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BATHYMETRIC SURVEY AND SEDIMENTATION ANALYSIS OF LOCH RAVEN AND PRETTYBOY RESERVOIRS

By

Richard A. Ortt, Jr., Randall T. Kerhin, Darlene Wells, and Jeff Cornwell

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and

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EXECUTIVE SUMMARY

As part of a larger Gunpowder Watershed study, Maryland Geological Survey (MGS) was contracted to study the bathymetry and sedimentation of the Prettyboy and Loch Raven reservoirs. In cooperation with the United States Geological Survey and the University of Maryland, bathymetric data were collected for both reservoirs; sedimentation rates for Loch Raven Reservoir were calculated; and, the chemical and textural characteristic of the bottom sediments of Loch Raven Reservoir were documented.

Bathymetric data for the reservoirs were collected in the Fall of 1998 and in the early Summer of 1998 for Loch Raven and Prettyboy reservoirs, respectively. This data was collected using differential global positioning service (DGPS) techniques and digital echosounding equipment. Over thirty-two thousand discrete soundings were collected and used to generate a current bathymetric model of Loch Raven Reservoir. Over forty-eight thousand discrete soundings were collected and used to generate a bathymetric model of Prettyboy Reservoir. The bathymetric models indicate a current storage capacity of 19.1 billion gallons [72.3 million cubic meters] and 18.4 billion gallons [69.7 million cubic meters] in Loch Raven and Prettyboy respectively.

Sediment accumulation rates within Loch Raven Reservoir were calculated using historical comparisons, volumetric comparisons, radiometric dating techniques, and visual identification of pre-reservoir surfaces using gravity cores and sub-bottom seismic-reflection records. All of these methods concluded that the sediment accretion rate within Loch Raven reservoir is between one and two centimeters per year. The annual percentage loss rate of capacity from this sediment accumulation is 0.13 percent or 26.8 million gallons.

Using only historical comparisons for Prettyboy reservoir computations, the annual percentage loss rate of capacity is estimated to be 0.12 percent or 23.1 million gallons.

These losses are significantly below the national average of 0.27 percent for other reservoirs (Morris, 1998).

The Loch Raven sedimentation rates may be misleading for future planning. The upper portion of the reservoir and the stream channels leading into the reservoir, that was not part of this study area, have reached a sediment balance and will no longer retain additional sediment. Consequently, sediment is transported increasingly further downstream into the reservoir resulting in an increasing rate of sedimentation.

Sediment in Loch Raven was analyzed for cadmium, chromium, copper, iron, manganese, nickel, lead, zinc, nitrogen, total carbon, organic carbon, reactive-organic carbon, sulfur, and phosphorous. Slightly elevated levels of zinc and lead were observed in the sediments collected from Long Quarter Branch of Loch Raven Reservoir. The chemistry showed no other significant findings.

The bathymetric and sediment data collected for this study establishes a solid baseline for future calculations of sediment accumulation rates and sediment chemistry changes.

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INTRODUCTION

Historical Context

The City of Baltimore first began using the waters of the Gunpowder River in 1873 for drinking water supply. In 1881 a masonry dam was constructed approximately 300 meters downstream of the current Loch Raven dam. The masonry dam created a reservoir that was 29 feet deep at the dam and impounded 510 million gallons of water [1.9 million cubic meters]. Siltation quickly became a great problem, and between the years of 1896 and 1911 about 3.3 million cubic yards [2.5 million cubic meters] of sediment were dredged from this reservoir (Brown, 1942). In 1914 the current Loch Raven dam was constructed to a height of 188 feet above mean sea level (MSL). In 1922 this dam was raised to it's present elevation of 240 feet above MSL to meet the increasing drinking water needs of Baltimore. In 1933 Prettyboy reservoir was created by building a dam to a height of 520.0 feet above MSL approximately 23 miles upstream from Loch Raven Dam. Prettyboy reservoir is used to maintain a minimum depth in Loch Raven reservoir which has economic benefits in terms of water quality and distribution for the City of Baltimore. No water is directly pumped from Prettyboy reservoir into the public drinking water supply. There have been no significant changes to the reservoirs' structures on the Gunpowder river since the construction of Prettyboy Dam.

Geological Background

The Gunpowder Falls watershed lies almost entirely in the eastern division of the Piedmont Province which is underlain by a structurally complex series of schist, gneiss, marble, gabbro, granite, and other highly metamorphosed igneous rocks of probable volcanic origin. Differential erosion of these various rock types has produced a distinctive, rugged topography in this part of the Piedmont.

The headwaters of the Gunpowder Falls are located in Pennsylvania, a few miles north of Lineboro, Carroll County, at an elevation approaching 900 feet above MSL. The river flows southeast through several distinct formations. The Prettyboy Reservoir and the 80 square miles of basin draining into the reservoir, representing the upper 20% of the total Gunpowder Falls watershed, lie almost entirely within the Prettyboy Schist (Figure 1). Part of the Wissahickon Group, the Prettyboy Schist consists of a uniform fine-grained plagioclase, chlorite, muscovite, quartz schist, with magnitite and albite prophyrobalsts. (Crowley, 1976).

Below Prettyboy dam, older formations of the Wissahickon Group are exposed and include Pleasant Grove Schist, Sykesville Formation, Piney Run Formation, and Loch Raven Schist. The Pleasant Grove Schist, Piney Run Formation, and Loch Raven Schist are all described as mica, quartz schists. The Sykesville Formation consists of gneiss and schist (Crowley, 1976). The formations of the Wissahickon group overlie the Cockeysville Marble and the Setters Formation. The Setters Formation, consisting of massive quartzite and quartzite rich schist and gneiss, lies unconformably on the Baltimore Gneiss, which is estimated to be 1 to 1.1 billion years old (Precambrian) and consisting predominately of quartzo-feldspathic gneiss. The Cockeysville Marble, Setters Formations and Baltimore Gneiss are exposed along dome, anticlinal and synclinal structures within the region.

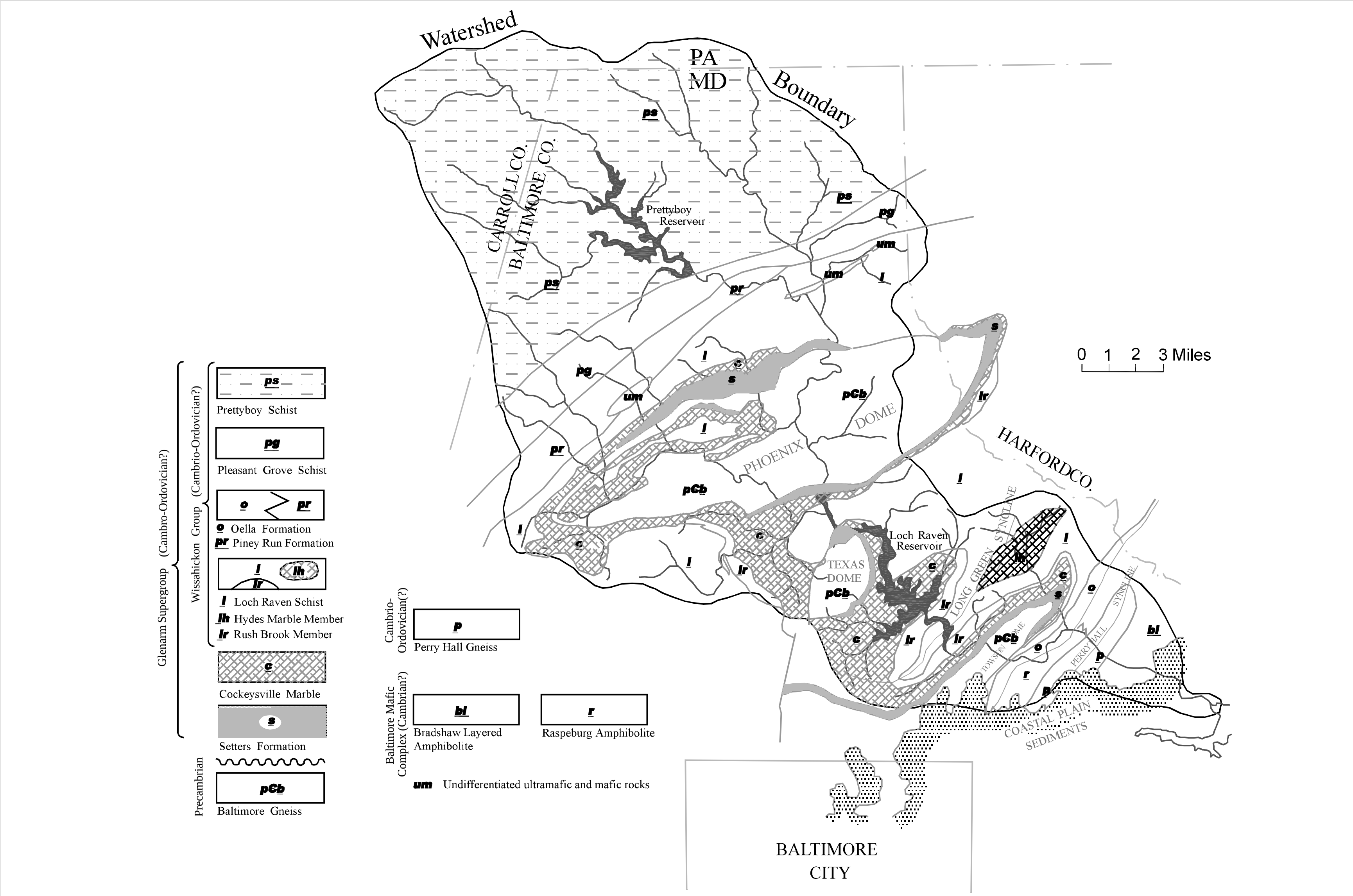

Figure 1. Geology of the Gunpowder Falls watershed.

Portions of Loch Raven Reservoir overlie the Cockeysville Marble, a highly erodible formation that forms the valleys between the Glenarm, Texas, and Phoenix areas of the Baltimore Gneiss and Setters Formation. The Cockeysville marble is recrystallized limestone and contains an abundance of magnesium making it essentially a dolomitic marble (Vokes and Edwards, 1957).

Below the Loch Raven Dam, the Gunpowder Falls flows through a series of synclinal features where both crystalline and marble formations are exposed, before reaching the unconsolidated sediments of the Coastal Plain.

PREVIOUS SEDIMENT SURVEYS

Methodologies

Prior to the mid 1970's, the only method of performing a hydrographic survey or determining reservoir capacity was the range method. This method utilized a number of transects to determine the cross-sectional area of the reservoir at different locations. By using techniques such as the Dobson Modified Prismoidal formula or the Average End Area method, reservoir volumes were calculated and from that the deposited sediment volumes were deduced. Using these methods, a small error in volume calculations can translate into a large error in the volume of sediment when the reservoir has not trapped a proportionately large amount of sediment.

The field method of collecting this data involved a raft or boat which was secured between the shorelines using aircraft cable. The raft was pulled between the shores and soundings using a lead line or a sounding pole were taken (in 1985, the surveys were conducted with a recording fathometer). Horizontal positioning of the raft was determined using a line meter which indicated how far from shore the raft was located.

The range method is based upon interpolating volume from one range transect to another. The further apart the transects, the more interpolation is involved, and the greater the possible error. To minimize error, it is critical that the range transects be at the same locations for all surveys. It is clear from the documentation that the surveys of these reservoirs did not have transects which were repeatable, and that practically every time a survey was conducted transects were either added or removed. Total errors in determining reservoir capacity volumes through the use of this method have been estimated to be between 10 and 30 percent (Morris, 1997) (Dunbar et al., 1999). The City of Baltimore determined that the error in previous surveys was in excess of 30 percent (City of Baltimore Department of Public Works, 1989). The large errors introduced in this methodology are often in excess of the deposited sediment volumes calculated.

Historical Results

Loch Raven

Surveys of the Loch Raven reservoir were conducted in 1913, 1943, 1961, 1972, and 1985. The 1913 Survey was conducted using traditional land surveying techniques as the reservoir was not constructed and the basin was not submerged. The results of the land survey were drawn on a 1 to 200 scale stable linen map with a ten foot vertical contour. This data was found to be in good condition and drawn with a high degree of horizontal and vertical accuracy (Banks and Lamotte, 1999). The methodology used to conduct the following surveys was the range method explained above. The number of range transects conducted changed with each survey except for the survey conducted in 1972. Table I summarizes the number of range transects used each year. The increase in ranges provides a greater accuracy in storage capacity; however, it biases the sediment data by giving a disproportionate amount of weighting to small tributaries and coves which could possibly have a higher rate of sedimentation.

Loch Raven Historical Surveys	
Survey Year	**Range Transects Performed**
1913	Contour
1943	18
1961	24
1972	24
1985	27

Table I. Surveys conducted on Loch Raven reservoir and range transects used in conducting the surveys.

The results of the surveys are presented in Table II. The beginning storage volume calculated from the 1913 survey was 86.5 million cubic meters [22.3 billion gallons]. The first range survey was conducted 29 years after the reservoir was created and the results showed a 6.6 million cubic meter [1.7 billion gallon] storage capacity loss due to presumed sediment accumulation in the reservoir. This storage capacity loss (presumed sediment accumulation) is comparable to derived sediment volumes based on the dredging records from the initial dam which documents 3.3 million cubic meters of maintenance dredged material were removed from the reservoir over a period of 15 years. All surveys after 1943 showed a substantial reduction in the rate of storage loss within the reservoir. Continuing with the analysis of this capacity data, sediment accretion rates are calculated and presented in Table III. The data presents a highly variable sediment accretion rate that is between 0.002 meters per year and 0.024 meters per year.

The variability in the calculated sediment accumulation rates is mostly due to the errors inherent in the surveying techniques. Changes in survey methodology between the initial storage estimate and the first bathymetric survey contribute to a large error. The subsequent surveys followed the same general methodology, and sediment thickness could be mapped by revisiting the same range transects. Unfortunately, historical literature does not document these measurements, and historical data worksheets are not organized well enough to derive adequate conclusions. The data presented is not sediment volume accumulation data, but it is actually storage capacity data. Small errors in the storage capacity calculations translate into proportionately large errors in sediment volume accumulation. For example, in 1943, Loch Raven reservoir was stated to have a capacity of 79.9 million cubic meters; in 1961, it was stated to have a capacity of 79.0 million cubic meters. The calculated volume of sediment which had accumulated between those dates is 0.9 million cubic meters. An error of 1 percent in calculating storage capacity during each survey could yield a calculated sediment volume of 2.49 million cubic meters. This one percent error exceeds the calculated amount by 210 percent. This translation and propagation of errors minimizes the value of data for calculating sedimentation.

LOCH RAVEN RESERVOIR (219.4 Mi.^{2} Drainage Area) (568.2 Sq. Km^2 Drainage Area) *				
Survey Year	**Capacity (ac. ft)** ***[m³]***	**Period Capacity Loss (ac. ft)** ***[m³]***	**Average Annual Loss (ac. ft/yr)** ***[m³/yr]***	**Average Annual Loss Per Sq. Mi. Drainage Area (ac. ft/yr/mi^2)** ***[m³/yr/km²]***
1913	70169 *86552179*	- -		
1943	64813 *79945651*	5356 *6606528*	185 *227811*	.618* *294*
1961	64072 *79031641*	741 *914010*	41 *50778*	.187 *89*
1972	63105 *77838864*	967 *1192777*	88 *108434*	.401 *191*
1985	62955 *77653842*	150 *185022*	11 *14232*	.052 *25*

* Prior to construction of upstream Pretty Boy Reservoir in 1933, drainage area was 299.4 mi.^{2} [775.4 Km²]

Table II. Historical survey results of Loch Raven reservoir. (Iivari, 1985)

The sediment trapping efficiency of this reservoir is nearly 100 percent. The low rates of sedimentation reported in the 1943 to 1961 and the 1972 to 1985 periods are unrealistic and undoubtedly result from the errors inherent in the range survey methodology.

Historical Sediment Accretion Rates in Loch Raven Reservoir				
Survey	**Capacity (acre feet)** ***[m³]***	**Capacity Change (acre feet)** ***[m³]***	**Surface Area (acres)** ***[m²]***	**Sediment Accretion Rate** ***[m/yr]***
1913	70169 *86552179*	- -	2391 *9675959*	-
1943	64813 *79945651*	5356 *6606528*	2337 *9457431*	*0.024*
1961	64072 *79031641*	741 *914010*	2332 *9437196*	*0.005*
1972	63105 *77838864*	967 *1192777*	2320 *9388635*	*0.012*
1985	62955 *77653842*	150 *185022*	2320 *9388635*	*0.002*

Table III. Analysis of Loch Raven surveys for sediment accretion rates.

Prettyboy

Prettyboy Reservoir was also surveyed using the range method in 1943, 1961, 1976, and 1985. These surveys all used different sets of transects. Table IV depicts the number of range transects used during different survey years.

Prettyboy Historical Surveys	
Survey Year	**Range Transects Performed**
1933	Contour
1943	14
1961	23
1976	65
1985	26

Table IV. Surveys conducted on Prettyboy reservoir and range transects used in conducting the surveys.

The same conclusions from the historical data of Prettyboy (Table V) can be made as with those of Loch Raven. The variability of the historical data is most likely due to the changes in the number of transects versus actual sediment changes. A direct reflection of this error is demonstrated in the 1976 survey. The 1976 survey had over twice the number of transects as the other surveys. The results from this more detailed survey yielded a twenty percent difference in storage capacity compared to either the preceding or proceeding surveys (Table VI).

PRETTYBOY RESERVOIR (80 $Mi.^2$ Drainage Area) (207.2 Km^2 Drainage Area)				
Survey Year	**Capacity (ac. ft)** ***[m^3]***	**Period Capacity Loss (ac. ft)** ***[m^3]***	**Average Annual Loss (ac.ft/yr)** ***[m^3/yr]***	**Average Annual Loss Per Sq. Mi. Drainage (ac.ft/yr/mi^2)** ***[m^3/yr/km^2]***
1933	60979 *75216482*	- -	-	-
1943	60410 *74514631*	569 *701851*	54.2 *66855*	.699 *323*
1961	59864 *73841150*	546 *673481*	30.3 *37374*	.391 *180*
1976*	46191 *56975754*	- -	- -	- -
1985	57672 *71137358*	2192 *2703792*	91.7 *113110*	1.183 *546*

** The 1976 survey utilized 65 transects and can not be compared with other surveys due to computational methodologies; however, it is a more accurate estimate of the reservoir capacity.*

Table V. Historical survey results of Prettyboy. (Iivari, 1985)

Historical Sediment Accretion Rates in Prettyboy Reservoir				
Survey	**Capacity (acre feet) *[m³]***	**Capacity Change (acre feet) *[m³]***	**Surface Area (acres) *[m²]***	**Sediment Accumulation Rate *[m/yr]***
1933	60979 *75216482*	- -	1498 *6062144*	-
1943	60410 *74514631*	569 *701851*	1498 *6062144*	*0.012*
1961	59864 *73841150*	546 *673481*	1467 *5936693*	*0.006*
1976*	46191 *56975754*	- -	- -	-
1985	57672 *71137358*	2192 *2703792*	1497 *6058097*	*0.019*

* Data can not be compared for this analysis.

Table VI. Analysis of Prettyboy surveys for sediment accretion rates.

STUDY OBJECTIVES

The objectives for this study were:

1) To establish a baseline surface for future surveys of Loch Raven and Prettyboy reservoirs.
2) To determine remaining storage capacity of Loch Raven and Prettyboy reservoirs.
3) To determine sediment accumulation in Loch Raven reservoir since dam construction.
4) To determine sediment accumulation rates over the last several decades in Loch Raven reservoir.
5) To conduct nutrient and trace chemical analyses on surficial sediments in Loch Raven reservoir.

METHODS

Study Approach

The study consisted of three components. The first was measuring and modeling the current bathymetry of the reservoirs. This was performed through the use of digital echosounding equipment and differential global positioning service (DGPS) equipment. The data was collected as discrete x, y, z points and processed with geographical information systems (GIS) to produce a modeled surface of the reservoir bottom. The second phase determined sediment thickness and sediment accumulation rates in Loch Raven reservoir. A variety of methods were used to achieve this result. Historical surveys were digitized and checked for accuracy. Sediment thickness maps were generated by subtracting the current bathymetry from the historical bathymetry. The sediment thicknesses reported using this method were checked through the use of sub-bottom seismic-reflections. Sediment cores were collected and analyzed with radiometric dating techniques to determine sediment age and sedimentation rates at the core sites. The third phase was to conduct chemistry analysis on the surficial sediments collected in the cores. All of these results assist in the development of a better understanding of the amount and type of sediment accumulation within the reservoirs.

Bathymetric Data Collection

Soundings

Track lines running perpendicular to the river channel were established for bathymetric surveying. These track lines were spaced 50 m apart and extended shoreline to shoreline. Tie-in lines were run perpendicular to the track lines approximately every 200 meters. These tie-in lines were used for quality control and quality assurance reasons. Survey track lines are illustrated in Figures 2 and 3 for Loch Raven and Prettyboy reservoirs. The Loch Raven bathymetry survey was conducted between October 20th 1997 and November 10th 1997. An additional day of surveying was conducted on June 16th 1998 to provide increased data coverage within 200 meters of the dam. Prettyboy reservoir was surveyed between June 12th 1998 and June 29th 1998. An additional day of surveying was conducted on December 4th 1998 to increase data coverage in spots with poor coverage.

Bathymetric data were collected using an Ashtech Reliance Sub-Meter GPS and a Lowrance LMS-350a Echosounder with a narrow beam (9 degree) transducer. Navigation was provided through a Lowrance GlobalNav 212 GPS interfaced to a Starlink MRB-2 DGPS receiver. DGPS differential corrections broadcast by the United States Coast Guard and a locally installed base station provided a real-time horizontal accuracy of 1 to 3 m [3 to10 feet]. Horizontal position was recorded in the Universe Transverse Mercator (UTM) system based upon the North American Datum of 1983 (NAD83). The horizontal data were collected in meters. The echosounder generated repetitive acoustic pulses for bottom recognition. Pulses were at a frequency of 198 KHz with a repetition rate of ten pulses per second and a pulse width varying between 0.2 milliseconds and 0.4 milliseconds. The acoustic wave reflected off the density gradient separating the water column from the bottom sediment. The reflections were then filtered for outliers and integrated within the echosounder to produce an accurate measurement from the transducer to the water/sediment interface every second. At an average vessel speed of 4 knots, a depth sounding was collected approximately every 2.0 m [6.6 ft] along the survey track-lines. This data was collected and time-stamped within the Ashtech GPS. The Ashtech GPS, the Lowrance GPS, and the echosounder were checked against known horizontal and vertical measurements before and after each survey day. The echosounder was also calibrated throughout the depth range of the reservoirs several times 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 water level measurements recorded by gauges located in both dams and operated by the City of Baltimore. These gauges have a resolution to the hundredth of a foot with an accuracy of two hundredths of a foot (Verbal communication with Baltimore City). This survey data was adjusted to Mean Pool Level (MPL) as defined by the City of Baltimore for each of the reservoirs. The MPL of Loch Raven reservoir is 240.0 feet above Mean Sea Level (MSL). The MPL of Prettyboy reservoir is 520.0 feet above MSL. These 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 post-processed horizontal GPS data is ±1.0 m [±3.3 ft].

Bathymetric Interpretation and Volumetric Calculations

Bathymetric data were interpreted with ArcInfo and Surfer software packages. In Surfer, the raw data was processed using a Triangulated Irregular Network (TIN) method. This method is based on the work of Watson and Philip (1986). A 5 meter regularly spaced grid was calculated by analyzing the depths on the TIN surface. In ArcInfo, the raw data was processed using an iterative finite-difference interpolation gridding technique (Banks and LaMotte, 1999). This method is based upon the work of Hutchinson (1998, 1996). The two techniques are quite dissimilar and produce slightly different results based upon their underlying assumptions and algorithms. The TIN method honors every data point and creates a surface which favors the collected data and shoreline. The finite-difference interpolation gridding technique is based upon basin modeling techniques and terrain characteristics. This technique favors a more idealized slope and terrain model based upon the data, stream channel inputs, and shoreline boundaries. In this study, both of these methods are valid due to the amount of data collected and the thoroughness of spatial coverage in each reservoir. After the regularly-spaced grids were created, volumes and thicknesses of sediments could be calculated between current and historical surfaces by comparison.

Error analysis was performed on the generated grids using residual and root mean square error analysis against the measured data.

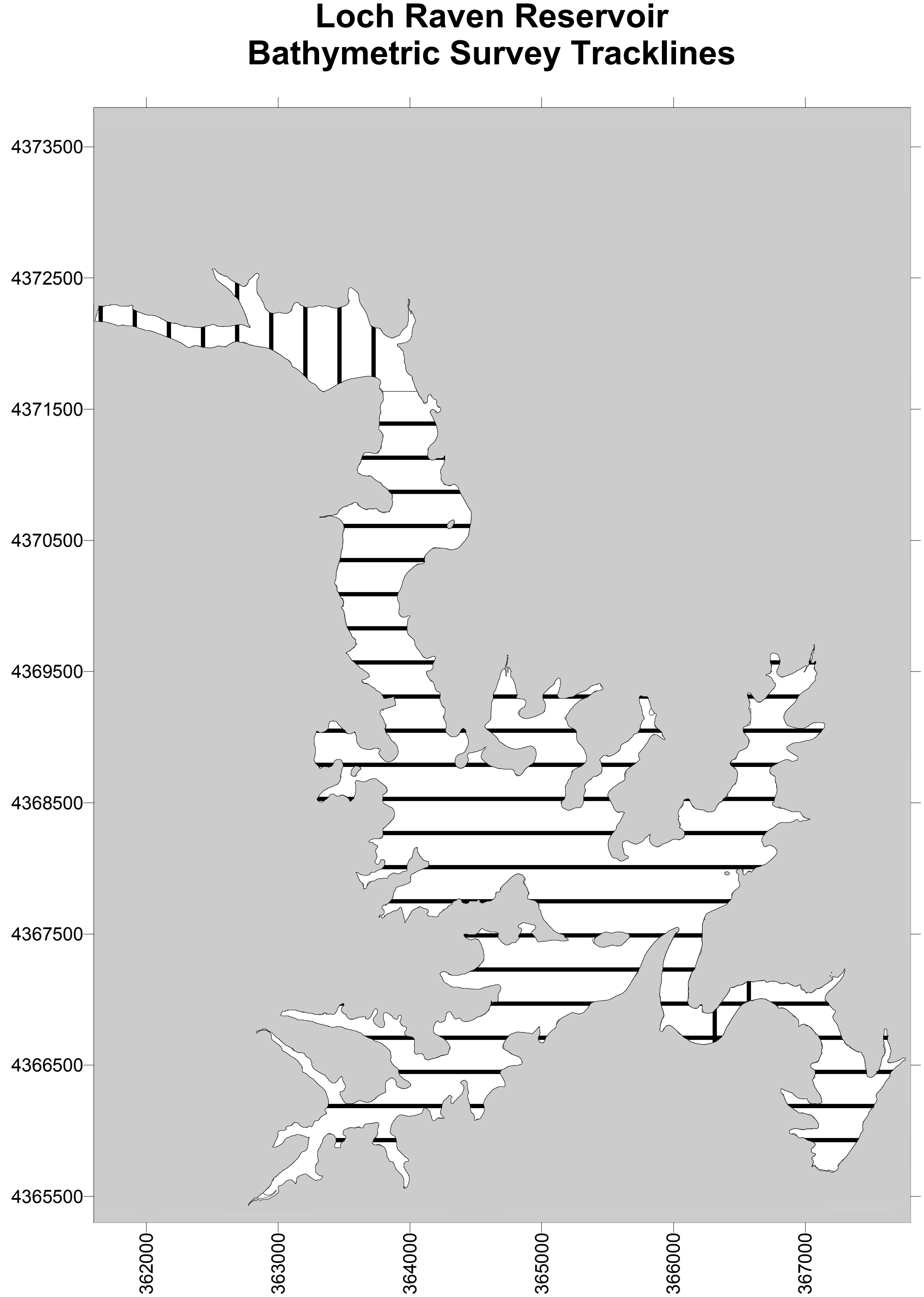

Figure 2. Bathymetric survey trackline orientation in Loch Raven reservoir. Displayed tracklines are representative of direction, not location. Tracklines were run every 50 meters on the UTM grid in either a north-south direction or a east-west direction (*i.e*. 366500, 366550, 366600 or 4369500, 4369550, 4369600). Horizontal coordinates are UTM – NAD83 – Meters.

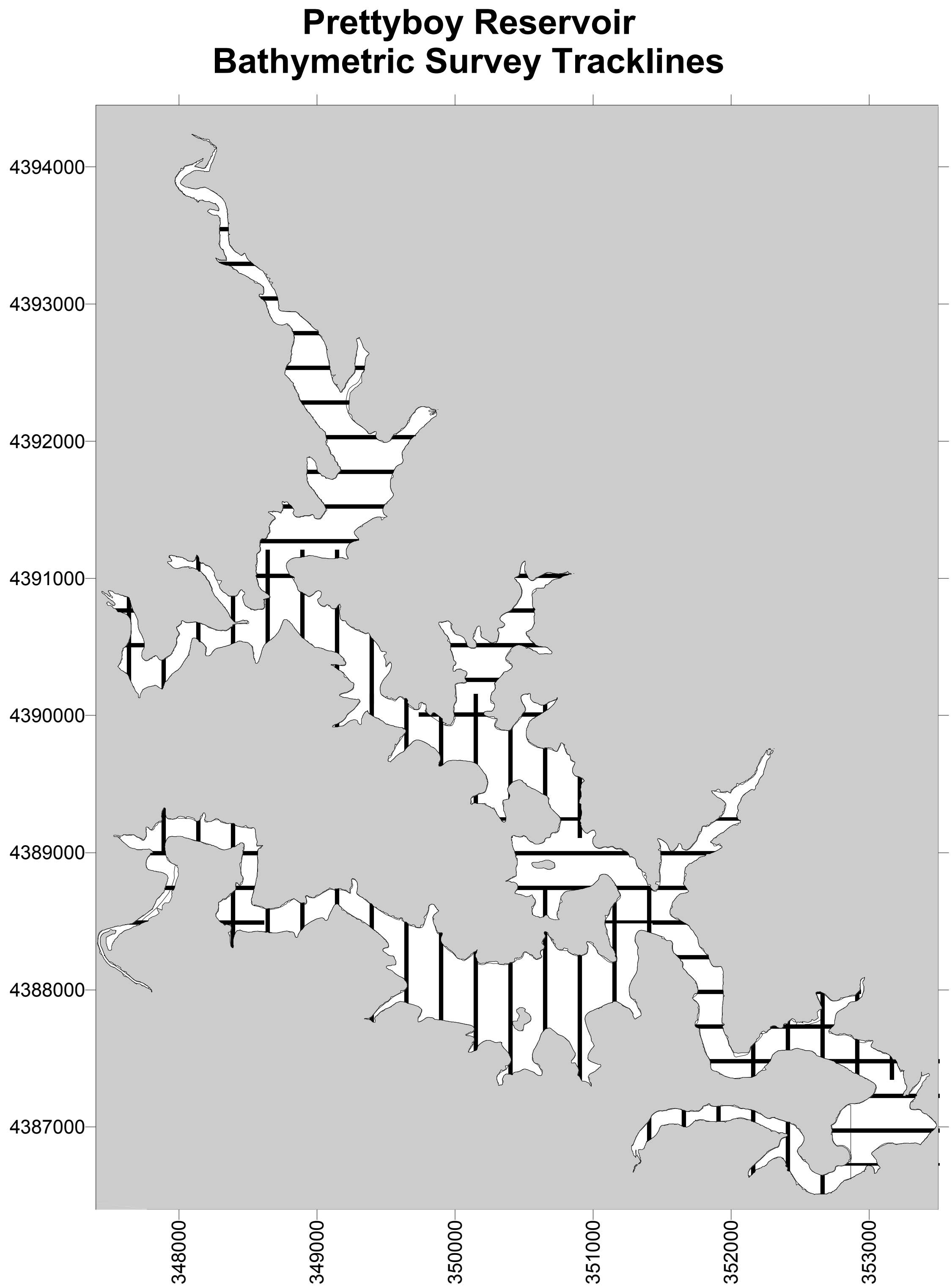

Figure 3. Bathymetric survey trackline orientation in Prettyboy reservoir. Displayed tracklines are representative of direction, not location. Tracklines were run every 50 meters on the UTM grid in either a north-south direction or a east-west direction (*i.e.* 348500, 348550, 348600 or 4392500, 4392550, 4392600). Horizontal coordinates are UTM – NAD83 – Meters.

Sub-Bottom Seismic Reflection Surveying

Sub-Bottom seismic reflections surveys were conducted in April 1998 by United States Geological Survey, Woods Hole.

Seismic reflection surveys were used to assist in verifying the thickness of sediment within Loch Raven reservoir. The surveys were conducted along tracklines oriented east-west and north-south and spaced approximately 200 m [650 ft] apart (Figure 4). These lines are coincident with lines which were run for bathymetric data collection.

Bottom and subbottom data were obtained using a Delph Elics topside data collection system, a Geopulse Boomer system, and an ORE 3.5 kHz Sub-Bottom system. Acoustic reflections are produced by differences in sound velocity through varying materials. By generating repetitive acoustic pulses, continuous echoes reflected from subbottom interfaces between acoustically dissimilar materials were recorded on the Delph Elics system and later printed on a thermal printer. 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 3.5 kHz is 0.15 meters [6 in].

Horizontal positioning was obtained through the use of a Department of Defense Grade P-Code GPS unit made by Rockwell. The real-time accuracy of the positioning unit was between 5 to 10 meters [16 to 32 feet]. Horizontal position was recorded in the Universe Transverse Mercator (UTM) system based upon the North American Datum of 1983 (NAD83). The horizontal data was collected in meters.

Ground-truthing of the sub-bottom reflections was accomplished by collecting a series of gravity cores throughout the reservoir.

Side-Scan Sonar Data Collection

Side-scan sonar data was collected in September 1998 in support of determining sedimentation near Loch Raven dam. Discussion of this and the associated results are presented in Appendix F.

A dual frequency 100KHz / 500KHz EG&G analog side-scan sonar with an integrated thermal printer was utilized in collecting data. This device transmits either a 100KHz or a 500KHz acoustical beam in a sweeping motion and analyzes the returned signal. By doing so in a continuous fashion while the sensor is being moved in a given direction, the signal creates a picture of the bottom or the target where it is aimed. The surveys collected on Loch Raven reservoir utilized only the 500KHz signal working on the starboard sensor of the instrument. The instrument was suspended at a depth of fifteen feet to obtain adequate imagery. The images were recorded such that a strong reflected signal appears as black and a weak or non-existent reflected signal is recorded as white.

Horizontal control was not kept as general environmental conditions were the goal of the survey.

Loch Raven Reservoir
Seismic and Coring Operations

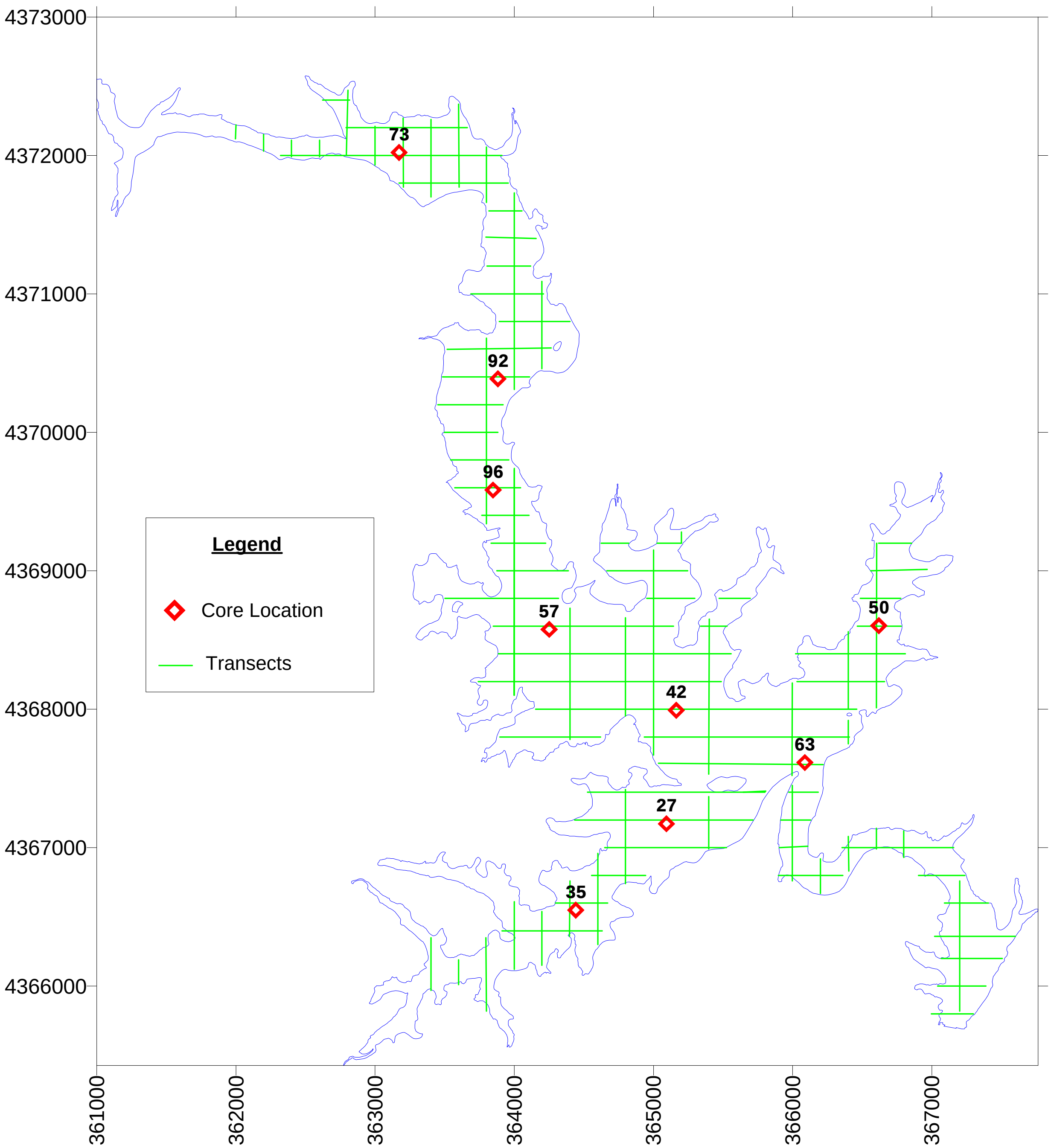

Figure 4. Sub-bottom seismic survey lines and gravity core locations in Loch Raven Reservoir. Gravity core identification numbers are labeled above the core location. Horizontal coordinates are UTM –NAD83 – Meters.

Field Collection of Gravity Cores

Nine sediment cores were collected in June of 1998. The coring sites are shown in Figure 4. Bottom sediments were collected in 6.7 cm [2.6 in] diameter cellulose acetate butyrate (CAB) core liners inserted into a Benthos open-barrel gravity corer with 20 Kg of added weight. The recovered cores were trimmed at the sediment-water interface, capped, and returned to the laboratory for physical description, bulk properties, granulometric analyses, and dating.

Horizontal control was provided through a Lowrance GlobalNav 212 GPS interfaced to a Starlink MRB-2 DGPS receiver. DGPS differential corrections broadcast by the United States Coast Guard provided a real-time horizontal accuracy of 2 to 5 m [7 to16 feet]. Horizontal position was recorded in the Universe Transverse Mercator (UTM) system based upon the North American Datum of 1983 (NAD83). The horizontal data was collected in meters.

Laboratory Analysis of Gravity Cores

Xeroradiography and Initial Core Processing

Prior to analyses, the cores were X-rayed using a TORR-MED medical X-ray unit. Instrument settings varied depending on the composition of the cores. The most frequently used settings ranged between 80 to 90 kV at 5 mA for 30 to 50 seconds.

X-ray images of the cores were developed using xeroradiography. The negative mode setting was used, producing a radiograph in which denser material such as sand or shells shows up as white images.

After X-ray images were obtained, each core was extruded from the plastic liner, split, photographed and described, noting any sedimentological structures and lithological changes. Sediment samples were taken at specific locations in the cores based on the visual and radiographic observations.

Digital scans of the core X-ray images are on the archived CD-ROM set (Appendix H).

Textural Analyses

Sediment samples were analyzed for water content, bulk density, and grain size (gravel, sand, silt, clay contents). Two homogeneous splits of each sample were 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.

$$\%Water = \frac{W_w}{W_t} * 100 \qquad \textbf{(1)}$$

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, drying the sediment at 65°C, and then re-weighing the dried sediment. Dried sediments were saved for chemical analyses.

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

$$p_b = \frac{W_t}{W_d / 2.72 + W_w} \qquad \textbf{(2)}$$

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 consisted 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 were 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 pipette analysis.

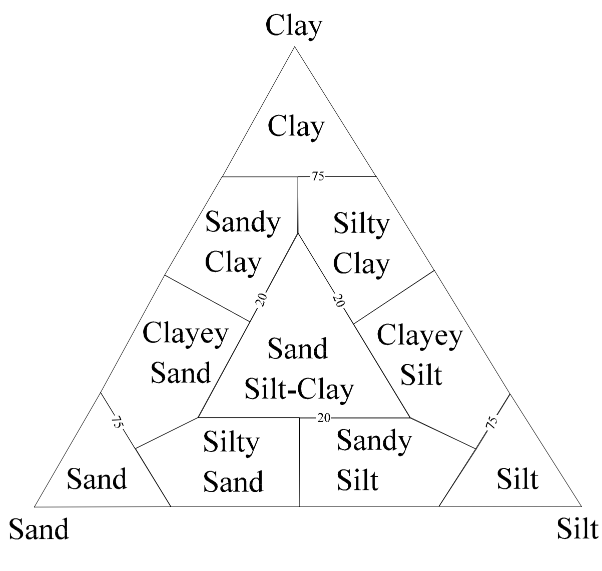

Figure 5. Shepard's (1954) classification of sediment types.

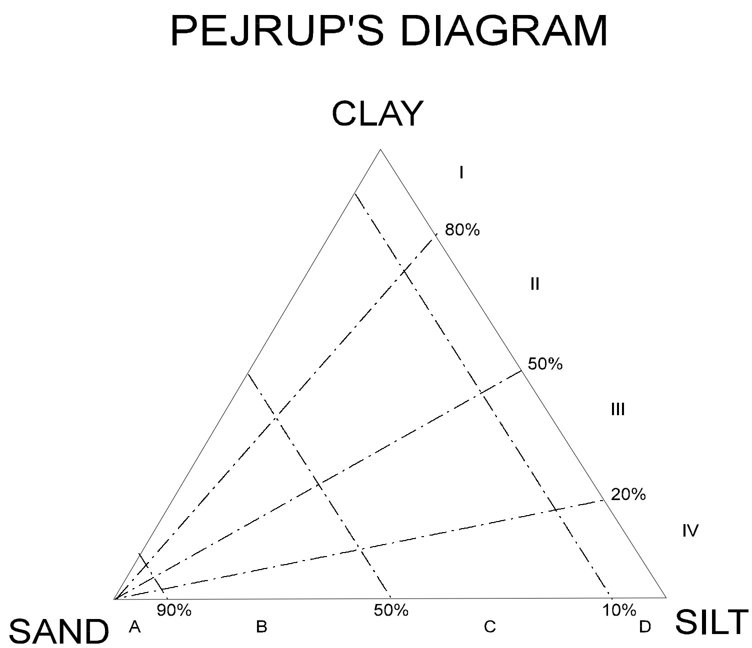

Figure 6. Pejrup's (1988) classification of sediment types

The separation of sand and silt-clay portions of the sample was accomplished by wet-sieving through a 4 phi mesh sieve (62.5 μm, U.S. Standard Sieve #230). The sand fraction was dried and weighed. The finer silt and clay sized particles were suspended in a 1000 ml cylinder in a solution of 0.26 percent sodium hexametaphosphate. The suspension was agitated and, at specified times thereafter, 20 ml pipette withdrawals were made (Carver, 1971; Folk, 1974). The rationale behind this process is that larger particles settle faster than smaller ones. 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 were calculated to permit the determination of the amount of silt (4 phi to 8 phi [62.5 μm to 4.0 μm]) and clay sized (finer than 8 phi [4 μm]) particles in the suspension. Withdrawn samples were dried at 65°C and weighed. From these data the percentages by dry weight of sand, silt, and clay were calculated for each sample and classified according to Shepard's (1954) nomenclature (Figure 5) and Pejrup's (1988)classification (Figure 6).

Chemical Analyses

Sediments dried for water content determination were analyzed for total elemental nitrogen, carbon, sulfur, and nine metals. 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), organic carbon, and non-reactive carbon using a Carlo Erba NA1500 analyzer. Untreated dried sediments were analyzed for total nitrogen, carbon and sulfur (NCS) contents. A split of dried sample was treated with 10% hydrochloric acid (HCl) to remove inorganic carbon (*i.e.*, $CaCO_3$ from carbonaceous minerals such as marble and limestone, or shell material). This treated sample was redried, reground, and analyzed for organic carbon content. A second split of dried sample was treated with 30% hydrogen peroxide (H_2O_2) to remove “reactive” carbon. This peroxide treated sample was dried, ground and analyzed for non-reactive carbon (Hennessee and others, 1986).

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, 5-chloro- 4-hydroxy- 3-methoxy-benzylisothiourea phosphate was used. Blanks (tin capsules containing only vanadium pentoxide) were run every 12 samples and standards. Replicates of every seventh sample were run. As secondary standards, one or more reference materials (NIST SRM #1646 - Estuarine Sediment; NIST SRM #2704 - Buffalo River Sediment, and the National Research Council of Canada PACS-1 - Marine Sediment) were run every 6 to 7 samples. Comparison of results of SRMs to their certified values are presented in the QA/QC discussion.

<u>Elemental Analyses</u>

Sediments were analyzed for nine elements: cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), phosphorus (P), and zinc (Zn). These elements were selected for several reasons. 1) These elements are non-volatile. As opposed to volatile elements, these elements are less likely to be lost during most analytical procedures, and therefore, allow better comparison with various studies. 2) Studies have shown that these elements can be used as environmental indicators (Hennessee and others, 1990; Hill, 1984; Cantillo, 1982; Sinex and Helz, 1981). 3) Comparable data for these elements are available for the Chesapeake Bay and other bodies of water (Cantillo, 1982; Helz and others, 1982; Hill and others, 1985; Sommer and Pyzik, 1974; Sinex and Helz, 1981; Callender and others, 1989; Lanthrop and others, 1989).

Concentrations of the nine elements were determined using a microwave digestion technique, followed by analyses of the digestate on an Inductively Coupled Argon Plasma Spectrophotometer (ICAP). The microwave digestion technique is detailed at the end of this section. Methods information is compiled in Table VII.

A Thermo Jarrel Ash AtomScan 25 sequential ICAP was used for the elemental analysis. The wavelengths and conditions selected for the elements of interest were determined using digested bottom sediments from the selected sites in Loch Raven reservoir and standard reference materials (SRM) from the National Institute of Standards and Technology (NIST SRM #1646a--Estuarine Sediment; NIST SRM #2704--Buffalo River Sediment) and the National Research Council of Canada (PACS-1 or PACS-2--Marine Sediment). Quality control was maintained using the method of bracketing standards (Van Loon, 1980) and include running a suite of the SRMs with every sample set. Results of the SRM analyses are presented in the QA/QC discussion.

Elemental Method Information for ICAP Analyses					
Element	**Wavelength (nm)**	**RF Power (watts)**	**Integration Time (sec)**	**Slit Height (mm)**	**High Voltage**
Cd	228.802	1350	4	6	1000
Cr	283.563	1350	2	6	714
Cu	327.396	1350	2	6	816
Fe	238.204	950	2	3	757
Mn	257.610	950	2	6	757
Ni	341.476	1350	2	9	824
P	178.287	1150	4	3	1000
Pb	220.353	1350	4	6	1000
Zn	213.856	1350	2	6	757

Table VII. Elemental method information for ICAP analyses.

Microwave Digestion Technique

The steps in microwave digestion, modified from EPA Method #3051 (Soil Sample Digestion Procedure for Floyd Digestion Vessels) *Note: Floyd is now within OI Analytical*, are as follows:

1. 0.5±0.0005 g of dried, ground sediment is weighed and placed in a Teflon digestion vessel.

2. 2.5 mL concentrated HNO_3 (trace metal grade) and 7.5 mL concentrated HCl (trace metal grade) is added to the Teflon vessel. (Preparation of blanks are made by using 0.5 mL of ultrapure (<5 MegaOhms conductivity) water plus the acids used in this step.)

3. The digestion vessel is capped and placed in a microwave carousel. A minimum of four vessels are processed in the microwave at one time.

4. The sediment and acid mixture is digested by irradiating the vessel according to the programmed steps recommended for the number of vessels in the microwave. The sample is brought to a temperature of 175^{o} C in 5.5 minutes, then maintained between 175-180^{o} C for 9.5 minutes. (The pressure during this time peaks at approximately 6 atm. for most samples.)

5. The vessel is allowed to cool to room temperature before opening. The contents of the vessel are transferred to a 100 mL graduated cylinder and diluted with ultrapure water to 75 mL.

6. The dissolved samples are transferred to polyethylene bottles and stored for analysis.

All surfaces that come into contact with the samples, including the sample storage bottles, are acid washed (3 days 1:1 HNO_3; 3 days 1:1 HCl), rinsed six times in ultrapure water, and stored filled with ultrapure water until use.

Core Dating Analyses

The ^{210}Pb dating technique has been applied to the determination of lacustrine sedimentation rates since the 1970's. With a 22.3 year half-life, this nuclide can provide sedimentation rates valid for up to 100 yr. There are numerous successful examples of studies in both large and small lakes, but in all studies, it is necessary to consider the assumptions and potential artifacts associated with the technique. Overall, the technique generally is robust and has provided good sedimentation estimates in many lakes and reservoirs.

Profiles of ^{210}Pb (or ^{210}Po) in aquatic sediments consist of two main components: 1) "excess" or "unsupported" ^{210}Pb, and 2) "supported" or background ^{210}Pb. Excess ^{210}Pb is that component of ^{210}Pb that is in excess of the ^{210}Pb generated *in situ* via the decay of ^{226}Ra. In this study, the concentration of ^{226}Ra was not measured and ^{226}Ra concentrations are estimated from the asymptotic ^{210}Po concentrations at depth; where asymptotes were not reached, we assigned a value of 0.69 dpm g^{-1} based on other Loch Raven cores; this value is similar to supported ^{210}Po activities the Chesapeake Bay (Helz et al., 1985).

The decay of radio nuclides is a first order process described by the equation:

$$A = A_0 e^{-lt} \quad \textbf{(3)}$$

where A is the activity at time t, A_0 is the activity at time zero and l is the decay coefficient (0.03114 for ^{210}Pb). This equation may be modified for sediments:

$$A = A_0 e^{(-lx/w)} \quad \textbf{(4)}$$

where A is the activity (dpm g^{-1}) at depth x (cm) and w is the sediment accretion rate (cm yr^{-1}). This formulation is the **c**onstant **i**nitial **c**oncentration model (CIC) of ^{210}Pb-based sedimentation. It depends on 1) constant input fluxes of both sediment and excess ^{210}Pb, 2) no post-depositional mobility of ^{210}Pb relative to sediment particles, and 3) no sediment mixing by biota or physical processes. In the ideal situation, excess ^{210}Pb is described by equation 4 and provides an exponential decrease in excess ^{210}Pb activity with depth. To apply this model, equation 4 is log transformed:

$$\ln A = \ln A_0 - (lx/w) \quad \textbf{(5)}$$

The linear regression of the natural log of activity versus cumulative mass provides a mass sedimentation rate.

Sediment sections were dried at 65°C and ground using a ceramic mortar and pestle. The measurement of ^{210}Pb ($T_{1/2}$ = 22.3 Yr) was carried out by the analysis of its daughter radio nuclide, ^{210}Po ($T_{1/2}$ = 138 days). The extraction procedure for ^{210}Po generally followed that of Sugai (1990). Briefly, ~ 1 g of dried sediment is added to a beaker and NIST-traceable ^{209}Po was added as a yield tracer. The sediment was digested at 70°C with 10 mL of HCl and 10 mL of HNO_3, centrifuged to remove particulates, and the acid was evaporated to near dryness overnight. After a small additional evaporation of added HCl, 100 mL of 0.01 N HCl and ~0.25 g of ascorbic acid was added to the beaker. The ^{210}Po and ^{209}Po was plated onto silver overnight and counted in alpha spectrometers. "Total" Pb was analyzed following Owens and Cornwell (1995). This extraction does not analyze the Pb associated with silicate minerals. 2 mL of HNO_3 and 2 mL of HCl was added to 0.25 g of sediment in a flask. The sample was digested at sub-boiling temperatures overnight, and the mixture was solubilized with 1 N HCl. A NIST Standard Reference Material sediment was digested simultaneously as a quality check. Lead was analyzed via flame atomic absorption spectrophotometry. The total Pb yields for the NIST samples were within the limits of their certified values.

RESULTS AND DISCUSSION

Bathymetric Results

The bathymetric surveys of Loch Raven conducted in 1997 and 1998 were analyzed and storage capacities for the reservoir were calculated. Data coverage was consistent throughout the reservoir except for some loss of data near Loch Raven dam due to horizontal positioning quality concerns caused by the steep rock faces on both sides of the reservoir (Figures 7 and 9). Small areas of the reservoir were subject to poor acoustical sounding data due to sub-aquatic vegetation (Appendix G). The upstream extent of the Loch Raven survey is the bridge of Warren and Merryman's Mill roads. At this location the reservoir was shallow enough that small islands were forming, deeply incised and narrow channels were also forming due to low water conditions, and the reservoir became unnavigable. All calculations were performed using the Warren and Merryman's Mill road bridge as the upper extent of the Loch Raven reservoir. ArcInfo and Surfer produced different volumes due to their methodologies. An average of the two were used in generating the numbers presented herein. The bathymetric survey of 1997 on Loch Raven reservoir yielded a storage capacity of 19.15 billion gallons [72.5 million cubic meters] and a surface area of 7.72 million square meters [1908 acres].

The bathymetric survey of 1998 on Prettyboy reservoir yielded a complete consistent dataset (Figures 8 and 10). Minor concerns for voids in the dataset were addressed and a small portion of the reservoir was resurveyed in December of 1998. This survey yielded a storage capacity for Prettyboy reservoir of 18.4 billion gallons [69.7 million cubic meters] and a surface area of 5.81 million square meters [1436 acres] (Table VIII).

Calculated Storage Capacities Billion Gallons *[Million Cubic Meters]*			
Reservoir	**ArcInfo**	**Surfer**	**Average**
Loch Raven 1913	21.4 *81.0*	-	21.4 *81.0*
Loch Raven 1997	19.2 *72.7*	19.0 *71.7*	19.1 *72.3*
Prettyboy 1998	18.6 *70.4*	18.2 *68.9*	18.4 *69.7*

Table VIII. Storage capacities calculated in this study.

Additionally, the topographic maps of Loch Raven reservoir of 1913 (Plate 3) were used to estimate the theoretical future storage capacity of the reservoir confined to the study area. This capacity was calculated using the contours that the surveyor's had drawn. No interpretation of the data was performed on water depths that existed at that time. This resulted in a slight underestimate of the initial storage capacity. The storage capacity calculated from the

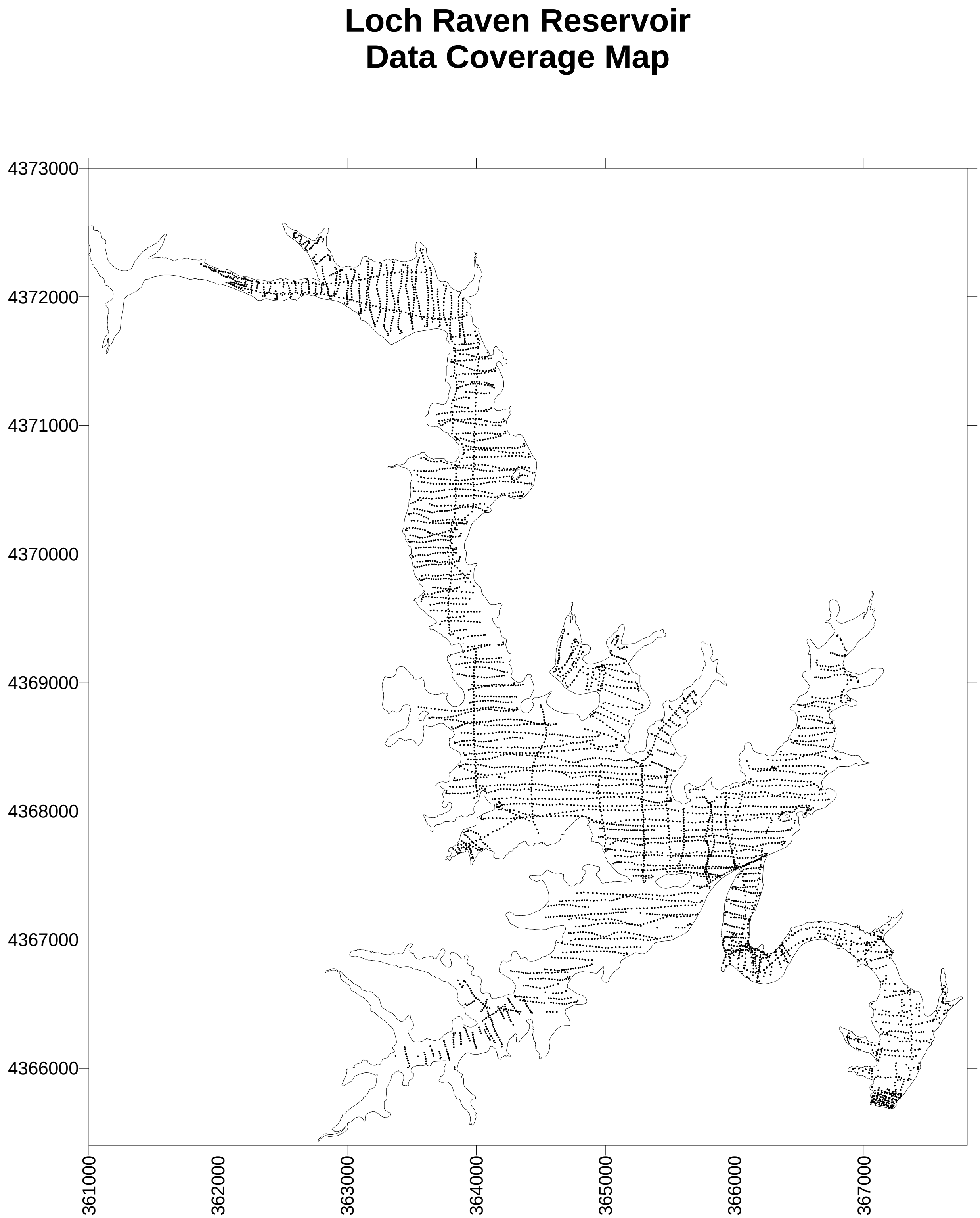

Figure 7. Data Coverage Map of 1997 Bathymetric Data for Loch Raven Reservoir. Every fifth data point is displayed. Horizontal units are UTM – NAD83 – Meters.

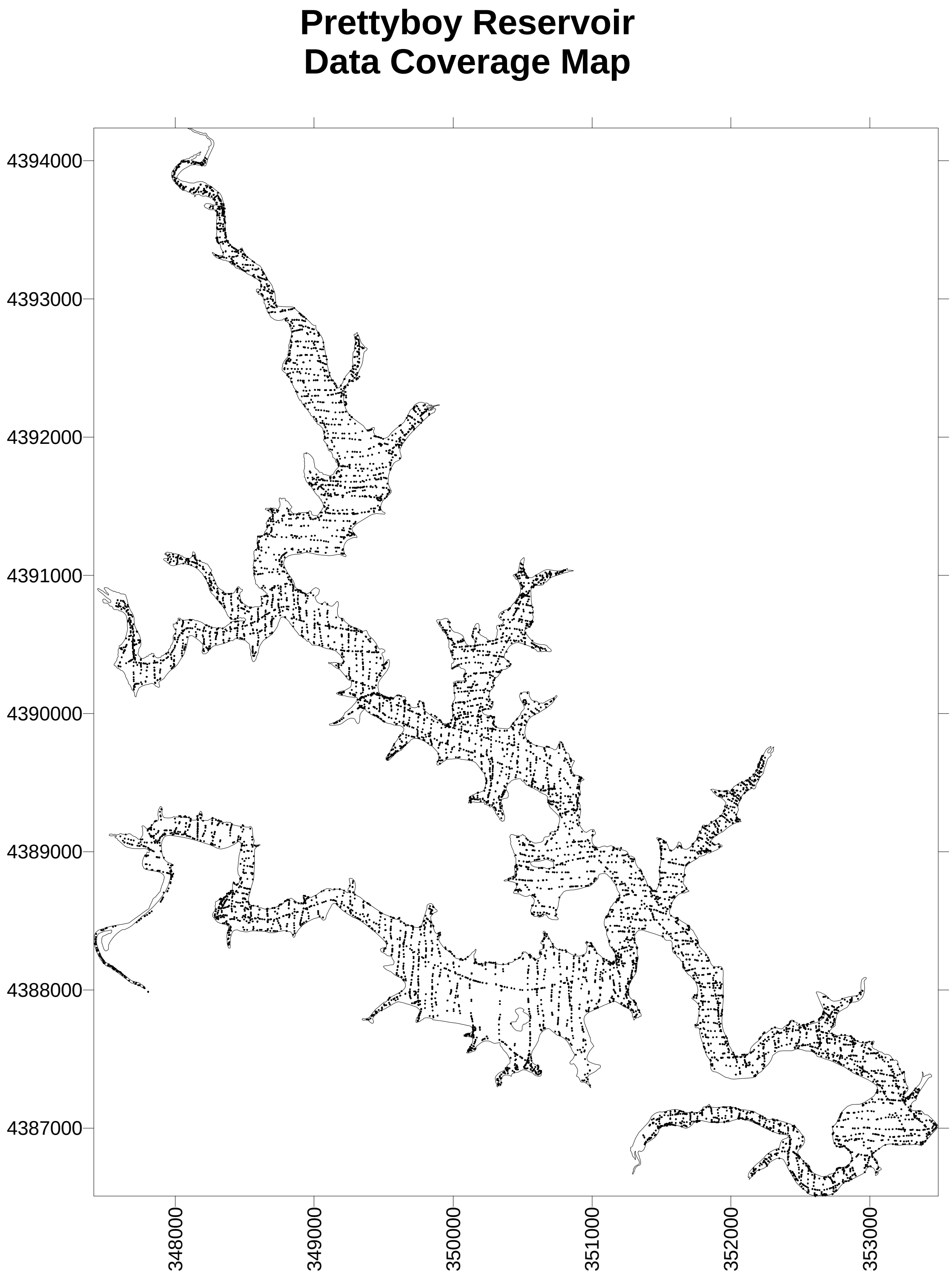

Figure 8. Data Coverage Map of 1998 Bathymetric Data for Prettyboy Reservoir. Every fifth data point is displayed. Horizontal units are UTM – NAD83 – Meters.

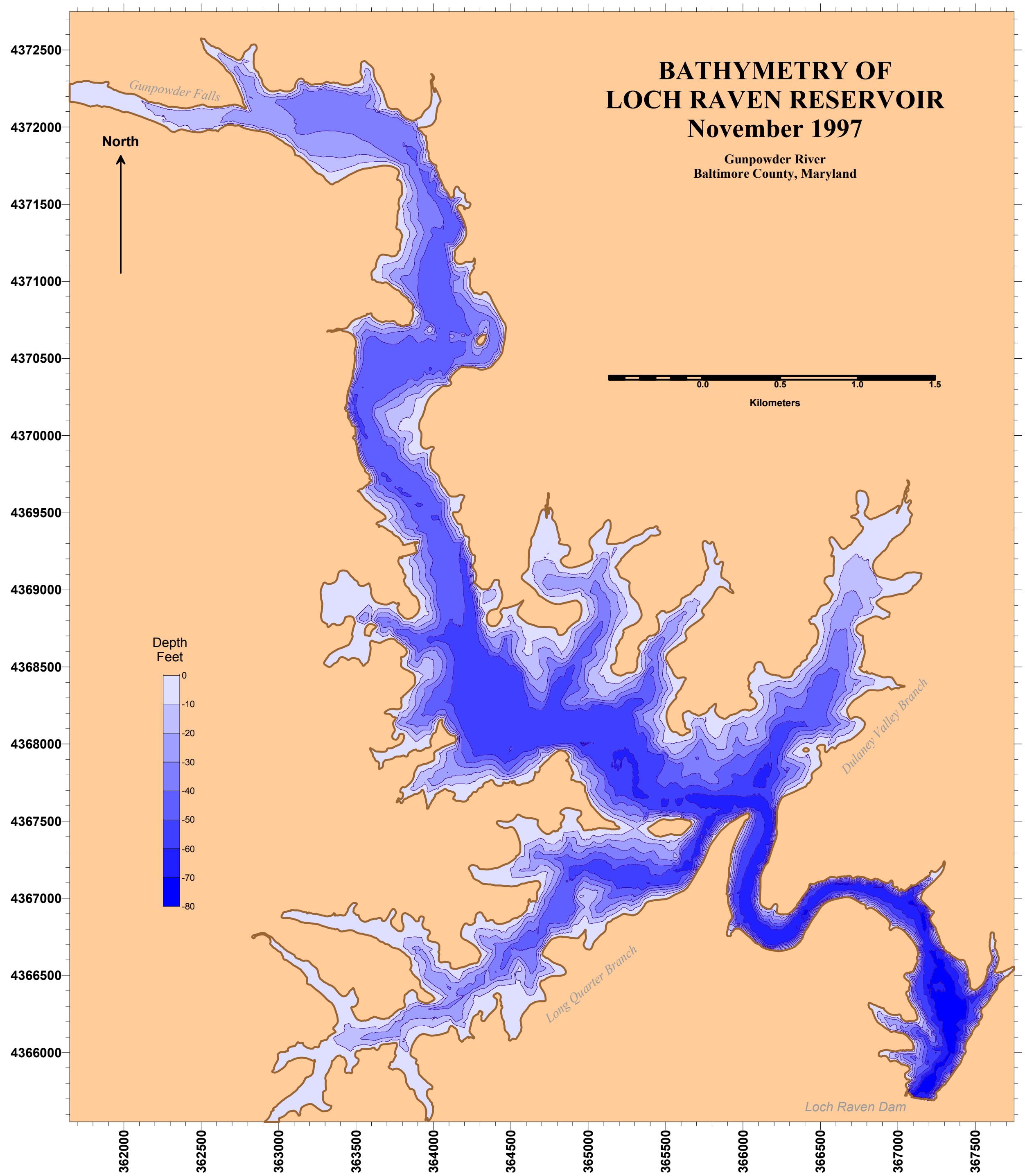

Figure 9. 1997 Bathymetry of Loch Raven reservoir. This map is enlarged in Plate 1. Horizontal coordinates are in UTM – NAD83 – Meters. Depth is in feet from mean pool level.

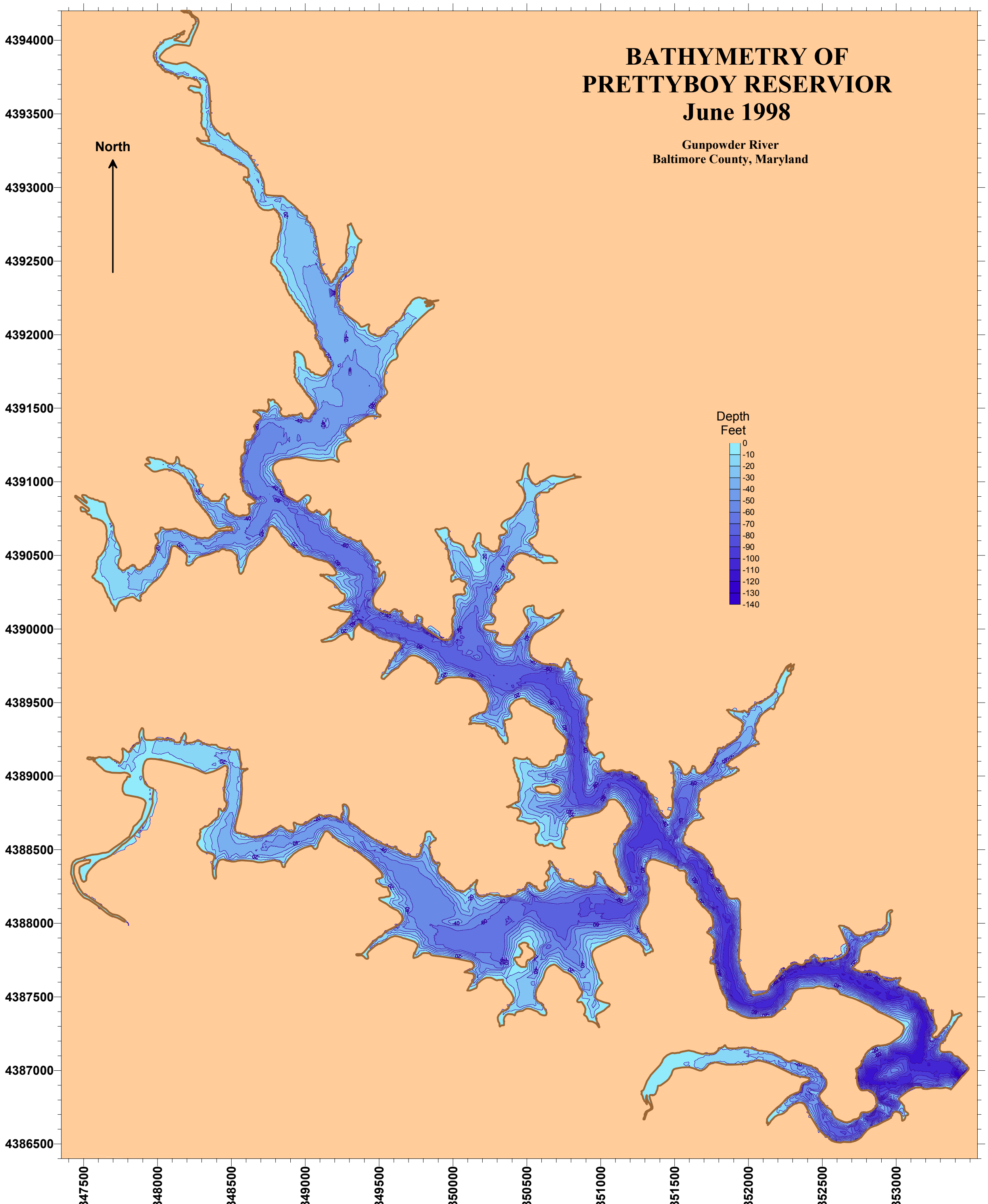

Figure 10. 1998 Bathymetry of Prettyboy reservoir. This map is enlarged in Plate 2. Horizontal coordinates are in UTM – NAD83 – Meters. Depth is in feet from mean pool level.

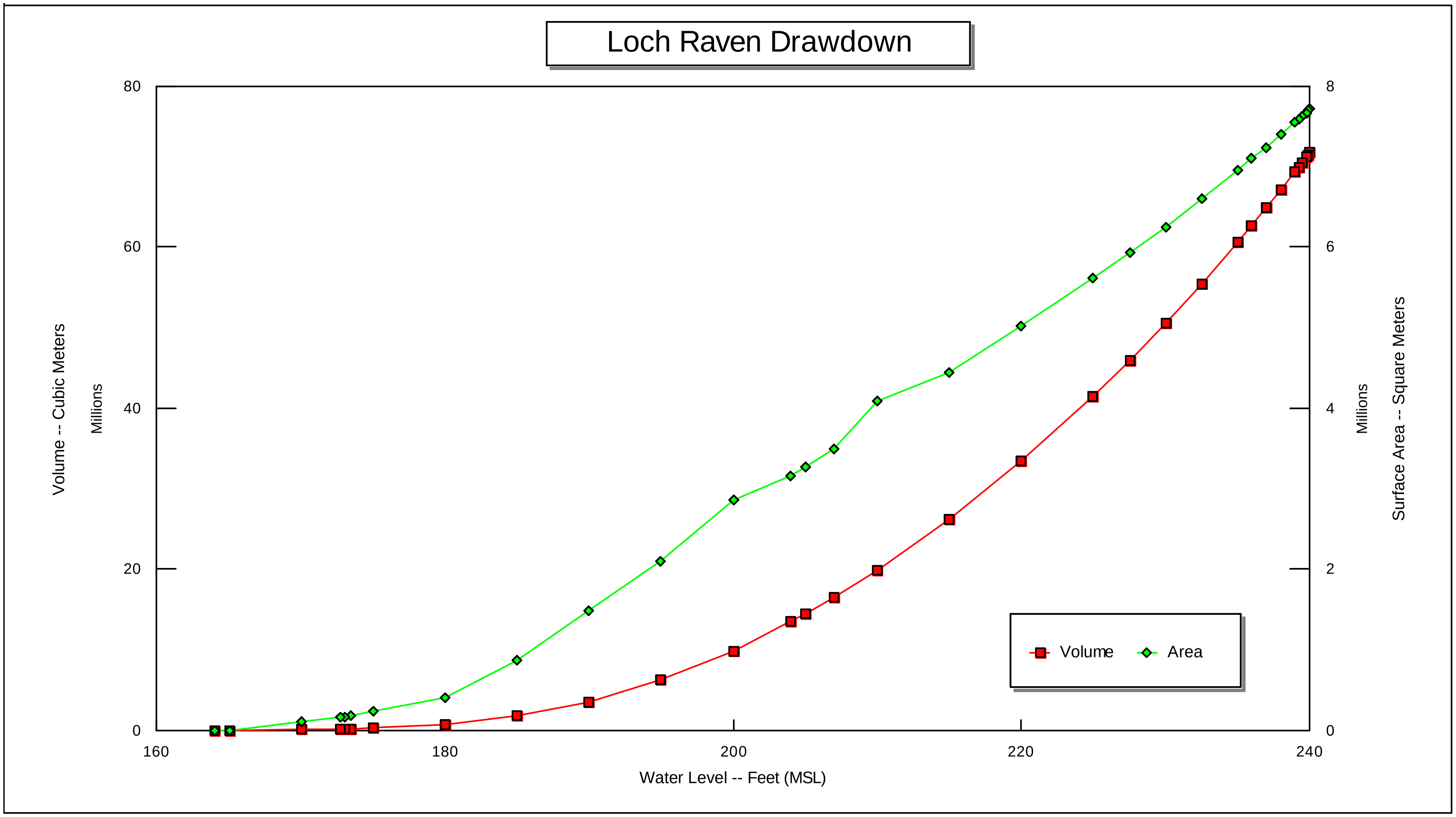

Figure 11. Volumetric Drawdown graph of Loch Raven Reservoir. Results are interpreted from the Surfer model of the 1997 bathymetry.

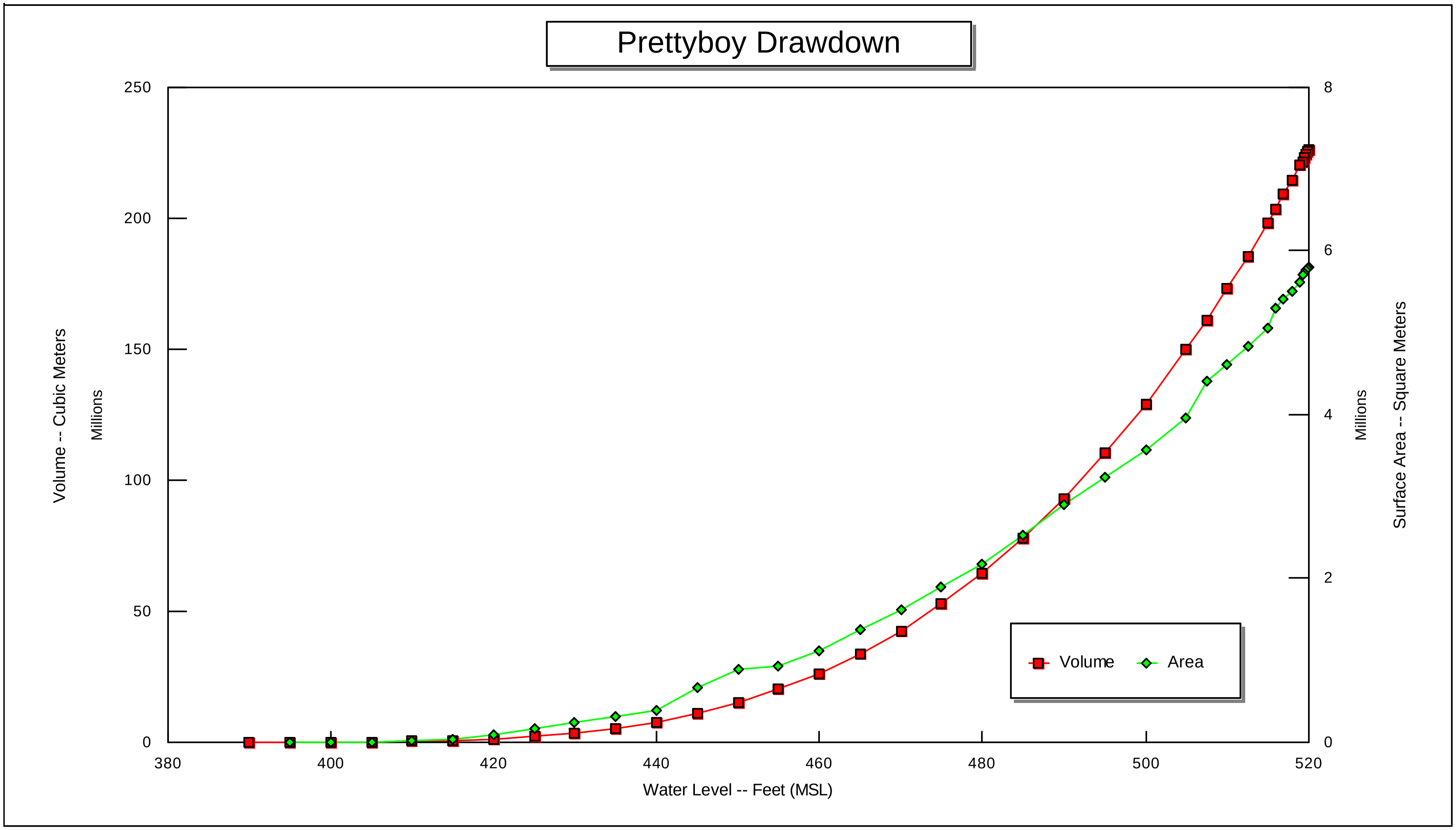

Figure 12. Volumetric Drawdown graph of Prettyboy Reservoir. Results are interpreted from the Surfer model of the 1998 bathymetry.

1913 topographical maps was 21.4 billion gallons [81.0 million cubic meters] (Banks and LaMotte, 1999). This calculation was only performed in the ArcInfo modeling software as the Surfer modeling software could not calculate surfaces from contour maps.

Modeling of the reservoirs allows the development of water volume estimate curves depending upon the height of the water. As the water level of the reservoir decreases so does the volume of the water. Figures 11 and 12 graph the effects of reservoir drawdown on volume and surface area in Loch Raven and Prettyboy reservoirs, respectively.

Comparison of the 1913 surface contained in the study area and the 1997 bathymetric surface of Loch Raven allowed an estimate to be computed for storage loss. A 2.3 billion gallon [8.7 million cubic meters] loss of storage capacity occurred between the 1913 survey and the 1997 survey due to sediment accumulation in the reservoir. This equates to a 10.8 percent decrease in volume from the original capacity calculated from the 1913 topographic maps (Table IX).

Loch Raven Storage Loss (sediment gain) Billion Gallons *[Million Cubic Meters]*			
	ArcInfo	**Surfer**	**Average**
Volume Lost	2.2 *[8.3]*	2.4 *[9.1]*	2.3 *[8.7]*
% Loss from 1913	10.3	11.2	10.8

Table IX. Storage Loss calculations for Loch Raven reservoir.

From the data gathered in the 1997 bathymetry survey and the 1913 topographic maps, accumulated sediment thickness can be calculated and mapped (Figure 13). It is evident that most of the sediment has collected at the stream and river input ends of the reservoir while the area near the dam has gathered much less sediment. Generally, the majority of the reservoir has collected sediment to a thickness of 1-2 meters [3.3-6.6 feet]. Areas of sediment thickness between 3-6 meters [9.8-19.7 feet] can be found in portions of the reservoir; however, they are mostly confined to the pre-existing channel of the Gunpowder Falls river prior to dam construction. The upstream extent of the reservoir show the most sediment accumulation. In that area, sediment thickness is documented to be between 14.5-18.0 meters [47.6-59 feet]. This thickness of sediment has also been collaborated with logs collected by a private contractor (E2SI) who has bridge borings in an area several miles upstream from our limit of survey.

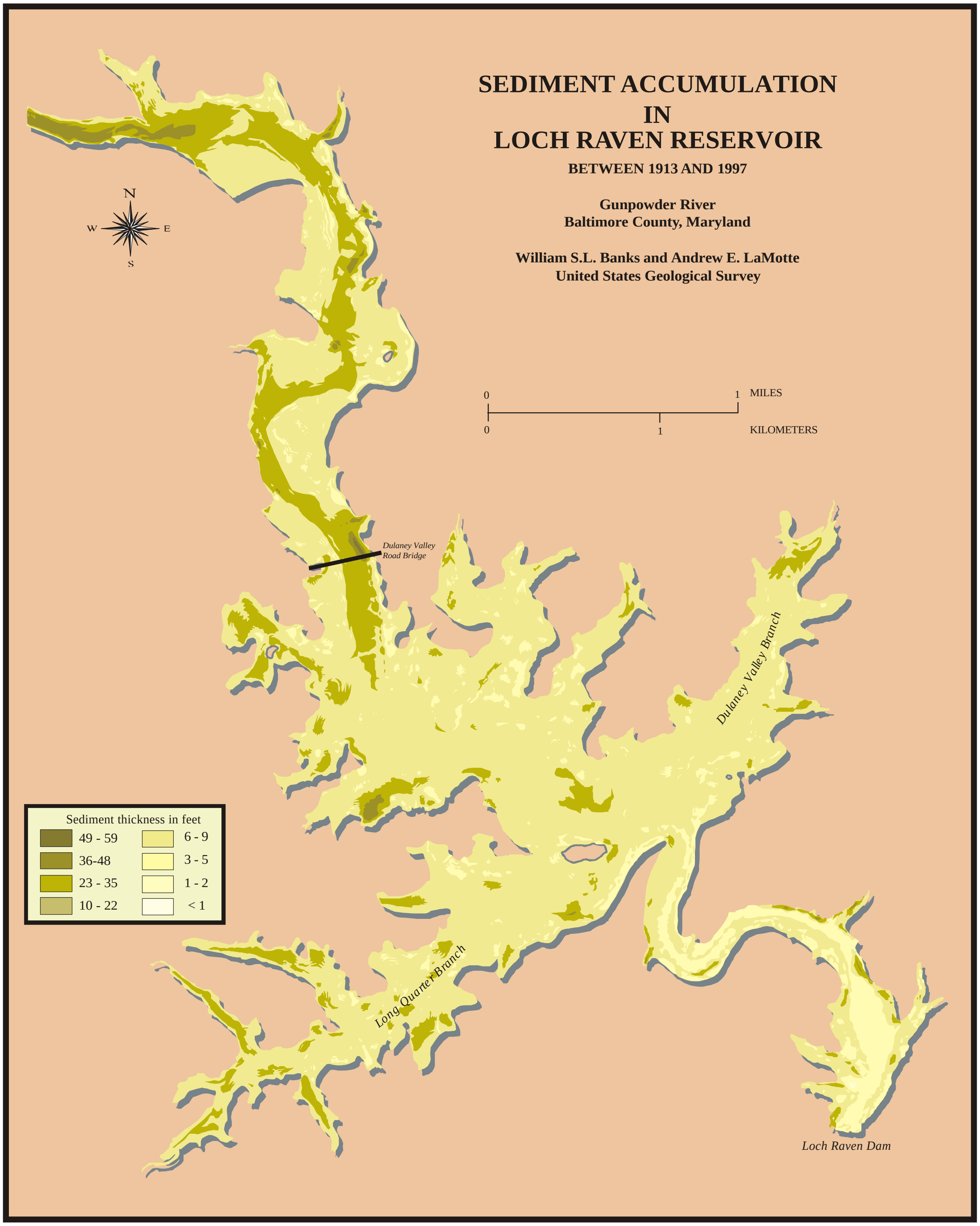

Figure 13. Sediment accumulation in Loch Raven reservoir between 1913 and 1997. Sediment thickness is in feet. An enlarged image of this map is published as Plate 4.

A sectional analysis was performed on the Loch Raven data so as to estimate which sub-watershed portions of the reservoir may have elevated terrestrial input (Figure 14)(Table X). Section A is located directly upstream from the dam and is also located the furthest from any input source which may contain sediment. An unknown volume of water contained in the existing reservoir in Section A was present during the 1913 topographic survey, and no interpretation was performed on that body of water since it's depths were not surveyed. An historical estimate of this unknown volume is 178 million gallons [0.674 million cubic meters] (Freeman and Sterns, 1908); however, without better quality control on the methods used to derive this number we must treat this volume as unknown. This unknown volume has since filled with sediment, and it is not accounted for in the analysis on Section A. Calculations show that Section A has lost 1 percent of it's 1913 volume; however, this calculation is very error-prone for the above mentioned reasons. Section B is the northeast arm of the reservoir and is named Dulaney Valley Branch. Section B has decreased in volume by eight percent of it's original calculated volume. A spatially disproportionate amount of this sediment is being collected in a delta formed at the reservoir and the mouth of Dulaney Valley Branch creek. Section C is the southwest arm of the reservoir known as Long Quarter Branch. Section C has decreased in volume by thirteen percent of it's original calculated volume. Most of this loss is in the infilling of small tributaries and the creation of deltas off of these small tributaries. Section D is the central portion of the reservoir and does not have any major inputs except for suspended material in the water column entering mostly from the upper portion of the reservoir. Section D has decreased in volume by nine percent of it's original volume. Most of this loss is uniformly distributed throughout the section; however, higher sediment thicknesses may be found in the historical river channel. Section E is the northernmost extent of the reservoir and can be characterized as the extension of the Gunpowder Falls River. The main source of water and sediment input in this section is the Gunpowder Falls River. This section has been shown to have lost the most amount of storage. Nineteen percent of it's original storage capacity is now occupied by sediment. The sediment accumulation pattern as seen in Loch Raven reservoir is expected in a flooded river valley reservoir.

Loch Raven Sectional Analysis					
Section	1913 Storage Capacity Billion Gallons	1997 Storage Capacity Billion Gallons	Percent Loss (%)	Sediment Gain Million cubic meters	Portion of total sediment load (%)
A	3.024	2.998	1	0.098	1
B	1.774	1.635	8	0.523	6
C	2.883	2.510	13	1.410	16
D	8.223	7.520	9	2.659	31
E	5.541	4.512	19	3.897	45
Total	21.445	19.175	10.6	8.587	

Table X. Sectional distribution of storage loss and sediment deposition. (Banks and LaMotte, 1999)

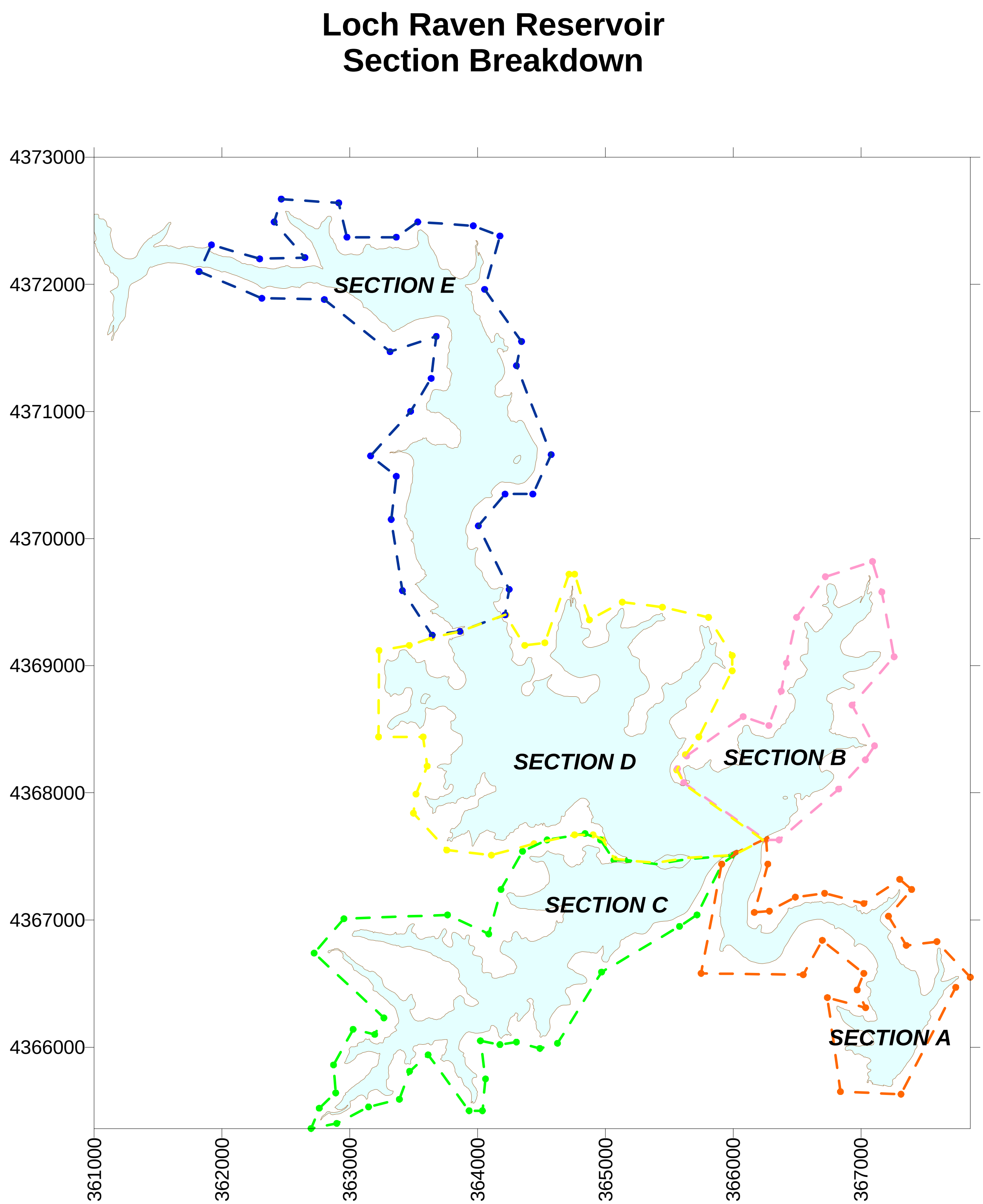

Figure 14. Section delineations used for analysis of Loch Raven reservoir. Horizontal units are UTM – NAD83 – Meters.

A baseline topographical survey of Prettyboy reservoir was conducted in 1933. The original dataset of the 1933 survey could not be located. Had this survey been available, storage capacity loss could have been calculated in a manner similar to Loch Raven reservoir. However, initial storage capacity volume estimates from this survey are reported in several Baltimore City documents (Iivari, 1985; Gottschalk, 1943; Holeman, 1965). Since the initial storage capacity was calculated using different methods, which are not documented, significant errors may exist in the loss calculation. The storage capacity loss calculated from 1933 to 1998 is 1.5 billion gallons [5.7 million cubic meters]. This is a 7.5 percent decrease from the original storage capacity. (Table XI)

Prettyboy Storage Loss (sediment gain) Billion Gallons *[Million Cubic Meters]*			
	ArcInfo	**Surfer**	**Average**
Volume Lost	1.3 *[4.9]*	1.7 *[6.4]*	1.5 *[5.7]*
% Loss from 1933	6.5	8.5	7.5

Table XI. Storage loss calculations for Prettyboy reservoir.

The storage capacity loss rate is a key component for calculating the remaining life of a reservoir. Using the volumes of accumulated sediment and the age of the reservoirs, annual storage capacity loss rates can be calculated. Loch Raven reservoir has lost storage capacity at a rate of 26.8 million gallons per year. Prettyboy Reservoir has lost storage capacity at a rate of 23.1 million gallons per year. As a percentage of the original storage volume, the loss rate for Loch Raven is 0.13 percent and for Prettyboy the loss rate is 0.12 percent (Table XII). The percentage loss of storage capacity per year compares favorably with national averages. The national mean annual storage depletion rate for reservoirs of comparable size is 0.43 percent. The national median annual storage depletion rate for reservoirs of comparable size is 0.27 percent (Morris, 1998). Both Loch Raven and Prettyboy are far below these national averages.

Further analyzing this data with the surface area of the reservoirs gives an estimate of the average sediment accretion rate which has occurred in each reservoir. The accretion rate in Loch Raven reservoir has averaged 1.4 centimeters per year [0.6 inches per year], and in Prettyboy reservoir it has averaged 1.5 centimeters per year [0.6 inches per year] (Table XII).

Storage Capacity Loss Rates [Sediment Accretion Rates] *Percent Loss Per Year*				
Reservoir	**Age at Survey years**	**ArcInfo Million Gallons / yr [cm/yr] %**	**Surfer Million Gallons / yr [cm/yr] %**	**Average Million Gallons / yr [cm/yr] %**
Loch Raven	84	25.0 [1.3] *0.12%*	28.6 [1.4] *0.13%*	26.8 [1.4] *0.13%*
Prettyboy	65	20.0 [1.3] *0.10%*	26.2 [1.7] *0.13%*	23.1 [1.5] *0.12%*

Table XII. Storage capacity loss rate calculations for Loch Raven and Prettyboy reservoirs.

Sediment accretion rates were calculated for each section shown in Figure 13 for Loch Raven reservoir. Table XIII outlines the results of this analysis. Section E, which is located at the upstream edge of the reservoir, has an accretion rate of about 190 percent greater than that of the rest of the reservoir. Section A's results are very likely in error as the accumulated sediment for that section is likely to be underestimated due to the unknown volume of the reservoir when the 1913 survey was conducted. An overall time-averaged accretion rate for Loch Raven reservoir between 1913 and 1997 is 1.3 cm per year.

Sediment Accretion Rates By Section in Loch Raven Reservoir			
Section	**Sediment Gain Million cubic meters**	**Surface Area Square kilometers**	**Accretion Rate cm/yr**
A	0.098	0.859	0.1
B	0.526	0.882	0.7
C	1.412	1.263	1.3
D	2.661	2.723	1.2
E	3.895	1.992	2.3
Total	8.592	7.723	1.3

Table XIII. Sediment accretion rates per section in Loch Raven reservoir.

Sub-Bottom Seismic Reflection Results

Sub-Bottom Seismic reflection data generally confirmed that the accumulated sediment attained a variable thickness of one to two meters. This data was highly variable due mainly to the topography of the original surface. The data provided fairly good interpretable results in the central portion of the reservoir. The data that was collected in the portion of Loch Raven reservoir above the Dulaney Valley Bridge and in Long Quarter Branch and Dulaney Valley Branch did not show any acoustical penetration into the existing sediments. This is most likely due to the organic-rich sediment which produces methane vesicles in the organic decay process. While conducting the survey, the field crew noticed gas being released from the sediment into the water column. The data also showed little to no penetration in the sediments near Loch Raven dam. This is most likely caused by the character of sediment. Sediment which is closer to the dam is also found to be of smaller grain size. The grain size of the accumulated sediment is acoustically identical to the preexisting sediment or soil which reduces any density gradients; and, thereby, reduces seismic reflections.

The data has been collected and archived on CD-ROM. Further analysis of this dataset may provide insight into other sediment related issues.

Gravity Core Results

Using the data collected from grain size, bulk water content and the visual observations of the cores and the x-ray lithographs, horizons which indicate the pre-reservoir surface were identified. This horizon provides, in each core, our estimate of the total amount of sediment that has accumulated at each site. However, this data can not account for changes in sedimentation rates over time nor changes which may have been due to erosion. Erosion is however not expected to be a significant factor because erosional forces are minimal in the depths where the cores were collected. Particular features which assisted in the identification of this pre-reservoir surface were roots, gravel, and water content changes. Four of the nine cores penetrated to this pre-reservoir surface. The sediment accretion rates that could be calculated from these observations are shown in Table XIV. Sediment accretion rates greater than 1 cm per year could not be calculated because of the length of the sediment cores. Cores 63, 35, 73, 92, and 42 did not penetrate to the pre-reservoir surface; hence, calculations can only be made for a minimum sediment accretion rate. The core observations demonstrate that there is locally variable sediment accretion rates within the reservoir; however, these rates are generally found to be approximately one centimeter per year.

Gravity Core Sediment Accretion Rates		
Core	**Depth to Pre-Reservoir Surface (cm)**	**Accretion Rate (cm/yr)**
27	80	0.95
50	52	0.62
96	89	1.10
57	75	0.89
63	> 94	> 1.10
35	> 92	> 1.10
73	> 82	> 1.0
92	> 92	> 1.10
42	> 76	> 0.9

Table XIV. Accretion rates calculated by sediment thickness in gravity cores.

Core Dating Results

Cores 27, 35, 50 and 92 show the distinct exponential character associated with a steady-state ^{210}Pb profile (Figure 15; Table XXX in Appendix D). The age where the profile reaches an asymptote is usually ~100 years; in this case, it would correspond to the construction of the dam (1914, ~ 80 yr). Using equation 5 the calculated rate of mass sedimentation for these cores is shown in Table XV.

Core Regression Data					
Core	**Water Depth (ft)**	**# of Points in Regression**	**R^2**	**Sedimentation Rate (g m^{-2} y^{-1})**	**Accretion Rate (cm y^{-1}) in top 20 cm**
27	53	10	.98	1540	2.0
35	41	12	.93	3040	1.2
50	36	9	.95	1820	2.0
92	50	8	.95	4560	1.0

Table XV. Core regression analysis for ^{210}Pb dating.

Cores 57, 73, and 96 had lower activity than the other 3 cores, and show a slower rate of decrease of ^{210}Pb. The regression model approach did not work with these cores (Figure 16) and the determination of reliable sedimentation rates was not possible. Given the relatively high ^{210}Pb activity at greater depths in these cores, these data generally suggest that these sites have very high rates of sediment accretion.

The total Pb profiles (Figure 17; Table XXXI in Appendix D) show a different pattern at the six sites with complete Pb profiles. At core location 27, a readily identifiable peak is observed. High variability is found in core 35, but the highest values are found at similar depths as those found in core 27. Surficial sediment Pb concentrations appear to be quite elevated at this site, perhaps reflecting it's proximity to the sewage pumping station. The alternating high and low concentrations may indicate some inputs of low Pb soil washing into the reservoir. Distinct patterns of Pb concentration are not evident in the other cores, though near-surface Pb concentrations at site 73 are consistent with the general decrease in Pb concentration over time, largely due to the removal of alkyl-lead from gasoline. In Figure 18, the Pb concentration is plotted against the ^{210}Pb-derived sediment age. In general, the data in cores 27, 35 and 50 show a mid-1970's peak in Pb concentration, consistent with the continental pattern observed elsewhere (Owens and Cornwell, 1995).

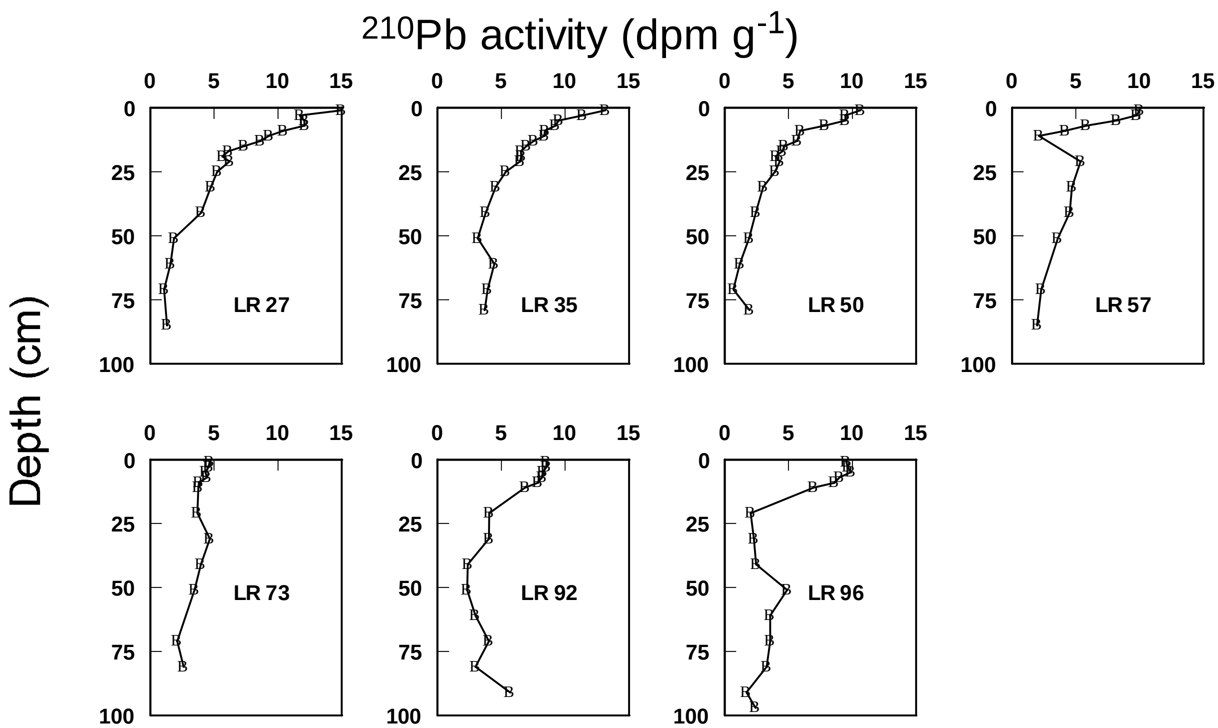

Figure 15. ^{210}Pb profiles of Loch Raven Cores

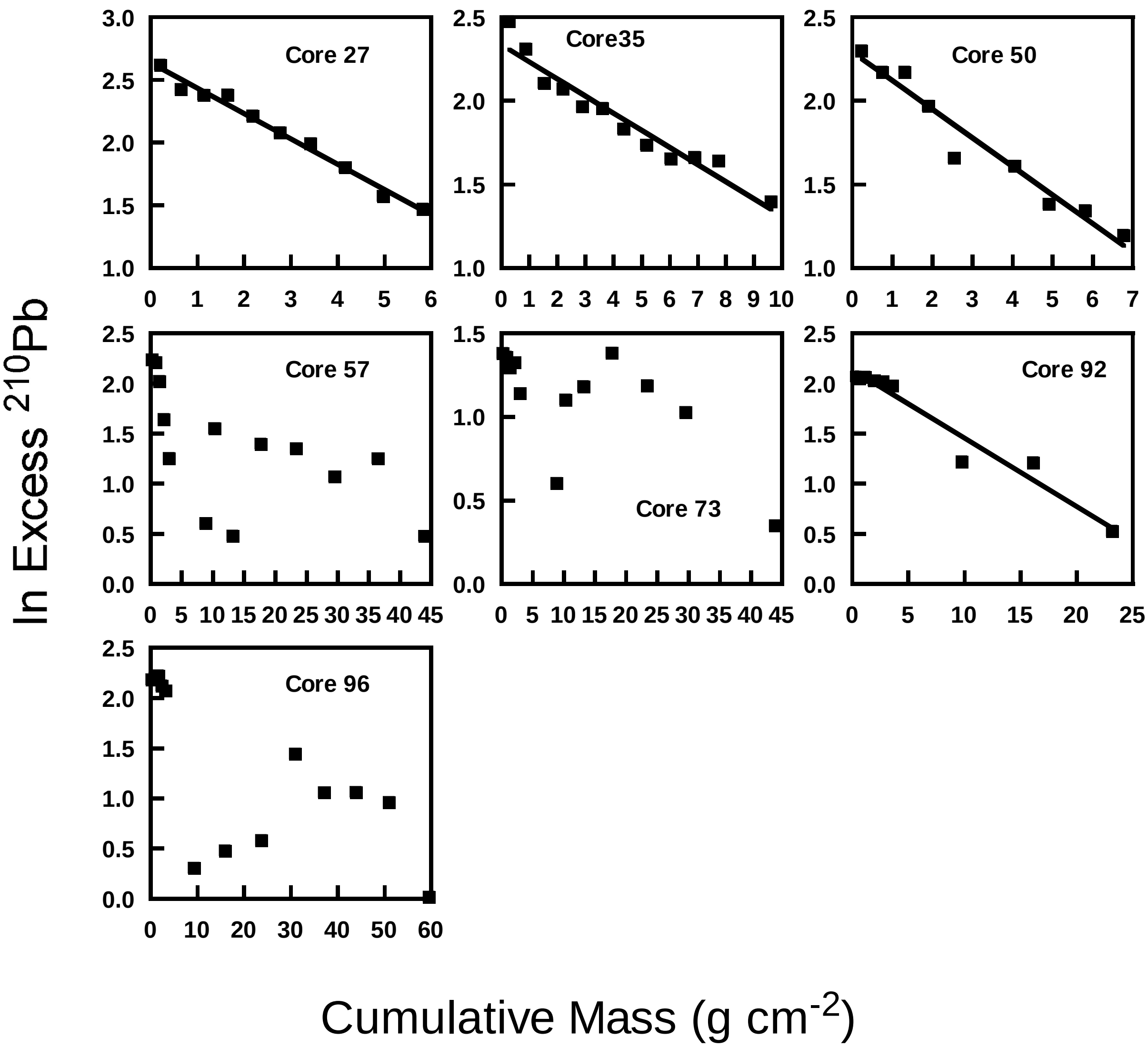

Figure 16. Linear regression of cumulative mass versus the natural log of the atmospheric component of radiometric lead.

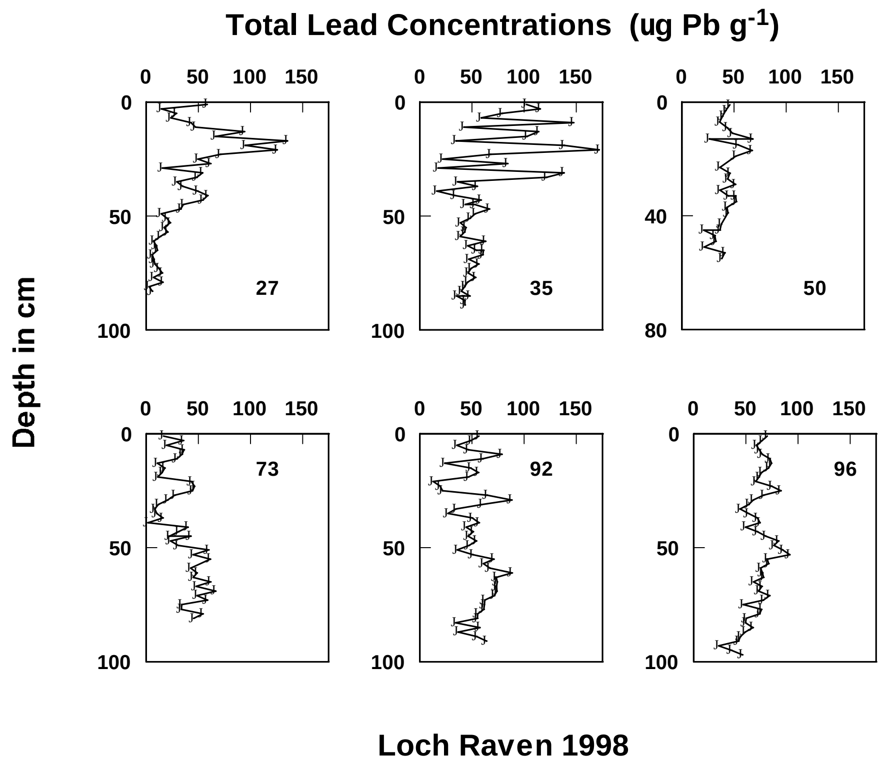

Figure 17.
Loch Raven Vertical Lead Profiles

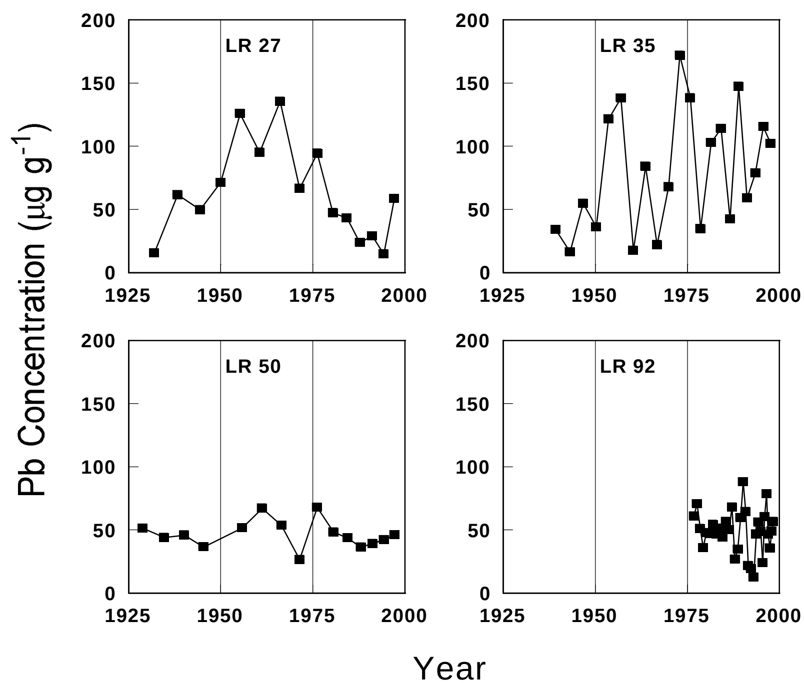

Figure 18.
Loch Raven Pb concentrations as a function of year.

Sediment Chemistry Results

Correlation

Correlation analyses between textural (Figure 19) and chemical parameters (water content, sand, silt, clay; carbon, nitrogen, sulfer, and element concentrations) were performed on core sediment data to detect any significant associations between variables. The correlation coefficients for the core sediment data are presented in Appendix E (Table XXXII).

The highest correlation is between silt and clay which is due, in part, to the way silt and clay content is determined, and to the fact that most of the sediments analyzed were silty clay or clayey silt, having little sand content. As a result, there is a strong inverse correlation between silt and clay; the more clay, the less the silt content and vice versa. Surprisingly, there are no significant correlations between water content and sand-silt-clay components. There are significant inverse relationships between silt and total phosphorus, Cr, Cu, Fe and Zn. Clay is positively correlated to these same components but the relationships are not as strong. Curiously, total nitrogen or carbon contents do not show any significant relationships with any of the textural components, but do with water content. These correlations (or lack of) suggest that water content may be influenced by the organic content in the Loch Raven sediment. However, the organic material is not adsorbed onto sediment particles *(i.e.*, clay minerals), but merely inter-dispersed with the sediments, and thus, not associated with any particular grain size. Total phosphorus exhibits a strong relationship with both silt and clay, and several metals (Cr, Cu, Fe, Mn and Ni), but not with nitrogen or carbon. These correlations suggest that most of the sediment phosphorus is not associated with organic material, but is inorganic in form, perhaps as apatite derived from the watershed, or adsorbed onto clays and ferric hydroxides. (See discussion of phosphorous under Nutrients section)

Nutrients

Carbon

The carbon found in the Loch Raven sediments consists of both inorganic and organic components. In a fresh water environment, the organic component is comprised largely of plant litter (leaf and woody debris) and algal matter. The inorganic component consists of mineral forms of carbon, carbonates such as marble and limestone. Based on the analyses of the upper 6 to 8 cm of bottom sediments (*i.e.* tops of the cores), total carbon contents ranged from 2.53% to 3.94%, averaging 3.17%. The organic carbon comprises, on the average, 83% of the total carbon measured in the sediments (Figure 20). Organic carbon contents ranged from 2.12% to 3.28% with a mean of 2.64%. Of the organic carbon, two-thirds is reactive carbon (i.e. readily available to the biological community). Reactive carbon contents ranged from 1.38% to 2.07%, averaging 1.78%.

Based on the analyses of five samples taken from core 42, total carbon decreases with depth below sediment surface. Both reactive and organic carbon also decrease with depth. The ratio of inorganic carbon to total carbon increases with depth suggesting that reactive carbon is preferably metabolized (consumed) after burial, thus proportionally decreasing downcore.

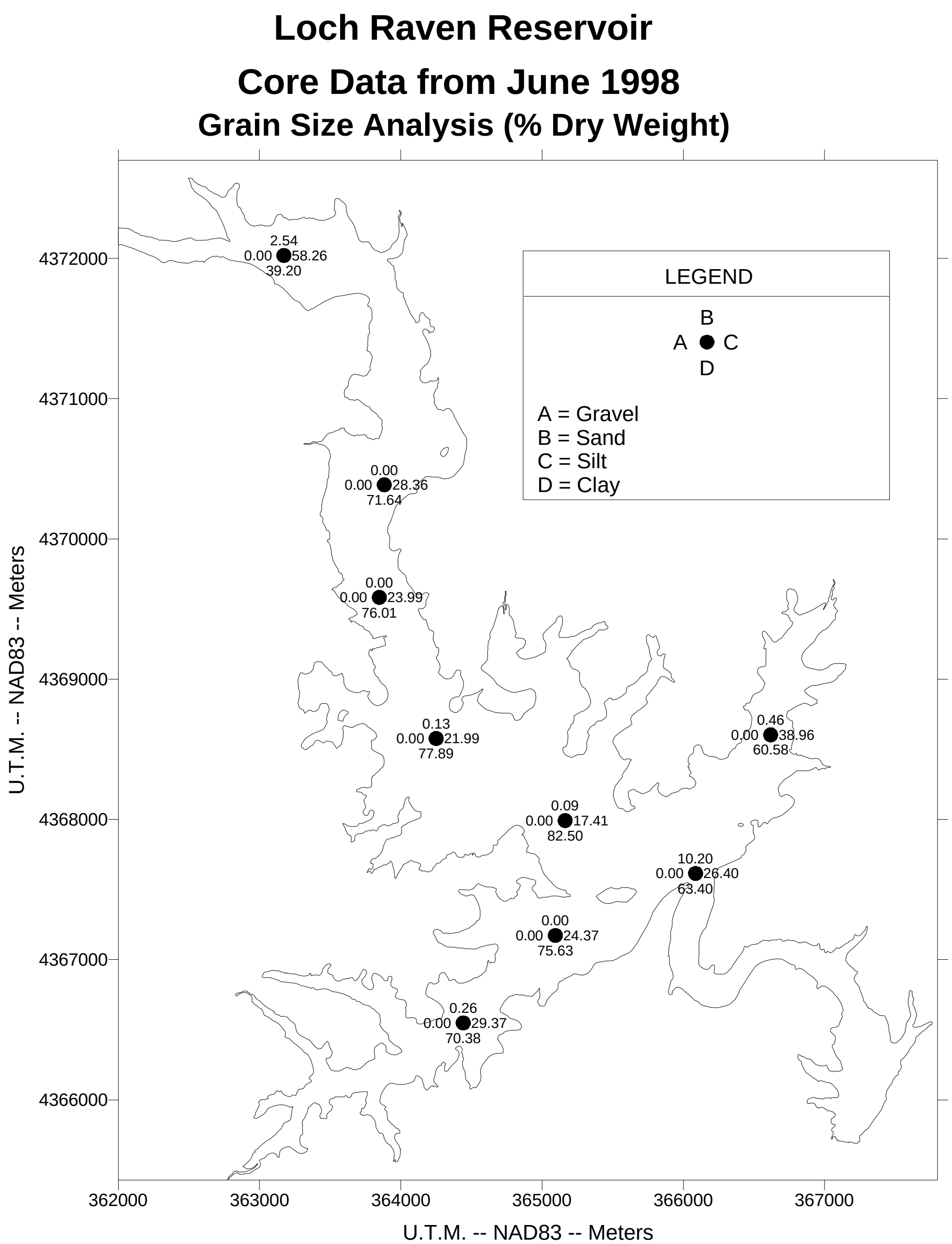

Figure 19. Distribution of grain size in the surficial sediments of Loch Raven reservoir.

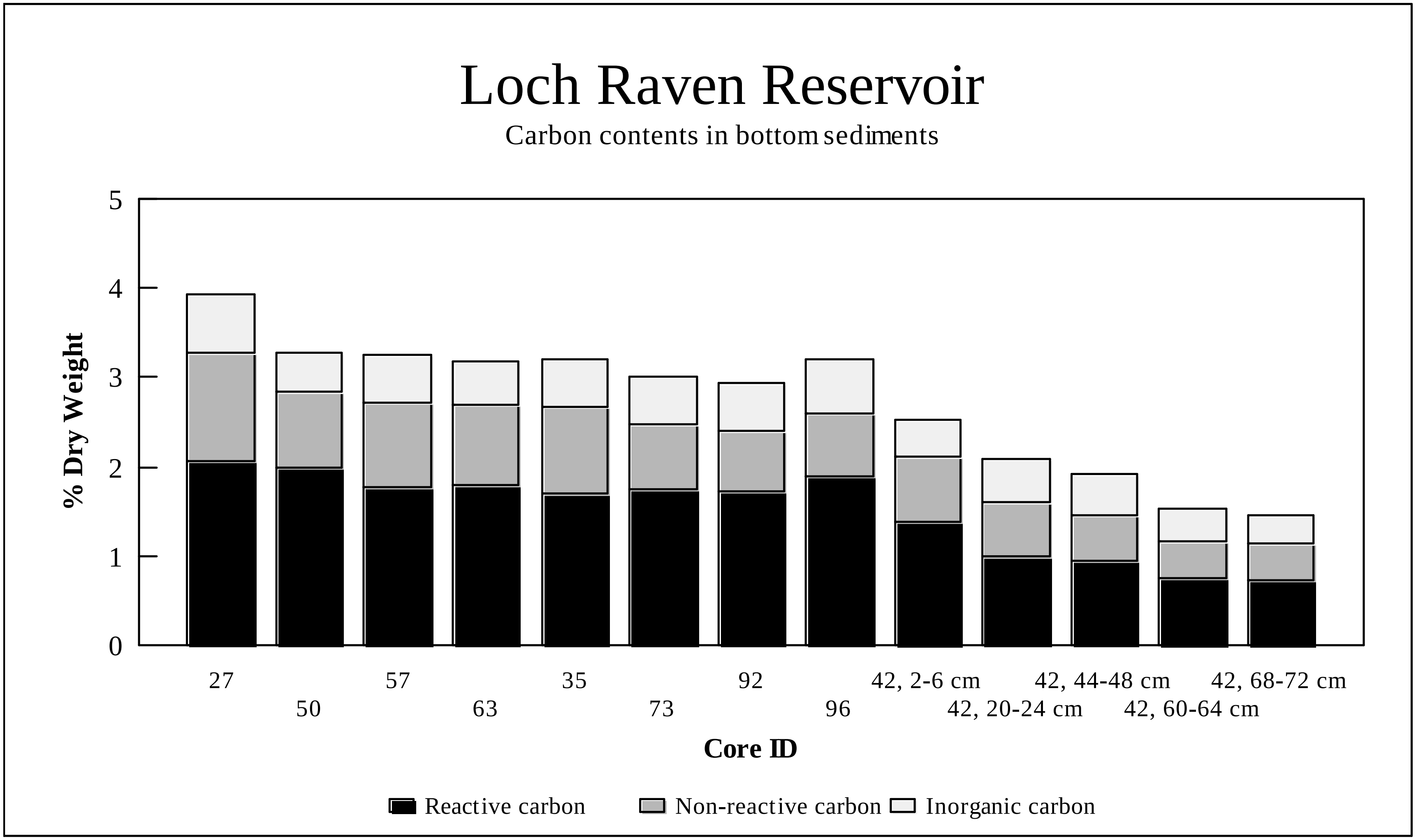

Figure 20. Histogram of carbon content in Loch Raven reservoir sediments. Carbon content is broken down into reactive, non-reactive, and inorganic carbon percentages. Percentages are in dry weight.

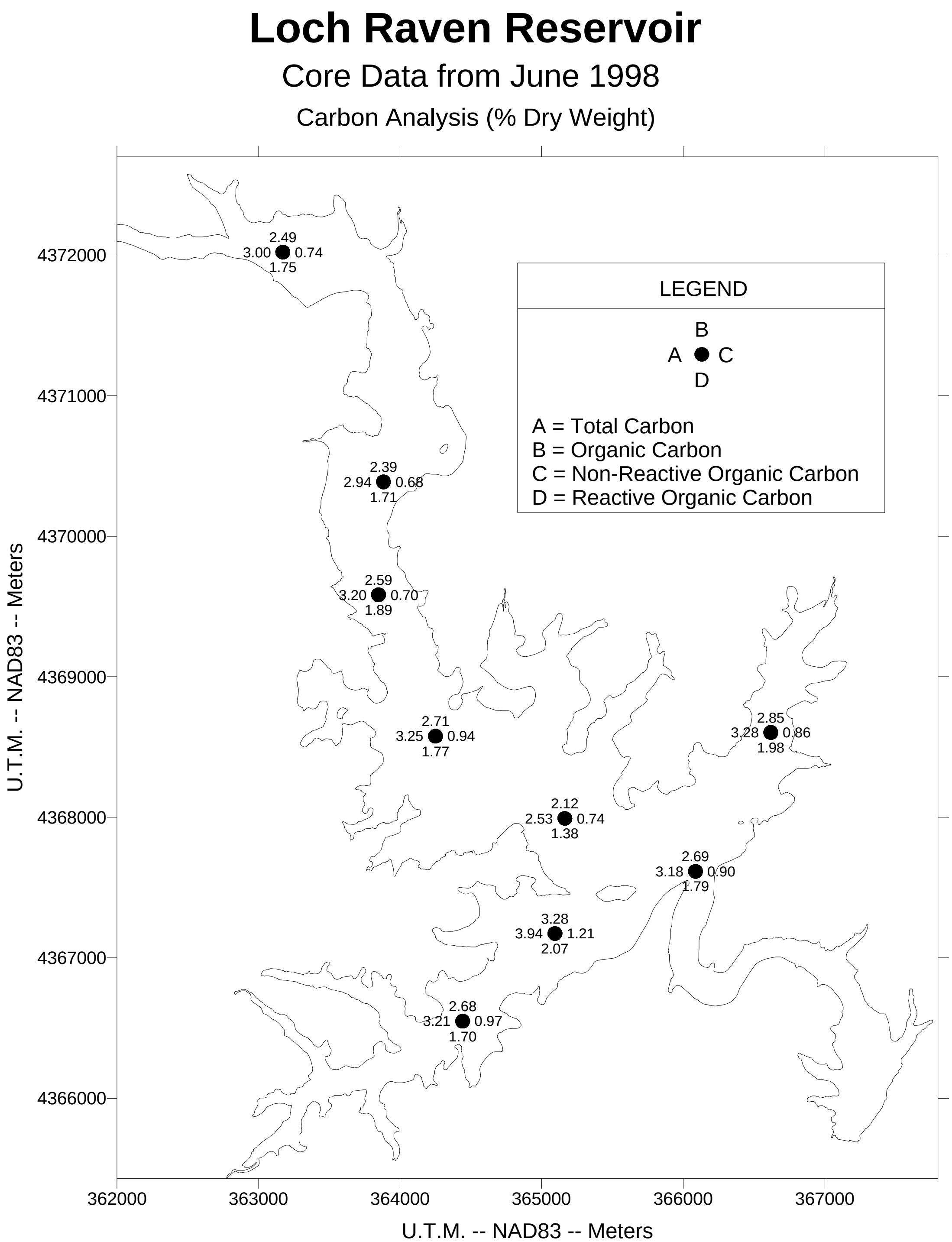

Figure 21. Distribution of carbon in the surficial sediments of Loch Raven reservoir.

Distribution of total carbon content in the surface sediments shows no discernable trend. However, for non-reactive carbon, the highest contents are found in Long Quarter Branch (Figure 21).

Nitrogen

Total nitrogen content measured in the surficial sediments ranged from 0.23% to 0.40%, with a mean of 0.32%. Total nitrogen decreases with depth below the sediment surface (Figure 22).

There is a good correlation between organic carbon and total nitrogen. ($r = 0.84$) (Appendix E). The strong relationship between nitrogen and carbon indicates the fact that nitrogen comes primarily from organic material (as opposed to inorganic or mineral sources). Therefore, nitrogen is expected to maintain a fairly constant proportionality with organic carbon content depending on the nature of the organic source. Molar ratios of organic carbon to nitrogen (C_{org}/N) range from 6.16 to 9.00. These ratios fall within the expected C_{org}/N (= 6.6) for fairly fresh organic matter derived from primary production within the reservoir (i.e., algae and plankton, see Table XVI) (Redfield and others, 1963; Kinzig and Socolow, 1994, Wetzel, 1983). Generally, high C_{org}/N values reflect a lot of cellulose type carbon, found in senescent leaf debris and secondary woody tissue (primarily non-reactive organic material), or organic matter that has undergone considerable decomposition resulting in loss of nitrogen. The highest C_{org}/N value was obtained from core 73-1248 which was collected at the head of the reservoir. Low C_{org}/N ratios, with values approaching those for algae and plankton, are found in the central part of the reservoir, suggesting one or two explanations. 1) Woody debris is not reaching the central portion of the reservoir, and/or 2) organic material within the central areas of the reservoir is entirely from autochthonous sources (derived from primary production -algae, bacterial, etc.), and is accumulating faster than it can decompose.

Carbon, Nitrogen, and Phosphorus Biogenic Ratios			
C/N	**C/P**	**N/P**	**Reference**
16	106	6.06	Marine plankton (Redfield and others, 1963)
15.48	103.16	6.67	Dried algae (Wetzel, 1983)

Table XVI. Molar ratios of organic carbon to nitrogen and phosphorus based on chemical composition of various plankton.

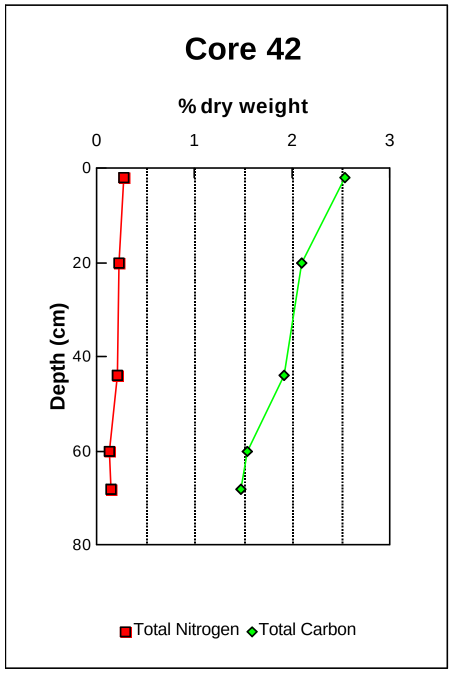

Figure 22. Downcore profiles of Nitrogen and Carbon in Core 42. Depth is in centimeters from the water and sediment interface.

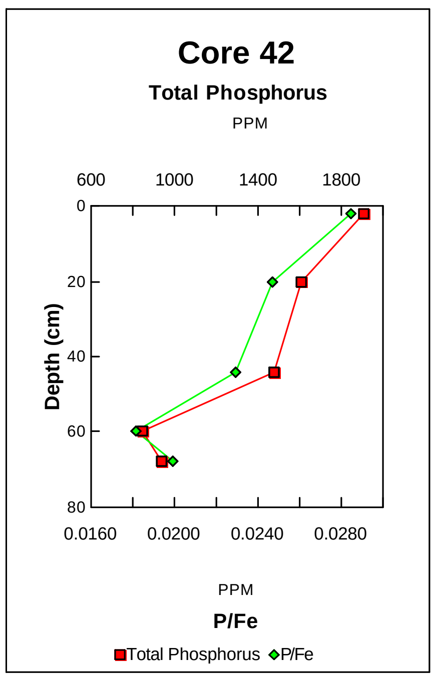

Figure 23. Downcore profiles of phosphorous and phosphorous/iron ratios in Core 42. Depth is in centimeters from the water and sediment interface.

Phosphorus

Total phosphorus contents, measured in the upper 6 to 8 cm of the sediments in Loch Raven Reservoir, averaged 1646 ppm, ranging from 1160 ppm to 1903 ppm. The phosphorus values are within the range of those obtained for sediments in other fresh water reservoirs (Callender and others, 1989; Lathrop and others, 1989; Ocean Surveys, Inc., 1997;Van Metre and Callender, 1997). Highest phosphorus contents were measured in core 42 collected in the middle of Loch Raven Reservoir, and core 35 collected in Long Quarter Branch. The lowest value was obtained from core 73 which was collected at the northern end of the reservoir. In general, total phosphorus was higher in the main portions of the reservoir toward the dam. Total phosphorus decreases with depth in the sediment column (Figure 23). In core 42, the phosphorus content is highest at the top of the core (1904 ppm), dropping to 848 ppm at 60 cm below the sediment surface. This decrease is due to several factors. The oxidized zone at the sediment surface is an efficient trap for phosphate, binding phosphate migrating from the lower sediments and from the overlying water column. The bottom of the core consisted of coarser sediments (*i.e*. less clay) compared to the top.

There is a moderately strong correlation between total phosphorus and clay. (r = 0.75). Phosphorus is strongly correlated with metals: Cr, Cu, Fe, Mn and Ni (r values of 0.92, 0.79, 0.93, 0.85 and 0.78, respectively) (Appendix E). Typically, most of the phosphorus in fresh water sediments is inorganic, in the form of apatite derived from the watershed, and as phosphate sorbed onto clays and in ferric hydroxides, where phosphate (PO_4^{-2}) tends to co-precipitate with iron, manganese, and carbonates. (Wetzel, 1983). The strong correlations present support the association of phosphorus with clay minerals or metal complexes.

Molar ratios of organic carbon to phosphorus (C_{org}/P) range from 4.3 to 8.9. The lowest C_{org}/P value was obtained from core 73 which was collected at the head of the reservoir. These ratios are well below the expected C_{org}/P (= 106) for autochthonous organic matter (*i.e.*, algae and plankton, see Table XVI) (Redfield and others, 1963; Kinzig and Socolow, 1994; Wetzel, 1983). The very low C_{org}/P values indicate that phosphorus is accumulating in the sediments. Lakes and reservoirs serve as natural sinks for phosphorus. Within the Loch Raven watershed, mineral phosphorus, derived from the underlying metamorphic rock, is introduced into the reservoir though run-off and shoreline erosion. Additional phosphorus is introduced from agricultural and residential land use, through fertilizers and septic seepage. Due to the high iron content, the sediments in Loch Raven have an enormous capacity to bind and retain phosphorus. Depending on the available Ca^{+2}, sediment phosphates undergo mineralization processes forming apatite. Phosphorus in the form of apatite, or absorbed onto clay, tends to be less labile. Due to sedimentation rates greater than one centimeter per year, the phosphorus is essentially rendered unavailable as the sediments are quickly buried.

Sulfur

Loch Raven reservoir sediments contains very little sulfur. Values range from BDL (below detection limit) to 0.15% by weight. Low sulfur contents are common in fresh water regimes. The sources of sulfur are plant material, minerals, and atmospheric loading of SO_4^{-2}. With the exception of the atmospheric source, sulfur from the other sources are limited within the Loch Raven reservoir watershed. Thus, bacterial mediated sulfur reduction process is not a significant process because of the limited sources of sulfate. In addition, based on visual examination of the sediments, the near surface environment is fairly aerobic, and any reduced sulfur species would be very unstable.

Metals

Results of the metal analyses for the Loch Raven sediments are presented in Appendix C, Table XXVIII. Concentration for iron (Fe) and manganese (Mn) generally are several magnitudes higher than the trace metals (Cr, Cu, Ni, Pb, and Zn). Reported concentrations for cadmium (Cd) are very low, with most samples yielding values below the detection limit of the analytical technique.

Metal concentrations are difficult to assess or compare with each other due to subtle differences in textural characteristics of the sediments. Geochemical studies have shown that metals are strongly associated with finer grain sediments. Although the sediments collected in Loch Raven are primarily clays and silty clays, the relative sand, silt, and clay components of the sediment vary. Silt content in the surficial sediments ranges from 17.4% (Core 42) to 58% (Core 73). Correlation analyses reveal strong to moderately strong inverse relationships ($r > 0.7$) between several metals (Cr, Cu, Fe, and Zn) and silt (Appendix E). Therefore, differences in metal contents may be due, in part, to texture.

There is significantly strong correlation between the metals themselves. The highest correlations are between Fe and Cr, Cu, Mn and Ni ($r = 0.90, 0.92, 0.80, 0.85$, respectively), between Cu and Ni ($r = 0.88$) and between Pb and Zn ($r = 0.93$). The high correlation between Pb and Zn is due to the fact that both metals come from anthropogenic sources (see discussion of Enrichment Factors).

Enrichment Factors

To reduce the effect of grain size, metal concentrations may be discussed in terms of enrichment factors (EF). The use of enrichment factors also allows for comparisons of sediments from different environments and the comparisons of sediments whose trace metal contents were obtained by different analytical techniques (Cantillo, 1982; Hill and others, 1990; Sinex and Helz, 1981).

Enrichment factor is defined as:

$$EF_{(X)} = \frac{(X/Fe)_{sample}}{(X/Fe)_{reference}} \qquad \textbf{(6)}$$

where: $\boldsymbol{EF_{(x)}}$ is the enrichment factor for the metal X;
$\boldsymbol{X/Fe_{(sample)}}$ is the ratio of the concentrations of metal X to Fe in the sample; and
$\boldsymbol{X/Fe_{(reference)}}$ is the ratio of the concentrations of metal X to Fe in a reference material, such as an average crustal rock.

Fe is chosen as the element for normalizing because anthropogenic sources for Fe are small compared to natural sources (Helz, 1976). The reference material used is Taylor's (1964) average continental crust which is suitable for the bottom sediments found in Loch Raven Reservoir given the surrounding Piedmont geology of the region. Enrichment factors referenced to this material will be useful as a relative indicator allowing comparison with other fresh water reservoirs and lakes.

Enrichment factors for the seven metals were calculated for the top sediments (2-8 cm) in each core and for all sediments sampled from core 42-1750. The enrichment factors are presented in Table XVII . Loch Raven sediments show no enrichment in Cu, Ni, Mn or Cd with respect to Taylor’s average crustal rock. However, they are enriched in Pb, Zn, and Cr. Overall, the EF values for Loch Raven Reservoir sediments are similar or lower than those obtained from other reservoirs (Table XVIII). The slightly elevated values of Cr is expected as Cr is naturally abundant within the drainage area of the reservoir. The source of Cr is primarily chromite which is found as an accessory mineral in ultrabasic igneous rocks and in serpentinites derived from them. The natural abundance of this mineral explains the spatial consistency and elevated EF values when compared to Taylor’s average crustal rock. Two metals, Pb and Zn, are consistently high in all reservoirs listed in Table XVIII. The highest Pb and Zn values were obtained from cores collected in Long Quarter Branch (cores 27, and 35) and near the dam (core 63). Both of these metals have a number of important urban and industrial uses, and both metals have significant atmospheric components.

Calculated Enrichment Factors								
Core	**Depth Interval (cm)**	**Cd**	**Cr**	**Cu**	**Mn**	**Ni**	**Pb**	**Zn**
27	2 - 6	0.28	1.75	0.85	1.09	0.83	11.49	4.07
50	2 - 6	BDL	1.52	0.87	1.31	0.83	2.49	2.49
57	2 - 6	BDL	1.59	0.85	1.28	0.83	3.50	2.71
63	4 - 8	BDL	1.58	0.82	1.23	0.88	4.46	2.70
35	4 - 8	BDL	1.66	0.81	1.46	0.84	5.94	3.22
73	2 - 6	BDL	1.64	0.92	1.15	0.90	2.37	2.64
92	2 - 6	BDL	1.57	0.89	1.23	0.92	2.40	2.55
96	2 - 6	BDL	1.65	0.83	1.31	0.96	2.14	2.63
42	2 - 6	BDL	1.65	0.81	1.19	0.79	4.33	2.79
42	20 - 24	20.23	1.62	0.90	1.46	0.81	3.09	3.49
42	44 - 48	BDL	1.57	0.80	1.86	0.79	1.86	1.99
42	60 - 64	BDL	1.63	0.83	1.46	0.70	1.22	2.03
42	68 - 72	BDL	1.58	0.84	1.34	0.66	2.28	2.00

Table XVII. Calculated enrichment factors for the metals indicated. Enrichment factors were calculated using equation 3, normalizing to the iron content. Taylor’s (1964) average crustal rock is used as the reference material.

Comparison of Average Enrichment Factors								
Reservoir	**Cd**	**Cr**	**Cu**	**Mn**	**Ni**	**Pb**	**Zn**	***N***
Loch Raven (This Study)	< 1	2	1	1	1	4	3	*9*
Tridelphia Reservoir (Ocean Survey, 1997)	---	1	1	1	1	5	3	*3*
Wisconsin Lakes (Lathrop and others, 1989)	64	1	2	2	1	20	6	*91*
White Rock Lake Reservoir, Tx (Van Metre and Callender, 1997)	2	2	1	2	1	4	4	*1*
Pueblo Reservoir, Co (Callender and others, 1988)	15	---	1	1	1	4	8	*3*

Table XVIII. Comparisons of average enrichment factors in various fresh water reservoirs and lakes. Enrichment factors are relative to Taylor's (1964) average crustal rock. *N* is the number of samples used to obtain the average factors. For this study, only the sediments from the top of the cores were used to calculate average EFs.

Plots of EF for the metals versus depth in sediment column show variations in metal enrichment over time (Figure 24). For Cr, Cu, Mn, and Ni, EF values show very little or no variation with depth. There has been no increased contribution of these metals into the reservoir. However, EF values for Pb and Zn show considerable variation through time. EF for Zn varied from 1.99 to 3.49 and EF for Pb varied from 1.22 to 4.33. These increases reflect changes in land use within the reservoir, with a shift from predominately forest and agriculture to urban areas. Additionally, changes in EF for Pb reflect increased use of leaded gasoline between the 1950's and 1975.

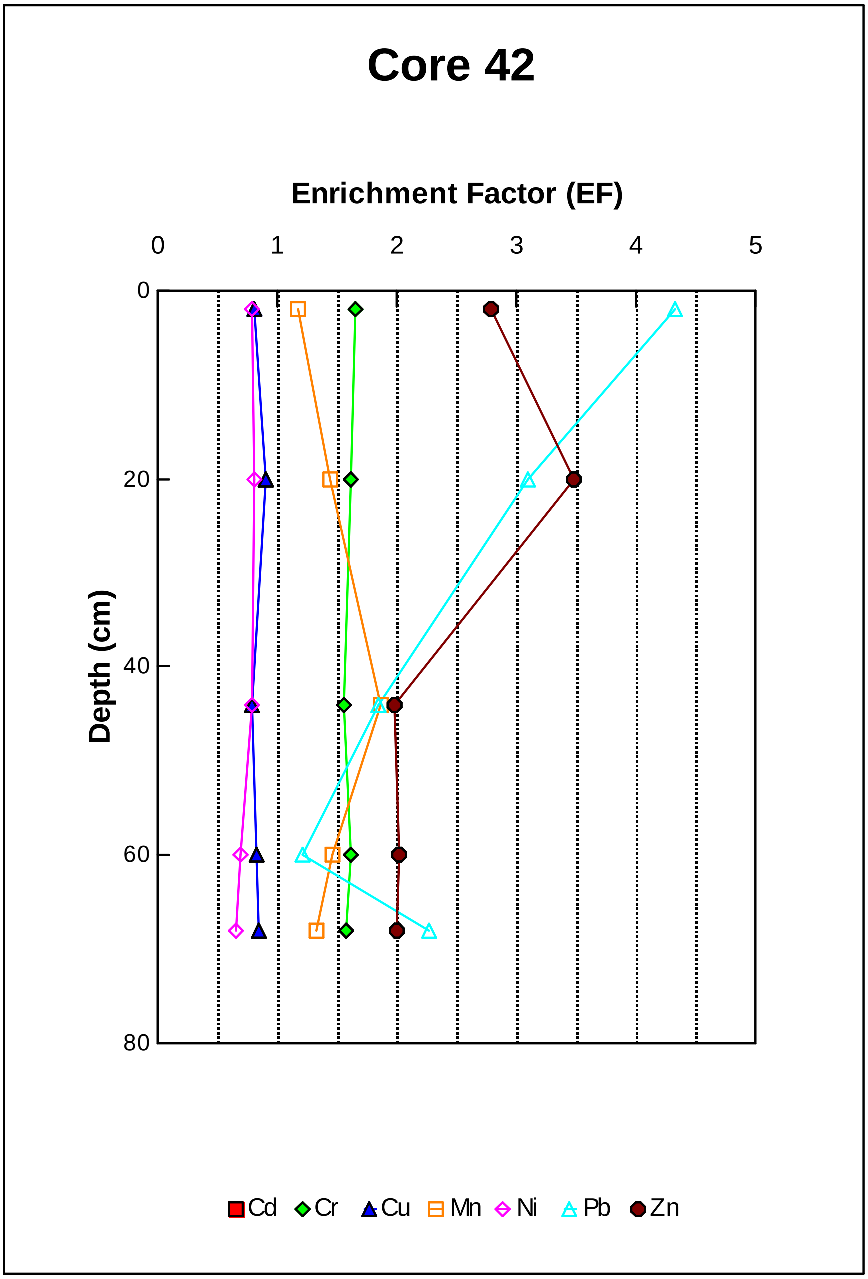

Figure 24. Downcore profile of Enrichment Factors in Core 42. Depth is in centimeters from the water and sediment interface.

CONCLUSIONS

Bathymetry

The current storage capacities of Loch Raven and Prettyboy reservoirs are 19.1 billion gallons [72.3 million cubic meters] and 18.4 billion gallons [69.7 million cubic meters] respectively. The bathymetric datasets from which these capacities have been calculated for both reservoirs are complete and uniformly distributed and will provide a solid base for future comparisons.

Sediment Accretion

Radiometric core dating, physical properties of the cores, historical volume computations, and sub-bottom seismic-reflection data all confirmed accretion rates in the range of 1-2 centimeters per year or a 0.13 percent decrease in storage capacity per year for Loch Raven reservoir. Based solely upon historical comparisons, Prettyboy reservoir has a 0.12 percent decrease in storage capacity per year. These rates are approximately half of what is seen nationally.

Changes in short-term sedimentation rates over the past several decades could not be resolved. The determination of short-term sedimentation rates is a problem which is facing many water supply agencies. This problem is mostly caused by the changes in technology that do not facilitate accurate comparisons to historical data. Current scientific thinking is to perform smaller surveys on selected parts of reservoirs to accurately gauge short-term sediment rates (Dunbar et al., 1999; Morris, 1998).

There is some concern for a future increase in this sediment rate due to the large amounts of sediment that has accumulated in the upper streambeds and pools particularly in Loch Raven Reservoir. Currently the upper headwaters of the reservoir and the pools at Merryman's Mill road and Paper Mill road are heavily silted to a point that navigation with a boat is impossible. These areas have historically acted as a sink for sediments, and some were constructed for that purpose. These areas have reached a sediment balance, and they will no longer act as a sediment sink; consequently, sediment is being transported further out into the reservoir.

Sediment Chemistry

Results of the chemical analyses of the reservoir sediments provide clues to chemical processes and nutrient cycling within the reservoir. Sediments contain 2 to 3% total carbon, an amount not considered high for reservoir sediments. Over 80% of the total carbon is organic. Based on C:N ratios, surficial sediment are not depleted of nitrogen, suggesting that the organic carbon is from primary productivity, and is fairly fresh, not decomposed. One factor that may contribute to the slow decomposition of organic matter is the sedimentation rate. Another explanation may be that some of the nitrogen is not organic in nature, but from anthropogenic sources such as fertilizers, or may be in a form not available for biotic utilization.

Like most lakes and reservoirs, Loch Raven Reservoir serves as a sink for phosphorus.

The phosphorus comes from natural sources such as minerals derived from the underlying metamorphic rock and from anthropogenic sources such as fertilizers and sewage seepage. Unlike nitrogen, some of which is lost from the reservoir sediments to the atmosphere through denitrification processes, phosphorus has no gaseous state and, thereby, eventually ends up in the sediments. A small portion of the phosphorus entering the system may be lost over the dam or in drinking water withdrawl. There is seasonal exchange of phosphorus between the sediment and overlying water column, the direction of that exchange (flux) depends on the ability of the sediment to retain the phosphorus, the conditions of the overlying water column, and the level of the biota within the sediments affecting biochemical processes. In most lakes, there is a net movement of phosphorus into the sediments (Wetzel, 1983). The cores collected for this project were taken in the late spring when bottom conditions were oxic and phosphorus levels in the upper sediment column were probably at a peak. It is not known at this time the amount of phosphorus exchange, nor what form the phosphorus takes in the sediments. High iron contents in the sediments and high correlation between phosphorus and Fe suggests that much of the phosphorus is bound to iron compounds or sorbed to clay minerals, and therefore, not readily available.

Elemental data show that the reservoir sediments are not enriched in Cd, Cu, Mn or Ni. A slightly enriched level of Cr was found; however, this is expected because the geology of the watershed is naturally enriched with chromite. The sediments are enriched in Pb and Zn which is not unexpected since these two elements are widely used in human activity. These two elements show an increase over time which may be related to an increase in urbanization of the area surrounding Loch Raven Reservoir.

Elevated levels of Pb and Zn as well as higher carbon contents were measured in sediments from two cores, both collected in Long Quarter Branch. The elevated levels may be related to specific land use in this sub-watershed area.

Recommendations for Future Work

To yield short-term sedimentation rates, additional bathymetric surveys need to be performed. It is suggested that specific areas be selected and surveyed at regular intervals of five years and after significant storm events. These smaller surveys will be able to assess current short-term sedimentation rates within the sub-watershed basins. This sampling strategy will allow a further analysis of the accretion rates with similar studies conducted nationwide.

Only very general observations could be made concerning sediment chemistry due to the limited number of samples analyzed in this study. More detailed sampling of both Loch Raven and Prettyboy reservoir would provide additional information on the physical and chemical character of the bottom sediments, and further delineate the effects of localized land use on the bottom sediment quality within the reservoir. Sampling should include some seasonal collection to quantify the extent of the phosphorus exchange between the sediments and overlying water column. Sediments should also be analyzed for organic compounds that may affect the quality of the raw water supply.

An analysis of the river section between Prettyboy dam and the crossing of Merryman's

Mill Road should be performed. Even though this area was outside the extent of this survey, the data indicated that a large amount of sediment is stored in this region. This sediment most likely has recorded changes in sedimentation within the watershed with much greater resolution than the cores collected within the reservoir. The accumulated sediment thickness potentially exceeds thirty-five feet in this area. A sediment core collected in this area could document historical changes within that drainage basin. Radio-nuclide dating would not be effective on those sediments due to the reduction in concentration of Radium from the elevated accretion rates. An alternative form of dating, such as pollen dating, should be performed along with sediment and chemical analyses along the length of the sediment core to document historical changes of the watershed.

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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 both Loch Raven and Prettyboy reservoirs. 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 the City of Baltimore report were specifically identified and minimized, as outlined below.

Calibration of the equipment was conducted several times throughout the data collection process. The GPS equipment was field checked every day against known horizontal control points. The echosounder was also checked against known depths to reduce errors. The echosounder was calibrated in the reservoirs throughout the entire range of water depths measured. The data collected and the regression of the calibration data is located in the spreadsheets contained in the CD-ROM set. 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 derived from the calibrations conducted in the field. The calibration equations for the data collection periods are located in Table XIX.

Calibration Equations for Echosounder			
Data Collection site and Timeframe	**Number of Observations**	**Equation y=Adjusted Depth x=Measured Depth**	**Correlation Coefficient (R^2)**
Loch Raven October 13 1997	13	y=0.99543x+0.083	0.9998
Loch Raven June 16 1998	14	y=1.003142x+0.9	0.999946
Prettyboy June 29 1998	17	y=0.9854x + 0.9	0.999866
Pretyboy December 4 1998	14	y=0.962117x + 0.9	0.999265

Table XIX. Calibration curves for the echosounder utilized in these studies.

Surveying was halted during times when GPS horizontal accuracy was affected. During post-processing the data was filtered on the following criteria to assist in reducing errors.

A) Number of satellites must be greater than or equal to 6.
B) PDOP value must be less than or equal to 4.
C) Resolved Horizontal accuracy must be less than or equal to one meter.
D) Resolved Vertical measurement must be less than or equal to 1.5 meters of known value.

Data points that did not meet these criteria were eliminated from the dataset.

The City of Baltimore recorded the water level heights of the reservoirs to a hundredth of a foot. For daily pool level adjustments, the readings conducted at 8am, noon, and 4 pm were averaged to obtain the adjustment for that day. During periods of low water, the measurements from the City of Baltimore were compared against a measured value on the dam face, and they were found to be in agreement. The recorded adjustments and raw data are in Appendix B, Table XXV.

Following the adjustments to depth and the removal of poor quality horizontal data, the data was further analyzed at the intersection of the tie-in lines. On each survey, tie-in lines were run perpendicular to the established transects. These intersections were visually identified and the surrounding data was analyzed for consistency and accuracy. Twenty five intersections were observed in the Loch Raven dataset, and thirty-three intersections were observed in the Prettyboy dataset. In all cases, 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 data of 1997, 1998, and 1913 needed to be gridded and modeled into three dimensional surfaces. The programs ArcInfo and Surfer can utilize a number of different methods to perform this analysis. Several methods including Kriging, Triangular-Irregular Network (TIN), Hutchinson's finite-difference, and Inverse Distance were computed and analyzed for proper fitting of the data. Grid resolutions of 50, 15, 10, 5, and 3 meters were also utilized in developing the final models.

The validity of the models was analyzed using a residual method. After the model was generated, it was compared to the original data set. The amount that the actual data differed from the model at that location is the residual. Residuals were calculated at all measured data points and a root mean square error analysis was performed.

Residual Root-Mean-Square Analysis of Computed Surfaces		
Surface	**Program**	**Residual RMS (feet)**
Loch Raven – 1913	ArcInfo	0.98
Loch Raven – 1997	ArcInfo	0.16
Loch Raven – 1997	Surfer	0.12
Prettyboy – 1998	ArcInfo	1.64
Prettyboy – 1998	Surfer	0.41

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

The residuals presented in Table XX represent those of the final surfaces utilized in the volumetric analyses. The higher residuals in Prettyboy reservoir were expected due to the high slope and the high degree of channeling within the reservoir. The elevated residual in the 1913

Loch Raven map can be attributed to the fact that the dataset was derived from a map of continuous contours rather than numerous discrete data points.

Sediment Analyses

Textural Analyses

The techniques used to determine sediment grain size are based on traditional analytical methods developed for sedimentology labs, and include some analytical error. For example, results can be affected by the 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 a 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.

The criteria for each of the internal checks are as follows:

1) Calculated sand, silt, clay and gravel (when present) percentages and Shepard's classification of the sediments are compared to the visual field and lab descriptions. If the results indicate an entirely different sample than what was described when collected, then the sample is reanalyzed.

2) Percentages are compared to calculated water contents. Table XXI lists the expected ranges of water content for each sediment type based on sediments collected in the coastal bays. This criteria is most applicable to surficial sediments. Sediments sampled from cores, particularly those taken at depths below the sediment surface, will have less water due to compaction. Nevertheless, the water content is useful in detecting obvious discrepancies due to mislabeling.

3) Sample loss (% dry weight) during cleaning is calculated for each sample. The calculated water content, which is usually measured shortly after the sample is collected, is used to determine weight loss. The degree of weight loss during the cleaning process is related to sediment type (grain size) as well as the organic and/or carbonate content of the sediment. Organic rich, fine grained sediments (*i.e.*, silty clay and clayey silt) may lose up to 30% dry weight during the cleaning process. Sand, which is fairly clean, usually yields the smallest weight loss, and often shows a negative weight loss due to errors inherent in water content determinations.

Water Content QA/ QC				
Sediment Type	**Water content (% wet weight)**		**Weight loss (% dry weight)**	
	Mean	**Range**	**Mean**	**Range**
SAND	22	17 - 27	1	-4 - 6
SILTY SAND	39	31 - 47	7	2 - 12
CLAYEY SAND	47	41 - 53	3	0 -6
SANDY SILT	48	42 - 54	13	5 - 21
CLAYEY SILT	60	53 - 67	20	13 - 27
SILTY CLAY	70	67 - 73	28	23 - 33
SAND SILT CLAY	56	49 - 63	13	2 - 24

Table XXI . Mean and range of water contents and calculated weight loss after cleaning for each sediment type (Shepard's Classification) based on sediments collected in Maryland's coastal bays. Means are rounded to nearest whole percentage. Range values are based on standard deviation from the mean.

Nitrogen, Carbon and Sulfur Analyses

As part of the QA/QC protocol, several standard reference materials (SRM) are analyzed every 6 to 7 samples as unknowns. Table XXII presents the comparisons of the MGS results and the certified values for total carbon, nitrogen and sulfur contents for the SRMs. Detection limit for this method is 0.01% for nitrogen, carbon and sulfur. There is good agreement between the SRM values and MGS's results for nitrogen and carbon. Average recoveries were greater than 95 % of certified values both carbon and nitrogen. Recoveries for sulfur were less than 80% for the Buffalo River and Canadian SRM (PACS-1), but were near 100% for the Estuarine SRM. The low recovery for the Buffalo River SRM (45%) is attributed to the relatively low amounts of sulfur in the SRM (<0.4%).

Elemental Analyses

For elemental analyses, quality control was maintained using the method of bracketing standards (Van Loon, 1980). Blanks were run once each hour. Replicates of every tenth sample were run. A set of reference materials (NIST #1646a, NIST #2704 and PACS-1 or PACS-2) was analyzed every hour. Results of the analyses of the four standard reference materials are compared to the certified values in Table XXIII.

The MGS's results indicate better than 90% recovery for most of the elements and better than 80% for all elements except Cu, Mn, and Pb. The lower recovery values for Mn (PAC) may be due to incomplete digestion during sample preparation or a persistent matrix problem during analysis. The low recoveries for Cu (NIST) and Pb (NIST) are attributed to the low concentrations of those elements in the NIST SRM.

Nitrogen, Carbon, Sulfer-- Standard Reference Material (SRM) Analyses									
Element	Certified Values			MGS Results					
	BR*	NIST*	PAC*	BR*	% Recovery	NIST*	% Recovery	PAC*	% Recovery
Nitrogen (%)	0.19[2]	0.18[1]	0.26[2]	0.19 ±0.00	97.4	0.18 ±0.0	98.3	0.27 ±0.01	102.8
Carbon (%)	3.35	1.72	3.69	3.31 ±0.05	98.8	1.66 ±0.03	96.6	3.65 ±0.01	98.9
Sulfur (%)	0.36	0.96[1]	1.32	0.16 ±0.01	45.3	1.00 ±0.0	103.8	1.01 ±0.04	76.3

*BR = NIST-SRM #2704 - Buffalo River Sediment
*NIST = NIST SRM #1646 - Estuarine Sediment
*PAC= National Research Council of Canada PACS-1 - Marine Sediment
[1] 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] The value of nitrogen was obtained from repeated analyses in-house.

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

Elements-- Standard Reference Material (SRM) Analyses									
Element	Certified Values			MGS Results					
	BR*	NIST*	PAC*	BR*	%Recovery	NIST*	%Recovery	PAC*	%Recovery
Cd (μg/g)	3.45 ±0.22	0.148 ±0.007	2.38 ±0.2	3.31 ±0.20	96.1	-	-	8.71 ±0.13	366.6
Cr (μg/g)	135 ±5	40.9 ±1.9	113 ±8	159.3 ±7.1	118.0	54.7 ±0.9	133.6	130.6 ±1.2	115.6
Cu (μg/g)	98.6 ±5	10.01 ±0.34	452 ±16	103.8 ±7.8	105.3	6.6 ±0.2	65.4	465 ±3.8	102.9
Fe (%)	4.11 ±0.1	2.008 ±0.039	4.87 ±0.12	3.76 ±0.1	91.4	1.90 ±0.02	94.8	4.19 ±0.03	86.0
Mn (μg/g)	555 ±19	234.5 ±2.8	470 ±12	538 ±10	96.9	193 ±3	82.2	344 ±6	73.2
Ni (μg/g)	44.1 ±3	23 NC	44.1 ±2	36.9 ±3.7	83.7	23.5 ±4.2	102.2	36.9 ±1.8	83.7
P (μg/g)	998 ±28	270 ±10	1017 ±79	944 ±25	94.6	282 ±2	104.6	1003 ±27	98.7
Pb (μg/g)	161 ±17	11.7 ±1.2	404 ±20	153.6 ±4.2	95.4	7.0 ±3.7	59.5	406.9 ±5.5	100.7
Zn (μg/g)	438 ±12	48.9 ±4.6	824 ±22	437 ±6.1	99.9	42.6 ±0.2	87.1	829 ±17.5	100.7

*BR = NIST-SRM #2704 - Buffalo River Sediment
*NIST = NIST SRM #1646a - Estuarine Sediment
*PAC= National Research Council of Canada PACS-1 - Marine Sediment

Table XXIII. Results of elemental analyses of standard reference materials compared to the certified values for elemental analyses of the surficial sediments.

Detection Limits

Detection limits for the ICP are determined by running a calibration blank (diluted aqua regia) as an unknown for each method. The ICP is set to sample the blank four to seven times for each element, reporting the mean and standard deviation for the run. The ideal detection limit (IDL) is calculated as three times the standard deviation (3s) and represents the theoretical threshold of detection. Three times the IDL (3 x 3s, or 9s) represents the actual instrument detection limit known as the method detection limit (MDL). The MDL represents a more quantifiable level for each element and is variable depending on wavelength and chosen method parameters (Michael O'Connor, ICP Technician for Thermo Jarrel Ash, pers. comm. July, 1999). Detection limits are determined for each new calibration blank.

Detection Limits for Elements		
Metal	**IDL (μg/g)**	**MDL (μg/g)**
Cd	0.88	2.63
Cr	0.55	1.66
Cu	0.65	1.94
Fe	0.00	0.00
Mn	0.36	1.08
Ni	5.36	16.08
P	13	40
Pb	7.72	23.15
Zn	0.47	1.41

Table XXIV . Detection limits for the elements based on the methods used in this study. All values are in μg/g except for Fe which is given in %.

APPENDIX B: Mean Pool Level Adjustments

Mean Pool Level Recordings and Adjustments					
Mean Sea Level (Feet)					
	Time (Local)			**Daily**	**Depth Adjustment**
Date	**0800**	**1200**	**1600**	**Average**	**Feet**
Loch Raven Reservoir					
17 Oct 97	234.73	234.72	234.72	234.72	5.28
20 Oct 97	234.91	234.89	234.90	234.90	5.10
21 Oct 97	234.89	234.89	234.89	234.89	5.11
22 Oct 97	234.89	234.89	234.86	234.88	5.12
23 Oct 97	234.86	234.85	234.85	234.85	5.15
24 Oct 97	234.84	234.83	234.83	234.83	5.17
4 Nov 97	234.56	235.56	235.56	235.56	4.44
5 Nov 97	235.57	235.56	235.55	235.56	4.44
6 Nov 97	235.55	235.53	235.51	235.53	4.47
10 Nov 97	237.30	237.28	237.29	237.29	2.71
16 Jun 98	240.67	240.64	240.62	240.64	-0.64
Prettyboy Reservoir					
17 Jun 98*	521.15	521.15	520.33	520.33	-0.33
18 Jun 98	520.33	520.25	520.25	520.28	-0.28
22 Jun 98	520.25	520.07	520.07	520.13	-0.13
23 Jun 98	520.07	520.07	520.07	520.07	-0.07
24 Jun 98	520.06	520.16	520.16	520.13	-0.13
25 Jun 98	520.16	520.16	520.16	520.16	-0.16
26 Jun 98	520.10	520.16	520.06	520.11	-0.11
29 Jun 98	520.06	520.06	520.06	520.06	-0.06
4 Dec 98	509.84	509.80	509.78	509.81	10.19

Table XXV. Mean Pool Level Recordings and Adjustments

***Note:** A telephone conversation with Mr. Anthony Rossie of the City of Baltimore explained the difference recorded between 1200 and 1600 on 17 Jun 98. The recorder was adjusted due to drift on 17 Jun 98 around 1400 hours. The correct water level reading for 17 Jun 98 is 520.33 feet MSL.

APPENDIX C: Sediment Sample Data (Maryland Geological Survey)

Textural Data for Loch Raven Core Samples									
Core	**Depth (cm)**	**Water Content (%)**	**Bulk Density (g/cm^3)**	**Gravel (%)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Shepard's (1954) Classification**	**Pejrup's (1988) Classification**
27	2-6	78.29	1.16	0.00	0.00	24.37	75.63	Clay	D,II
	18-22	66.74	1.27	0.00	0.29	19.77	79.94	Clay	D,I
	46-50	45.38	1.53	0.00	0.97	50.17	48.86	Clayey-Silt	D,III
	66-70	26.02	1.88	0.03	74.15	16.58	9.24	Silty-Sand	B,III
50	2-6	76.73	1.17	0.00	0.46	38.96	60.58	Silty-Clay	D,II
	20-24	63.35	1.30	0.00	0.26	37.34	62.40	Silty-Clay	D,II
	40-44	51.42	1.44	0.00	0.07	34.51	65.42	Silty-Clay	D,II
	52-56	41.21	1.59	0.11	8.86	57.72	33.31	Clayey-Silt	D,III
	68-72	39.14	1.63	16.42	29.24	34.12	20.22	Sand-Silt-Clay	C,III
57	2-6	73.97	1.20	0.00	0.13	21.99	77.89	Clay	D,II
	20-24	50.91	1.45	0.00	2.28	58.64	39.08	Clayey-Silt	D,III
	44-48	56.39	1.38	0.00	0.07	15.32	84.62	Clay	D,I
	70-74	42.77	1.57	0.00	4.72	43.20	52.07	Silty-Clay	D,II
	80-84	43.34	1.56	0.00	6.10	61.03	32.87	Clayey-Silt	D,III
63	4-8	73.37	1.20	0.00	10.20	26.40	63.40	Silty-Clay	C,II
	24-28	58.44	1.36	0.00	1.03	27.89	71.08	Silty-Clay	D,II
	64-68	50.61	1.45	0.00	0.30	16.95	82.75	Clay	D,I
	90-94	45.28	1.53	0.00	0.07	32.11	67.81	Silty-Clay	D,II
35	4-8	72.03	1.21	0.00	0.26	29.37	70.38	Silty-Clay	D,II
	20-24	63.02	1.31	0.00	0.41	24.06	75.53	Clay	D,II
	40-44	54.98	1.40	0.00	0.14	19.52	80.34	Clay	D,I
	80-84	53.24	1.42	0.00	0.55	33.76	65.69	Silty-Clay	D,II
73	2-6	60.72	1.33	0.00	2.54	58.26	39.20	Clayey-Silt	D,III
	22-26	59.39	1.35	0.00	4.83	60.51	34.67	Clayey-Silt	D,III
	32-36	55.48	1.39	0.00	2.27	55.89	41.84	Clayey-Silt	D,III
	50-54	53.05	1.42	0.00	0.83	55.93	43.24	Clayey-Silt	D,III
	76-80	50.55	1.46	0.00	2.30	60.92	36.78	Clayey-Silt	D,III

Textural Data for Loch Raven Core Samples									
Core	**Depth (cm)**	**Water Content (%)**	**Bulk Density (g/cm^3)**	**Gravel (%)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Shepard's (1954) Classification**	**Pejrup's (1988) Classification**
92	2-6	68.30	1.25	0.00	0.00	28.36	71.64	Silty-Clay	D,II
92	28-32	54.96	1.40	0.00	0.15	21.89	77.96	Clay	D,II
	58-62	51.24	1.45	0.00	0.14	17.11	82.76	Clay	D,I
	84-88	52.41	1.43	0.00	0.06	14.46	85.48	Clay	D,I
96	2-6	71.72	1.22	0.00	0.00	23.99	76.01	Clay	D,II
	16-20	60.87	1.33	0.00	0.00	21.06	78.94	Clay	D,II
	36-40	47.84	1.49	0.00	6.66	55.03	38.31	Clayey-Silt	D,III
	66-70	51.09	1.45	0.00	0.22	11.19	88.59	Clay	D,I
	92-96	38.47	1.64	0.00	31.85	38.35	29.80	Sand-Silt-Clay	C,III
42	2-6	65.40	1.28	0.00	0.09	17.41	82.50	Clay	D,I
	20-24	62.80	1.31	0.00	0.09	19.19	80.72	Clay	D,I
	44-48	52.31	1.43	0.00	0.07	19.62	80.31	Clay	D,I
	60-64	45.52	1.53	0.00	0.65	56.38	42.97	Clayey-Silt	D,III
	68-72	44.55	1.54	0.00	0.06	47.61	52.33	Silty-Clay	D,II

Table XXVI. Textural data for Loch Raven core samples.

Nutrient Data for Loch Raven Cores

Core	Depth (cm)	Total Nitrogen (%)	Total Carbon (%)	Organic Carbon (%)	Reactive Carbon (%)	Total Sulfur (%)	Total Phosphorus (ppm)
27	2-6	0.402	3.938	3.281	2.067	0.059	1430
50	2-6	0.339	3.280	2.846	1.984	BDL*	1310
57	2-6	0.340	3.247	2.713	1.772	0.065	1841
63	4-8	0.356	3.184	2.686	1.789	0.146	1843
35	4-8	0.303	3.214	2.676	1.704	0.116	1851
73	2-6	0.237	3.004	2.487	1.751	BDL	1169
92	2-6	0.286	2.943	2.390	1.710	0.039	1672
96	2-6	0.322	3.195	2.594	1.889	0.044	1807
42	2-6	0.270	2.535	2.116	1.379	0.040	1904
42	20-24	0.224	2.096	1.607	0.996	0.057	1609
42	44-48	0.202	1.908	1.466	0.940	BDL	1477
42	60-64	0.127	1.534	1.171	0.743	BDL	848
42	68-72	0.138	1.466	1.130	0.719	BDL	940

* BDL = Below Detection Limits

Table XXVII . Nutrient contents for Loch Raven core samples analyzed by the Maryland Geological Survey.

Elemental Data for Loch Raven Cores									
Core	**Depth (cm)**	**Cd (ppm)**	**Cr (ppm)**	**Cu (ppm)**	**Fe (%)**	**Mn (ppm)**	**Ni (ppm)**	**Pb (ppm)**	**Zn (ppm)**
27	2 - 6	0.1	177.7	47.3	5.70	1045.7	62.8	145.5	288.3
50	2 - 6	BDL	155.4	49.3	5.77	1279.6	63.8	31.9	178.4
57	2 - 6	BDL	182.9	53.8	6.49	1406.0	72.1	50.4	218.5
63	4 - 8	BDL	191.4	54.7	6.83	1413.1	79.7	67.7	229.3
35	4 - 8	BDL	181.1	48.8	6.14	1511.3	68.3	80.9	245.6
73	2 - 6	BDL	148.1	45.3	5.07	980.1	56.2	24.9	164.7
92	2 - 6	BDL	172.0	53.4	6.16	1283.5	75.6	32.9	195.4
96	2 - 6	BDL	189.1	52.6	6.46	1426.9	82.8	30.6	211.3
42	2 - 6	BDL	196.7	52.8	6.69	1338.4	70.4	64.3	232.3
42	20 - 24	4.7	187.9	57.4	6.52	1600.7	70.0	44.8	282.6
42	44 - 48	BDL	179.7	50.6	6.44	2026.5	67.9	26.6	159.7
42	60 - 64	BDL	134.8	37.8	4.66	1148.7	43.7	12.6	117.6
42	68 - 72	BDL	132.4	38.9	4.71	1065.0	41.3	23.8	117.0

* BDL = Below Detection Limits

Table XXVIII. Elemental concentrations for Loch Raven core samples analyzed by the Maryland Geological Survey.

APPENDIX D: Core Dating Dataset (University of Maryland)

Percent Water Data								
Depth	**Core 27**	**Core 35**	**Core 50**	**Core 57**	**Core 63**	**Core 73**	**Core 92**	**Core 96**
0-2	81.0	76.3	78.9	75.2	70.0	65.9	68.2	72.4
2-4	79.6	73.1	76.2	75.1	69.3	61.4	68.1	71.1
4-6	78.6	72.0	76.3	73.8	72.1	59.6	68.1	69.7
6-8	76.9	71.7	73.6	67.3	70.0	59.3	67.9	69.3
8-10	76.6	71.2	72.3	63.8	70.3	57.0	65.9	66.8
10-12	73.8	69.7	69.5	60.5	66.8	55.6	64.6	66.1
12-14	71.6	69.3	66.2	60.3	66.3	56.9	61.5	62.1
14-16	68.4	65.6	65.2	53.7	66.0	62.0	62.4	60.0
16-18	65.8	65.5	64.0	52.2	60.4	57.0	58.2	60.2
18-20	66.2	66.4	61.7	51.3	52.0	56.6	57.7	55.9
20-22	68.0	65.6	62.9	49.0	51.3	57.3	52.5	55.8
22-24	66.9	62.4	62.2	50.5	50.9	56.0	52.5	56.8
24-26	64.8	63.8	64.1	48.4	50.6	59.2	53.6	55.4
26-28	62.2	61.2	62.4	47.8	61.3	58.7	55.5	52.2
28-30	62.2	61.8	60.9	45.9	73.1	58.4	55.2	48.1
30-32	63.7	60.3	58.7	53.3	49.3	58.1	53.8	47.2
32-34	61.3	61.7	53.6	55.7	52.3	55.7	52.5	48.9
34-36	59.4	60.2	56.3	57.5	18.8	54.6	50.9	48.5
36-38	57.7	59.0	52.5	58.5	84.6	53.9	50.1	41.9
38-40	56.5	58.4	53.0	61.1	55.3	55.8	48.6	60.9
40-42	56.0	54.9	51.2	57.7	50.0	54.6	48.0	29.5
42-44	55.3	54.5	51.1	57.5	58.4	55.4	47.8	47.4
44-46	49.8	51.7	49.3	54.8	60.7	56.2	47.2	51.3
46-48	47.0	52.9	50.1	55.2	57.2	52.5	47.3	53.5
48-50	44.5	53.2	49.2	53.5	56.0	49.5	45.7	55.0
50-52	39.2	51.3	50.1	51.6	54.2	52.1	45.9	55.9
52-54	38.2	48.8	45.4	50.2	54.5	52.1	45.4	57.6
54-56	39.0	54.4	41.2	51.5	55.4	51.8	47.4	56.3
56-58	40.9	55.2	35.2	51.9	53.8	50.7	48.3	53.2
58-60	44.8	57.7	31.8	50.7	51.2	50.6	48.5	54.3
60-62	45.4	58.6	46.0	50.6	46.0	48.6	49.9	52.1
62-64	29.4	57.9	26.7	50.6	48.3		49.8	53.2
64-66	27.3	57.1	30.2	49.6	52.0	50.2	50.9	51.7
66-68	22.2	57.8	31.2	49.2	50.1	48.7	52.3	50.8
68-70	25.0	57.5	29.8	45.4	49.0	47.8	53.9	51.2
70-72	26.2	57.8	29.3	44.1	47.7	45.4		50.1
72-74	26.0	56.5	26.1	42.1	44.0	48.1	49.7	50.9
74-76	30.4	56.5	29.4	40.8	44.7	51.6	49.5	51.5
76-78	26.6	56.0		41.0	44.4	49.2	50.3	49.7
78-80	26.3	54.0	40.0	41.1	44.4	49.0	52.4	50.0
80-82	26.0	55.4		42.3	44.9	45.9	50.3	49.3
82-84	25.7	54.6		40.1	44.7		48.7	48.0
84-86		54.3		38.4	44.3		49.2	47.3
86-88		52.6			43.4		49.2	42.7
88-90		52.2			44.6		49.0	36.4
90-92		50.5			44.0		43.8	38.6
92-94					44.2			38.0
94-96								39.6
96-98								42.0

Table XXIX. Percent water of sediments collected in Loch Raven reservoir cores.

^{210}Pb activity in dpm g^{-1}.								
Depth	**Core 27**	**Core 35**	**Core 50**	**Core 57**	**Core 63**	**Core 73**	**Core 92**	**Core 96**
0-2	8.54	13.16	10.63	10.01		4.65	8.54	9.52
2-4	8.53	11.37	9.44	9.76		4.57	8.53	9.64
4-6	8.25	9.50	9.45	8.20		4.33	8.25	9.88
6-8	8.19	9.24	7.82	5.82		4.44	8.19	9.00
8-10	7.88	8.43	5.92	4.18		3.81	7.88	8.60
10-12	6.86	8.36		2.13		3.76	6.86	6.97
12-14		7.55	5.67					
14-16		6.98	4.66					
16-18		6.53	4.51					
18-20		6.57	3.99	2.51		2.51		
20-22	4.06	6.46	4.31	5.38		3.69	4.06	2.04
22-24								
24-26		5.35	3.94	2.30		3.94		
26-28								
28-30								
30-32	4.03	4.56	3.03	4.71		4.66	4.03	2.30
32-34								
34-36								
36-38								
38-40								
40-42	2.38	3.78	2.45	4.54		3.96	2.38	2.47
42-44								
44-46								
46-48						3.46		
48-50								
50-52	2.32	3.17	1.92	3.59		3.48	2.32	4.90
52-54								
54-56								
56-58								
58-60								
60-62	2.97	4.45	1.19	4.17			2.97	3.56
62-64								
64-66						2.59		
66-68								
68-70								
70-72	4.02	3.93	0.69	2.30		2.11	4.02	3.57
72-74								
74-76								
76-78						2.98		
78-80			1.94	1.97				
80-82	2.99					2.61	2.99	3.29
82-84								
84-86								
86-88								
88-90								
90-92	5.68	3.70					5.68	1.70
92-94								
94-96								
96-98								2.40

Table XXX. ^{210}Pb activity in Loch Raven reservoir cores.

Total Pb in mg g^-1						
Depth	**Core 27**	**Core 35**	**Core 50**	**Core 73**	**Core 92**	**Core 96**
0-2	58.5	102.1	46.1	16.5	56.6	70.5
2-4	14.7	115.4	42.3	35.5	49.2	65.6
4-6	28.9	78.7	39.2	19.6	35.6	60.2
6-8	23.7	58.9	36.3	36.2	46.5	63.0
8-10	43.2	147.2	43.6	34.4	78.5	65.7
10-12	47.3	42.3	48.4	29.6	60.4	73.2
12-14	94.4	113.9	67.9	10.8	23.9	74.8
14-16	66.5	102.8	53.7	17.8	48.8	71.8
16-18	135.5	34.6	67.2	15.3	56.1	65.3
18-20	95.1	138.2	51.7	11.1	46.7	62.8
20-22	125.7	171.9		43.5	12.7	59.5
22-24	71.3	67.8	36.5	46.5	19.5	75.1
24-26	49.6	22.0	45.9	44.4	21.7	83.5
26-28	61.6	83.9	44.1	27.5	64.6	67.1
28-30	15.6	17.5	51.3	20.6	88.0	57.3
30-32	54.2	137.9	36.5	11.7	59.7	52.9
32-34	48.7	121.4	48.2	8.3	34.7	44.4
34-36	29.5	36.1	52.3	10.2	26.9	52.6
36-38	35.0	54.7	43.3	16.0	59.1	61.1
38-40	49.4	16.2	44.1	1.8	56.7	59.5
40-42	58.8	34.0		39.9	44.4	63.7
42-44	54.3	58.5	37.8	31.0	51.3	55.5
44-46	35.8	48.1	36.6	22.4	46.4	69.0
46-48	33.4	66.5	21.1	42.6	54.3	81.5
48-50	14.6	53.1	31.6	23.4	47.5	77.0
50-52	19.9	48.1	32.6	30.6	35.9	78.4
52-54	23.0	39.0	21.4	59.8	50.9	85.5
54-56	17.3	44.0	41.1	45.1	70.7	81.5
56-58	20.6	42.9	38.3	61.4	61.0	71.8
58-60	13.5	38.6		42.8	67.0	64.2
60-62	7.2	62.8		48.9	88.2	66.1
62-64	9.9	46.0		45.1	73.3	67.0
64-66	10.9	57.5		61.7	74.2	61.4
66-68	5.8	60.3		48.0	73.4	62.5
68-70	7.5	47.0		66.7	70.1	56.8
70-72	8.2	56.3		49.0	71.5	72.8
72-74	12.2	49.0		58.7	62.3	66.9
74-76	15.3	46.3		34.2	61.8	47.5
76-78	7.1	53.3		33.7	61.3	65.3
78-80	16.2	45.7		54.3	55.4	56.8
80-82	2.8	42.8		45.7	55.2	49.9
82-84	6.0	39.7			34.4	56.9
84-86	7.3	41.4			57.3	49.4
86-88		43.3			36.7	44.9
88-90		43.3			53.3	25.3
90-92		44.4			63.7	43.1
92-94						24.0
94-96						41.2
96-98						46.8

Table XXXI. Total Lead in Loch Raven reservoir cores.

APPENDIX E: Sediment Correlation Matrix

	H_2O	Sand	Silt	Clay	TN	TC	OC	RC	TP	TS	Cr	Cu	Fe	Mn	Ni	Pb	Zn
Sand	-0.010 (9) *0.980*	1.00															
Silt	-0.449 (9) *0.225*	0.117 (9) *0.764*	1.00														
Clay	0.423 (9) *0.257*	-0.368 (9) *0.330*	-0.967 (9) *0.000*	1.00													
TN	0.942 (9) *0.000*	0.150 (9) *0.700*	-0.464 (9) *0.209*	0.396 (9) *0.292*	1.00												
TC	0.758 (9) *0.018*	-0.028 (9) *0.943*	-0.014 (9) *0.972*	0.020 (9) *0.959*	0.819 (9) *0.007*	1.00											
OC	0.797 (9) *0.010*	0.012 (9) *0.976*	0.014 (9) *0.971*	-0.017 (9) *0.967*	0.838 (9) *0.005*	0.987 (9) *0.000*	1.00										
RC	0.687 (9) *0.041*	0.003 (9) *0.994*	0.209 (9) *0.589*	-0.197 (9) *0.612*	0.696 (9) *0.037*	0.891 (9) *0.001*	0.893 (9) *0.001*	1.00									
TP	0.111 (9) *0.777*	0.097 (9) *0.805*	-0.826 (9) *0.006*	0.749 (9) *0.020*	0.092 (9) *0.814*	-0.321 (9) 0.400	-0.357 (9) *0.346*	-0.508 (9) *0.163*	1.00								
TS	0.339 (7) *0.457*	0.786 (7) *0.036*	0.479 (7) *0.277*	-0.809 (7) *0.028*	0.301 (7) *0.512*	0.189 (7) *0.685*	0.255 (7) *0.582*	0.114 (7) *0.808*	0.258 (7) *0.576*	1.00							
Cr	0.204 (9) *0.599*	0.149 (9) *0.702*	-0.901 (9) *0.001*	0.805 (9) *0.009*	0.282 (9) *0.462*	-0.150 (9) *0.701*	-0.190 (9) *0.625*	-0.384 (9) *0.308*	0.916 (9) *0.001*	0.163 (7) *0.727*	1.00						
Cu	0.144 (9) *0.711*	0.273 (9) *0.477*	-0.704 (9) *0.034*	0.589 (9) *0.095*	0.146 (9) *0.708*	-0.367 (9) *0.331*	-0.377 (9) *0.318*	-0.346 (9) *0.362*	0.793 (9) *0.011*	0.030 (7) *0.949*	0.706 (9) *0.033*	1.00					
Fe	0.220 (9) *0.570*	0.278 (9) *0.469*	-0.835 (9) *0.005*	0.710 (9) *0.032*	0.227 (9) *0.557*	-0.310 (9) *0.416*	-0.313 (9) *0.413*	-0.406 (9) *0.279*	0.926 (9) *0.000*	0.262 (7) *0.570*	0.900 (9) *0.001*	0.918 (9) *0.001*	1.00				
Mn	0.259 (9) *0.502*	0.089 (9) *0.819*	-0.600 (9) *0.088*	0.538 (9) *0.135*	0.095 (9) *0.807*	-0.271 (9) *0.480*	-0.262 (9) *0.496*	-0.301 (9) *0.431*	0.849 (9) *0.004*	0.412 (7) *0.358*	0.647 (9) *0.060*	0.699 (9) *0.036*	0.803 (9) *0.009*	1.00			
Ni	0.194 (9) *0.617*	0.255 (9) *0.507*	-0.661 (9) *0.052*	0.554 (9) *0.122*	0.201 (9) *0.605*	-0.196 (9) *0.613*	-0.251 (9) *0.516*	-0.143 (9) *0.713*	0.782 (9) *0.013*	0.084 (7) *0.858*	0.730 (9) *0.026*	0.879 (9) *0.002*	0.850 (9) *0.004*	0.734 (9) *0.024*	1.00		

	H_2O	Sand	Silt	Clay	TN	TC	OC	RC	TP	TS	Cr	Cu	Fe	Mn	Ni	Pb	Zn
Pb	0.513 (9) *0.158*	-0.003 (9) *0.994*	-0.412 (9) *0.271*	0.386 (9) *0.304*	0.646 (9) *0.060*	0.636 (9) *0.066*	0.622 (9) *0.074*	0.258 (9) *0.503*	0.090 (9) *0.818*	0.205 (7) *0.660*	0.342 (9) *0.368*	-0.220 (9) *0.570*	0.027 (9) *0.945*	-0.163 (9) *0.675*	-0.180 (9) *0.643*	1.00	
Zn	0.526 (9) *0.146*	-0.033 (9) *0.933*	-0.670 (9) *0.048*	0.636 (9) *0.065*	0.640 (9) *0.064*	0.509 (9) *0.162*	0.473 (9) *0.199*	0.116 (9) *0.766*	0.415 (9) *0.266*	0.207 (7) *0.656*	0.629 (9) *0.069*	0.055 (9) *0.888*	0.326 (9) *0.392*	0.136 (9) *0.727*	0.131 (9) *0.737*	0.935 (9) *0.000*	1.00

Table XXXII. Correlation matrix for sediment textural data and chemical concentrations based on sediment samples collected at the top of the gravity cores from Loch Raven Reservoir. The correlations were calculated using Pearson product-moment technique (Johnson and Wichern, 1982). The top number in each cell is the correlation coefficient (*r* value) which measures the strength of the linear relationship between the variables. Shown in parentheses is the number of pairs of data values used to compute each coefficient. The number in italics is a *P-value* which tests the statistical significance of the estimated correlations. *P-values* < 0.05 indicate statistically significant non-zero correlations at the 95% confidence level. In general, the higher correlations (*i.e.*, r > 0.7) were significant; these coefficients are shaded. Abbreviations in column and row headings are: H_20 = water content; Sand = sand content (% by weight); Silt = silt content; clay = clay content; TN = total nitrogen content; TC = total carbon content; OC = organic carbon content; RC = reactive carbon content; TP = total phosphorus concentration; Cr...Zn = metal concentrations.

APPENDIX F: Detailed Analysis of Sediment Accumulation at Loch Raven Reservoir Dam

Introduction

At the request of the City of Baltimore, a study was performed to assess the degree of sediment accumulation near the water supply intake gates at Loch Raven reservoir. This request was made due to an unexplained increase in turbidity of the raw water entering the water filtration and processing plants. Given that little historical data of the area existed, current bathymetric and side-scan sonar methods were employed. Additional bathymetric data were collected using the methodology presented in this report with the exception that survey lines were run at a spacing of 25 meters within 200 meters of the dam. This increased transect density yielded a higher resolution of bathymetric data. Cross-sections of the reservoir near the dam were created and analyzed (Figure 25). Side-scan sonar data which was collected is presented in Figure 26.

Results and Discussion

The bathymetry of the area suggests that little additional sediment has accumulated adjacent to the intake gates. The first two cross sections sampled at 25 meters (cross section A) and 45 meters (cross section B) upstream of the dam show no evidence of sediment build-up (Figure 25). Both cross sections show a deeply incised river channel with steep slopes and irregular bottom surfaces. The two cross sections upstream at 75 meters (cross section C) and 115 meters (cross section D) show a smooth flat bottom possibly indicating sediment build-up at a depth of -21 meters [70 feet](Figure 25).

The side-scan sonar imagery clearly shows the bottom of the intakes which appear as white shadows forming an L-like shape (Figure 26). There appears to be some localized sediment buildup near these intakes which, in some cases, reaches the bottom of the intake screens. This is most evident in the intake screens labeled 1 and 3 in Figure 26. The localized sediment buildup volume is estimated to be 1-5 cubic meters. The intake screens labeled 2 and 4 do not appear to have any sediment build-up and it is estimated that the bottom of these screens are 0.5-1.5 meters from the surface of the toe of the dam. The toe of the dam and gatehouse can also be seen in the imagery. This toe separates the intake screens from the reservoir bottom by approximately 3.5 meters.

The side-scan imagery does not show any signs of sediment scour near the intake screens or the sediment surface at the toe of the dam. The initial hypothesis for the increase in suspended sediment in the Loch Raven source water was that it was due to sediment resuspension. This presents a conflict. If increased sediment was present in the bottom waters of Loch Raven, this material would be deposited and accumulated during periods of low water withdrawal. During times of high water withdrawal, the deposited sediment would be scoured from around the intakes producing distinct scour markings which would be evident on the side-scan sonar imagery. As this is not shown, there is most likely other factors contributing to the increase in intake water suspended sediment.

Conclusions and Recommendations

Data clearly shows that sediment is not accumulating around the dam or the gatehouse at a rate greater than the accretion rate found throughout the reservoir. The amount of localized sediment can not account for the increase in suspended sediment loads which the City of Baltimore is observing. A further analysis of the hydrodynamics around the intake screens should be conducted. By determining the water flow around the intakes and the gatehouse a better determination can be made of the source of suspended sediment in the source water.

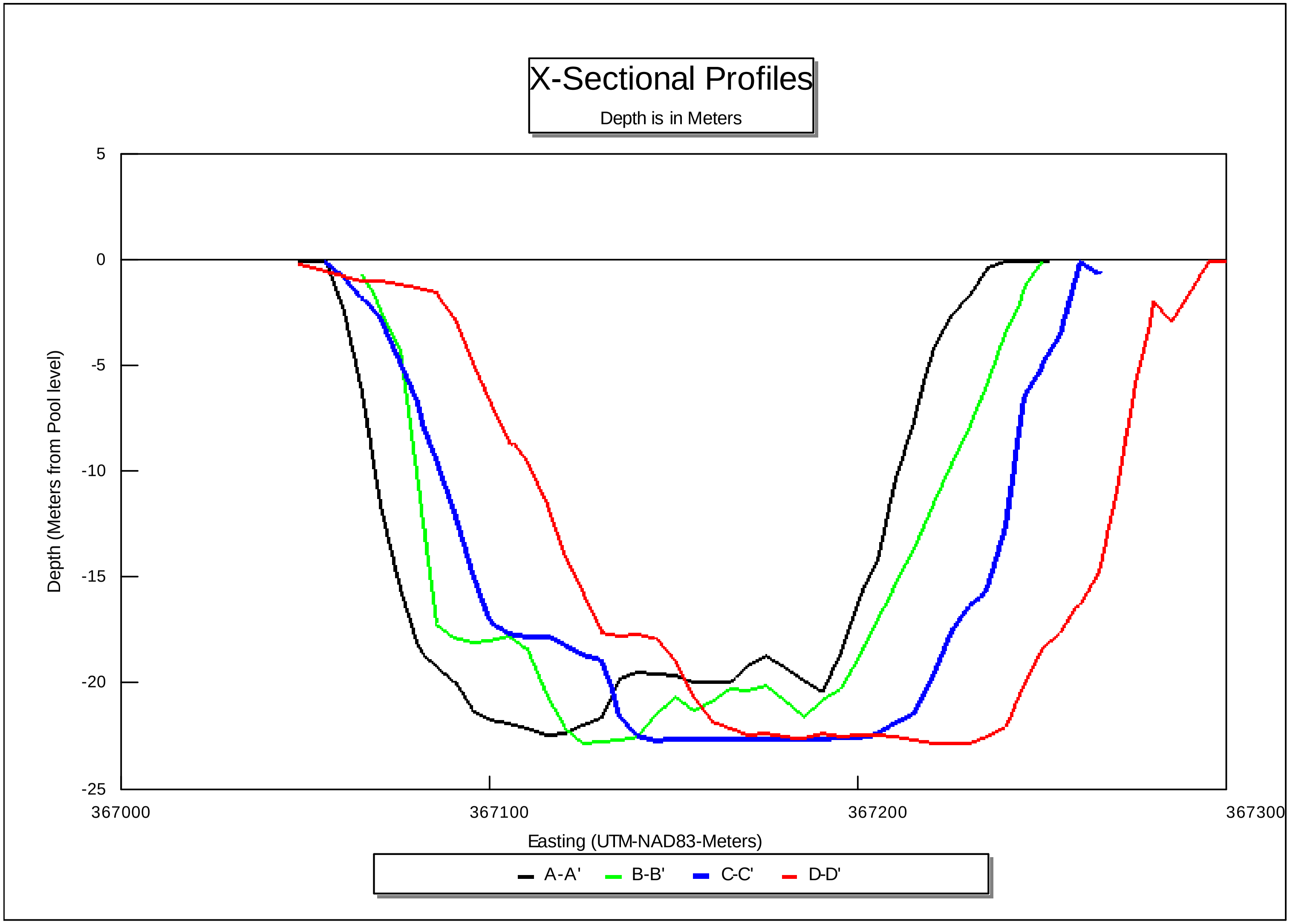

Figure 25. Cross sectional profiles of Loch Raven reservoir near Loch Raven Dam. Depth is in meters from Mean Pool Level. Horizontal Coordinate is in UTM – NAD83 – Meters. All cross section run parallel to the dam face. Cross section A is 25 meters upstream from the dam face. Cross section B is 45 meters upstream from the dam face. Cross section C is 75 meters upstream from the dam face. Cross section D is 115 meters upstream from the dam face.

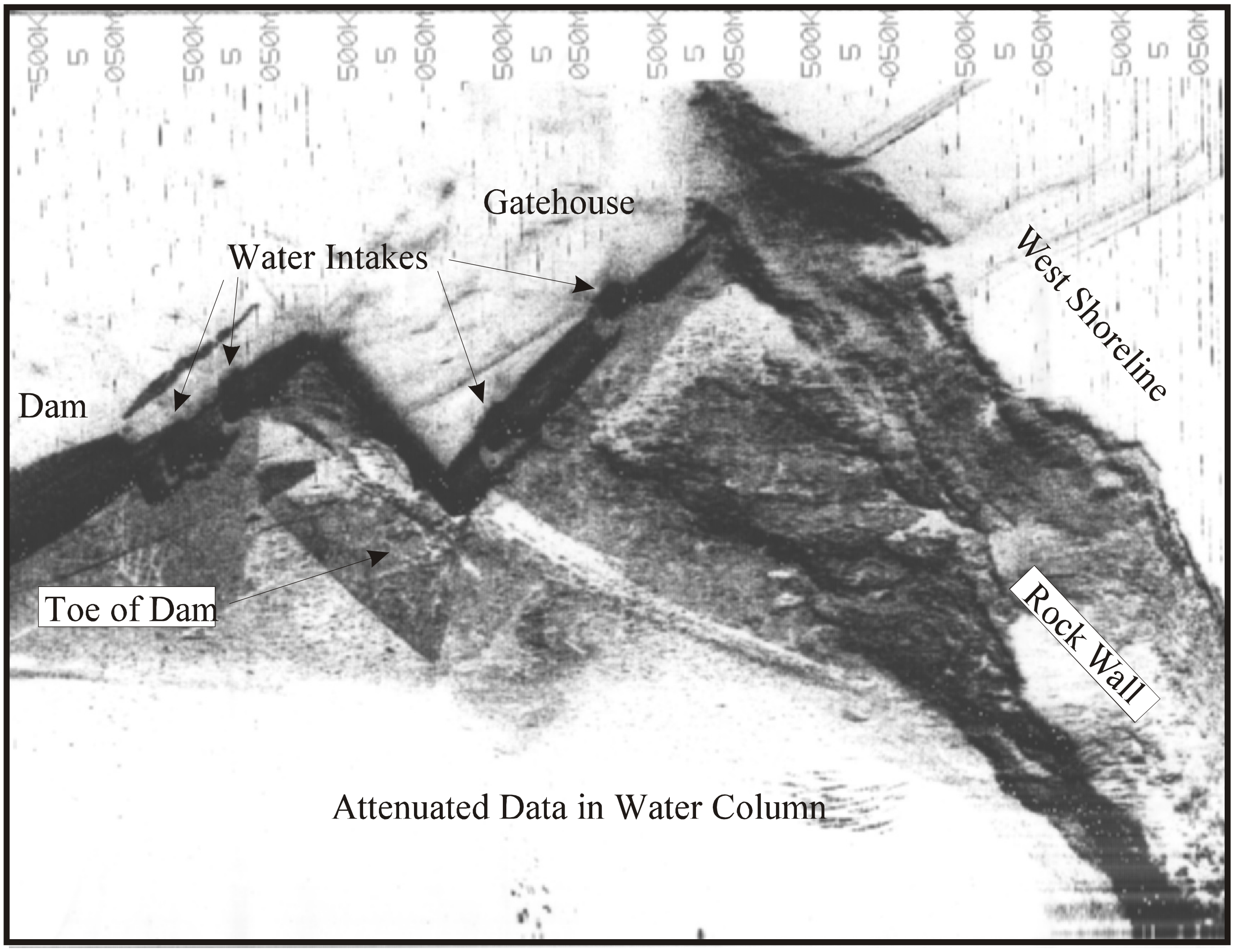

Figure 26. Side-scan image of Loch Raven Dam. The direction of travel of the sonar was from northwest to southeast. The image is oriented so that up is southwest. The image was collected with a frequency of 500KHz and a range of 50 meters.

APPENDIX G: Sub-Aquatic Vegetation Map of Loch Raven Reservoir

In the course of the fieldwork for this study, certain areas were found to be acoustically impenetrable due to the density of sub-aquatic vegetation (SAV). Sub-aquatic vegetation generates and traps oxygen and other gases in small vesicles. The acoustical data collection techniques utilized in this study were hindered due to the change in acoustical densities between the water and these gas vesicles. The areas which experienced this hindrance are presented in Figure 27.

This data is based upon visual identification by the field personnel and remote detection through the acoustical sampling equipment. This data should only be used for general purposes and reconnaissance efforts in the way of studying SAV habitat in Loch Raven reservoir. As the field party is not trained in SAV species identification, no attempts at identifying types of SAV were made.

Prettyboy reservoir did not have any areas where the density of SAV was high enough to create problems for the acoustical sampling equipment. This is most likely due to the severe changes in pool level which Prettyboy reservoir experiences.

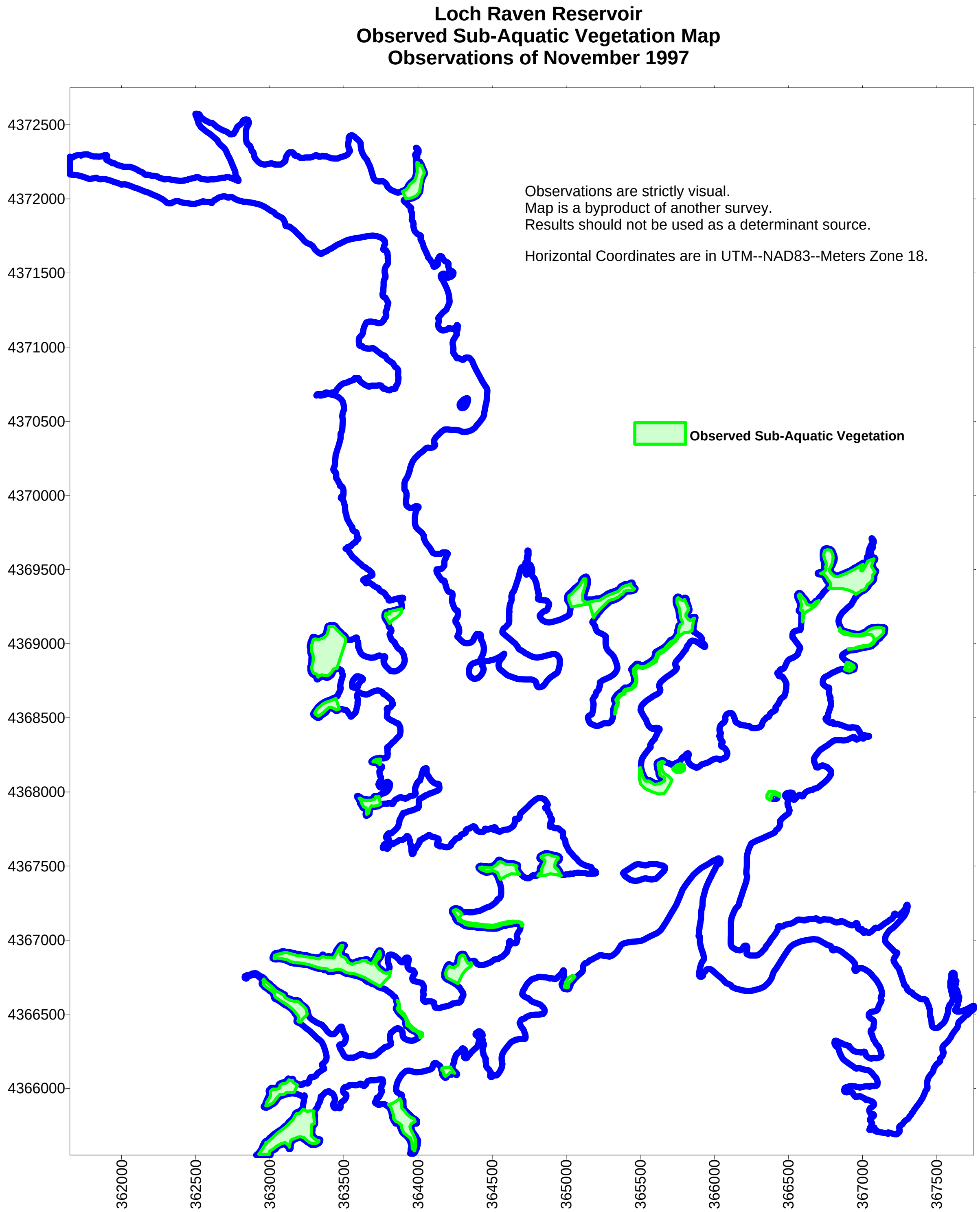

Figure 27. Observed Sub-Aquatic Vegetation (SAV) map of Loch Raven reservoir in November 1997. SAV areas were documented by visual observations coincident with bathymetric data collection. Data was collected in November 1997. Horizontal coordinates are UTM – NAD83 – Meters.

APPENDIX H: CD-ROM Contents and Repository

The datasets collected, interpolated, and analyzed in this report are too large to be include in printed format. The digital datasets are archived on a series of CD-Roms. The format of these CD-Roms is ISO9660. These CD-Roms are archived at the organizations listed below.

Maryland Geological Survey
Publications
2300 Saint Paul Street
Baltimore, MD 21218
(410)554-5505
publications@mgs.md.gov

Maryland Department of the Environment
Water Supply Program
2500 Broening Highway
Baltimore, MD 21224
(410) 631-3000

City of Baltimore
3001 Druid Park Drive
Baltimore, MD 21215
(410)396-0732

Contents of the CD-Roms

CD-Rom #1–Bathymetric and Lab Data
- Adobe Portable Document Format of this report
- Metadata for all datasets generated in this report
- Loch Raven and Prettyboy X, Y, Z Soundings in ASCII and Lotus v.4 Formats
- Digital Scan of X-Ray images of Loch Raven cores
- Plate Illustrations in Adobe PDF Format

CD-Rom #2–3.5 KHz Seismic-Reflection Data
- Unprocessed 3.5 KHz SEG-Y Data collected in Loch Raven reservoir
- Metadata for the dataset
- Supplemental programs used for viewing the data

CD-Rom #3–Boomer and 3.5 KHz Seismic-Reflection Data
- Unprocessed Boomer SEG-Y Data collected in Loch Raven reservoir
- Metadata for the dataset