

In cooperation with the Pennsylvania Department of Environmental Protection

Bathymetry and Sediment-Storage Capacity Change in Three Reservoirs on the Lower Susquehanna River, 1996–2008



Scientific Investigations Report 2009–5110

Cover.

**Photograph showing Conowingo Dam and Reservoir, south of Conowingo, Md. View is looking north.
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Bathymetry and Sediment-Storage Capacity Change in Three Reservoirs on the Lower Susquehanna River, 1996–2008

By Michael J. Langland

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**U.S. Department of the Interior
U.S. Geological Survey**

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Conversion Factors, and Datums

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
Area		
acre	4,047	square meter (m ²)
acre	0.4047	square hectometer (hm ²)
acre	0.004047	square kilometer (km ²)
Volume		
acre-foot (acre-ft)	1,233	cubic meter (m ³)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm ³)
Flow rate		
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
Mass		
ton, short (2,000 lb)	0.9072	megagram (Mg)
Density		
pound per cubic foot (lb/ft ³)	16.02	kilogram per cubic meter (kg/m ³)
pound per cubic foot (lb/ft ³)	0.01602	gram per cubic centimeter (g/cm ³)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Bathymetry and Sediment-Storage Capacity Change in Three Reservoirs on the Lower Susquehanna River, 1996–2008

By Michael J. Langland

Abstract

The Susquehanna River transports a substantial amount of the sediment and nutrient load to the Chesapeake Bay. Upstream of the bay, three large dams and their associated reservoirs trap a large amount of the transported sediment and associated nutrients. During the fall of 2008, the U.S. Geological Survey in cooperation with the Pennsylvania Department of Environmental Protection completed bathymetric surveys of three reservoirs on the lower Susquehanna River to provide an estimate of the remaining sediment-storage capacity. Previous studies indicated the upper two reservoirs were in equilibrium with long-term sediment storage; only the most downstream reservoir retained capacity to trap sediments. A differential global positioning system (DGPS) instrument was used to provide the corresponding coordinate position. Bathymetry data were collected using a single beam 210 kHz (kilohertz) echo sounder at pre-defined transects that matched previous surveys. Final horizontal (X and Y) and vertical (Z) coordinates of the geographic positions and depth to bottom were used to create bathymetric maps of the reservoirs.

Results indicated that from 1996 to 2008 about 14,700,000 tons of sediment were deposited in the three reservoirs with the majority (12,000,000 tons) being deposited in Conowingo Reservoir. Approximately 20,000 acre-feet or 30,000,000 tons of remaining storage capacity is available in Conowingo Reservoir. At current transport (3,000,000 tons per year) and deposition (2,000,000 tons per year) rates and with no occurrence of major scour events due to floods, the remaining capacity may be filled in 15 to 20 years. Once the remaining sediment-storage capacity in the reservoirs is filled, sediment and associated phosphorus loads entering the Chesapeake Bay are expected to increase.

Introduction

Sediment, nitrogen, and phosphorus enrichment has adversely affected the Chesapeake Bay. Excess nutrients stimulate algal blooms that decay and consume dissolved oxygen, causing areas with low concentrations of dissolved oxygen in

the bay. Algal blooms and sediment block the sunlight needed by submerged aquatic vegetation. Excessive sediments can remain in suspension also reducing sunlight and can obstruct fish gills. In the mid-1980s, the Chesapeake Bay Program (CBP), a partnership between the Commonwealths of Pennsylvania and Virginia, the State of Maryland, the District of Columbia, the Federal Government, and the Chesapeake Bay Commission, began efforts to reduce nutrients and sediments in the bay. Improvement in water-quality conditions in the bay has been slow; the bay was listed as an “impaired” water body under the regulatory statutes related to the Clean Water Act. The CBP developed water-quality criteria for the bay (U.S. Environmental Protection Agency, 2003) and is implementing measures to reduce nutrients and sediments entering the bay in an attempt to meet these criteria by 2010.

In a year of normal streamflow, the Susquehanna River contributes nearly 50 percent of the freshwater discharge to the Chesapeake Bay. It also transports the greatest amount of nutrients—estimates of nearly 66 percent of the nitrogen and 40 percent of the phosphorus load—from non-tidal areas in the Chesapeake Bay Basin (Langland and others, 1995). The Susquehanna River in a normal-flow year also contributes about 25 percent of the sediment load from non-tidal areas to the bay (Langland and others, 1995).

A system of three reservoirs in the lower Susquehanna River (fig. 1) currently traps a substantial part of the phosphorus and suspended-sediment load and to a lesser extent the nitrogen load (Ott and others, 1991). The U.S. Geological Survey (USGS) completed bathymetry studies in the reservoirs in 1990, 1993, and 1996 to document change in depth to bottom and to determine remaining sediment-storage capacity.

Purpose and Scope

For each of the three reservoirs in the lower Susquehanna River, this report (1) presents results of the bathymetric surveys (depth to bottom) during the fall of 2008, (2) documents the change in water and sediment-storage capacity, (3) provides estimates of the remaining sediment-storage capacity, and (4) examines long-term capacity changes since 1929. In addition, the methods and equipment used to collect, estimate, and quality assure these data are summarized.

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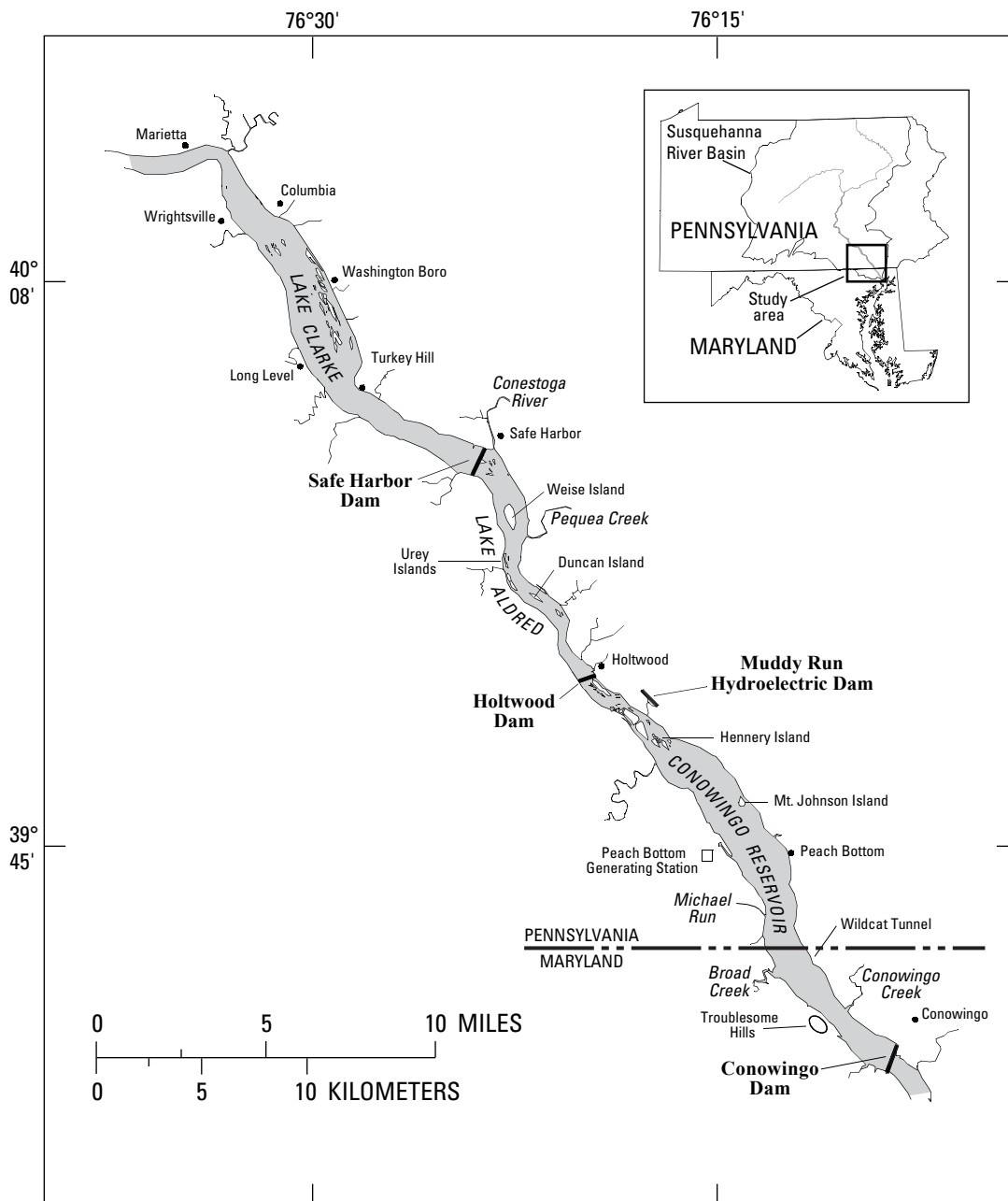


Figure 1. Location of the three reservoirs in the lower Susquehanna River Basin.

Study Area

The Susquehanna River Basin extends from south-central New York State near Cooperstown, N.Y., through central and southern Pennsylvania and northeastern Maryland, draining 27,510 mi², and enters the Chesapeake Bay near Havre de Grace, Md. Forests cover about two-thirds of the basin and are concentrated in the northern and western parts of the basin. Agricultural land use makes up about one-quarter of the basin area. Most agricultural land is tilled and is predominantly located along the river valleys in southern New York/northern Pennsylvania and in southern Pennsylvania. Urban settings comprise about one-tenth of the basin, mostly in the southern part of the basin. Annual precipitation ranges from an average of about 34 in. in southern New York State to over 46 in. in areas of central Pennsylvania. The lower Susquehanna River Basin is defined as the area downstream from the confluence of the West Branch Susquehanna River near Sunbury, Pa., to the mouth of the river (Sprague and others, 2000).

Three hydroelectric dams are located in the lower part of the Susquehanna River Basin near its terminus with the Chesapeake Bay. Two of the dams (Safe Harbor and Holtwood) are in south-central Pennsylvania, and the third dam, Conowingo, is in northern Maryland (fig. 1). The most upstream dam is Safe Harbor Dam. Constructed in 1931, it forms Lake Clarke and is located 32 mi upstream from Chesapeake Bay. Lake Clarke extends about 9.5 mi from Safe Harbor, Pa., to Columbia, Pa., and the reservoir width ranges from 800 to 6,600 ft. The design water-storage capacity of Lake Clarke was 150,000 acre-ft. The middle dam, Holtwood Dam, is about 25 mi upstream from Chesapeake Bay and forms Lake Aldred. Holtwood Dam was constructed in 1910 and is the oldest of the three dams. Lake Aldred extends upstream from the dam about 8 mi to just below Safe Harbor Dam. The impoundment is relatively narrow along its entire reach (reservoir width ranges from 1,100 to 3,800 ft) and had an original water-storage capacity of 60,000 acre-ft. The largest and most-downstream impoundment, Conowingo Reservoir, was formed by the construction of Conowingo Dam in 1928. The dam is about 10 mi upstream from Chesapeake Bay and was originally designed to store 300,000 acre-ft of water. A more-detailed summary of dam and impoundment characteristics is provided by Hainly and others (1995).

Previous Investigations

Previous studies have documented changes in the bottom-surface profile in all three reservoirs since 1929. Surveys of Lake Clarke by Schuleen and Higgins (1953) reported an original water-storage capacity of 144,600 acre-ft in 1931, with the volume gradually decreasing to a remaining capacity of 78,800 acre-ft in 1950. Six subsequent surveys, completed in 1950, 1951, 1959, and 1964 for the Pennsylvania Power and Light Company (E.T. Schuleen, Pennsylvania Power and Light Company, written commun., 1965), 1990 (Hainly and others,

1995), and 1993 (Reed and Hoffman, 1997) indicated little change in water-storage capacity since 1950. This indicates that the reservoir had reached the sediment-storage capacity with incoming sediment loads. In 1996, a major ice jam in the upper section of Lake Clarke broke and released backed-up water. A subsequent survey concluded that this water combined with the already high river discharge to produce a major scour event that increased water-storage capacity in all three reservoirs (Langland and Hainly, 1997).

Siltation surveys in Lake Aldred in 1939, 1950, and 1961 were described by Ledvina (1962) and suggested the amount of sediment stored in the reservoir decreased over time. Subsequent surveys by the USGS in 1990 (Hainly and others, 1995) and 1993 (Reed and Hoffman, 1997) indicated no appreciable changes since 1961. Reasons for the reduction in sediment storage prior to 1961 included coal dredging and construction of the upstream Safe Harbor Dam (Reed and Hoffman, 1997).

Whaley (1960) concluded that the water-storage capacity in Conowingo Reservoir was reduced from the original 300,000 acre-ft to about 235,000 acre-ft. Subsequent bottom-surface profiles in 1990 and 1993 indicated continuing reductions in water-storage capacity to about 169,000 acre-ft in 1993 (Reed and Hoffman, 1997). As a result of a major scour event in January 1996, a survey completed in 1997 concluded that the remaining sediment-storage capacity in Conowingo Reservoir actually increased to 170,600 acre-ft (Langland and Hainly, 1997). For this current study, the value of 170,600 is rounded to 171,000 acre-ft.

Methods and Approach

To accomplish this project, several primary tasks were performed. These tasks included office preparation, data collection and analysis, and quality assurance. The following sections describe each of the tasks in more detail and the approach used in this study.

Office Preparation

Initially, the USGS contacted the hydroelectric dam utility owners to inform them of plans to resurvey the reservoirs. Geo-referenced aerial photographs of York and Lancaster Counties in south-central Pennsylvania showing the reservoirs and surrounding areas were acquired and geo-referenced for incorporation into navigation-support software HYPACK™. Aerial photographs were not acquired for northern Maryland; however, the reservoir boundaries were obtained from digitized maps. HYPACK™ is a navigation software package that integrates the reservoir-bottom depths with the Differential Geo-Positional Satellite (DGPS) positional data and displays the location of the boat on a geo-referenced aerial photo of the reservoir to aid in navigation. Using latitude and longitude coordinates from previous surveys, the pre-existing transects were plotted within HYPACK™. These transects were

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determined by complexities inherent in each reservoir such as geometry, alignment of the shore, and features such as islands and confluence points of tributaries. In general, the transect lines were perpendicular to the shore edge. Spacing between transects averaged 2,000 ft. The transect lines were used to guide the boat during the survey and improve overall boat navigation. Equipment used in the survey was assembled at the office and tested in the reservoirs to verify proper operation.

Data Collection

Various pieces of equipment were used to ensure accurate depth and geo-spatial locations of the surveys. A standard field method of data collection was established to maintain consistency in the bathymetric surveys among the three reservoirs.

Equipment

A brief list of the field equipment used in this study is presented below. Additional information can be found in Hittle and Ruby (2008).

- DGPS data-processing software.
- An 18-ft Boston Whaler accommodating a crew of two people with some protection from the elements.
- An echo sounder and transducer with an appropriate frequency for the depth of the reservoirs. This survey used a 210 kHz (kilohertz) ODOM™ transducer and a Navisound™ 210 Reson echo sounder, a depth range from 0.6 to 600 m (Reson Inc., 2005), and thermal recording paper as backup.
- A Trimble™ DGPS system and a differential correction service from Omni Star™.
- A backup DGPS unit from Rockwell™.
- A laptop computer with the HYPACK™ software package installed.
- A second monitor for the boat operator to view the pre-defined transects, boat location, and heading, allowing the boat operator to follow the transects and maintain safe operation of the boat.
- A laser range finder with a compass module enabling determination of azimuth and distance measurements from the boat to the shoreline.

Field Methods

The staff required to collect the bathymetry and geo-referenced position data consisted of two people: the boat operator and the equipment operator. The ODOM™ transducer was mounted on the port (left) side of the boat with the

DGPS antenna mounted directly above the transducer. Each day before starting, an offset corresponding to the depth of the transducer in the water was measured and entered into the Navisound™. The laser range finder was used to make the shoreline measurements from as close to the transducer position as possible to correlate to the boat position.

Data collection in each reservoir followed the pre-defined transect lines created in HYPACK™ to ensure the data collected would closely correspond to the previously collected bathymetry data (Langland and Hainly, 1997). The procedure for each of the pre-defined transect lines included (1) the boat was held stationary at one end of the transect near the shore while the laser range finder measured the distance and azimuth (bearing) reading to the shoreline, (2) the echo sounder (depth) and DGPS (position) were started and simultaneously recorded within HYPACK™, (3) the boat proceeded to the opposite end of the transect and was stopped near the shore where distance and bearing readings were again recorded, and (4) the recording was stopped and the boat proceeded to the next transect to repeat the process. If any gaps or problems in the data were identified after the transect was completed, the transect was rerun. The completed transects for each reservoir are presented on figures later in the report.

Data Analysis

The methods for the analysis of the bathymetry data and subsequent estimation of remaining sediment-storage capacity are documented in Langland and Hainly (1997). In summary, cross-sectional profile data were collected in the reservoirs on at least nine occasions from 1939 to 1996. The most recent surveys (1990, 1993, and 1996) and new profile data collected in 2008 were used to produce bathymetry (depth to bottom) contour maps, one for each reservoir, and provide a new estimate of remaining reservoir capacity to store sediment. The majority of the cross sections profiled in 1993 and 1996 were re-profiled in 2008 to document elevation change.

Water-level elevations fluctuate due to hydroelectric activity. One-half to one hour interval water-level elevations were obtained from each of the dam operators, adjusted to the normal lake level elevations, and prorated over the time of each transect. This insured that the bathymetry was referenced to the same pool elevation levels used in previous reports. Bottom-elevation contours in each reservoir were developed from the 2008 data by plotting the cross-sectional water-depth data and connecting lines of equal depth using Geographic Information System (GIS) software and manual interpretation. The resultant bathymetry maps have a contour interval of 10 ft; therefore, sediment deposition and sediment scour less than 10 ft are not shown.

Changes in water and sediment-storage capacity and sediment mass were estimated in Lake Clarke, Lake Aldred, and Conowingo Reservoir by computing the change in water volume. Using the mid-point method, cross-sectional length multiplied by width between adjacent cross sections multiplied

by the average depth equaled the volume. By using the same transects as in previous studies, the cross-sectional area was the same. Therefore, changes in average depth from the 1996 and 2008 surveys indicated the change in water volume. Using a normalized density of dry sediment of 67.8 lb/ft³, as suggested by Reed and Hoffman (1997), multiplied by the change in volume, a change in sediment mass for a cross section was estimated.

The estimated change in sediment mass based on bathymetry also was compared to the overall load entering and leaving the reservoirs to provide an overall estimate of “error” and some verification of the change in sediment mass in the reservoirs. The sediment loads entering and leaving the reservoirs were estimated from water-quality and discharge data from two streamflow-gaging stations, the Susquehanna River at Marietta (USGS 01577600) and the Conestoga River at Conestoga (USGS 01576757) using the USGS ESTIMATOR software program (Cohn and others, 1989) and comparing the estimated loads to the Susquehanna River at Conowingo Dam (USGS 01578310) for multiple time periods. This provided estimated changes in storage capacity, average riverine sediment transport, reservoir trapping efficiency, and deposition rates.

Quality Assurance

Even though a complete analysis of the accuracy of the vertical (elevation) and horizontal (geographic position) data was beyond the scope of this study, every effort was made to minimize error. For example, the equipment and procedures used in the collection of the bathymetric data were based on methods used in other USGS bathymetric survey studies (Wilson and Richards, 2006; Hittle and Ruby, 2008). Several quality-assurance diagonal transects were created and surveyed so the depths collected at the same point from two different paths could be compared.

The Navisound™ 210 Reson echo sounder has an accuracy of 0.06 ft at 210 kHz (Reson Inc., 2005). A built-in bar-check utility allowed for depth verification using a correction for the speed of sound. Following the advice of the U.S. Army Corps of Engineers (2002) to adequately calibrate a fathometer, a multi-depth bar check of the echo sounder was undertaken each day to ensure accurate depth soundings. The calibration involved lowering a 2 ft by 4 ft plate to a known depth of 6 ft below the transducer. If the calibration depth was sensed correctly, the speed-of-sound setting was verified. If the calibration depth was sensed incorrectly, the echo sounder was calibrated to the correct depth. In this study, the echo sounder always reported the correct depths for the bar check. The precision of the bar checks was affected by wave action on the reservoirs. The vertical accuracy of the echo sounder was conservatively estimated to be ± 0.5 ft. The echo sounder recorded the depth data in both analog and digital formats. A thermal paper recorder was used for backup to the digital data during office processing.

To ensure accurate coordinate-system data, two DGPS units were operated. One DGPS recorded and the other was used for quality-assurance purposes. Multiple daily field checks verified that the units were both within 5–10 ft horizontally. Because of hydroelectric power generation, the reservoir elevations could change substantially during the time when the data were collected. Using one-half hour or hourly interval water-level-elevation data collected from each hydroelectric facility, the bathymetry data were adjusted to the normal lake-level elevations unique for each reservoir. To help improve the accuracy of the distance and bearing measurements from the transducer location to the shoreline point, the equipment setup on the boat was configured so that the transducer was mounted on the port side with the DGPS antenna mounted directly above the transducer. The operator of the laser range finder would make the shoreline-edge measurements from this position and the boat operator on the starboard (right) side reduced the roll of the boat during surveys. In addition, the equipment operator took detailed notes (weather, current transect number, starting and ending points, etc.) to aid in field and office processing of the data.

Raw bathymetry data were processed within HYPACK™ to filter (1) multiple-return acoustic signals in shallow water, (2) erroneous DGPS signals, and (3) redundant areas (backtracking) caused by equipment limitations. Raw data were viewed (fig. 2) and edited (fig. 3). The edited X and Y (horizontal position coordinates) and Z (vertical depth coordinate) were exported into X, Y, Z data files. On the basis of the speed of the boat (4 mi per hour) and number of data points collected (10 per second), questionable data (spikes) were generally removed if the recorded depth of the spike was less than one-half of a second (approximately 5 ft of surface travel). The X, Y, Z data files were used for the analysis of remaining reservoir water and sediment-capacity change and various GIS applications.

Bathymetry and Sediment-Storage Capacity Change from 1996 to 2008

This section provides an estimate of change in sediment on the basis of the volume change from the 1996 and 2008 surveys, a discussion of long-term transport to reservoirs to help determine the rate of capacity loss (fill-in), and an estimate of time remaining until the reservoir system is at sediment-storage capacity.

The depth-to-bottom data collected from each reservoir were adjusted to the normal lake-level elevations established by the hydroelectric power utilities. GIS was used to filter data points and produce maps showing contoured 10-ft water depths. The water depths shown on the maps for the three reservoirs **should not** be used as a boating guide. The release of stored water can cause lake levels to change rapidly and sediment bars can form in unexpected locations because of changes in local currents from storm to storm. In addition, the

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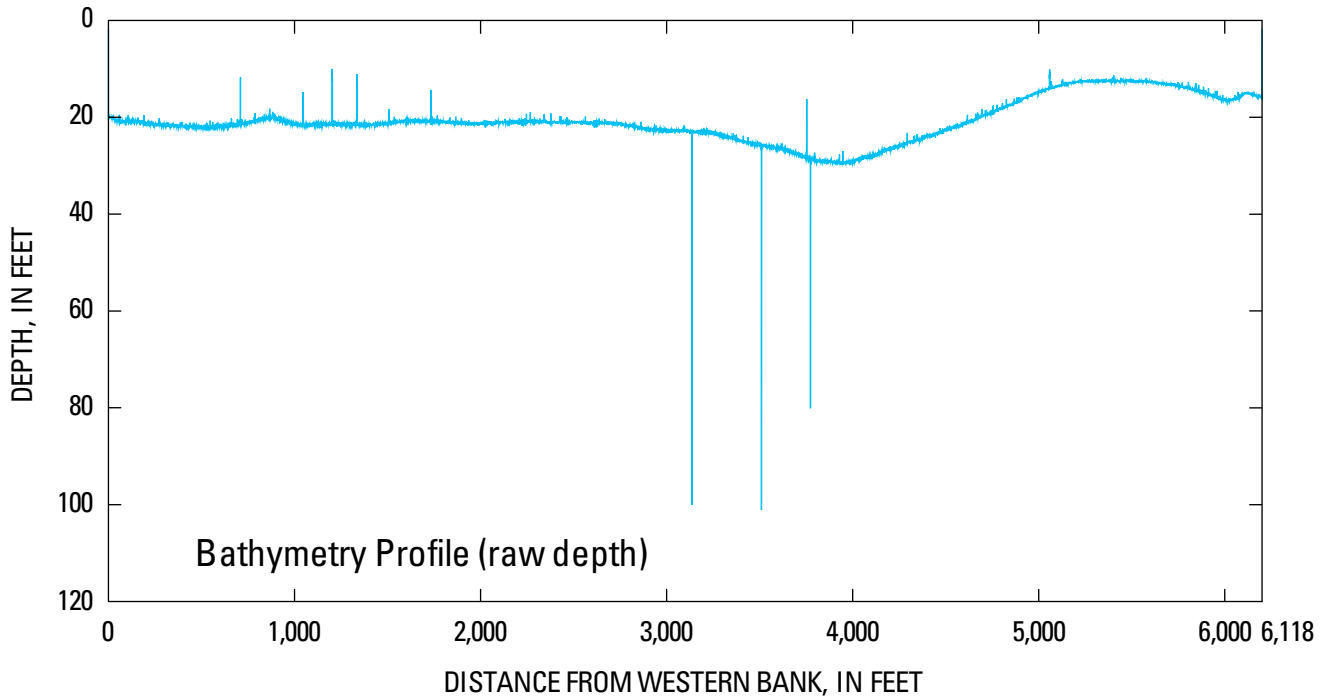


Figure 2. An example of a raw graph of the relation between depth (vertical axis) and distance (horizontal axis) collected and displayed in HYPACK™ in Conowingo Reservoir transect number 17.

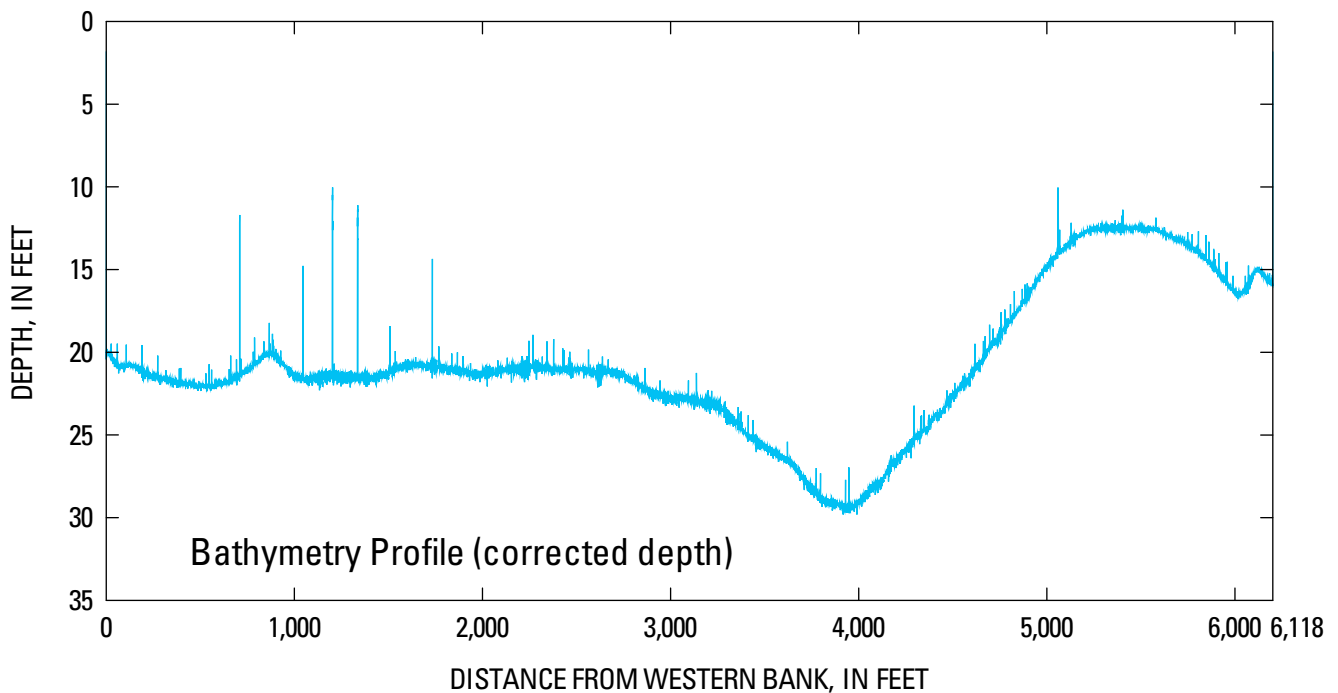


Figure 3. A generalized example of an edited graph of the relation between depth (vertical axis) and distance (horizontal axis) displayed in HYPACK™ in Conowingo Reservoir transect number 17. Erroneous data shown as spikes in figure 2 were removed. Note that the depth scales differ between figures 2 and 3.

reservoirs contain many partially or fully submerged obstacles such as bedrock ledges, rocks, trees, and stumps that were not within the transects, and were therefore not mapped.

A change in the depth to bottom elevation of a reservoir reflects a change in the volume of water and, therefore, the storage capacity of the reservoir. Changes in bottom surface indicate a change in the quantity of sediment caused by scour or deposition or represent movement in bottom sediments. Although major scour events increase the storage capacity in the short term, the mass of incoming sediments in the reservoirs fills that capacity relatively quickly, 2–4 years for most scour events (Langland and Hainly, 1997). The extreme case was Hurricane Agnes in 1972, when an estimated 20,000,000 tons of sediment was scoured from the reservoirs (Gross and others, 1978) and most likely took about a decade to fill back in (Reed and Hoffman, 1997). In this report, changes in bottom-surface elevations are discussed and compared in two ways: (1) cross-sectional data collected in 1996 and 2008 were used to estimate change in bottom elevation, water volume, storage capacity, and sediment mass within the

reservoirs, and (2) net sediment-mass change estimated from the cross-sectional data was compared to the sediment loads entering and leaving the reservoirs estimated from the monitoring data.

A streamflow threshold of at least 390,000 ft³/s (Lang, 1982) is usually required to scour sediments in the reservoirs. Color changes in the monitored sediments (from light brown to dark brown and black) provide an indication when streamflows begin to scour the darker anoxic bottom sediments. Between the 1996 and 2008 surveys, three flood events occurred with streamflows capable of scouring sediments in the reservoirs (fig. 4). On September 19 and 20, 2004, the daily mean streamflows at Conowingo were 495,000 and 545,000 ft³/s, respectively. On April 4, 2005, the daily mean streamflow was 394,000 ft³/s, and on June 29, 2006, the daily mean streamflow was 403,000 ft³/s. The highest instantaneous streamflow (620,000 ft³/s) occurred on September 19, 2004. Using the nonlinear relation between streamflow and bed-sediment scour (Langland and Hainly, 1997), an estimated

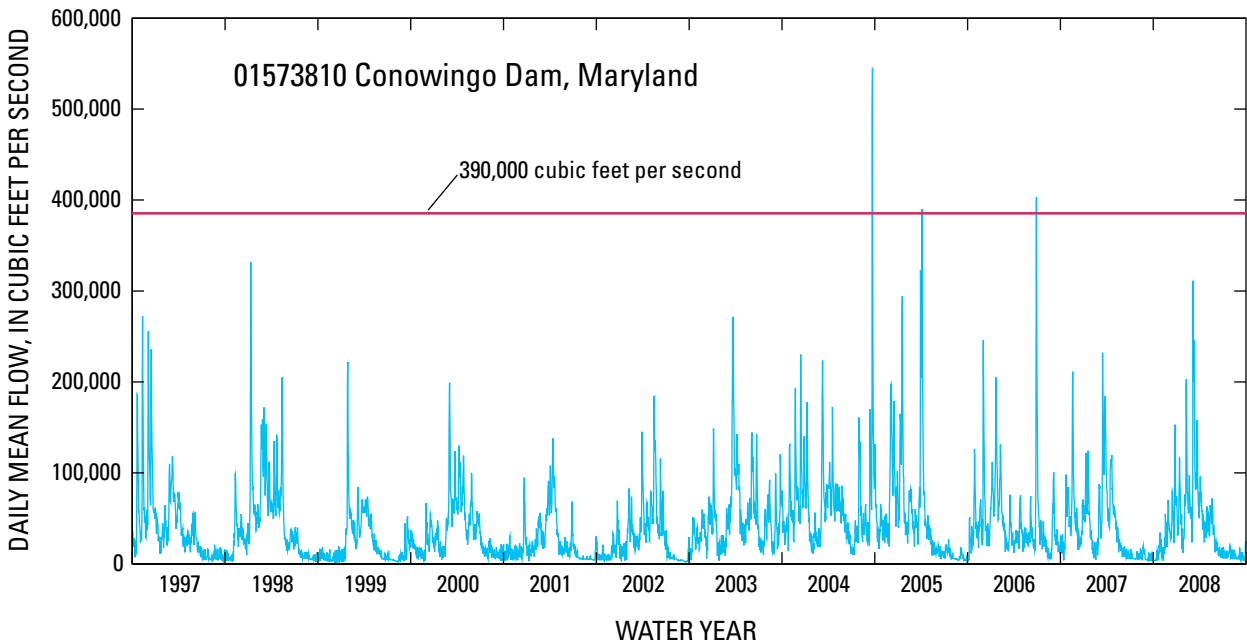


Figure 4. Daily mean hydrograph for U.S. Geological Survey streamflow-gaging station 01578310, Conowingo Dam, Maryland, 1996–2008. The red line represents the estimated flow at which scour of bottom sediments occurs.

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2,500,000 tons of sediment was scoured from the reservoirs between the 1996 and 2008 surveys.

Safe Harbor Dam and Lake Clarke

Depth to bottom data were collected from 19 cross sections in Lake Clarke (fig. 5) and were adjusted to the normal lake elevation of 227.2 ft above sea level. The deepest areas of the lake are closest to the dam and range from 30 to 50 ft (fig. 6). The old Susquehanna and Tidewater Canal forms one of the deeper areas in the reservoir close to the west bank, running from just upstream of the dam to Fishing Creek (transect number 16). The upper half of the lake is generally shallow; average lake depths are about 10–15 ft on the west side, with many islands and sand and coal bars on the east side near Washington Boro. When the lake level is low, much of the area around Washington Boro is too shallow for boating.

Schuleen and Higgins (1953) reported Lake Clarke has been in long-term equilibrium with sediment storage (they called it “sediment saturation”) except for an area from the dam to a distance upstream of approximately 7,000 ft by 1950. Subsequent surveys in 1951, 1959, and 1964 revealed this area was filled, and the total amount of deposited sediment

remained constant (E. Schuleen, Pennsylvania Power and Light Company, written commun., 1965). Short-term changes have occurred since 1965 because of scour events. The scoured sediment was quickly replaced, returning the reservoir to equilibrium. Because of the lack of high scour-producing streamflows, net changes in bottom-elevation data from the 1996 to 2008 survey were minimal (table 1). An estimated net change of 1,700,000 tons of sediment was deposited in Lake Clarke between 1996 and 2008. The 1996 study estimated 2,300,000 tons of sediment were scoured and removed from Lake Clarke, so a net deposition was expected. The area of greatest amount of scour from the 1996 survey (cross-sections 24–29) was largely filled. Total deposition of sediment in Lake Clarke was estimated at 92,400,000 tons in 2008, and the 1990 and 1993 studies estimated 90,700,000 tons. The difference (1,700,000 tons or 1.8 percent) was within the error introduced by rounding and averaging cross-sectional areas and depths, further indicating sediment transport in Lake Clarke has been in long-term equilibrium. The total amount of sediment upstream from cross-section 18 is estimated at 18,700,000 tons, and the total amount of sediment from cross-section 18 to the dam is estimated at 73,700,000 tons (table 1).

Table 1. Estimated water volume, net sediment change, and total sediment deposition in Lake Clarke since 1931, computed using bathymetry data collected in 1996 and 2008. Cross-section locations are shown in figure 5.

Lake Clarke						
Cross-section number (2008)	Distance upstream from dam (feet)	Water volume (acre feet)			Sediment (tons)	
		1996 Volume	2008 Volume	Volume change	Deposition (+) or scour (-)	Total deposition since 1920
29	685	5,407	4,929	478	692,258	7,132,000
28	2,330	3,989	3,830	160	230,912	5,542,000
27	3,510	3,960	3,691	269	389,693	5,341,000
26	5,360	4,062	4,044	18	25,778	5,852,000
25	7,400	4,349	4,317	33	47,319	6,246,000
24	10,000	5,067	5,026	41	59,128	7,273,000
23	12,860	4,528	4,545	-17	-24,914	6,577,000
22	15,000	4,435	4,456	-21	-29,849	6,447,000
21	17,540	4,956	4,935	21	30,645	7,140,000
20	19,780	4,372	4,392	-20	-28,372	6,355,000
19	21,930	4,030	3,991	39	56,073	5,776,000
18	24,000	2,740	2,713	28	40,054	3,925,000
4-17	to 47,520	12,801	12,660	141	203,547	18,723,000
Total		64,698	63,529	1,170	1,692,300	92,400,000

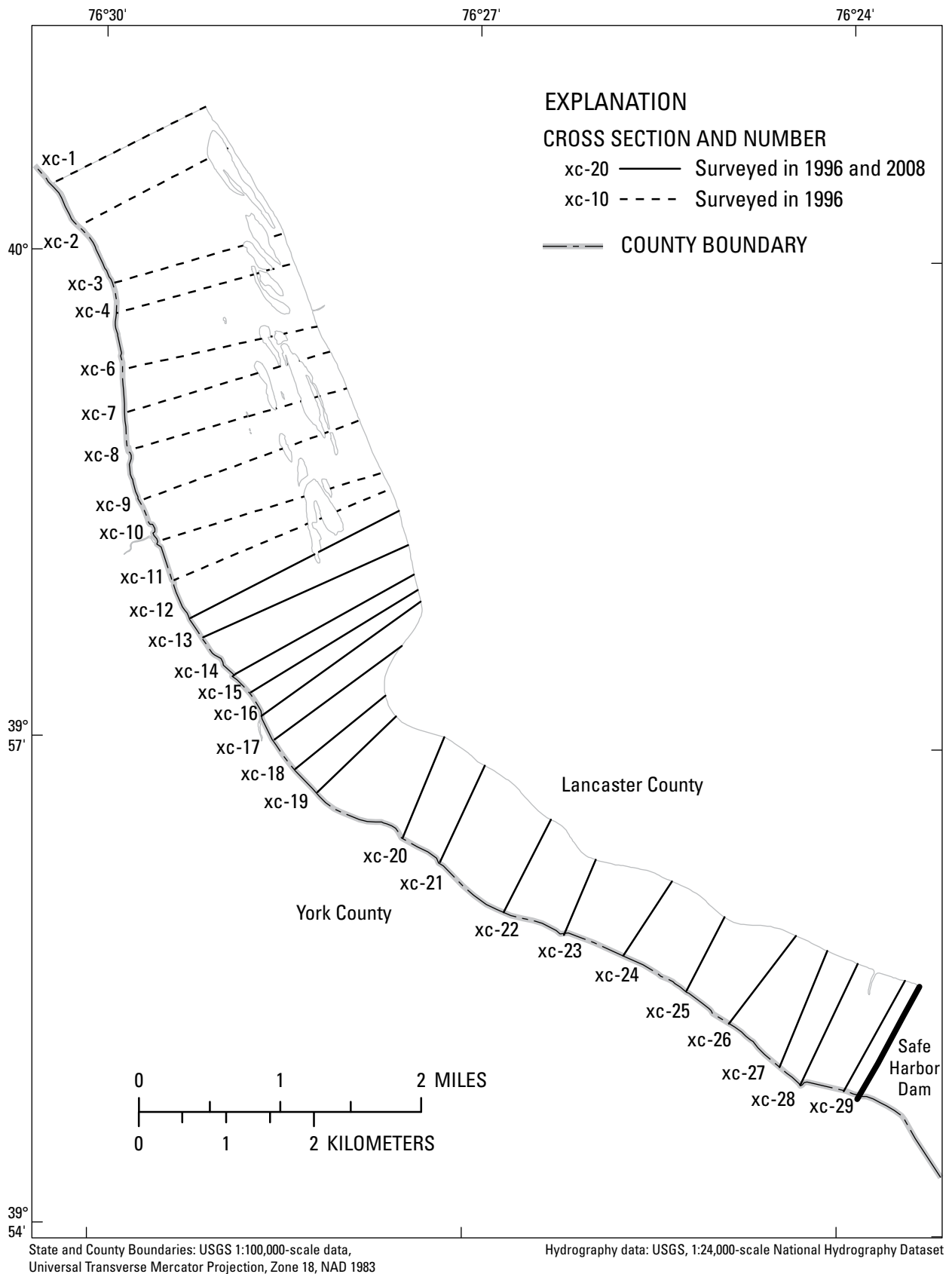


Figure 5. Bathymetric survey transects surveyed in Lake Clarke, lower Susquehanna River.

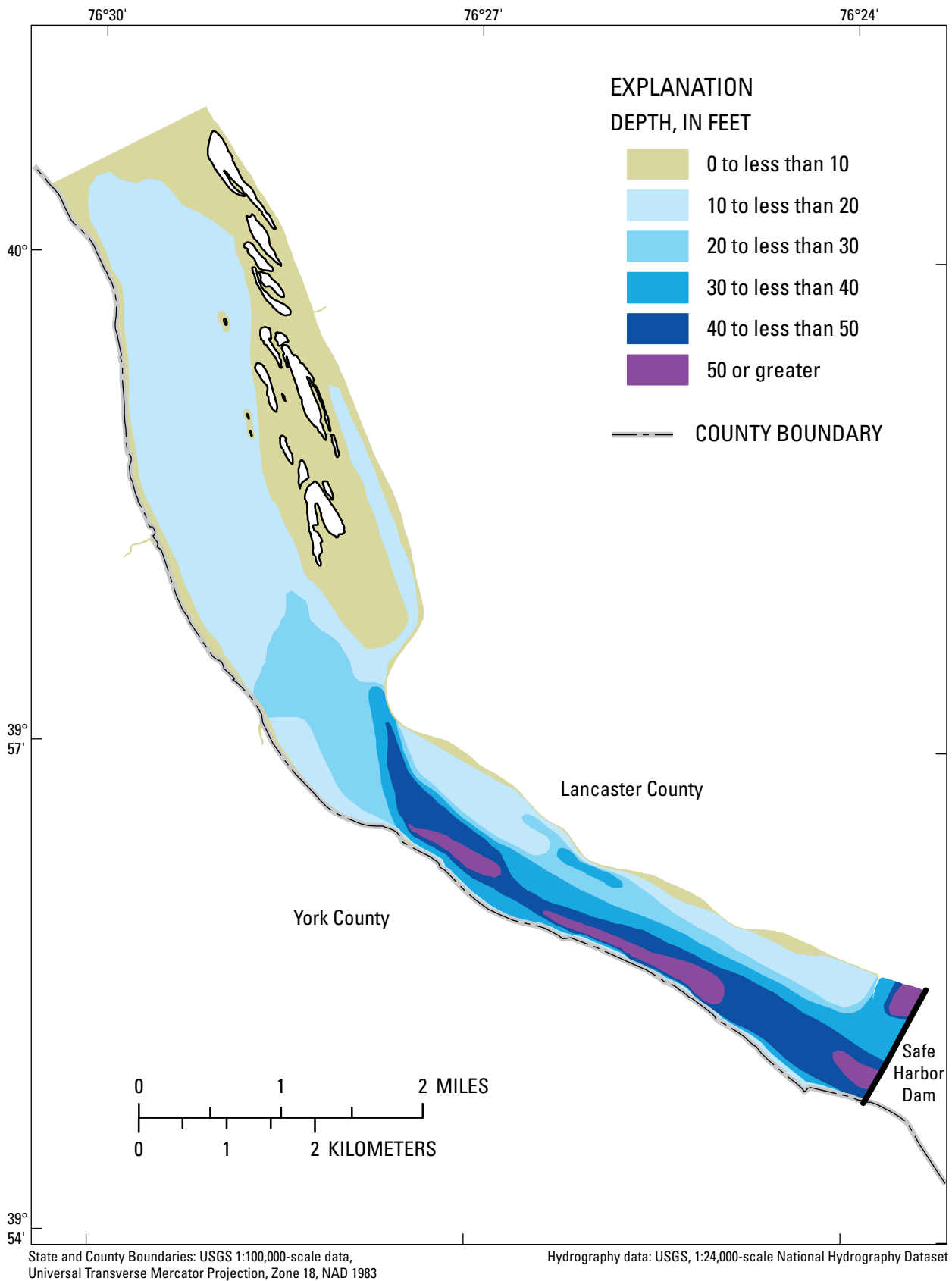
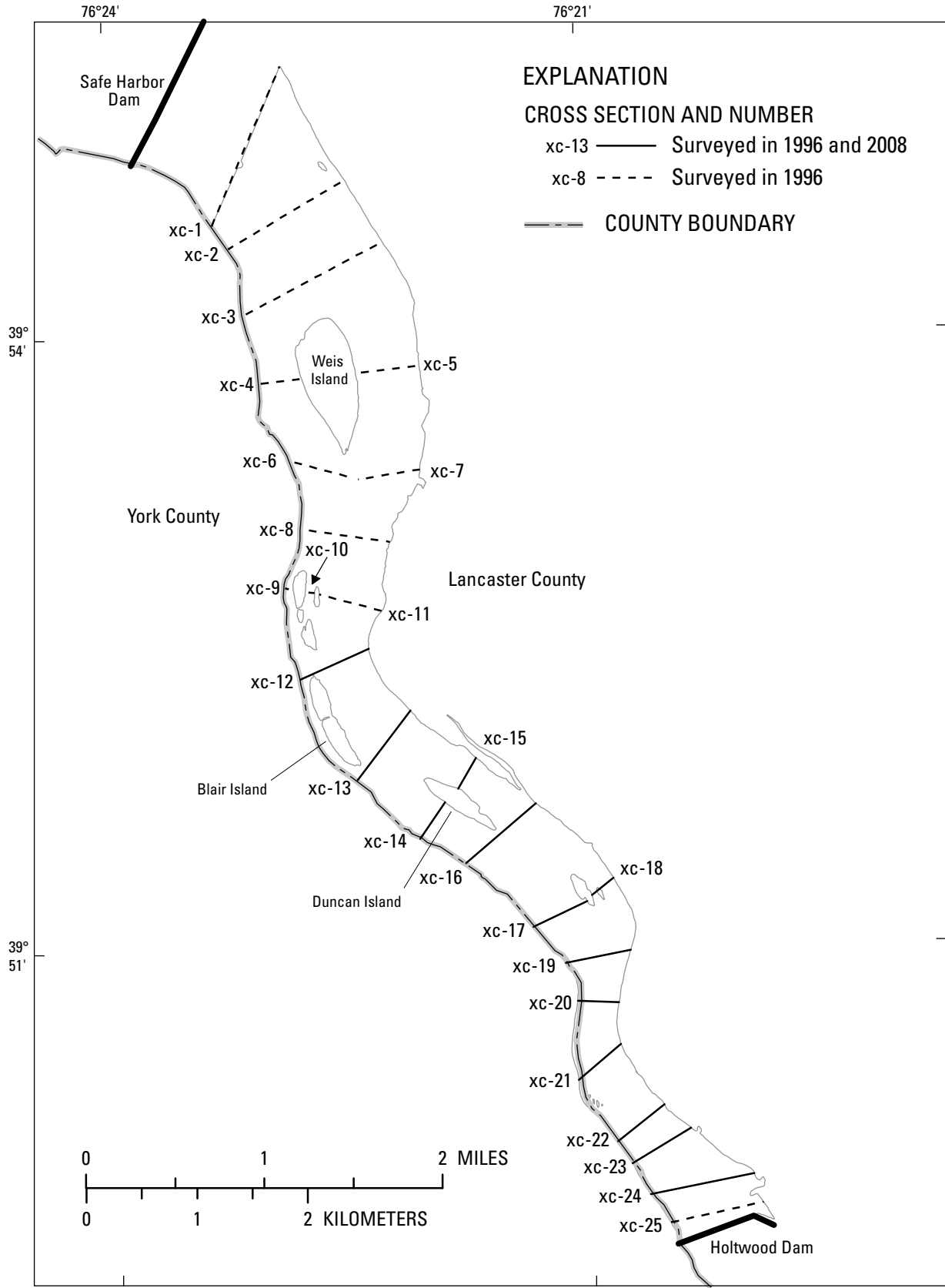


Figure 6. Bathymetry showing 10-foot depth ranges in Lake Clarke, lower Susquehanna River.

Holtwood Dam and Lake Aldred

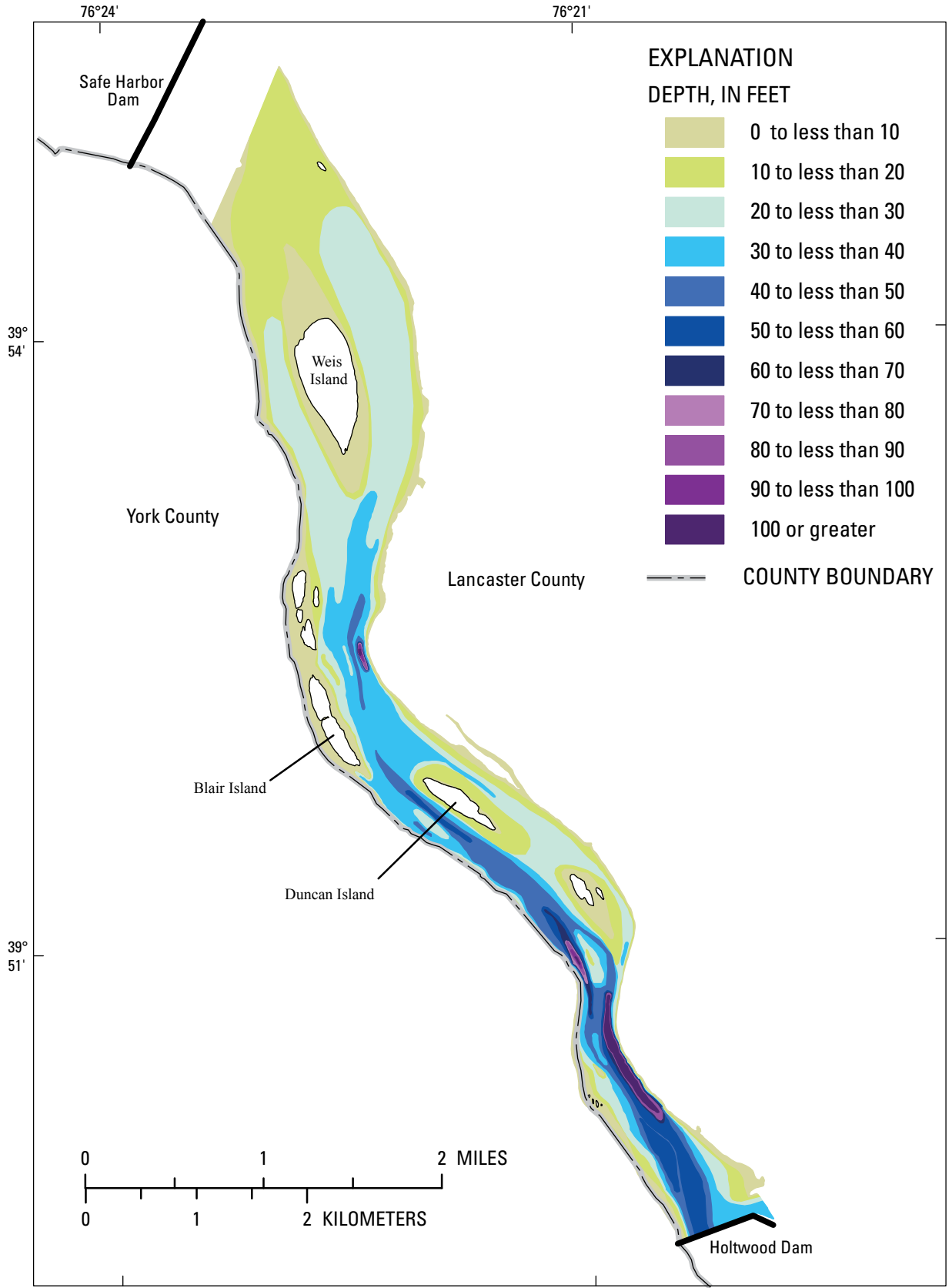
Depth to bottom data were collected in 2008 from 13 cross sections in Lake Aldred (fig. 7) and adjusted to the normal lake elevation of 169.75 ft above sea level. In general, depths are shallowest in the upper part of the lake near Weis Island where depths range from 10 to 30 ft (fig. 8). Depths increased with distance downstream through the narrow gorge and decreased again near Holtwood Dam. Unlike Safe Harbor Dam, Holtwood Dam contains no flood gates, thus sediment can accumulate near the dam rather than exit from the bottom near the flood gates. The deepest areas are in spoon-shaped depressions, which are called “the deeps,” that are located in the middle and lower parts of the lake (fig. 8). When Holtwood Dam was built in 1910, a coffer dam exposed six of these “deeps.” Five transects (12, 19, 20, 21, and 22) reveal three of these deeps. The depth to the bottom of these “deeps” ranges from 80 to 130 ft. Although it is unknown how these deeps actually formed, they are all in the narrowest section of the reservoir, leading to the common conjecture that the deeps formed during the last glacial retreat 10,000 years ago when they were “drilled” into the bedrock by whirlpool-type action.

Previously, Reed and Hoffman (1997) estimated 13,600,000 tons of sediment are stored in Lake Aldred, considerably less than in the other two reservoirs. The amount of deposited sediment has remained consistent since 1961 (Ledvina, 1962), and subsequent surveys in 1990 and 1993 confirmed the lake is in equilibrium in terms of deposited sediment. The 1996 survey indicated areas of scour and deposition but the overall change in deposited sediment in Lake Aldred was minimal (Langland and Hainly, 1997). The current study estimated the change in stored sediment since 1996 as approximately 1,000,000 tons. As previously mentioned, scour-producing flood events between the 1996 and 2008 studies were minimal, thus changes in water and sediment capacities also were minimal. With minimal change since 1996, sediment thickness remains less than 10 ft throughout most of the lake.



State and County Boundaries: USGS 1:100,000-scale data, Universal Transverse Mercator Projection, Zone 18, NAD 1983
 Hydrography data: USGS, 1:24,000-scale National Hydrography Dataset

Figure 7. Bathymetric survey transects surveyed in Lake Aldred, lower Susquehanna River.



State and County Boundaries: USGS 1:100,000-scale data, Universal Transverse Mercator Projection, Zone 18, NAD 1983

Hydrography data: USGS, 1:24,000-scale National Hydrography Dataset

Figure 8. Bathymetry showing 10-foot depth ranges in Lake Aldred, lower Susquehanna River.

Conowingo Dam and Conowingo Reservoir

Depth to bottom data were collected in 2008 from 26 cross sections in the Conowingo Reservoir (fig. 9) and adjusted to the normal lake elevation of 108.5 ft above sea level. This bathymetry study confirmed the deepest areas of the reservoir are still near the dam (fig. 10). Along the spillway gates, which are located along the dam from the east bank to about two-thirds of the way across the river, depths averaged about 50 ft. Reservoir depths averaged about 60 ft near the turbine gates, which are located along the remaining third of the dam. The spillway and turbine gates are well below the normal water surface. The average depths were considerably less than in 1996 and are discussed later in this section. Additional deeper areas were across from the Peach Bottom Power Plant, an area just south of the Pennsylvania-Maryland state line and below the confluence with Broad Creek. These deeper areas probably resulted from natural hydraulic scouring caused by the stream reservoir shape. The shallowest areas were in the

upper one-third of the reservoir where depths averaged about 15 ft (fig. 10).

The reservoir was divided into three subareas to estimate changes in cross-sectional volumes—the lower part (cross-sections 17 to 26), the middle part (cross-sections 6 to 16), and the upper part (cross-sections 1 to 5) (fig. 9, table 2). Cross-sections 1 to 5 are not presented in table 2 because they were not surveyed in 1996; however, they are discussed later in this section. Results from the survey indicated approximately 12,000,000 tons of sediment were deposited in Conowingo Reservoir between 1996 and 2008 (table 2). All the net deposition occurred in the lower part of the reservoir. Total sediment deposition in the lower part of the reservoir increased by 13,800,000 tons (table 2) to about 103,000,000 tons from 1996 to 2008. Sediment depths increased in every transect in the lower part of the reservoir (fig. 11); the majority increased by 8–10 ft. The largest change in water volume (1,983 acre-ft) was at cross-section 26, nearest the dam (table 2).

Table 2. Estimated water volume, net sediment change, and total sediment deposition in Conowingo Reservoir since 1929, computed using bathymetry data collected in 1996 and 2008.

		Conowingo				
Cross-section number (2008)	Distance upstream from dam	Water volume (acre-feet)			Sediment (tons)	
		1996 Volume	2008 Volume	Volume change	Deposition (+) or scour (-)	Total deposition since 1929
26	1,700	15,205	13,222	1,983	2,680,300	
25	3,150	10,437	10,052	385	586,900	
24	5,530	11,278	9,807	1,471	2,130,120	
23	7,950	7,171	5,976	1,195	1,781,480	
22	9,880	6,761	5,201	1,560	2,186,230	
21	12,275	5,901	4,650	1,251	1,857,460	
20	14,050	5,863	5,183	679	776,430	
19	16,650	7,736	6,947	789	914,470	
18	19,300	6,724	6,086	638	839,350	
17	21,700	7,742	7,706	36	52,400	
Subtotal					13,800,000	103,000,000
16	24,400	6,723	6,254	469	452,780	
15	26,850	6,306	6,159	147	212,360	
14	29,450	6,710	6,812	-102	-147,590	
13	33,150	6,509	6,851	-343	-496,050	
12	35,800	7,616	8,178	-562	-740,100	
11	37,500	4,876	4,708	168	243,480	
10	39,990	3,195	3,375	-180	-260,460	
9	42,150	4,797	5,117	-320	-463,060	
8	44,250	4,927	5,389	-462	-557,830	
7	47,010	6,472	6,877	-405	-585,760	
6	49,800	6,422	6,097	325	470,860	
Subtotal					-1,800,000	59,500,000
Total		149,371	140,417	8,954	¹ 12,000,000	² 162,500,000

¹ Numbers may not sum to total due to rounding

² Does not include the total sediment deposited in the upper section (numbers 1 to 5) estimated to be 11,000,000 tons.

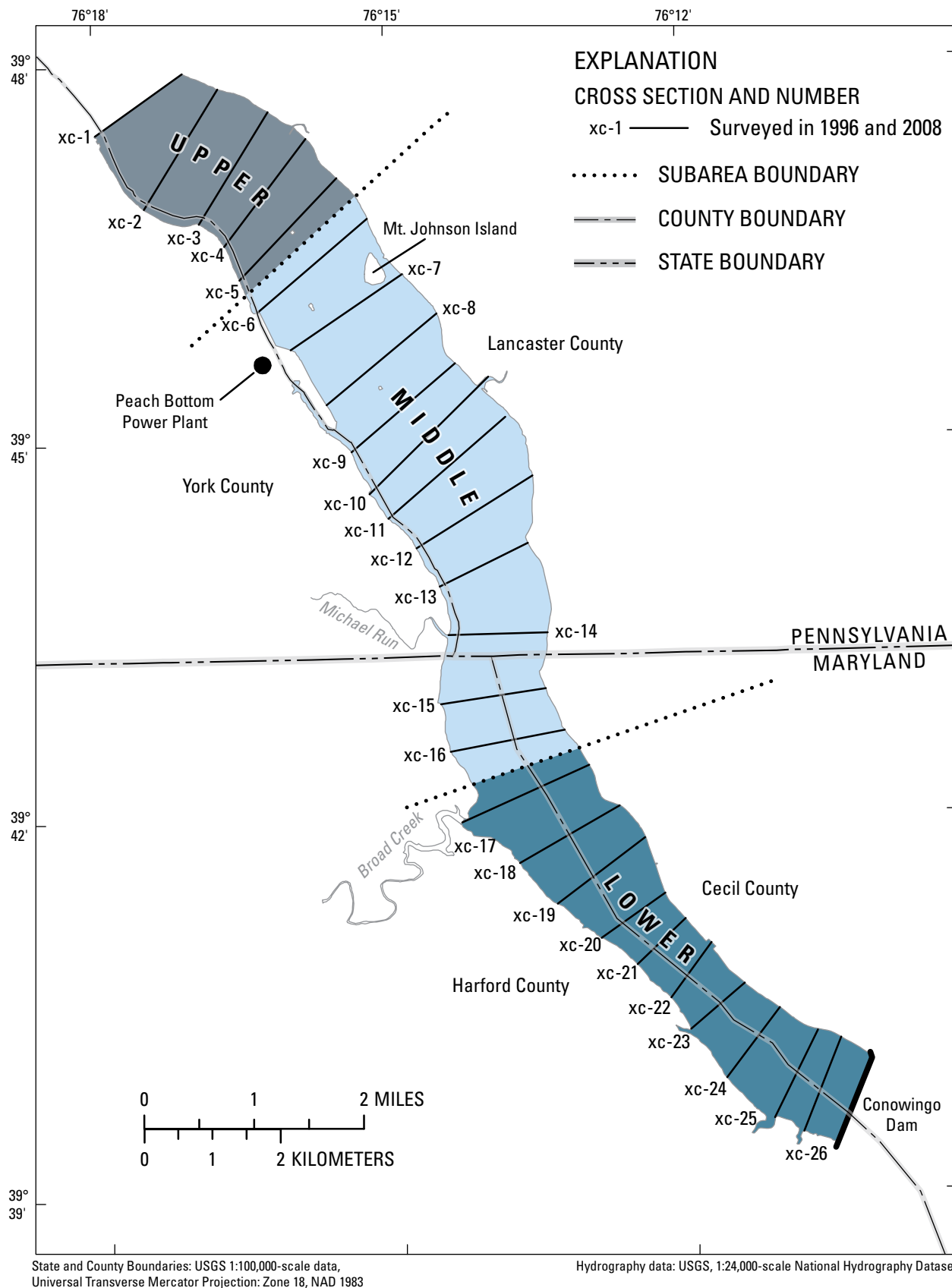


Figure 9. Bathymetric survey transects surveyed in Conowingo Reservoir, lower Susquehanna River.

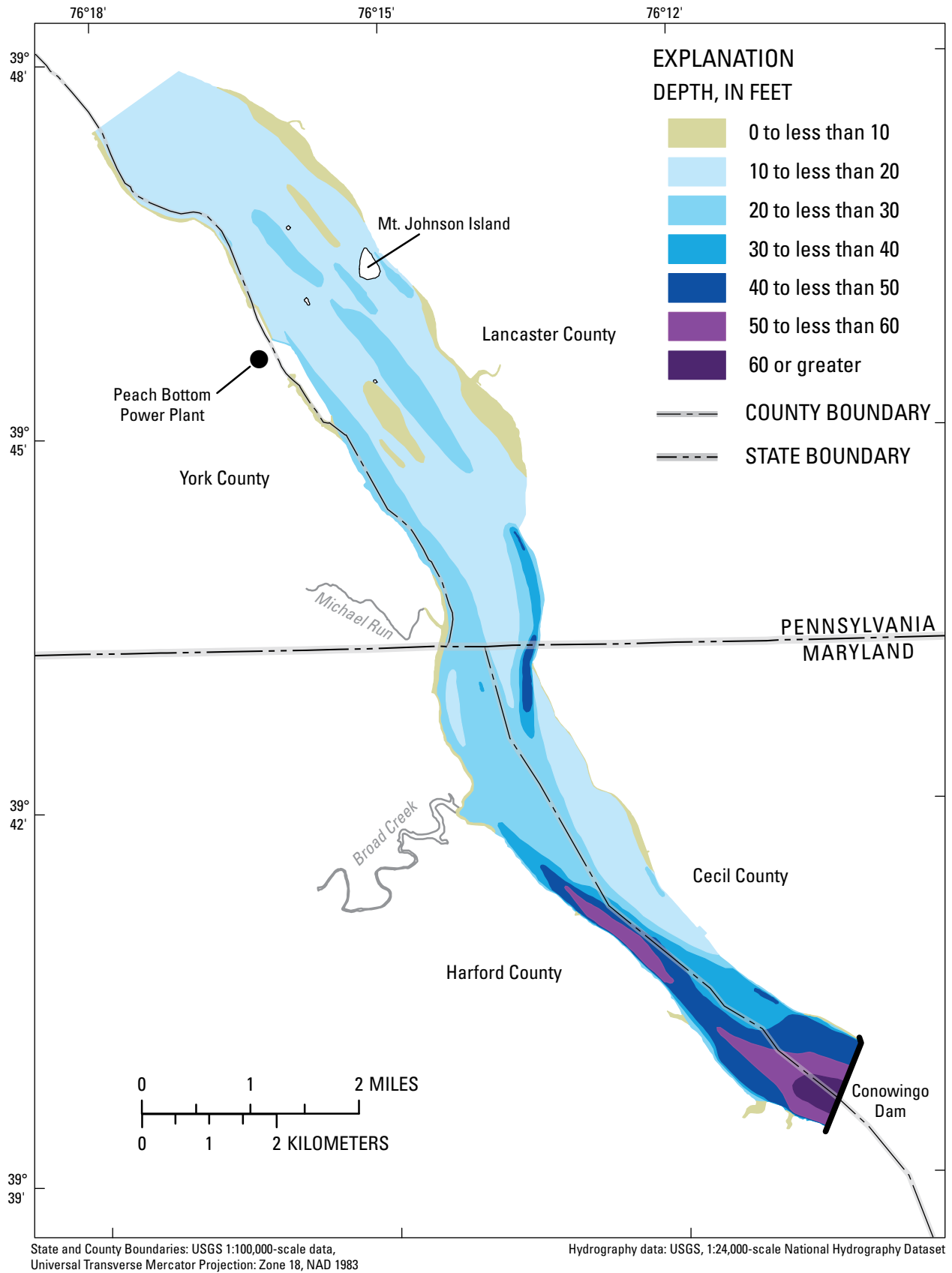


Figure 10. Bathymetry showing 10-foot depth ranges in Conowingo Reservoir, lower Susquehanna River.

Previously, Hainly and others (1995) estimated the area affected by turbulence to be within 1.25 mi upstream of the dam (transect number 24). This turbulent area is due to bottom-release mechanisms that allow water to enter the turbines about 98 ft below the normal lake-surface elevation of 108.5 ft. Turbulence from these mechanisms caused sediment deposition to be less near the turbine gates and greater with increased distance away from the gates. In addition, flood gates are positioned about 40 ft below the normal lake surface, resulting in turbulence from the flood gates affecting sediment deposition in the same manner as the turbine gates, although the effect on sediment deposition is less (fig. 9).

From 1996 to 2008, the middle part of the reservoir, cross-sections 6 to 16, indicated a net sediment decrease of about 1,800,000 tons (table 2) to about 59,500,000 tons. Reed and Hoffman (1997) reported the area between cross-sections 6 and 16 had been “near” sediment-storage capacity since about 1959 and some minor capacity changes (about 5 percent of total volume) may have occurred within cross-sections 6 and 16, probably as a result of small scour events. As previously mentioned, scouring events were minimal from 1996 to 2008, with several streamflows at or just exceeding the scour threshold. It is possible these “less than 1 day” scour threshold streamflows did not have enough energy to scour and keep sediment in suspension long enough for it to be removed from the reservoir, but only transported sediment downgradient in the reservoir.

Although not surveyed in 1996, the upper part of the reservoir was surveyed in 2008. Total sediment deposition in

the upper part of the reservoir was estimated in 1993 to be 11,000,000 tons. At that time, this area contained less than 15 percent of the total sediment in the reservoir. The sediment thickness was minimal, consisting of mostly sand. Since 1959, nearly all the sediment deposition has been below Michael Run (cross-section 14, fig. 9). In 2008, change in sediment deposition in the upper area of the reservoir (cross-sections 1 to 5) was less than 1 percent, confirming conclusions of previous studies that this area was in equilibrium with respect to sediment-storage capacity.

The predicted change in sediment deposition in the reservoir system using bathymetry data was compared to the difference in monitored sediment load estimates entering and leaving the reservoirs. From 1997 to 2007, the USGS estimated 31,800,000 tons of sediment entered the reservoirs and 15,100,000 tons of sediment exited the system (Blomquist and others, written commun., 2008). This includes an estimated 2,500,000 tons of scoured sediments. Estimates were made of reservoir sediment transport on the basis of 2008 streamflow and long-term sediment-transport rates. For 2008, an additional 2,100,000 tons was estimated to have entered the reservoirs and 1,400,000 tons exited (Blomquist and others, U.S. Geological Survey, written commun., 2008). The difference of 16,900,000 tons from 1997 to 2008 was considered the total deposition in the reservoirs. This compares reasonably well to 14,700,000 tons estimated to have deposited in the reservoirs using bathymetry mapping and volume calculations.

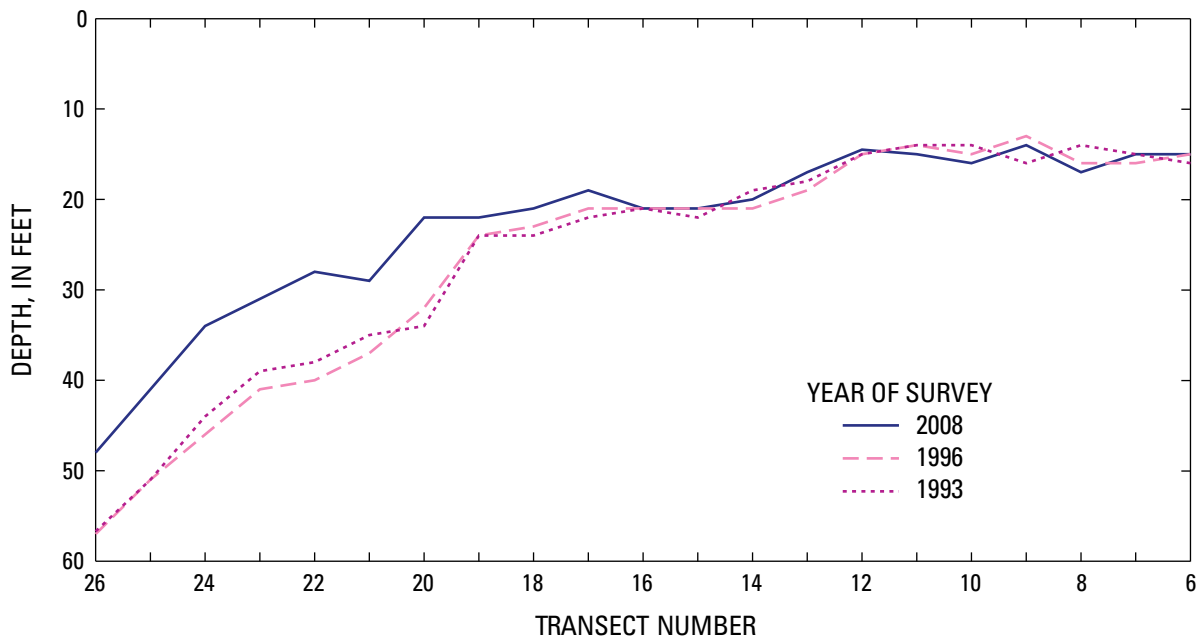


Figure 11. Change in depth to bottom surface by transect in Conowingo Reservoir, lower Susquehanna River, 1993 to 2008. Transect location shown on figure 9.

Sediment-Storage Capacity Change in Conowingo Reservoir 1929–2008

Conowingo Reservoir extends about 15.2 mi from the dam upstream to near the base of the Holtwood Dam. From Hennery Island (about 11.5 mi upstream from the Conowingo Dam and above transect 1), accumulation of sediment was minimal because of the high water velocities released from the Holtwood hydroelectric plant, the effects of a pump-storage generation station between Holtwood Dam and Hennery Island, and the natural narrow reservoir channel. Therefore, the change in capacity was computed from Hennery Island downstream to the Conowingo Dam. The storage capacity between Hennery Island and Holtwood Dam was estimated at 20,000 acre-ft.

Changes in cross-sectional area since 1929 and resultant changes in storage capacity are shown for the years 1959, 1990, 1993, 1996, and 2008 (fig. 12 and table 3). Each successive bathymetric survey indicated a decrease in reservoir capacity. The exception was 1996 when reservoir capacity increased due to scour from an ice-jam flood event. Reed and Hoffman (1997) computed a “sediment-storage capacity line”

using hydrologic conveyances. The difference between the lines for the dated surveys and the sediment-storage capacity represents the remaining storage capacity in the reservoir (fig. 12).

In 1929, the original storage capacity from Hennery Island to Conowingo Dam was approximately 280,000 acre-ft (table 3). By 1959, the capacity was reduced to 215,000 acre-ft (Whaley, 1960), an average decrease of about 2,170 acre-ft per year. By 1993, the remaining storage capacity was further reduced by 46,000 acre-ft to 169,000 acre-ft, an average decrease of about 1,800 acre-ft per year, which included the 20,000,000 and 2,400,000 tons of sediment scoured in 1972 and 1975, respectively (Gross and others, 1978). From 1996 to 2008, storage capacity in the Conowingo Reservoir was further reduced by approximately 9,000 acre-ft to 162,000 acre-ft, which equates to an additional 12,000,000 tons of sediment deposited based on volume change (table 3).

Current reservoir capacity from the dam to Hennery Island is 162,000 acre-ft—indicating a sediment deposition volume of about 118,000 acre-ft. This sediment volume is equivalent to approximately 174,000,000 tons of deposited sediment (table 3). About 20,000 acre-ft or 30,000,000 tons of sediment can be deposited before reaching the

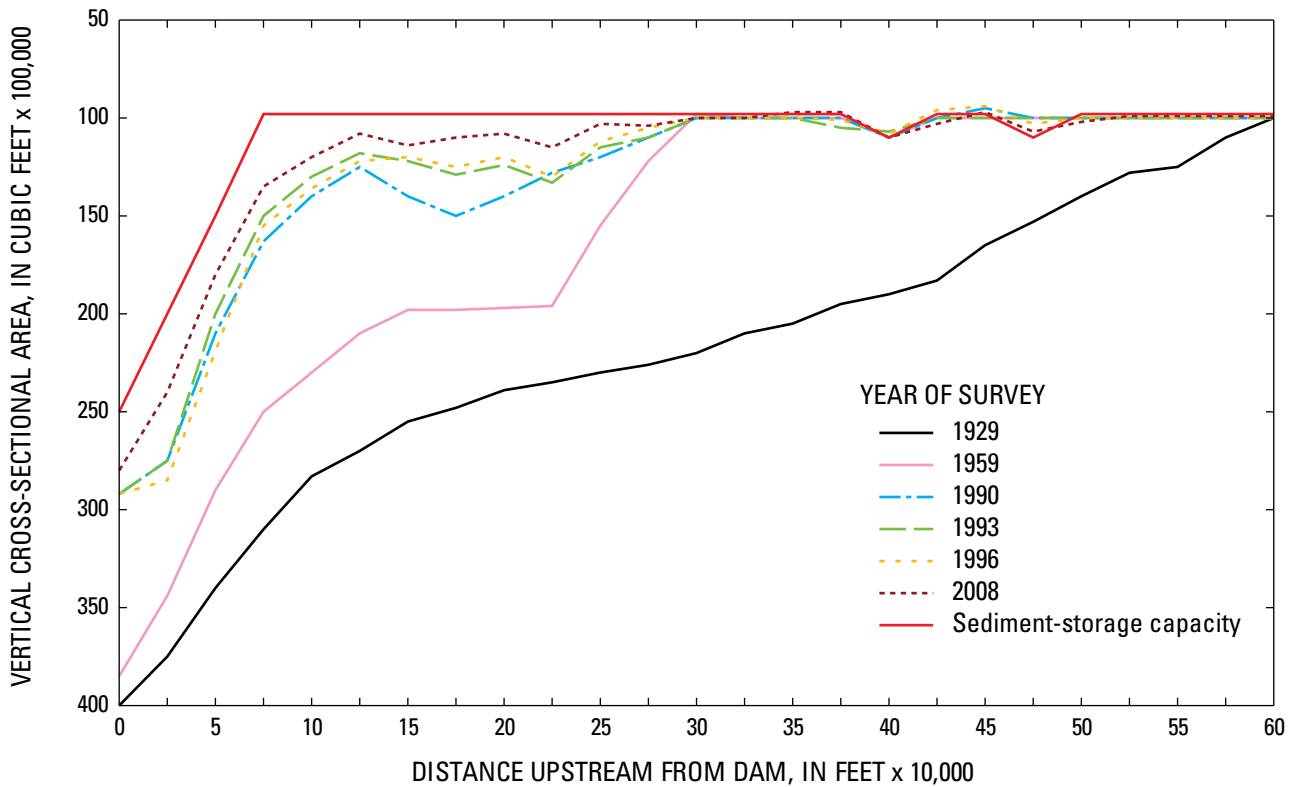


Figure 12. Changes in vertical cross-sectional area for selected years and remaining sediment-storage capacity in Conowingo Reservoir, lower Susquehanna River.

Table 3. Estimated changes in remaining capacity and sediment deposition from the Conowingo Dam to 11.5 miles upstream in Conowingo Reservoir, lower Susquehanna River, 1929–2008.

Year	Reservoir capacity (acre-feet)	Sediment deposition (acre-feet)	Sediment deposition (tons)
1929	280,000	0	0
1959	215,000	65,000	96,000,000
1990	175,000	105,000	155,000,000
1993	169,000	111,000	164,000,000
1996	171,000	109,000	162,000,000
2008	162,000	118,000	174,000,000
Water and sediment-storage capacity	142,000	138,000	204,000,000

sediment-storage capacity (table 3). This is a reduction of 9,000 acre-ft (12,000,000 tons of sediment) and about 30 percent of the remaining capacity since the 1996 survey. Once the sediment-storage capacity is reached, sediments will no longer be effectively trapped and loads transported out of the reservoir will approach the loads transported into the reservoir. However, the reservoirs will not be constantly filled to capacity with sediments because of short-term changes from storms that cause scour and a subsequent reduction in exported sediments until the scoured amount is refilled. Therefore, the amount of sediment transported out of the reservoirs will not always be in equilibrium with the amount of sediment transported into the reservoirs.

Estimating the time remaining until Conowingo Reservoir reaches the sediment-storage capacity is difficult because of possible changes in sediment-deposition rates, changes in the amount of sediment transported into the reservoir, and the effects of large scour events. Annual deposition rates in the Conowingo Reservoir vary depending on the length of time and period examined (table 3). Data from 1929 to 1958 indicated the highest deposition rates at 3,100,000 tons per year and data from 1959 to 1993 indicated deposition decreased to about 2,500,000 tons annually. This decrease was most likely related to forest regrowth and more recent implementation of sediment-erosion and runoff-control practices and may also indicate a decreasing trend in reservoir trap efficiency. More recently, Ott and others (1991) reported an estimated 1,800,000 tons of sediment deposited per year from 1985 to 1989 in the Conowingo Reservoir. During this time, no scour events occurred and 2 of the 5 years had an annual mean streamflow well below normal. From 1996 to 2008, the current study estimated 1,500,000 tons of annual sediment deposition. Similar to the Ott and others (1991) sediment-deposition estimate, minimal scouring events occurred during the interval studied, and streamflow was well below normal in 3 of 4 consecutive years (1999–2002).

Studies from 1959 to 2008 give an average reservoir sediment-deposition rate of 2,000,000 tons per year. Using this rate, a reservoir trapping efficiency of 55 percent (Langland

and others, 1997), and assuming there will be no scour from large storms, the Conowingo Reservoir could reach the remaining sediment-storage capacity of 20,000 acre-ft (approximately 30,000,000 tons of sediment) in about 15–20 years. However, additional time could be added if the rate at which sediment is transported into the reservoir is reduced. For example, if sediment-transport rates are reduced 20 percent, an additional 5 to 10 years would be needed to reach sediment-storage capacity. Additional time also could be added if the sediment trap efficiency is reduced. As the reservoir fills, cross-sectional areas will decrease, velocities will increase, and sediment trapping efficiency could decrease. It is expected that a reduction in trapping efficiency or loss of sediment storage will result in increased sediment and nutrient loads to the upper part of the Chesapeake Bay.

Summary

Bathymetric surveys of Lake Clarke, Lake Aldred, and Conowingo Reservoir in the lower Susquehanna River Basin were completed in the fall of 2008 in cooperation with the Pennsylvania Department of Environmental Protection. Bathymetry data were collected to provide an updated analysis of reservoir capacities and sediment deposition. Bathymetric data were collected using HYPACK™ software integrating a 210 kHz echo sounder, single beam transducer, and DGPS unit. Within HYPACK™, transects of the depth data were acquired along pre-defined intervals for each reservoir and displayed on a geo-referenced aerial photo. Post-processing of the raw data sets eliminated erroneous spikes verified from analog data recorded on thermal paper. Diagonal transects were used to quality assure depth readings.

Bathymetry data were collected at many of the same transects previously surveyed in 1990, 1993, and 1996. A change in the depth to bottom elevations of a reservoir reflects a change in the volume of water and storage capacity of the reservoir. Changes in bottom surface usually indicated a change

in the quantity of sediment caused by scour or deposition, or represented movement in bottom sediments. The streamflow threshold to scour sediments is estimated at 390,000 ft³/s. Between the 1996 and 2008 surveys, three flood events exceeded that streamflow and scoured an estimated 2,500,000 tons of sediment out of the reservoirs.

Depth to bottom data were collected from 19 cross sections in Lake Clarke. The deepest areas of the lake were closest to the dam and ranged from 30 to 50 ft. The upper half of the lake was generally shallow; average lake depths were about 10–15 ft on the west side, with many islands and sand and coal bars on the east side. Previous studies indicated Lake Clarke was in long-term equilibrium with sediment storage. An increase of 1,700,000 tons of sediment deposition was estimated in Lake Clarke between 1996 and 2008; total deposition in Lake Clarke was 92,400,000 tons of sediment. The 1996 study estimated 2,300,000 tons of sediment was scoured and removed from Lake Clarke, so a net deposition was expected. The areas of greatest scour in the 1996 survey (cross-sections 24–29) were largely filled.

Depth to bottom data were collected in 2008 from 13 cross sections in Lake Aldred. Generally, depths were shallowest in the upper part of the lake and increased with distance downstream through the narrow gorge and decreased again near Holtwood Dam. The deepest areas were in spoon-shaped depressions called “the deeps” located in the middle and lower parts of the lake. The location of six deeps were known and depths were greater than 80 ft with one deep reaching a depth of about 130 ft, which extends below sea level. A total of 13,600,000 tons of sediment was estimated to be contained in Lake Aldred, considerably less than is contained in the other two reservoirs. The amount of deposited sediment has remained consistent since 1961; subsequent surveys in 1990, 1993, and 1996 confirmed the lake was at equilibrium with minor changes in deposited sediment. The 2008 study estimated the change in sediment deposition as approximately 1,000,000 tons, thus changes in water and sediment capacities were minimal.

Depth to bottom data were collected from 26 cross sections in the Conowingo Reservoir. The deepest areas of the reservoir were near the dam along the spillway gates (50 ft) and near the turbine gates (60 ft). The depths were substantially less than in 1996. The shallowest areas were in the upper one-third of the reservoir where reservoir depths averaged about 15 ft. Results indicated approximately 12,000,000 tons of sediment were deposited in Conowingo Reservoir between 1996 and 2008; all the deposition was in the lower part of the reservoir. From 1996 to 2008, total sediment deposition in the lower part of the reservoir increased by 13,900,000 tons to about 103,000,000 tons. Depths decreased in every transect in the lower part of the reservoir by 8–10 ft. The middle part of the reservoir, cross-sections 6 to 16, indicated a net sediment decrease of about 1,800,000 tons from 1996 to 2008 to about 59,500,000 tons. This suggested some minor capacity changes (about 5 percent of total volume) were occurring within cross-sections 6 and 16. The upper part of reservoir contained

11,000,000 tons of sediment and remained unchanged from 1996 to 2008.

The change in sediment deposition in the reservoir system using bathymetry data was compared to the difference in monitored sediment load estimates entering and leaving the reservoirs. The difference in monitored loads was about 16,900,000 tons and considered the total deposition in the reservoir system. This compared reasonably well to 14,700,000 tons deposited in the reservoirs estimated using bathymetry data and volume calculations.

In 1929, the original capacity from Hennery Island to Conowingo Dam was approximately 280,000 acre-ft. This was reduced to 215,000 acre-ft by 1959, and further reduced to 169,000 acre-ft by 1993. Current reservoir capacity from the dam to Hennery Island is 162,000 acre-ft—indicating a deposited sediment volume of about 118,000 acre-ft (174,000,000 tons). About 20,000 acre-ft or 30,000,000 tons of sediment remain to fill before reaching the sediment-storage capacity. At the current long-term rate of filling (2,000,000 tons per year) and with no occurrence of scour events, this capacity could be filled in 15–20 years.

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