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BATHYMETRY AND SEDIMENT ACCUMULATION OF LITTLE SENECA LAKE

By

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Acronyms and Abbreviations used in this report	
Abbreviation	***Description***
DGPS	Differential Global Positioning System
DTM	Digital Terrain Model (surface model)
DVD-R	Digital Versatile/Video Recordable Dics
GIS	Geographical Information System
JMT	Johnson, McCordic & Thompson Surveyors
KHz	Kilohertz
MGS	Maryland Geological Survey
MPL	Mean pool level
MSL	Mean sea level
NAD83	North America [Horizontal] Datum of 1983
NAVD88	North America Vertical Datum of 1988
NGVD	National Geodetic Vertical Datum (of 1929), also MSL of 1929
NIST	National Institute of Standards and Technology
NRCS	Natural Resource Conservation Service
OSI	Ocean Surveys, Inc.
PDOP	Positional Dilution of Precision
RESCAP	Reservoir Capacity-Range
RMS	Root mean Square
SRM	Standard Reference Material
TIN	Triangulated Irregular Network
US SCS	U.S. Soil Conservation Service (in 1994, name changed to NRCS)
UTM	Universal Transverse Mercator (coordinate system)
WSSC	Washington Suburban Sanitary Commission

Conversion Factors

Multiply	by	To obtain
	LENGTH	
foot (ft)	0.3048	meters (m)
mile (mi)	1.609	kilometers (km)
	AREA	
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	VOLUME	
acre ft (ac. ft)	1,233.482	cubic meter (m^3)
gallons (gal.) (US, liquid)	0.003785	cubic meter (m^3)
acre ft (ac. ft)	325,851.433	gallon (gal.) (US, liquid)

EXECUTIVE SUMMARY

In response to a request by the Washington Suburban Sanitary Commission, Maryland Geological Survey (MGS) was contracted to study the bathymetry and sedimentation of Little Seneca Lake located in Montgomery county in the State of Maryland. Bathymetric data were collected for the reservoir, current storage capacity and a drawdown curve were determined, and the volume of sediment accumulation for the reservoir was calculated. The collection, analysis, and presentation of this report were made to be consistent with the most recent bathymetric and sedimentation reports from Triadelphia and Rocky Gorge Reservoirs (Ortt et al, 2007), Loch Raven and Prettyboy Reservoirs (Ortt et al, 2000), and Liberty Reservoir (Ortt and Wells, 2003) located within the State of Maryland.

Bathymetric data for the reservoir was collected in July and August of 2010. This data was collected using differential global positioning service (DGPS) techniques and digital echosounding equipment. Over two hundred thousand discrete soundings were collected and used to generate a current bathymetric model of Little Seneca Lake. Several methods of analysis were used to generate the models. The bathymetric models indicate a current storage capacity of 3.92 billion gallons [14.846 million cubic meters] with a surface area of 473 acres [1.91 million square meters].

Analysis was performed on the pre-dam construction topography and the bathymetric survey of 1996. The current capacity of the reservoir is more than the calculated capacity from the 1996 survey. A greater density of data in the 2010 survey is the most likely reason for this difference. The total storage volume loss calculated from the pre-construction topography to the current bathymetry is 337 acre-feet [0.416 million cubic meters]. The average annual loss rate is 12.5 acre-feet per year [0.015 million cubic meters] or 0.1% of the original volume.

INTRODUCTION

Historical Context

Little Seneca Lake is a contingency water supply for the Washington Suburban Sanitary Commission (WSSC). It also provides a recreational area in Montgomery County, Maryland. The Lake was constructed beginning in 1983 and completed in 1985. There has been only one survey of the Lake since its construction, and that was in 1996 by OSI (OSI, 1997). This survey provides a thorough survey of the lake and an assessment of the sedimentation within the lake using contemporary data collection equipment and methods for analyses.

Physical and Geological Setting

Little Seneca Lake lies on Little Seneca Creek, a tributary of the Great Seneca River. The lake was formed by construction of an earthen dam on Little Seneca Creek downstream of the convergence of Little Seneca Creek, Tenmile Creek, and Cabin Branch. These creeks are the significant tributaries into the lake. The Little Seneca Creek watershed is a large subbasin of the Great Seneca watershed which drains a significant portion of the western Montgomery County. Approximately half of the Little Seneca Lake watershed is forested: the other half is a mixed developed and agricultural land use (MDE, 2006)(Figure 1).

The watershed for Little Seneca Lake lies within Maryland's Piedmont Province which is characterized by hilly, rolling topography. The lake itself lies within metasedimentary crystalline rocks of the Ijamsville formation and Marburg schist (Cleaves, et al, 1968). The Ijamsville formation consists of blue, green and purple phyllites and phyllitic slates. The Marburg Schist consists of bluish gray fine-grained muscovite-chlorite-albite-quartz schist with interbedded quartizites.

The soils immediately surrounding the lake are the Brinklow-Baile-Occoquan association (U.S. Department of Agriculture, Soil Conservation Service, 1995). These fine-grained loamy soils range from poorly drained to well drained and moderately deep to deep (MDE, 2010).

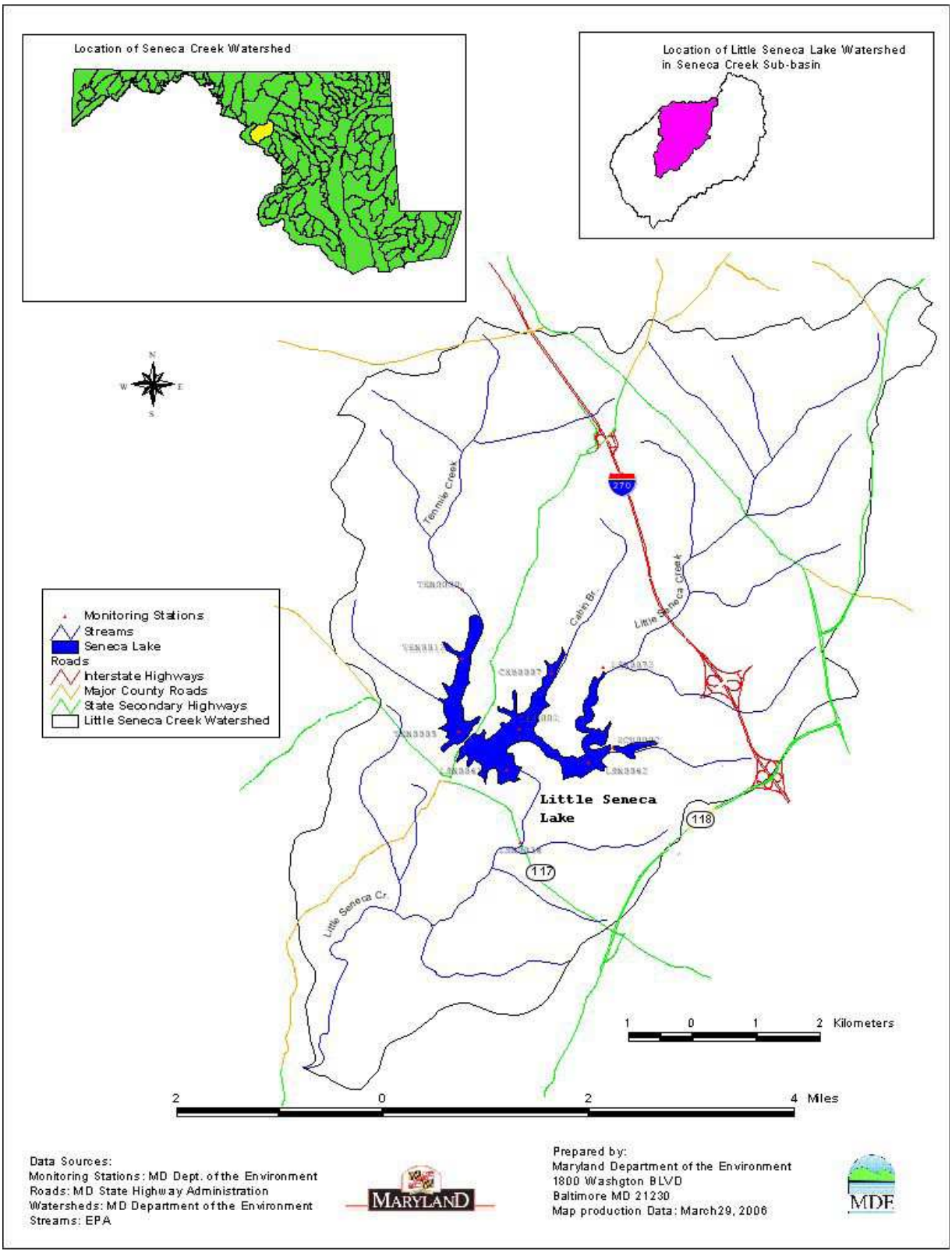

Figure 1. Location of Little Seneca Reservoir and watershed (MDE, 2006).

PREVIOUS SEDIMENT SURVEYS

As a young reservoir, Little Seneca Lake had only two prior surveys. The original survey was conducted in 1979 as a topographic survey prior to the construction of the reservoir. In this survey, traditional topographic surveying techniques were used and a topographic contour map with two foot vertical contour intervals was created. In 1996, OSI was contracted to perform a bathymetric survey of Little Seneca Lake. This survey utilized similar methods to the survey performed for this contract. Acoustic echosounding, adjusted for lake level, along with GPS for horizontal positioning was utilized to record individual depths within the lake. The collected points were analyzed and processed to create a model of the lake bottom. This model and the transects from it were used to calculate the reservoir storage volume. These surveys created a time specific representation of the bottom of the lake.

Little Seneca Reservoir		
Survey Year	**Capacity (ac. ft)** ***[Million m³]***	**Capacity Loss since 1979 (ac. ft)** ***[Million m³]***
1979	12315* *[15.190]*	0
1996	11852 *[14.619]*	463 *[5.711]*

Table I. Reservoir capacity and sediment volumes based on OSI calculation of original and 1996 bathymetry data using 3D computer modeling. *Note that these volumes do not include the Little Seneca Creek forebay which is calculated to be 37 acre feet in 1979. (OSI, 1997)

OSI used a three-dimensional surface modeling software (QuickSurf) to analyze the hydrographic data to determine the 1996 reservoir capacity. OSI also digitized and recalculated the original reservoir capacity. The original capacity was determined by digitizing the pre-construction topographic sheets provided by WSSC, and analyzing the digitized data using QuickSurf. OSI used the 385-ft (MSL) contour line from the original topography for the shoreline in both surveys. OSI results using QuickSurf indicate that sediment accumulation in Little Seneca Lake averaged 35.6 acre feet per year using 1983 as the start date of the reservoir. (OSI, 1997)

STUDY OBJECTIVES

The objectives for this study were:

1. To determine current storage capacity of Little Seneca Lake.
2. To determine sediment accumulation in Little Seneca Lake since dam construction.

METHODS

Study Approach

The study consisted of an assessment phase and a historical comparison phase. The assessment phase was accomplished through the measuring and modeling of the current bathymetry of the reservoir. Hydrographic surveys were collected using digital echosounding equipment and differential global positioning system (DGPS) equipment. The data was collected as discrete x, y, z points and processed with Surfer ®, a three-dimensional surface modeling software package, and various geographical information systems (GIS) to produce a modeled surface of the reservoir's bottom.

The second phase determined sediment thickness and sediment accumulation rates in the reservoir through historical data comparison. Digitized original topography of the reservoir was obtained through OSI and WSSC. Sediment volume and sediment thickness maps were generated by subtracting the current bathymetry from the original topography. The sediment thickness reported using this method was checked through the use of sub-bottom seismic-reflections and bottom characteristics. The results assisted in the development of a better understanding of the amount and temporal rates of sediment accumulation and erosion within the reservoir.

Bathymetric Data Collection

Hydrographic Surveys

Track lines running perpendicular to the river channels were established for bathymetric surveying. These track lines were spaced 50 meters apart and extended from shoreline to shoreline. When possible, survey lines were navigated on UTM-NAD83 lines running either east-west or north-south. Tie-in lines were run perpendicular to the survey lines and along the axial channels of the reservoirs. Additionally, survey track lines were run along the perimeter of the reservoirs and also between the centerline and shoreline to assist in the surface modeling analysis following the recommendations of the OSI 1996 survey. Survey track lines are illustrated in Figure 2. The bathymetry surveys were conducted in July of 2010. The sediment forebays at the headwaters of Little Seneca Creek, Tenmile Creek, and Cabin Branch were surveyed on July 30, 2010 using a handheld GPS and a stadia rod. An additional day of hydrographic surveying was performed in August 2010 to collect data to enhance the dataset.

Bathymetric data were collected using a Thales Navigation (Ashtech) DGPS (model DG-16; L1 code and carrier with SBAS and differential beacon corrections; 5Hz Update rate) and a Knudsen 320B/P dual frequency echosounder with sounding frequencies of 200 KHz and 28 KHz. The echosounder transducer is a KEL771 dual frequency transducer with a 200 KHz beam angle of 4 degrees and a 28 KHz beam angle of 29 degrees. The echosounder generated acoustic pulses for bottom recognition at a rate of 4 Hz. The pulse width was set to automatically change between 0.2 milliseconds (mS) and 0.8 mS depending on the depth of the water. The transmitted acoustic wave reflected off the density gradient separating the water column from the bottom

sediment. The returned acoustic wave is received by the transducer, and the time separation between the sent and the returned wave is recorded. This time separation is directly proportional to distance. The recordings were then filtered for points that were outside of the tracking gate window (2 meters) and integrated within the echosounder to produce an accurate measurement from the transducer to the water/sediment interface. At an average vessel speed of 4 knots, a depth sounding was collected approximately every 0.5 meters [1.6 feet] along the survey track-lines. This data was stored along with the GPS location and positional latency in a laptop computer. Navigation was provided through a Lowrance LCX-15MT interfaced to a Lowrance DGPS beacon receiver. DGPS differential corrections broadcast by the United States Coast Guard provided a real-time horizontal accuracy of +/- 1 meter [3.3 feet] using the Annapolis and Hagerstown DGPS sites. The Thales Navigation (Ashtech) DGPS, the Lowrance GPS, and the echosounder were checked against known horizontal and vertical measurements during the survey. The echosounder was also calibrated throughout the depth range of the reservoir during the study period. (Appendix A)

Mean Pool Level Adjustment

The bathymetric data collected presented measurements based upon the distance between the surface of the water in the reservoir and the top of the water-sediment interface. Due to fluctuations in the reservoir level, the bathymetric data was adjusted to a known reference level using recorded water levels. Water level measurements were recorded by two independent gauges operated by WSSC and MGS. The collected survey data was adjusted to the Mean Pool Level (MPL) of 385.0 feet above Mean Sea Level (MSL 1929). These water levels and adjustments are documented in Appendix B.

Data Accuracy

The accuracy of the post-processed bathymetric data is ± (0.1 ft + 1% of the water depth) to MPL. The accuracy of the horizontal DGPS data is ±1.0 m [±3.3 ft].

Digitizing 2009 Reservoir shorelines

Reservoir shorelines were interpreted from high resolution, natural color digital orthophotography taken during the Spring of 2009. The imagery was taken when the trees had leaves causing portions of the shoreline to be obscured. In the areas where the shoreline was obscured, the shoreline was digitized using 2007 Color Infrared imagery. Portions of the shoreline were then field verified with a Thales Promark 3 GPS. A shoreline survey with the surveying vessel was conducted throughout the main body of the reservoir to further verify the shorelines.

Bathymetric Interpretation and Volumetric Calculations

Bathymetric data were interpreted with the Surfer software package. In Surfer, the raw data was processed using four methods: 1) Triangulated Irregular Network (TIN); 2) Kriging; 3) Minimum Curvature; and, 4) Inverse Distance, to create a three-dimensional surface (bottom

topography) model. A one-meter regularly spaced grid was then calculated by analyzing the depths on the surface model. After the regularly-spaced grids were created, volumes and thicknesses of sediments were calculated by subtracting the historical grid from the current (2010) grid.

Error analysis was performed on the generated grids by comparing raw data with the generated grid. Differences between the actual data values and the grid values at the same location are called residuals. A root mean square error analysis of these residuals was used to quantify and assess the fit of the models to the data. The results for error analysis for the generated surfaces are presented in Appendix A.

Sub-Bottom Seismic Reflection Surveying

Sub-Bottom seismic reflection surveys were conducted concurrent with the bathymetry survey using the Knudsen's low frequency of 28 KHz. The 28 KHz is ideal for identifying shallow and thin deposits as it has penetration power while maintaining resolution due to it's short wavelength. Previous experience with this equipment has identified geologic horizons under 25 meters of sediment in riverine systems and sediment layers less than 10 centimeters.

The acoustic records permitted a differentiation of the recently deposited, less dense, finer sediment from the underlying, denser and coarser pre-reservoir bottom sediment. The theoretical resolution (1/3 of a wavelength) of the acoustic profiling equipment operating at 28 KHz is 0.017 meters [0.6 inches].

The 28KHz signal was routinely used to identify and verify the bottom location in areas where sub aquatic vegetation was present.

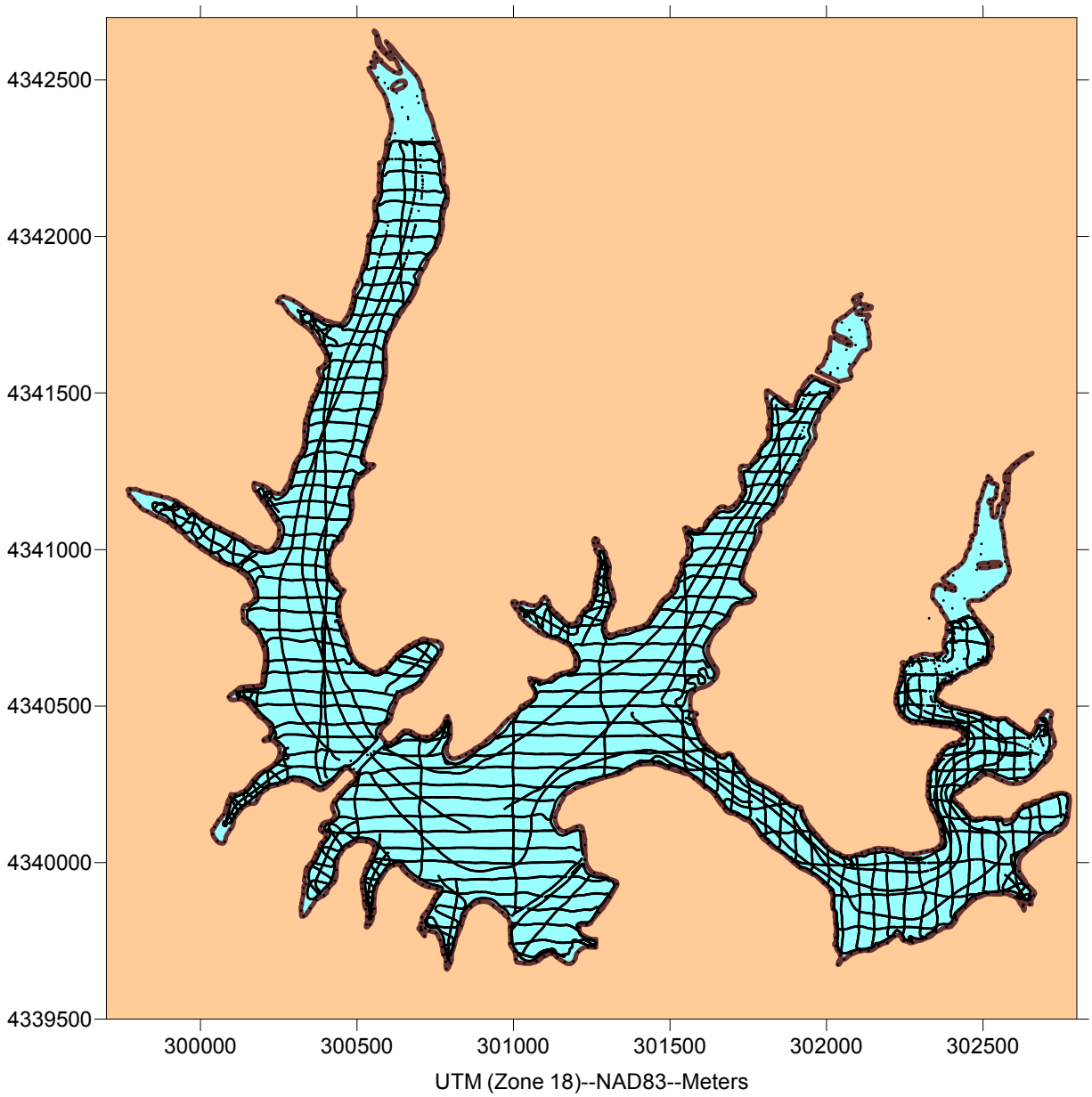

Figure 2. Sounding map of Little Seneca Reservoir with collected data points. Every fifth point is plotted. The digitized 2009 shoreline is also plotted in brown. The reservoir surface area, defined by the 2009 shoreline, is 473 acres (1.91 million m^2) and the shoreline length is 15.6 miles (25.2 km)

RESULTS AND DISCUSSION

Bathymetric Results

The 2010 bathymetry for Little Seneca Lake is presented in Plate 1. The deepest portion of the reservoir, with depths up to 67 feet (20.3 meters), is just upstream (approximately 150 meters) of the dam near the location of the buoy line. The reservoir depths gradually decrease toward the upstream ends of the tributaries.

The calculated storage volumes of the reservoir are presented in Table II. Multiple methods were used to determine the volume. The most accurate method, based on a residual analysis for the collected dataset, is the Kriging method. Due to the high spatial density of collected data and the one meter grid resolution, all modeling methods generated similar accuracies (residual RMS range between 0.090 and 0.108 meters) (Appendix A, Table A-2) and volumes. In Little Seneca Lake, the calculated storage volume is 3.922 billion gallons [14.846 million cubic meters].

Calculated Storage Capacities Billion Gallons *[million cubic meters]*			
Inverse Distance	**Kriging**	**TIN**	**Minimum Curvature**
3.941 *[14.920]*	**3.922** ***[14.846]***	3.921 *[14.842]*	3.956 *[14.976]*

Table II. Storage capacities calculated based on bathymetry collected in this study.

Using the Kriging model developed for Little Seneca Lake, volumes and surface areas were calculated with differing reservoir water levels yielding a stage curve (drawdown graph) which is helpful in assessing volumes in times of pool level decline. Figure 3 displays the results of this analysis.

Historical Data Modeling Results

The original topographic maps, which were digitized for the OSI study (OSI, 1997), were also modeled using Surfer to generate storage capacity estimates. Since these maps consisted of continuous contour lines at a close vertical interval (2 feet), it was important to select a modeling method that would extrapolate data values without introducing depths which exceeded the contour interval. Models were created using the Kriging, Minimum Curvature, and TIN methods. Both the Minimum Curvature and Kriging methods introduced errors greater than the contour interval. They generated unrealistic hills and valleys in the areas between contour lines. The TIN method created the most realistic model of the original topography and the model accuracy was verified through a residual analysis (Appendix A, Table A-2). The TIN method also preserved the integrity of the elevations between contour lines. The TIN method was used to create the surfaces and volumes of the original topography (Table III).

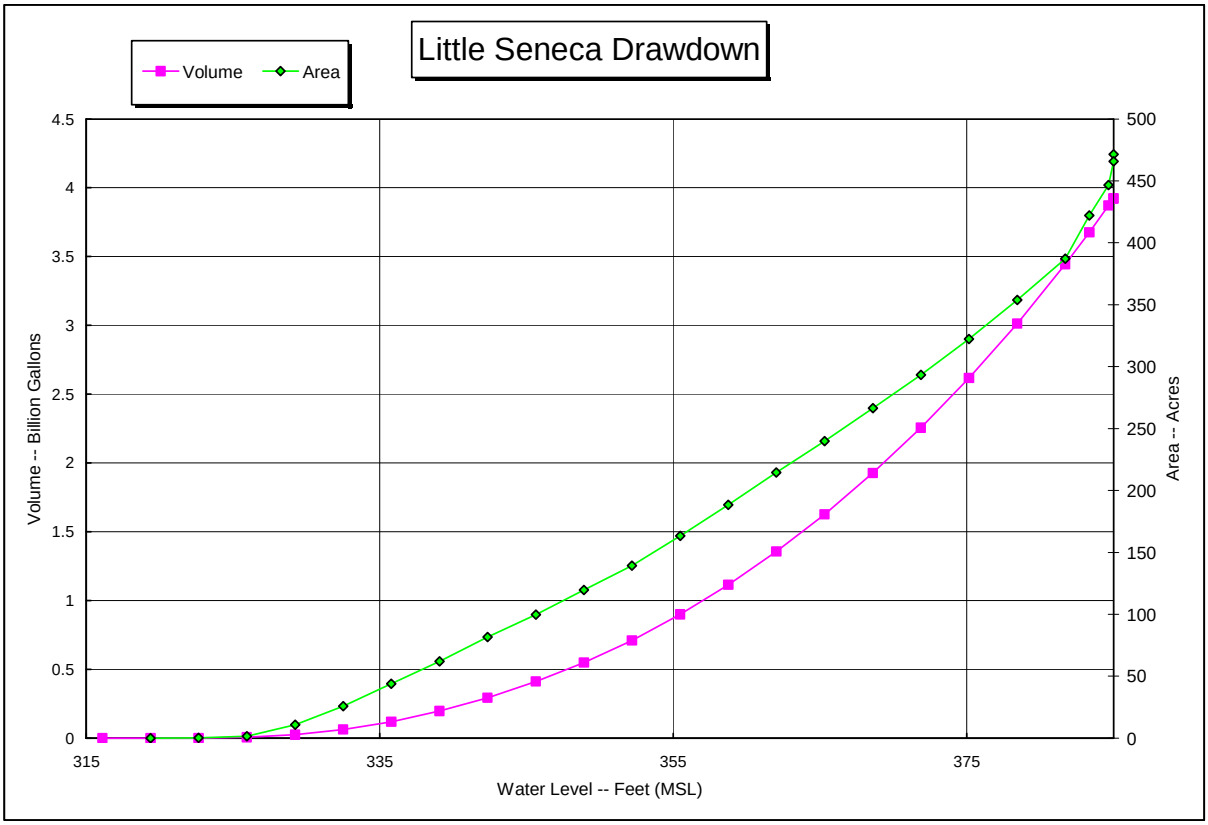

Figure 3. Drawdown curve of storage capacity and surface area versus water height in Little Seneca Lake.

Little Seneca Reservoir (20.8 Mi.^{2} Drainage Area) (53.9 Km^2 Drainage Area)				
Survey Year	**Capacity (ac. ft)** ***[Mill m³]***	**Period Capacity Loss (ac. ft)** ***[Mill m³]***	**Average Annual Loss (ac. ft/yr)** ***[Mill m³/yr]***	**Average Annual Loss Per Annual Loss over Drainage Area (ac. ft/yr/mi^2)** ***[m³/yr/km²]***
1979*	12373 *[15.262]*	0	0	0
1996	11600 *[14.309]*	773 *[0.953]*	59.5 *[0.073]*	2.86 *[1354]*
2010	12036*[14.846]*	-436 *[-0.537]*	-31.1 *[-0.039]*	-1.50 *[724]*
Total		337 *[0.416]*	12.5 *[0.015]*	0.60 *[286]*

Table III. Calculated storage capacity loss rates for Little Seneca Reservoir from this study. *Note that calculations were performed beginning in 1983. Calculated losses in 2010 are shown in negative to indicate a calculated gain in capacity between the OSI survey of 1996 and the MGS Survey of 2010.

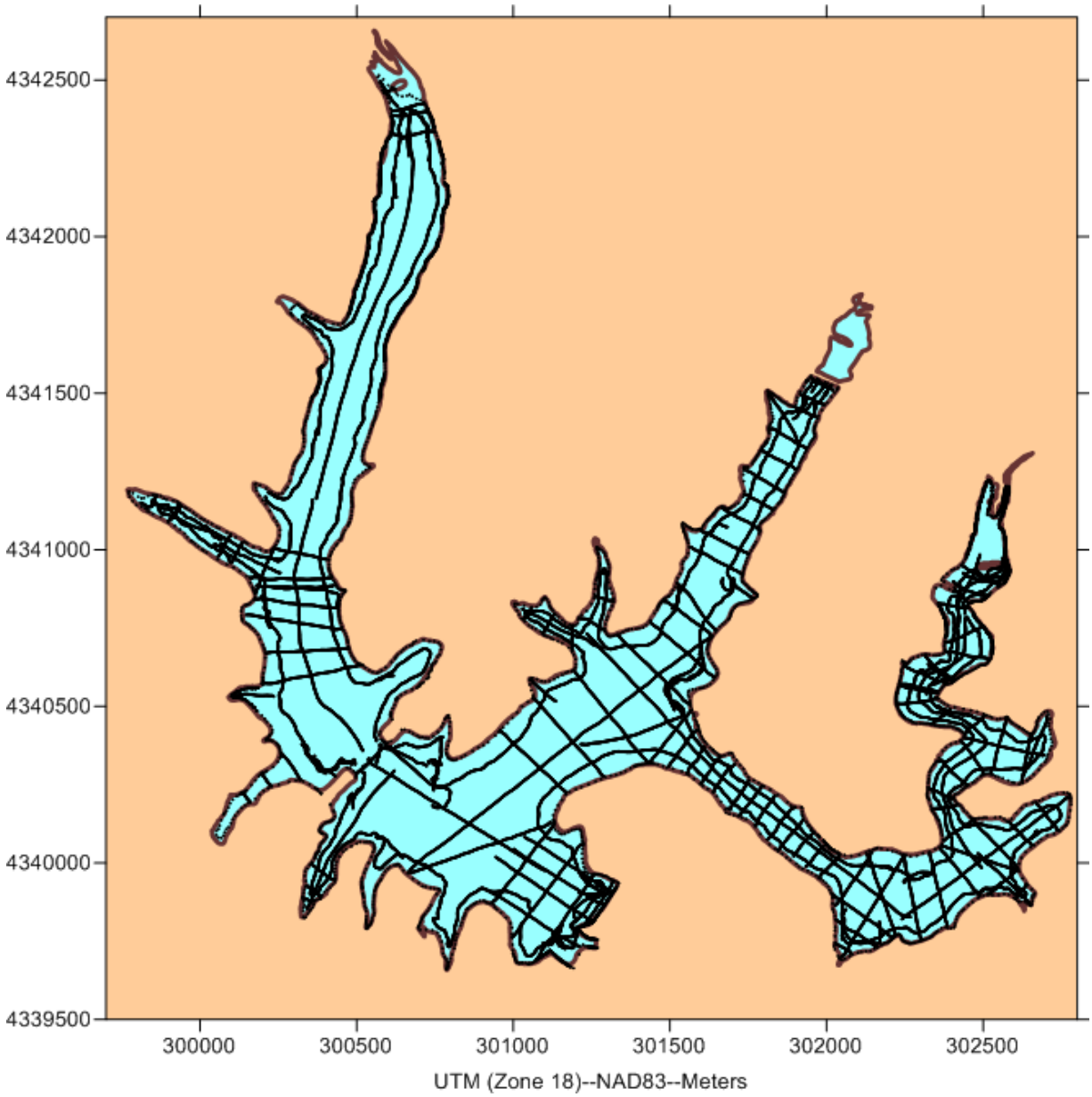

Figure 4. Sounding map of Little Seneca Lake conducted by OSI in 1996. Every other survey point is plotted.

The OSI data from the 1996 survey was processed using the same techniques for the 2010 survey. Kriging, Minimal Curvature, Inverse Distance, and TIN models were created and verified for accuracy using the residual analysis described earlier. While all of these models performed well in respect to honoring the collected data points, the surfaces demonstrated a high dependence on the spatial density of the collected survey lines. Figure 4 is a plot of the OSI survey lines. Little Seneca and Cabin Branch tributaries are well covered; however, the Tenmile Creek arm and the dam region of the reservoir were surveyed less densely than the rest of the reservoir. This lack of data results in a very poor representation of the bottom topography when

compared to the historical pre-construction topography and 2010 bathymetry.

The subtraction of the 2010 bathymetry survey from the original topographic survey yields a positive volume of 650 acre feet [0.802 million cubic meters] and a negative volume of 313 acre feet [0.386 million cubic meters]. The net sediment volume change is a gain of 337 acre feet [0.416 million cubic meters]. This translates to an average annual capacity loss of 12.5 acre feet [0.015 million cubic meters] per year since construction in 1983.

The volumes calculated are much lower than those calculated using either the published 1996 volumes by OSI or the recalculated OSI 1996 volumes. An analysis of the generated grids from the OSI data explains the offsets from the recalculated data. The storage volume of the Tenmile Creek arm of the reservoir is significantly under calculated when compared to the 2010 bathymetry.

A spatial distribution of the sediment accretion and erosion amounts is presented in Figure 8. The most significant observation is the broad area of sediment accumulation in the sediment forebays. These forebays are performing their function of sediment trapping and only allowing a small portion of sediment to be transported further into the reservoir. A separate forebay analysis is provided in Appendix E. The other broad areas of change are most likely anthropogenic. The route 121 (Clarksburg Road) bridge pillars, the Little Seneca Lake Dam, and the construction equipment staging yards are clearly evident on the map. Other smaller features identified on the map are likely to be errors generated by slight offsets in the original contour lines. This is evident in the very steep sloped and channelized portion of the reservoir where the Little Seneca Creek arm of the reservoir joins the Cabin Branch Arm.

Analysis of the current bathymetry shows very little sedimentation within the main portion of the reservoir. Cross-sections at various portions of the reservoir were performed. (Examples: Figures 5, 6, and 7). The historic stream channels are clearly evident throughout the reservoir, and they still are well incised. These historic channels are the deepest portions of the reservoir, and typically, they are the first locations for sediments to collect. The lack of accumulated sediment within these channels suggests a very low sedimentation rate.

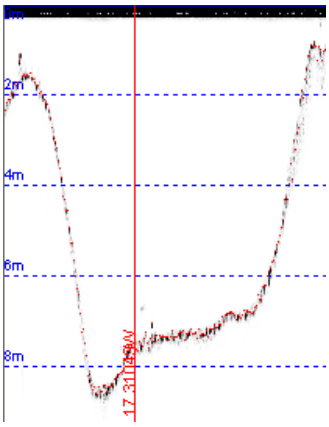

Figure 5. Cross-Section of Little Seneca Creek arm at 4340200 Northing (line runs from west to east)

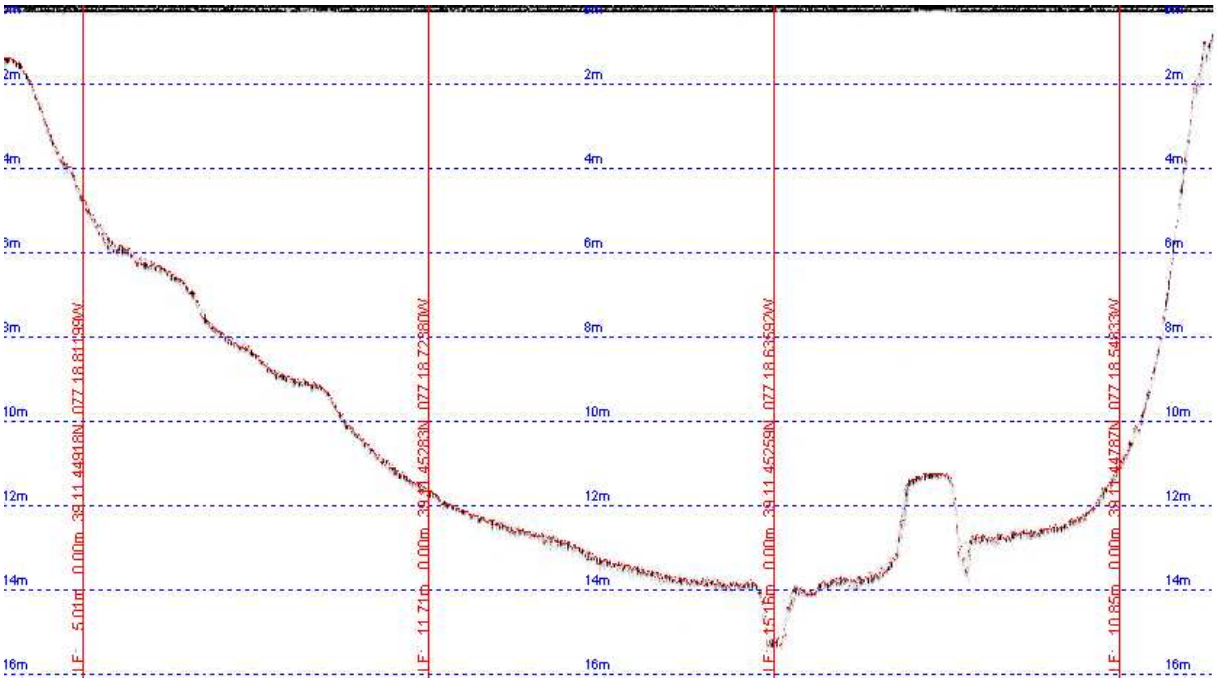

Figure 6. Cross-Section of Cabin Branch arm at 4340500 Northing (line runs from west to east)

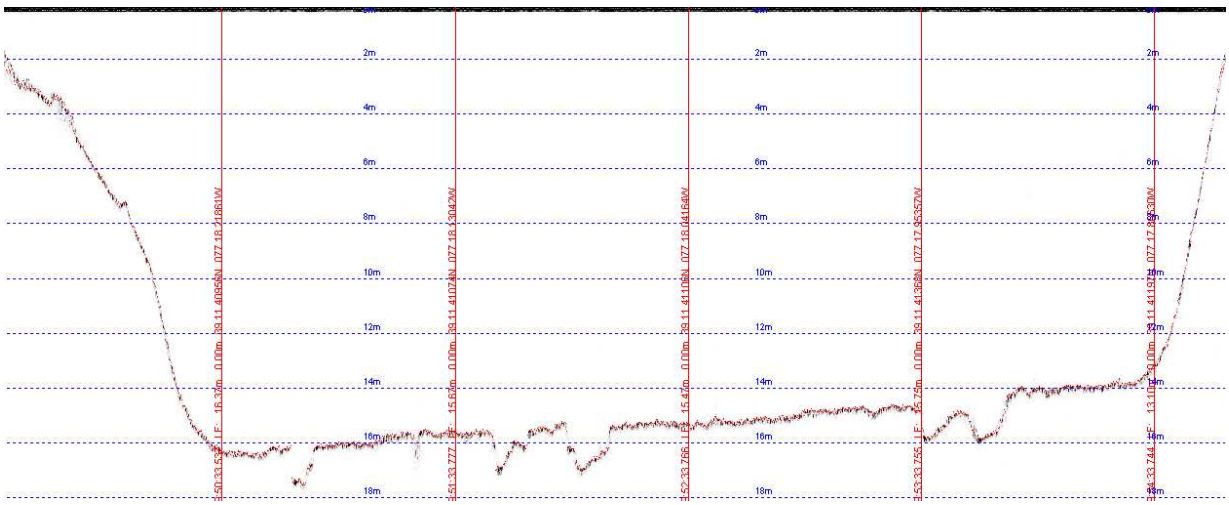

Figure 7. Cross-Section of Tenmile Creek arm at 4340400 Northing (line runs from west to east)

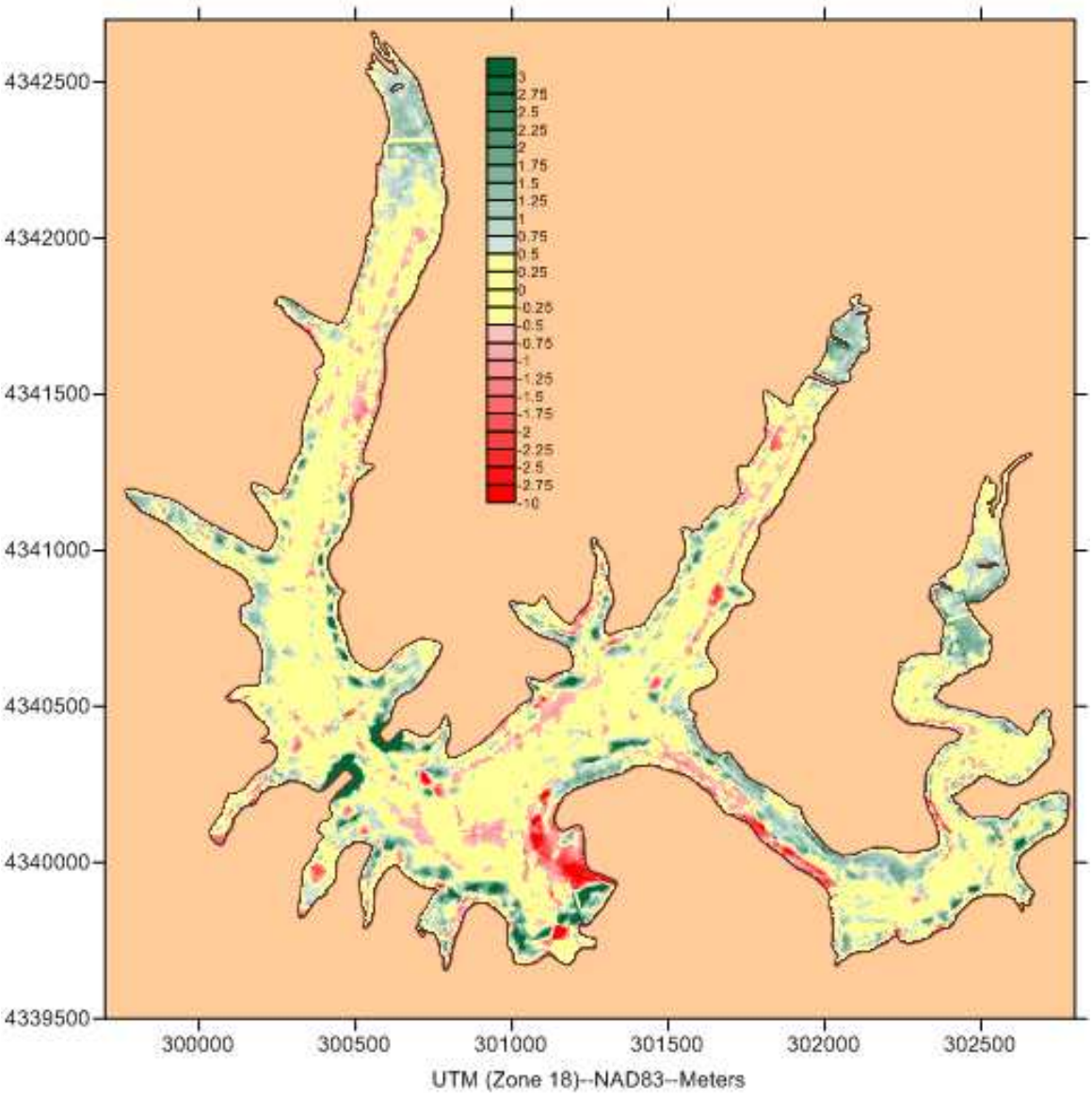

Figure 8. Isopach map displaying depth changes between 2010 and 1979. Range is in meters. Green indicates deposition. Red indicates erosion. Yellow indicates no discernable change.

Sub-Bottom Seismic Reflection Results

Sub-bottom seismic data did not reveal any large areas where sediments had accumulated. Sub-bottom seismic data was not run in the forebays where the greatest deposition is calculated due to the inability to navigate in those areas. The headwater areas were investigated in detail, and no discernable sediment layers could be identified. Sediment was minimally observed in the bottom of the historic creek beds which are easily identifiable throughout the entire lake. Throughout the survey, the signal strength return from both the 200KHz and the 28Khz signal was very strong indicating hard bottom or highly organic (gas rich) sediments.

The sub-bottom seismic data was used to identify the reservoir bottom throughout the survey.

CONCLUSION

The current storage capacity of Little Seneca Reservoir is 14.846 million cubic meters [3.92 billion gallons]. The calculated storage loss is 337 acre-feet [0.416 million cubic meters] since 1983 yielding an average loss rate of 12.5 acre-feet per year [15,000 cubic meters per year] or 0.1% of the original capacity per year.

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Appendix A: Quality Assurance / Quality Control

Bathymetric Surveying

Great attention was devoted to the quality of data recorded and analyzed in the bathymetric survey of Little Seneca Reservoir. The identification of possible sources of error helped to design and execute a data collection methodology that reduced the risk of collecting and utilizing erroneous data. Errors identified in other regional reservoir bathymetry reports were specifically identified and minimized as outlined below (City of Baltimore Department of Public Works, 1989; OSI, 1997). Specifically, additional survey lines were collected between mid-channel and shoreline as identified by OSI in their 1997 report.

Calibration of the equipment was conducted during the data collection process. The GPS equipment conducts a self-test every day, and it was field checked against known horizontal control points. An annual accuracy validation is performed on the GPS. The echosounder was checked against known depths to reduce errors. The echosounder was calibrated in the reservoir throughout the entire range of water depths measured. The data collected and the regression of the calibration data is presented in Table A-1. All initial depth recordings were made using a speed of sound of 1500 meters per second. The recorded depths were adjusted after collection using a calibration equation and an adjustment made for pool level.

The calibration curve for Little Seneca is quite complex due to the temperature variance within the water column. Typically, in well mixed water bodies, a linear calibration curve is utilized; in very well setup water bodies, a bilinear calibration is used; however, Little Seneca Lake did not demonstrate a hard thermocline nor a well mixed water column. It demonstrated warmer surface waters which gradually changed with depth. Analysis of the calibration showed that a third order polynomial fit is the best calibration equation to utilize with the data. A first order fit of the data yielded residuals up to 0.82m from the measured results. A second order fit yielded residuals up to 0.46m from the measured results. A third order fit yielded acceptable results with a maximum of 0.03m from the measured results.

Surveying was halted during times when GPS horizontal accuracy was affected. The GPS is set to stop determining positions if any of the following conditions are met:

1. Number of useable satellites falls below 5.
2. PDOP value exceeds 6.
3. Differential correction updates are older than 30 seconds.
4. Carrier lock is lost on the satellites.

Additionally an elevation mask of 15 degrees was set to filter out satellites that were low on the horizon and which could insert errors into the position solution. Any sounding that was tagged with a GPS position that was greater than 350 milliseconds old was deleted from the dataset.

Known Depth		Measured Depth (meters)				Notes
		Downcast		Upcast		
(feet)	(meters)	200KHz	28KHz	200KHz	28KHz	
2	0.6096	0.39		0.39		
5.05	1.53924	1.3	1.3	1.29	1.29	
10	3.048	2.8	2.79	2.81	2.8	
15	4.572	4.29	4.28	4.32	4.31	
20	6.096	5.89	5.84	5.84	5.79	
25	7.62	7.36	7.36	7.35	7.34	
30	9.144	8.99	8.98	8.91	8.89	
34.95	10.65276	10.55	10.52	10.5	10.51	
40	12.192	12.09	12.09	12.09	12.09	
45	13.716	13.68	13.68	13.68	13.69	
50	15.24	14.96	14.87	15.26	15.26	
55	16.764	16.86	16.88	16.88	16.9	

Table A-1. Echosounder Calibration on July 14, 2010. Regression analysis yields the following calibration equation: Actual Depth = (1.030181 * Measured Depth) + (-0.00452 * Measured Depth ^{2}) + (0.0000987 * Measured Depth ^{3}) + 0.209 Meters. R^2= 0.99999. Residuals ranged between -0.034 meters and 0.028 meters with an average of 0.0003 meters.

The sounding data was verified through multiple techniques. During collection, a minimum and a maximum depth were provided to assist in the selection of the bottom. Various filters are used internally of the echosounder to accurately track the bottom. Occasionally, the echosounder would lose bottom lock, and it would track a multiple, thermocline, sub aquatic vegetation, or water column noise. These data errors were determined through visual observation and filtered from the dataset. This manual filtering of the data was paramount in the processing of the data due to the amount of erroneous bottom detections caused by the sub aquatic vegetation (SAV) population. The SAV significantly interferes with acoustic bathymetry data collection techniques. SAV errors were found throughout the reservoir but most dominantly in the Little Seneca Creek arm. Figure A-1 displays line 111 located in Little Seneca Creek. The blossoms of SAV hide the true bottom of the reservoir. Echosounder readings in these locations were adjusted to accurately track the true bottom. These adjustments were performed using the 200KHz collected records, the 28KHz collected records, visual identification, and professional judgment.

Water level heights were collected by WSSC and by MGS. Water levels during the survey period are documented in Appendix B. Continuous water level readings were made from July 9, 2010 to August 3, 2010. (Appendix B, Figure B-1)

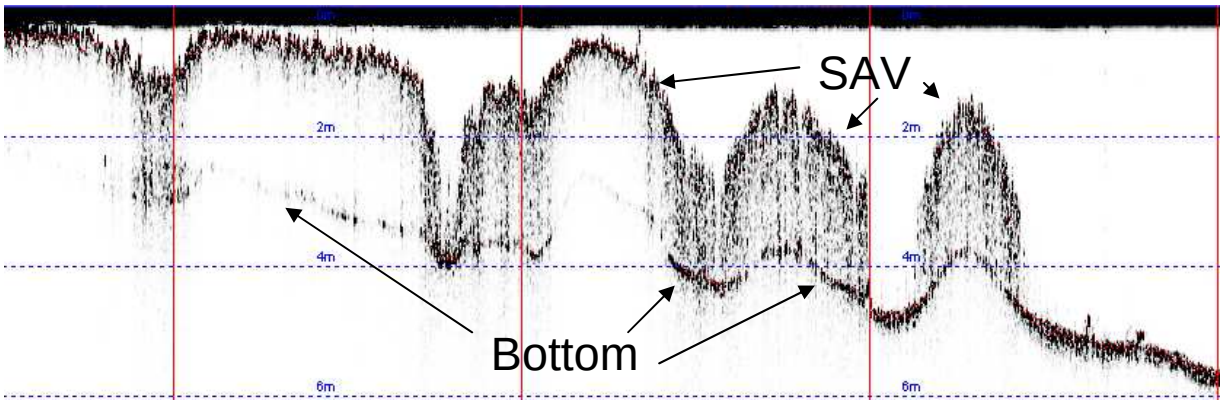

Figure A-1. Sub aquatic vegetation induced depth errors in Little Seneca Lake (survey line 111).

Following the adjustments to depth and the removal of poor quality horizontal and vertical data, the data was further analyzed at the intersection of the tie-in lines. Tie-in lines were run perpendicularly to the established transects. These intersections were visually identified and the surrounding data was analyzed for consistency and accuracy. A minimum of forty-five intersections were visually identified and compared. In all observations, the processed depths at the intersection points exceeded the accuracy standard of +/- (0.1 feet + one percent of the water depth).

Bathymetric Modeling

To perform a consistent analysis, the bathymetric and topographic data of Little Seneca Lake needed to be gridded and modeled into three dimensional surfaces. The modeling program Surfer can utilize a number of different methods to perform this analysis. Several methods including Kriging, Triangular-Irregular Network (TIN), Inverse Distance, and Minimum Curvature were computed and analyzed for proper fitting of the data. A grid resolution of 1 meter was utilized in developing the final models.

The validity of the models was analyzed by calculating residuals from the original data points against the modeled surface. After the model was generated, the original data set was compared to it. The amount that the actual raw data differed from the model at the data point's location is the residual for that data point. Residuals were calculated at all measured data points and a root mean square error analysis was performed on these residuals. Based on the results of this residual analysis and the error range, the model which best fit the raw data was determined.

Residual Root-Mean-Square Analysis of Computed Surfaces		
Surface	**Grid Method**	**Residual RMS (meters)**
Little Seneca 2010	TIN	0.1045
Little Seneca 2010	Minimum Curvature	0.0945
Little Seneca 2010	**Kriging**	**0.0906**
Little Seneca 2010	Inverse Distance	0.1077
Little Seneca 1996 (OSI)	**Kriging**	**0.0370**
Little Seneca 1996 (OSI)	Minimum Curvature	0.0420
Little Seneca 1996 (OSI)	Inverse Distance	0.0583
Little Seneca 1996 (OSI)	TIN	0.0534
Little Seneca 1979 (JMT)	**TIN**	**0.0533**

Table A-2. Residual root-mean-square analyses of the bathymetric data compared.

Appendix B: Mean Pool Level Adjustments

Mean Pool Level Recordings and Adjustments					
Mean Sea Level (Feet) Mean Pool Level of Little Seneca Reservoir is defined to be 385.0 Feet MSL (1929)					
Date	**Water Level**			**Daily**	**Depth Adjustment**
	10:00 AM	**3:00 PM**		**Average**	**Feet**
LITTLE SENECA RESERVOIR					
July 12, 2010	384.51	384.51		384.51	0.49
July 13, 2010	384.63	384.63		384.63	0.37
July 14, 2010	384.78			384.78	0.22
August 2, 2010	384.44	384.44		384.44	0.56
August 3, 2010	384.43			384.43	0.57

Table B-1. Mean Pool Level Recordings and Adjustments

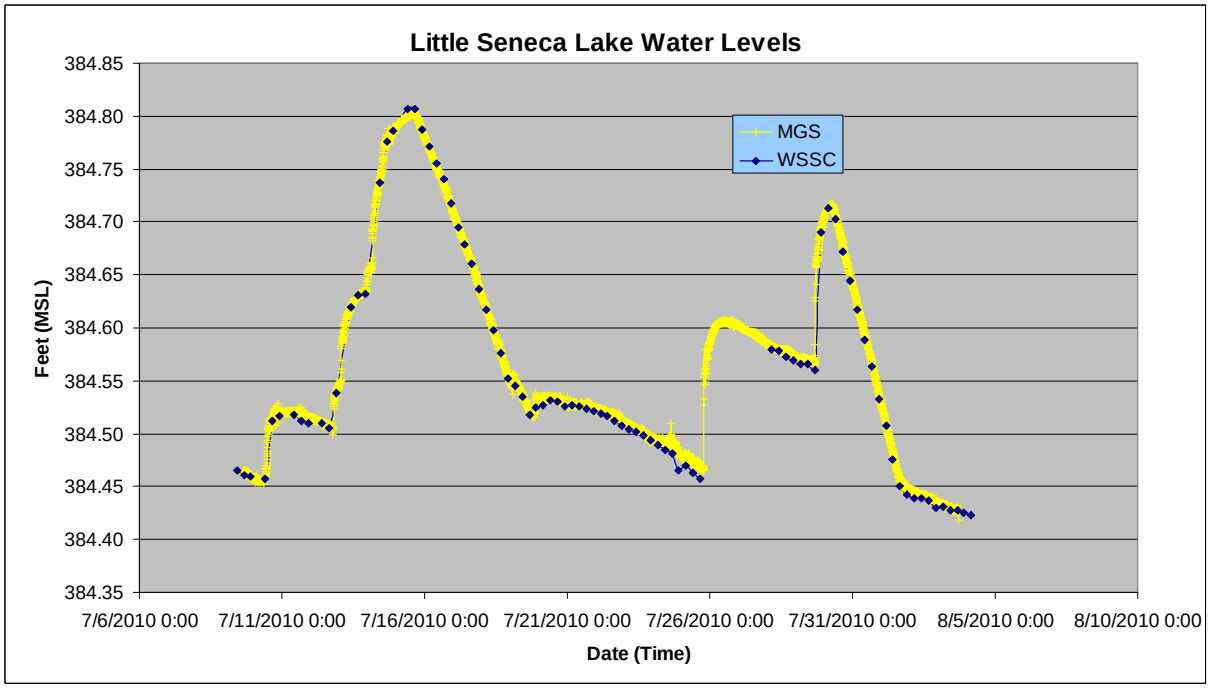

Figure B-1. Water level Recordings collected during the survey period.

Appendix C: CD Contents and Repository

The datasets collected, interpolated, and analyzed in this report are too large to be included in printed format. The digital datasets are archived on a DVD disc. The disc is archived at the organization listed below. WSSC also maintains a set of this data.

Maryland Geological Survey
Publications
2300 Saint Paul Street
Baltimore, MD 21218
(410)554-5505
http://www.mgs.md.gov

Contents of DVD-R disc:

Adobe Portable Document Format of this report
Plate Illustrations in Adobe PDF Format
Reservoir X, Y, Z Soundings in ASCII format
Raw Echosounder Data in KEA and KEB formats
KEB file viewer program (Windows XP or higher)

Appendix D: Surficial Sediments

Methods

Field Collection of Sediment Samples

MGS collected eleven sediment grab samples for this study. Samples were collected at sites along the mid-channel in the upstream portion of the three major branches of the lake (Figure D-1). The samples were collected to document upstream character of the of the bottom sediments.

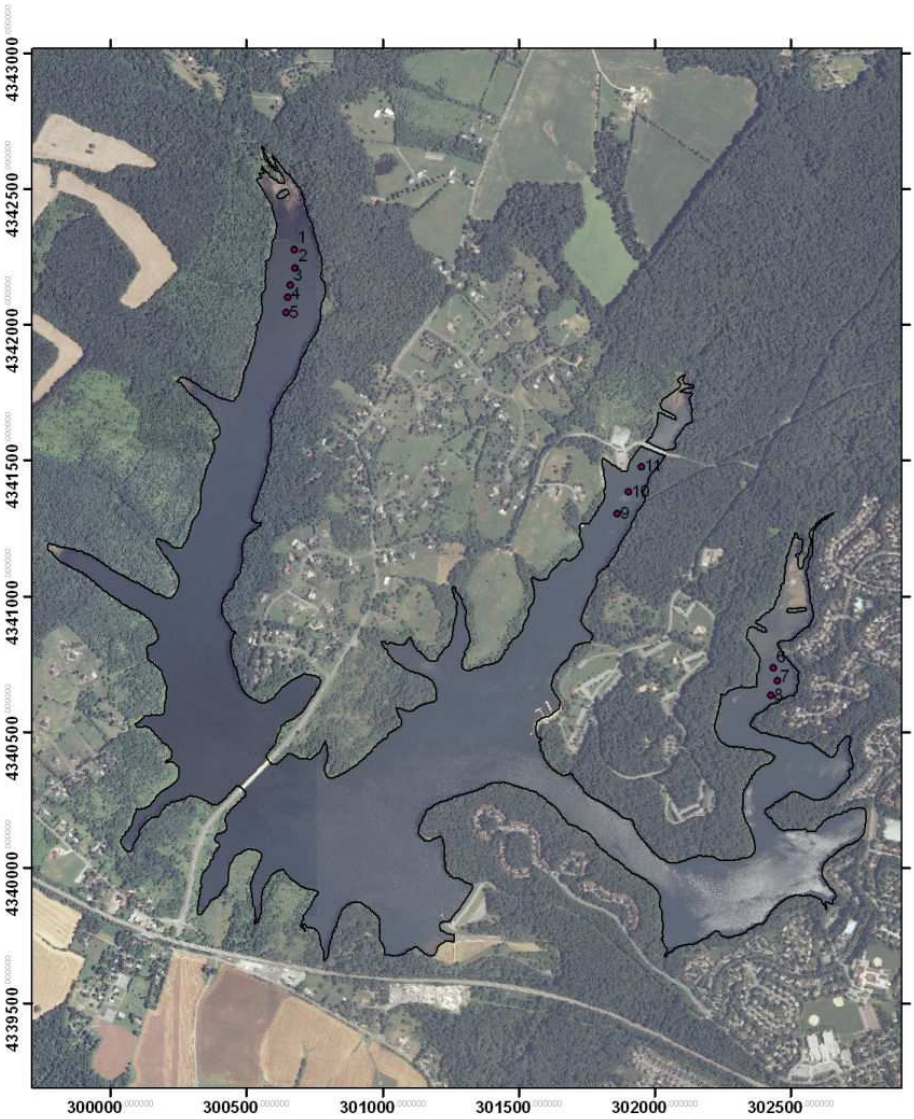

Figure D-1. Sample locations.

Samples were collected on August 3, 2010. Locations of the sediment samples were documented using a Thales Navigation Promark 3 GPS receiver. Location coordinates were recorded in UTM, NAD83, meters.

Sediment samples were collected using a hand-operated LaMotte stainless-steel dredge which sampled a bottom surface area of 19 cm x 14 cm and a mean sediment depth of 5 cm. Upon collection, the samples were placed in Whirl-Pak™ bags and kept cool until delivery to the MGS laboratory where they were refrigerated at 4˚ C. until analyses.

Laboratory Analyses

Textural Analyses

All sediment samples were analyzed for water content, bulk density, and grain size (sand, silt, clay contents, as well as gravel, when present). Two homogeneous splits of each sample are processed, one for bulk property analyses and the other for grain-size characterization. Analyses were performed as soon as possible after sample collection, and all samples were refrigerated in sealed Whirl-Pak™ plastic bags prior to analysis.

Water content was calculated as the percentage of water weight to the weight of the wet sediment using equation 1.

$$\%Water = \frac{W_w}{W_t} * 100 \qquad \text{Equation 1}$$

where: $\boldsymbol{W_w}$ is the weight of water; and
$\boldsymbol{W_t}$ is the weight of wet sediment.

Water content was determined by weighing 20-30 g of sediment; the sediment was dried at 65°C, and then re-weighing the dried sediment. Dried sediments were saved for chemical analyses (see **Chemical Analyses** section).

Bulk density (ρ_B) is calculated from water content utilizing equation 2 by assuming an average grain density (ρ_s) of 2.72 g/cm^3 and saturation of voids with water of density ρ_w = 1.0 g/cm³. This method was adopted from the work of Bennett and Lambert (1971):

$$\rho_B = \frac{W_t}{W_d \ / \ 2.72 + W_w} \qquad \text{Equation 2}$$

where $\boldsymbol{W_d}$ is the weight of dry sediment.

Sand, silt and clay contents were determined using the textural analysis detailed in Kerhin and others, (1988). Grain size analysis consists of cleaning the samples in solutions of 10 percent hydrochloric acid and 6 or 15 percent hydrogen peroxide (determined by water content) with subsequent rinsing with deionized water. This process removed soluble salts, carbonates, and organic matter that could interfere with the dis-aggregation of the individual grains. The samples are then treated with a 0.26 percent solution of the dispersant sodium hexametaphosphate ($(NaPO_3)_6$) to ensure that individual grains did not re-aggregate during analysis.

The separation of sand and silt-clay portions of the sample is accomplished by wet-sieving through a 4-phi mesh sieve (0.0625 mm, U.S. Standard Sieve #230). The sand fraction is dried and weighed. The finer silt and clay-sized particles are suspended in a 1000 ml cylinder in a solution of 0.26 percent sodium hexametaphosphate. The suspension is agitated and, at specified times thereafter; 20 ml pipette withdrawals are made (Carver, 1971; Folk, 1974). The rationale behind this process is that larger particles settle faster than smaller ones (Stoke's law). By calculating the settling velocities for different sized particles, times for withdrawal can be determined at which all particles of a specified size will have settled past the point of withdrawal. Sampling times are calculated to permit the determination of the amount of silt (4 phi) and clay sized (8 phi) particles in the suspension. Withdrawn samples are dried at 65°C and weighed. From these data the percentages by dry weight of sand, silt, and clay are calculated for each sample and classified according to Shepard's (1954) nomenclature (Figure D-2). Result of textural analyses are presented in Table D-5.

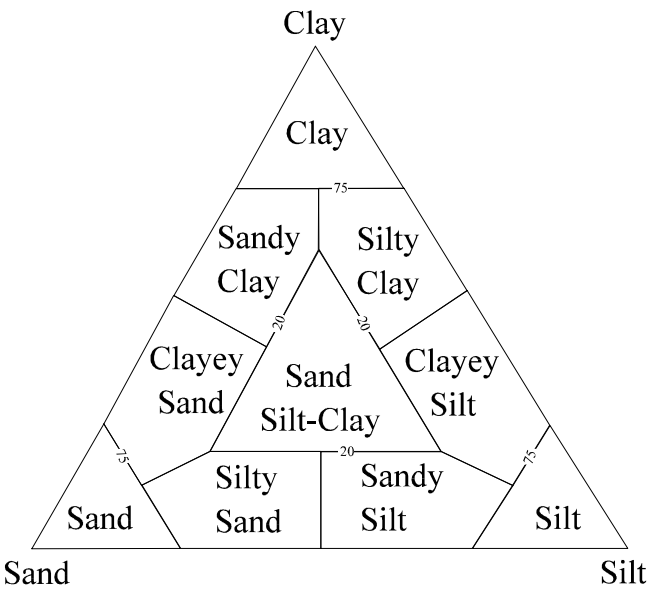

Figure D-2. Shepard's (1954) classification of sediment types

Although the techniques used to determine grain size are based on traditional analytical methods developed for the sedimentology lab, some analytical error is inherent to the techniques. For example, results can be affected by level of technician skill and/or changes in laboratory conditions (such as sudden temperature changes). Furthermore, there is no standard reference material available that includes the broad range of particle sizes and shapes contained in natural sediment. To maximize consistency of textural analysis, several "checks" are used to monitor results. The calculated sand, silt, clay and gravel (when present) percentages are checked against 1) sample field descriptions; 2) calculated water contents; and 3) calculated weight loss of sample during processing. These comparisons are made to determine if the size components match the visual description of the sample and/or fall within an expected classification with respect to water content and weight loss. Any discrepancy is "flagged" and the results are reviewed further to determine if re-analysis is warranted.

Chemical Analyses

Sediments dried for water content determination were saved for elemental analyses. The dried sediments were pulverized in tungsten-carbide vials using a ball mill, then placed in Whirl-Pak™ bags and stored in a desiccator.

Nitrogen, Carbon and Sulfur Analyses

The sediments were analyzed for total nitrogen, carbon and sulfur (NCS using a Carlo Erba NA1500 analyzer. Untreated dried sediments were analyzed for total nitrogen, carbon and sulfur (NCS) contents. Approximately 10-15 mg of dried sediment was weighed into a tin capsule. The exact weight (to the nearest µg) of the sample was recorded. To ensure complete combustion during the analysis, 15-20 mg of vanadium pentoxide (V_2O_5) was added to the sediment. The tin capsule containing the sediment and vanadium pentoxide mixture was then crimped to seal and stored until analysis.

The sediment sample, contained in a tin capsule, was dropped into a combustion chamber where the sample was oxidized in pure oxygen. The resulting combustion gases (N, C, H, and S), along with pure helium used as a carrier gas, were passed through a reduction furnace to remove free oxygen and then through a sorption trap to remove water. Separation of the gas components was achieved by passing the gas mixture through a chromatographic column. A thermal conductivity detector was used to measure the relative concentrations of the gases.

The NA1500 Analyzer was configured for NCS analysis using the manufacturer's recommended settings. As a primary standard, Sulfanilamide was used. Blanks (tin capsules containing only vanadium pentoxide) were run at the beginning and end of sample set. Replicates of every fifth sample were run. As secondary standards, one or

more reference materials (NIST SRM #1646 - Estuarine Sediment and NIST SRM #8704 - Buffalo River Sediment) were run every 5 samples. Comparisons of results of SRMs to their certified values are presented in the Table D-1. Results of the NCS analyses are presented in Table D-6.

Table D-1. Results of nitrogen, carbon, and sulfur analyses of the standard reference materials (SRMs) compared to the certified or known values. MGS values were obtained by averaging the results of all SRM analyses run during this study.

Element	NIST SRM 2704- Buffalo River			NIST SRM 1646a- Estuarine Sediments		
	NIST Values [1]	MGS Results	% Recovery	NIST Values [2]	MGS Results	% Recovery
Total Nitrogen (% dry weight)	0.19 +/- 0.001	0.172 +/- 0.005	90.7	0.056	0.054 +/-0.001	96.0
Carbon (% dry weight)	3.348 +/- 0.02	3.292 +/- 0.021	98.3	0.583	0.555 +/-0.008	95.2
Sulfur (% dry weight)	0.397 +/- 0.004	0.283 +/- 0.034	71.2	0.352 +/- 0.004	0.348 +/-0.038	98.9

[1] For NIST 2704, the value for carbon is certified by NIST. The sulfur value is the non-certified value reported by NIST. The value of nitrogen was obtained from repeated analyses in-house and by other laboratories (Haake Buchler Labs and U.S. Dept. of Agriculture).
[2] For SRM the values for sulfur are certified values reported by NIST; nitrogen and carbon values were obtained from repeated analyses in-house and by Actlabs

Elemental Analyses

Two to three-gram splits of the dried sediments were shipped to Activation Laboratories, Ltd. (Actlabs) of Ancaster, Ontario, Canada., to be analyzed for 34 elements including total phosphorus. Actlabs used a four-acid, “near total” digestion process, followed by analysis of the digestate by inductively coupled plasma emission spectroscopy (ICP-OES). The four-acid digestion employed perchloric ($HClO_4$), hydrochloric (HCl), nitric (HNO_3), and hydrofluoric (HF) acids. SRM NIST #8704 was included as double- blind samples with the reservoir sediment shipped to Actlabs. The Actlabs’ results of the analyses of the SRM are listed in Table D-2 . Elemental analysis results for the surficial samples are listed in Table D-7.

Table D-2. Quality Assurance / Quality Control Values from elemental analysis by Actlab, Inc. Results of analyses of Standard Reference Material (NIST SRM #8704 - Buffalo River Sediment) submitted as blind unknowns with the Little Seneca Lake surficial samples. Also given are the method detection limits for each element reported by Actlabs.

				NIST certified values		Actlabs results		
Element	**Abbrev.**	**Unit**	**Detection Limit**	**Certified value**	**Std dev**	**Average**	**Std dev**	**% recovery**
Silver	Ag	ppm	0.3			< 0.3		
Aluminum	Al	%	0.01	6.1	0.18	4.155	0.01	68.1
Arsenic	As	ppm	0.5	17		14.5	0.71	85.3
Barium	Ba	ppm	50	413	13	388.5	3.54	94.1
Beryllium	Be	ppm	1			2	0.00	
Bismuth	Bi	ppm	2			< 2		
Calcium	Ca	%	0.01	2.641	0.083	2.79	0.03	105.6
Cadmium	Cd	ppm	0.3	2.94	0.29	3.4	0.00	115.6
Cerium	Ce	ppm	3	66.5	2			
Cobalt	Co	ppm	1	13.57	0.43	16	0.00	117.9
Chromium	Cr	ppm	2	121.9	3.8	110.5	12.02	90.6
Cesium	Cs	ppm	1	5.83	0.12			
Copper	Cu	ppm	1			103	12.73	
Europium	Eu	ppm	0.2	1.31	0.038			
Iron	Fe	%	0.01	3.97	0.1	3.765	0.05	94.8
Gallium	Ga	ppm	1			18.5	0.71	
Hafnium	Hf	ppm	1	8.4	1.5			
Mercury	Hg	ppm	1			1.5	0.71	
Potassium	K	%	0.01	2.001	0.041	1.98	0.01	99.0
Lanthanum	La	ppm	0.5					
Lithium	Li					42.5	0.71	
Magnesium	Mg	%	0.01	1.2	0.018	1.195	0.01	99.6
Manganese	Mn	ppm	1	544	21	588.5	16.26	108.2
Molybdenum	Mo	ppm	1			1	0.00	
Sodium	Na	%	0.01	0.553	0.015	0.605	0.02	109.4
Neodymium	Nd	ppm	5					
Nickel	Ni	ppm	1	42.9	3.7	46	1.41	107.2
Phosphorus	P	%	0.001			0.0805	0.00	
Lead	Pb	ppm	3	150	17	143	4.24	95.3
Sulfur	S	%	0.01			0.37	0.00	
Antimony	Sb	ppm	0.1	3.07	0.32	< 5		
Scandium	Sc	ppm	0.1	11.26	0.19	11	0.00	97.7

Table D-2. Quality Assurance / Quality Control Values from elemental analysis by Actlab, Inc. Results of analyses of Standard Reference Material (NIST SRM #8704 - Buffalo River Sediment) submitted as blind unknowns with the Little Seneca Lake surficial samples. Also given are the method detection limits for each element reported by Actlabs.

				NIST certified values		Actlabs results		
Element	**Abbrev.**	**Unit**	**Detection Limit**	**Certified value**	**Std dev**	**Average**	**Std dev**	**% recovery**
Strontium	Sr	ppm	1			127.5	3.54	
Tellurium	Te	ppm				5.5	0.71	
Thorium	Th	ppm	0.2	9.07	0.16			
Titanium	Ti	%	0.01	0.457	0.02	0.395	0.02	86.4
Thallium	Tl	ppm				< 5		
Uranium	U	ppm	0.5	3.09	0.13	< 10		
Vanadium	V	ppm	2	94.6	4	63	4.24	66.6
Tungsten	W	ppm	1			5.5	0.71	
Yttrium	Y	ppm	1			21.5	0.71	
Zinc	Zn	ppm	1	408	15	392	1.41	96.1

Results and Discussion

Textural analyses of the 11 surficial sediment samples (representing the top 5 cm of the sediment column) indicate that the majority of the samples collected are fine-grained sediments. Ten out of the 11 samples fall within the clayey-silt classification, ClSi (Table D-5); sample 11 is classified as Sand-Silt-Clay. Sand is a relatively minor component. Silt is a major component of the collected sediments, which is not unexpected given the silty characteristics for the soils and underlying rock within the watershed. The sediments from Little Seneca Branch contain slightly more silt compared to Cabin Branch or 10-Mile Creek.

Total N, C and P content of the surficial sediments average 0.29%, 3.25% and 0.08% respectively. Total N, C and P contents in the Little Seneca Lake surficial sediments are comparable to those of other freshwater lakes in Maryland (Table D-3). Contents of nutrients do not vary significantly between the major branches within the lake.

The elemental analyses for the surficial sediments yielded concentrations within the ranges reported for other fresh water lakes in Maryland. Most elements measured are within background levels given in the NOAA SQuirTs (Screening Quick Reference Tables) (Buchman, 2008). Likewise, enrichment factors calculated for the surficial samples using Fe are very similar to those reported for other lakes. Elements having significantly high enrichment (i.e., >2 for Fe based EF values) include arsenic (As), cadmium (Cd), lead (Pb) and zinc (Zn) (Table D-4). While the high enrichment may

reflect a natural regional abundance of the elements, these four element often reflect anthropogenic sources. Comparison of EFs indicate no significant difference between the major branches of the lake.

Table D-3. Comparison of total N, C. and P in surface sediment in Maryland fresh water reservoirs.

	% N		**% C**		**% P**	
	Average	**Range**	**Average**	**Range**	**Average**	**Range**
Loch Raven (Ortt et al, 1999)	0.32	0.24-0.40	3.17	2.53-3.94	0.16	0.12-0.19
Little Seneca Lake	**0.29**	**0.18-0.34**	**3.25**	**2.07-5.06**	**0.08**	**0.06-0.14**
Triadelphia Reservoir (Wells et al, 2007)	0.26	0.11-0.48	2.77	1.48-4.12	0.10	0.04-0.17
Rocky Gorge Reservoir (Wells et al, 2007)	0.22	0.05-0.41	2.67	0.83-4.17	0.09	0.03-0.16
New Germany (Ortt and Wells, 2009)	0.51	0.09-0.81	6.20	2.02-7.54	0.06	0.01-0.10
Deep Creek Lake (Wells and Ortt, 2011)	0.33	0.12-0.62	4.11	1.55-9.60	0.06	0.01-0.13

Table D-4. Summary of average Enrichment factor normalized to Fe content and referenced to Taylor's (1964) average continental crust rock element abundance. EF values were average for all samples and for each branch.

	Al	**As**	**Ba**	**Cd**	**Co**	**Cr**	**Cu**	**Mg**	**Mn**
All samples	0.97	4.57	1.93	3.14	1.55	0.76	0.91	0.24	0.90
10-mile Creek	0.95	5.02	1.77	2.87	1.63	0.74	0.95	0.24	0.97
Little Seneca	1.10	2.36	2.35	4.03	1.52	0.93	1.00	0.27	0.71
Cabin Branch	0.87	5.22	1.78	2.71	1.45	0.63	0.77	0.20	0.95
	Ni	**Pb**	**Sc**	**Sr**	**Ti**	**V**	**Y**	**Zn**	
All samples	0.77	2.86	0.97	0.30	1.07	0.85	0.79	2.37	
10-mile Creek	0.81	2.94	0.97	0.32	0.82	0.76	0.64	2.24	
Little Seneca	0.90	3.34	1.10	0.33	1.35	1.02	0.99	2.82	
Cabin Branch	0.59	2.26	0.83	0.24	1.21	0.85	0.83	2.11	

Textural and Chemical Data

Table D-5. Physical characteristics of sediment samples.

Sample ID	UTM, NAD83, m		Branch	% Water	Bulk Density (g/cm^3)	Size component (% by weight)				Shepherd's Classification
	Northing	Easting				Gravel	Sand	Silt	Clay	
1	4342277	300676	Tenmile Creek	67.65	1.26	0.00	0.98	57.09	41.93	Clayey-Silt
2	4342211	300679	Tenmile Creek	63.75	1.30	0.00	1.73	60.53	37.75	Clayey-Silt
3	4342147	300660	Tenmile Creek	69.82	1.24	0.00	0.68	55.36	43.96	Clayey-Silt
4	4342103	300650	Tenmile Creek	65.95	1.27	0.00	2.80	55.24	41.95	Clayey-Silt
5	4342045	300645	Tenmile Creek	73.42	1.20	0.00	1.93	54.72	43.35	Clayey-Silt
6	4340737	302434	Little Seneca	72.54	1.21	0.00	5.60	58.82	35.57	Clayey-Silt
7	4340690	302449	Little Seneca	69.05	1.24	0.00	2.12	60.89	37.00	Clayey-Silt
8	4340636	302427	Little Seneca	68.19	1.25	0.00	1.85	59.93	38.21	Clayey-Silt
9	4341306	301861	Cabin Branch	74.84	1.19	0.00	3.57	48.50	47.93	Clayey-Silt
10	4341386	301904	Cabin Branch	69.73	1.24	0.00	3.14	49.19	47.67	Clayey-Silt
11	4341479	301951	Cabin Branch	56.34	1.38	0.00	25.87	46.97	27.15	Sand-Silt-Clay

Table D-6 . Major nutrient contents in Little Seneca Lake surfical sediment. Values are percent dry weight.

Sample ID	%N	%C	%S	%P
1	0.298	3.354	0.120	0.079
2	0.272	3.145	0.118	0.064
3	0.303	3.176	0.121	0.072
4	0.275	3.092	0.105	0.062
5	0.316	3.286	0.107	0.077
6	0.327	5.063	0.095	0.072
7	0.270	2.941	0.084	0.077
8	0.271	2.926	0.076	0.078
9	0.321	3.181	0.131	0.138
10	0.335	3.468	0.154	0.109
11	0.178	2.074	0.076	0.063

Table D-7. Results of elemental analyses from Actlabs. Phosphorus is report with nutrient data. All values are reported as ppm unless otherwise noted. Values preceded by "<" indicate result below detection limit.

Sample ID	As	Ba	Be	Bi	Ca (%)	Cd	Co	Cr	Cu	Fe (%)	Ga
1	10	652	3	3	0.2	0.5	39	84	48	5	29
2	< 3	670	4	< 2	0.22	0.5	37	71	47	5.12	26
3	< 3	699	4	< 2	0.2	0.5	35	48	47	5.33	26
4	6	683	4	< 2	0.23	0.5	36	50	47	4.96	25
5	< 3	702	4	< 2	0.23	0.6	37	83	48	5.11	29
6	3	730	3	< 2	0.27	0.6	29	77	45	3.98	25
7	< 3	759	3	< 2	0.23	0.6	28	66	34	4.42	25
8	< 3	743	3	< 2	0.22	0.6	28	65	43	4.19	26
9	< 3	698	3	3	0.18	0.6	34	66	42	5.95	29
10	9	731	3	< 2	0.2	0.5	32	61	42	5.66	29
11	7	624	3	< 2	0.16	0.4	32	47	32	4	22

Table D-7 (cont.). Results of elemental analyses from Actlabs. Phosphorus is report with nutrient data. All values are reported as ppm unless otherwise noted. Values preceded by "<" indicate result below detection limit.

Sample ID	Hg	K (%)	Li	Mg (%)	Mn	Mo	Na (%)	Ni	Pb	Sb	S (%)
1	< 1	2.32	64	0.49	919	5	0.75	52	26	< 5	0.12
2	< 1	2.44	66	0.51	846	< 1	0.77	57	37	< 5	0.13
3	2	2.51	69	0.52	850	< 1	0.8	56	34	< 5	0.13
4	2	2.46	66	0.51	766	< 1	0.78	56	35	< 5	0.11
5	1	2.51	67	0.51	803	2	0.78	54	35	< 5	0.13
6	1	2.54	46	0.47	601	3	0.48	52	34	< 5	0.12
7	2	2.69	49	0.49	454	< 1	0.51	51	31	< 5	0.1
8	2	2.63	48	0.47	443	2	0.49	48	28	< 5	0.1
9	< 1	2.40	47	0.44	948	4	0.44	43	26	< 5	0.14
10	< 1	2.61	48	0.46	662	2	0.45	44	27	< 5	0.15
11	1	2.31	39	0.38	827	< 1	0.53	35	24	< 5	0.07

Table D-7 (cont.). Results of elemental analyses from Actlabs. Phosphorus is report with nutrient data. All values are reported as ppm unless otherwise noted. Values preceded by "<" indicate result below detection limit.

Sample ID	Sc	Sr	Te	Ti (%)	Tl	U	V	W	Y	Zn	Zr
1	18	100	10	0.74	< 5	< 10	120	10	16	137	170
2	19	109	5	0.34	< 5	< 10	98	< 5	20	142	142
3	20	109	4	0.20	< 5	< 10	70	< 5	18	151	74
4	20	109	4	0.26	< 5	< 10	72	< 5	20	142	93
5	20	112	6	0.57	< 5	< 10	106	< 5	21	140	166
6	17	93	9	0.55	< 5	< 10	98	< 5	25	150	196
7	18	92	7	0.55	< 5	< 10	100	< 5	25	148	176
8	19	90	8	0.62	< 5	< 10	108	< 5	23	143	171
9	16	77	12	0.71	< 5	< 10	115	< 5	23	146	196
10	17	83	9	0.53	< 5	< 10	106	< 5	24	151	76
11	16	85	9	0.62	< 5	< 10	91	< 5	26	111	221

Appendix E: In-Depth Analysis of Sediment Forebays

Little Seneca Lake was designed with three sediment forebays to serve as a better management practice of sediment control. These forebays have been collecting sediment since the construction of the reservoir, and they have been minimizing sediment accumulating in the remainder of the reservoir from the three main tributaries (TenMile Creek, Cabin Branch, and Little Seneca Creek). These forebays act as a settling basin where the current flow from the tributaries is dissipated across a large area to allow for the entrained sediment to settle and collect prior to the water being transported into the main portion of the reservoir.

Table E-1 presents the volumes of the forebays from the original topographic maps and also from the 2010 bathymetry survey. There exists no historical documentation nor does anyone at WSSC recall any dredging or modifications to the sediment forebays. Little Seneca Creek and Cabin Branch forebays have lost approximately fifty percent of their volume and TenMile Creek has lost approximately sixty percent of its original volume.

Calculated Storage Capacities and Areas				
Forebay	**1979 Volume Million Gallons [Cubic Meters]**	**2010 Volume Million Gallons [Cubic Meters]**	**2010 Area Acres [Square Meters]**	**Remaining Volume % of Original Capacity**
TenMile	11.053 [41842]	4.202 [15907]	7.36 [29783]	38
Cabin Branch	12.654 [47900]	6.089 [23050]	5.30 [21455]	48
Little Seneca	16.336 [61840]	8.464 [32041]	10.98 [44426]	52

Table E-1. Forebay volume analysis.

The volumes reported in Table E-1 are when the reservoir is at mean pool level (385.0 ft MSL). These volumes quickly decrease with a decreased pool level as they are very shallow (Figures E-1, E-2, E-3). Also, as the water level decreases, the sediments become closer to the active energy zone of the current flow, and the possibility exists that the sediments may become resuspended (scour) and enter into the reservoir.

Various researchers have attempted to model the sediment trapping efficiencies of reservoirs and basins. Brown, Brune, Heinemann, and Churchill have all developed models to determine the trapping efficiency using watershed area, storage capacities, flow rates, and basin dimensions. While all of these models were run to determine the trapping efficiency of the forebays, Churchill's model is clearly the best model for this environment. Churchill's model uses measured volume inflow, the basin's storage capacity, the basin's area, and the length of the basin to determine the period of retention of the sediment-laden water and the velocity of this water through the basin. Ultimately, these calculated values determine if a particle has enough time to fall out of suspension to be deposited within the basin or if it remains entrained exiting the basin into the reservoir. (Brown, 1943; Brune, 1953; Churchill, 1948; Heinemann, 1981) As a model, the results are an estimate, and should be confirmed with field findings. Additionally, this is an estimate throughout the year, and it does not model storm flow which is when the bulk of sediment is transported. (Leopold et al., 1964)

Calculated Trapping Efficiencies (Churchill Method)		
Forebay	**1979 T.E. (%)**	**2010 T.E. (%)**
TenMile	*98*	*92*
Cabin Branch	*102*	*99*
Little Seneca	*99*	*95*

Table E-2. Estimated Trapping Efficiencies at MPL and USGS measured daily flows.

The calculated sediment trapping efficiencies of the originally constructed forebays were nearly 100 percent meaning that all sediment (entering via the tributaries) would be contained within the forebays. As the forebays became sediment-laden and the storage capacities of these forebays decreased, the trapping efficiency of the forebays has decreased. The current estimated trapping efficiencies of the forebays are now ninety-two percent for TenMile Creek, ninety-nine percent for Cabin Branch, and ninety-five percent for Little Seneca Creek. A one foot drop in water level (384.0 ft MSL) changes these trapping efficiencies to the low eighty percents. (Table E-2)

Figure 8 clearly shows sediments escaping the forebays of TenMile Creek and Little Seneca Creek while very little sediment is shown outside of the forebay for Cabin Branch. It is unlikely that these escaped sediments are sourced from entrained fine-grained sediments as they would likely be transported further into the reservoir due to the amount of energy needed to maintain them in suspension as well as the increased depth of the reservoir. Instead, these sediments are likely to be scoured sediments which fell out of suspension immediately when the cross-sectional area of the reservoir increased and the flow energy decreased. The Cabin Branch forebay may also have additional sediment trapping capability due to its construction design. The Cabin Branch forebay is connected to the main body of the reservoir through two culverts. These culverts focus the flow through a very small portion of the forebay allowing a greater part of the forebay to act as a settling basin.

It is clear that the forebays in TenMile Creek and Little Seneca Creek, while still functioning, could be trapping more sediment if they were maintained at a deeper depth. However, maintenance of the forebays is based on the management plan of the reservoir. Forebays can be used for sediment control, habitat development, nutrient reduction, and recreation. Depending on how these forebays are integrated into the management plan, a maintenance plan should be developed to support those goals.

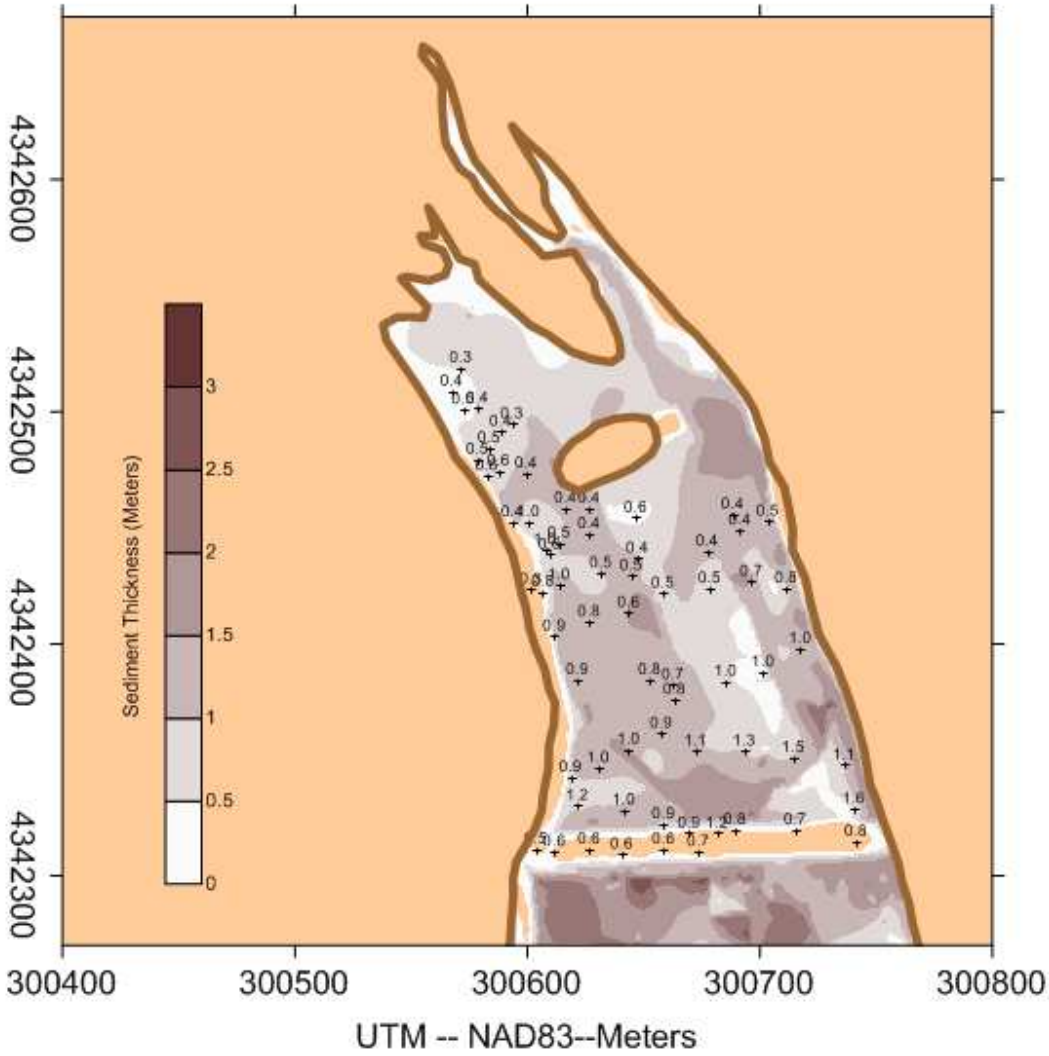

Figure E-1. TenMile Creek Forebay. Shaded area is the sediment thickness calculated from the 1979 JMT topographic survey and the 2010 MGS bathymetry survey. Individual depths are plotted from the 2010 MGS bathymetric survey indicating the 2010 depths within the forebay.

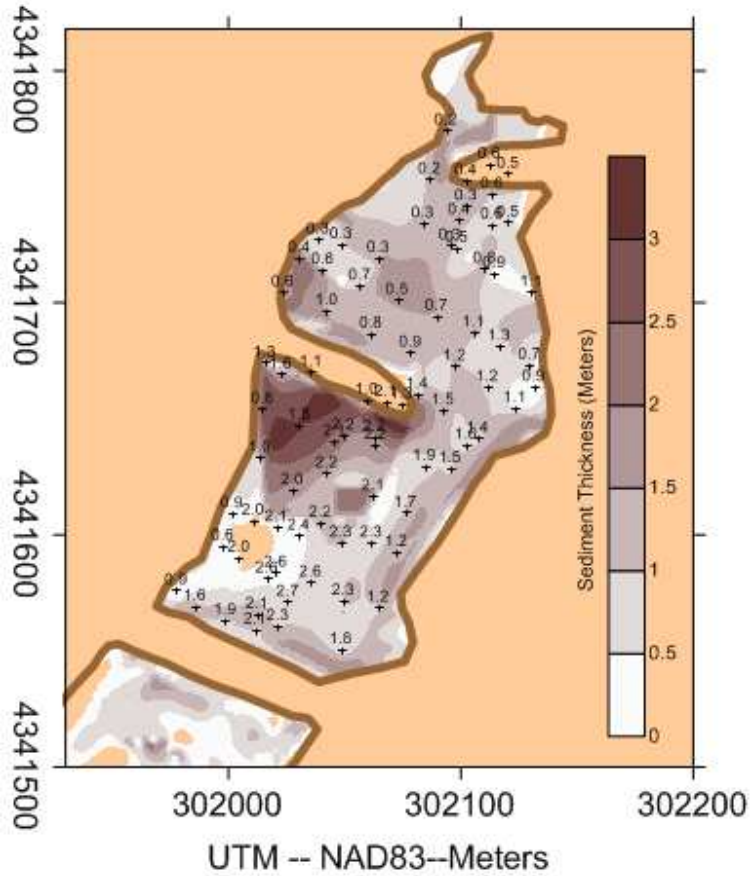

Figure E-2. Cabin Branch Forebay. Shaded area is the sediment thickness calculated from the 1979 JMT topographic survey and the 2010 MGS bathymetry survey. Individual depths are plotted from the 2010 MGS bathymetric survey indicating the 2010 depths within the forebay.

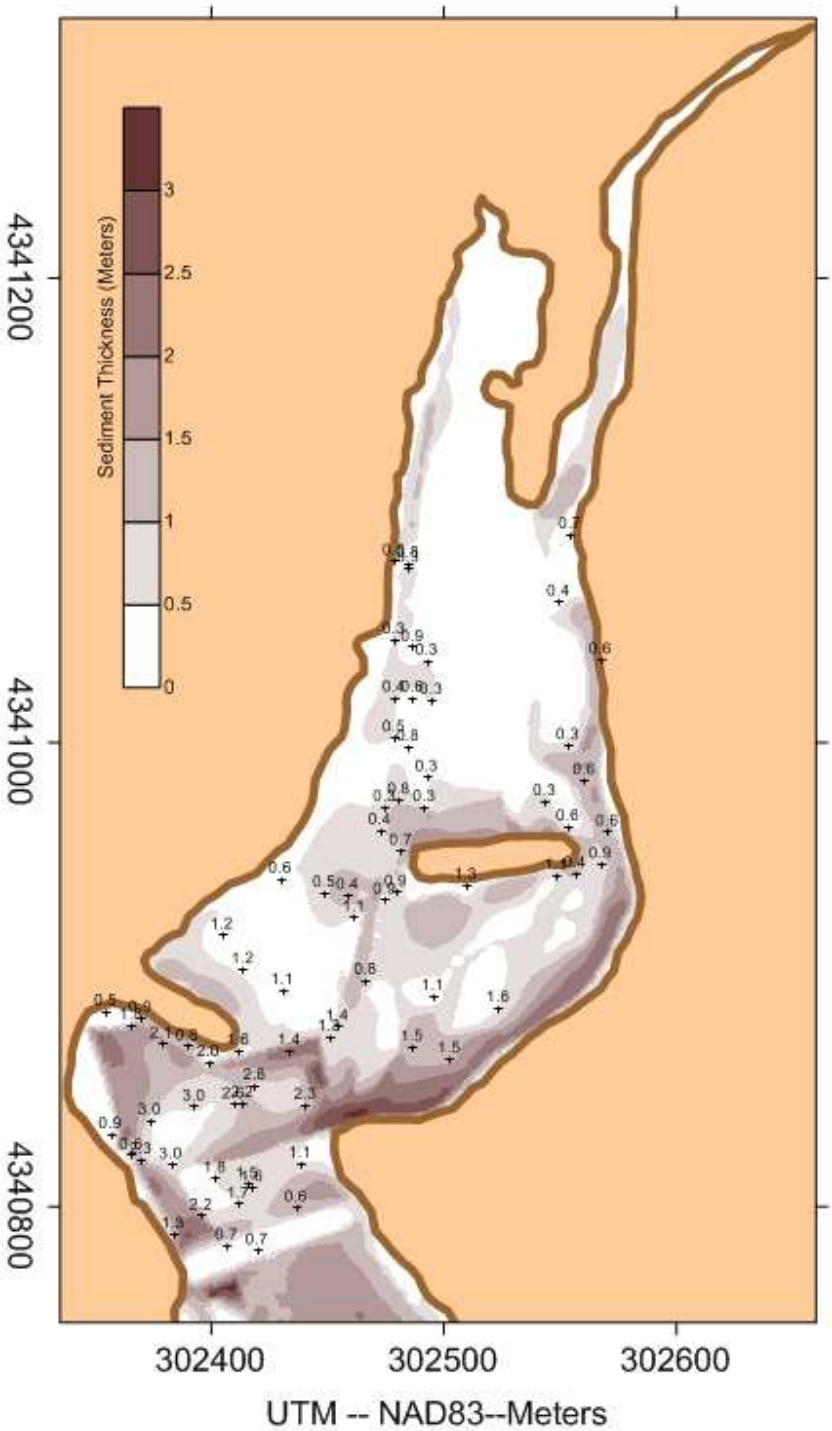

Figure E-3. Little Seneca Creek Forebay. Shaded area is the sediment thickness calculated from the 1979 JMT topographic survey and the 2010 MGS bathymetry survey. Individual depths are plotted from the 2010 MGS bathymetric survey indicating the 2010 depths within the forebay.