounding, more poorly sorted till (Wilson, 1991; Tiedeman et al., 1997; Scheutz 2002; Harte, 1997).

Several groups believe that this sand and gravel unit represents a major sink for lake water to the groundwater system and is responsible for the very high seepage rates (-300 cm/day) observed along the southwest shore of Mirror Lake (Tiedeman et al., 1997; Rosenberry and Winter, 1993; Scheutz, 2002). A similar model has been used to explain high seepage in Trout Lake, Wisconsin (Krabbenhoeft and Anderson, 1986).

In-seepage has been observed elsewhere in the lake, such as within the northeast inlet (Asbury, 1990) where we imaged a contaminant plume. The stream at this inlet has both gaining and losing reaches (Rosenberry et al., 1999).

Water from the stream’s basin enters the groundwater system via the losing reaches and is discharged to Mirror Lake. This basin area includes developed areas, including a major highway.

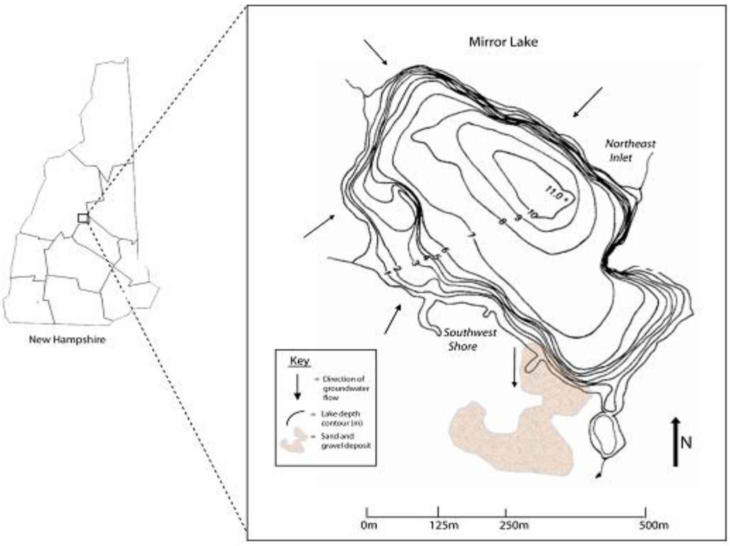

Figure 1: Project Study Site. Mirror Lake is a Small (15 Hectare) Post-Wisconsin Glacial Lake, Underlain by up to 50 Meters F Poorly Sorted Till (Winter, 1985). Hydraulic Conductivity of this Till is Generally Low, Except Along the Southwest Shore of Mirror Lake, Where There is Evidence for a Hydraulically Conductive Sand and Gravel Deposit (Tiedeman Et Al., 1997; Scheutz, 2002; Wilson, 1991). ***Modified from Moeller, 1975***

ELECTRICAL RESISTIVITY METHOD

Towed-Cable Electrical Resistivity

For the towed-cable survey, an electrode cable (40-m long, 2-m electrode spacing), connected to the Superstring, was towed parallel to the shoreline behind a 14- foot boat (Figure 2). Towed surveys were conducted at an average of about 3 m from shore, where lake water was approximately 2 m deep. Though closer approach of the shoreline would have been desirable, shallow water and near-shore debris (fallen logs, boulders and etc.) generally made closer approach impossible. The length of the cable also made imaging coves and peninsulas difficult (Figure 3).

The first two electrodes of the towed cables were graphite and were dedicated current electrodes (Figure 2). The next 9 electrodes were stainless steel and were dedicated potential electrodes, paired to measure voltage drop across 8 dipoles for each firing event. Total depth of penetration, including the water column, was approximately 6 m; thus, deep water limits sediment imaging. The cable was suspended at the surface of the water by means of small pool floats wire-tied to the cable between electrodes. Measurements were made every 4 seconds as the boat travelled along the Measurements Made Every 4 Seconds. Electrodes A and B are Dedicated Current Electrodes, While P1-P9 Are Dedicated Potential Electrodes and Work in Pairs ao Measure Voltage Drop for Each Injection of Current. On-Board Gps Connected Directly to the Supersting Records Time and Position Information for Each Voltage Measurement. From Agi Supersting® Marine Manual

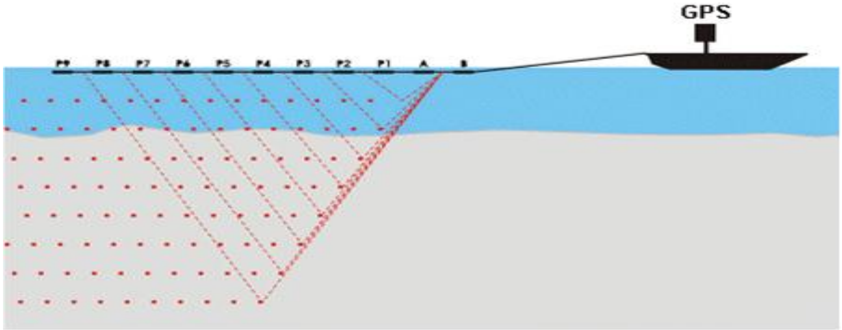

Figure 2: Towed-Cable Survey Electrode Array. In Our Towed-Cable Resistivity Surveys an 11- Electrode Cable is Towed Behind a Boat at a Rate of 2-3 Km per Hour and Resistivity

Perimeter of the lake. Position information for each resistivity measurement was gathered via a GPS unit connected directly to the SuperSting. The relative position of the sets of apparent resistivities were calculated and inverted using AGI's *Marine Log Manager* and *EarthImager 2D*, programs which knit together and then model the collection of apparent resistivities gathered in a survey.

Stationary Cable Resistivity Survey

Stationary-cable has been conducted surveys by stretching a 28-electrode, 27-m long cable along the lake-bottom, either parallel with or perpendicular to shore. We measured the depth to each electrode before connecting the cable to the SuperSting so that we could constrain the thickness of the water column during the inversion process. All stationary-cable surveys were setup using a dipole-dipole array. We conducted a total of 23 stationary-cable resistivity surveys parallel to shore and 20 perpendicular to shore. In some cases we overlapped survey areas by approximately 50% so that we could later merge datasets from adjacent regions. The maximum depth of penetration with the 27-meterlong cable was approximately 6 meters.

Our stationary (lakebottom) cable surveys, in which the electrodes lay directly upon lake bottom, had a resolution 4 to 5 times that of the towed surveys. The stationary cable surveys provided higher resolution images because (1) the electrical current did not have to penetrate a thick water column before reaching the target of the survey, (2) the density of resistivity measurements per unit area surveyed was far greater than for towed surveys, and (3) the electrode spacing of our lake-bottom cable was 1 m rather than the 2-m spacing we used in the towed-cable surveys.

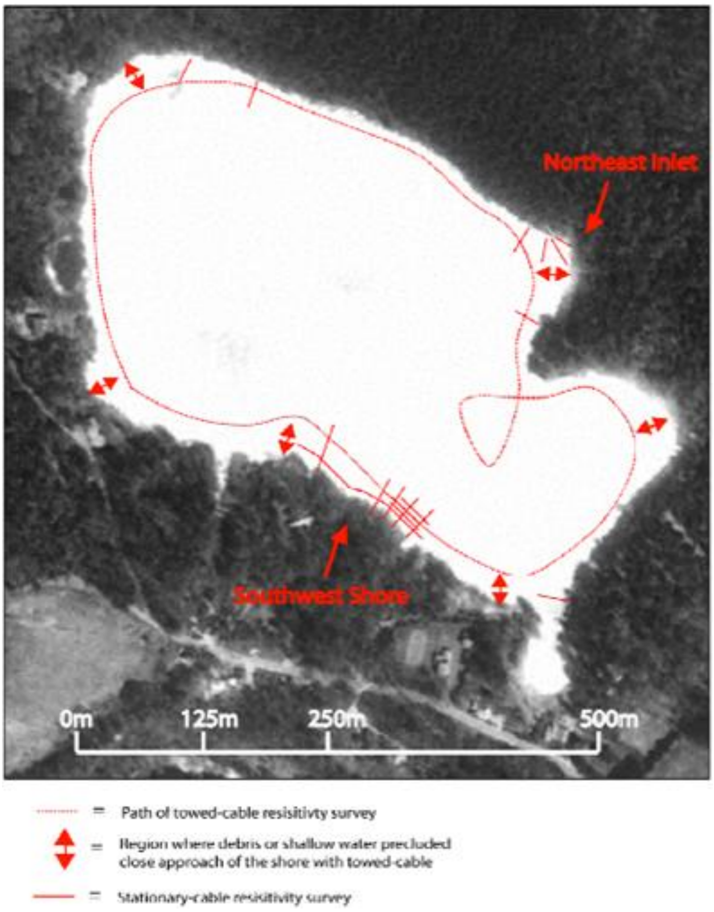

Figure 3: Location of Towed and Stationary-Cable Surveys. Red Arrows Indicate Regions Where Approach of the Shoreline Closer Than Approximately 5 Meters was Impossible. The Large Loop Taken Along the Eastern Edge of Mirror Lake with the Towed-Cable Survey was Made to Avoid Snagging the Cable on the Peninsula

Seepage Meters

In-situ measurements of seepage at 80 points in Mirror Lake were conducted to provide data for groundtruth of resistivity measurements. We used seepage meters of the design (Figure 4) suggested by Lee (1977) and modified by Rosenberry (2005). One half of a 55-gallon (0.208 m3) drum was pressed into the sediment above the region of interest, left undisturbed for at least one hour to allow re-equilibration of seepage in the region, and then attached to a plastic measuring bag partially filled with a known quantity of water. A region dominated by in-seepage will draw down the contents of the measuring bag. Out-seepage will add to it. From the known cross-sectional area of the seepage meter, the weight of the collection bag before and after the measurement, and the length of the measurement period, we calculated seepage and expressed the rates in centimeters per day. Repeat measurements were made at each point to determine the consistency and reproducibility of results.

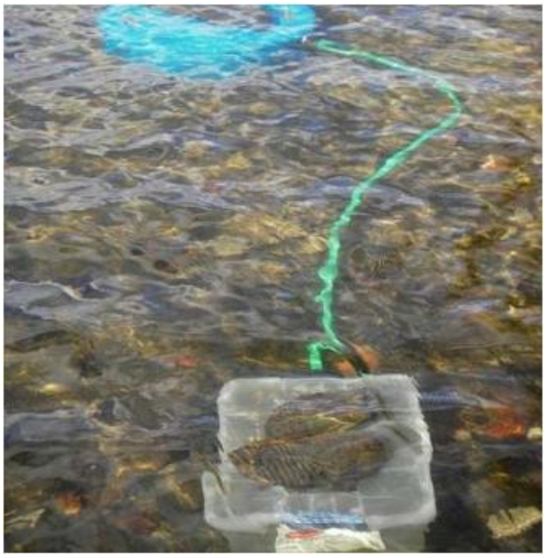

Figure 4: Seepage Meter (Blue Cylinder) Attached to Measuring Bag (Protected From Waves and Wind by the Clear Plastic Case)

RESULTS AND DISCUSSIONS

Resistivity surveys has been combined with a dense array of seepage measurements to observe a relationship between seepage and resistivity along the southwest shore where high seepage rates were previously observed. We found the stationary cable survey to be particularly useful in this task. Seepage rates are generally at their maximum within a meter or two of the lake s shore, and decline exponentially with distance from that shoreline (McBride and Pfannkuch, 1975; Winter, 1976). Measurements of seepage at Mirror Lake showed major decline in seepage rates with distance from shore, although the pattern is somewhat more complex than simple exponential decline (Asbury, 1990; Rosenberry, 2005). Because the majority of seepage occurred in the near-shore environment, geophysical tools capable of approaching that environment were most useful. The southwest side of Mirror Lake was shallow enough that with the towed cable survey we could not approach the shore more closely than approximately 5 meters. The stationary-cable survey, on the other hand, suffered no such limitations, and with it we could image the area where the highest seepage rates were observed. The results of our southwest shore seepage and resistivity measurements are summarized in Figure 5. Seepage rates were highest (average = -98 cm/day, with a high of -282 cm/day) where resistivity values were intermediate (≈ 1500 Ω-m). Seepage rates were lowest (average = -22 cm/day, with a high of -62 cm/day in the center of the section) where resistivity values were ≥3000 Ω-m or ≤100 Ω-m. Regions where resistivity values were low had deposits of organic matter, and it was owing to the fineness of the material in these deposits that we attributed the low seepage rates there. The source of the transition from intermediate (1500 Ω-m) resistivity to higher (≥3000 Ω-m) in the middle of the southwest shore study area, on the other hand, was interpreted based on Archie's law. Bulk resistivity is, according to Archie's law, dependent upon porosity, pore fluid conductivity, saturation, and characteristics inherent to a given lithology. Saturation was constant in this case because we were dealing with an underwater environment. We also expected pore fluid conductivity to remain constant because all seepage in that region was out-seepage: all pore water would represent lake water rather than groundwater. The source of variation in resistivity was therefore either a change in porosity or lithology along that shore. Slug tests, groundwater flow modeling and previous analysis of on-shore core samples suggest the presence of a hydraulically conductive deposit of relatively well-sorted sand and gravel along the southwest shore (Harte, 1997; Tiedeman et al. 1997; Wilson, 1991; Scheutz, 2002). Archie's law suggests that such a deposit would have a lower bulk resistivity than the surrounding, more poorly sorted till because of its better sorting and resultant higher porosity. That is, we believe the zone of intermediate (1500 Ω.m) resistivity observed along the southwest shore is probably reflective of the deposit of relatively higher porosity material. We believe that this higher porosity material also has a higher hydraulic conductivity and that this higher conductivity allows the high rates of seepage there. The coincidence of the zone of intermediate resistivities with the highest seepage rates further supports the hypothesis that our resistivity surveys show the extent of a high K sand and gravel deposit

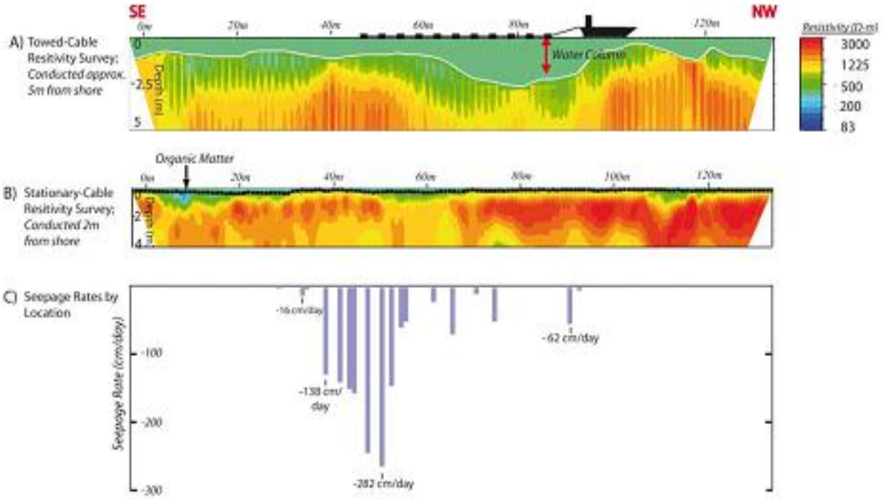

Figure 5: Resistivity and Seepage Results from the Southwest Shore of Mirror Lake. (5A) the Results of a Towed-Cable Survey Conducted at Approximately 5 M from Shore. Shallow Water and Debris Precluded Nearer Approach with the Towed Cable. (5B) the Merged Results of 9 Stationary Cable Surveys Conducted Over the Same Terrain but at a Distance of 2 M from Shore. The Inability of the Towed-Cable Survey to Approach the Near-Shore (≤2 M) Environment of the Shallow Southwest Shoreline Meant that it Failed to Image the Heterogeneity we Observed with the Stationary Cable Survey and which we Believe was Related to Seepage Rates. (5C) the Results of Seepage Measurements Made Approximately Every 5 Meters Along the Same 130-M Stretch of Shoreline

Northeast Inlet

Towed resistivity surveys revealed a zone of anomalously low (<100 Ω-meter) electrically resistive sediment within the basin area of the northeast inlet stream (Figure 6A). Previous studies at the lake reported concerns about road-salt contamination in the northeast inlet (Rosenberry et al., 1999). We were interested to see if resistivity surveys could confirm the presence of road-salt contamination and perhaps map its extent. We conducted four lake-bottom resistivity surveys over the northeast inlet area, two of which were overlapped in order to transect an area 40-m long (Figure 6). All surveys confirmed the existence of a region of very low resistivity material, and that that zone of low resistivity extended to a depth of 4- 5 m, 3-4 m below the depth of organic matter deposits. Analysis of pore-water samples from the shallow (≈ 40 cm) subsurface revealed chloride content three times the level observed in the lake (9 mg/L Cl in pore water versus 2.5

mg/L Cl in the lake). Archie's law calculations show that a 3x increase in pore fluid conductivity (ρw) will lead to a 3x decrease in resistivity. The shape of the region of very low resistivity is similar to that which one would expect of a contaminant plume. These results collectively suggest that the electrical resistivity surveys have imaged road-salt contamination within the northeast inlet. The presence of a contaminant plume within lake sediment confirms earlier research (Rosenberry et al., 1999) that the losing reach of the northeast inlet stream contributes road-salt-impacted water to groundwater: this groundwater, imaged in our resistivity surveys,discharges to Mirror Lake.

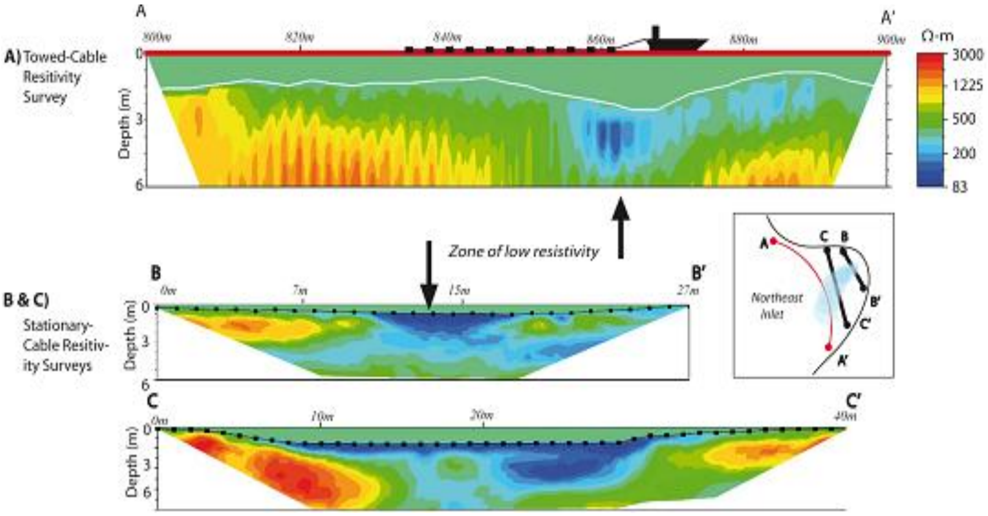

Figure 6: Resistivity Results from the Northeast Inlet Area of Mirror Lake. Towed-Cable Survey (6A) of the Northeast Inlet Revealed A Zone of Very Llow (<100 Ω-m) Resistivity. Stationary Cable Resistivity Surveys (6B and 6C) Confirmed the Existence of this Zone and Showed that it Extends to a Depth of 4-5 m. The Pockets of Low Resistivity Observed in 6A, B and C Show the Extent of the Road-Salt Contaminant Plume. The Inferred Extent of this Plume is Represented Schematically by the Pale-Blue Plume Shape of the Inset Map

CONCLUSIONS

Our work at Mirror Lake confirmed the efficacy of using towed and stationary cable resistivity surveys to study seepage. The rapidity of the towed-cable survey makes it useful for developing a general sense of a lake's lithology and guiding placement of the more time-consuming stationary cable surveys and seepage measurements. Though towed-cable resistivity surveys are useful for developing a sketch of a lake's lithology, the technique has several limitations: first, one cannot generally tow the cable closer than 3 m from shore, and in some cases not closer than 5-6 m. Shallow water, fallen logs, and boulders generally preclude close data collection passes. Because lake seepage rates are generally maximum within a meter or two of the shoreline, with a towed-cable resistivity survey one may not be able to image the environment (≤2 m) where a majority of seepage occurs. Second, the length of the cable used in the towed surveys is great enough that when making turns to follow a cove or peninsula, the electrodes at the tail end of the survey cable take a different path than those closest to the boat. This means that, as illustrated in Figure 3, a towed-cable resistivity survey will reveal only limited information where the shoreline is irregular. With the stationary-cable resistivity surveys the researcher can overcome previously mentioned limitations of the towed-survey, as stationary-cable surveys can be conducted close to shore and in coves. The improvement comes at the expense of time: a stationary cable survey of a 100-meter stretch of shoreline takes several hours to complete where a towed-survey would take only a few minutes to cover the same distance. These findings are exemplified by the imaging of a hypothesized road-salt contaminant plume in the northeast inlet area of Mirror Lake. Towed-cable surveys of that area suggested the presence of a region of salt contamination. Subsequent stationary-cable surveys both supported its existence and suggested its shape and extent. Our work at Mirror Lake also highlighted the versatility of correlating electrical resistivity surveying to seepage. Variations in resistivity along the southwest shore of

Mirror Lake probably resulted from changes in porosity, which at that site appear to relate to the hydraulic conductivity of sediment. Variations in resistivity within the northeast inlet were the product of changes in pore-fluid conductivity. Both have implications for characterizing underwater seepage: the former in terms of its ability to suggest the geologic variations which control seepage, the latter in terms of evidence of flow paths within a lake. In this way geophysical surveys can highlight geologic heterogeneities which control seepage and guide point measurement of that seepage.

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