Examining Pathways for Water Loss from Mountain Lake, Giles County, VA

William Lucas Joyce

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In

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Madeline E. Schreiber, Committee Chair

Chester F. Watts

James A. Spotila

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Abstract

Located in Giles County, Virginia, Mountain Lake has a documented history of dramatic water level fluctuations. Previous water balance studies have documented that the main cause of water loss is outflow to groundwater. However, the flow paths of water exiting the lake are unknown. This study applied hydrologic, geophysical, and dye tracer methods to examine the pathways for water loss and the possible geologic controls on these flow paths.

Continuous lake level monitoring data show seasonal trends of draining and filling over a three year period. Electrical resistivity profiles suggest the presence of a large low-resistivity zone beneath the northern end of the lake. A dye tracer study yielded limited positive results, but dye detection in one stream and within the lake suggest complex flow dynamics. The most likely reasons for the lack of dye recovery include dilution of the dye during lake recovery, seepage of water below monitoring site locations, or formation of a temporary seal in the depressions created by influx of sediment during periods of lake bed exposure.

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1. Introduction

First documented by British surveyor Christopher Gist in 1751(Johnston, 1898), Mountain Lake is a unique hydrologic feature in the unglaciated portions of the southern Appalachian Mountains. Located in Giles County, Virginia, it is one of two naturally formed freshwater lakes in Virginia and the highest in elevation east of the Mississippi River. The lake lies on private property owned by the Mountain Lake Conservancy and Hotel. The site was operated as a resort as early as 1857; the current hotel structure was erected in 1936 and is still in use today. The Mountain Lake Conservancy was founded in 1989 to help manage and protect the 2,600 acres of Mountain Lake property and provide environmental and cultural education to the public (www.mountainlakehotel.com).

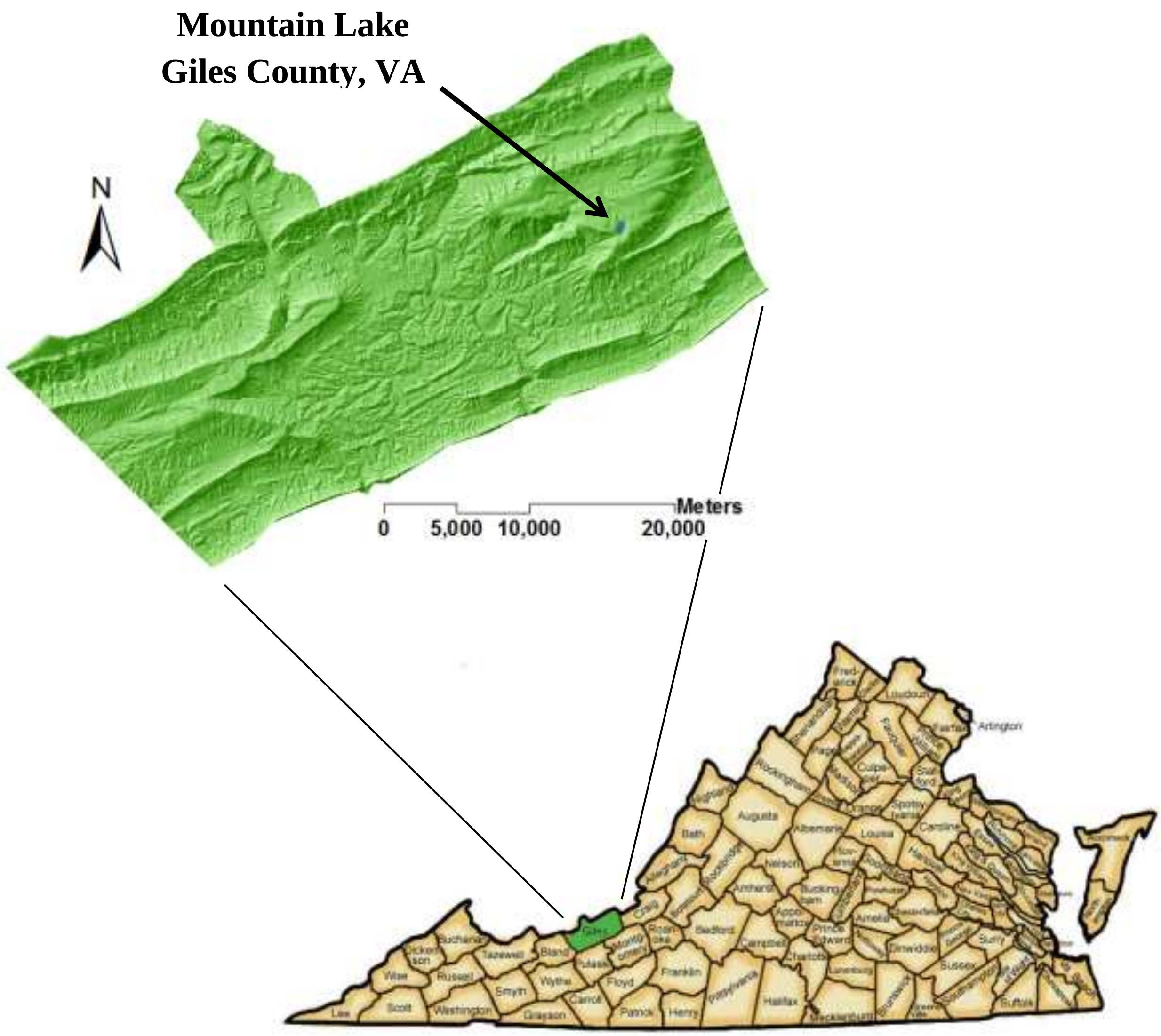

Figure 1: Location of study area
[Map Sources: USGS 1/3 arc second DEM and www.gilescounty.net]

1.1 Site Geology and Geomorphology

Mountain Lake is situated on the axis of the doubly-plunging Bane Anticline and is underlain by three sedimentary rock units (Bartholomew et al., 2000) [Figure 2]. The Ordovician Reedsville shale and Trenton Formation (Ort), also known as the Martinsburg Formation, underlies the southern end of the lake bed. The upper portion of this unit is dominated by mudstone and sandstone, while the lower portion is composed of 2 to 15 cm thick beds of limestone and calcareous mudstone. A surface stream incising through lacustrine sediments has exposed the Ordovician Juniata Formation (Oj) in the middle of the lake bed. The lower Juniata is dominantly fine-grained sandstone with interbedded shale, grading upward into interbedded medium-grained sandstone and siltstone. The Silurian Tuscarora Formation (Stu), also referred to as the Clinch Formation, is a locally conglomeritic orthoquartzite found in outcrop along Mountain Lake road to the west of the lake and as colluvium in the lake bed at the northern end of the lake. The Silurian Rose Hill Formation (Srh), a hematitic sandstone with irregularly interbedded shale, is also present in the lake bed as float (Bartholomew et al., 2000).

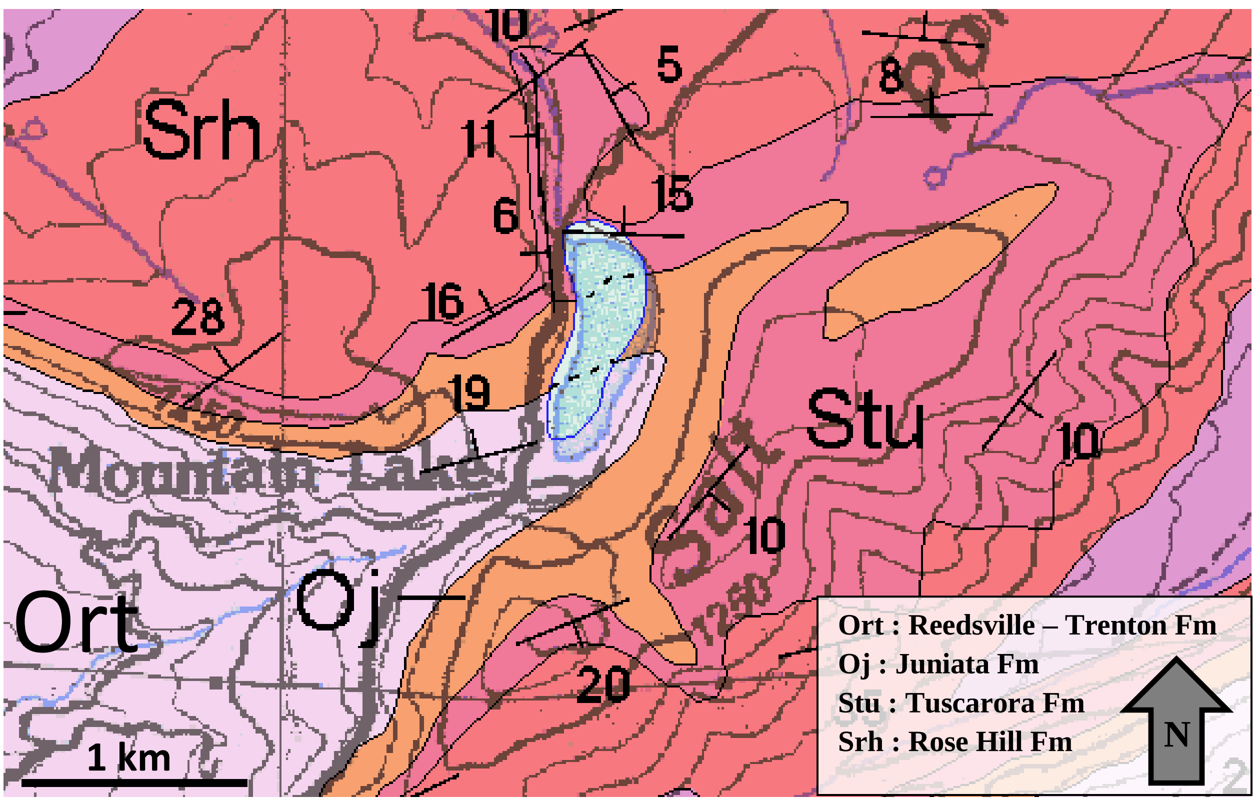

Figure 2: Geologic formations underlying Mountain Lake
[Map Source : (Bartholomew et al., 2000)]

1.1.1 Theories on the origins of Mountain Lake

Multiple theories on the geomorphic origins of Mountain Lake have been put forth. Parker et al. (1975) suggested that the dam formed by damming the headwaters of Pond Drain with “talus (sliderock)”. In this theory, the resistant sandstones of the Clinch likely collapsed into the valley below as Pond Drain eroded headward and undercut the adjacent ridges during a periglacial climate about 10,000 YBP. The interstices of the colluvium were progressively infilled with alluvial sediments, creating a more complete seal of the dam. Parker et al. (1975) stressed that the boulder dam was not completely sealed and allowed for leakage, resulting in lake level fluctuations. This theory of lake origin is in agreement with or similar to previous work by Rogers (1884), Hutchinson and Pickford (1932), (Sharp, 1933), and(Marland, 1967). Cawley et al. (2001b) mapped a northwesterly lineation, likely a fault, using electrical resistivity measurements along Pond Drain and the north end of the lake. Cawley et al. (2001b) proposed that in addition to probable water loss through the boulder dam, water loss and gains could be associated with this deep crevice or fault aligned with the deepest depression at the north end of the lake. Roningen (2011) was unable to confirm this feature in the field, but did not dismiss it as an important structural feature.

Some authors have suggested karst dissolution having an influence on lake formation. Ferguson et al. (1939) attributed the lake’s formation to “a natural collapse basin” caused by dissolution of a carbonate layer in the upper Martinsburg, an idea first proposed by Holden (1938). A 2-m thick carbonate layer was also described at the top of the Martinsburg by Butts (1940) north of Narrows, Virginia, about 24 km west of Mountain Lake. The Martinsburg and Juniata have been described as containing thin beds of limestone or elevated amounts of carbonate in the vicinity of the lake [Marland (1967) and Parker et al. (1975)]. Others have argued that no sinkholes have been found elsewhere in the Martinsburg and that the formation would maintain its structural integrity even if dissolution did occur based on structural evidence in a tunnel cutting through a complete section of the unit [Cooper (1964) and Fiedler (1967)].

1.2 Site Hydrology

The base of Mountain Lake lies approximately 666.67 meters above the New River, which serves as local base level for the area [Appendix A]. At full pond, lake volume has been calculated to be approximately 1.87×10^6 m^3, with a surface area of 1.94×10^5 m^2 (Roningen, 2011). The eastern edge of Mountain Lake's 1.3 km^2 watershed lies along the eastern continental divide, separating the Ohio and Mid-Atlantic Hydrologic units [Figure 3]. Three prominent stream systems flow away from Mountain Lake. To the east of the lake and the eastern continental divide, Johns Creek flows north/northeast towards the Chesapeake Bay. Pond Drain flows northwest into Little Stony Creek, which discharges to the New River. Doe Creek flows southwest into the New River. The New River joins the Ohio River, which empties into the Mississippi River.

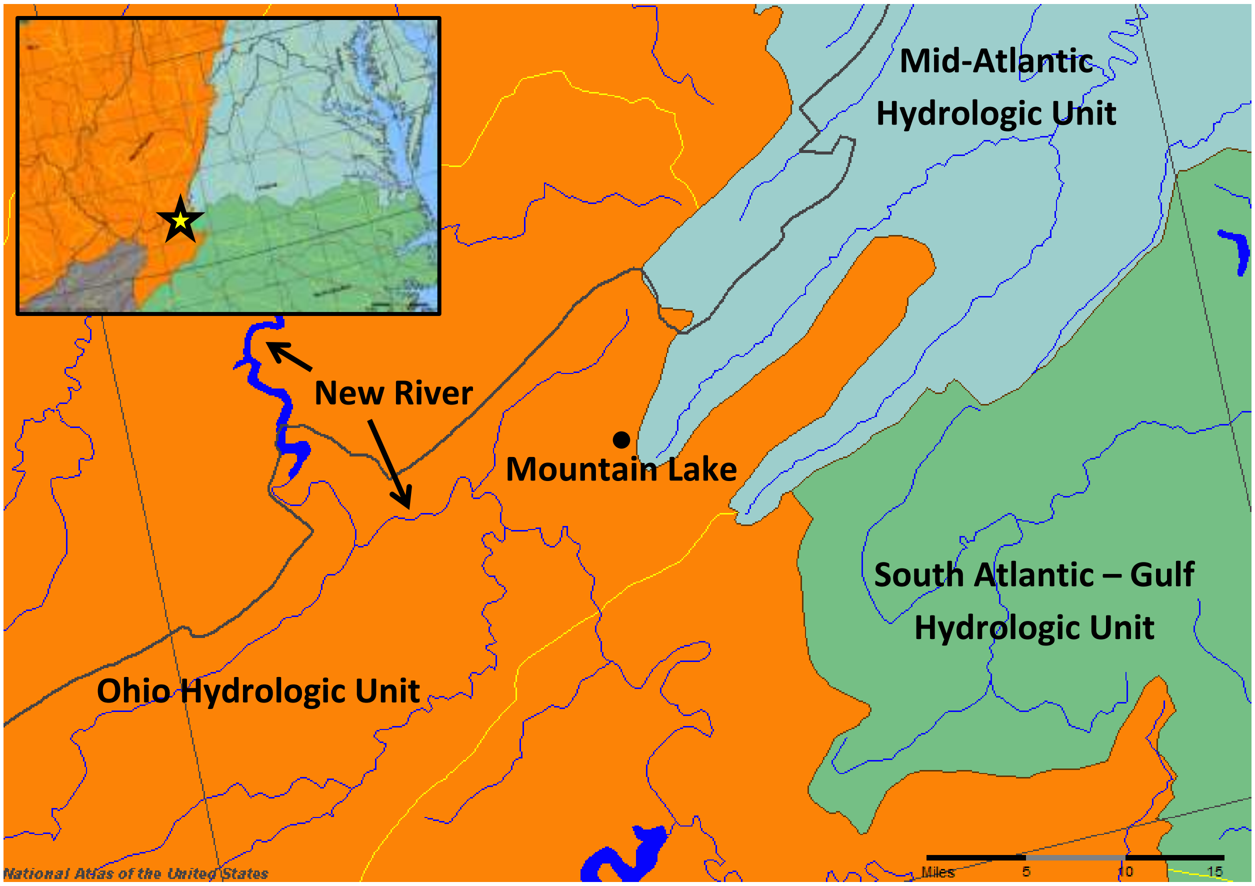

Figure 3: Location of Mountain Lake within USGS hydrologic units [Map source: National Atlas of the United States, 2010]

1.2.1 Water level fluctuations at Mountain Lake

Mountain Lake has a documented history of dramatic water level fluctuation (Jansons et al., 2004). Sediment core and tree-ring analysis provide biological evidence of lake level changes over geologic time. Marland (1967) found zones of littoral cladocerans in sediment cores, suggesting past low water levels. Using tree ring analysis, Parker et al. (1975) documented low water levels over a two decade period 1655±80 YBP. Cawley et al. (2001a) interpreted data from sediment core analyses and radiocarbon dating of pollen, spore, and microfossil assemblages to indicate six prolonged periods when the lake was nearly dry or water levels were low. These low water levels occurred at about 100, 400, 900, 1200, and 4100 YBP. The core contents also indicated a full lake at about 6100 YBP.

Since 2009, daily lake levels have been measured using pressure transducers [Figure 4]. The pattern shown indicates lake level declines during summer and fall, and increasing levels during winter and spring.

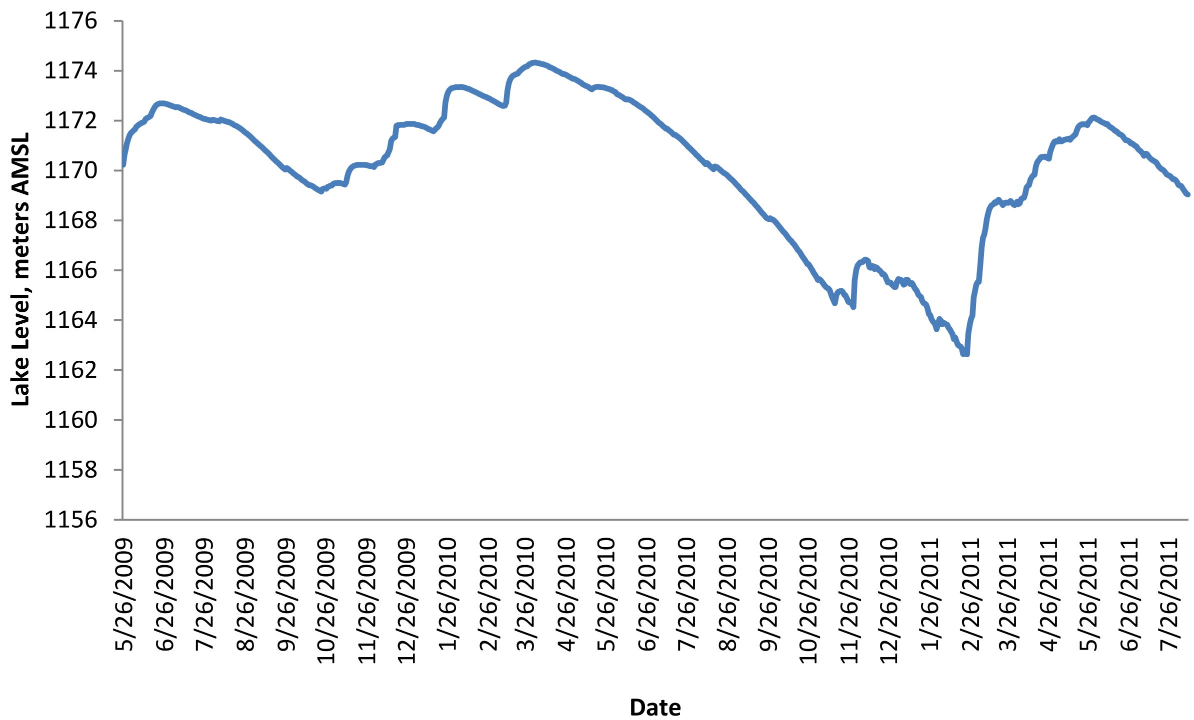

Figure 4: Lake level changes from May 2009 – August 2011 (Full pond at 1184 meters AMSL)

1.2.2 Water Balance

Multiple studies have been conducted to quantify water loss from the lake. Jansons et al. (2004) calculated a monthly water balance using lake level and precipitation data between February 2002 and September 2003, a time when lake level dropped a maximum of 6.6 m below full pond. Results of his water balance yielded a net subterranean outflows ranging from 2.6 to 107 liters per second on a monthly basis, with an annual average of 43 liters per second. This water balance by was reevaluated by Roningen (2011) with a higher-resolution dataset in order to quantify the variation in net groundwater outflows over time. Roningen's calculations reveal average net groundwater outflow to be 44 liters per second, which is similar to the average value from Jansons et al. (2004). However, Roningen's water balance shows lake outflows to be relatively uniform throughout the year, while Jansons et al. (2004) reported more variation.

Research Question

Previous work has documented lake level fluctuation in at Mountain Lake, and recent studies have used water balances to quantify temporal patterns of water loss from the lake. However, there are several unanswered questions about where water exiting the lake goes and possible geologic controls on these flow paths. This study applied hydrologic, geophysical, and dye tracer methods to address these questions. Continuous lake level monitoring was conducted to document daily changes in lake level, building upon the dataset on lake levels started by Roningen (2011). Side scanning sonar profiling of the lake was conducted to characterize lake bed morphometry and to calculate lake volume. Electrical resistivity profiling of the dry lake bed was used to identify possible subsurface reservoirs or pathways for water to exit the lake. Last, a dye tracer study was implemented to help delineate possible subterranean pathways for water exiting the lake.

2. Methods

2.1 Lake level monitoring

Lake level monitoring was conducted using a pressure transducer (In-Situ level TROLL 300) deployed in the lake. Data collection with this transducer began in October 2010 and continued until August 2011. These data were combined with data collected by Roningen (2011) from May 2009 – October 2010 to develop a longer-term dataset. Additional lake level data were collected using an In-Situ Mini-Troll with a vented cable from August 2011 – May 2012. The use of a transducer with a vented cable allowed for data to be collected from the lake surface without having to retrieve the transducer from the lake.

2.2 Sonar Bathymetry

Bathymetric maps of the lake bed have been developed previously using depth soundings, sonar, differentially corrected global positioning system (GPS) data, and geographic information systems (GIS) [(Cawley, 1999); (Roningen, 2011)]. However, a higher resolution bathymetric map was required by this study for calculating lake volume in preparation for the dye study. Data were collected in August 2011 using a Hummingbird Model 998ci HD GPS/Side-Scan Sonar and Depth Sounder when lake depth was measured to be approximately 10m inside the deepest depression. Several traverses were made across the lake surface while the Hummingbird equipment recorded depth and GPS coordinates. The data were processed using Dr. Depth Bathymetric Mapping Software (Version 4.6). Lake volumes were calculated using Dr. Depth with bathymetric data and water level measurements from the pressure transducer at the north end of the lake.

2.3 Electrical resistivity

Electrical resistivity (ER) was used to locate possible underground reservoirs or conduits for water loss from the bottom of the lake. ER uses direct electrical current applied at the ground surface to measure potential difference between two points (Burger et al., 2006). Two-dimensional profiling of resistivity data is commonly used for determining distribution of electrical resistance in the subsurface for use in environmental, geological, and archeological studies (Seaton and Burbey, 2002). This technique has been used to locate the water table, saturated fracture zones, depth to bedrock, faults, and karstic conduits for subsurface water flow [(Cawley, 1999); (Seaton and Burbey, 2000); (Burger et al., 2006); (Roningen, 2011)]. ER does not distinguish between ponded and flowing water in the subsurface, but increased hydraulic conductivity may be inferred from low-resistivity zones evident on two-dimensional profiles.

Several data collection techniques are available for electrical resistivity surveys, each taking a series of voltage and current measurements from an array of electrodes at the ground surface along a line of section (Seaton and Burbey, 2002). Seaton and Burbey (2002) found the dipole-dipole array yielded the deepest profile and finest resolution among several common ER arrays in a fractured crystalline rock setting in the Blue Ridge Province of Virginia. Roningen (2011) used the dipole-dipole array while characterizing the hydrogeologic controls on lake level at Mountain Lake. The dipole-dipole array was chosen for identifying zones of low resistivity beneath the lake bed in this study.

Low lake levels allowed for an ER survey to be completed in areas of the lake previously inaccessible. Data for seven ER profiles were collected for this survey on the exposed lake bed using an Advanced Geosciences, Inc. Supersting 8 –

channel resistivity meter. Measurements were made with 32 electrodes at various spacings dictated by accessibility and good connectivity. ER data were inverted using Res2DInv. Topographic data of profiles, collected using Delomre PN40 handheld GPS, were included in the inversions. Large variations in near-surface resistivity were often present, so model cell sizes were set to one half of electrode spacing to account for this variability. True depths of subsurface features cannot be measured from the models. But if parameters used to calculate apparent depths are uniformly applied, then apparent depths can be compared between profiles and interpretation of connected zones of similar resistivity can be made.

2.4 Dye tracer study

A dye tracer experiment was conducted in winter 2011 - spring 2012 to examine possible pathways for water loss from the lake. Fluorescent dyes have been successfully used as a tool in studying of a variety of hydrologic systems for more than 100 years [(Smart and Laidlaw, 1977); (Kass, 1998); (OUL, 2002)]. The ideal tracer is: (1) easily introduced into the system, (2) travels at or near the speed of water, (3) relatively resistant to sorption, (4) detectable at low concentrations, (5) relatively inexpensive, and (6) environmentally safe [(Smart and Laidlaw, 1977); (Field et al., 1995)]. Fluorescent dyes are organic compounds that absorb light from the ultraviolet part of the spectrum and emit light at a longer wavelength when excited (Kass, 1998). Ozark Underground Laboratory (OUL) was consulted during the design and implementation of the tracer study due to their prior experience in both conducting dye studies and analyzing samples.

Several factors were considered during selection of the day for this study. The effectiveness of dyes may be influenced by water chemistry, temperature, photodegradation, chemical decay, biodegradation, adsorption of media which dye comes in contact with (OUL, 2002). Fluorescein ($C_{20}H_{10}O_5Na_2$), also known as uranine, was chosen as it is considered the most effective fluorescent tracer for groundwater studies due to its resistance to adsorption, quantity needed for a successful trace, and ability to be eluted from activated carbon samplers during analysis (OUL, 2002 and personal comm).

Sampling for tracer dyes can be accomplished either with activated carbon packets or with water samples. The packets continuously adsorb and accumulate dye over time, whereas water samples are "grabbed" and only represent a small time interval. Due to the remoteness of locations where lake water may be detectable at the surface and the associated sampling intervals, activated carbon packets were chosen for sampling streams in the vicinity of Mountain Lake. OUL manufactures and analyzes packets, which are composed of approximately 4.25 grams of coconut shell charcoal with a surface area of 1150 m^2/g. The charcoal is contained in a fiberglass screening with intervals to retain 99% of the charcoal, while allowing water to flow through the packets.

2.4.1 Monitoring site locations

Fifteen monitoring sites for the dye study were selected in streams flowing away from Mountain Lake [Figure 5]. Packets were independently anchored at each site. Measures were taken to position packets in areas not exposed to prolonged periods of direct sunlight, thereby reducing likelihood of photochemical decay of fluorescein.

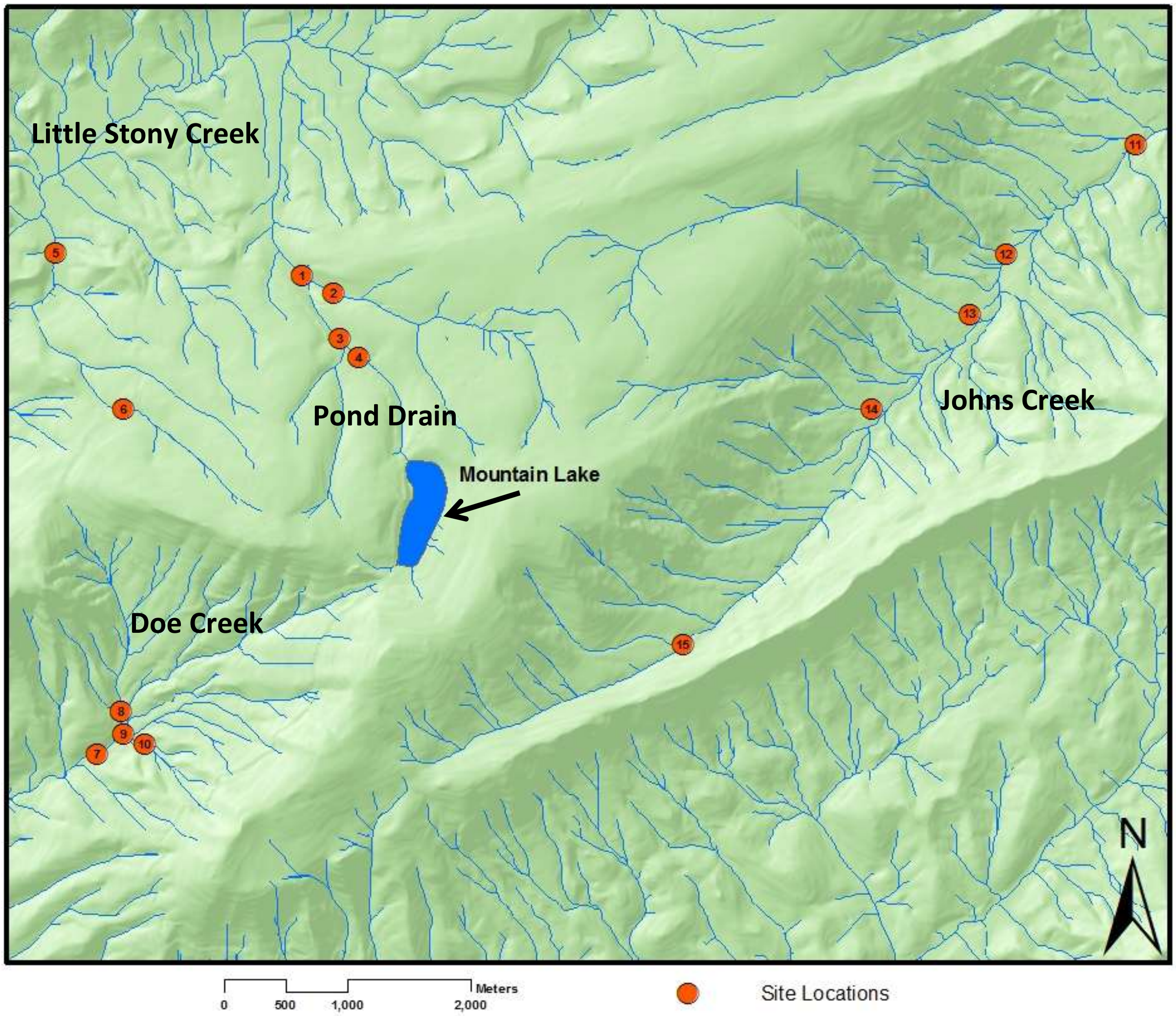

Figure 5: Site locations for dye tracer study

Pond Drain/Little Stony Creek

Surface water exits Mountain Lake through a concrete spillway at the crest of the naturally formed dam and down Pond Drain at full pond. As discussed above, Parker et al. (1975) described the dam as having an incomplete seal, accounting for lake level fluctuations. Cawley et al. (2001b) suggested water losses and gains may also be associated with the northwesterly structure aligned with Pond Drain, in addition to losses through the dam. Exit head elevations for Pond Drain were calculated to be from 936-1081m AMSL (Roningen, 2011). Six sites were chosen in this drainage to determine if water exiting the lake becomes exposed on the surface.

Site 1 is the most downstream location in Pond Drain. Site 2 is located in Hunters Branch above its convergence with Pond Drain. Sites 3 and 4 are located in Pond Drain approximately 670m and 875m upstream of the confluence of Hunters Branch and Pond Drain, respectively. Site 5 is located in Little Stony Creek downstream from the confluence of Pond Drain. Site 6 is located in Hemlock Branch upstream from its confluence with Little Stony Creek. Sites 1, 2, and 6 are located at elevations within the range of exit head elevations proposed by Roningen (2011), while Site 5 is located 3m below lower end of this range.

Doe Creek

Site 7 is located in Doe Creek about 30m below the confluence of its upstream tributaries where Sites 8, 9, and 10 are located. Site 8 is located in the western most limb, Site 9 is located in the center limb, while Site 10 is in the eastern most limb.

Johns Creek

Dye-tracer tests have routinely shown that conduit flow paths commonly extend beneath topographic drainage divides and, in some places, beneath perennial streams, and that water in one watershed may be transferred via subsurface flow routes into adjacent basins (Ray, 2001). Joint sampling on several outcrops in the vicinity of Mountain Lake by Roningen (2011) revealed a joint trend existing in the north-northeasterly direction between N50E and N80E, possibly associated with a breached Bane Anticline. This lineament aligns with the headwaters of Sartain and Saltpeter Branch, which flow into the Johns Creek basin across the continental divide to the east of the lake. The structural feature identified by Cawley et al. (2001b) is sub-perpendicular to the lineament described by Roningen

(2011) and intersects Johns Creek when projected to the southeast across the continental divide.

Five sites were selected in the Johns Creek drainage. Site 11 is the most downstream site in Johns Creek. Site 12 is also located in Johns Creek, just below the confluence of Saltpeter Branch with the trunk stream. Site 13 and 14 are located above confluence with Johns Creek in Saltpeter Branch and Sartain Branch, respectively, which were chosen to test if joints create preferential flowpaths in the subsurface across the eastern continental divide. Site 15 is located downstream from where the structural feature referenced by Cawley et al. (2001b) intersects Johns Creek when projected across the drainage divide.

Mountain Lake

Packets were deployed in Mountain Lake 8 weeks after dye introduction to determine if any fluorescein remained in the lake. Packets were secured at varying depths in the vicinity of the two deepest depressions at the north end of the lake and collected during Rounds 6 and 7. This group of packets is referred to as Site 16. No background fluorescence data were collected in the lake itself prior to dye injection.

2.4.2 Background sampling

Packets were deployed prior to dye injection at sites 1 (Pond Drain), 5 (Little Stony Creek), 7 (Doe Creek), and 11 (Johns Creek) to examine background fluorescence. Other tracer dyes, natural compounds, or manmade compounds with similar fluorescence characteristics may exhibit fluorescence peaks in or near the acceptable wavelength range of fluorescein during analysis (OUL, 2002). Any background fluorescence present in a particular stream can therefore be accounted for if positive results are found during analysis. The packets were collected 21 days after deployment and analyzed prior to dye injection.

2.4.3 Dye injection

After the background sampling, and once packets were secured at each monitoring site, four pounds of dye powder, 75% fluorescein by weight, were injected into Mountain Lake on January 16, 2012 in the vicinity of the four depression location in northern end of the lake (one pound per depression). Injection points were selected using the bathymetric map and handheld GPS to locate the depressions from the surface of the lake. One pound of fluorescein powder was mixed with one gallon of distilled water on site to achieve a concentration of about 90.5 g/liter or 90583.4 ppm. A treme pipe was used to inject the dye within 2m of each depression in an attempt to reduce the amount of time available for dilution of the mixture.

2.4.4 Packet collection and analysis

After the dye injection, packets were collected from monitoring sites at 10-14 day intervals. This period was recommended by OUL to reduce the amount of natural compounds adsorbed on the activated carbon, limit biological growth on the samplers, and limit time available for photodegradation to occur. Care was exercised during packet collection (e.g., use of gloves) to avoid contamination during recovery. Packets were placed in whirly bags and mailed to OUL in a refrigerated cooler.

All dye analyses were conducted at OUL using a spectrofluorophotometer operating with a synchronous scan protocol and a method detection limit of 0.0100 ppb. Packets received by OUL are washed using dye-free unchlorinated water prior to being eluted. OUL elutes the tracer dye from the activated carbon using a mixture of 5% aqua ammonia and 95% isopropyl alcohol solution, with sufficient potassium hydroxide flakes to saturate the solution. Positive tests for fluorescein in elutant are indicated by emission peak wavelengths of 510.7 nm to 515.0 nm. A more thorough discussion of elution and analysis procedures can be found in OUL's Groundwater Tracing Handbook (2002).

3. Results

3.1 Lake level data

Water level fluctuations at Mountain Lake are similar to seasonal trends observed prior to the beginning of this study and show sensitivity to precipitation [Figure 6]. Lake levels steadily declined until mid-November, when water levels began to recover. The lake continued to recharge throughout the winter and spring while the dye tracer study was on-going.

The two gaps in Figure 6 represent occasions when the pressure transducer was out of the water and not data was recorded. As lake levels declined during fall 2011, water levels fell lower than the level of the transducer on October 20, 2011. The pressure transducer was relocated into the deepest depression at the north end of the lake on October 29, 2011.

The buoy, to which the top of the transducer cable was attached, was found upside down on December 11, 2011. The transducer and cable were removed from the anchor line to verify the equipment was not damaged. The transducer was reattached to the anchor line on December 14, 2011. This represents the second gap in the dataset shown in Figure 6.

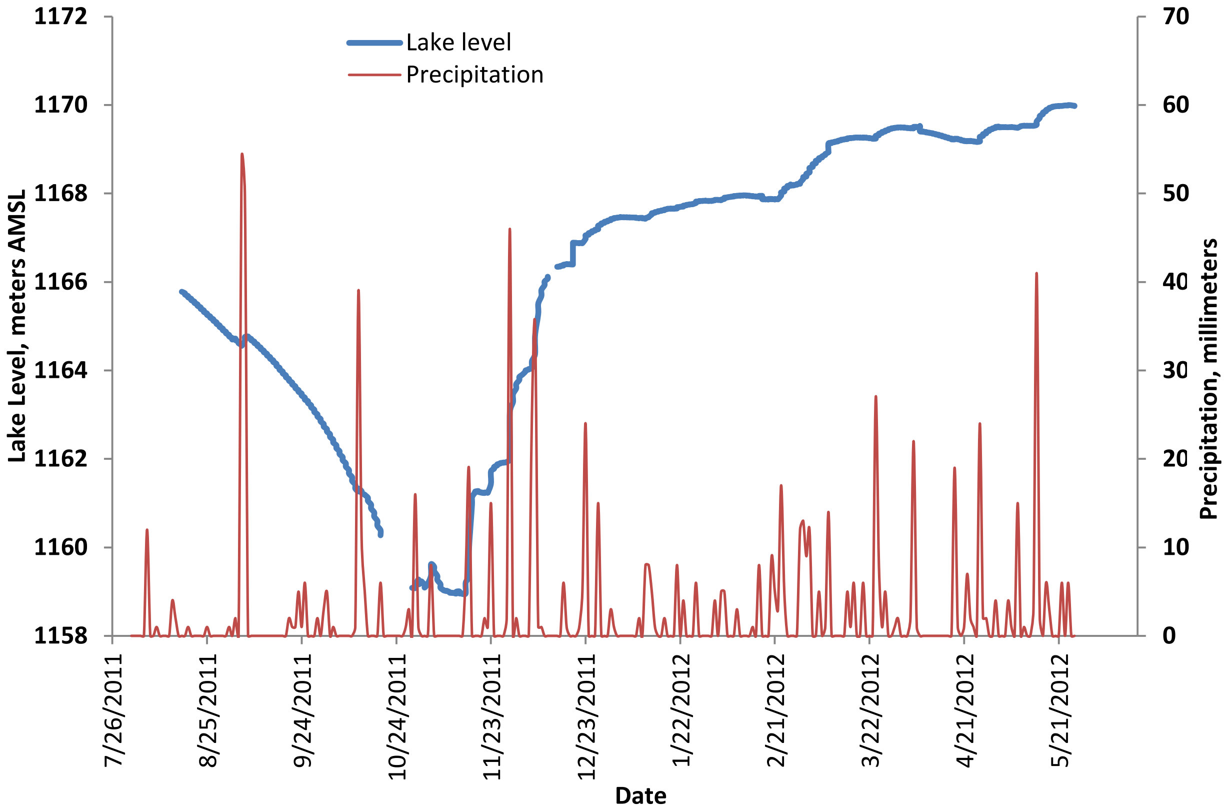

Figure 6: Lake level changes with precipitation from August 2011 – May 2012 (Full pond is 1184 meters AMSL)

3.2 Lake bathymetry

Figure 7 shows the bathymetry map produced by Dr. Depth Bathymetric Mapping Software (Version 4.6). The body of water had a surface area of 4.62 x 10^4 m^2, with volume calculated to be 1.64 x 10^5 m^3, on August 11, 2011 when the data were collected. This volume of water is approximately 8.8% of full lake volume (Roningen, 2011). Four pronounced depressions are apparent at the north-northwest end of the lake. The deepest depression had approximately 9.8m of water above it at the time data were collected.

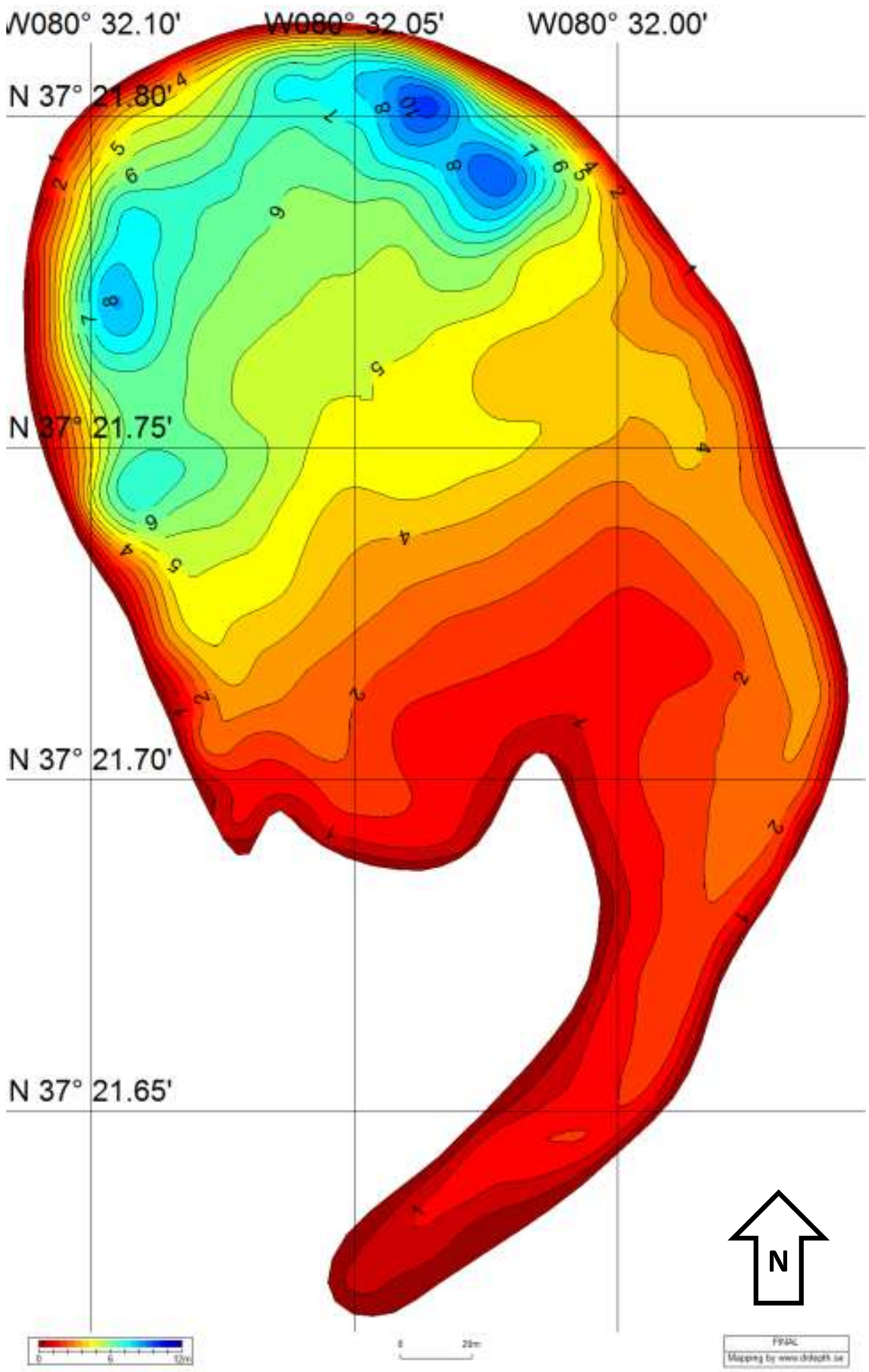

Figure 7: Bathymetric map of lake bed during study

(Data collected on August 11, 2011)

3.3 Electrical resistivity

ER profiles were labeled in order of which data were collected, beginning with MLLN1, moving north towards the deeper end of the lake (Figure 8).

Figure 8: Location of ER profiles at Mountain Lake

[Background image source: Google Earth, 2011]

The most significant results of the electrical resistivity survey are discussed below, while additional profiles can be found in Appendix B. Profiles MLLN4, MLLN5, and MLLN7 are displayed in this section. The results display variations in resistivity from the average on a log scale, but the resistivity scale is not fixed from profile to profile. The length along each profile is shown in meters away from the first electrode of a respective array. Apparent elevations are shown in meters AMSL.

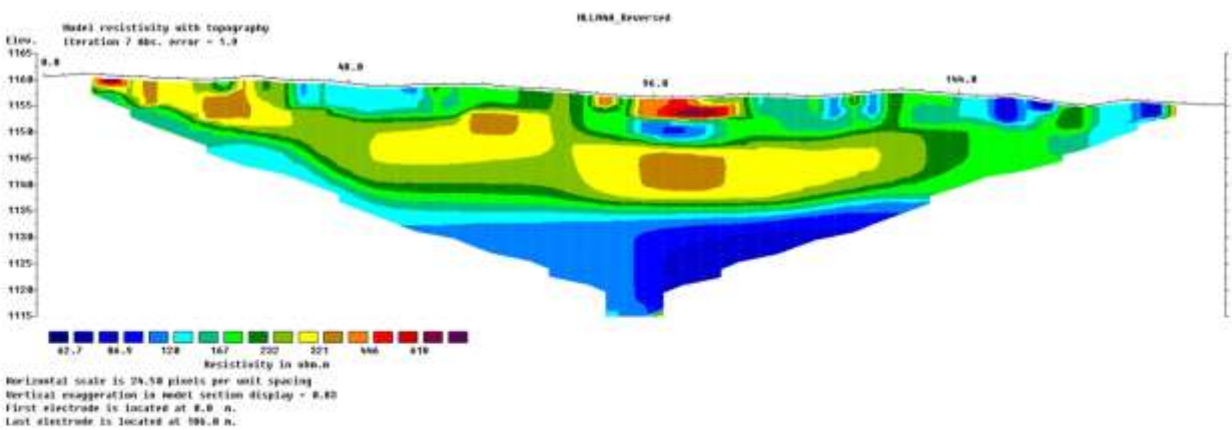

Figure 9: ER Line MLLN4

Figure 9 is a NE-SW profile approximately 250m south of the northern extent of the lake. This profile displays an area of low resistivity (<100 ohm.m) at approximately 6m below the surface (1151m AMSL). A second area of low resistivity is apparent approximately 30m below the surface (1133m AMSL). This zone extends from the center of the profile to the eastern extent of the profile.

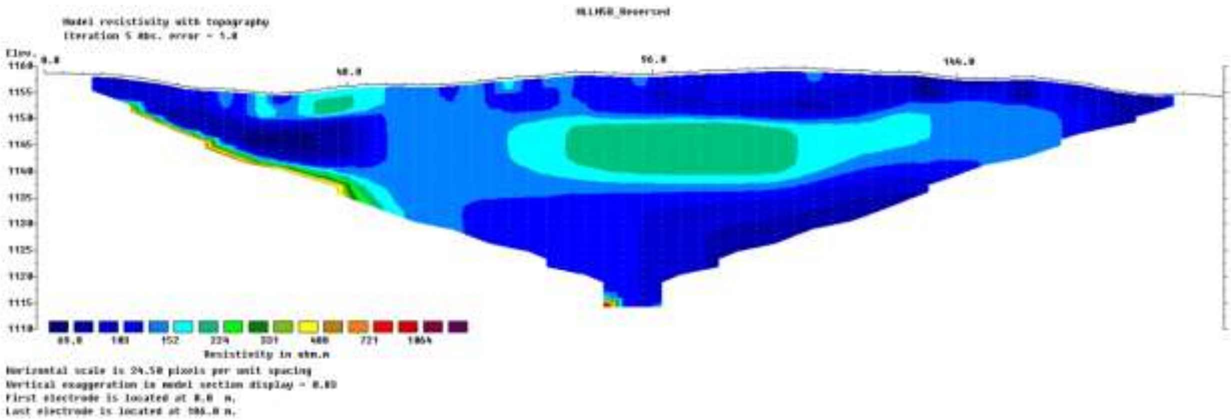

Figure 10: ER Line MLLN5

Figure 10 is a NE-SW profile across the lake bed across the northern end of the lake bed. There is an area of very low resistivity near the western edge of the profile approximately 9m below the surface (1146m AMSL). This feature correlates well with the two pronounced depressions to the western side of the bathymetry map in the vicinity of the naturally formed dam (Figure 7). A larger zone of low resistivity appears between 27m below the surface (1130m AMSL) and the bottom of the profile. The deeper zone of low resistivity extends to the eastern extent of the profile. Note that the majority of the profile indicates low resistance to the current injected by the resistivity meter. This may be explained by the profile's proximity to the small pool of water to the north of the line when data were collected. The lake bottom had only recently been exposed when data were collected and moisture content of materials in the subsurface were likely higher than that of profiles located to the south, which are at a higher elevation and exposed for a longer amount of time.

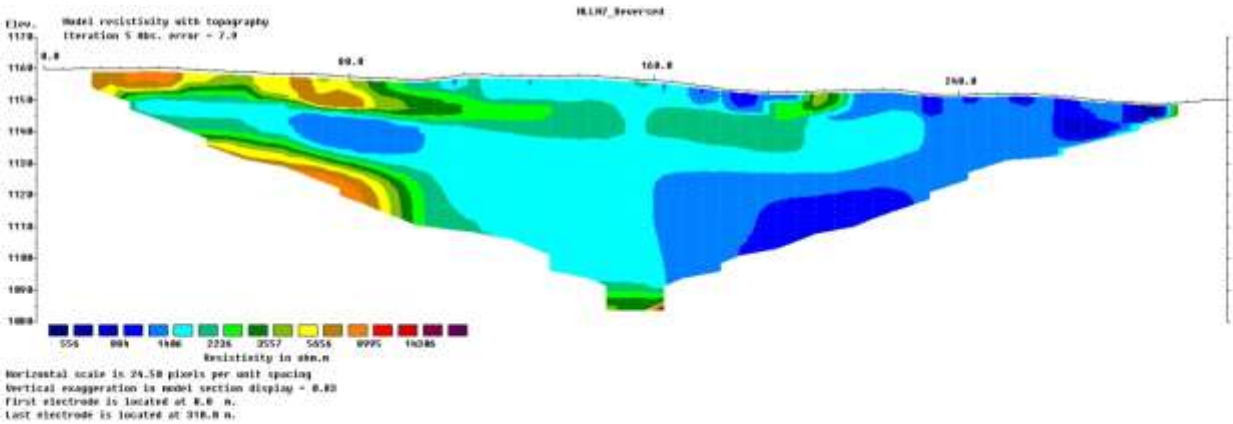

Figure 11: ER Line MLLN7

Figure 11 is a south/north profile through the center of the lake bed that intersects profiles MLLN4 and MLLN5 at a sub-perpendicular angle. A zone of low resistivity is apparent at approximately 16 meters (1140m AMSL) beneath the lake bed on the western half of the profile. This zone appears in the vicinity of the intersections of MLLN4 and MLLN7. A second zone of low resistivity begins approximately 30 meters (1127m AMSL) below the lake bed near the intersection of MLLN5 and MLLN7. The area of low resistivity near the surface at the eastern edge of the profile represents the small pool of water contained in the two deepest depressions visible on the bathymetry map at time of the survey.

MLLN7 (Figure 11) has a considerably higher absolute error than Profiles MLLN4 and MLLN 5: 7.9% compared to 1.9% and 1.8%, respectively. The range of apparent resistivity values displayed in Figure 11 is much greater than that of Profiles MLLN4 and MLLN5. In fact, Res2Dinv utilized direct smoothing of model resistivity values because the maximum apparent resistivity is >300 times greater than the minimum. This increase in uncertainty is likely related to the removal of 55 data points associated with a bad electrode connection at the surface during data collection. During data collection, the eleventh electrode in the array (located 100m along the profile at the surface) repeatedly indicated a problem while checking test resistances before data collection began. The removal of these data points likely increased the absolute error percentage calculated in Res2Dinv while the data were inverted.

3.4 Dye study

Results of the dye study are shown in Table 1.

Packets were placed at Site 1, Site 5, Site 7, and Site 11 in December 2011 and left in place for 21 days to account for any background fluorescence present in streams prior to dye injection. No background fluorescence was detected at any of the monitoring sites where packets were deployed (OUL, personal communication).

No dye was detected in any of the packets during the first 54 days after injection (Rounds 1-5; Table 1). After 54 days (Round 6), packets were installed in the lake to determine if dye was still present in the lake and labeled Site 16. The packets were secured at varying depths in the vicinity of the two deepest depressions at the north end of the lake.

After 54 days (Round 6), dye was detected at two locations: Site 2 and Site 16 (Table 1). At Site 2, dye concentration was measured to be 0.449 parts per billion (ppb) at a peak wavelength of 512.6nm. This positive test was not replicated during subsequent analysis of Round 7 packets (82-107 days) at the same location. Lake packets from Round 6 revealed a dye concentration of 1.57 ppb at a peak wavelength of 515.6 nm. Analysis of packets from the same location for Round 7 found a concentration of 2.63 ppb at a peak wavelength of 515.2nm.

	Description	Elevation AMSL (m)	Background	Round 1 0 - 11 days	Round 2 11 - 22 days	Round 3 22 - 32 days	Round 4 32 - 43 days	Round 5 43 - 54 days	Round 6 54 - 82 days	Round 7 82 - 107 days
Pond Drain										
Site 1	Pond Drain downstream	1056.8	ND!	ND	ND	ND	ND	ND	ND	ND
Site 2	Hunters Branch	1067.2	n/a	ND	ND	ND	ND	ND	0.449 / 512.6*	ND
Site 3	Pond Drain middle	1112.2	n/a	ND	ND	ND	ND	ND	ND	ND
Site 4	Pond Drain upstream	1124.1	n/a	ND	ND	ND	ND	ND	ND	ND
Little Stony Creek										
Site 5	Little Stony Creek	932.7	ND!	ND	ND	ND	ND	ND	ND	ND
Site 6	Hemlock Branch	1057.7	n/a	x	x	x	ND	ND	ND	ND
Doe Creek										
Site 7	Doe Creek downstream	778.0	ND!	ND	ND	ND	ND	ND	ND	ND
Site 8	Doe Creek left limb	820.2	n/a	ND	x	x	ND	ND	ND	ND
Site 9	Doe Creek middle	809.2	n/a	ND	x	x	ND	ND	ND	ND
Site 10	Doe Creek right limb	806.2	n/a	ND	x	x	ND	ND	ND	ND
Johns Creek										
Site 11	Johns Creek downstream	636.9	ND!	ND	ND	ND	ND	ND	ND	ND
Site 12	Johns Creek middle	663.0	n/a	ND	ND	ND	ND	ND	ND	ND
Site 13	Saltpeter Branch	685.9	n/a	ND	ND	ND	ND	ND	ND	ND
Site 14	Sartain Branch	737.6	n/a	ND	ND	ND	ND	ND	ND	ND
Site 15	Johns Creek upstream	900.2	n/a	ND	ND	ND	ND	ND	ND	ND
Mountain Lake										
Site 16	Lake packets	varies	n/a	n/a	n/a	n/a	n/a	n/a	1.57 / 515.6*	2.63 / 515.2*

Notes:

ND = No Dye Detected

n/a = Packets not in place at this time

x = Sample not analyzed

* = Concentration (ppb) / Peak fluorescence (nm)

! = Background analysis for Fluorescein, eosine, RWT, and SRB

Table 1: Dye study results from packet analysis at OUL

4. Discussion

4.1 Hydrologic characterization of Mountain Lake

Lake levels followed a similar trend to that documented during previous studies by Jansons et al. (2004) and Roningen (2011) [Figure 6]. Mountain Lake experienced a dramatic decrease in water level during summer and fall of 2011, followed by filling of the lake during winter and spring of 2012. Roningen (2011) observed the lowest lake levels in October 2009 and November 2010 during her study. Lake level reached a low of 1158.97m AMSL on November 11, 2011, approximately 25m below full pond elevation of 1184m AMSL. After this date, lake levels began to recover and continued this trend until the termination of the dye tracer study in May 2012.

The bathymetry map developed during this study shows similarities to those produced by Cawley (1999) and Roningen (2011). The scale at which the bathymetric map was created for this study allowed for recognition of the two smaller depressions at the northwest end of the lake that were not well defined in bathymetry maps previously produced. As lake levels declined during fall 2011, water was observed exiting through both of these smaller depressions, as puddles formed after a heavy rain were drained completely over the course of several hours. The observation of these additional drain holes reinforced the idea that water is exiting the lake through several pathways, not just the larger, deeper holes at the north end of the lake.

Water depth over the deepest depression on the day of dye injection was estimated to be approximately 7.6 meters based on pressure transducer data and depth soundings at each of the four injection sites. The volume of water in the lake was calculated to be approximately 12,225 m^3 at the time dye was introduced. This value is approximately 0.7% of the lake full volume calculated by Roningen (2011).

4.2 Subsurface Characterization of Mountain Lake

The shallow zones of lower resistivity visible in profiles MLLN4 and MLLN5 are separated from the deeper zones by a layer with elevated apparent resistivity approximately 15m thick. The top of this layer is at an elevation of approximately 1150 to 1151m AMSL. MLLN7 intersects these two profiles and shows a similar zone of elevated apparent resistivity at a similar elevation and sloping deeper into the subsurface moving towards the north. The lower boundary of the zone of elevated resistivity values in profiles MLLN4 and MLLN5 is located at an elevation between 1130 to 1133m AMSL. Profile MLLN7 intersects these two profiles and again shows zones of lower resistivity at similar elevations from 168m along the surface of the profile to its northern extent.

Profiles shown in Figures 9, 10, and 11 suggest the presence of an aquiclude separating the upper and lower zones of resistivity. The apparent resistivity values of this aquiclude do not appear to be indicative of rock, but the gentle slope of this feature into the subsurface moving towards the north end of the profile mimics the dip of stratigraphy shown in Figure 2. This zone of elevated apparent resistivity values may represent an intact section of the Juniata formation dipping towards the north/northwest, or perhaps a thick layer of sediments held up by more rigid structures at depth. The deeper zones of low resistivity may indicate the presence of a series of saturated fractures or cavities, or a larger reservoir in the subsurface approximately 27 to 30m beneath the surface at the northern end of the lake. This deeper feature may be associated with a breached Bane Anticline underlying the lake, a large karst feature present in the Martinsburg, or a number of other possibilities. Due to the limited length of profiles along the surface and the decrease in resolution at depth in ER inversions, it is difficult quantify the size of these features.

4.3 Pathways for water loss

Monitoring Site 2 - Hunters Branch

The positive test at Site 2 during Round 6 analysis is difficult to interpret. The emission peak wavelengths of this positive test could have been a small amount of fluorescein, or a false positive caused by human activity upstream (Tom Aley, personal communication). Fluorescence interference can come from the dye itself, as well as other compounds (OUL, 2002). Several anthropogenic activities upstream of the sampling location may have caused the positive test. Mountain Lake Road and the MLBRS are located near the headwaters of Hunters Branch and may have contributed to the positive result via automotive coolant leaks or "leak tracers" used by plumbers. However, there had reportedly been no chemical spills or leak tests during the span of this dye study (Tom McNamara, Facilities Manager for MLBRS, personal communication).

While the dye detection at Site 2 from Round 6 analysis was not replicated during subsequent analysis during Round 7, it is still possible that fluorescein from the lake did actually pass through Site 2 in Hunters Branch. The elutant from the packets had a fluorescein concentration of 0.449 ppb with an emission peak wavelength of 512.6nm. The emission peak wavelength of this positive result falls within the normal acceptable range for fluorescein in elutant at OUL.

Hydraulic conductivity values were calculated assuming the dye detection in Hunters Branch during Round 6 analysis was caused by the presence of fluorescein. A distance of 1.7 km was estimated between the north end of the lake and Site 2. Site 2 is situated at an elevation approximately 87.5 m below the deepest depression at the north end of the lake (1067.2 m AMSL). Several assumptions need to be made in order to quantify the hydraulic conductivity of the material through which lake water may have traveled to arrive at Site 2. Hydraulic conductivity (K) was calculated using Darcy's Law:

$$K = \frac{-V * ne}{\left(\frac{dh}{dl}\right)}$$

where V is average linear velocity having units of length/time (L/T), ne is effective porosity (dimensionless), and $\frac{dh}{dl}$ is the hydraulic gradient (L/L). The average linear velocity was calculated for the interval during which Round 6 packets were deployed (54-82 days after injection). Hydraulic gradient was calculated using elevation data for the monitoring site in Hunters Branch and the estimated elevation of the bottom of the lake. A range of values for effective porosity for shale, sandstone, limestone, and karstic limestone from Domenico and Schwartz (1990) was used to account for the heterogeneity in the subsurface between the north end of the lake and the monitoring site at Hunters Branch. Using the values above, hydraulic conductivity was calculated to be between 3.2 x 10^{-6} cm/sec and 2.1x 10^{-7} cm/sec, representing the maximum range of K-values for material between the injection sites and Site 2. These values fall in the range of K-values for sandstone and limestone (Freeze and Cherry, 1979).

Monitoring Site 16 – Lake Packets

Dye concentration in the lake between 54 and 82 days after injection (Round 6) was 1.57 ppb, with an emission peak wavelength of 515.6nm. Round 7 analyses at the same location showed a dye concentration of 2.63 ppb with an emission peak wavelength of 515.2nm.

Each of these emission peak wavelengths falls just outside of the normal acceptable range for fluorescein in elutant of 510.7 nm to 515.0 nm (OUL, 2002). The peak emission fluorescence wavelengths of tracer dyes are a function of the dye and its matrix, as well as water chemistry at the sampling location. It was the opinion of OUL that the emission peaks of these samples were due to the presence fluorescein in the lake (Tom Aley, personal communication).

Lake levels reached the lowest point of the study in November 2011. During the design of the dye study, lake levels began to recover. Once materials arrived and field reconnaissance was complete, the lake had recovered to a level of approximately 7.6m above the deepest depression. Lake volume during dye introduction was calculated to be approximately 12,225 m^3. The lake continued to recharge for the duration of the dye study, as indicated by pressure transducer data shown in Figure 6. The study was designed to inject dye as close to the four depressions where water was observed exiting the lake during low water levels as possible. The treme pipe was believed to have injected dye within 2m of each of the four pronounced depressions visible on the bathymetry map. If net groundwater outflows are constant as suggested by Roningen (2011), mixing (and subsequent dilution) would be limited as the dye was expected to be quickly transported into the subsurface. If net groundwater losses are constant at 44L/sec, the volume of water contained in the lake when dye was injected should have drained in approximately 3.2 days with all inputs removed. Assuming a net groundwater outflow of 2.6 L/sec, the lowest value calculated by Jansons et al. (2004), the volume of water in the lake when dye was injected would still drain completely in approximately 54.3 days with all inputs removed.

However, the positive dye detection for lake packets from Round 6 and Round 7 coupled with the rising lake level suggest complex dynamics within Mountain Lake. Considering the initial concentration of fluorescein in the lake immediately after injection, the concentration of fluorescein in elutant from lake packets during Rounds 6 and 7 was not substantially reduced given the amount of time between injection and sampling events. Even if inputs into the lake were increased, the fluorescein was expected to be flushed from the lake during the 54 day interval after dye was introduced into the lake.

Observations made during this study suggest that net groundwater outflow may not be constant over time as suggested by Roningen (2011), but may fluctuate. as suggested by Jansons et al. (2004). Further work would be needed to address this issue.

4.3.1 Reasons for limited positive results

Several reasons may explain the lack of dye recovery at the monitoring site locations.

Dilution below detection limit

Four slugs of fluorescein dye were introduced on injection day, each having a concentration of approximately 90583 ppm (90.58 Kg/m3). The dye was injected into a body of water having a volume of approximately 12,225 m^3. In a well-mixed, closed system, this volume of water would dilute the concentration of fluorescein to approximately 113 ppb (1.11 $x10^{-4}$ Kg/m^3), a dilution factor of 801,619. Lake levels continued to rise for the duration of the dye study, eventually exceeding the level when bathymetry data were collected. This rise in water level added a minimum of 151,775 m^3 to the volume of water contained in the lake on injection day (extent of the bathymetric map developed during this study from which volume can be calculated using Dr. Depth). Adding this volume of water would further dilute the concentration of fluorescein in the lake to approximately 8.3 ppb. This value represents the maximum dilution possible based on volume calculated from the bathymetric map using Dr. Depth.

Data from the ER survey were not sufficient to quantify volumes of water associated with subsurface features exhibiting low resistivity values. However, these features must be considered while discussing dilution of tracer dyes. While zones of low apparent resistivity values are not necessarily indicative of fractures or open cavities filled with water, the frequency and size of these features suggest that a volume of water comparable to that contained in the lake when dye was introduced. The presence of additional fresh water available to mix with fluorescein already in solution in the subsurface would further dilute the mixture before entering any of the streams where monitoring sites were located.

If water exiting the lake reached any of the monitored streams, further dilution would occur due to mixing with water drained from the surrounding area of a respective sampling location. It is difficult to quantify the additional dilution at sampling locations since discharge values vary substantially between sites, even during baseflow conditions. For example, assuming that the positive test at Site 2 during Round 6 analyses was indeed caused by the presence of fluorescein, it would be expected to see a trace of fluorescein at Site 1 downstream below the confluence of Pond Drain and Hunters Branch. But since the concentration of fluorescein was so low (<0.5 ppb), the addition of water flowing in Pond Drain prior to joining with Hunters Branch could have diluted any dye below the detectable limit of equipment at OUL.

The presence of the dye in the lake 54 days after dye introduction may suggest that there may be inflows of groundwater, in addition to surface water, into the lake during periods of recharge. Groundwater additions interacting with surface water inputs would further dilute dye remaining in the lake. The change in hydraulic gradient would also cause the dye to remain in the lake. This may explain the detection of fluorescein in packets located in the deeper end of the lake as groundwater additions interact with surface water inputs, further diluting dye remaining in the lake, but not allowing all of the dye to exit the lake

Seepage under monitoring sites

The lack of positive results from laboratory analysis of the packets may also be caused by seepage beneath sampling locations. Monitoring site locations were selected assuming that water leaving Mountain Lake flows along relatively shallow pathways and reaches surface streams a short distance away from the lake. Water exiting Mountain Lake may travel along deeper flow paths that do not surface locally. For example, the dip of stratigraphy [Figure 2] is steeper than the gradient between the assumed bottom of the lake and monitoring sites in Pond Drain. If water exiting the lake through any of the depressions shown on the bathymetric map followed stratigraphic dip, it could flow under all four of the monitoring sites located in Pond Drain before reaching the surface.

Adsorption

A wide range of sediment compositions are present in the study area, to which fluorescein could possibly adsorb. Fluorescein is a derivative of xanthene, having only negative functional groups [(Smart and Laidlaw, 1977); (Kasnavia et al., 1999)] and is readily adsorbed onto positively charged surfaces (i.e. alumina and carbonate groups), but has limited interaction with anionic surfaces (i.e. silica sands or sandstones)(Kasnavia et al., 1999). Since the majority of the parent material underlying the Mountain lake watershed is described as containing sandstones (Bartholomew et al., 2000), the likelihood of adsorption to these materials appeared to be minimal when compared to other fluorescent dyes. The lower Martinsburg formation is described as containing limestone and calcareous mudstone (Bartholomew et al., 2000), which could erode into sediment with positive surfaces which fluorescein may adsorb to. However, this section of the Martinsburg is not mapped in the Mountain Lake watershed and is likely well below the bottom of the deepest depression at the north end of the lake. OUL suggested that the benefits of using fluorescein instead of another fluorescent dye outweighed the concerns of dye losses due to adsorption (Tom Aley, personal communication).

Photochemical decay

Photochemical decay rates are very high for fluorescein with prolonged exposure to bright sunlight (Smart and Laidlaw, 1977). Monitoring sites were selected partially based on their likelihood of exposing the packets prolonged periods of direct sunlight. All of the monitoring sites were located in shaded areas for the majority of daylight hours. Shaded monitoring site locations, coupled with the frequent sample collections, greatly reduced the likelihood of photodegradation of any fluorescein that may have come in contact with the activated carbon. Photochemical decay was therefore not considered a likely cause of significant dye loss prior to laboratory analysis.

Lake sediments form temporary seal within depressions

One cause of the rising and lowering of water levels at Mountain Lake that has not been suggested previously involves partial sealing of exits with lake sediment. As lake levels declined during summer and fall in recent years, lake sediments became exposed at the northern end of the lake. Sediment can then transported down gradient towards the deeper depressions and deposited. Sediment transport was observed during fall 2011 when water levels declined as stream channel deltas within the exposed lake bed prograded towards the deepest depressions visible on the bathymetric map. The influx of fine grained sediment into the depressions could create a temporary seal, slowing outflows and allowing water levels to recover during the winter and spring. As water levels continue to rise, the temporary seal is held in place until a critical point is reached when the seal is breached. This breach could be caused by a) pressure head in the lake that exceeds the strength of the temporary seal; b) seismic activity that alters the position of sediment and/or rocks in the vicinity of the drain holes or c) other hydrodynamic processes that affect the seal.

5. Summary

During this study, lake levels within Mountain Lake fluctuated seasonally, similar to patterns observed in previous studies. A bathymetric map of the lake identified several pronounced depressions at the northern end of the lake, suggesting water loss occurs though multiple exits. However, a tracer study in which dye was injected into the depressions yielded limited detections at monitoring sites in drainages surrounding Mountain Lake. While the dye tracer study was unsuccessful in delineating pathways for water exiting the lake, dye detection in Hunters Branch and within the lake suggest complex flow dynamics. The most likely reasons for the lack of dye detection include dilution of the dye during lake recovery, seepage of water below the monitoring locations, or formation of a temporary seal in the depressions created by influx of sediment during periods of lake bed exposure.

ER profiles suggest the presence of a series of subsurface fractures or reservoir approximately 25 - 30 meters below the deepest part of the lake bed. The upper bound of this zone may be a layer of fine grained sediment, or a section of the Juniata formation overlying a series of cavities associated with the Bane Anticline or dissolution of a carbonate layer in the Martinsburg formation. The presence of this deep zone of low resistivity under the lake bed has not been previously documented.

6. Suggestions for future work

The evaluation of possible lake level management practices is of interest to property owners and should be considered during future projects. Before this can occur, additional research is needed to better understand the complex hydrologic system at Mountain Lake.

Any geologic investigation at Mountain Lake would benefit from having a more detailed characterization of the subsurface. Locating the contacts of underlying lithology, or confirming the presence of a subsurface reservoir beneath the lake bed, would help shed light on possible flow paths for water exiting the lake. This could be accomplished by creating a site specific cross section of the site by logging existing water wells in the vicinity of the lake bed, coupled with test borings on an exposed lake bed. Additional subsurface profiling using seismic refraction may be successful in determining depth to bedrock in the lake bed, as well as the thickness of material composing the dam at the northwest end of the lake.

A second dye tracer study should be deployed as water levels are declining, perhaps with a different fluorescent dye. If seasonal lake level fluctuations follow the same trend observed between May 2009 and May 2012, dye detection may occur at more monitoring sites that did during this study. Other tracing techniques are available, such as evaluating evaporative signatures, and may also be effective at identifying subsurface pathways for water loss.

Characterization of surficial deposits in the lake bed and those contained in the naturally formed dam could help support the concept of partial sealing of the dam by alluvial sediments while lake levels are low. This could be accomplished, in part, by developing a high resolution erodibility map of the Mountain Lake watershed, collection of samples during drilling in the lake bed, or examining the pipability of sediments in the vicinity of the dam.

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Appendix

A. Height above base level

Roningen (2011) reports maximum depth of 29.33 meters using sonar bathymetry, while Williams [1930] estimated maximum depth of 33.5 meters using a plumb line. Bathymetry and transducer data from this study agree with Roningen (2011), therefore the maximum depth of the lake for this study is assumed to be 29.33 meters. A depth of 29.33 meters is subtracted from the estimated elevation of 1184m AMSL on the base of the spillway considered as the crest of the dam (maximum elevation of water in Mountain Lake at full pond). The elevation of the New River is measured to be approximately 488m AMSL near Pembroke, VA. For this study, the base of the deepest depression is considered to reside at 1154.67m AMSL, or 666.67m above local base level at the New River near Pembroke, VA.

B. Additional ER Profiles

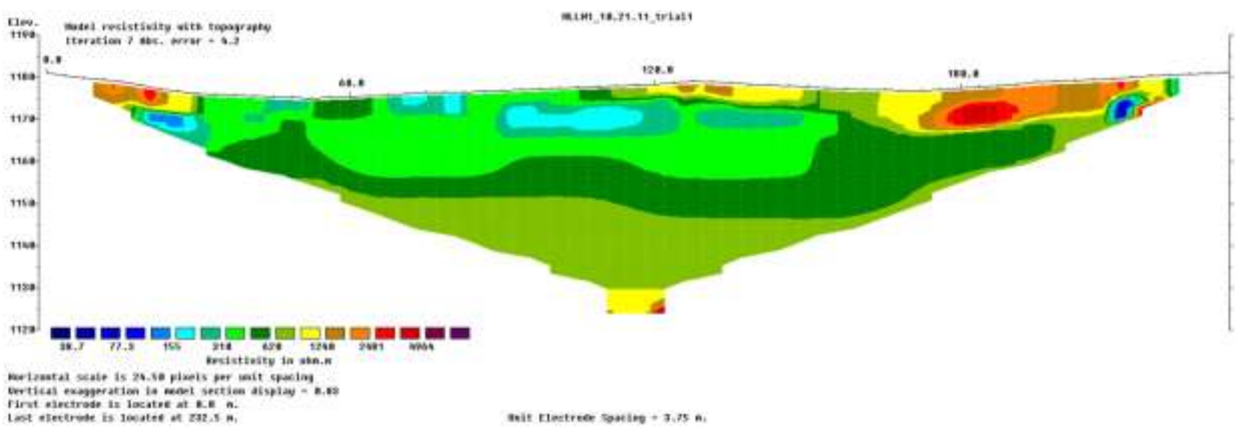

Figure 12: ER line MLLN1

Figure 12 is an east/west profile and is the southern-most profile for which data was collected. A small zone of low resistivity is apparent approximately 10m beneath the lake bed (1169m AMSL).

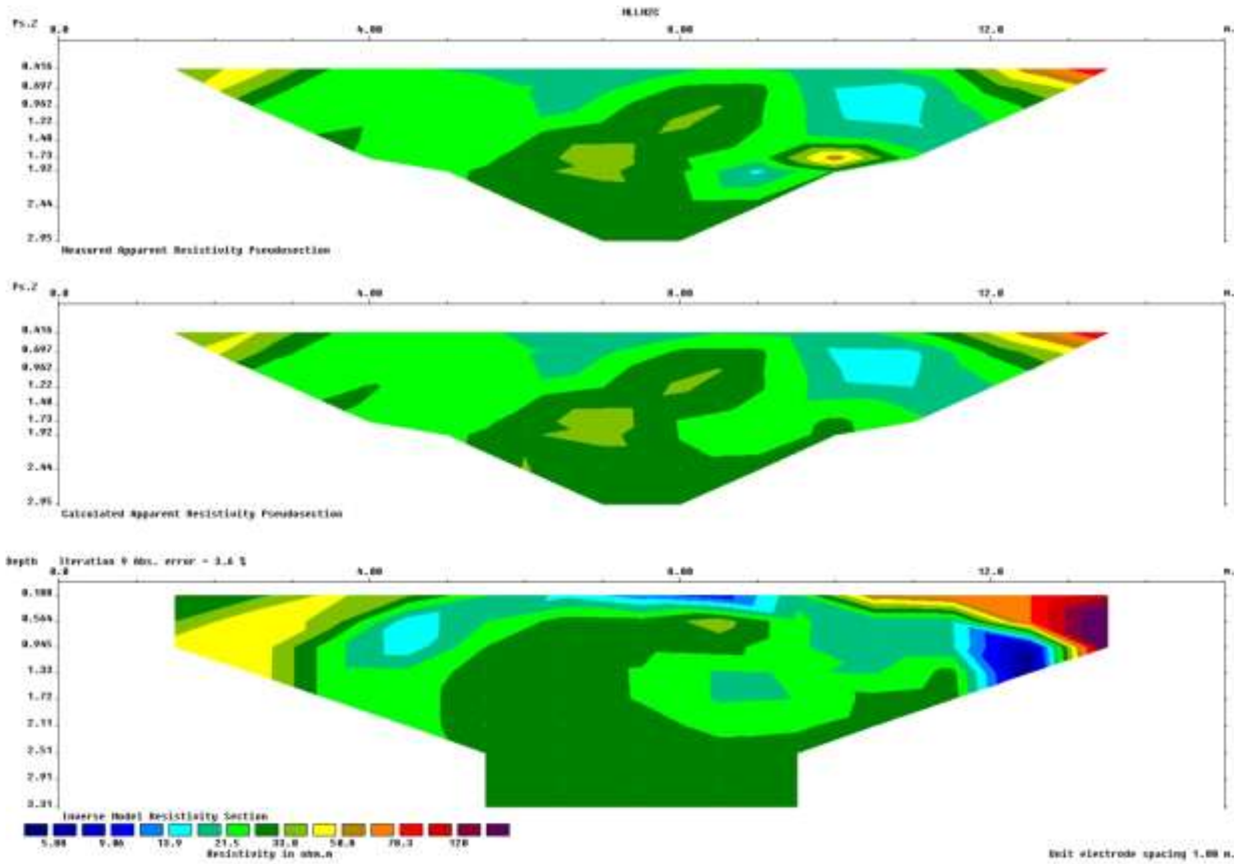

Figure 13: MLLN2

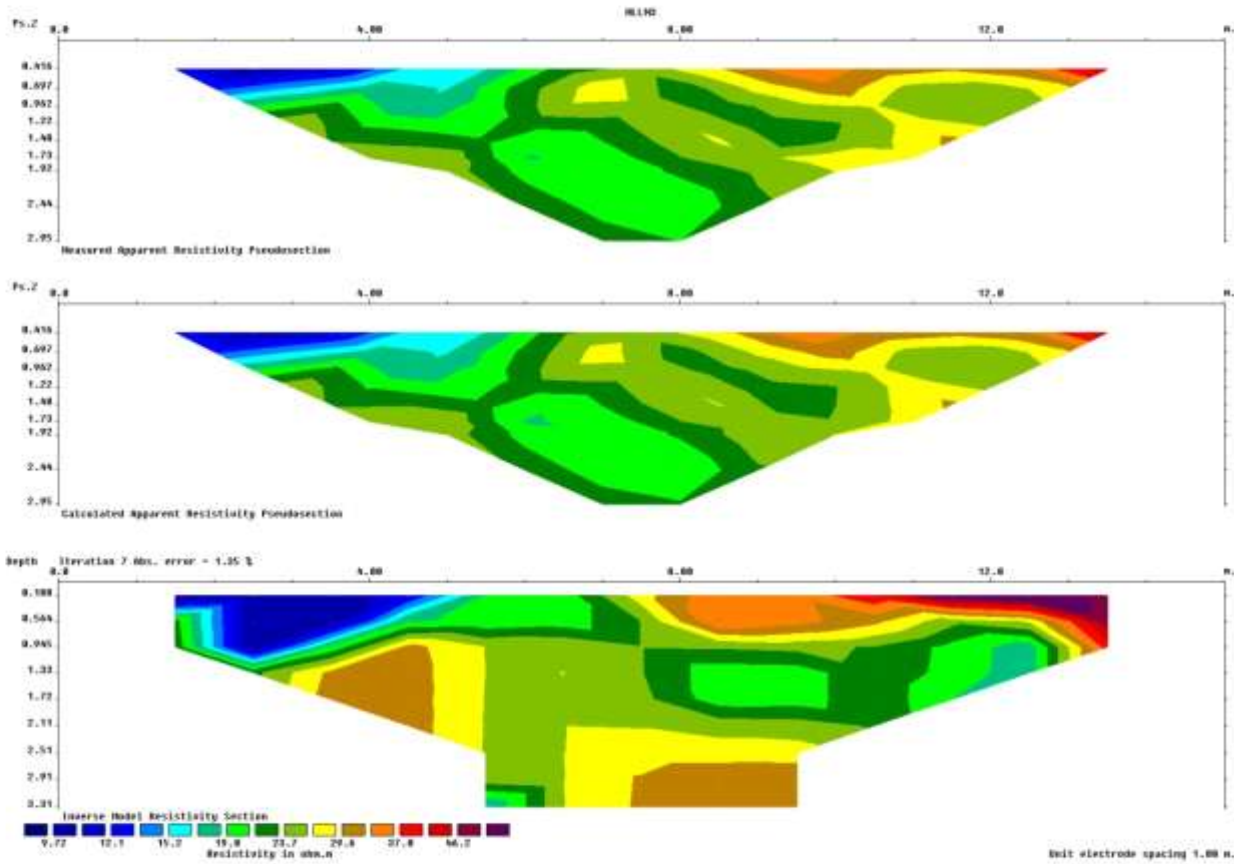

Figure 14: ER line MLLN3

Figures 13 and 14 show data collected for profiles MLLN2 and MLLN3, respectively. Only 16 of the 32 electrodes in the array actually took measurements. It is unclear why this happened, but the lack of data made the inversions for both of these profiles unuseful while attempting to characterize the subsurface at Mountain Lake.

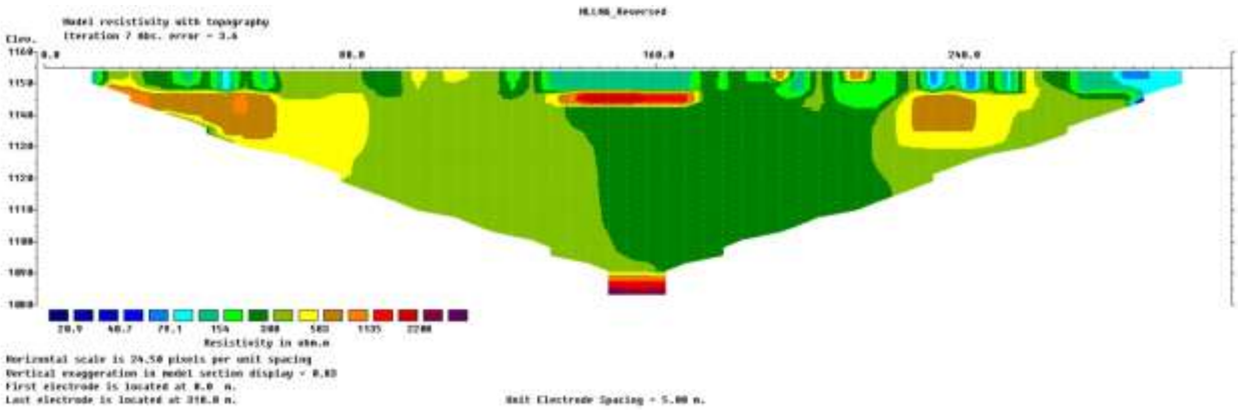

Figure 15: ER line MLLN6

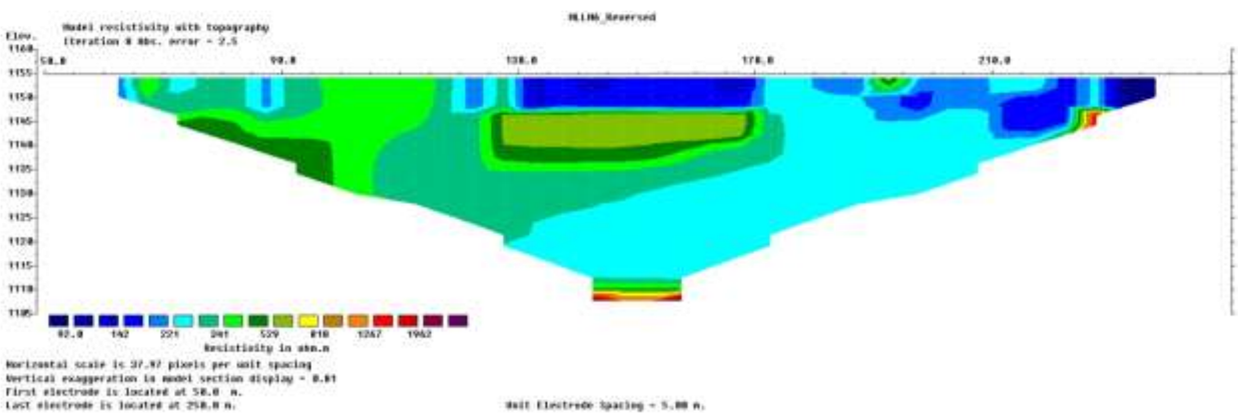

Figure 16: ER line MLLN6 only inverting data from 50m to 250m along profile

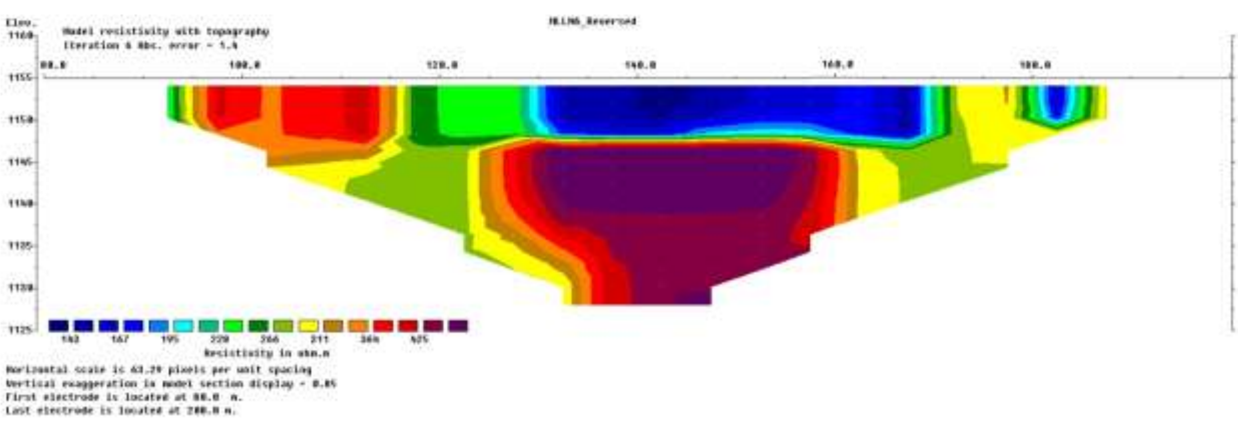

Figure 17: ER Line MLLN6 only inverting data from 80m to 220m along profile