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BATHYMETRY AND SEDIMENT ACCUMULATION OF TRIADELPHIA AND ROCKY GORGE RESERVOIRS

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

Conversion Factors

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

EXECUTIVE SUMMARY

In response to a request by the Watershed Services division of the Department of Natural Resources, State of Maryland, Maryland Geological Survey (MGS) was contracted to study the bathymetry and sedimentation of Triadelphia and Rocky Gorge Reservoirs located in Howard, Montgomery and Prince George's counties in the State of Maryland. Bathymetric data were collected for the reservoirs, current storage capacities and drawdown curves were determined, and volumes of sediment accumulation for the reservoirs were calculated. The collection, analysis, and presentation of this report were made to be consistent with the most recent bathymetric and sedimentation reports from Loch Raven and Prettyboy Reservoirs (Ortt et. al, 2000) and Liberty Reservoirs (Ortt et al, 2004) located within the State of Maryland.

Bathymetric data for the reservoirs was collected in May and June of 2004 for Triadelphia and in April and August of 2005 for Rocky Gorge. This data was collected using differential global positioning service (DGPS) techniques and digital echosounding equipment. Over four hundred thousand discrete soundings were collected and used to generate a current bathymetric model of Triadelphia and Rocky Gorge Reservoirs. Several methods of analysis were used to generate the models. The bathymetric models indicate a current storage capacity of 6.66 billion gallons [25.2 million cubic meters] for Triadelphia reservoir with a surface area of 824 acres [3.33 million square meters] and 5.54 billion gallons [21.0 million cubic meters] for Rocky Gorge reservoir with a surface area of 618 acres [2.50 million square meters].

INTRODUCTION

Historical Context

Triadelphia and Rocky Gorge reservoirs are important sources of water for the Washington Suburban Sanitary Commission (WSSC), which serves Montgomery and Prince George's counties. Routine studies have been conducted to document the reservoirs' water storage capacities (EA Engineering, 1989; Ocean Surveys, Inc., 1997). Methods used to collect information necessary for water storage and sediment accumulation investigations in the reservoirs have changed over the past two decades. These methodology changes substantially affect the ability to quantitatively compare results between surveys and temporal changes in sediment accumulation. This survey provides a follow up assessment of sediment accumulations and related water capacity changes in each of the reservoirs using contemporary data collection equipment and methods for analyses.

This report summarizes the results from the first and second phases of the current reservoir investigation. The first phase included measurement of the current reservoir bathymetries and capacities. Comparisons of the current bathymetries with the historic conditions documented in previous surveys are presented in Phase II. Phase III involves the evaluation of sediment accumulation in reservoir tributary deltas, and is reported separately (Smith *et al*, 2007).

Geological Background

The Triadelphia and Rocky Gorge Reservoirs are located on the Patuxent River mainstem between Washington D.C. and Baltimore (Figure 1). The reservoirs and their watersheds lie within Maryland's Piedmont Province (Cleaves *et al*., 1968). Triadelphia is located within the Hampstead and Glenwood Uplands geomorphic districts, which collectively cover an extensive portion of the Piedmont and are characterized by a dominance of gneiss and schist bedrock and modest landscape dissection. Rocky Gorge is located downstream from Triadelphia Reservoir in the Fall Zone Region. The Fall Zone is a unique geomorphic transition zone from the Piedmont to the Coastal Plain physiographic province. It is characterized by a mix of metamorphic rocks with some overlying unconsolidated gravels, sands, silts, and clays. Bedrock outcrops are distinctly visible in well-defined narrow gorges that can be observed in the waterways that traverse through it. This characteristic morphology is apparent in the confined width of the Rocky Gorge Reservoir.

Both reservoirs were formed by dam construction across the valley of the Patuxent River mainstem. The inundated areas include the Patxuent River mainstem channel and adjacent floodplains, tributary channels at their confluences with the Patuxent River mainstem valley, and the lower portions of the Patuxent River and tributary valley side walls. Hence, the original reservoir bottoms were largely composed of quaternary alluvium deposits that formed the Patuxent River valley floodplain. The reservoir bottoms are now composed of sediments that have accumulated since dam construction and backwatering.

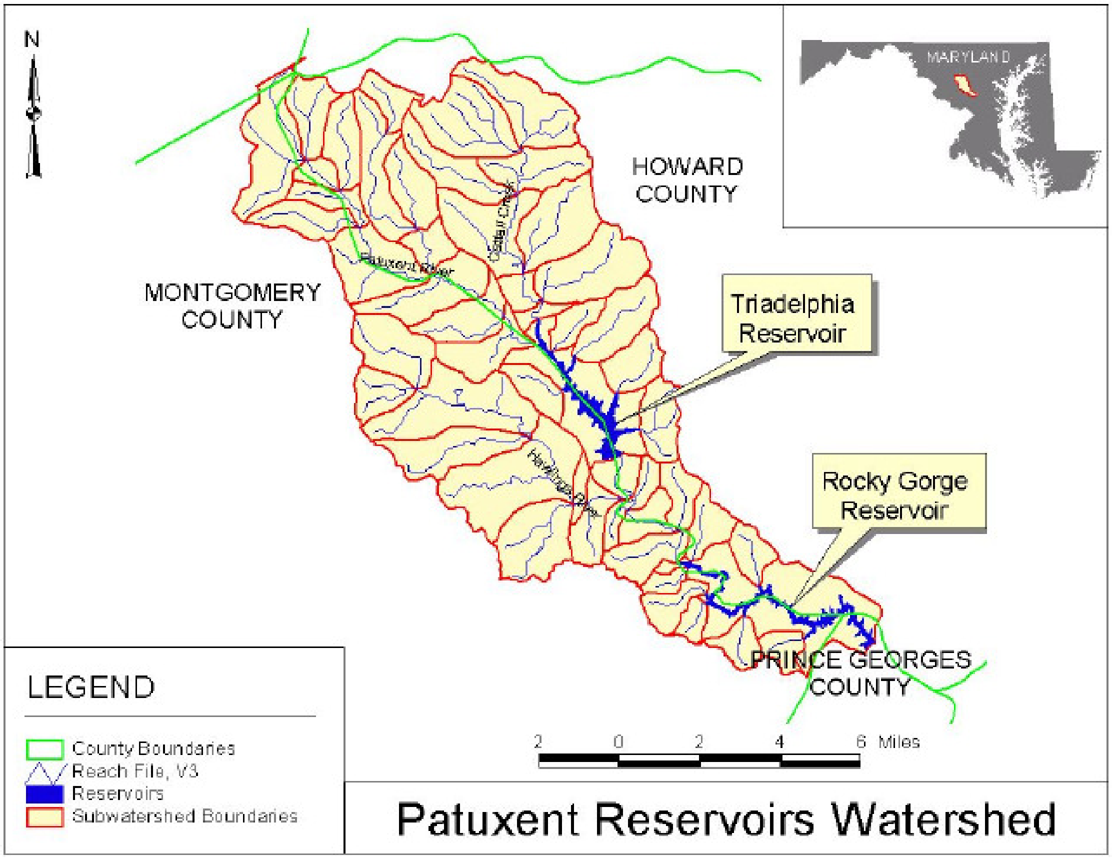

Figure 1. Locations of Triadelphia and Rocky Gorge Reservoirs (map from Tetra-Tech, Inc. and RMC, 2002). Watershed areas for Triadelphia and Rocky Gorge Reservoirs are 79 and 53 square miles, respectively, with a combined total watershed area of 132 square miles (DNR, 1998).

PREVIOUS SEDIMENT SURVEYS

Prior to the mid-80's, the Natural Resource Conservation Service (NRCS), formerly known as the U.S. Soil Conservation Service (US SCS), surveyed Triadelphia and Rocky Gorge Reservoirs approximately once every 10 years to determine the amount and rate of sediment accumulation. To determine reservoir capacity the NRCS used the range method, which utilized a number of transects to determine the cross-sectional area of the reservoir at different locations. Reservoir volumes were calculated and from that, the deposited sediment volumes were deduced. Results of the NRCS 1974 and 1984 surveys indicated that sedimentation in both reservoirs was rapidly increasing. Based on those results, WSSC projected that the reservoirs would lose 50% of their original capacity within 30 years (EA Engineering, 1989). The WSSC contracted EA Engineering, Science and Technology, Inc. (EA Engineering) to analyze the NRCS data to identify the areas of the reservoirs where maximum sedimentation was occurring. In the course of analyzing the data, EA Engineering discovered several flaws and discrepancies in the original NRCS volume calculations (EA Engineering, 1989). As a result, EA wrote a computer program (RESCAP) to reanalyze the NRCS data. The results of the EA Engineering work demonstrated the NRCS analyses grossly overestimated the sediment volumes. The EA Engineering reanalysis suggested that it would take 100+ years for the reservoirs to lose 50% of original capacity, as opposed to 30 years. EA Engineering's recalculated volumes are listed in Table I.

Triadelphia Reservoir			Rocky Gorge Reservoir		
Survey Year	**Capacity (ac. ft)** ***[Million m³]***	**Capacity Loss since 1942 (ac. ft)** ***[Million m³]***	**Survey Year**	**Capacity (ac. ft)** ***[Million m³]***	**Capacity Loss since 1954(ac. ft)** ***[Million m³]***
1942	22109 *[27.27]*	0			
1950	21938 *[27.06]*	171 *[0.211]*	**1954**	19638 *[24.22]*	0
1964	20938 *[25.83]*	1171 *[1.44]*	**1964**		
1974	20646 *[25.47]*	1463 *[1.80]*	**1974**		
1984	20040 *[24.72]*	2069 *[2.55]*	**1984**	18229 *[22.49]*	1409 *[1.74]*

Table I. Reservoir capacity and sediment volumes based on EA Engineering (1989) recalculation of NRCS data using "RESCAP" program (EA, 1989).

WSSC contracted Ocean Surveys, Inc. (OSI) to determined current capacity of the reservoir and estimate long-term sediment infill by comparing the updated capacity with historical data. OSI conducted standard hydrographic surveys in Triadelphia Reservoir in 1995 and in Rocky Gorge Reservoir in 1996. OSI used a three-dimensional surface modeling software (QuickSurf) to analyze the hydrographic data to determine 1995/96 reservoir capacities. Original capacity for each reservoir was determined by digitizing original pre-construction topographic sheets provided by WSSC, and analyzing digitized data using QuickSurf (Tables II and III). OSI also recalculated original reservoir capacity for Triadelphia Reservoir using EA Engineering's RESCAP program and cross-sectional areas based on digitized topography (Table II). OSI used the 370-ft (MSL) contour line and the 290-ft (MSL) contour line from the original topography for Triadelphia and Rocky Gorge Reservoirs, respectively. OSI interpolated the location of the shoreline (water's edge) at the respective mean pool levels when they calculated the historical and 1995/96 reservoir surface areas and capacities. OSI concluded that capacity calculations using the RESCAP method are less accurate than those obtained using 3-D surface modeling techniques. A small error in volume calculations using the range method can translate into a large error in the volume of sediment when the reservoir has not trapped a proportionately large amount of sediment. Total errors in determining reservoir capacity volumes using this method have been estimated to be between 10 and 30 percent (Morris and Fan, 1997; Dunbar et al., 1999). OSI results using QuickSurf indicate that sediment accumulation in Triadelphia Reservoir has averaged 40 acre feet per year since dam construction and Rocky Gorge Reservoir has averaged 32.5 acre feet per year since 1954. OSI did not report RESCAP recalculations for Rocky Gorge Reservoir.

In order to evaluate further sediment thickness and sedimentation rates, OSI collected 40 sediment cores in Triadelphia Reservoir.

Survey	RESCAP results (1989 data recalculated in 1997 by OSI)		QuickSurf results	
	Capacity (acre ft)	Volume of sediment accumulation (since 1942) (acres ft)	Capacity (acre ft)	Volume of sediment accumulation (since 1942) (acres ft)
1942	21987	0	21903	0
1995	20651	1336	19785	2118

Table II. Reservoir capacity and sediment volumes for Triadelphia Reservoir based on OSI (1997) study.

Survey	QuickSurf results	
	Capacity (acre ft)	Volume of sediment accumulation (since 1954) (acres ft)
1954	18934	0
1996	17570	1364

Table III. Reservoir capacity and sediment volumes for Rocky Gorge based on OSI (1997) study. The OSI study did not report RESCAP recalculations for Rocky Gorge Reservoir.

STUDY OBJECTIVES

The objectives for this study were:

1. To establish a surface for comparison of future surveys of Triadelphia and Rocky Gorge reservoirs.
2. To determine remaining storage capacity of Triadelphia and Rocky Gorge reservoirs.
3. To determine sediment accumulation in Triadelphia and Rocky Gorge reservoirs since dam construction.

METHODS

Study Approach

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

The second phase determined sediment thickness and sediment accumulation rates in the reservoirs through historical data comparison. Digitized original topography of the reservoirs were obtained and checked for accuracy. Sediment volume and sediment thickness maps were generated by subtracting the current bathymetry from the original topography. The sediment thicknesses reported using this method were minimally checked through the use of sub-bottom seismic-reflections. These results assist in the development of a better understanding of the amount and temporal rates of sediment accumulation within the reservoir.

Bathymetric Data Collection

Hydrographic Surveys

Track lines running perpendicular to the river channels were established for bathymetric surveying. These track lines were spaced 50 m apart and extended shoreline to shoreline. Tie-in lines were run perpendicularly to the survey lines and along the axial channels of the reservoirs. Additionally, survey track lines were run along the perimeter of the reservoirs to assist in the surface modeling analysis. Survey track lines are illustrated in Figure 2 and Figure 3. The bathymetry surveys were conducted in May and June of 2004 for Triadelphia Reservoir and in April of 2005 for Rocky Gorge Reservoir. An additional day of surveying was performed in August 2005 to collect additional data in Rocky Gorge Reservoir.

Bathymetric data were collected using a Thales Navigation (Ashtech) DGPS (model DG-16; L1 code and carrier with SBAS and differential beacon corrections; 5Hz Update rate) and a Knudsen 320B/P dual frequency echosounder with sounding frequencies of 200 KHz and 28 KHz. The echosounder transducer is a KEL771 dual frequency transducer with a 200 KHz beam angle of 4 degrees and a 28 KHz beam angle of 29 degrees. The echosounder generated acoustic pulses for bottom recognition at a rate of 2 Hz. The pulse width was set to automatically change between 0.2 mS and 0.8 mS depending on the depth of the water. The transmitted acoustic wave reflected off the density gradient separating the water column from the bottom sediment. The returned acoustic wave is received by the transducer, and the time separation between the sent and the returned wave is recorded. This time separation is directly proportional to distance. The recordings were then filtered for points that were outside of the gate window (2 meters) and integrated within the echosounder to produce an accurate measurement from the transducer to the water/sediment interface. At an average vessel speed of 4 knots, a depth sounding was collected approximately every 1.0 m [3.3 ft] along the survey track-lines. This data was stored along with the GPS location and positional latency in a laptop computer. Navigation was provided through a Lowrance GlobalNav 212 GPS interfaced to a Lowrance DGPS beacon receiver. DGPS differential corrections broadcast by the United States Coast Guard provided a real-time horizontal accuracy of +/- 1 meter [3.3 feet] using the Annapolis and Hagerstown DGPS sites. The Thales Navigation (Ashtech) DGPS, the Lowrance GPS, and the echosounder were checked against known horizontal and vertical measurements during the survey. The echosounder was also calibrated throughout the depth range of the reservoir during the study period. (Appendix A)

Mean Pool Level Adjustment

The bathymetric data collected presented measurements based upon the distance between the surface of the water in the reservoir and the top of the water-sediment interface. Due to fluctuations in the reservoirs level, the bathymetric data was adjusted to a known reference level using water level measurements recorded by a gauge operated by WSSC. This survey data was adjusted to the Mean Pool Level (MPL) of 366.4 feet above Mean Sea Level (MSL) for Triadelphia and 286.4 feet above MSL for Rocky Gorge. These water levels and adjustments are documented in Appendix B.

Data Accuracy

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

Digitizing 2004 Reservoir shorelines

Reservoir shorelines were interpreted from high resolution, natural color digital orthophotography with a pixel size of 0.8 feet (0.24 m) (EarthData International of Maryland, LLC, 2004). The orthophotography covering the study area was taken on April 15, 2004 (Raquel Charrois, EarthData International of Maryland, LLC, per comm. March 3, 2008), at a time when the trees were without leaves ('leaf off'). The shoreline was digitized on-screen using TNT MIPS® GIS software. The water's edge, which corresponded to the vegetation demarcation in most areas, was interpreted to represent the shoreline at MPL. However, on the day the photography was flown, a Triadelphia Reservoir pool level was 2.23 feet (0.68 m) below mean pool level and Rocky Gorge Reservoir was 5.2 feet (1.6 m) below MPL (Table IV). Because of the lower water levels, the water's edge was shifted lakeward of the vegetation demarcation along portions of the shoreline. The amount of the shift is dependent on the steepness of the shoreline. While the shift was minimal (< meter) for Triadelphia Reservoir (Figure 4), large shifts were noted in the extreme upstream areas and distal ends of the side coves in Rocky Gorge Reservoir (Figure 5). The surface area of Rocky Gorge Reservoir defined by the digitized 2004 shoreline vector is smaller than the area defined at maximum pool levels. The surface area discrepancies are estimated to contribute less than 0.2% error and 1.5% error to Triadelphia and Rocky Gorge Reservoirs capacity (volume) calculations, respectively.[*]

Bathymetric Interpretation and Volumetric Calculations

Bathymetric data were interpreted with Surfer, ArcInfo, MicroImages TNT and AutoCad software packages. In Surfer, the raw data was processed using three methods: 1) Triangulated

[*] The estimates assume an average 1:5 shoreline slope for both reservoirs. Thus the wedged shape volume around Triadelphia Reservoir is calculated to be 35,034 m (perimeter based on 2004 shoreline) x ½ [0.68 m (depth below MPL) x (5*0.68)] , or 40,499 m^3 (0.16% of total volume). For Rocky Gorge Reservoir, the volume is 50,086 m (perimeter) x 1/2[1.58 m x (5*1.58m)], or 312,587 m^3 (1.5% of total volume).

Irregular Network (TIN); 2) Kriging; and 3) Minimum Curvature, to create a three-dimensional surface (bottom topography) model. A two-meter regularly spaced grid was then calculated by analyzing the depths on the surface model. After the regularly-spaced grids were created, volumes and thicknesses of sediments could be calculated by subtracting the historical grid from the current (2004-2005) grid.

Error analysis was performed on the generated grids by comparing raw data with the generated grid. Differences between the actual data values and the grid values at the same location are called residuals. A root mean square error analysis on these residuals was used to assess how well the models fit the data. The results for error analysis for Triadelphia 2004 surface and Rocky Gorge 2005 surface are presented in Appendix A

Mean Pool Level (MPL) of Triadelphia Reservoir is defined to be 366.4 Feet Mean Sea Level (MSL) Mean Pool Level of Rocky Gorge Reservoir is defined to be 286.4 Feet MSL.				
Date	**Water Level**		**Daily Average**	**Depth below MPL Feet**
	6:00 a.m.	**6:00 p.m.**		
TRIADELPHIA RESERVOIR				
April 15, 2004	364.25	364.08	364.17	2.23
ROCKY GORGE RESERVOIR				
April 15, 2004	281.40	280.99	281.20	5.20

Table IV. Recorded pool levels for Triadelphia and Rocky Gorge Reservoirs on the day that the Howard County orthophotography covering the study area was flown. Pool level data from Todd Supple (per comm. March 3, 2008).

Sub-Bottom Seismic Reflection Surveying

Sub-Bottom seismic reflection surveys were conducted concurrent with the bathymetry survey using the Knudsen's low frequency of 28 KHz. The 28 KHz signal does not provide as much penetrating power as traditional sub-bottom systems at 3- 7 KHz; however, it is designed to provide a greater resolution in the near surface sediments due to a shorter wavelength. Previous experience with this equipment has identified geologic horizons under 5 meters of sediment.

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

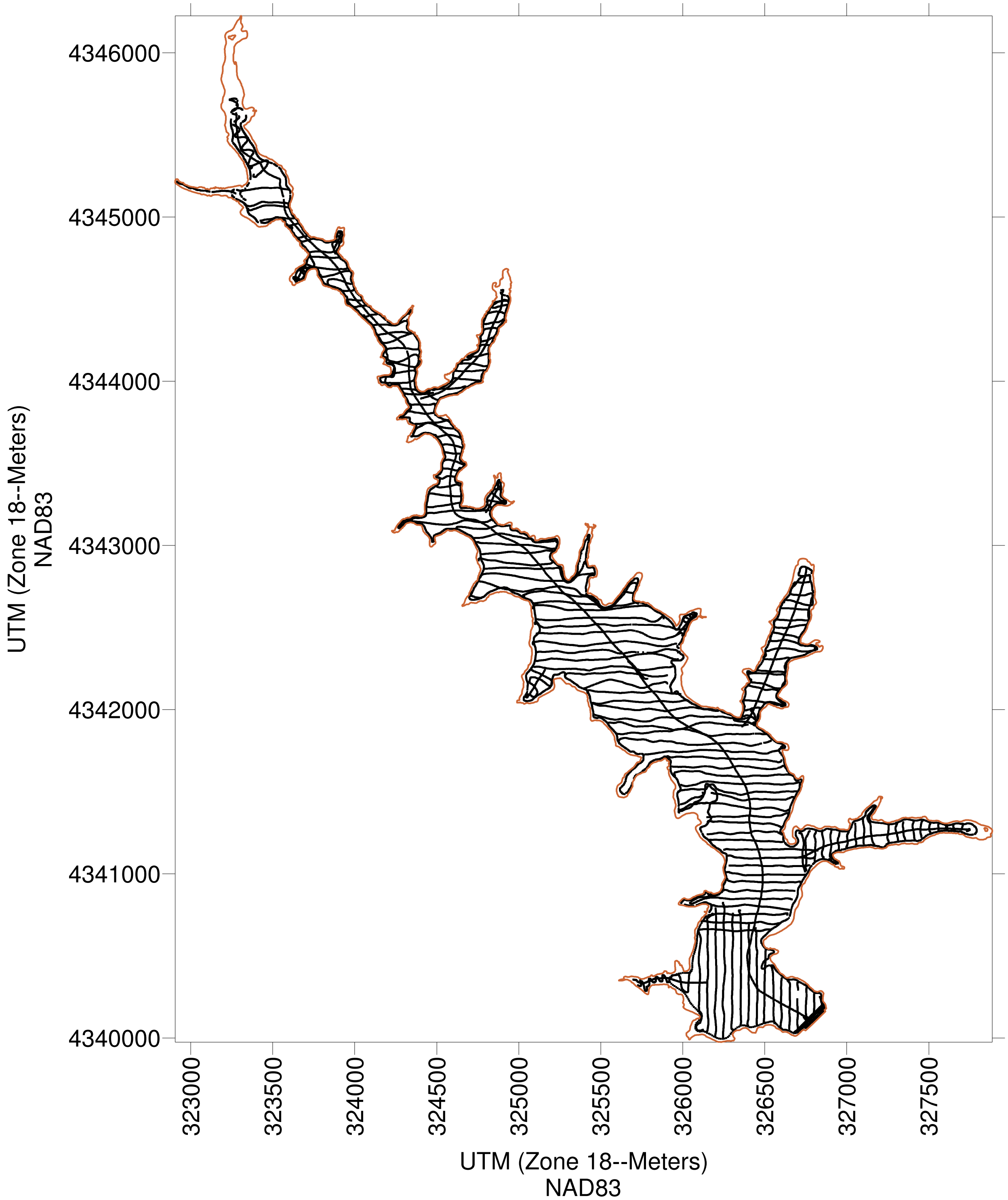

Figure 2. Sounding map of Triadelphia Reservoir with collected data points. Every tenth point is plotted. The digitized 2004 shoreline is also plotted in brown. The reservoir surface area defined by the 2004 shoreline is 824 acres (3.33 million m^2) and the shoreline length is 21 miles (35 km)

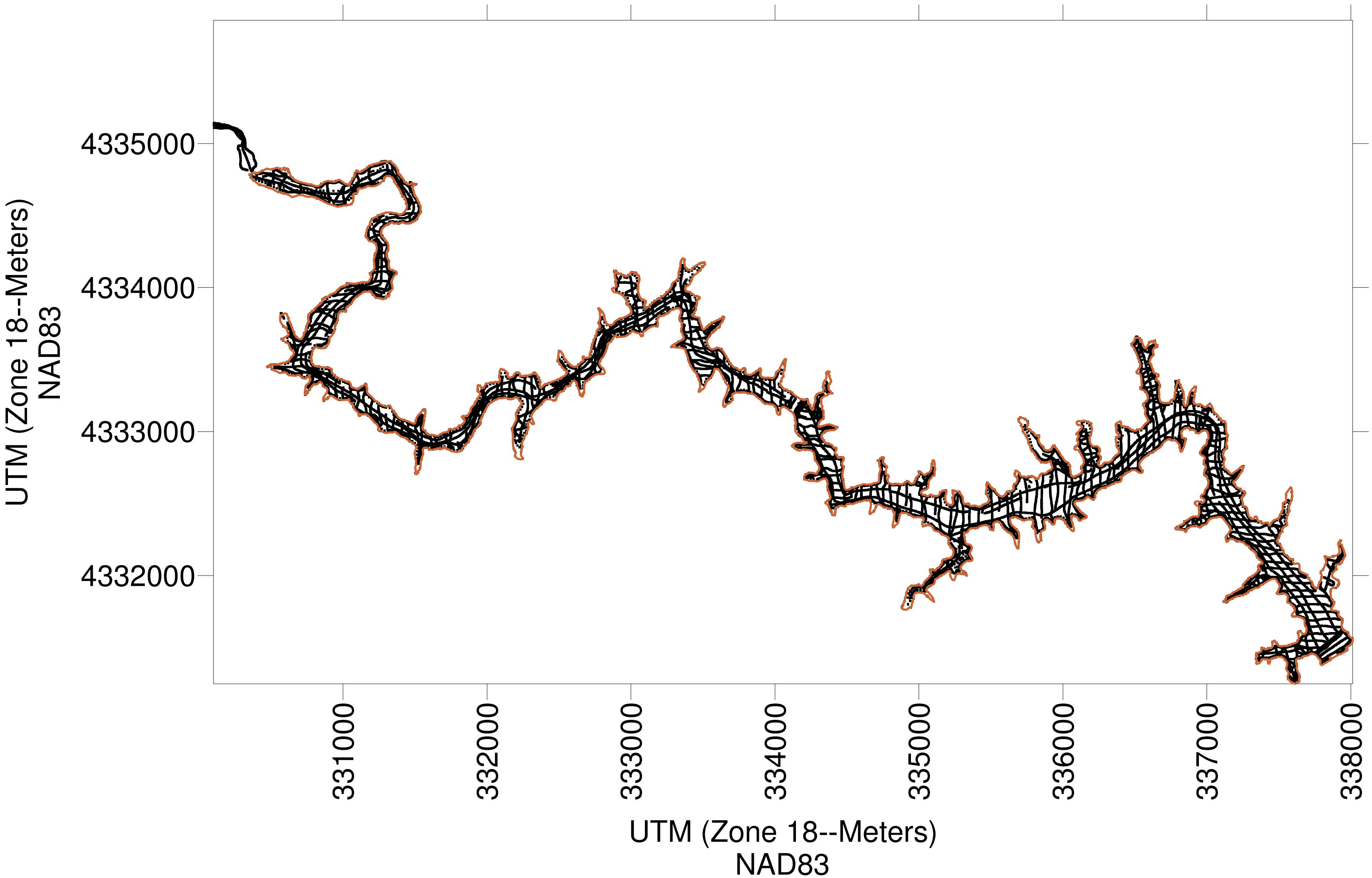

Figure 3. Sounding map of Rocky Gorge Reservoir with collected data points. Every tenth point is plotted. The digitized 2004 shoreline is also plotted in brown. The reservoir surface area defined by the 2004 shoreline is 618 acres (2.50 million m^2) and the shoreline length is 31 miles (50 km)

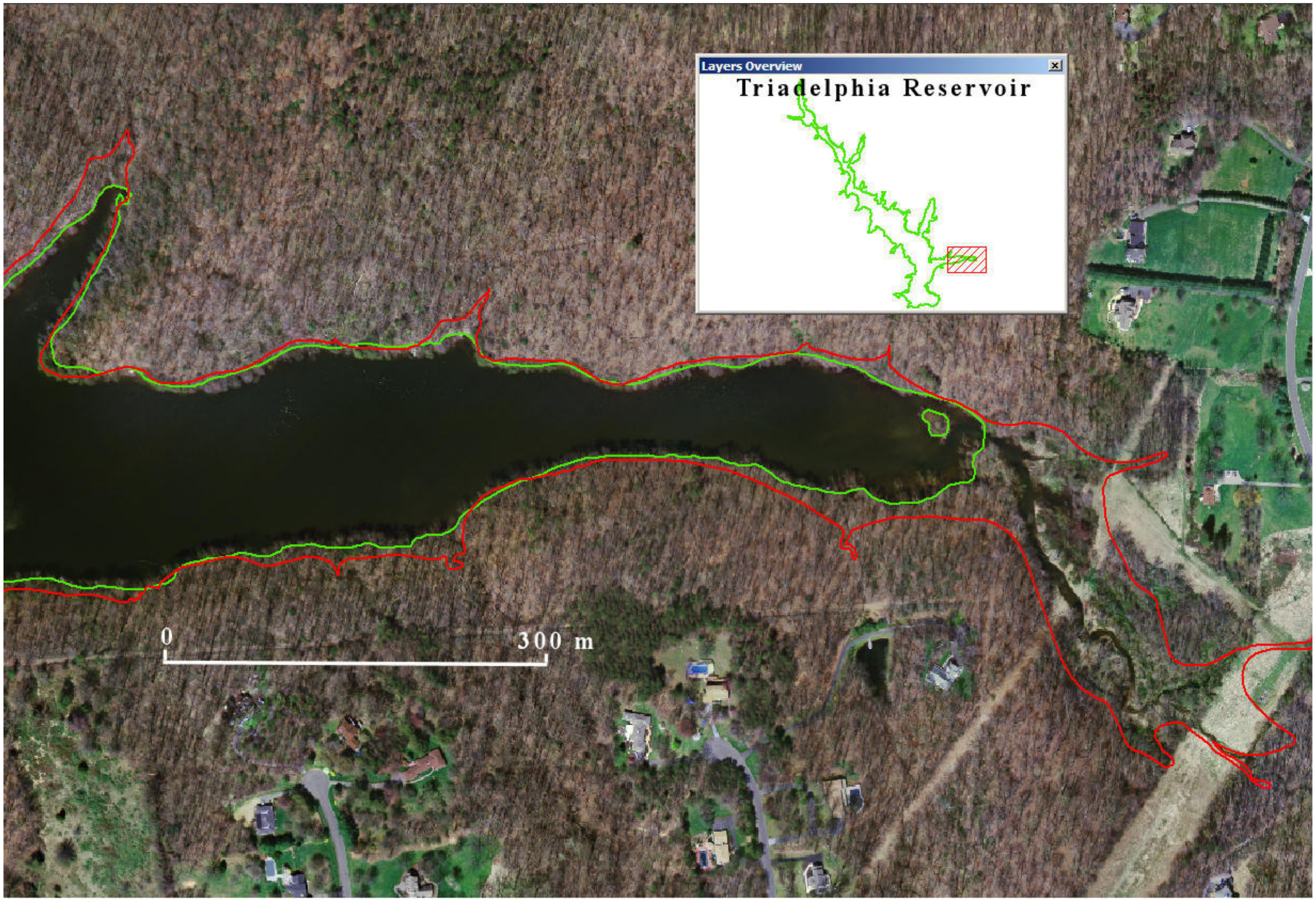

Figure 4. An example of 2004 high resolution orthophotography from which the shoreline (green line) for Triadelphia Reservoir was digitized for this study. Although the water level in Triadelphia Reservoir was reported to be 2.23 ft (0.68 m) below the mean pool level (366.4 ft MSL), there appears to be minimal displacement of the water's edge from vegetation demarcation. The 370-ft contour (MSL) from the original topographic survey (OSI, 1997) is shown in red.

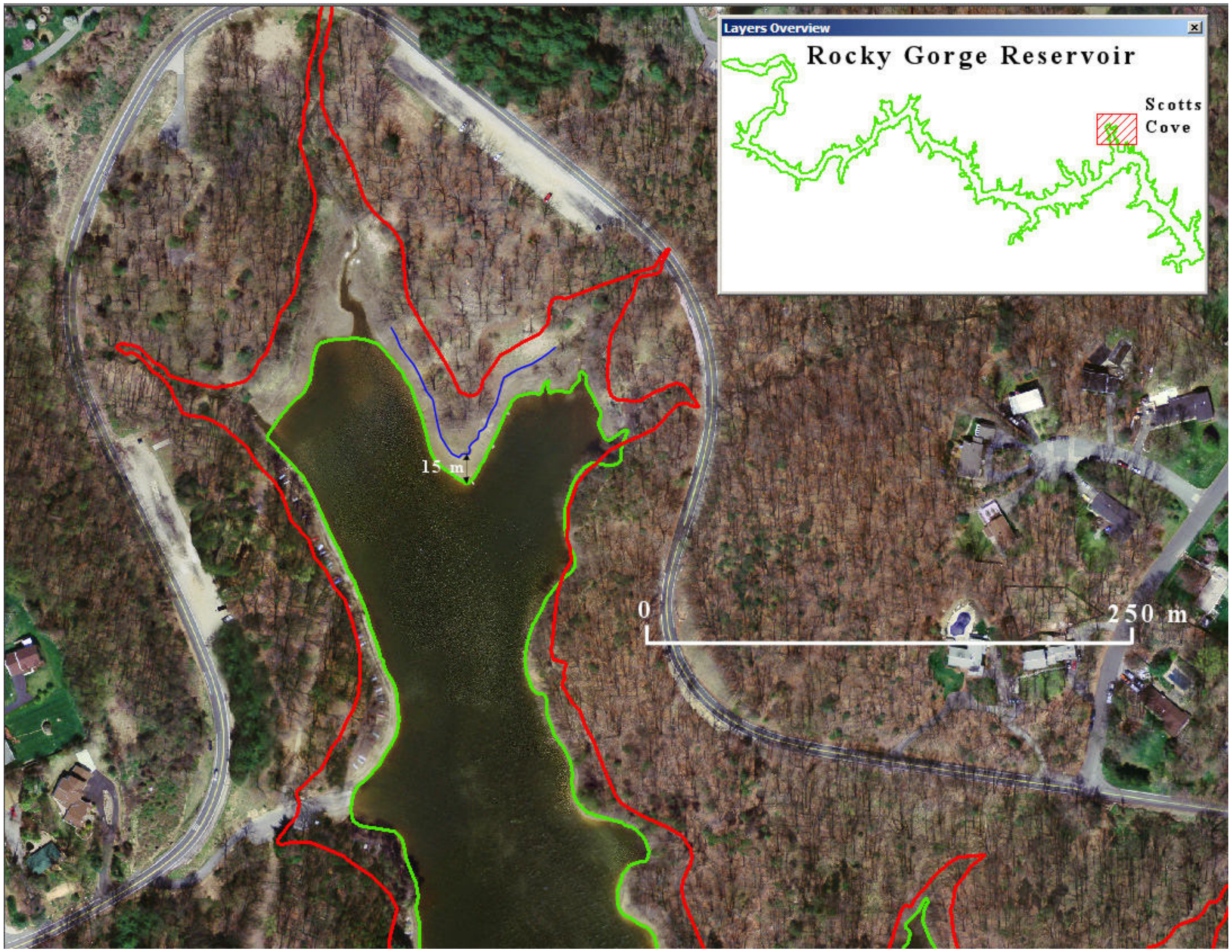

Figure 5. An example of 2004 high resolution orthophotography from which the shoreline (green line) for Rocky Gorge Reservoir was digitized for this study. The 290-ft contour (MSL) of the original topographic survey is shown in red. The aerial photography was taken when the water level in Rocky Gorge was 5.2 ft (1.58 m) below the mean pool level (286.4 ft MSL). As a result, the water's edge, normally representing the shoreline, was shifted lakeward. The greatest shifts were in the shallow distal ends of the coves, such as Scott's Cove shown in the aerial photograph. Here, the blue line marks the approximate location of where the shoreline should be (at maximum pool level). In the main stem of the reservoir, the water's edge displacement was minimal due to the steep shoreline.

RESULTS AND DISCUSSION

Bathymetric Results

The 2004 bathymetry for Triadelphia Reservoir is presented in Plate 1. The central river valley is discernable but not as well defined as seen in the original topography (Plate 3). The deepest portion of the reservoir, with depths up to 62 ft (19 m), is just above (upstream) of the dam. The reservoir depths gradually decrease toward the upstream ends of the main stem and tributaries.

The 2005 bathymetry for Rocky Gorge Reservoir is presented in Plate 2. The central river bed is clearly mapped in the down stream end, but becomes less defined in the upstream areas. Like Triadelphia, the deepest portion of the Rocky Gorge is near the dam, where depths up to 106 ft (32 m) are mapped.

The calculated storage volumes of the reservoirs are presented in Table V. Multiple methods were used to determine the volumes, and the most accurate method is identified in bold. Due to the high spatial density of collected data and the bowl shape of a reservoir, the method that presented the most accurate (lowest residual RMS) results in both reservoirs is the Minimum Curvature method (Appendix A, Table X). Though the TIN method honors every data point and creates a surface that preserves the original data points and shoreline, this method is known to be an under-estimator method for reservoir volumes as it connects points in a straight line rather than following bathymetric trends. In Triadelphia Reservoir, the calculated storage volume is 6.66 billion gallons [25.2 million cubic meters]. In Rocky Gorge Reservoir, the calculated storage volume is 5.54 billion gallons [21.0 million cubic meters].

Calculated Storage Capacities
Billion Gallons *[million cubic meters]*

Reservoir	Kriging	TIN	Minimum Curvature
Triadelphia	6.51 *[24.6]*	6.59 *[24.9]*	**6.66** ***[25.2]***
Rocky Gorge	5.72 *[21.7]*	5.44 *[20.6]*	**5.54** ***[21.0]***

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

Multiple volumes and surface areas were calculated with differing reservoir water levels yielding stage curves that are helpful in assessing volumes in times of pool level decline. Figures 6 and 7 display the results of this analysis. The drawdown curves of Rocky Gorge Reservoir have a much greater slope than those of Triadelphia Reservoir, indicative of the much more incised flooded river valley of Rocky Gorge.

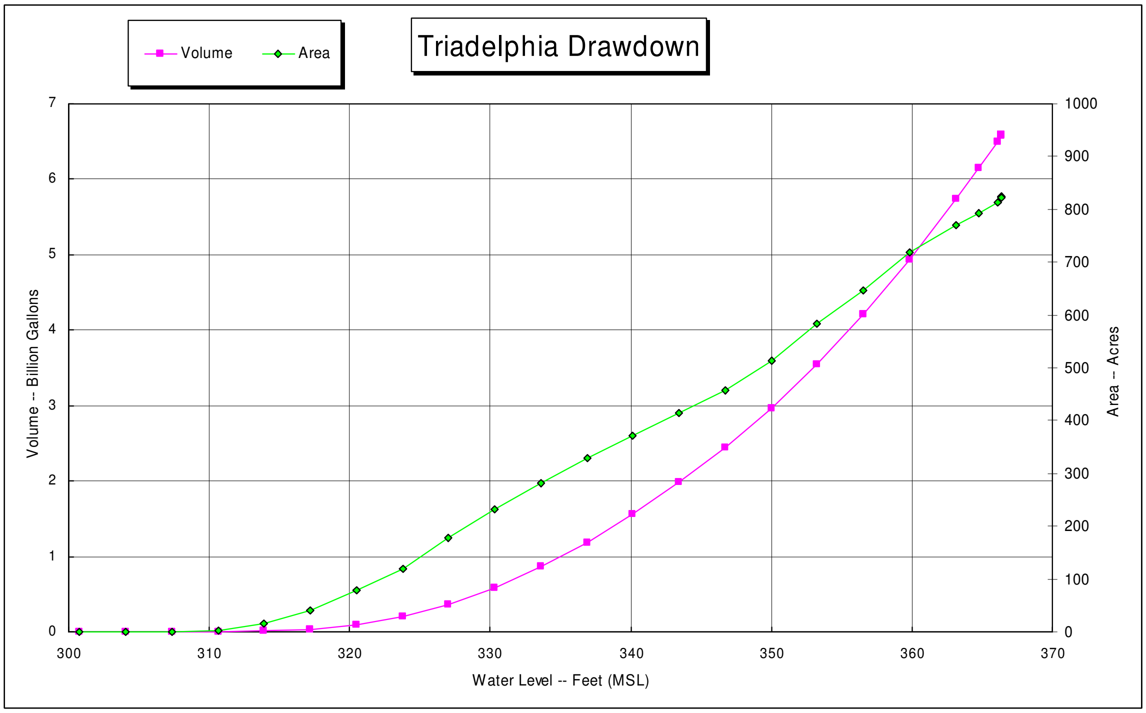

Figure 6. Drawdown curve of storage capacity and surface area versus water height in Triadelphia Reservoir.

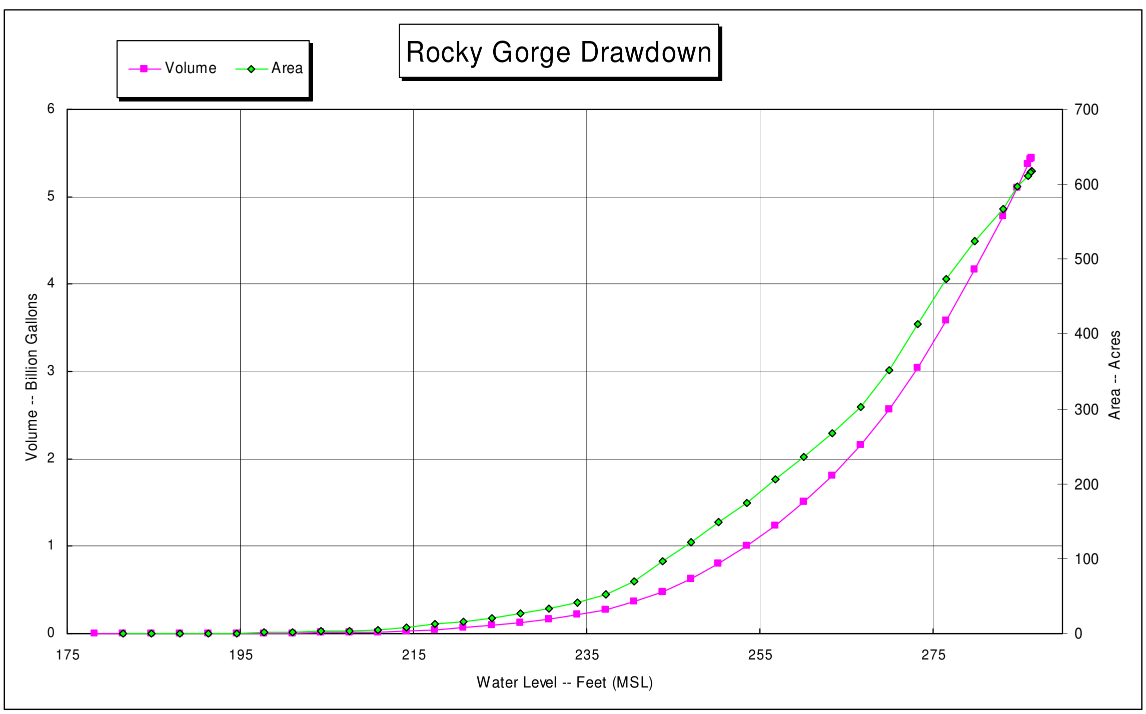

Figure 7. Drawdown curve of storage capacity and surface are versus water height in Rocky Gorge Reservoir.

Historical Data Modeling Results

The original topographic maps that were digitized for the OSI study (OSI, 1997) were also modeled using Surfer and used to generate storage capacity estimates. Since these maps consisted of contour lines rather than distinct points that were digitized it was important to select a modeling method that would extrapolate data values between the contour lines. The TIN method was not used for these maps as it would not extrapolate any values; rather, it would draw straight lines between the contour lines and create flat planar areas that are unrealistic. Minimum Curvature method yielded the smallest residual root mean square error; therefore was used to calculate original and current capacity for the reservoirs (Tables VI and VII). Analysis for a smaller time interval was not done because the raw data was not available (*i.e.,* 1995/96 bathymetric soundings collected by OSI).

TRIADELPHIA RESERVOIR (79.0 Mi.^{2} Drainage Area) (204.8 Km^2 Drainage Area)				
Survey Year	**Capacity (ac. ft)** ***[Mill m³]***	**Period Capacity Loss (ac. ft)** ***[Mill m³]***	**Average Annual Loss (ac. ft/yr)** ***[Mill m³/yr]***	**Average Annual Loss Per Sq. Mi. Drainage Area (ac. ft/yr/mi^2)** ***[m³/yr/km²]***
1942	21931 *[27.05]*	0	0	0
2004	20434 *[25.20]*	1497 *[1.85]*	24.2 *[0.03]*	0.31 *[146]*

Table VI. Calculated storage capacity loss rates for Triadelphia Reservoir from this study.

ROCKY GORGE RESERVOIR (53.5 Mi.^{2} Drainage Area) (138.4 Km^2 Drainage Area)				
Survey Year	**Capacity (ac. ft)** ***[Mill m³]***	**Period Capacity Loss (ac. ft)** ***[Mill m³]***	**Average Annual Loss (ac. ft/yr)** ***[Mill m³/yr]***	**Average Annual Loss Per Sq. Mi. Drainage Area (ac. ft/yr/mi^2)** ***[m³/yr/km²]***
1954	18437 *[22.7]*	0	0	0
2005	16986 *[21.0]*	1451 *[1.79]*	28.5 *[0.04]*	0.53 *[253.6]*

Table VII. Calculated storage capacity loss rates for Rocky Gorge Reservoir.

A subtraction of Triadelphia 2004 bathymetry from the original topographic surveys yields a positive volume (sediment gain) of 1919 acre feet (2.37 million m^3) and a negative volume (internal erosion, dam/reservoir construction, offsets) of 422 acre feet (520,292 m^3). Net sediment volume change is a gain of 1497 acre feet (1.85 million m^3) of sediment, which translates to an average annual capacity loss of 24.2 acre feet per year since construction in 1942.

A subtraction of the Rocky Gorge 2005 bathymetry from the original topographic surveys yields a positive volume of 1970 acre feet (2.43 million m^3) of sediment and a negative volume of 519 acre feet (639,499 m^3) of sediment. Net sediment volume change is a gain of 1451 acre feet (1.79 million m^3) of sediment. Since construction in 1954, the average annual capacity loss of Rocky Gorge is estimated at 28.5 acre feet per year. This annual loss is more than Triadelphia Reservoir which has a larger watershed area.

The volumes are lower than expected, especially when compared to the capacities and sediment volumes reported by EA Engineering (1989) and OSI (1997) for shorter time intervals (Tables I, II, and III). The MGS 2004 volume for Triadelphia Reservoir does not include any sediment removed by dredging. WSSC has an active dredging program of the upper "ponds" of the reservoir.

There are several other possible sources of error in the calculations. The mainstem shorelines derived for the digitized original topographic surveys for the reservoirs aligned well the 2004 shorelines and surveys. However, the 2004 shorelines did not extend as far upstream as the original topography shorelines, and, thus, encompass a smaller area compared to the original topographic shorelines (Figures 4 and 5). In addition, the MGS volumes are based on the area extent of the bathymetric surveys which did not go as far upstream as the 2004 shoreline. Furthermore, the original topographic surveys were conducted in the 1940s and 50s, but referenced to updated horizontal datum and vertical datum (NAD83 and NAVD88, respectively). The contour interval on the topography is 5 feet. This yields an uncertainty of 2.5 feet at any location. The 2004-2005 bathymetry resolution is to the centimeter, but accuracy is +\-0.1m + 1% of water depth. Additionally any areas which are now land rather than water would not be captured in this simple subtraction. Additional errors from the modeling method (minimum curvature) are also introduced. Many minor trends and intermediate values within the contour interval are lost when modeling surfaces from contour lines (Weng, 2002). Adding these elevation errors and multiplying over the current area of the reservoir yields an error estimate of 3,113,179 m^3 (3,322,496 m^2 x 0.94m), or 12% error, for Triadelphia Reservoir, and an error estimate of 2,456,910 m^3 (2,613,735 m^2 x 0.94 m), or 11% error, for Rocky Gorge Reservoir.

Another source of error is the amount of sediment which is not being accounted for in the river channel during the original topographic survey. The topographic survey did not perform a bathymetric survey of the existing river; however, the modeling technique did force a river channel into the reservoir based upon the surrounding data.

However, even with all of these errors, the isopach maps of accumulated sediment since construction in the two reservoirs are probably realistic in that they show a distinct pattern of mixed sediment deposition and erosion (Plates 3 and 4). Large sediment accumulations are shown in the river channel in the upstream areas of Triadelphia Reservoir (Plate 3). This is not so further downstream where the reservoir is wider and subjected to larger wind fetch, resulting in localized scouring of sediments. Here the pattern is mixed accumulation and erosion. Generally, the sediment thicknesses on the map agree with those values reported by OSI for their core locations using the same method (DTM method) (OSI, 1997).

Sediment accumulation pattern in Rocky Gorge Reservoir indicates a slightly different distribution (Plate 4). Sediments have accumulated in the upstream area and largely confined to the original river channel downstream. Erosion is indicated along the shoreline on both sides of central channel. OSI (1997) described a similar pattern of erosion and deposition.

Sub-Bottom Seismic Reflection Results

Sub-bottom seismic data revealed areas where sediments had accumulated. However, penetration of the 28 kHz seismic acoustic signal was ‘spotty’, indicating a heterogeneous nature of the recently accumulated sediments. The signal generally was not able to penetrate recently deposited sediment thicker than 1 to 1.5 meter, and/or having courser texture. The sub-bottom data provided limited confirmation of recently accumulated sediment thicknesses calculated by other methods used in this study. Large portions of the reservoirs presented very strong reflections documenting a hard bottom.

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

CONCLUSION

The current storage capacity of Triadelphia Reservoir is 25.2 million cubic meters [6.66 billion gallons] and the capacity of Rocky Gorge Reservoir is 21.0 million cubic meters [5.54 billion gallons]. The bathymetric datasets from which these capacities were calculated represent complete coverages of the reservoirs and include up-dated shorelines and shoreline perimeter surveys. OSI (1997) had recommended perimeter surveys be included in future surveys to ensure more accurate surface modeling. The data points included in MGS datasets are uniformly distributed, and will provide a solid base for future comparisons.

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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 Triadelphia and Rocky Gorge. The identification of possible sources of error helped to design and execute a data collection methodology that reduced the risk of collecting and utilizing erroneous data. Errors identified in other regional reservoir bathymetry reports were specifically identified and minimized as outlined below (City of Baltimore Department of Public Works, 1989).

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

Known Depth		Measured Depth (Meters)	
(feet)	(meters)	200KHz	Notes
14.18	4.322063862	4.05	
19.78	6.028943807	5.78	
22.78	6.943343778	6.70	
26.08	7.949183746	7.73	
29.58	9.015983711	8.84	
32.88	10.02182368	9.84	
36.08	10.99718365	10.80	
37.88	11.54582363	11.38	
38.48	11.72870362	11.60	
3.89	1.185671962	1.02	
6.49	1.978151937	1.78	
10.44	3.182111898	2.99	
13.64	4.157471867	3.96	
17.09	5.209031833	5.04	

Table VIII. Echosounder Calibration on August 25, 2004 (Triadelphia). Regression analysis = Actual=0.9968*Measured Depth +0.22 meters. $R^2 = 0.9999$. The equivalent speed of sound in water derived from this calibration is 1495 meters per second.

Known Depth		Measured Depth (meters)				Notes
		Downcast		Upcast		
(feet)	(meters)	200KHz	28KHz	200KHz	28KHz	
2.04	0.622	0.36	No fix	0.34	No fix	
5.06	1.543	1.25	1.23	1.25	No fix	
10.04	3.061	2.77	2.73	2.78	2.74	
15.00	4.572	4.31	4.35	4.30	4.28	
19.98	6.090	5.85	5.82	5.89	5.86	
24.96	7.607	7.44	7.40	7.41	7.42	
29.96	9.131	9.00	9.03	9.01	8.97	
34.94	10.649	10.62	10.53	10.53	No fix	
39.92	12.167	12.17	12.08			

Table IX. Echosounder Calibration on April 28, 2005 (Rocky Gorge). Regression analysis = Actual=0.9771*Measured Depth +0.33 meters. $R^2 = 0.9999$. The equivalent speed of sound in water derived from this calibration is 1465 meters per second.

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

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

Additionally an elevation mask of 15 degrees was set to filter out satellites that were low on the horizon and which could insert errors into the position solution. Any sounding that was tagged with a GPS position that was greater than 650 milliseconds old was deleted from the dataset.

The sounding data was verified through multiple techniques. During collection, a minimum and a maximum depth are provided to assist in the selection of the bottom. Various filters are used internally of the echosounder to accurately track the bottom. Occasionally, the echosounder will lose bottom lock, and it will track a multiple, thermocline, or water column noise. These data are determined through visual observation and filtered from the dataset to ensure accurate data is provided to the modeling program.

Water level heights were collected by WSSC and reported to MGS shortly after data collection. Water levels during the survey period are documented in Appendix B.

Following the adjustments to depth and the removal of poor quality horizontal and vertical data, the data was further analyzed at the intersection of the tie-in lines. 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. A minimum of twenty-five intersections were visually identified and compared on each dataset. In all observations, the processed depths at the intersection points exceeded the accuracy standard of +/- (0.1 feet + one percent of the water depth).

Bathymetric Modeling

To perform a consistent analysis, the bathymetric and topographic data of Triadelphia (2004), Rocky Gorge (2005), and pre-construction topography needed to be gridded and modeled into three dimensional surfaces. The modeling program Surfer can utilize a number of different methods to perform this analysis. Several methods including Kriging, Triangular-Irregular Network (TIN), and Minimum Curvature were computed and analyzed for proper fitting of the data. A grid resolution of 2 meters was utilized in developing the final models.

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

Residual Root-Mean-Square Analysis of Computed Surfaces

Surface	**Grid Method**	**Residual RMS (meters)**
Triadelphia 2004	TIN	0.089
Triadelphia 2004	Minimum Curvature	0.005
Triadelphia 2004	Kriging	0.247
Rocky Gorge 2005	TIN	0.511
Rocky Gorge 2005	Minimum Curvature	0.138
Rocky Gorge 2005	Kriging	0.863

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

APPENDIX B: Mean Pool Level Adjustments

Mean Pool Level Recordings and Adjustments					
Mean Sea Level (Feet) Mean Pool Level of Triadelphia Reservoir is defined to be 366.4 Feet MSL Mean Pool Level of Rocky Gorge Reservoir is defined to be 286.4 Feet MSL					
Date	**Water Level**			**Daily**	**Depth Adjustment**
	Survey Start	**Survey End**		**Average**	**Feet**
TRIADELPHIA RESERVOIR					
May 12, 2004	362.14	362.16		362.15	4.25
May 13, 2004	362.23	362.23		362.23	4.17
May 14, 2004	362.29	362.29		362.29	4.11
May 24, 2004	363.83	363.86		363.85	2.55
June 1, 2004	363.02	363.02		363.02	3.38
June 2, 2004	363.02	363.06		363.04	3.36
June 21, 2004	363.99	363.97		363.98	2.42
ROCKY GORGE RESERVOIR					
April 15, 2005	284.55	284.43		284.49	1.91
April 18, 2005	284.3	284.15		284.22	2.18
April 19, 2005	284.29	284.18		284.24	2.16
April 20, 2005	284.30	284.08		284.19	2.21
April 28, 2005	283.93	283.89		283.91	2.49
August 8, 2005	280.08	279.91		279.99	6.41

Table XI. Mean Pool Level Recordings and Adjustments

APPENDIX C: CD Contents and Repository

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

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

Contents of DVD-R disc:

Adobe Portable Document Format of this report
Plate Illustrations in Adobe PDF Format
Reservoir X, Y, Z Soundings in ASCII format
Metadata and Index Map for sounding data
Raw Echosounder Data in KEA and KEB formats
KEB file viewer program (Windows 98 or higher)