CHANGES IN BOTTOM-SURFACE ELEVATIONS IN THREE RESERVOIRS ON THE LOWER SUSQUEHANNA RIVER, PENNSYLVANIA AND MARYLAND, FOLLOWING THE JANUARY 1996 FLOOD—IMPLICATIONS FOR NUTRIENT AND SEDIMENT LOADS TO CHESAPEAKE BAY

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 97-4138

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PLATES

[In pocket]

FIGURES

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CONVERSION FACTORS, ABBREVIATED WATER-QUALITY UNITS, AND VERTICAL DATUM

Multiply	By	To obtain
Length		
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
Area		
square mile (mi^2)	2.590	square kilometer
Volume		
acre-foot (acre-ft)	1,233	cubic meter
Flow		
cubic feet per second (ft^3/s)	0.02832	cubic meter per second
Mass		
pound (lb)	0.4536	kilogram
ton, short	0.9072	megagram
Temperature		
degree Fahrenheit (F)	°F=1.8 °C+32	degree Celsius
Density		
pounds per cubic foot (lb/ft^3)	16.02	kilograms per cubic meter

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated water-quality units used in report:

- mg/kg, milligrams per kilogram
- g, gram
- mm, millimeter

CHANGES IN BOTTOM-SURFACE ELEVATIONS IN THREE RESERVOIRS ON THE LOWER SUSQUEHANNA RIVER, PENNSYLVANIA AND MARYLAND, FOLLOWING THE JANUARY 1996 FLOOD—IMPLICATIONS FOR NUTRIENT AND SEDIMENT LOADS TO CHESAPEAKE BAY

by Michael J. Langland and Robert A. Hainly

ABSTRACT

The Susquehanna River drains about 27,510 square miles in New York, Pennsylvania, and Maryland, contributes nearly 50 percent of the freshwater discharge to the Chesapeake Bay, and contributes nearly 66 percent of the annual nitrogen load, 40 percent of the phosphorus load, and 25 percent of the suspended-sediment load from non-tidal parts of the Bay during a year of average streamflow. A reservoir system formed by three hydroelectric dams on the lower Susquehanna River is currently trapping a major part of the phosphorus and suspended-sediment loads from the basin and, to a lesser extent, the nitrogen loads.

In the summer of 1996, the U. S. Geological Survey collected bathymetric data along 64 cross sections and 40 bottom-sediment samples along 14 selected cross sections in the lower Susquehanna River reservoir system to determine the remaining sediment-storage capacity, refine the current estimate of when the system may reach sediment-storage capacity, document changes in the reservoir system after the January 1996 flood, and determine the remaining nutrient mass in Conowingo Reservoir. Results from the 1996 survey indicate an estimated total of 14,800,000 tons of sediment were scoured from the reservoir system from 1993 (date of previous bathymetric survey) through 1996. This includes the net sediment change of 4,700,000 tons based on volume change in the reservoir system computed from the 1993 and 1996 surveys, the 6,900,000 tons of sediment deposited from 1993 through 1996, and the 3,200,000 tons of sediment transported into the reservoir system during the January 1996 flood. The January 1996 flood, which exceeded a 100-year recurrence interval, scoured about the same amount of sediment that normally would be deposited in the reservoir system during a 4- to 6-year period.

Concentrations of total nitrogen in bottom sediments in the Conowingo Reservoir ranged from 1,500 to 6,900 mg/kg (milligrams per kilogram); 75 percent of the concentrations were between 3,000 and 5,000 mg/kg. About 96 percent of the concentrations of total nitrogen consisted of organic nitrogen. Concentrations of total phosphorus in bottom sediments ranged from 286 to 1,390 mg/kg. About 84 percent of the concentrations of total phosphorus were comprised of inorganic phosphorus. The ratio of concentrations of plant-available phosphorus to concentrations of total phosphorus ranged from 0.6 to 3.5 percent; ratios generally decreased in a downstream direction.

About 29,000 acre-feet, or 42,000,000 tons, of sediment can be deposited before Conowingo Reservoir reaches sediment-storage capacity. Assuming the average annual sediment-deposition rate remains unchanged and no scour occurs due to floods, the reservoir system could reach sediment-storage capacity in about 17 years. The reservoir system currently is trapping about 2 percent of the nitrogen, 45 percent of the phosphorus, and 70 percent of the suspended sediment transported by the river to the upper Chesapeake Bay. Once the reservoir reaches sediment-storage capacity, an estimated 250-percent increase in the current annual loads of suspended sediment, a 2-percent increase in the current annual loads of total nitrogen, and a 70-percent increase in the current annual loads of total phosphorus from the Susquehanna River to Chesapeake Bay can be expected. If the goal of a 40-percent reduction in controllable phosphorus load from the Susquehanna River Basin is met before the reservoirs reach sediment-storage capacity, the 40-percent reduction goal will probably be exceeded when the reservoir system reaches sediment-storage capacity.

INTRODUCTION

Reducing nutrient loads into Chesapeake Bay is an important environmental issue in the Commonwealths of Pennsylvania and Virginia, the State of Maryland, and the District of Columbia. The Chesapeake Bay Commission, the U.S. Environmental Protection Agency (USEPA), and numerous state and local environmental agencies and private universities have invested major resources toward meeting an agreed-upon goal of a 40-percent reduction in controllable nutrient loads to the Bay from 1985 to the year 2000. The U.S. Geological Survey (USGS) supports this effort by collecting and interpreting hydrologic data and providing vital information to water-resource managers.

Nearly 50 percent of the freshwater discharge to the Chesapeake Bay comes from the Susquehanna River *(*Langland and others, 1995*)*, and the river has been identified as a major source of nitrogen, phosphorus, and suspended-sediment loads to the Bay. During a year of average streamflow, nearly 66 percent of the annual nitrogen load, 40 percent of the phosphorus load (Langland and others, 1995), and 25 percent of the suspended-sediment load contributed to the Bay by areas upstream of the Fall Line [1]*(*C. Bell, U.S. Geological Survey, Richmond, Va., oral commun., 1997*)* are estimated to originate from within the Susquehanna River drainage area.

A reservoir system formed by three hydroelectric dams on the lower Susquehanna River (fig. 1) is currently trapping a major part of the phosphorus and suspended-sediment loads from the basin and, to a lesser extent, the nitrogen loads (Ott and others, 1991). Previous studies (Schuleen and Higgins, 1953; Ledvina, 1962) have shown that the two upper reservoirs (Lake Clarke and Lake Aldred) have reached their sediment-storage capacity. The third and most downstream reservoir (Conowingo) is steadily approaching its sediment-storage capacity. Most recent reports (Hainly and others, 1995; Reed and Hoffman, 1997) indicate that the Conowingo Reservoir will reach capacity in 10 to 20 years. When that occurs, the reservoir system will no longer act as a trap for sediment and nutrients, and annual loads discharged to the Chesapeake Bay will increase dramatically.

In 1990, 1993, and 1996, the USGS collected bathymetric data to determine the remaining sediment-storage capacity of the reservoir system and the deposition rate in the reservoirs. The particle-size distribution and the nutrient content of the bottom sediments

[1] The Fall Line is a term used to describe an area with a distinct change in slope that generally represents the upstream limit of the tidal zones. This area is represented by a “line” running southwest to northeast through the basin and coincides with the boundary between hard crystalline rocks of the Piedmont Physiographic Province and softer sediments of the Coastal Plain.

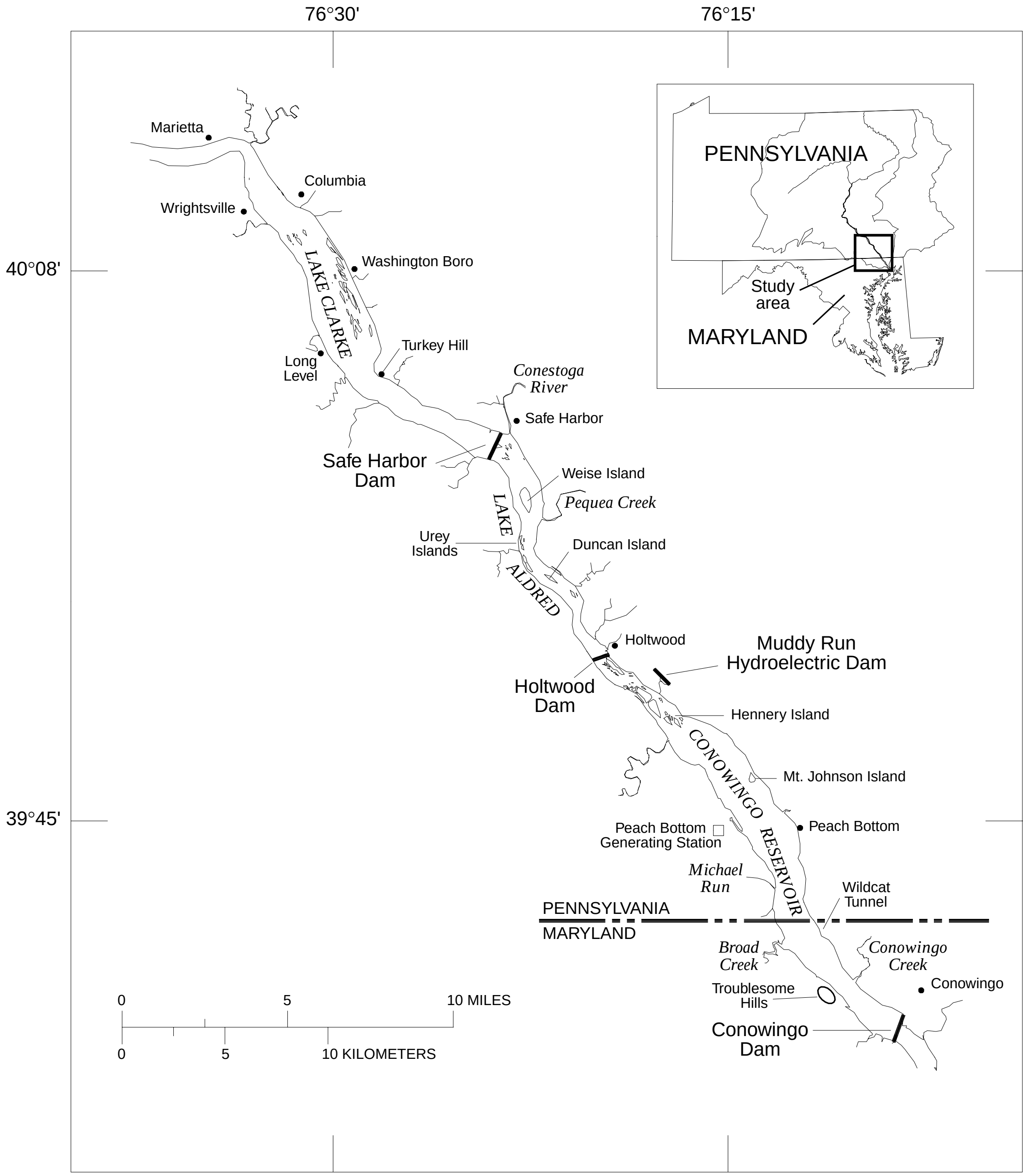

Figure 1. The location of the three hydroelectric dams and reservoirs on the lower Susquehanna River.

also was determined in 1990 and 1996. The objective of the 1996 study was to determine the remaining sediment-storage capacity in the reservoir system and the remaining nutrient mass in the most-downstream reservoir after the January 1996 flood.

PURPOSE AND SCOPE

This report (1) documents and interprets change in the bottom-surface elevations in the Susquehanna River reservoir system from 1993 to 1996, (2) documents water-storage capacity change in the most-downstream reservoir from 1928 to 1996, (3) summarizes the particle-size distributions and nutrient concentrations measured in bottom sediments of the reservoir system, (4) describes the spatial variability of the particle-size distributions and nutrient concentrations measured in bottom sediments of the most-downstream reservoir, and (5) estimates the mass of deposited sediment and the mass of total nitrogen, total phosphorus, and plant-available phosphorus remaining in the more-easily scoured bottom sediments of the most-downstream reservoir.

This report will focus on interpreting the bathymetric, particle-size, and nutrient data collected from the lower Susquehanna River reservoir system from August through October 1996. Particle-size and nutrient data were determined from sediment cores collected to a maximum depth of about 2 ft. Nutrient-mass estimates were determined from concentrations measured in these shallow cores. Historical bathymetric and nutrient data collected from the reservoirs will be related to the most-recently collected data to determine trends or substantiate conclusions.

DESCRIPTION OF THE STUDY AREA

The Susquehanna River Basin drains 27, 510 mi^2 of south-central New York State, central Pennsylvania, and northeastern Maryland. The headwaters of the river are near Cooperstown, N.Y., and the river enters the Chesapeake Bay near Havre de Grace, Md. About two-thirds of the basin is covered by forest—concentrated in the northern and western parts of the basin. Agricultural uses make up about one-quarter of the basin area. Most agricultural area is tilled and is commonly located along the river valleys in southern New York / northern Pennsylvania and in southern Pennsylvania. About one-tenth of the basin area is urban—mostly in the southern part of the basin. Annual precipitation ranges from an average of about 34 in. in southern New York State to more than 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 Susquehanna River.

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

PREVIOUS INVESTIGATIONS

Bathymetric data are available from pre-construction surveys of the river channel and from siltation surveys of the reservoirs during the period from completion of construction through 1993. Surveys of Lake Clarke were described by Schuleen and Higgins (1953). They report an original capacity of 144,600 acre-ft in 1931; the volume gradually decreased to a remaining capacity of 78,800 acre-ft in 1950. 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) show little change in water-storage capacity since 1950. This indicates that the reservoir has reached the sediment-storage capacity with incoming sediment loads.

Ledvina (1962) describes siltation surveys completed in Lake Aldred in 1939, 1950, and 1961. The surveys indicate that the quantity of sediment stored in the impoundment decreased during the period. Surveys conducted in 1990 (Hainly and others, 1995) and 1993 (Reed and Hoffman, 1997) show no appreciable changes since the 1961 survey. Reed and Hoffman (1997) conclude that the decreasing sediment storage is probably related to concurrent coal dredging operations in Lake Aldred and the trapping of sediment in Lake Clarke—impounded in 1931. Reed and Hoffman (1997) further conclude that Lake Aldred probably reached a "steady state" condition in 1920, about 10 years after the construction of Holtwood Dam, and has been in "steady state" since then.

The 300,000 acre-ft design capacity of Conowingo Reservoir in 1928 was reduced by siltation to 235,000 acre-ft by 1959 (Whaley, 1960). USGS siltation surveys in 1990 (Hainly and others, 1995) and 1993 (Reed and Hoffman, 1997) determined remaining water-storage capacities of 195,000 and 189,000 acre-ft, respectively. Reed and Hoffman (1997) indicated that considerable filling has occurred in the upstream-most six-tenths of Conowingo Reservoir and the storage capacity in that part of the reservoir appears to be at the sediment-storage capacity. The lower part of Conowingo Reservoir has about 21,000 to 25,000 acre-ft of sediment storage remaining. If Conowingo Reservoir continues to fill at a constant rate, based on an estimated annual sediment load of 3.1 million tons (Ott and others, 1991), the reservoir will reach sediment-storage capacity in the next 10 to 20 years (Reed and Hoffman, 1997).

Nutrient concentrations of bottom sediment are available from a USGS study conducted in 1990 by Hainly and others (1995). The objective of the study was to evaluate deposition of sediment, nutrients, and selected metals in the three reservoirs, describe patterns of spatial variability, and determine potential loads of selected constituents to Chesapeake Bay. As a result of particle-size distribution, percentage of coal, dry density, and concentrations of selected nutrients and metals species determined from 54 core samples collected in the 3 reservoirs, the reservoir system was found to contain nearly 260 million pounds of sediment; more than half of which was stored in Conowingo Reservoir. All sediment-quality data collected for the study are published in Durlin and Schaffstall (1992).

DESCRIPTION OF THE JANUARY 1996 FLOOD

January 1996 witnessed an extremely unusual and widespread flood. A series of meteorological and hydrological events caused extensive flash flooding that approached or exceeded previously recorded flood peaks (Thompson, 1996) in many areas of the Susquehanna River Basin. Prior to January 18, after an extended period of temperatures well-below normal, 3 or 4 ft of snow cover was common throughout the basin as was the presence of thick ice on the Susquehanna River.

On January 18th, warm, southerly winds gusting up to 50 mi per hour warmed temperatures quickly from the low 30's to the mid 50's. The snow became saturated and began to melt. The National Weather Service indicated the water equivalent was from 3 to 5 in. basin wide. Then on January 19th, an average of 3 additional inches of rain fell across the basin; most of the rain fell in a short time. Because the ground was still frozen, most rainfall and snowpack melt ran off directly into the streams and rivers. The rapid increase in river levels broke up the ice pack, which formed many ice jams around bridges and natural obstructions in the rivers.

An ice jam formed just downstream of Harrisburg on the evening of January 19, causing river levels to rise 8 ft in 1 hour. Approximately 27,800 acre-ft of water was stored behind the ice jam. When the jam broke at about 3:00 a.m. on January 20, approximately 19,000 acre-ft of water was released during the next 4 hours (Susquehanna River Basin Commission, written commun., 1996). The increased flow and ice from Harrisburg reached the streamflow-gaging station at Marietta shortly before 6:00 a.m. on the 20th (fig. 2). Soon after 10:00 a.m., an ice jam occurred in Lake Clarke about 2.5 mi upstream from the Safe Harbor Dam and downstream from Turkey Hill (fig. 1). Behind the ice jam, the lake level rose an average of 10 ft (the maximum rise near the ice jam was 17 ft), storing about 100,000 acre-ft of backwater and causing flooding in the middle and upper parts of Lake Clarke (Susquehanna River Basin Commission, written commun., 1996).

When the ice jam broke in Lake Clarke around 1:00 p.m. on January 20, most of the backwater was released in a very short time (2.5 hours), resulting in a surge of water and ice of approximately 400,000 ft^3/s. At the same time as the ice jam release, a natural river flow (flow unaffected by ice) of about 450,000 ft^3/s was recorded at Marietta. The dam at Safe Harbor contains flood gates that allow some control regulating streamflow in excess of plant capacity. Attempts were made by plant operators to reduce the flood surge by opening and closing flood gates. A peak flow of approximately 826,000 ft^3/s was estimated through Safe Harbor Dam. The flood surge and ice entered Lake Aldred. Because the Holtwood Dam has no flood gates, river flow in excess of plant capacity flows over the top of the dam. The peak flow through Holtwood Dam occurred about 4:00 p.m. on the 20th and was estimated to be about 830,000 ft^3/s.

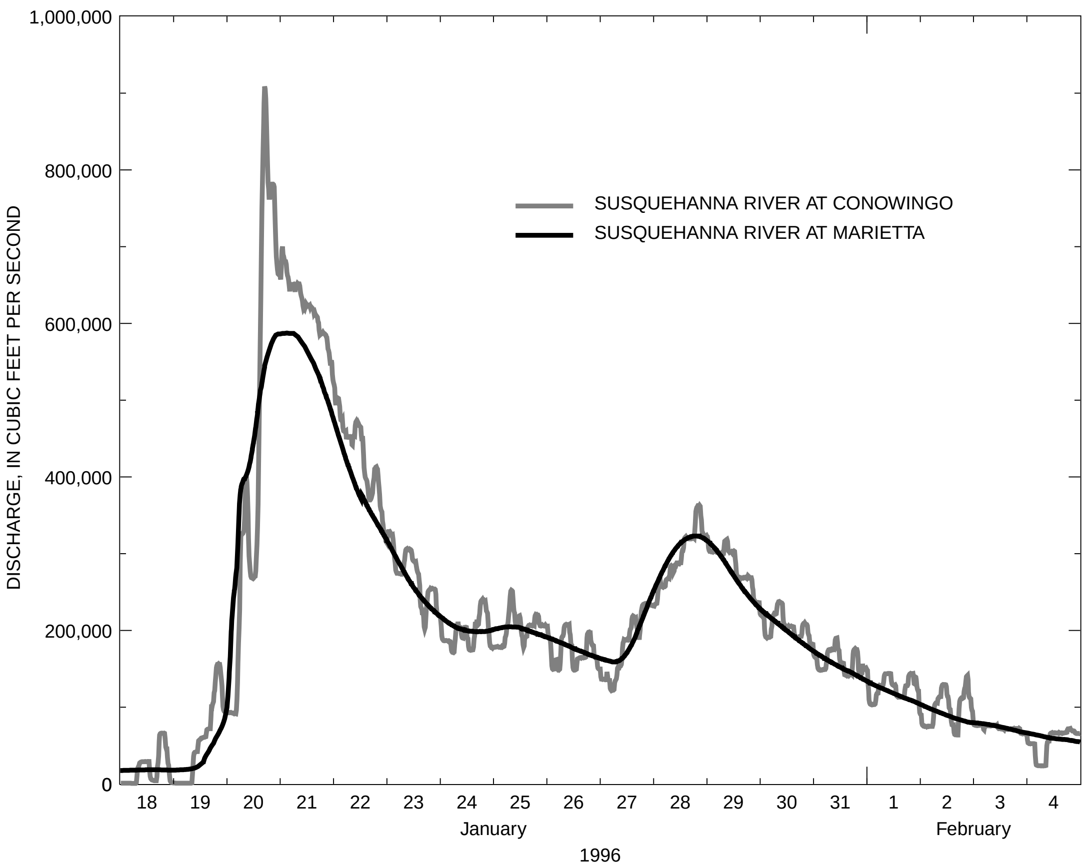

Figure 2. Hydrographs from the Susquehanna River streamflow-gaging stations at Conowingo and Marietta for the period January 19 through February 4, 1996.

The flood surge continued into the Conowingo Reservoir. Operators at the dam opened up to 42 flood gates to help the surge pass. The peak flow at Conowingo Dam was about 909,000 ft^3/s. As the ice jam broke and quickly traveled through all three reservoirs, the Susquehanna River was still rising. The flood peak at Marietta occurred after the flood peak at Conowingo (fig. 2). The flood peak at Marietta was just under 600,000 ft^3/s (R.D. Durlin, U.S. Geological Survey, oral commun., 1997) and represented the flow that would have occurred naturally if not for the ice jam in Lake Clarke. By January 22, and for the following 2 weeks, all the flow coming into the reservoirs (Marietta) nearly equalled the flow leaving the reservoirs (Conowingo) (fig. 2).

In summary, the January 1996 flood was caused by an unusual sequence of meteorological and hydrological events having the hydraulic power to scour large amounts of sediments in the Susquehanna River reservoir system. This report quantifies the transport of sediments from the reservoir system, evaluates the remaining sediment storage, estimates nutrient storage, and discusses future conditions and implications to the Chesapeake Bay.

STUDY APPROACH AND METHODS

Bathymetric data were collected from the three lower Susquehanna River reservoirs in the summer and fall of 1996 along 64 of the 68 cross sections surveyed in 1993 (Reed and Hoffman, 1997). The cross sections are located at approximately 0.5-mi intervals from near the upper ends of the impoundments to near the upstream side of the hydroelectric dams.

The bathymetric data collected in this study were used to develop current bottom-surface elevation maps for all three reservoirs. The data were compared to similar data collected in 1993 (Reed and Hoffman, 1997) in Lake Clarke and Conowingo Reservoir to determine short-term bottom-elevation changes from 1993 to 1996 and after the January 1996 flood. Historical bathymetric data collected in 1928, 1959, 1990, and 1993 from Conowingo Reservoir were combined with data collected in this study to determine the trend in water-storage capacity in Conowingo Reservoir and to estimate when the reservoir could reach sediment-storage capacity.

A total of 40 bottom-sediment samples were collected at locations along selected cross sections. A few samples were collected along cross sections in the downstream segments of Lakes Clarke and Aldred to provide a cursory evaluation of the nutrient content of the bottom sediments considered most-available for transport into the next reservoir. The majority of the samples were collected along cross sections in the lower half of Conowingo Reservoir. Nutrient and particle-size analyses of these samples were used to document the content of the bottom sediments in all three reservoirs and to estimate the accumulated mass of nutrients in the lower part of Conowingo Reservoir. Available measured loads of suspended sediment and nutrients into and out of the reservoir system during selected storms will be compared to the data from this study to provide an estimate of the loads of suspended sediment and nutrients that would be expected to be transported from the reservoir system in relation to water discharge over the dam at Conowingo.

A short description of approach and methods used to collect bathymetric data and bottom-sediment samples and equipment used is provided to indicate limitations of the data on interpretations and so others may use similar methods to further the understanding of the reservoir system. Laboratory and non-routine data-analysis methods also are presented along with quality-assurance practices and results.

Bottom-Sediment Sample Collection and Laboratory Analyses

Bottom-sediment sample collection was completed in conjunction with the bathymetric survey of the three reservoirs. Sediment cores were collected to a maximum depth of about 2 ft with a 2-in. diameter stainless-steel core sampler equipped with a plastic liner. The intent of the sampling exercise was to remove only the uncompacted material near the surface of the bottom sediment that might be easily transported in flood conditions. This material was removed from the bottom by hammering the core sampler into the bottom until resistance was met. A visual inspection of the sampled cores indicated that this method was successful and did not retrieve tightly-compacted material.

A total of 29 samples was collected along 9 cross sections in the lower half of Conowingo Reservoir, 5 samples were collected along 3 cross sections in the lower half of Lake Aldred, and 6 samples were collected along 2 cross sections in the downstream end of Lake Clarke. Generally, three samples were collected along each transect at approximate right-center, center, and left-center locations. The sediment from each core sample along each transect was extruded from the plastic liner directly into pre-cleaned and sealed plastic containers, taking care not to capture any overlying water that could have been trapped during the sampling process. The material from the single core sample collected from each location was composited, and these composites (a total of 40) were treated as discrete samples.

Samples for water content and nutrient analysis were stored chilled at 4°C in sealed plastic containers. Chilled 100-g aliquots from each sample were shipped in plastic containers to the Colorado State University Soil Testing Laboratory in Fort Collins, Colo., for analysis. All bottom-sediment samples were analyzed for percent solids and concentrations of total nitrogen, organic nitrogen, ammonia as nitrogen, nitrate as nitrogen, organic phosphorus, and inorganic phosphorus. Standard analytical methods for determining these concentrations are described in Chemical and Microbiological Properties (Page and others, 1982).

The fraction of inorganic phosphorus available to plants also was determined. This fraction was extracted by use of ammonium bicarbonate and diethylenetriaminepentaacetic acid (DTPA). The method is described in Chapter 24, Section 5.5 of Chemical and Microbiological Properties (Page and others, 1982). The ammonium bicarbonate method of phosphorus extraction has indirectly been compared favorably to the sodium hydroxide method used most commonly to measure “biologically available” phosphorus. Results of the ammonium bicarbonate method are highly correlated with the sodium bicarbonate method, commonly known as the “Olsen test” (Soltanpour and Schwab, 1977). Wolf and others (1985) found that the Olsen test was as good a predictor of labile phosphorus as the commonly used sodium hydroxide extraction method. The method also correlated fairly well with tests for algae-available phosphorus.

Air-dried aliquots of 14 selected bottom-sediment samples were analyzed for their particle-size distribution at the USGS District Laboratory in Lemoyne, Pa. Samples were fractionated for the portion less than 0.5, 0.25, 0.125, and 0.062 mm by a wet-sieve method. The fraction less than 0.004 mm was determined by the one-withdrawal pipette method. The methods used to perform the particle-size analyses are standard analyses and are described in detail by Guy (1969).

Bathymetric Data Collection

During the 1990 and 1993 surveys, a recording (paper) fathometer was used to determine water depth. During the 1996 survey, an electronic and paper recording fathometer were used. The electronic fathometer operated at 200 kilohertz, and depth to bottom was recorded along with the position data. The paper recording fathometer operated at 192 kilohertz and was used to obtain a permanent copy of the bottom profile. Any missing depth-to-bottom-surface data was estimated by use of the paper recording fathometer. Position data were determined by use of a global positioning system (GPS). Position data were recorded every 2 seconds and depth-to-bottom data recorded every 4 seconds at a constant boat speed of 4 mi per hour. Between 150 and 200 depth-to-bottom data points were recorded along each cross section. Water-stage recorders were used to record any changes in reservoir water-level elevations while bathymetric measurements were recorded.

Data Analyses

Cross-sectional profile data were collected in one or more of the reservoirs on at least nine occasions from 1939 to 1996. Profile data from 1990 and 1993 were collected to determine the elevation of the sediment. Additional cross sections in the reservoirs were profiled in 1993 to map the elevation of bottom sediments. Many cross sections profiled in 1993 were re-profiled in 1996 to document elevation change.

Bottom-elevation contours in each reservoir were developed from the 1996 data by plotting the cross-sectional water-depth data and connecting lines of equal depth. Contours were estimated from the most-downstream cross section to the dam in each reservoir by use of 1993 contour data (Reed and Hoffman, 1997) and knowledge of near-dam hydraulics. In most areas, the depth to bottom was contoured in 5-ft intervals. Maps of sediment deposition and scour were developed for all three reservoirs by overlaying and comparing mapped contour lines from the 1993 and 1996 reservoir surveys. The areas where depth to sediment changed between 1993 and 1996 are shown on the maps. The minimum contour line interval was 5 ft, therefore, movement in sediment deposition and sediment scour less than 5 ft are not shown.

Changes in water-storage capacity and sediment mass were estimated in Lake Clarke and Conowingo Reservoir by computing the change in water volume. Water-storage capacity did not change significantly in Lake Aldred. Cross-sectional length times width between adjacent cross sections times the average depth equalled the volume. Changes in average depth from the 1993 and 1996 surveys indicated the change in volume. By use of an average density of dry sediment of 67.8 lb/ft^3, as suggested by Reed and Hoffman (1997), times the change in volume, a change in sediment mass for a cross section was estimated.

The sediment load entering the reservoir system (river input) and the sediment load leaving the reservoir system (river output) were estimated by plotting sediment concentrations along with the instantaneous flows collected at Marietta and Conowingo Dam (fig. 1). The difference between river input plus sediment-storage change within the reservoir system and river output from the reservoir system provided an overall estimate of error in sediment mass change in the reservoir system.

Chemical concentrations determined by the Colorado State University Soil Testing Laboratory were reported in units of percentage or milligrams per kilogram. All units were converted to milligrams per kilogram for comparison purposes. For data-analysis purposes, each sample was treated as a discrete concentration measurement. The spatial composition of the sampling network in the upper two reservoirs does not allow averaging of measurements. Three sample containers were broken during shipment to the lab. The water content of these samples was compromised but nutrient analyses were conducted on the samples. A review of nutrient concentrations of samples collected in the same vicinity indicates that concentrations measured in these samples were relatively unaffected.

Quality Assurance

The quality of the bathymetric data was assured by "ground-truthing" the data provided by the fathometer. Several cross-sectional measurements were repeated with a graduated rod to measure the actual distance from the water surface to the sediment surface. Differences between fathometer measurements and physical measurements were consistently within the 1-ft limit of accuracy for the instrument and the environmental conditions.

Information concerning quality assurance of the bottom-material chemical measurements is available from two sources. One replicate sample was collected during the 3-day sampling period and precision data are available along with descriptions of the laboratory analytical methods. The replicate sample was collected sequentially at the same location as the environmental sample. The objective of the replicate sampling was to determine the reproducibility of the sampling procedure. Selected chemical measurements from the two samples and the precision of the analytical methods were compared (table 1). It appears that the bottom-material sampling method provided reasonably precise results. Some error may be indicated by the replicate sample concentrations because all of the concentration differences are positive. This is most probably related to the inability to duplicate the exact location of the initial sample.

Table 1. Summary of selected replicate nutrient concentrations determined from two sequential samples collected in Conowingo Reservoir, August 1996, and the precision for the laboratory methods

[mg/kg, milligrams per kilogram; n/a, not available]

Transect number[1]	Sample location	Total nitrogen as N (mg/kg)	Organic nitrogen as N (mg/kg)	Total phosphorus as P (mg/kg)	Plant-available phosphorus as P (mg/kg)
XC-10	Left center	4,560	4,400	916	6.8
XC-10	Left center	4,870	4,600	1,020	9.3
Concentration difference between replicates		+310	+200	+104	+2.5
Percentage difference between replicates		+6.8 percent	+4.5 percent	+11.4 percent	+36.8 percent
Laboratory method precision[2]		n/a	± 5 percent	n/a	± 20

[1] Locations of transects are shown on figure 5, p. 16.
[2] Page and others, eds., 1982.

CURRENT BOTTOM-SURFACE ELEVATIONS AND CHANGES, 1993 THROUGH 1996

The data presented in this section represent only the estimated “net” change in sediment based on volume change between the 1993 and 1996 surveys and does not include the amount of sediment estimated to have been deposited and subsequently removed between 1993 and 1996.

After adjusting the depth-to-bottom data collected from each reservoir to normal lake level elevations, maps showing contoured water depths were produced by use of a Geographic Information System (GIS). Contour intervals of 5 ft were used in most areas to show depth-to-bottom surface. The water depths shown on the maps for the three reservoirs (plates 1, 2, and 3, included at the back of this report) should not be used as a boating guide. Lake levels can change rapidly because of the release of stored water in each reservoir. Also, sediment bars can form in unexpected locations because of changes in local currents from storm to storm. In addition, the reservoirs contain many partially or fully submerged obstacles such as bedrock ledges, rocks, trees, and stumps that were not mapped.

A change in the bottom-surface elevation of a reservoir reflects a change in the volume of water and storage capacity of the reservoir. Changes in bottom surface usually indicate a change in the quantity of sediment caused by scour or deposition or represent movement in bottom sediments. Changes in bottom-surface and sediment elevations are discussed and compared in three ways: (1) cross-sectional data collected in 1993 and 1996 were used to estimate elevation change in the three reservoirs; (2) probable areas of sediment deposition and scour were mapped on the basis of the elevation change in the three reservoirs; and (3) the change in cross-sectional area was used to estimate change in water volume, storage capacity, and sediment-mass change within the reservoir system.

A streamflow of at least 400,000 ft^3/s (Lang, 1982) is usually required to scour sediments in the reservoirs. The only flood with flows capable of scouring the reservoirs between the 1993 and 1996 surveys was in January 1996. In January, the peak flow at Conowingo was 909,000 ft^3/s. The highest instantaneous flow other than the January 1996 flood was 365,000 ft^3/s and occurred on March 26, 1994. Therefore, little, if any, scour occurred between the 1993 study and the January 1996 flood.

LAKE CLARKE

Current Elevations - Lake depths, collected from 26 cross sections in Lake Clarke (fig. 3), were adjusted to the normal pool elevation of 227.2 ft above sea level and are shown on plate 1. The deepest areas of the lake are closest to the dam and range from 30 to 50 ft. The deeper channel close to the left bank, running from just upstream of the dam to Fishing Creek, is the remnant of the old Susquehanna and Tidewater Canal. The upper half of the lake is generally shallow; the average lake depth is about 15 ft, with many islands and sand and coal bars near Washington Boro. When the lake level is low, much of the area around Washington Boro is too shallow for boating.

Changes in Elevation - The high flows that occurred shortly after the ice dam broke in January 1996 caused significant changes in Lake Clarke. The ice dam formed between cross sections 21 and 22 (fig. 3). Large amounts of sediment were deposited upstream of the ice jam (brown-shaded areas in fig. 3), and even larger amounts of sediment were scoured near and downstream of the ice jam (red-shaded areas in fig. 3). Most sediment was deposited between cross sections 4 and 17, especially near the islands and sand bars. The ice jam caused a rise in backwater of about 10 ft in this area. In the area affected by backwater, sediment deposition was estimated to be about 800,000 tons.

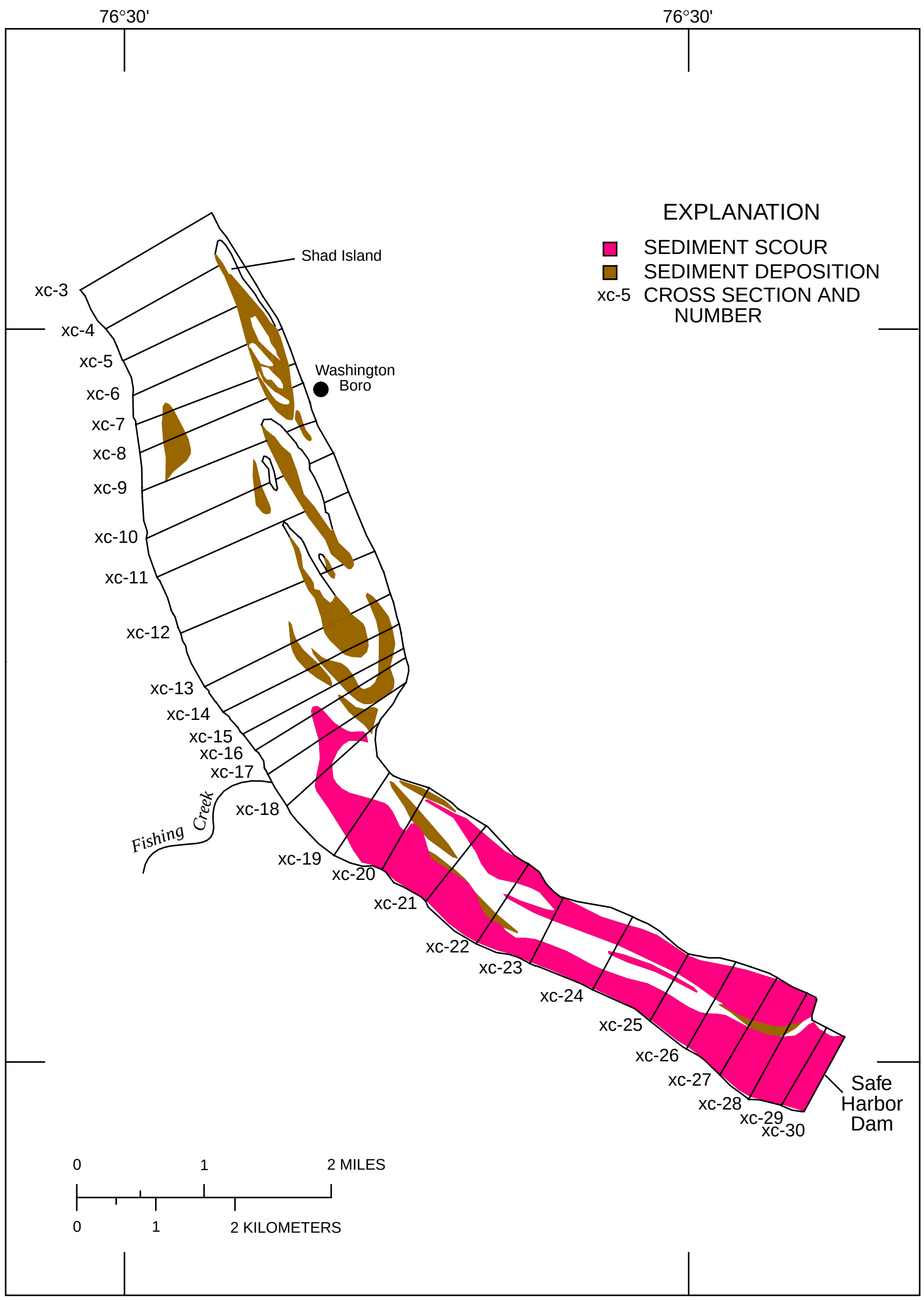

Figure 3. Estimated areas of scour and deposition in Lake Clarke, 1993-96.

A total of 2,300,000 tons of sediment (table 2) was estimated to have been scoured from Lake Clarke between 1993 and 1996, nearly all occurring in the January 1996 flood. Nearly all the scoured sediment came from near and downstream of cross section 18 to Safe Harbor Dam. Almost 30 percent of the total-sediment scour occurred near the ice jam (cross sections 20 and 21, fig. 3). Using sediment-load data from 1959 to 1993 to compute an average annual sediment deposition rate of 2,500,000 tons in the Susquehanna River, the scoured areas in Lake Clarke will probably fill in 1 to 2 years.

Prior to the January flood, the 1990 and 1993 studies estimated the total amount of sediment upstream of cross section 18 to be about 28,700,000 tons. The two studies also estimated the total amount of sediment from cross section 18 to the dam to be about 62,000,000 tons.

Table 2. Estimated water volume and net sediment change in Lake Clarke from 685 to 24,000 feet upstream of the dam, computed using data collected in 1993 and 1996

Cross-section number[1]	Distance upstream of dam (feet)	Water		Sediment	
		1993 volume (acre-feet)	1996 volume (acre-feet)	Volume change (acre-feet)	Deposition (+) or scour (-) (tons)
29	685	4,380	4,640	-260	-380,000
28	2,330	3,720	3,830	-110	-160,000
27	3,510	3,610	3,800	-190	-280,000
26	5,360	4,060	4,220	-160	-230,000
25	7,400	4,200	4,350	-150	-220,000
24	10,000	4,800	5,070	-270	-400,000
23	12,860	4,320	4,510	-190	-280,000
22	15,000	4,480	4,430	50	70,000
21	17,540	4,660	4,950	-290	-430,000
20	19,780	4,040	4,350	-310	-460,000
19	21,930	3,540	3,470	340	100,000
18	24,000	2,450	2,740	-290	-430,000
4 to 17	47,520	62,490	61,980	510	800,000
Total		110,750	112,340	-1,590	-2,300,000

[1] The locations of the cross sections are shown on figure 3, p. 12.

Lake Aldred

Current Elevations - Depth-to-bottom data, collected in 1996 from 16 cross sections in Lake Aldred (fig. 4) and adjusted to the normal pool elevation of 169.75 ft above sea level, are shown on plate 2. The deepest areas of the lake are not located near the dam but in spoon-shaped depressions called “deeps” located in the middle and lower parts of the lake. When Holtwood Dam was built in 1910, a coffer dam, built to divert water away from construction, exposed six “deeps” along the west bank. Three deeps are shown on the lake-elevation map and have depths greater than 80 ft; one deep reaches a depth of about 120 ft, which extends below sea level. How these deeps formed is uncertain but is a common subject for geology classes and local geological groups. The shallowest area in the lake is the upper part near Weise Island. Unlike Lake Clarke, lake depths decrease near the dam. Because Holtwood Dam contains no flood gates, sediment is able to accumulate near the dam rather than exit from the bottom near the flood gates.

Changes in Elevation - Between the 1990 and 1993 studies, only one flood with flow sufficient to cause scour occurred. On April 2, 1993, the flow at Conowingo reached 500,000 ft^3/s. A subsequent survey in 1993 indicated no appreciable changes in sediment distribution since the 1961 survey (Reed and Hoffman, 1997). A total of about 13,600,000 tons of sediment is contained in Lake Aldred, considerably less than is contained in the other two reservoirs. Although both deposition and scour occurred in Lake Aldred during the January 1996 flood (fig. 4), the net change in reservoir storage capacity and sediment mass most likely was minimal. Generally, deposition occurred in the upstream part of the reservoir near Duncan and Weise Island, and scour occurred from the middle part of the reservoir to the dam. Most sediment is deposited in the middle (Blair Island to Reed Island) and upper (Weise Island) areas of the lake. Sediment thickness is less than 10 ft throughout the lake.

CONOWINGO RESERVOIR

Current Elevations - Depth-to-bottom data, collected in 1996 from 23 cross sections in the Conowingo Reservoir (fig. 5) and adjusted to the normal pool elevation of 108.5 ft above sea level, are shown on plate 3. The deepest areas of the lake are located near the dam. Lake depths average about 55 ft along the spillway gates, which are located along the dam from the east bank to about two-thirds of the way across the river. Lake depths average about 70 ft near the turbine gates, which are located along the remaining third of the dam. The spillway and turbine gates are located well below the normal water surface. Two other deep areas, one across from the Peach Bottom Power Plant and the other below the confluence with Broad Creek, probably resulted from natural hydraulic scouring caused by the stream channel shape. The shallowest areas are located in the upper one-third of the reservoir; lake depths in this area average about 15 ft.

Changes in Elevations - In order to estimate changes in cross-sectional volume, the reservoir was divided into three subareas—the lower part (cross sections 8 to 17), the middle part (cross sections 1b to 7), and the upper part (cross sections above 1b) (fig. 5). By use of data from the 1990 and 1993 studies, total sediment deposition in the lower part of the reservoir in 1993 was approximately 89,000,000 tons, and total sediment deposition in the middle part of the reservoir was 61,300,000 tons. Cross-sectional data was not collected above cross section 1b in 1996 because this area contains less than 7 percent (10,500,000 tons) of the total sediment in the reservoir, the sediment thickness is minimal and consists of mostly sand, and since 1959, nearly all the sediment deposition has been below Michael Run (cross section 5a, fig. 5).

Areas of deposition (brown-shaded areas in fig. 5) and scour (red-shaded areas in fig. 5) occurred at all of the cross sections surveyed in the Conowingo Reservoir in 1996. Results from the survey indicate approximately 4,880,000 tons of sediment were scoured from sections of the reservoir between 1993 and 1996. However, results also indicate about 2,530,000 tons of sediment were either re-deposited or are new deposits in the reservoir. A net change of about 2,400,000 tons of sediment were scoured from the reservoir between 1993 and 1996 (table 3).

Of the total amount of net sediment scour, about 85 percent occurred in the lower part of the reservoir. About 2,010,000 tons were removed between cross section 8 and the dam. The largest change in volume (490 acre-ft) was at cross section 15, about 5,530 ft above the dam (table 3). Conowingo Dam was built with bottom-release mechanisms that

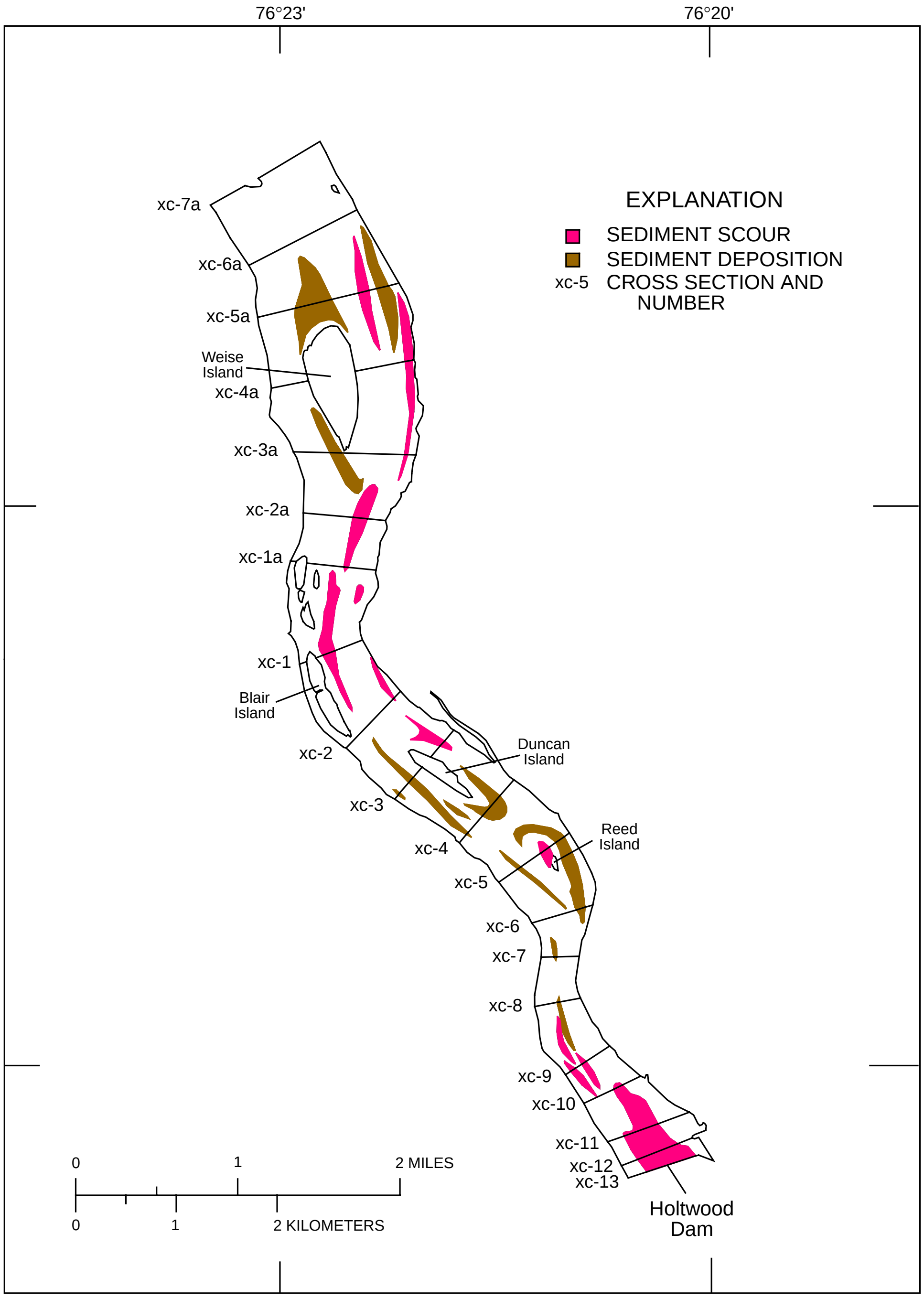

Figure 4. Estimated areas of scour and deposition in Lake Aldred, 1993-96.

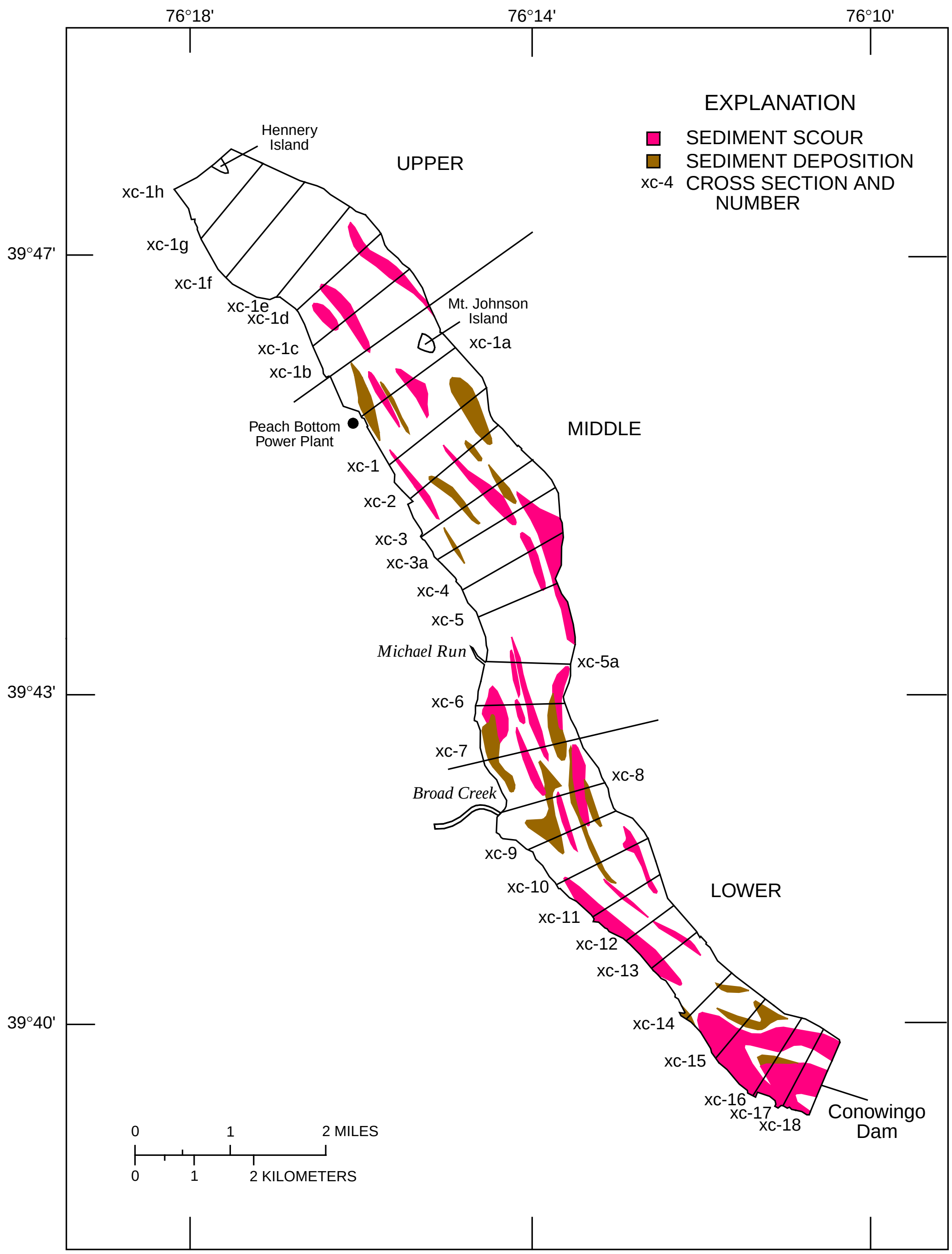

Figure 5. Estimated areas of scour and deposition in Conowingo Reservoir, 1993-96.

Table 3. Water volume and net sediment change in Conowingo Reservoir from 1,700 to 50,000 feet upstream of the dam, computed using data collected in 1993 and 1996

Cross section number[1]	Distance upstream of dam (feet)	Water		Sediment	
		1993 volume (acre-feet)	1996 volume (acre-feet)	Volume change (acre-feet)	Deposition (+) or scour (-) (tons)
17	1,700	14,990	15,230	-240	-350,000
16	3,150	10,360	10,440	-80	-120,000
15	5,530	10,790	11,280	-490	-720,000
14	7,950	6,890	7,170	-280	-410,000
13	9,880	6,330	6,760	-430	-640,000
12	12,275	5,550	5,900	-350	-520,000
11	14,050	6,020	5,860	160	240,000
10	16,650	7,700	7,740	-40	-60,000
9	19,300	6,960	6,720	240	350,000
8	21,700	7,890	7,740	150	220,000
7	24,400	6,480	6,740	-260	-380,000
6	26,850	6,380	6,310	70	100,000
5a	29,450	6,520	6,710	-190	-280,000
5	33,150	6,410	6,510	-100	-150,000
4	35,800	7,630	7,610	20	30,000
3	39,990	7,420	7,980	-450	-660,000
2	42,150	5,080	4,800	280	410,000
1	44,250	5,390	4,930	460	680,000
1a	47,010	6,070	6,470	-400	-590,000
1b	49,800	6,750	6,420	330	490,000
Total		147,600	149,200	-1,600	[2]-2,400,000

[1] Locations of cross sections are shown on figure 5, p. 16.
[2] Numbers may not total because of rounding

allow water to enter the turbines about 98 ft below the normal lake-surface elevation of 108.5 ft. Turbulence from these mechanisms causes sediment deposition to be less near the turbine gates and greater as distance increases away from the gates. Turbulence from the flood gates probably effects sediment deposition in the same manner as the turbine gates. Because the bottom of the flood gates are positioned about 40 ft below the normal pool surface, the effects of turbulence from the flood gates on sediment deposition is less. Hainly and others (1995) estimated the area unaffected by turbulence to be about 1.25 mi upstream of the dam, the approximate location of cross section 15.

The middle part of the reservoir, cross sections 1b to 7, indicated a net sediment decrease of about 350,000 tons, about 15 percent of the total mass change in the reservoir. Above cross section 5a, the net-sediment change was about 3 percent. Reed and Hoffman (1997) reported that the area upstream of cross section 5a (Michael Run) has been near sediment-storage capacity since about 1959. The shaded polygons (brown and red) in the downstream area of the middle part of the lake indicate sediments were deposited in close proximity from where they were scoured (fig. 5). On the basis of an average annual sediment deposition rate of 2,500,000 tons in the Susquehanna River from 1959 to 1993 (see table on page 18), the net amount scoured from the Conowingo Reservoir (2,400,000 tons) will probably be replaced in 2 to 3 years depending on the amount of sediment trapped in Lake Clarke.

Annual deposition rates in the Conowingo Reservoir vary depending on the length of time and period examined. Four different time frames are shown below.

Year	Source	Total sediment deposition (acre feet)	Total sediment deposition (tons)	Average annual deposition (tons)
1928-58	(Whaley, 1960)	64,500	95,300,000	3,100,000
1959-93	(Reed and Hoffman, 1977)	61,340	90,600,000	2,500,000
1985-89	(Ott and others, 1991)	6,160	9,100,000	1,800,000
1990-93	(Reed and Hoffman, 1977)	10,900	9,000,000	2,300,000

The first two lines of data in the table above suggest a decrease in the average annual sediment deposition over the 66-year period. This may be related to the sediment-erosion and runoff-control practices implemented in the past 10 to 20 years and may also indicate a decreasing trend in reservoir trap efficiency. From 1985 to 1989, only 1,800,000 tons of sediment per year were estimated to be deposited in the Conowingo Reservoir (Ott and others, 1991). This deposition amount probably is lower than that estimated for other time periods because no storm events producing scour occurred, and 2 of the 5 years had an annual mean flow well below normal. The estimate of 2,500,000 tons for 1959-93 probably is more representative of annual sediment deposition because of the longer time period used for the estimate and because the estimate includes storms when scour occurred. In this report, 2,500,000 tons is used to estimate the remaining time until the reservoir system reaches sediment-storage capacity. However, to estimate the amount deposited from 1993 to 1996, the most recent figure of 2,300,000 will be used.

CAPACITY CHANGE IN CONOWINGO RESERVOIR, 1928 THROUGH 1996

Although Conowingo Reservoir extends about 15.2 mi from the dam upstream to near the base of the Holtwood Dam, very little sediment accumulates from Hennery Island (about 11.5 mi upstream of the Conowingo Dam) to the Holtwood Dam. Accumulation of sediment is minimal above Hennery Island 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 that increased daily mean instantaneous discharges from 27,000 ft^3/s to about 57,000 ft^3/s (Hainly and others, 1995), and the naturally narrow channels. Therefore, the change in capacity was computed from Hennery Island to the Conowingo Dam. The storage capacity between Hennery Island and Holtwood Dam is estimated to be about 20,000 acre-ft.

The original capacity from Hennery Island to Conowingo Dam was approximately 280,000 acre-ft in 1928 (table 4). By 1959, the original capacity had been reduced to 215,000 acre-ft (Whaley, 1960), an average decrease of about 2,170 acre-ft per year. By 1993, the 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 includes the 20,200,000 and 2,400,000 tons of sediment scoured in 1972 and 1975, respectively (Gross and others, 1978). Changes in cross-sectional area since 1928 and resultant changes in storage capacity are shown for the years 1959, 1990, 1993, and 1996 (fig. 6). The difference between the sediment-storage capacity line (Reed and Hoffman, 1997) and the lines for the dated surveys represents the remaining storage capacity in the reservoir. As a result of scouring during the January 1996 flood, cross-sectional areas from the 1996 survey nearly equal those from the 1993 survey from the dam to an area about 10,000 ft upstream.

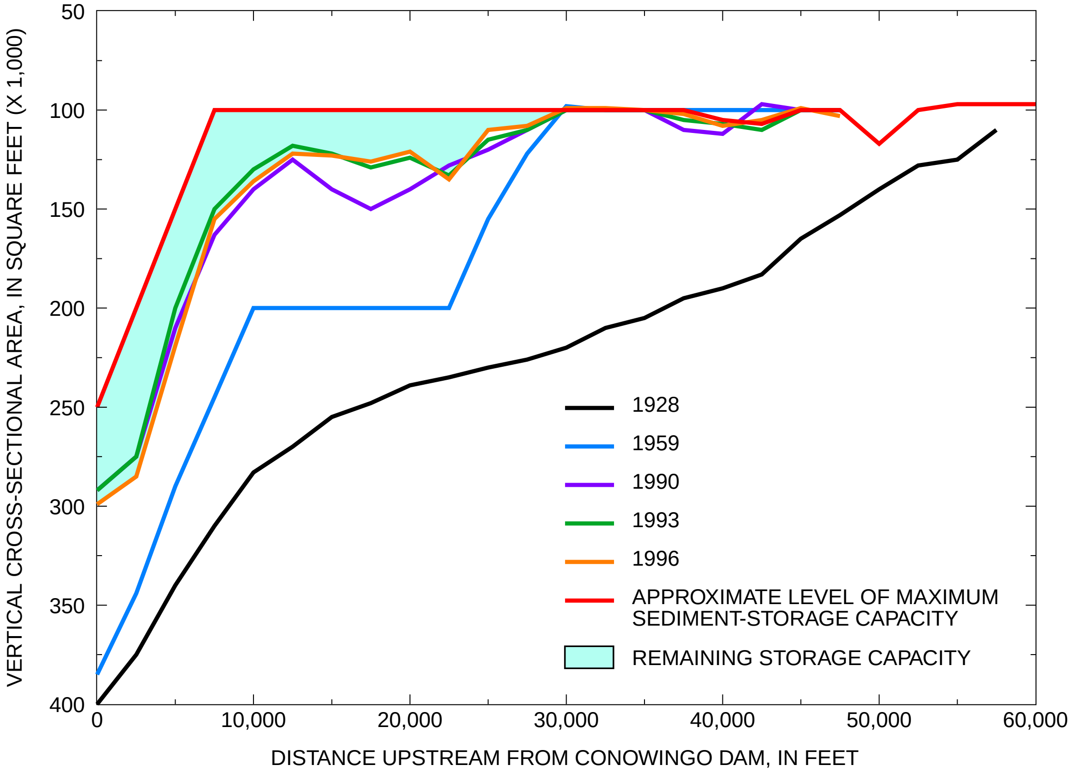

Figure 6. Changes in vertical cross-sectional area for selected years and cross-sectional area at sediment-storage capacity in the Conowingo Reservoir.

Table 4. Estimated changes in capacity and sediment deposition upstream of dam to 60,000 feet (Hennery Island) in Conowingo Reservoir, 1928-96

Year	Reservoir capacity (acre-feet)	Sediment deposition (acre-feet)	Sediment deposition (tons)
1928	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	170,600	109,400	162,000,000
Sediment-storage capacity	142,000	138,000	204,000,000

As a result of the January 1996 flood, storage capacity in the Conowingo Reservoir increased by approximately 1,600 acre-ft (or about 2,400,000 tons) of sediment based on volume change using 1993 and 1996 survey data (table 3). By 1996, total sediment deposition in the reservoir from the dam to Hennery Island was 162,000,000 tons in 1996 (table 4). About 29,000 acre-ft (or 43,000,000 tons) of sediment remain to fill before the sediment-storage capacity is reached. Once the capacity is reached, sediments will no longer be trapped and loads transported out of the reservoir will approach the loads transported into the reservoir. Currently, the reservoirs trap about 70 percent of the sediment transported into the reservoir system each year (Ott and others, 1991). It is important to note that the reservoir system will be in a state of flux with sediments because of short-term changes from storms that cause scour. Therefore, the amount of sediment transported out of the reservoir system will not always be in equilibrium with the amount of sediment transported into the system.

Estimating the time remaining until the 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 like the January 1996 flood. By use of the average estimated sediment deposition of 2,500,000 tons per year from 1959 to 1993 and the assumption that there is no scour from large storms, the Conowingo Reservoir could reach sediment-storage capacity with the remaining 29,000 acre-ft of capacity in about 17 years or about the year 2015. 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 by the year 2000, an additional 5 to 10 years would be needed to reach capacity. Additional time also could be added if the sediment trap efficiency (currently about 70 percent) is reduced. As the reservoir fills, cross-sectional areas will decrease, velocities will increase, and sediment trapping efficiency could decrease.

RESERVOIR SYSTEM SEDIMENT TRANSPORT DURING THE FLOOD OF JANUARY 1996

A simple input/output model can be used to represent the reservoir system. In this model, the load of sediment transported into the reservoirs plus the sediment-capacity change (net deposition or scour) should approximate the sediment load transported from the reservoir system. Any difference would be the model error. By use of sediment concentrations from samples collected at Marietta by the Susquehanna River Basin Commission (C.S. Takita, Susquehanna River Basin Commission, written commun., 1997) and streamflow from the USGS streamflow-gaging station at Marietta, 3,200,000 tons of sediment were estimated to have been transported by the Susquehanna River into the reservoir system from January 20 to February 2, 1996. Included in this estimate are sediment loads from the Conestoga River and Pequea Creek, the two largest sediment sources to the reservoir system below Marietta. The net amount of sediment estimated to scour from the reservoir system was 4,700,000 tons (2,300,000 tons from Lake Clark, no change in Lake Aldred, and 2,400,000 tons from the Conowingo Reservoir).

On the basis of streamflow measurements and sediment concentrations from samples collected by the USGS just below the Conowingo Dam, sediment discharge past Conowingo Dam (output) was estimated to be 7,000,000 tons from January 20 to February 4, 1996. The total sediment input was estimated to be about 14,800,000 tons. This includes sediment transported into the reservoir system (3,200,000 tons) plus the net sediment change within the three reservoirs (4,700,000 net tons scoured) plus the 6,900,000 tons estimated to have been deposited between the 1993 and 1996 surveys. This amount should approximate the measured sediment output from the system (7,000,000 tons). The difference of 7,800,000 tons of sediment indicates that more than 50 percent of the sediment was unaccounted for in this model. Most of this error is related to the probable underestimation of sediment discharge (output) through the Conowingo Dam. Because of the dangerous conditions at the dam, USGS personnel were not able to sample the peak streamflow. Other sources of error include rounding depths to bottom surface on the basis of the fathometer’s “1-ft” level of accuracy, averaging depths to calculate the cross-sectional area, and interpreting missing data from the backup paper charts; sediment inputs from the smaller tributaries within the reservoir system also are unaccounted for.

IMPLICATIONS OF CURRENT AND FUTURE RESERVOIR CONDITIONS

Historical and current sediment and nutrient loading data, estimates of reservoir bottom-sediment scour, and measurements of peak and daily mean streamflow were combined to provide a predictive tool to estimate the bottom scour of sediments and nutrients from Conowingo Reservoir. The predictions were developed on the basis of peak and daily mean streamflow past Conowingo Dam. This regression model was developed with data from storms in which peak streamflow exceeded 400,000 ft^3/s, the scour threshold reported by Lang (1982) and Reed and Hoffman (1997). These estimates are based on measured loads into and from the reservoir system during selected storms (Schuleen and Higgins, 1953; Lang, 1982) or on the average conveyance of the reservoirs and the computed stream velocity through the reservoir system (Reed and Hoffman, 1997).

Reservoir scour will be combined with estimates of loads transported past Conowingo Dam (Ott and others, 1991) to provide an estimate of sediment and nutrient loads that leave the reservoir system during various flow conditions. Current and expected future conditions of the reservoir system will be incorporated into these estimates to provide short- and long-term estimates of sediment and nutrient loads from the Susquehanna River Basin to Chesapeake Bay. The mechanism of reservoir filling adopted for these estimates is documented and described by Reed and Hoffman (1997). Their data show that Lake Clarke filled with sediment at a relatively constant rate from the time of dam construction until it approached its sediment-storage capacity. The amount of sediment deposited in the lake has remained fairly constant since that time.

Estimates of Sediment Scour in Conowingo Reservoir

Because the maximum energy available to cause scour of reservoir bottom sediments during a storm occurs during the passage of the peak streamflow, this factor would, at first guess, appear to be the most reliable indicator of the amount of material scoured during a storm. Daily mean streamflow also was investigated as an indicator of bottom-sediment scour because it may better reflect the total energy of a storm. For example, the streamflow hydrograph for the flood that occurred in June 1972 shows a long, sustained peak over a 2-day period. The instantaneous peak streamflow past Conowingo Dam was 1,130,000 ft^3/s, and the mean flow for the 24-hour period centered on the time of the peak was 1,120,000 ft^3/s. In January 1996, failure of an ice dam in Lake Clarke created a peak streamflow at Conowingo Dam of 909,000 ft^3/s, but the mean flow for the 24-hour period centered on the time of the peak was only about 530,000 ft^3/s. The period during which streamflow was above the scour threshold was much longer in 1972, even though the peak streamflows were similar.

The relation between bottom-sediment scour from Conowingo Reservoir and daily mean and peak streamflow was determined on the basis of the six storms from 1972 to 1996 that had peak streamflows at Conowingo Dam that exceeded the scour threshold of 400,000 ft^3/s (fig. 7). These storms comprise all the available data from 1972 to 1996. Because of the relatively slow rise and fall of a storm hydrograph that large rivers normally exhibit, differences in peak and daily mean streamflow for those sites are usually small. Mean streamflows used to develop the relation are the mean streamflow for the day on which the peak occurred except for the mean streamflow for the flood of January 1996. Because this extremely rapid rise occurred late in the day (fig. 2), a 24-hour mean streamflow centered around the time of the peak streamflow was computed.

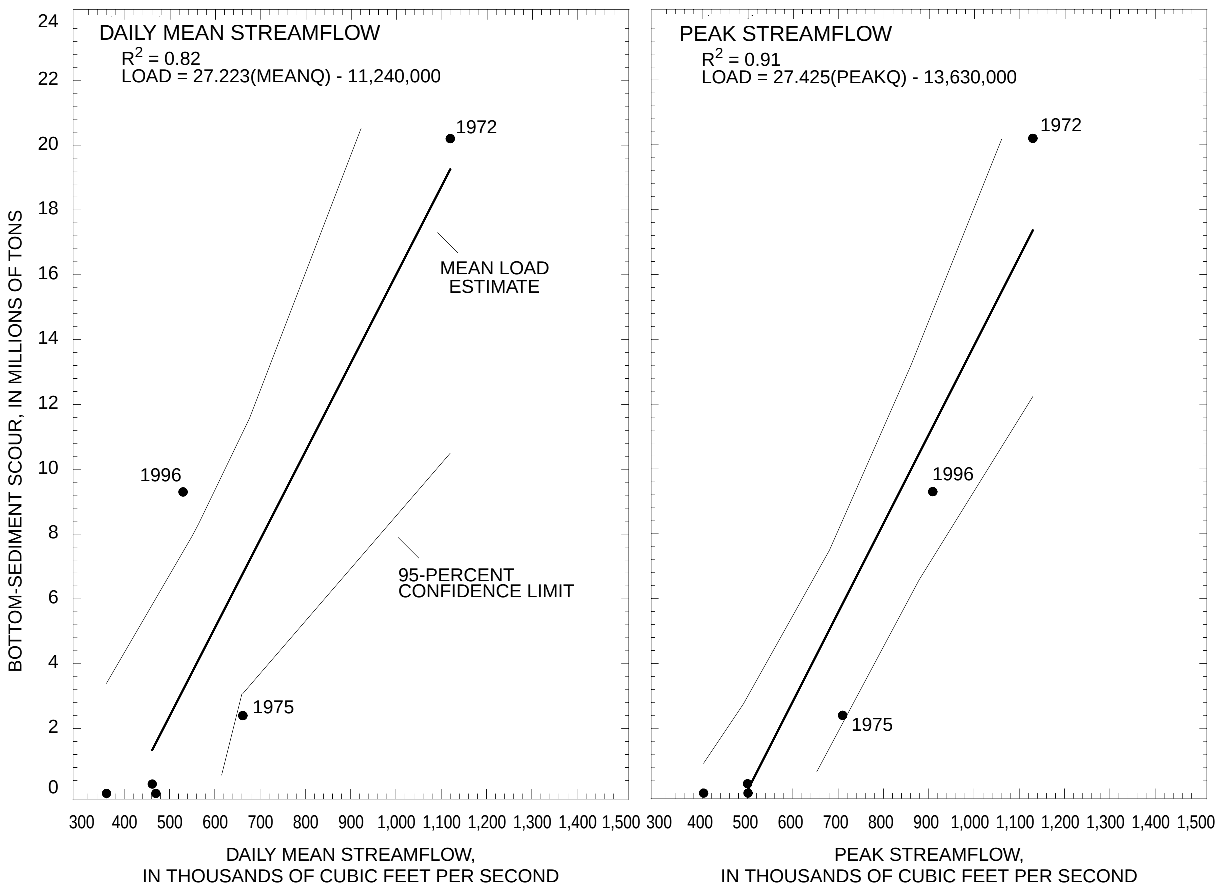

Figure 7. Estimates of scour from Conowingo Reservoir based on daily mean streamflow and peak streamflow of floods from 1972 to 1996 at Conowingo Dam, Maryland.

The scour loads for the six storms were estimated or computed using the entire load from the multiple-day event. Scour loads for storms that occurred in 1979 through 1996 are based on measured input and output loads of the reservoir system. Scour loads for the two earlier storms (1972 and 1975) were estimated by Gross and others (1978). The validity of the statistically based regression techniques and the accuracy of estimates of bottom-sediment scour are limited because of the small amount of available data. A 95-percent band of confidence around the estimated mean load is included on the graphs (fig. 7) to provide an indication of the amount of error in the estimates. The relation between streamflow and scour appears to be best described by peak streamflow. Averaging the streamflow over the entire flood may provide a better estimate of scour load from the reservoir, but this method was not pursued in this investigation.

ESTIMATED SEDIMENT LOADS TO CHESAPEAKE BAY

Average annual streamflows that are much greater than normal are generally caused by one extreme event or multiple flood events that occur throughout the year. During floods that exceed a peak streamflow of 400,000 ft^3/s, sediment is scoured from the reservoir system. Current estimates of annual loads of suspended sediment to Chesapeake Bay given by Ott and others (1991) are based on the ratio of annual mean streamflow to long-term average streamflow. The estimates were developed from data collected during 1985-89, when no flood exceeded the scour threshold. The use of these estimates to predict an average annual load during a year when scour would probably occur may underestimate the actual load.

The effect of bottom-sediment scour and reservoir sediment-storage capacity on the loads discharged from the reservoir system were summarized (table 5). An estimate of bottom-sediment scour caused by a flood with a peak streamflow of 600,000 ft^3/s over Conowingo Dam is included in the load estimate from the reservoir system. This magnitude of peak streamflow over Conowingo Dam has occurred three times in the last 25 years (1972, 1975, and 1996). Because of the relatively short period of record (29 years), a recurrence-interval computation for streamflows over Conowingo Dam is not valid. A peak streamflow of 700,000 ft^3/s in the Susquehanna River at Harrisburg (107 years of record) has a recurrence interval of about 75 years. The drainage area at Harrisburg is about 90 percent of the drainage area at Conowingo Dam.

The inclusion of a scour estimate simulates a hydrologic condition in which only one major flood occurs during the year. Reservoir sediment-storage capacity also was included in the two loading scenarios: (1) Conowingo Reservoir below sediment-storage capacity (current condition), and (2) Conowingo Reservoir at sediment-storage capacity (future condition). A 210 to 275 percent increase in the current annual loads of suspended sediment from the Susquehanna River to Chesapeake Bay is estimated after the reservoir reaches sediment-storage capacity. An even greater increase in the annual sediment and nutrient loads transported to Chesapeake Bay could occur when peak streamflows exceed the scour threshold.

Table 5. Estimates of average annual loads of suspended sediment discharged into, passing through, and scoured from the lower Susquehanna River Basin reservoir system during years with and without a flood event, before and after Conowingo Reservoir reaches sediment-storage capacity

[INPUT, flow or load into reservoir system; OUTPUT, flow or load past Conowingo Dam; CHANGE, difference between below sediment-storage and at sediment-storage capacity loads]

Scour condition	Annual suspended sediment load[1] (tons × 1,000) INPUT	Sediment load due to scour (tons × 1,000) OUTPUT	Below sediment-storage capacity: Annual suspended sediment load (tons × 1,000) OUTPUT	At sediment-storage capacity: Annual suspended sediment load (tons × 1,000) OUTPUT	Range of estimate[2] (percent) CHANGE
No flood event	3,100	0	890	3,100	+ 210 - 275
With flood event	3,100	[3]2,820	3,710	5,920	+ 50 - 75

[1] Loads based on an annual mean streamflow that is equivalent to the long-term average streamflow (Ott and others, 1991).
[2] Range based on combined prediction errors of inflow, scour, and outflow loads.
[3] Loads based on a flood event with a peak streamflow of 600,000 cubic feet per second over Conowingo Dam.

Estimated Nutrient Loads to Chesapeake Bay

The spatial variability and composition of nutrient concentrations measured in bottom-material samples from the three reservoirs affect the loads of nutrients discharged from the reservoirs during flood events that produce scour. For bottom material, an average of 96 percent of the concentration of total nitrogen was organic nitrogen and 84 percent of the concentration of total phosphorus was inorganic phosphorus. Total nitrate and ammonia as nitrogen and organic phosphorus as phosphorus were relatively minor components of the nutrient content of the bottom material. The distribution of concentrations of total nitrogen was fairly uniform throughout the reservoir system—organic nitrogen ranged from 89 to 100 percent of total nitrogen. The ratio of inorganic phosphorus to total phosphorus throughout the reservoir system was more variable spatially and ranged from 56 to 98 percent. Although several species of nitrogen and phosphorus were measured, only concentrations of total nitrogen as nitrogen, total phosphorus as phosphorus, and plant-available phosphorus as phosphorus will be discussed in detail. Clay content of the samples also will be described. All nutrient concentrations and particle-size data collected during this study are published in Water Resources Data for Pennsylvania, 1996 Water Year, Volume 2 (Durlin and Schaffstall, 1997).

Only a few samples were collected from the downstream parts of Lakes Clarke and Aldred to describe the content of bottom material most-likely to be scoured and transported into the next impoundment. Nutrient concentrations and clay content for data at selected cross sections in Lakes Clarke and Aldred are summarized in table 6.

With a few exceptions, concentrations of total nitrogen and total phosphorus were fairly uniform throughout Lake Clarke. In Lake Aldred, concentrations of total nitrogen as nitrogen and total phosphorus as phosphorus were not distributed as uniformly as those in Lake Clarke. Even though fewer samples were collected, the concentration patterns observed in this study are similar to those reported for the 1990 study by Hainly and others (1995).

The percentage of clay in bottom-material samples is an indicator of areas where nutrients that adsorb to sediment may be deposited. In river systems, a major part of the loads of organic nitrogen and total phosphorus is commonly transported and deposited together with sediment particles. The four measurements of clay content in Lakes Clarke and Aldred are insufficient to identify patterns or adequately document any changes in

Table 6. Summary of nutrient concentrations and clay content determined from samples collected in Lakes Clarke and Aldred, August 1996

[mg/kg, milligrams per kilogram; XC, cross section; RC, right center, facing downstream; C, center; LC, left center, facing downstream; —, not measured]

Local identifier[1]	Cross section location (feet upstream of dam)	Cross section width (feet)	Total nitrogen as N (mg/kg)	Total phosphorus as P (mg/kg)	Plant-available phosphorus as P (mg/kg)	Clay content (percent)
			Lake Clarke			
XC-23 (RC)	12,680	2,500	3,700	1,020	11.8	—
XC-23 (C)	12,680	2,500	3,300	1,150	7.4	29
XC-23 (LC)	12,680	2,500	3,600	1,140	4.9	—
XC-26 (RC)	5,360	1,940	4,000	1,210	6.3	—
XC-26 (C)	5,360	1,940	5,300	813	6.8	27
XC-26 (LC)	5,360	1,940	4,700	861	4.3	—
			Lake Aldred			
XC-2 (LC)	18,200	2,600	5,700	440	3.7	—
XC-9 (RC)	4,200	1,750	1,200	438	13.1	9
XC-11 (RC)	1,500	2,950	2,000	291	7.4	—
XC-11 (C)	1,500	2,950	5,500	257	6.8	8
XC-11 (LC)	1,500	2,950	4,300	486	9.9	—

[1] Corresponds to identification number used in the 1996 water year Water Resources Data Report for Pennsylvania, Volume 2.

clay content within each reservoir. However, the lower clay content measured in the samples collected in Lake Aldred does indicate a possible change in the particle-size distribution of the bottom material in the downstream area of the impoundment since 1990. In 1990, Hainly and others (1995) observed similar percentages of clay content in Lake Clarke as were measured in 1996. Clay percentages in the downstream area of Lake Aldred ranged from 20 to 30 percent, whereas the 1996 study measured 8 and 9 percent clay in the bottom material in the same area.

Concentrations of total nitrogen from 29 discrete samples of the uppermost layer of bottom sediments deposited in the lower part of Conowingo Reservoir ranged from 1,500 to 6,900 mg/kg; the average was 3,780 mg/kg. Seventy-five percent of the concentrations were between 3,000 and 5,000 mg/kg (fig. 8). The lowest concentrations were measured in samples collected in the mid-section of the reservoir (the upper end of the collection area) and the highest were along the cross sections immediately downstream of the confluence of Broad Creek. Concentrations of total nitrogen at the lower end of the reservoir and immediately upstream of Conowingo Dam generally reflect the mixing of upstream bottom-sediment concentrations. Concentrations of total nitrogen in the area within 1 mi upstream of the dam averaged about 3,600 mg/kg. These concentrations compare fairly well to those collected in 1990 by Hainly and others (1995). They reported an average concentration of organic nitrogen of 3,020 mg/kg for samples collected in this lower area of Conowingo Reservoir. On the basis of the composition of nitrogen species in samples collected for this study, this would correspond to a concentration of total nitrogen of about 3,150 mg/kg. The lower concentrations reported by Hainly and others (1995) could be the result of the greater depth of core samples collected for that study. Their cores averaged about 6 to 8 ft in depth, and concentrations of organic nitrogen commonly decrease with depth (E. Callender, U.S. Geological Survey, Reston, Va., written commun., 1997). Cores for this study averaged about 2 ft in depth.

Unlike concentrations of total nitrogen, concentrations of total phosphorus from 29 samples of bottom sediments of the lower half of Conowingo Reservoir did not exhibit any patterns. Concentrations ranged from 286 to 1,390 mg/kg and averaged 720 mg/kg (fig. 9). Some of the highest and lowest concentrations were at or immediately downstream of the mouth of Broad Creek, an indicator of the influence this stream’s loads may have on the nutrient bottom-sediment concentrations in this area of the reservoir. The average concentration of total phosphorus in the 1-mi area upstream of Conowingo Dam was about 850 mg/kg, slightly higher than the average for the entire sampled area. This concentration is very similar to the 920 mg/kg concentration determined from samples collected in the same area during 1990 by Hainly and others (1995).

The amount of total phosphorus available to plants also was determined. The ammonium bicarbonate method used for this phosphorus extraction provides analytical and bioassay results comparable to the most commonly used method—a sodium hydroxide extraction (Soltanpour and Schwab, 1977; Wolf and others, 1985). No spatial patterns for concentrations were evident in the sampled area (fig. 9). As with total phosphorus, the largest concentrations of plant-available phosphorus were measured at or near the mouth of Broad Creek. The ratio of concentrations of plant-available phosphorus to concentrations of total phosphorus ranged from 0.6 to 3.5 percent, and the ratio generally decreased in a downstream manner. The percentage of plant-available phosphorus was fairly uniform in the downstream area of the reservoir near Conowingo Dam. The average ratio in the entire sampled area was about 1.25 percent. In the 1-mi area upstream of the dam, the average ratio was nearly 1 percent, and the average concentration of plant-available phosphorus was 8.5 mg/kg.

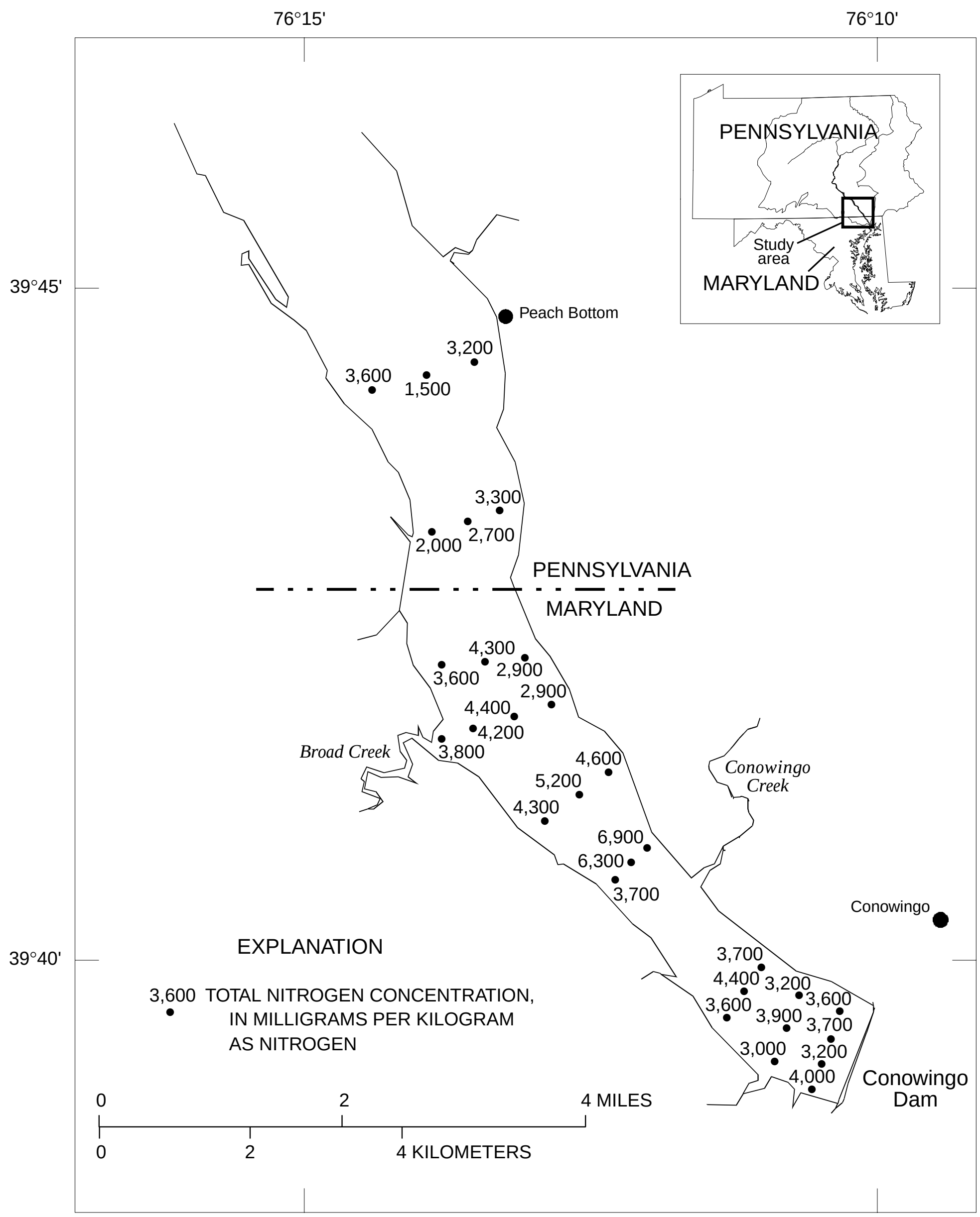

Figure 8. Concentrations of total nitrogen measured in Conowingo Reservoir bottom sediments, August 1996.

The clay content of six bottom-sediment samples in the Conowingo Reservoir was measured to support the description of spatial variability of nutrient concentrations. The spatial patterns of clay percentages (less than 0.004 mm) and silt and clay percentages (less than 0.062 mm) in the lower part of Conowingo Reservoir were similar to those exhibited by total nitrogen—of which a large component is organic nitrogen. Silt and clay percentages of the bottom material increased dramatically in a downstream fashion—from about 10 percent in the upper part of the sampled area to about 70 percent near Conowingo Dam.

In 1990, Hainly and others (1995) found clay to make up 30 to 40 percent of the bottom material deposited downstream of the confluence of Broad Creek. On the basis of the six samples collected for this study, the clay content ranged from 7 to 19 percent and

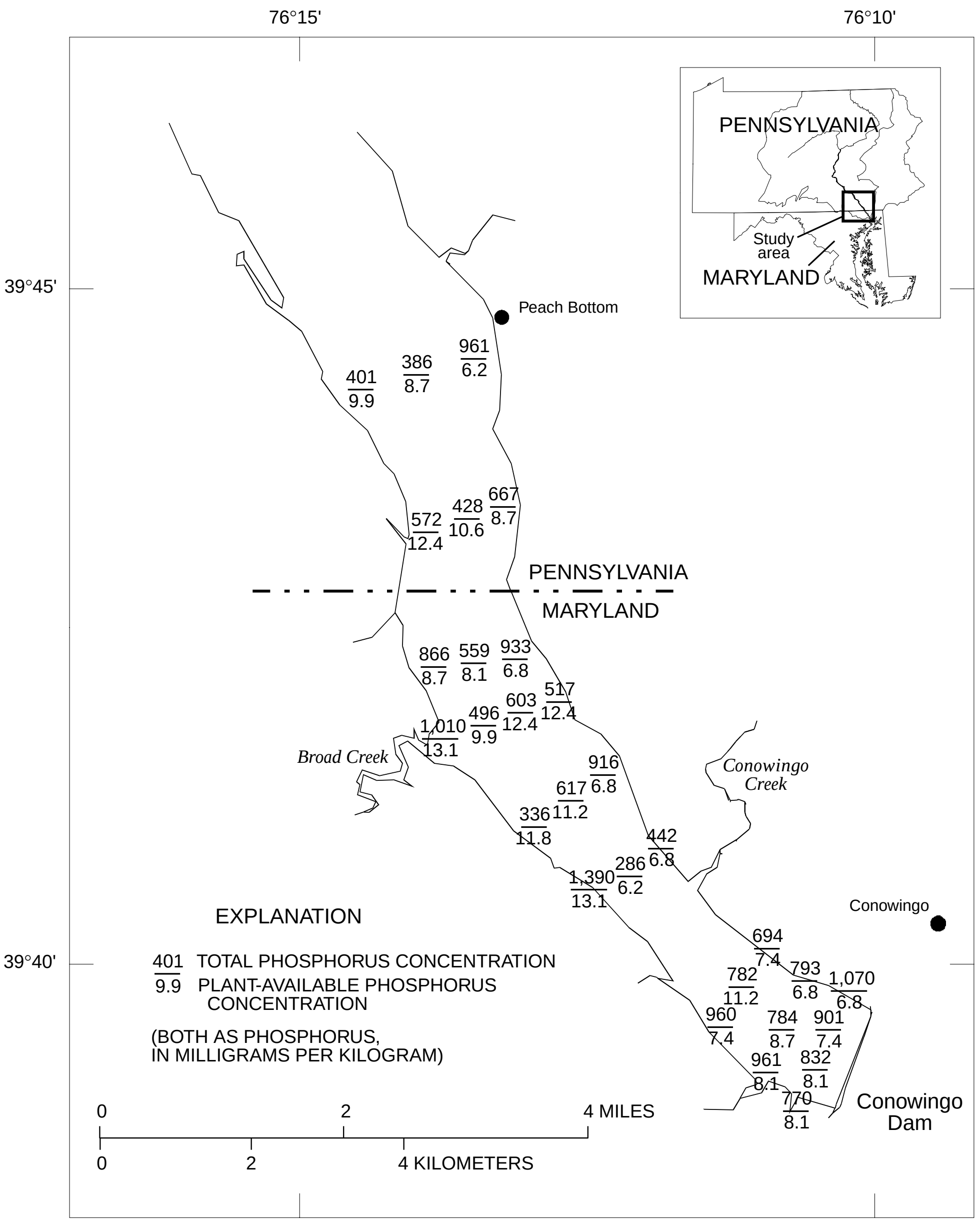

Figure 9. Concentrations of total phosphorus and plant-available phosphorus measured in Conowingo Reservoir bottom sediments, August 1996.

averaged about 12 percent—a substantial decrease. This indicates that a major part of the fine material stored in the lower part of Conowingo Reservoir may have been removed and carried the adsorbed nutrients with it.

An estimate of the nutrient mass remaining within the lower part of Conowingo Reservoir (figs. 8 and 9) after the January 1996 flood can be determined from the original mass estimate provided by Hainly and others (1995), the change in mass determined by Reed and Hoffman (1997) and this study, and average concentrations of total nitrogen and phosphorus from bottom material collected in this study. The use of an average surficial nutrient concentration reduces the effects that any sample variability could have on the mass estimate.

A vertical distribution of nutrient concentrations in lake bottom sediments is common (E. Callender, U.S. Geological Survey, Reston, Va., written commun., 1997), however, the core samples collected by Hainly and others (1995) in 1990 were composited, as were those collected for this study. Because the concentration distribution in Conowingo Reservoir sediments is unknown, vertical uniformity of concentrations is assumed and was used in the mass estimate determinations. This assumption may create an overestimate in the nutrient mass. The areas delineated by Hainly and others (1995) and later studies differ slightly, reducing the accuracy of the estimates for nutrient mass remaining in Conowingo Reservoir. Calculations were based on a 67.8 lb / ft^3 average density of dry bottom sediment suggested by Reed and Hoffman (1997).

The original design capacity of the area from cross section 4 to Conowingo Dam is approximately 235,000 acre-ft. This study determined that approximately 115,000 acre-ft of storage capacity remains in this part of Conowingo Reservoir. If the average concentrations of total nitrogen (3,780 mg / kg) and total phosphorus (720 mg / kg) from bottom material collected in this area are applied to the estimated 120,000 acre-ft of deposited sediment, the result is an estimate of nearly 670,000 tons of total nitrogen and slightly less than 130,000 tons of total phosphorus stored in the lower part of Conowingo Reservoir. These amounts are equivalent to 9 times the annual load of nitrogen and about 50 times the annual load of total phosphorus transported to the Chesapeake Bay by the Susquehanna River during a year of average streamflow. From data collected in 1990, Hainly and others (1995) estimated that about 440,000 tons of total nitrogen and about 125,000 tons of phosphorus were stored in the same area of Conowingo Reservoir. The estimates from the two independent studies compare favorably. The smaller estimate of total nitrogen mass in 1990 could be related to the greater sampling depth in that study and the tendency for nitrogen concentrations to decrease with depth in bottom sediments. The relation suggested by concentrations of total phosphorus and plant-available phosphorus measured in this study indicates that about 1,600 tons of plant-available phosphorus also could be contained in the deposited sediment.

Nutrient loads as a result of bottom-sediment scour for various peak streamflows over Conowingo Dam also can be estimated from average concentrations of total nitrogen and phosphorus from bottom material collected in this study. The relation between peak streamflow over Conowingo Dam and bottom-sediment scour (fig. 7) was used to compute the bottom-sediment scour loads (table 7). Estimates of loads of total nitrogen and total phosphorus are based solely on the amount of scoured bottom sediment and do not incorporate any other physical or chemical transformations that may occur during the re-suspension and transport process.

The estimates of average annual loads of nutrients during a year of average streamflow supplied by Ott and others (1991) can be incorporated with estimates of nutrients scoured during a storm that exceeds the scour threshold streamflow to indicate the relative magnitude of loads from scour in comparison to average annual loads and to determine changes in nutrient loads that may occur as the reservoir system approaches sediment-storage capacity (table 8). A peak streamflow of 600,000 ft^3 / s, the same peak streamflow used in table 5, was selected to provide estimates of storm scour. This magnitude of peak streamflow, using data from the discharges measured at Harrisburg, is expected to occur every 35 years but has been exceeded three times in the last 25 years.

The compilation of existing annual nutrient-load estimates, predicting nutrient loads as a result of a relatively small scour-producing storm, and changing reservoir conditions as the system approaches sediment-storage capacity provides a scenario that has at least a 50-percent chance of occurring within the next 20 years. When the reservoir reaches sediment-storage capacity, an estimated increase of 2 percent (1,500 tons) in loads of total nitrogen with or without the occurrence of a storm event that slightly exceeds the scour threshold is expected. The expected increase is small for both situations because of the reservoir system's low trap efficiency for nitrogen.

The change in phosphorus load is markedly different. Without the occurrence of a storm event that exceeds the scour threshold, annual loads of phosphorus to Chesapeake Bay are expected to increase about 1,800 tons (70 percent) when the reservoir system reaches sediment-storage capacity. Loads of plant-available phosphorus are expected to increase a similar amount. Because of the relatively large magnitude of phosphorus load introduced by scour from the selected storm event (about 80 percent of the current annual load during a year of normal streamflow), a scour event coupled with reservoir conditions at sediment-storage capacity produces only about a 35-40 percent increase in the estimated annual load of phosphorus to Chesapeake Bay. Regardless of the occurrence of a scour-producing event, the reduced trap efficiency of phosphorus that will occur as the reservoir system approaches sediment-storage capacity will have a profound effect on the annual load of phosphorus transported to Chesapeake Bay by the Susquehanna River. If the goal of a 40-percent reduction in the phosphorus load from the Susquehanna River Basin is met before the reservoirs reach sediment-storage capacity, the 40-percent reduction goal will probably be exceeded when the reservoir system reaches capacity.

Table 7. Estimates of loads of sediment, total nitrogen, and total phosphorus as a result of bottom-sediment scour from the lower Susquehanna River Basin reservoir system for selected peak streamflows

[>, greater than; <, less than]

Peak streamflow at Conowingo Dam (cubic feet per second)	Predicted scour load, in tons × 1000				
	Streamflow recurrence interval[1] (years)	Sediment	Total nitrogen[2]	Total phosphorus[3]	Plant-available phosphorus[4]
500,000	15	82	0.3	<0.1	<0.01
600,000	35	2,820	10.7	2.0	.02
700,000	75	5,570	21.0	4.0	.05
800,000	150	8,310	31.4	6.0	.08
900,000	270	11,000	41.6	7.9	.10
1,000,000	>500	13,800	52.1	9.9	.12

[1] Estimate based on recurrence intervals determined for peak streamflows recorded at the station on the Susquehanna River at Harrisburg, Pa. (107 years of record). Drainage area at Harrisburg is about 90 percent of drainage area at Conowingo Dam.
[2] Estimate based on an average concentration of total nitrogen in bottom sediments of 3,780 milligrams per kilogram.
[3] Estimate based on an average concentration of total phosphorus in bottom sediments of 720 milligrams per kilogram.
[4] Estimate based on a ratio of average concentration of plant-available phosphorus to concentration of total phosphorus of 1.25 percent.

Table 8. Estimates of average annual loads of total nitrogen discharged into, passing through, and scoured from the lower Susquehanna River Basin reservoir system during years with and without a flood event, before and after Conowingo Reservoir reaches sediment-storage capacity

[INPUT, flow or load into reservoir system; OUTPUT, flow or load past Conowingo Dam; CHANGE, difference between below sediment-storage and at sediment-storage capacity loads]

Scour condition	Total nitrogen load				
	Annual load[1] (tons × 1,000) INPUT	Scour load (tons × 1,000) OUTPUT	Below sediment-storage capacity Annual load (tons × 1,000) OUTPUT	At sediment-storage capacity Annual load (tons × 1,000) OUTPUT	Range of estimate,[2] (percent) CHANGE
No flood event	75	0	[3]73.5	75	0.2 - 5.2
With flood event	75	[4]10.7	84.2	85.7	0.2 - 4.2

[1] Load based on an annual mean streamflow that is equivalent to the long-term average streamflow (Ott and others, 1991).
[2] Range based on combined prediction errors of inflow, scour, and outflow loads.
[3] When reservoir is below sediment-storage capacity, annual deposition rate is 1,500 tons (Ott and others, 1991).
[4] Loads based on a flood event with a peak streamflow of 600,000 cubic feet per second over Conowingo Dam.

Table 9. Estimates of average annual loads of total phosphorus discharged into, passing through, and scoured from the lower Susquehanna River Basin reservoir system during years with and without a flood event, before and after Conowingo Reservoir reaches sediment-storage capacity

[INPUT, flow or load into reservoir system; OUTPUT, flow or load past Conowingo Dam; CHANGE, difference between below sediment-storage and at sediment-storage capacity loads]

Scour condition	Total phosphorus load				
	Annual load[1] (tons × 1,000) INPUT	Scour load (tons × 1,000) OUTPUT	Below sediment-storage capacity Annual load (tons × 1,000) OUTPUT	At sediment-storage capacity Annual load (tons × 1,000) OUTPUT	Range of estimate,[2] (percent) CHANGE
No flood event	4.35	0	[3]2.56	4.35	64 - 76
With flood event	4.35	[4]2.0	4.56	6.35	33 - 43

[1] Load based on an annual mean streamflow that is equivalent to the long-term average streamflow (Ott and others, 1991).
[2] Range based on combined prediction errors of inflow, scour, and outflow loads.
[3] When reservoir is below sediment-storage capacity, annual deposition rate is 1,790 tons (Ott and others, 1991).
[4] Loads based on a flood event with a peak streamflow of 600,000 cubic feet per second over Conowingo Dam.

SUMMARY

Reducing nutrient loads into Chesapeake Bay is an important environmental issue in Pennsylvania, Virginia, Maryland, and the District of Columbia. Numerous federal, state, and local agencies, environmental groups, and private universities have invested major resources toward meeting an agreed-upon goal of a 40-percent reduction in controllable nutrient loads to the Bay from 1985 to the year 2000 and then maintaining that cap beyond the year 2000. Nearly 50 percent of the freshwater discharge to the Bay comes from the Susquehanna River. Estimates of nearly 66 percent of the annual nitrogen load, 40 percent of the phosphorus load, and 25 percent of the suspended-sediment load contributed to the Bay by areas upstream of the Fall Line originate from within the Susquehanna River drainage area.

A reservoir system consisting of Lakes Clarke and Aldred and Conowingo Reservoir is formed by three consecutive hydroelectric dams on the lower Susquehanna River. Conowingo Reservoir discharges directly to Chesapeake Bay and is currently trapping about 2 percent of the nitrogen, 40 percent of the phosphorus, and 70 percent of the suspended-sediment loads that would otherwise be discharged to the Bay. During the period from 1990 to 1996, the USGS collected bathymetric data and bottom-sediment samples to determine the remaining sediment-storage capacity in the reservoir system, estimate when the reservoir may reach sediment-storage capacity, and determine the nutrient mass remaining in the most-downstream reservoir after a major flood in January 1996.

January 1996 witnessed an extremely unusual and widespread flood event—extensive flash flooding occurred that approached or exceeded previously recorded flood peaks in many areas of the Susquehanna River Basin. Warm winds, 3-4 ft of snow on the ground with a water equivalent of 3-5 in., and an additional 3 in. of rain falling in a short time created a rapid increase in river levels that broke up the ice pack, forming many ice jams around bridges and natural obstructions in the rivers. An ice jam formed just downstream of Harrisburg causing river levels to rise 8 ft in 1 hour. When that jam broke, the increased flow and ice from Harrisburg reached a constriction in the reservoir system and another ice jam formed in Lake Clarke about 2.5 mi upstream of the Safe Harbor Dam. Behind the ice jam, the lake level rose an average of 10 ft (the maximum rise near the ice jam was 17 ft), causing extensive flooding in the middle and upper parts of Lake Clarke.

When the ice jam broke in Lake Clarke, most of the backwater was released in 2.5 hours resulting in a surge of water and ice of approximately 400,000 ft^3/s. At the same time as the ice jam release, the river flow was about 450,000 ft^3/s. A peak flow of approximately 826,000 ft^3/s was estimated through Safe Harbor Dam. The flood surge continued through Lake Aldred into Conowingo Reservoir. The peak flow at Conowingo Dam was about 909,000 ft^3/s.

The high flows that occurred shortly after the ice jam broke in Lake Clarke during the January 1996 flood had a major effect on the stored bottom sediment. Large amounts of sediment were deposited upstream of the ice jam and even larger amounts of sediment were scoured near and downstream of the ice jam. A net amount of 2,300,000 tons of sediment was estimated to have been scoured from Lake Clarke between 1993 and 1996, nearly all occurring in the January 1996 flood event. By use of average sediment deposition rates from 1959 to 1993, the scoured areas in Lake Clarke will probably fill in 1-2 years.

Areas of deposition and scour occurred throughout the entire length of Conowingo Reservoir. Comparison of the 1993 and 1996 surveys indicates approximately 4,900,000 tons of sediment were removed by scour from the reservoir between 1993 and 1996. However, results also indicate about 2,500,000 tons of sediment were deposited during the same time period. Therefore, a "net" change of about 2,400,000 tons of sediment were scoured from the reservoir between 1993 and 1996. Slightly more than 80 percent of the total sediment scour was in the lower part of the reservoir. On the basis of an average annual sediment deposition rate from 1959 to 1993, the amount scoured from the Conowingo Reservoir will probably be replaced in 1-2 years.

As a result of scour during the January 1996 flood, storage capacity in the Conowingo Reservoir increased by approximately 1,600 acre-ft—an equivalent of 2,400,000 tons of sediment. About 29,000 acre-ft remain to be filled or 42,000,000 tons of sediment can be deposited before reaching sediment-storage capacity. Estimating the time remaining until the reservoir reaches sediment-storage capacity is difficult because of changes in sediment-deposition rates, changes in the amount of sediment transported into the reservoir, and the effects of large scour events like the January 1996 flood. Annual average sediment deposition (from 1959 to 1996) is about 2,500,000 tons. Assuming that this rate of sediment deposition remains unchanged and no scour occurs because of flood events, the reservoir could reach sediment-storage capacity in about 17 years.

A simple input-output model was used to represent sediment transport through the reservoir system during the January 1996 flood. The total sediment input was estimated to be about 14,800,000 tons. This includes sediment transported into the reservoir system (3,200,000 tons) plus the net sediment change within the three reservoirs (4,700,000 net tons scoured) plus the 6,900,000 tons estimated to have been deposited since the 1993 survey. This amount should approximate the measured sediment output from the system (7,000,000 tons). The difference of 7,800,000 tons of sediment indicates more than 50 percent of the sediment was unaccounted for in this model. Most of this error is probably related to the underestimation of sediment discharge (output) through the Conowingo Dam and the fathometer's "1-ft" level of accuracy.

On the average, 96 percent of the concentrations of total nitrogen were comprised of organic nitrogen and 84 percent of the concentrations of total phosphorus were comprised of inorganic phosphorus. With a few exceptions, concentrations of total nitrogen and total phosphorus were fairly uniform throughout Lake Clarke and Lake Aldred. Concentrations of total nitrogen are fairly uniform throughout Conowingo Reservoir—ranging from 1,500 to 6,900 mg/kg and averaging about 3,780 mg/kg. The lowest concentrations were measured in samples collected in the mid-section of the reservoir, and the highest were along the cross sections immediately downstream of the confluence of Broad Creek.

Concentrations of total phosphorus in bottom sediments of the lower half of Conowingo Reservoir did not exhibit any uniform patterns. Concentrations ranged from 286 to 1,390 mg/kg and averaged about 720 mg/kg. The most variable concentrations were measured in samples collected at or immediately downstream of the mouth of Broad Creek. The ratio of concentrations of plant-available phosphorus to concentrations of total phosphorus ranged from 0.6 to 3.5 percent, and the ratio of these two concentrations tended to decrease in a downstream direction. The average ratio of plant-available phosphorus to concentrations of total phosphorus in the lower part of Conowingo Reservoir was slightly more than 1 percent.

Historical and current sediment and nutrient loading data, estimates of reservoir bottom-sediment scour, and measurements of peak and daily mean streamflow were used to develop a relation between bottom-sediment scour from Conowingo Reservoir and streamflow past Conowingo Dam. This regression can be used to estimate scour on the basis of peak streamflow. Estimates of bottom-sediment scour on the basis of peak streamflows were incorporated with daily loads of suspended sediment, total nitrogen, and total phosphorus to estimate the same loads for scenarios that incorporate Conowingo Reservoir capacity conditions at less than and approaching sediment-storage capacity.

Results of this study indicate that if current conditions remain constant, a 210 to 275-percent increase in the current annual loads of suspended sediment, a 0.2 to 5.2-percent increase in the current annual loads of total nitrogen, and a 64 to 76-percent increase in the current annual loads of total phosphorus from the Susquehanna River to Chesapeake Bay could be expected once the Conowingo Reservoir reaches sediment-storage capacity. Also, after capacity has been reached, an even greater increase in the annual loads of sediment and nutrients transported to Chesapeake Bay will occur if major floods with peak flows greater than the 400,000 ft^3/s scour threshold occur. If the goal of a 40-percent reduction in phosphorus loads from the Susquehanna River Basin is met before the reservoirs reach sediment-storage capacity, the increased phosphorus loads solely due to the lack of reservoir deposition could cause the phosphorus-load reduction cap to be exceeded.

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