Department of Natural Resources
MARYLAND GEOLOGICAL SURVEY
Richard A. Ortt, Jr., Director

COASTAL AND ESTUARINE GEOLOGY
FILE REPORT NO. 15-9

BATHYMETRY AND SEDIMENT ACCUMULATION OF TRIADELPHIA AND ROCKY GORGE RESERVOIRS

By

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Prepared For

Washington Suburban Sanitary Commission (WSSC)

December 2015
(Revised December 2016)

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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 Disc
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 Washington Suburban Sanitary Commission (WSSC), State of Maryland, Maryland Geological Survey (MGS) was contracted to study the bathymetry and sedimentation and collect side scan sonar imagery 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 since the 2004/2005 MGS surveys 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), Liberty Reservoirs (Ortt et al., 2004), and Triadelphia and Rocky Gorge Reservoirs (Ortt et al., 2007) located within the State of Maryland.

Bathymetric and side scan sonar data for the reservoirs was collected in April 2015 for Triadelphia and 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 6.45 billion gallons [24.4 million cubic meters] for Triadelphia reservoir with a surface area of 824 acres [3.33 million square meters] and 5.49 billion gallons [20.8 million cubic meters] for Rocky Gorge reservoir with a surface area of 620 acres [2.51 million square meters]. The side scan imagery shows hardened banks along the shoreline and softer central basins within both reservoirs with the hardened shorelines being broader in Rocky Gorge Reservoir. The side scan data also revealed the pre dam stream bed thalwegs throughout the lower portions of both reservoirs with decreased presence in the upriver portions and coves where historic sediment deposition has been higher. Very little sediment accumulation behind the dams with minimal debris behind Brighton Dam in Triadelphia Reservoir and several large rock clusters with some amount of debris behind the T. Howard Duckett Dam in Rocky Gorge Reservoir were indicated on the side scan imagery.

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; Maryland Geological Survey, 2007). This survey provides a follow up assessment of sediment accumulations and related water storage capacity changes in each of the reservoirs using contemporary data collection equipment and methods for analyses. The same equipment and methodologies used in 2004/2005 for data collection and processing were repeated for this study to provide the most accurate comparison of each of the 2015 reservoir datasets.

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 Patuxent 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.

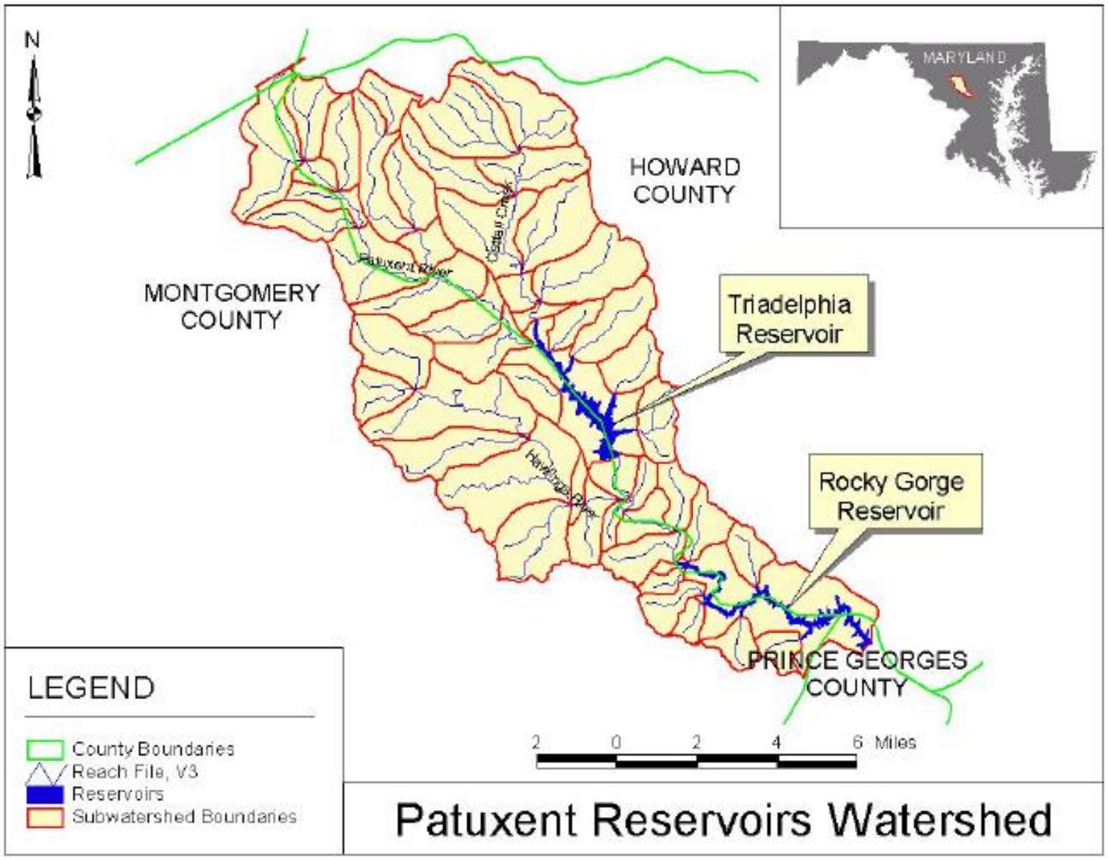

Figure 1. Locations of Triadelphia and Rocky Gorge Reservoirs (map from Tetra-Tech, Inc. and RMC, 2002). Watershed areas for Triadelphia and Rocky Gorge Reservoirs are 79 and 53 square miles, respectively, with a combined total watershed area of 132 square miles (DNR, 1998).

PREVIOUS SEDIMENT SURVEYS

Prior to the mid-1980'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 recalculation of NRCS data using "RESCAP" program (EA Engineering, 1989).

WSSC contracted Ocean Surveys, Inc. (OSI) to determine current capacity of the reservoirs and estimate long-term sediment infill by comparing the updated capacities 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 as the mean pool level elevations 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) (acre ft)	Capacity (acre ft)	Volume of sediment accumulation (since 1942) (acre 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) (acre ft)
1954	18934	0
1996	17570	1364

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

Maryland Geological Survey digitized the 2004 shorelines and conducted bathymetric surveys of Triadelphia Reservoir in 2004 and Rocky Gorge Reservoir in 2005. New baseline reservoir volumes, 2004/2005 capacities, and sediment accumulation rates were calculated using Surfer software.

STUDY OBJECTIVES

The objectives for this study were:

1. To determine remaining storage capacity of Triadelphia and Rocky Gorge reservoirs.
2. To determine sediment accumulation in Triadelphia and Rocky Gorge reservoirs since 2004/2005.
3. Collect side scan sonar imagery and create mosaic raster map for Triadelphia and Rocky Gorge reservoirs.

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 and collection of side scan sonar imagery. 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. Side scan sonar data was processed and merged to create a mosaic for each reservoir to assess reservoir bed sediment hardness (acoustic reflectivity) and any debris behind the dams.

The second phase determined sediment thickness and sediment accumulation rates in the reservoirs through historical data comparison. Sediment volume and sediment thickness maps were generated by subtracting the current bathymetry from the bathymetry data collected between 2004 and 2005. 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

<u>Hydrographic Surveys</u>

Track lines running perpendicular to the river channels were established for bathymetric surveying. These track lines were spaced 50 meters 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 April of 2015 for Triadelphia and Rocky Gorge Reservoirs.

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. The DGPS position and Knudsen depth data were integrated real time using HYPACK software. 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 using the Thales Navigation DGPS integrated with the HYPACK software and HYPACK planned lines. 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 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. MGS also installed a water level gauge during data collection as a reference to the recorded WSSC gauge recordings. 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].

Side Scan Sonar Data Collection

An EdgeTech 4200 FS side scan sonar system, using dual frequencies of 120 and 410 kHz, was used to image each of the lakebeds. The system was adjusted to a horizontal range of 75 meters. The underwater sensor (fish) was placed approximately 1 meter below the waterline off the bow of the survey vessel. Side scan data was logged using EdgeTech's proprietary "Discover" software in the proprietary ".jsf" file format. The side scan data was georeferenced using a Thales Navigation (Ashtech) DGPS (model DG-16; L1 code and carrier with SBAS and differential beacon corrections; 5Hz Update rate). The DGPS antenna was placed directly above the side scan fish therefore eliminating any need for horizontal position offsets during post processing. Post processing was done using Chesapeake Technology's SonarWiz 5.

Digitizing 2004 Reservoir shorelines

The digitized shorelines created for the use in interpretation of the 2004/2005 bathymetric data sets were used for the 2015 study to enable direct grid comparisons. 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, the 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.*

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).

Bathymetric Interpretation and Volumetric Calculations

Bathymetric data were interpreted with Surfer and ArcInfo software packages. In Surfer, the raw data was processed using three methods: 1) Triangulated 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 2004/2005 grid from the current (2015) grid.

* 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 ½ [1.58 m x (5*1.58m)], or 312,587 m^3 (1.5% of total volume).

Error analysis was performed on the 2004/2005 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 (RMS) 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. For direct comparison of the 2015 dataset to the 2004/2005 datasets, the Minimum Curvature model data was used in 2015 since this model contained the lowest root mean square.

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].

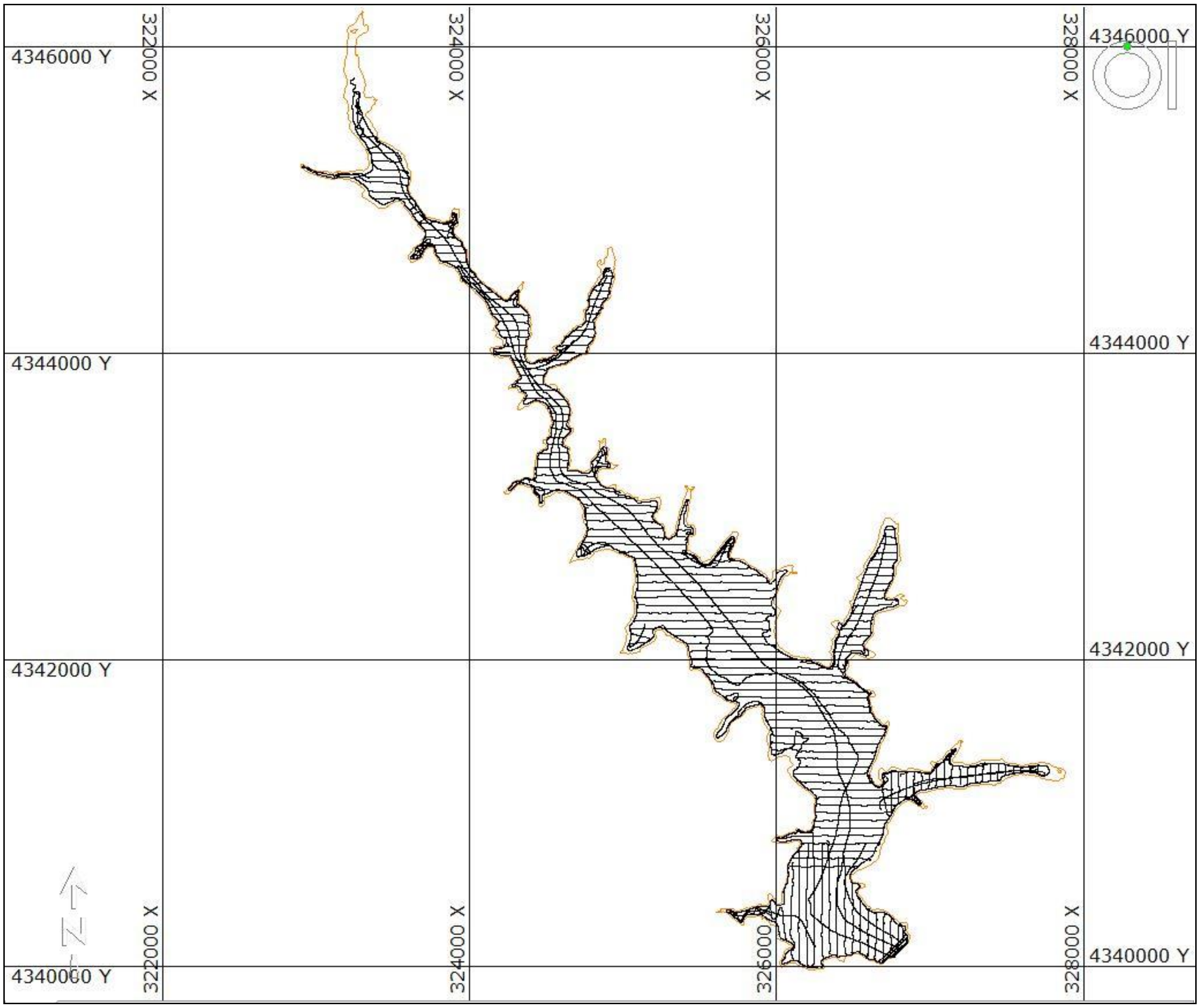

Figure 2. Sounding map of Triadelphia Reservoir with collected data points. The digitized 2004 shoreline is also plotted in brown. The reservoir surface area defined by the 2004 digitized shoreline is 824 acres (3.33 million m^2) and the shoreline length is 21 miles (35 km).

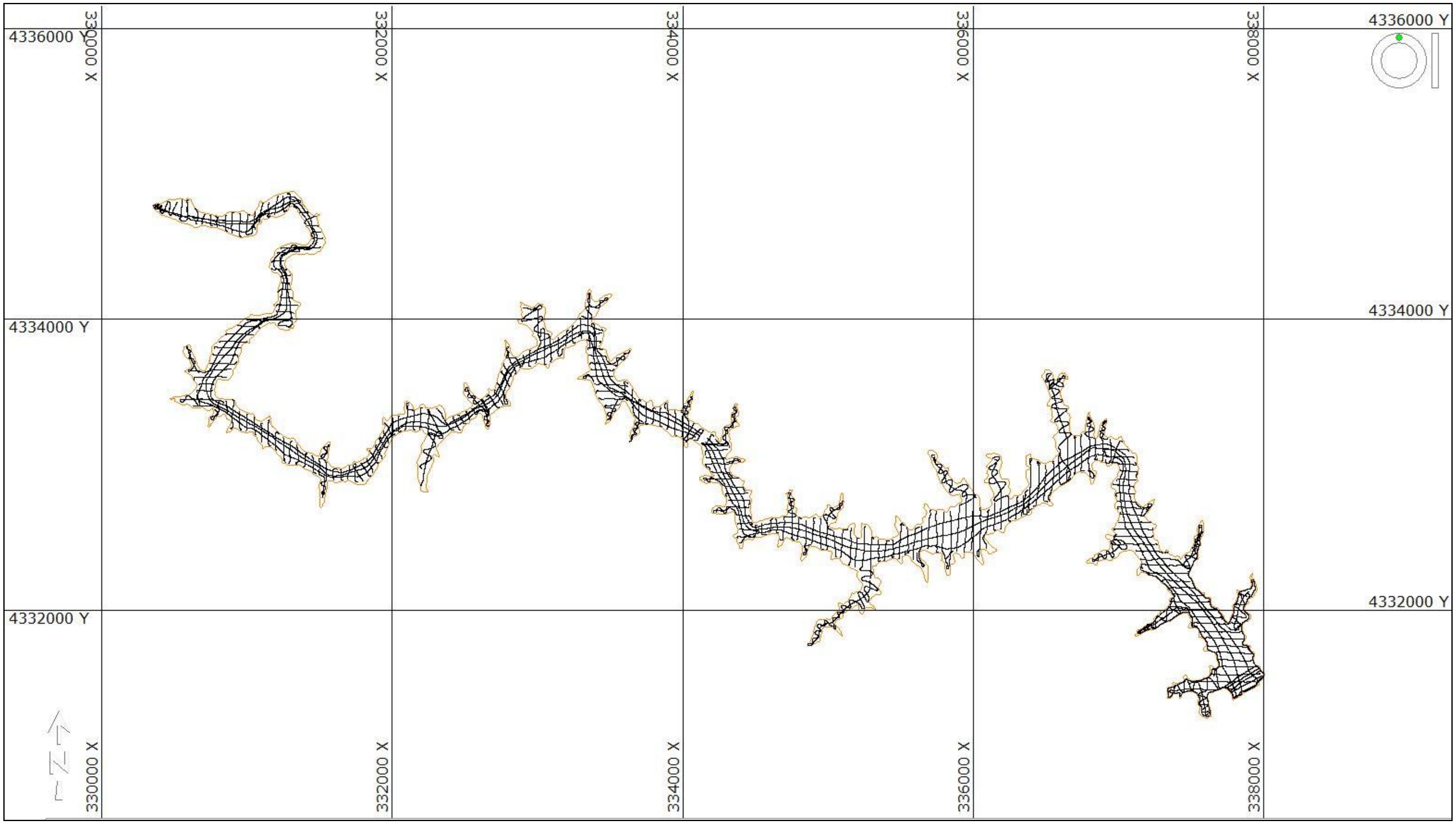

Figure 3. Sounding map of Rocky Gorge Reservoir with collected data points. The digitized 2004 shoreline is also plotted in brown. The reservoir surface area defined by the 2004 digitized shoreline is 620 acres (2.51 million m^2) and the shoreline length is 31 miles (50 km).

RESULTS AND DISCUSSION

Bathymetric Results

The 2015 bathymetry for Triadelphia Reservoir is presented in Plate 1. 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 2015 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 based on 2004-2005 residual assessment (Appendix A, Table IX). 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 6.45 billion gallons [24.4 million cubic meters]. In Rocky Gorge Reservoir, the calculated storage volume is 5.49 billion gallons [20.8 million cubic meters].

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

Reservoir	Kriging	TIN	Minimum Curvature
Triadelphia	6.41 *[24.3]*	6.41 *[24.3]*	**6.45 *[24.4]***
Rocky Gorge	5.44*[20.6]*	5.40 *[20.5]*	**5.49 *[20.8]***

Table V. Storage capacities calculated based on bathymetry collected during the 2015 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 4 and 5 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.

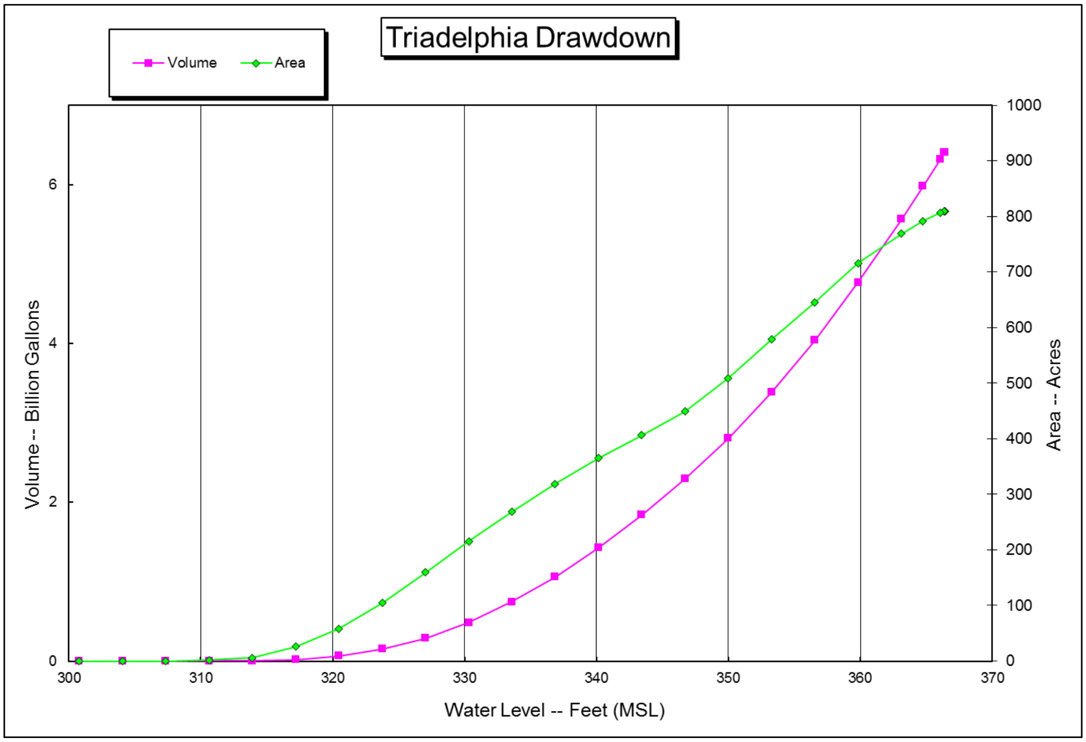

Figure 4. Drawdown curve of storage capacity and surface area versus water height in Triadelphia Reservoir.

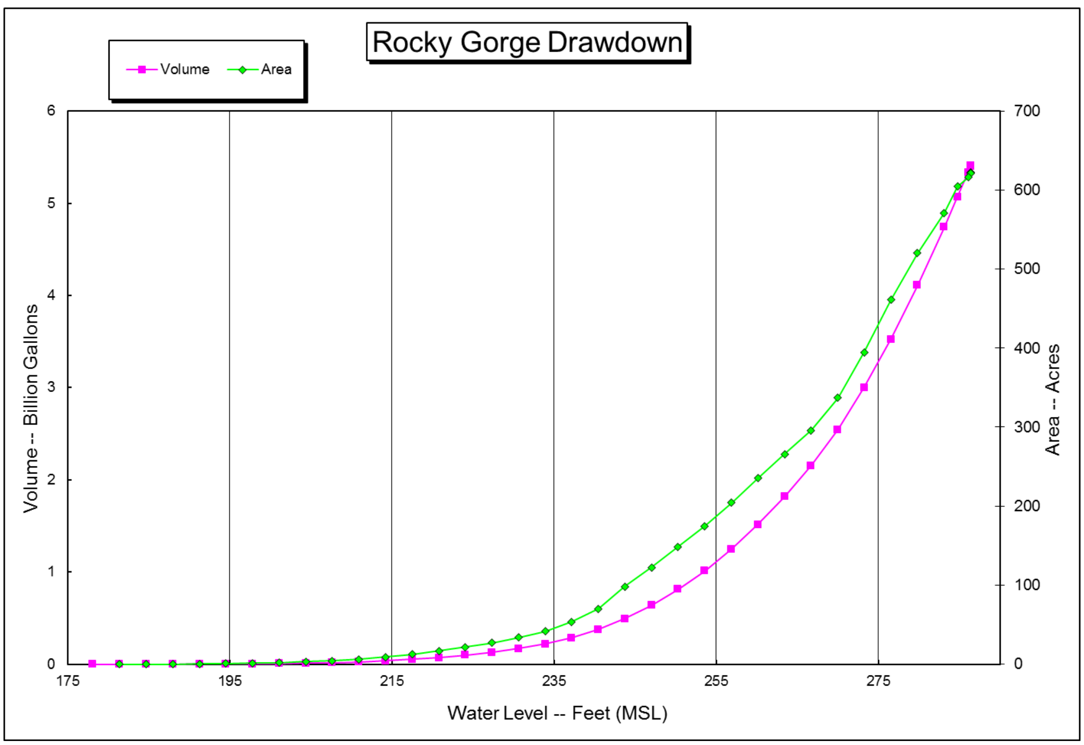

Figure 5. Drawdown curve of storage capacity and surface are versus water height in Rocky Gorge Reservoir.

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 in 2015. 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 RMS error; therefore was used to calculate original, 2004/2005, and 2015 capacity for the reservoirs (Tables VI and VII).

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]*
2015	19785 *[24.4]*	648 *[0.8]*	59 *[0.07]*	0.75 *[355]*

Table VI. Calculated storage capacity loss rates for Triadelphia Reservoir.

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]*
2015	16836 *[20.8]*	150 *[0.19]*	15 *[0.02]*	0.28 *[134]*

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

A subtraction of Triadelphia 2015 bathymetry from the 2004 bathymetry yields a positive volume (sediment gain) of 894 acre feet (1.10 million m^3) and a negative volume (internal erosion, offsets) of 245 acre feet (302,247 m^3). Net sediment volume change over 11 years is a gain of 648 acre feet (799,965 m^3) of sediment, which translates to an average annual capacity loss of 59 acre feet per year since 2004. This 11-year period average annual capacity loss is more than double the 24.2 acre feet calculated for the period between 1942 and 2004. However, the EA Engineering (1989) rates of loss varied from about 30 acre feet per year between 1964 and 1974 to as much as 71 acre feet per year between 1950 and 1964 (Table I). The OSI (1997) QuickSurf results yielded an average annual rate of loss of 40 acre feet between 1995 and 1942 (Table II). Because the average annual lose between 2004 and 2015 has increased, the cumulative average annual loss from 1942 to present has also increased from 24.2 acre feet to 29.4 acre feet per year (Table VI). The MGS volumes for Triadelphia Reservoir do not include any sediment removed by excavation during occasional periods of significantly lower water levels. WSSC has an active sediment removal program of the upper tributary confluence areas of the reservoir.] A permit application to MDE prepared in 2006 states that ~49,100 cubic yards would be excavated from the area at the confluence of Cattail Creek and Patuxent River. Based on this information, the removal of ~30.4 ac-ft can be assumed sometime in the 2006-2007 timeframe (M. Chandler, personal communication, May 17, 2016).

A subtraction of the Rocky Gorge 2015 bathymetry from the 2005 bathymetry yields a positive volume of 688 acre feet (849,247 m^3) of sediment and a negative volume of 538 acre feet (664,099 m^3) of sediment. Net sediment volume change over 10 years is a gain of 150 acre feet (185,087 m^3) of sediment, which translates to an average annual capacity loss of 15 acre feet per year since 2005. This 10-year period annual loss is significantly less than Triadelphia Reservoir which has a larger watershed area and is nearly half the annual loss calculated for the 1954 to 2005 period. The lower average annual loss between 2005 and 2015 decreases the cumulative average annual loss since 1954 from 28.5 to 24.5 acre feet per year (Table VII). These capacity losses remain lower than the average annual loss of 47 acre feet between 1984 and 1954 (Table I) and the OSI Quick Surf results of 42 acre feet per year between 1996 and 1954 (Table III).

There are several possible sources of error in the calculations. The MGS volumes are based on the area extent of the bathymetric surveys which did not go as far upstream as the 2004 shoreline. The 2004/2005 and 2015 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 1,139,275 m^3 (3,300,333 m^2 x 0.35 m), or 4.7% error, for Triadelphia Reservoir, and an error estimate of 866,980 m^3 (2,511,530 m^2 x 0.35 m), or 4.2% error, for Rocky Gorge Reservoir. These error estimates are much lower than the values comparing the 2004/2005 data to the original topography which yielded errors of 12% for Triadelphia Reservoir and 11% for Rocky Gorge Reservoir, due to the datums and the 5 foot contour intervals on the 1954 topography dataset (Ortt et. al., 2007).

However, even with 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). Slightly variable sediment accumulations are shown in the low relief central portions of Triadelphia Reservoir with erosional areas predominately in restricted channels and along higher relief edges (Plate 3). The general pattern is mixed accumulation and erosion. The isopach map for Triadelphia Reservoir also shows two distinct yet small areas of high deposition seen as darker red that are a result of the survey points in 2015 being collected a few meters apart from those collected in 2004. Due to the high relief in these areas, a very small shift in survey line position created a higher than realistic depositional isopach contour.

Sediment accumulation patterns in Rocky Gorge Reservoir indicate a slightly different distribution (Plate 4). As was recorded in 2005, sediments have accumulated predominantly in the upstream area. The downstream area shows a mix of both accumulation and erosion with more erosional areas than were shown in the 2005 isopach map. Erosion is indicated along the shoreline on both sides of central channel. The Rocky Gorge Reservoir isopach map also shows a very deep erosional surface immediately behind the dam. Similar to the two depositional outliers in Triadelphia Reservoir, this erosional area is due to a survey line being collected closer to the dam in 2015 which pulled the bathymetric contours closer to the dam.

Side Scan Sonar Results

The side scan sonar data provides an additional interpretive imagery layer to the bathymetric datasets. The side scan data returns are an indication of the seabed reflectivity or hardness. For the Triadelphia and Rocky Gorge reservoir datasets, the stronger returns (harder surface) are mapped as lighter brown to bright yellow while weaker returns (softer surface) are mapped as darker browns. Areas of no data shown as black are indicative of the water column or shadows created behind obstructions such as rocks, boulders, or stumps.

The side scan mosaic for Triadelphia Reservoir shows the hardened banks along the shoreline and a softer central basin (Plate 5). Pre dam stream beds are seen entering from the coves and the meandering river thalweg can still be seen throughout the lower portions of the reservoir where historic sediment deposition has been lower. The Brighton Dam structure shows minimal debris behind the dam and the river thalweg is still clearly defined (Figure 6).

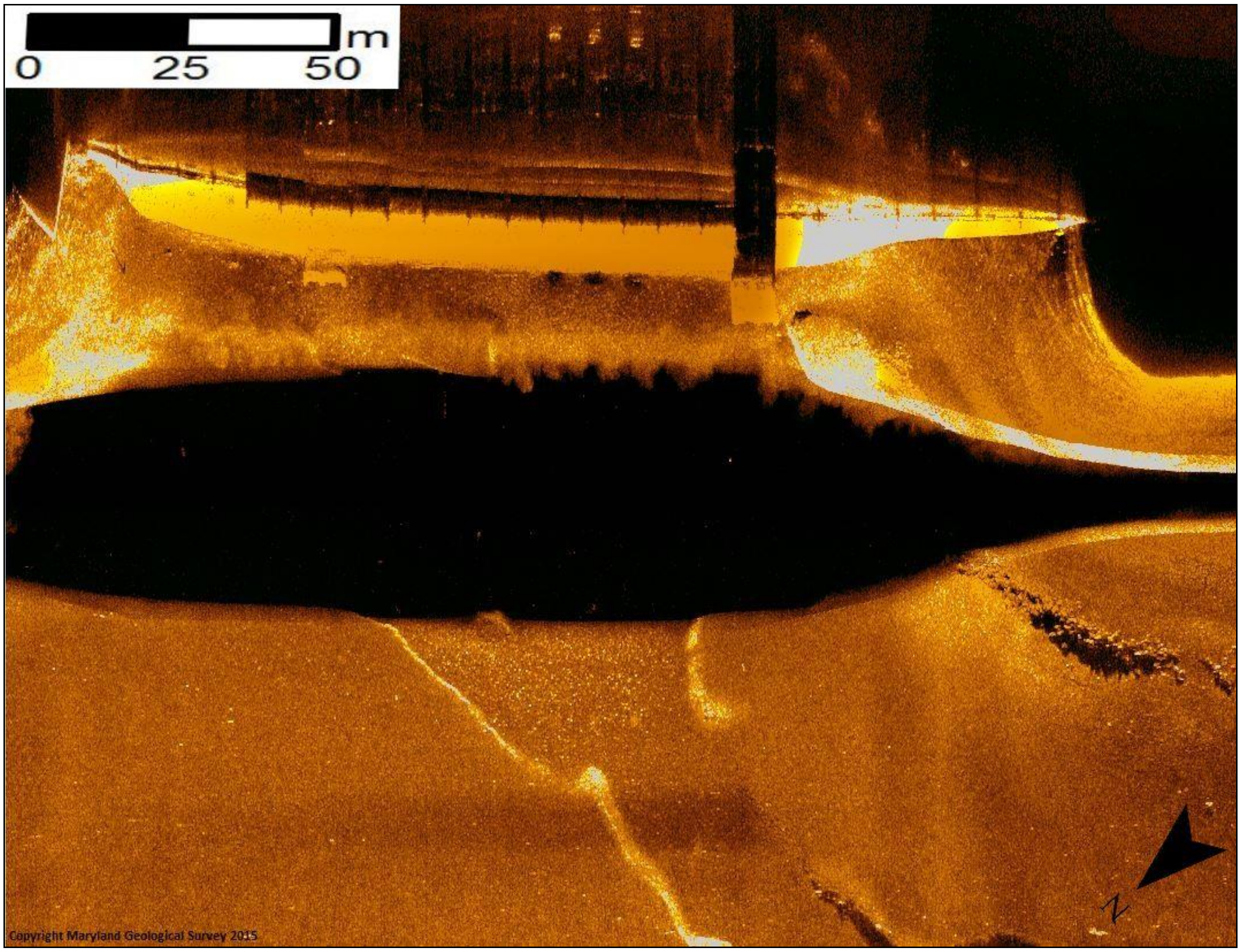

Figure 6. Side scan imagery of Brighton Dam structure on Triadelphia Reservoir.

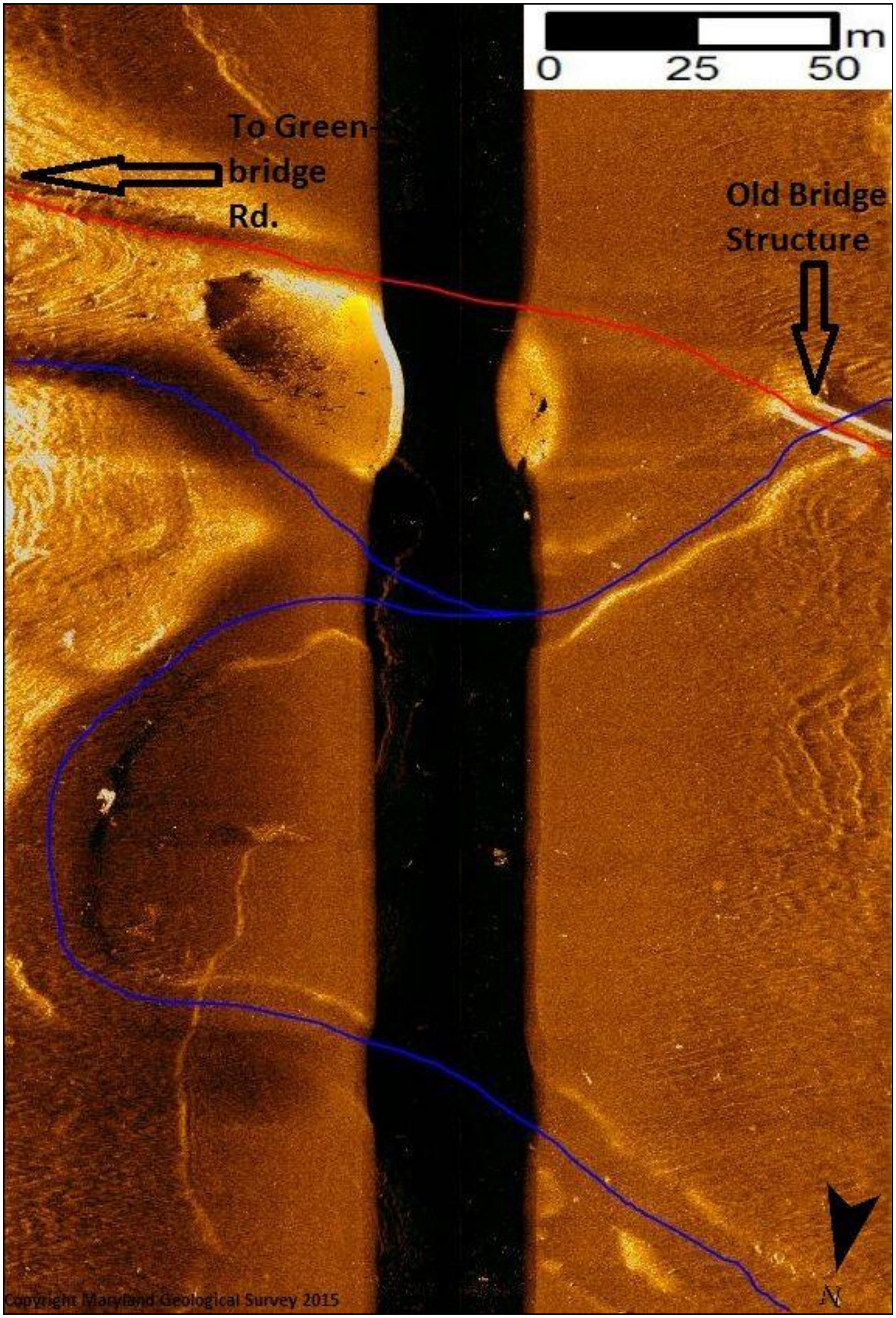

Figure 7. Side scan imagery of Triadelphia Reservoir lakebed structures. Blue line marks pre dam river thalweg and red line marks roadbed extending out from Greenbridge Road boat ramp leading to remnant bridge structure.

The thalweg is still clearly defined in the area of Greenbridge Road where the extension of the roadbed, which is currently used as the boat ramp, is seen extending out to a remnant bridge structure which crosses the meandering thalweg (Figure 7). The thalweg remains deeper than the surrounding lake bed as seen in the slight increase in the distance between the side scan towfish and the first return. The thalweg edges are also clearly defined by the hardened edges of the pre dam river, seen as brighter yellow meandering lines on either edge of the thalweg.

The Rocky Gorge Reservoir side scan mosaic also shows hardened banks along the shoreline and a softer central basin (Plate 5). However, due to the steeper topography, the hardened edges are broader in Rocky Gorge Reservoir, especially in the eastern half, which is near the dam. The pre dam river thalweg is again visible throughout much of the reservoir but becomes less defined in the upriver portion. The side scan near the dam shows the deeper water depths in comparison to Triadelphia Reservoir as well several large rock clusters and some amount of debris behind the dam (Figure 8). The rows of aerators that were operating during data collection were also clearly defined in the side scan data along the lakebed as well as within the water column due to the change in density created by the air bubbles (Figure 9). The thalweg continues to be clearly defined slightly northwest of the Route 29 Bridge, as seen where the pre dam streambed meanders around the hardened, rocky point along the southern shoreline about 650 yards (600 meters) upriver of the bridge (Figure 10).

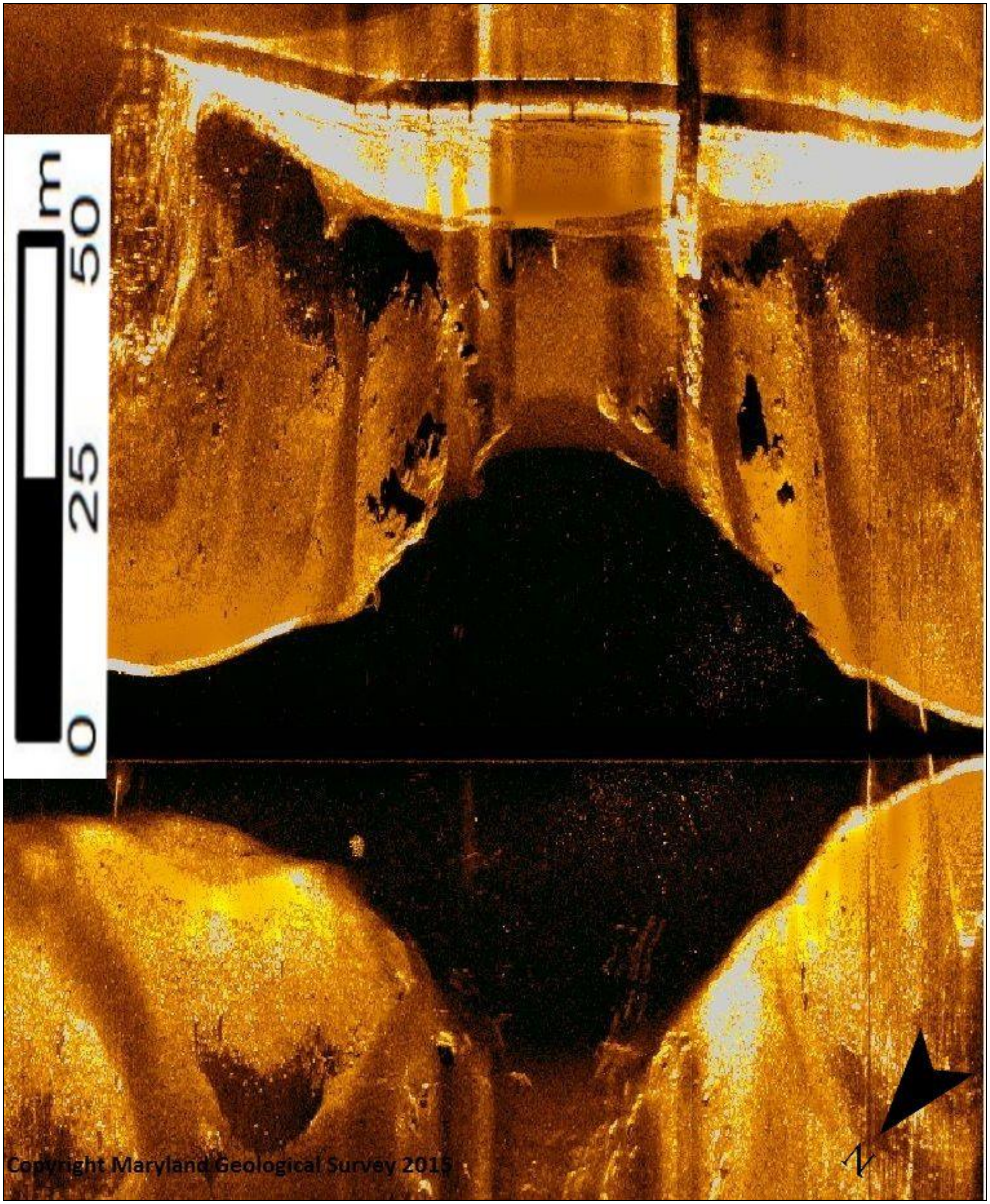

Figure 8. Side scan imagery of Rocky Gorge Reservoir dam structure.

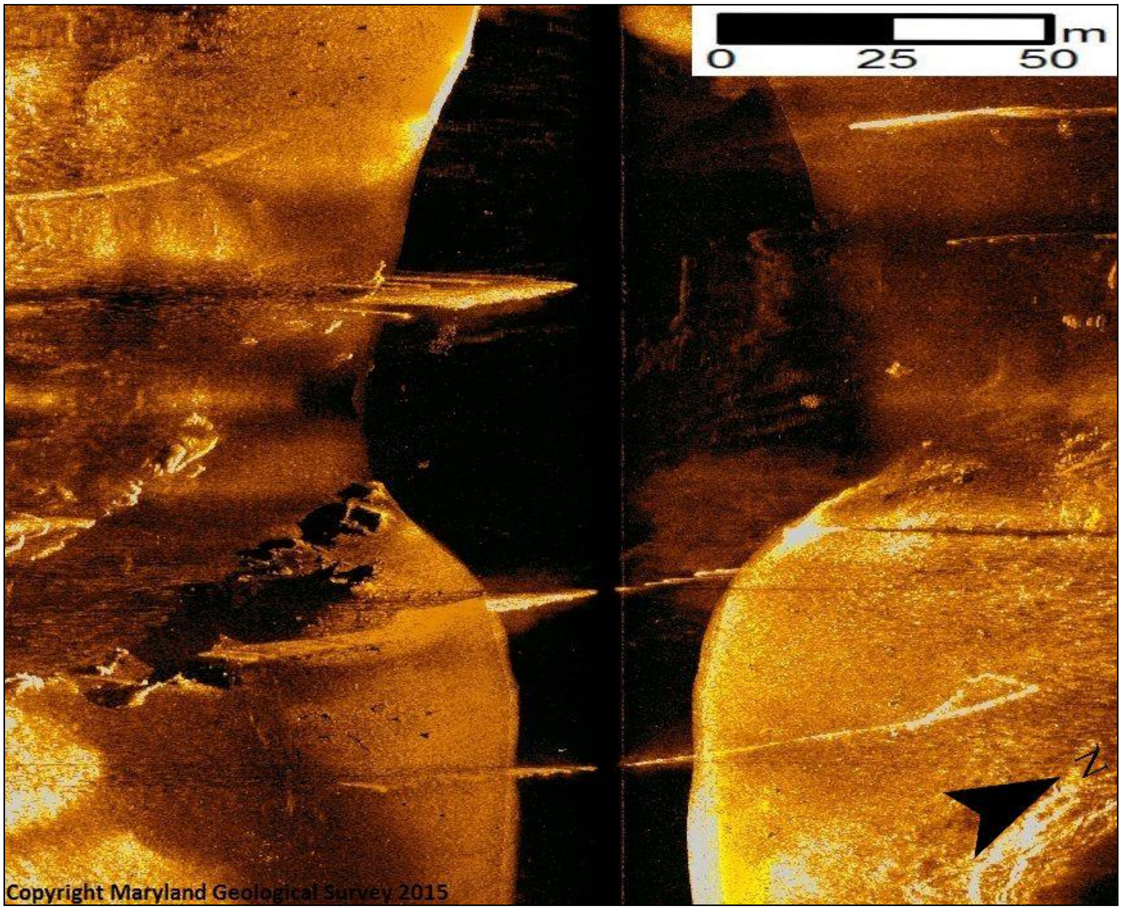

Figure 9. Side scan imagery of aerators operating in Rocky Gorge Reservoir.

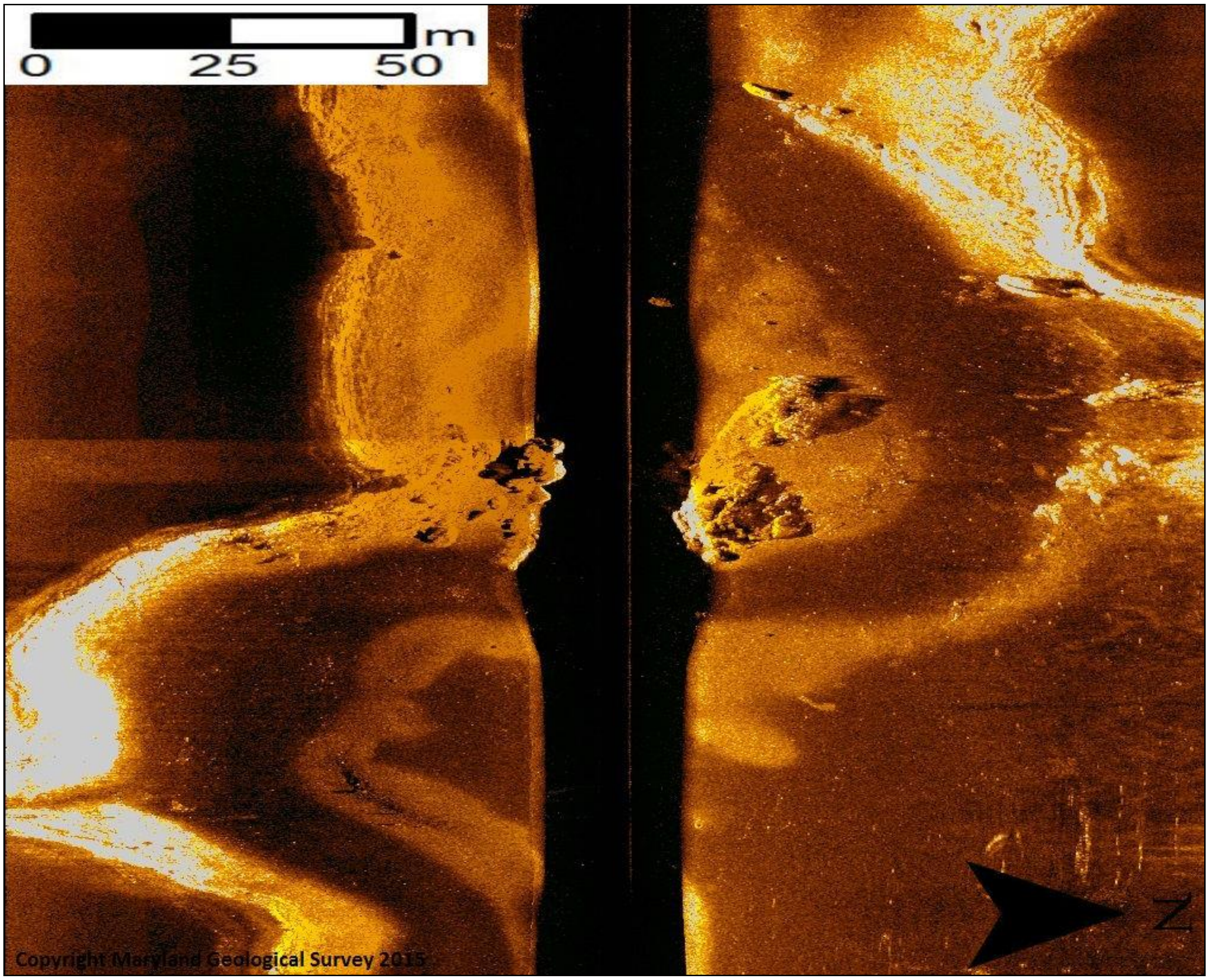

Figure 10. Side scan imagery of pre dam river thalweg meandering around rocky point along the southern shoreline about 650 yards (600 meters) upriver of the Route 29 bridge in Rocky Gorge Reservoir.

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 (refer to Appendix C). Further analysis of this dataset may provide insight into other sediment related issues.

CONCLUSION

The current storage capacity of Triadelphia Reservoir is 24.4 million cubic meters [6.45 billion gallons] and the capacity of Rocky Gorge Reservoir is 20.8 million cubic meters [5.49 billion gallons]. The bathymetric datasets from which these capacities were calculated represent complete coverages of the reservoirs. The data points included in MGS 2004/2005 datasets were uniformly distributed to provide a solid base for future comparisons. The 2015 MGS data points followed the previous distribution pattern to allow direct comparisons between the two datasets while using the same digitized shoreline for consistency. This resulted in the volumetric errors being decreased in Triadelphia and Rocky Gorge Reservoirs from 12% to 4.7% and 11% to 4.2%, respectively, when comparing the 2004/2005 study to the 2015 study. The results reveal that both reservoirs continue to have a mix of both depositional and erosional environments and the bathymetry in conjunction with the side scan imagery show that the depositional environments are predominately in the northern extents of Triadelphia Reservoir and western extents of Rocky Gorge Reservoir. The side scan imagery shows hardened banks along the shoreline and softer central basins within both reservoirs with the hardened shorelines being broader in Rocky Gorge Reservoir. The side scan imagery also revealed the pre dam stream bed thalwegs throughout the lower portions of both reservoirs with decreased presence in the upriver portions and coves where historic sediment deposition has been higher. The imagery behind both dams indicated there is very little sediment accumulation behind the dams with minimal debris behind Brighton Dam in Triadelphia Reservoir and several large rock clusters with some amount of debris behind the T. Howard Duckett Dam in Rocky Gorge Reservoir.

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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 reservoirs 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)	Known Depth		Measured Depth (Meters)
(feet)	(meters)	(going down)	(feet)	(meters)	(going up)
2	0.6096	0.33	60	18.288	18.65
3	0.9144	0.63	55	16.764	17.06
4	1.2192	0.97	50	15.24	15.49
5	1.524	1.31	45	13.716	13.92
10	3.048	2.86	40	12.192	12.29
15	4.572	4.42	35	10.668	10.7
20	6.096	5.96	30	9.144	9.18
25	7.62	7.55	25	7.62	7.56
30	9.144	9.11	20	6.096	6.02
35	10.668	10.72	15	4.572	4.43
40	12.192	12.33	10	3.048	2.86
45	13.716	13.86	5	1.524	1.33
50	15.24	15.44	4	1.2192	1
55	16.764	16.98	3	0.9144	0.68
60	18.288	18.56	2	0.6096	0.34

Table VIII. Echosounder Calibration on April 20, 2015. Regression analysis = Actual=0.9683*Measured Depth +0.28 meters. $R^2 = 1.00$. The equivalent speed of sound in water derived from this calibration is 1446 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 and comparison of all datasets, the bathymetric and topographic data of Triadelphia (2004), Rocky Gorge (2005), Triadelphia (2015), and Rocky Gorge (2015) 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 2015 models was analyzed using residuals in the 2004/2005 data sets. 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 (RMS) error analysis was performed on these residuals. The 2015 data was gridded using identical grid geometry that was used for the 2004/2005 dataset to include grid size, spacing and min/max coordinates in conjunction with the same blanking files to define the shoreline. Therefore, for direct comparison of the 2015 data to the 2004/2005 data, the Minimum Curvature model was replicated for this study. If a different grid method were used to model the 2015 data, the 2004/2005 data would also have needed to be modeled using the same grid method resulting in higher RMS error.

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 IX. Residual root-mean-square analyses of the 2004-2005 bathymetric data compared (Ortt et al., 2007).

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 and Time (EST)	**Water Level (ft)**	**Depth Adjustment (ft)**
TRIADELPHIA RESERVOIR		
4/24/2015 6:00	364.26	2.14
4/24/2015 18:03	364.27	2.13
4/27/2015 6:03	364.44	1.96
4/27/2015 18:03	364.35	2.05
4/28/2015 6:03	364.18	2.22
4/28/2015 18:03	364.01	2.39
4/29/2015 6:03	363.84	2.56
4/29/2015 18:00	363.73	2.67
ROCKY GORGE RESERVOIR		
4/20/2015 6:00	283.56	2.84
4/20/2015 18:00	284.00	2.40
4/21/2015 6:00	284.10	2.30
4/21/2015 18:00	284.00	2.40
4/22/2015 6:00	283.90	2.50
4/22/2015 18:00	283.65	2.75
4/23/2015 6:00	283.40	3.00

Table X. Mean Pool Level Recordings and Adjustments

APPENDIX C: DVD 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
2300 Saint Paul Street
Baltimore, MD 21218
(410)554-5500
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
Surfer Grid and XYZ Dat files
Raw Echosounder Data in KEA and KEB formats
KEB file viewer program (Windows 98 or higher)
Side Scan waterfall imagery PNG files
Side Scan Mosaic GeoJPG files