Sediment Transport and Capacity Change in Three Reservoirs, Lower Susquehanna River Basin, Pennsylvania and Maryland 1900–2012

Open-File Report 2014–1235

U.S. Department of the Interior
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Cover. Susquehanna River at Conowingo Dam, September 9, 2004. Photo by Wendy McPherson, U.S. Geological Survey.

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U.S. Geological Survey
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Conversion Factors

Multiply	By	To obtain
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Mass	
ton per year (ton/yr)	0.9072	metric ton per year
	Density	
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

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

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

Elevation, as used in this report, refers to distance above the vertical datum.

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By Michael J. Langland

Abstract

The U.S. Geological Survey (USGS) has conducted numerous sediment transport studies in the Susquehanna River and in particular in three reservoirs in the Lower Susquehanna River Basin to determine sediment transport rates over the past century and to document changes in storage capacity. The Susquehanna River is the largest tributary to Chesapeake Bay and transports about one-half of the total freshwater input and substantial amounts of sediment and nutrients to the bay. The transported loads are affected by deposition in reservoirs (Lake Clarke, Lake Aldred, and Conowingo Reservoir) behind three hydropower dams. The geometry and texture of the deposited sediments in each reservoir upstream from the three dams has been a subject of research in recent decades. Particle size deposition and sediment scouring processes are part of the reservoir dynamics. A Total Maximum Daily Load (TMDL) for nitrogen, phosphorus, and sediment was established for Chesapeake Bay to attain water-quality standards. Six states and the District of Columbia agreed to reduce loads to the bay and to meet load allocation goals for the TMDL. The USGS has been estimating annual sediment loads at the Susquehanna River at Marietta, Pennsylvania (above Lake Clarke), and Susquehanna River at Conowingo, Maryland (below Conowingo Reservoir), since the mid-1980s to predict the mass balance of sediment transport through the reservoir system. Using streamflow and sediment data from the Susquehanna River at Harrisburg, Pennsylvania (upstream from the reservoirs), from 1900 to 1981, sediment loads were greatest in the early to mid-1900s when land disturbance activities from coal production and agriculture were at their peak. Sediment loads declined in the 1950s with the introduction of agricultural soil conservation practices. Loads were dominated by climatic factors in the 1960s (drought) and 1970s (very wet) and have been declining since the 1980s through 2012. The USGS developed a regression equation to predict the sediment scour load for daily mean streamflows greater than 300,000 cubic feet per second for the Lower Susquehanna River reservoirs. A compilation of data from various sources produced a range in total sediment transported through the reservoir system and allowed for apportioning to source (watershed or scour) for various streamflows. In 2011, Conowingo Reservoir was estimated to be about 92 percent of sediment storage capacity. Since construction of Conowingo Dam in 1929 through 2012, approximately 470 million tons of sediment was transported down the Susquehanna River into the reservoir system, approximately 280 million tons were trapped, and approximately 190 million tons were transported to Chesapeake Bay. Spatial and estimated total sand deposition in Conowingo Reservoir based on historical sediment cores indicated continued migration of sand downgradient toward the dam and the winnowing of silts and clays near the dam due to scour.

Introduction

The Susquehanna River is the largest tributary to Chesapeake Bay and transports about one-half of the total freshwater input and substantial amounts of sediment, nitrogen, and phosphorus to the bay (Langland, 2009). The loads transported by the Susquehanna River to the bay are substantially affected by the deposition of sediment and nutrients behind three hydroelectric dams on the lower Susquehanna River near the mouth (Reed and Hoffman, 1996). The three consecutive reservoirs (Lake Clarke, Lake Aldred, and Conowingo Reservoir) that formed behind the three dams (Safe Harbor, Holtwood, and Conowingo, respectively) involve nearly 32 miles of the river and have a combined design storage capacity of 510,000 acre-feet (acre-ft) at the normal pool elevations (fig. 1). The normal pool elevation is the height in feet above sea level at which a section of a river is to be maintained behind a dam. A fourth dam (York Haven) is located approximately 44 miles upstream from Conowingo Dam. Because of the low water head (28 feet) and low storage area (7,800 acre-ft), the sediment retention at York Haven is substantially less than that of the dams located downstream and is not considered in this project. A water-storage facility (Muddy Run, located just below Holtwood Dam) is a pump-storage release facility where water

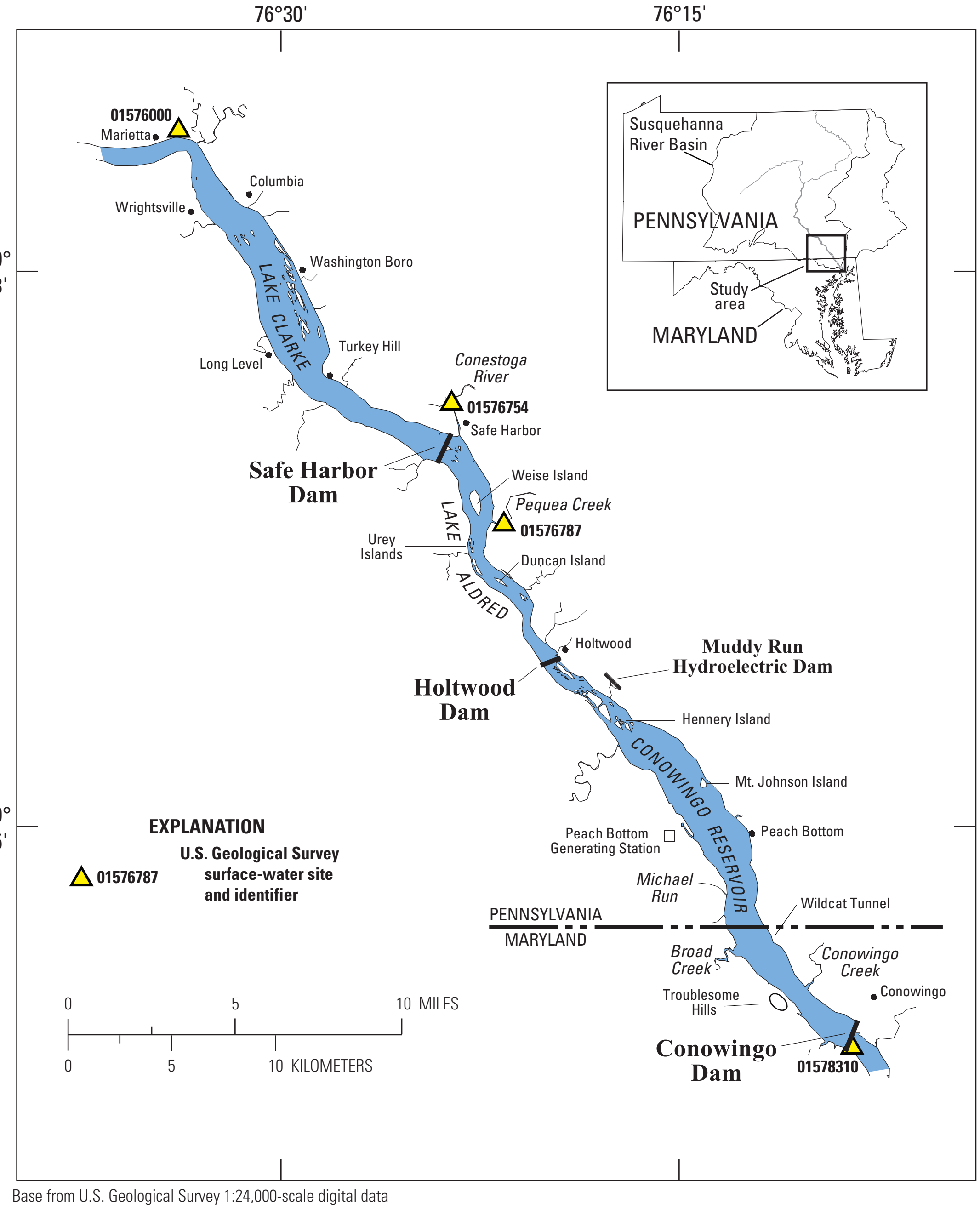


Figure 1. Location of the three major reservoirs—Lake Clarke, Lake Aldred, and Conowingo Reservoirs—in the Lower Susquehanna River Basin, Pennsylvania and Maryland.

from Conowingo Reservoir is pumped approximately 400 feet uphill to be released when demand for electricity is high also is not considered in this project.

Safe Harbor Dam, built in 1931 with a dam height of 80 feet (North American Vertical Datum, 1988, referred to as “NAVD 1988”) forms the uppermost reservoir, has a design capacity of about 150,000 acre-ft, and is considered to have reached the capacity to store sediment in the early 1950s. Holtwood Dam, built in 1910 with a dam height of 60 feet NAVD 1988, is the smallest of the three dams, has a design capacity of about 60,000 acre-ft, and is considered to have reached the capacity to store sediment in the mid-1920s. Conowingo Dam, built in 1929, is the largest and most downstream dam, has a height of 110 feet NAVD 1988, and has a design capacity of about 300,000 acre-ft. Conowingo Reservoir has limited capacity to store sediment and may be in equilibrium (Hainly and others, 1995; Reed and Hoffman, 1996).

Plan to Reduce Loads to Chesapeake Bay

The District of Columbia, the six states with waterways draining into Chesapeake Bay (Maryland, Pennsylvania, Virginia, New York, West Virginia, and Delaware), the Chesapeake Bay Commission, and the U.S. Environmental Protection Agency (EPA) have agreed to a plan to reduce nutrient loads to Chesapeake Bay in an attempt to restore and protect the estuarine environment of the bay. The EPA has established a Total Maximum Daily Load (TMDL), which mandates sediment and nutrient (nitrogen and phosphorus) allocation goals for each of the six states (table 1) with waterways draining into Chesapeake Bay (U.S. Environmental Protection Agency, 2010). The six states and the District of Columbia have each written Watershed Implementation Plans (WIPs) to reduce loads to the Bay and to meet load allocation goals for the TMDL. Each of the states’ plans can be accessed at *http://www.chesapeakebay.net/about/programs/watershed*. Of particular interest are the allocations for New York, Pennsylvania, and Maryland, the states that have waters draining into at least one the three reservoirs in the Lower Susquehanna River.

Previous Studies on the Three Reservoirs

Previous studies by Ott and others (1991), Hainly and others (1995), Reed and Hoffman (1996), Langland and Hainly (1997), Langland (2009), and Gomez and Sullivan Engineers (2012) have documented important information on the Lower Susquehanna River reservoirs, including the reservoirs’ bottom-sediment profiles, reduced storage capacity, and trap efficiency. Several studies also have determined sediment chemistry (Hainly and others, 1995; Langland and Hainly, 1997; and Edwards, 2006) and the effects of large storm events on the removal and transport of sediment out of the reservoir system and into the upper Chesapeake Bay (Langland and Hainly, 1997; Langland, 2009; Gomez and Sullivan Engineers, 2012).

Langland (2009) provides a historical perspective on reservoir filling rates and projects when sediment storage capacity may be reached in the Conowingo Reservoir. When storage capacity is reached, a dynamic-equilibrium condition will exist between incoming and outgoing sediment and nutrient loads discharged through the reservoir system to Chesapeake Bay. In the dynamic-equilibrium condition, constituent loads may increase during high streamflow scour events, thereby affecting the WIPs to meet sediment and nutrient allocation TMDL goals set by the EPA and the State of Maryland water-quality standards for dissolved oxygen, water clarity, and chlorophyll A. With respect to TMDLs, increased loads may have a greater effect on sediment and phosphorus, which tend to be transported in the particulate (solid) phase, and less of an effect on nitrogen, which tends to transported in the dissolved phase.

Table 1. Nutrient and sediment load allocation goals for the six states with waterways draining into Chesapeake Bay to meet the Total Maximum Daily Loads set by the U.S. Environmental Protection Agency (2010).

Jurisdiction	Total maximum daily load allocations					
	Nitrogen		Phosphorus		Sediment	
	Tons per year	Million pounds per year[1]	Tons per year	Million pounds per year[1]	Tons per year	Million pounds per year[1]
Delaware	1,500	3	150	0.3	28,900	58
District of Columbia	1,200	2.3	50	0.1	5,600	11
Maryland	19,600	39.2	1,400	2.7	609,000	1,219
New York	4,400	8.8	300	0.6	146,000	293
Pennsylvania	36,900	74	1,400	2.9	992,000	1,984
Virginia	26,700	53	2,700	5.4	1,289,000	2,579
West Virginia	2,800	5.5	300	0.6	155,000	311

[1]Rounded.

However, in this dynamic-equilibrium condition, loads may decrease for a short duration owing to increased deposition as a result of, and related to, the length of time since a preceding scour event. Hirsch (2012) concludes that the reservoirs are very close to this equilibrium condition and that nutrient and sediment concentrations and loads have been increasing at the Conowingo Dam (the furthest downstream and closest to Chesapeake Bay) for the past 10–15 years. Hirsch (2012) implies that increasing concentrations and loads are due to the loss of storage capacity and a possible decrease in the scour threshold of 400,000 cubic feet per second (ft^3/s). Reasons for the increase are not certain, but likely involve changes in particle-falling velocities owing to increased water velocity, transport capacities, and bed shear.

Dams create a change in hydrological dynamics affecting sediment transport and deposition. With increased depth, streamflow velocities are reduced within the reservoir. Owing to streamflow deceleration as the water enters the reservoir, sediment-transport capacity decreases, and the coarser-size fractions of the incoming sediment fall out of the water column and are deposited near the upstream end of the reservoir, forming a delta near the entrance to the reservoir (fig. 2). As the water and sediment continue to flow into the reservoir, the delta continues to extend in the direction of the dam, eventually filling the entire sediment storage volume. The process is usually slow, governed by the amount of incoming sediment, sediment particle size, and streamflow variability. Generally, low streamflow results in deposition, whereas during higher streamflow some of the sediment is scoured from the upper end of the reservoir and transported downstream with a portion transported out of the reservoir. Large reservoirs receiving runoff with substantial sediment from natural and (or) anthropogenic sources typically fill (reach equilibrium) in 50 to 100 years (Mahmood, 1987).

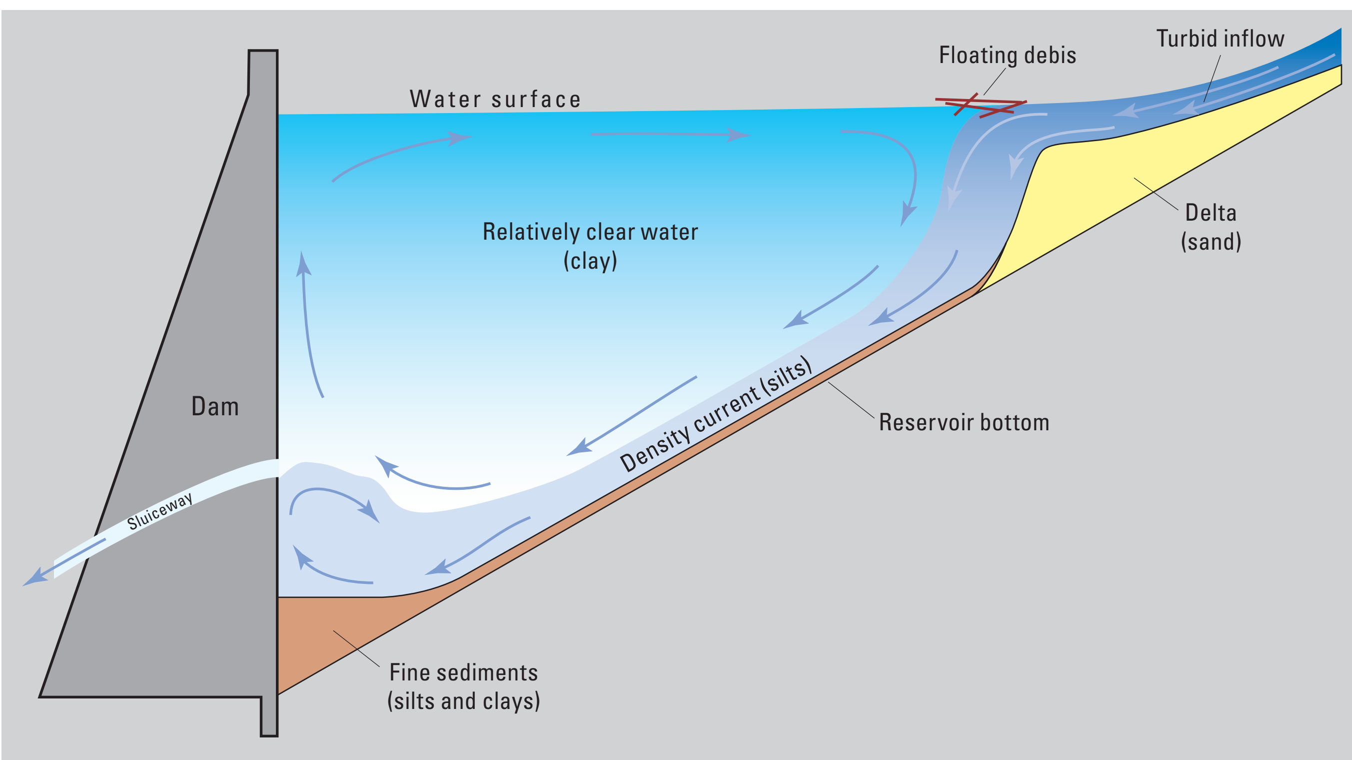


Figure 2. Idealized schematic of a reservoir and the dynamic of circulation and deposition (From Sloff,1997).

Purpose and Scope

For this report, the primary objective is to provide a historical perspective on sediment transport and to document resultant changes in reservoir capacity within three reservoirs in the Lower Susquehanna River Basin (fig. 1). Streamgages at Susquehanna River at Marietta, Pennsylvania, located above Lake Clarke (01576000), with a drainage area (DA) of approximately 25,990 square miles (mi^2), and the Susquehanna River at Conowingo, Maryland (01578310), located below Conowingo Reservoir, with a DA of approximately 27,100 mi^2, are considered to be representative of the streamflow and sediment input to, and output from, the reservoir system. Owing to the lack of sediment information from the upper two reservoirs (Lake Clarke and Lake Aldred), the streamflow and sediment results are considered the cumulative effect of all three reservoirs. In addition, the streamgage at Susquehanna River at Harrisburg, Pennsylvania (01570500), was used to estimate streamflow at Marietta prior to 1987.

This report presents decadal changes in sediment transport, recurrence intervals for streamflow at two U.S. Geological Survey (USGS) streamgages, river and scour sediment transport values, and an evaluation of streamflow and sediment transport in the reservoirs. Additional information presented in this report includes locations and dates of all sediment cores collected by the USGS historically in the Conowingo Reservoir, with grain-size distribution and total deposition of sand, silt, and clay for specific locations for multiple time periods. Information provided in this report may be useful to managers when considering a range of management options dealing with streamflow and sediment dynamics in the Lower Susquehanna River reservoir system.

Susquehanna River Sediment Transport

Using current and historical streamflow (1900–1987) and sediment data (1962–1981) from the Susquehanna River at Harrisburg, Pa. (01570500), approximately 25 miles upstream from Marietta, and streamflow and sediment data (1987–2010) from the Susquehanna River at Marietta, Pa. (01576000), sediment loads were estimated from 1930 to 2010 (by decade) at Marietta, and these values were considered to represent input to the reservoirs (fig. 3). Loads historically were estimated using the USGS ESTIMATOR model (Cohn and other, 1989) and more recently using the Weighted Regression on Time Discharge and Season (WRTDS) model (Hirsch, 2010). Loads were greater in the early to mid-1900s, averaging approximately 87 million tons per decade (8.7 million tons per year), owing to large land disturbance activities, including coal extraction and agriculture (Williams and George, 1972). In the 1950s, agricultural conservation measures were enacted (Wedin, 2002; Westra, 2003), helping to reduce sediment loads from 87 million tons in previous decades to approximately 60 million tons. Sediment loads have generally decreased

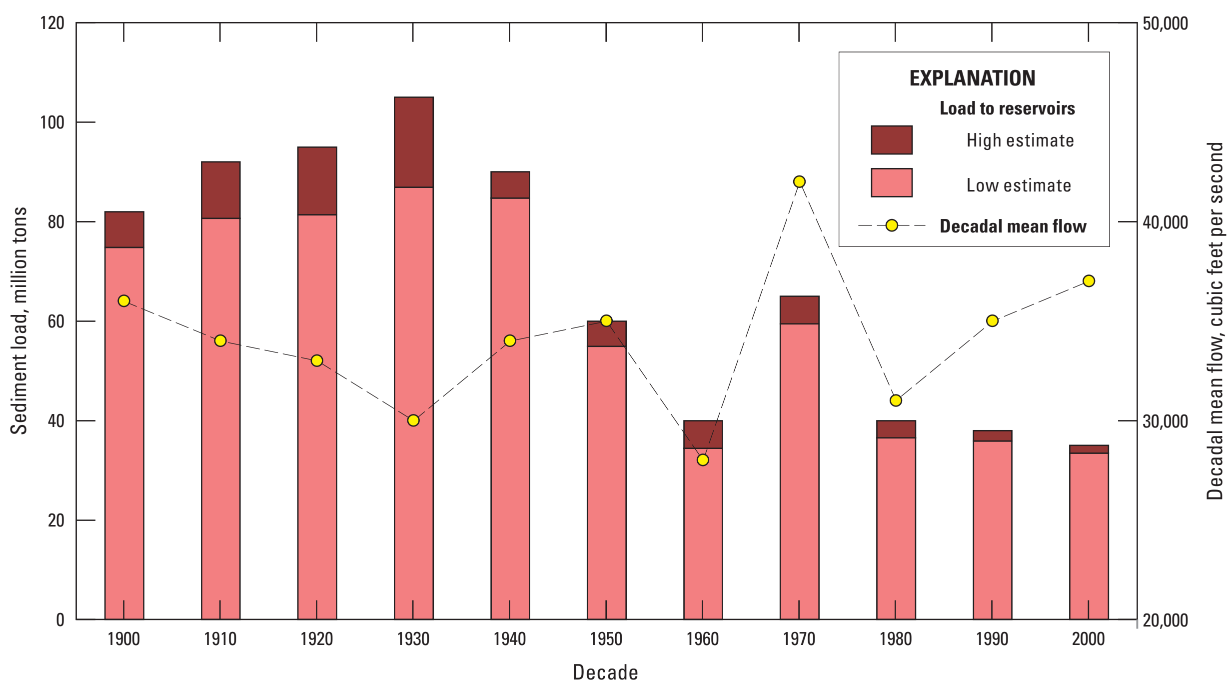


Figure 3. Total estimated sediment transported from the Susquehanna River into three reservoirs in Pennsylvania and Maryland, 1900–2010.

from the 1960s through the 1980s as a result of more land reverting to forest from farm abandonment, a decrease in land disturbance from coal production, and new best-management actions to control sediment (table 2). Loads continued to decline to an average of 3.5 million tons per year over the last 20 years (1991–2012). If not for the large decreases in sediment from the basin, the Conowingo Reservoir may have reached sediment storage capacity resulting in increased loads to Chesapeake Bay decades ago. The larger decreases in the loads into the reservoirs versus the nearly stable loads out to Chesapeake Bay indicate a loss of trapping efficiency over time (table 2). Trapping efficiencies can exhibit a wide variation and are dependent on climatic conditions in a given time frame.

Climatic extremes are indicated in figure 3, when during the 1960s, streamflow every year was below the normal annual mean, and 1970–79 was the wettest decade on record since 1900. Two storm events that caused major flooding occurred during the 1970s in the Chesapeake Bay region (Tropical Storm Agnes in 1972 and Tropical Storm Eloise in 1975). Tropical Storm Agnes produced the highest recorded streamflows at many locations in the Susquehanna River Basin, including Conowingo Dam. Since the 1980s, the decadal mean streamflow has increased by approximately 17 percent, whereas the decadal sediment loads continued to decrease by approximately 9 percent, an indication that management practices in the Susquehanna River Basin may be helping to control sediment that would otherwise reach the streams.

Sediment input from two monitored tributaries flowing into the reservoir system (Conestoga River at Conestoga [01576754] with a drainage areas [DA] of approximately 470 mi^2 and Pequea Creek at Martic Forge [01576787] with a DA of approximately 148 mi^2), both with long-term streamflow records (1985–2012), was estimated to account for the majority of the sediment load entering from the Susquehanna River below Marietta, Pa., and into the three reservoirs. Although Conestoga River and Pequea Creek have much smaller DAs and streamflows than the Susquehanna River, these two tributaries in the Lower Susquehanna River Basin have large sediment loads from agricultural and urbanization activities. On an annual basis, the sediment load from these two tributaries represent less than 10 percent of the total suspended-sediment load entering the reservoirs for 21 out the 26 years (1987–2012). More importantly, only 1 storm event exceeded 10 percent when streamflows exceeded 400,000 cfs. (fig. 4). Generally, an inverse relation exists between the percentage of the total sediment load from the Conestoga River and Pequea Creek and the total load transported into the reservoirs, indicating a greater influence from the larger Susquehanna River Basin as streamflows increase.

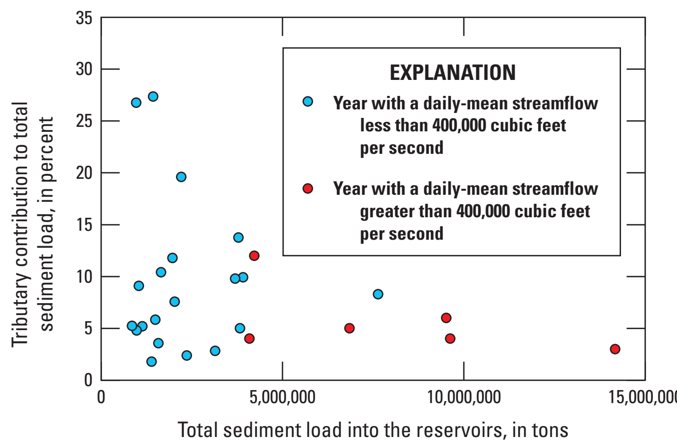


Figure 4. The annual percent of the total sediment load from the Conestoga River and Pequea Creek tributaries, Pennsylvania, in relation to the total sediment load transported into the reservoir system, Lower Susquehanna River Basin, 1987–2012.

Table 2. Average annual sediment loads transported into and out of the Lower Susquehanna River reservoir system and estimated trapping efficiency for multiple time periods.

Time period	Average annual sediment load to reservoirs (million tons/year)	Reservoir trapping (percent)	Average annual sediment load trapped (million tons/year)	Average annual sediment load to bay (million tons/year)
1928–1940	8.7	70–75	6.3	2.4
1941–1950	8.5	65–70	5.8	2.7
1951–1970	5.1	55–60	3.1	2.0
1971–1990[1]	4.9	50–55	2.6	2.3
1991–2012[2]	3.5	45–50	1.3	2.2

[1]Includes Tropical Storms Agnes and Eloise, June 1972 and September 1975.

[2]Includes Tropical Storm Lee, September 2011.

Recurrence Intervals and Total and Scour Sediment Loads

Expected streamflows for many recurrence intervals (RI) are presented in table 3. A recurrence interval is a statistical estimate of the likelihood that a given streamflow will occur, based on historical data. The annual exceedance probability is the chance that a given streamflow event will occur in the current year. The relation between RI and streamflow is illustrated in figure 5 for the two USGS Susquehanna River streamgages representing inflow and outflow from the reservoir system—the Susquehanna River at Marietta, Pennsylvania (01576000), and the Susquehanna River at Conowingo, Maryland (01578310), respectively—during 1968–2012. Streamflows corresponding to various RIs were computed for this study using methods described in Flynn and others (2006). Station skew for frequency distribution was used at both stations, and historical peak streamflows prior to 1968 were not used in the analysis. No low outliers were detected. Useful information about short-term streamflow includes the bankfull streamflow (RI of about 1.5 years) and the mean peak streamflow for the period of record (RI of 2.33 years).

A general coincidence in streamflow between the two Susquehanna River sites up until about the 1.5-year RI (bankfull discharge) is indicated in figure 5, then an increasing divergence occurs in RIs as streamflow increases. This is most likely due to differences in drainage area between the two sites (6 percent) and streamflow regulation and storage of three hydroelectric facilities between the streamgages.

The USGS has been estimating sediment loads at Susquehanna River at Marietta, Pennsylvania, since 1987 and at Susquehanna River at Conowingo, Maryland, since 1979. The annual loads are used to develop a simple in/out model to predict the mass balance of sediment transport through the reservoir system. The annual loads are used to calibrate a scour-prediction equation and estimate the sediment deposition and remaining capacity in Conowingo Reservoir.

Since 1972, there have been 11 storms with daily mean streamflows greater than 400,000 ft^3/s (5-year RI), the streamflow when an average mass wasting event begins, defined as the point at which large areas of the bed begin to move (Hainly and others, 1995) scouring the sediment in the reservoirs. Most likely some of the finer silt and sand particles begin to move before 400,000 ft^3/s. Cohesive sediments such as clays and fine silts may begin to move off the reservoir bottom at streamflows around 200,000 ft^3/s, whereas the heavier sand and gravels may not move until streamflows are greater than 600,000 ft^3/s (Schuleen and Higgins, 1953). A recent 2-dimensional model simulation of Conowingo Reservoir indicated silt and clay movement at around 250,000 ft^3/s (Steve Scott, U.S. Army Corps of Engineers,

Table 3. U.S. Geological Survey estimated recurrence intervals, annual exceedance probabilities, and estimated peak-streamflow estimates at two Susquehanna River streamgages, Lower Susquehanna River Basin, 1968–2012.

[ft^3/s, cubic feet per second]

Station 01576000 Susquehanna River at Marietta, Pennsylvania (1968–2012)			Station 01578310 Susquehanna River at Conowingo, Maryland (1968–2012)		
Estimated recurrence interval (years)	Annual exceedance probability	Estimated peak streamflow (ft^3/s)	Estimated recurrence interval (years)	Annual exceedance probability	Estimated peak streamflow (ft^3/s)
1	0.995	113,000	1	0.995	131,000
1.01	0.99	121,000	1.01	0.99	138,000
1.05	0.95	144,000	1.05	0.95	164,000
1.11	0.9	162,000	1.11	0.9	182,000
1.25	0.8	188,000	1.25	0.8	212,000
1.5	0.667	221,000	1.5	0.6667	248,000
2	0.5	265,000	2	0.5	298,000
2.33	0.4292	287,000	2.33	0.4292	323,000
5	0.2	402,000	5	0.2	436,000
10	0.1	514,000	10	0.1	590,000
25	0.04	685,000	25	0.04	798,000
50	0.02	835,000	50	0.02	984,000
100	0.01	1,010,000	100	0.01	1,200,000
200	0.005	1,210,000	200	0.005	1,500,000
500	0.002	1,510,000	500	0.002	1,860,000

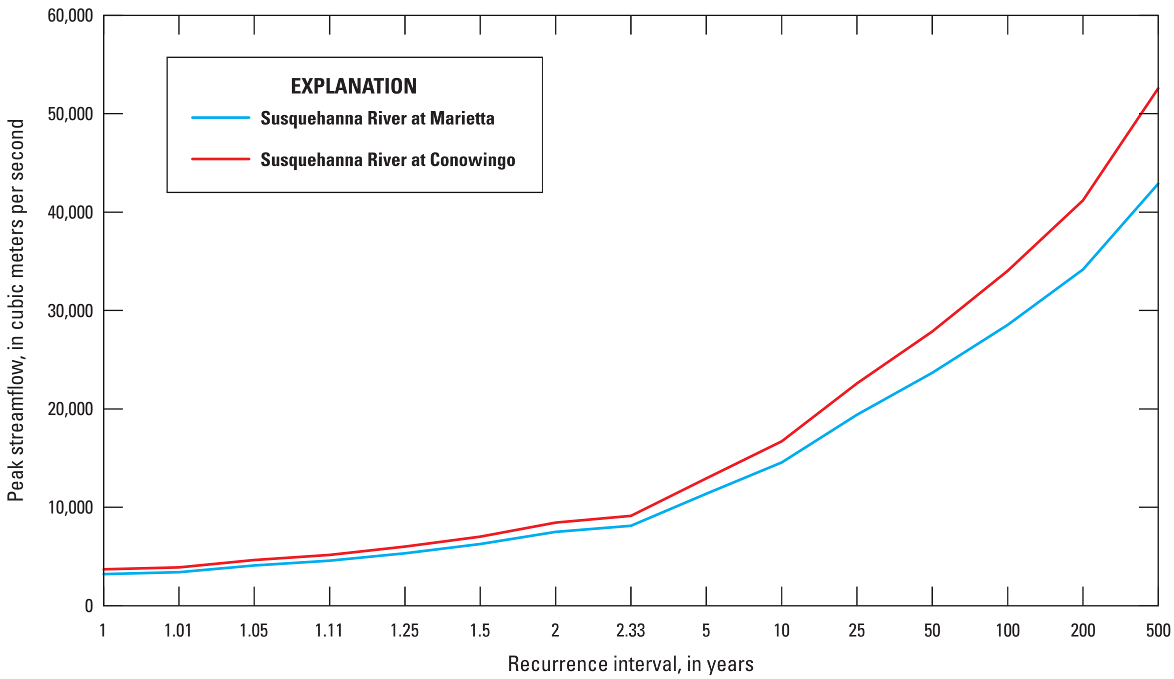


Figure 5. Peak streamflows, by recurrence interval, for the Susquehanna River at Marietta, Pennsylvania, and Susquehanna River at Conowingo, Maryland, streamgages.

written commun., 2014). For flows less than 400,000 ft^3/s, the majority of the scoured silts and sands are re-deposited in the reservoir system. Daily mean streamflow and number of storm days are plotted for 11 storms for the Susquehanna River at Conowingo, Maryland, streamgage (fig. 6). Note the general pattern of rapid increase on the rising limb to the peak and a more general decrease in streamflow on the falling limb. This is a typical high-flow response in many rivers and indicates that at higher streamflows the reservoirs do not have the capacity to store much water above normal pool elevations; these reservoirs are normally referred to as “run-of-the-river” reservoirs. The number of days with streamflows greater than 400,000 ft^3/s ranged from 1 to 5; the average was about 3 days. The 1972 event (Tropical Storm Agnes) was the largest flood in the Susquehanna River Basin since 1889, when recording of streamflow began at Harrisburg, Pa. The second largest recorded flood event, using daily mean streamflow data, in the Susquehanna River Basin since 1972 was in 2011 (Tropical Storm Lee; fig. 6). Note that more than one event is plotted for 1984 and 2011.

Streamflow can also be examined on a seasonal basis to determine the volume and timing of streamflow events over a given time period. To increase the number of streamflow events, daily mean streamflows greater than 300,000 ft^3/s at Susquehanna River at Conowingo were tabulated and are shown in figure 7. The highest number of daily mean streamflow events greater than 300,000 ft^3/s occurred during March–May (spring), whereas the greatest daily mean streamflows per storm event occurred during June–August (summer) and September–November (fall). The summer value was most likely biased high owing to the daily mean streamflow for 3 of the 8 events, each more than 1,000,000 ft^3/s during Tropical Storm Agnes. The higher streamflows tended to occur in the spring and fall, coinciding with the spring “freshet,” usually a result of snowmelt, and the fall Atlantic Ocean hurricane season, respectively.

The USGS developed a regression equation to predict the sediment scour load for daily mean streamflows greater than 300,000 ft^3/s for the Lower Susquehanna River reservoirs (fig. 8). The equation is based primarily on streamflow and estimated loads from six storm events during 1993–2011 (table 4), on bathymetry (bed-elevation change) data for the reservoirs using the Reed and Hoffman (1996), Langland and Hainly (1997), Langland (2009), and Gomez and Sullivan Engineers (2012) studies, and on a comparison of estimates of sediment inflow and outflow from the reservoirs. Additional information for Tropical Storm Agnes (1972) and Tropical Storm Eloise (1975) (Gross and others, 1978) was used to calibrate the curve. The regression equation was then used to predict scour loads for an additional three storms between 1972 and 1990 and for nine storms prior to 1972, with little to no sediment or bathymetric data, for daily mean streamflow greater than 400,000 ft^3/s (table 4), on the basis of historical trapping efficiency (table 2) and storage. For the 1936 sediment scour estimate, the current regression equation totaled approximately 5 million tons; however, owing to the small

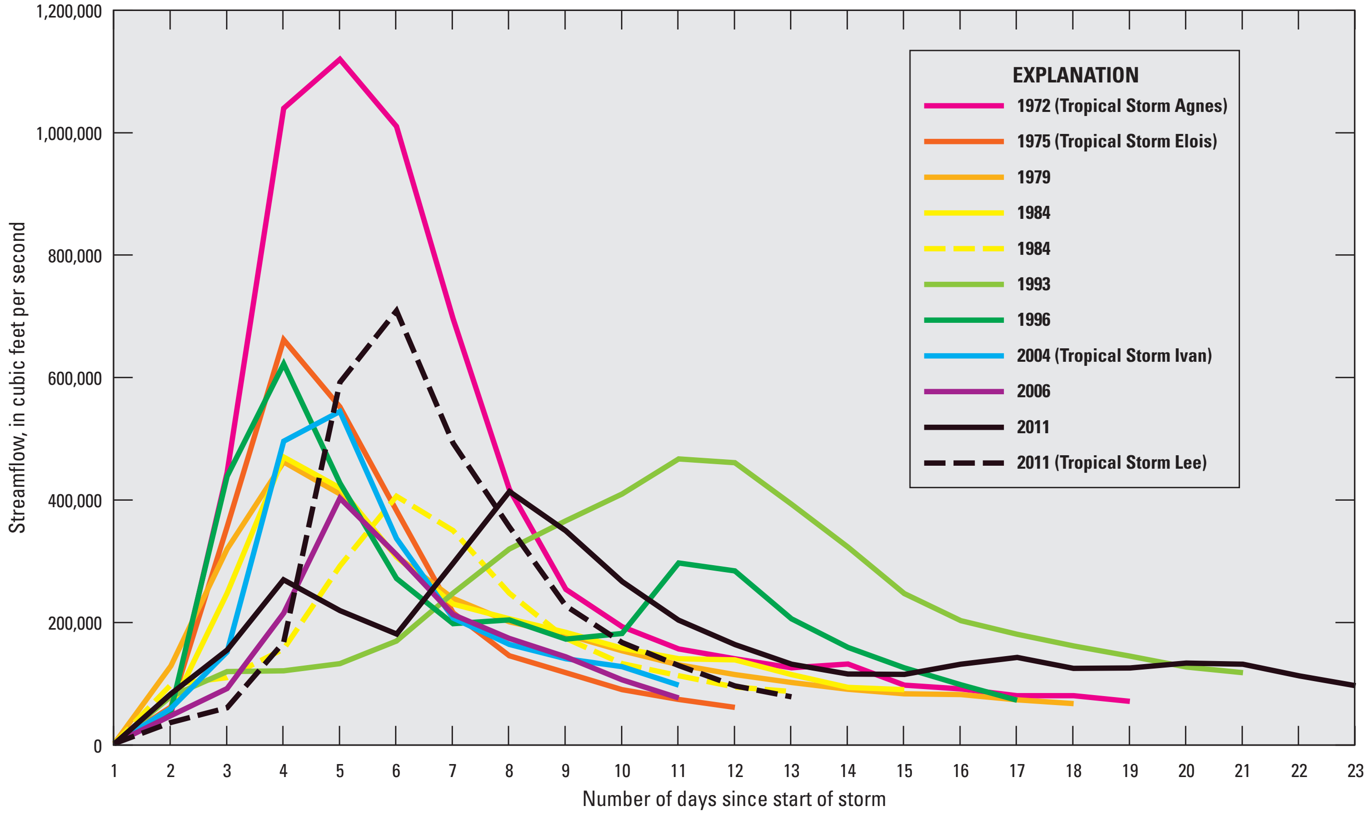


Figure 6. Daily mean streamflow hydrographs for 11 storms with greater than 400,000 cubic feet per second since 1972 at the Susquehanna River at Conowingo, Maryland, streamgage. (Hydrograph years with no associated storm name represent unnamed storms.)

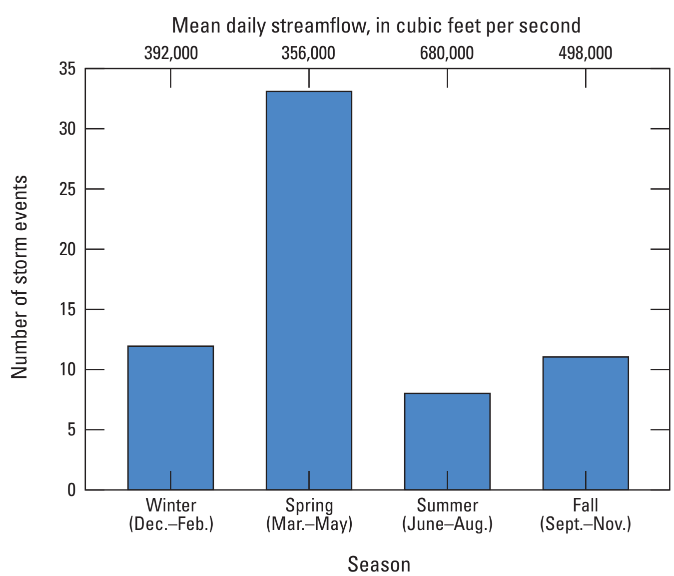


Figure 7. Number of storm events and mean daily streamflow by season at Susquehanna River at Conowingo, Maryland, 1967–2012. A storm event is defined as daily mean discharge greater than 300,000 cubic feet per second.

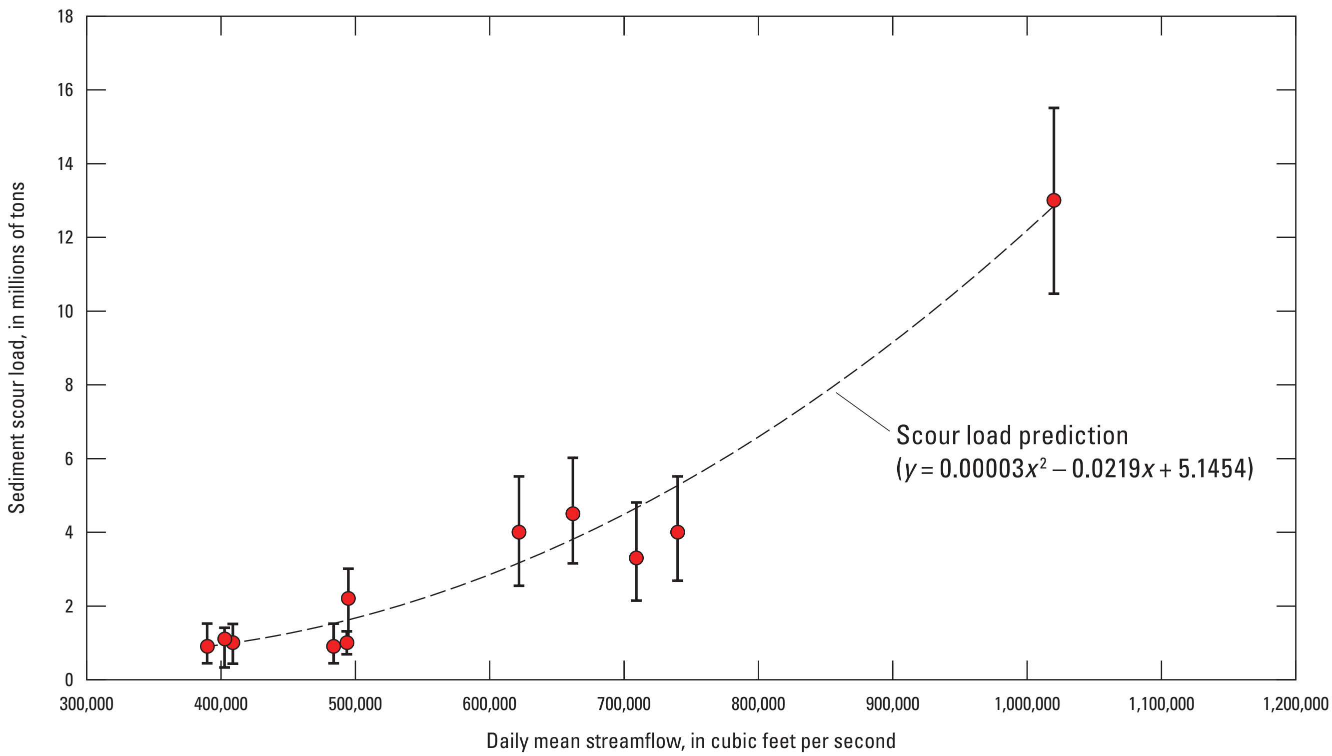


Figure 8. Daily mean streamflow in relation to sediment scour load and U.S. Geological Survey scour equation used to predict scour using streamflows generally exceeding 400,000 cubic feet per second in the Lower Susquehanna River reservoir system.

amount of sediment estimated to be stored in Conowingo Reservoir at the time, the estimate was reduced to 3.5 million tons of scoured sediment. Revisions to the equation sometimes result from updates with data from new flood events.

The curve and subsequent scour prediction provide a useful and quick reference for potential scour from the reservoir system to the upper Chesapeake Bay at or soon after flooding events when information may be needed quickly to ascertain potential environmental effects. Although not exact as a scour predicting tool, the equation is updated with data from each flood event, resulting in a new, slightly different equation. Complications in the predictions include errors in the methods used to estimate the daily and monthly loads, the amount of sediment entering the reservoir system, and the amount of streamflow and time above a certain scour threshold, generally 400,000 ft^3/s. In addition, the length of time since a previous scour event, which may increase or decrease the amount of scoured sediment, and the changing scour/deposition dynamics resulting from increased velocities (potential to lower the scour threshold) as Conowingo Reservoir nears storage capacity, all contribute to scour prediction error.

Using the data from table 3 and converting the annual exceedence probability to percent, changes in bottom surface based on the bathymetric studies, the annual sediment load estimates from Marietta and Conowingo (above and below the reservoirs), plus estimates of scour, were combined to produce a range in total sediment transported through the reservoir system and an apportioning to source (percent scour to total load) for various streamflows (table 5). The ranges in scour and estimates of total loads transported out the reservoir system allow for differences in season, total volume of potential scour streamflow, and errors in the estimates. As previously discussed, the streamflow when mass scour is estimated to begin is approximately 400,000 ft^3/s. Results from a U.S. Army Corps of Engineers two-dimensional model and a recent USGS report by Hirsch (2012) indicate that the threshold has decreased with time. Because figure 8 indicates scour might occur at streamflows below 400,000 ft^3/s, table 5 shows estimated scour as low as 300,000 ft^3/s. The uncertainty associated with scour estimates less than 400,000 ft^3/s is greater than the uncertainty for scour estimates greater than 400,000 ft^3/s.

The percent scour to total load, based on frequency of streamflow events, ranges from 20 percent to 37 percent (average 30 percent) for streamflows of 400,000–800,000 ft^3/s. A streamflow of 800,000 ft^3/s has a recurrence interval of 25 years. As indicated in table 5, streamflows greater than 800,000 ft^3/s generate the greatest amounts of scour and an increasingly higher proportion of total sediment load. The load from bed scour has an upper limit owing to the maximum sediment carrying capacity of the water and increasing bed shear as a result of compaction of the bed sediments. This upper limit was not determined as part of this study.

Table 4. Predicted sediment scour loads for storms with an average daily-mean discharge at Conowingo, Maryland, greater than 400,000 cubic feet per second.

[ft^3/s, cubic feet per second]

Date	Daily-mean discharge[1] (ft^3/s)	Sediment scour storm load event (million tons)
May 1936	740,000	3.5
January 1940	493,000	1.3
January 1943	486,000	1.2
May 1946	528,000	0.9
November 1950	495,000	1.8
April 1960	451,000	1.5
February 1961	466,000	1.6
February 1970	434,000	1.3
March 1964	571,000	2.9
June 1972	1,020,000	[2]13.5
September 1975	662,000	[2]4.4
March 1979	462,000	1.6
February 1984	470,000	1.7
March 1986	406,000	0.8
April 1993	409,000	1.1
January 1996	622,000	4.0
September 2004	495,000	2.1
June 2006	403,000	0.5
March 2011	403,000	0.5
September 2011	709,000	3.5
Total estimated scour		49.7

[1]All flow estimates prior to 1968 are based on a drainage-area ratio with the streamflow gage at Susquehanna River at Harrisburg, Pa.

[2]Revised estimates from Gross and others, 1978.

Table 5. Recurrence intervals for selected streamflows, percent chance of streamflow event, predicted scour, total sediment load, and percent scour to total load for Conowingo Reservoir, Lower Susquehanna River Basin, Pennsylvania and Maryland.

[Total sediment load is scour plus watershed load.]

Streamflow (cubic feet per second)	Recurrence interval (years)	Percent chance of flow event per year	Predicted sediment scour range[1] (million tons)	Range in predicted total sediment load[2] (million tons)	Range in percent scour to total load
1,000,000	60	1.7	10.5–15.5	27.1–31.0	39–49
900,000	40	2.5	6.6–11	21.8–26.2	30–42
800,000	25	4	4.5 -7.5	17.2–20.2	26–37
700,000	17	5.9	3.5–6	13.1–15.6	27–38
600,000	10	10	1.8–4	7.9–10.1	22–40
500,000	5.7	17.5	1–3	4.9–6.9	20–42
400,000	4.8	21	0.5–1.5	2.4–3.4	21–44
300,000	2.1	52	0–0.5	0.5–1.5	0–33

[1]Predicted scour from U.S. Geological Survey scour equation, bathymetry results, and literature estimates.

[2]Predicted total load based on transport regression equation, bathymetry results, and literature estimates.

Capacity Change and Total Sediment Deposition

On the basis of previous studies (Whaley, 1960; Hainly and others, 1995; Reed and Hoffman, 1996; Langland and Hainly, 1997; Langland, 2009; and Gomez and Sullivan Engineers, 2012), capacity and volume change were estimated for six time intervals for which bathymetric results were available (table 6; fig. 9). From construction in 1929 to the first survey in 1959 (30 years), the Conowingo Reservoir lost about half of the sediment storage capacity (96 of 198 million tons). The capacity to store sediment was reduced by an additional 31 percent by the next survey 31 years later in 1990 (155 of 198 million tons), indicating a reduction of incoming sediment, a loss of trapping efficiency, or both. The largest flood event during 1959–90 occurred in June 1972 when Tropical Storm Agnes removed approximately 13.5 million tons of sediment from Conowingo Reservoir (fig. 9). Table 6 indicates that in 2011, the Conowingo Reservoir was about 92 percent full and that 17 million tons storage capacity remained of an estimated equilibrium sediment storage capacity of approximately 198 million tons.

Figure 9 shows that the rate of filling continues to follow a non-linear pattern since construction in 1929. Tropical Storm Agnes in 1972 had the greatest effect with regard to sediment removal in the reservoir system over 80 years; the reservoir most likely was refilled by the end of the 1970s. The rate of filling has slowed as a result of a reduction in incoming sediments from the basin and changes in reservoir scour and deposition dynamics. As the reservoir fills with sediment, the velocity of water increases owing to diminished volume, which could increase the bed shear thus inducing more scour and reducing the amount of time for sediments to settle out of the water column, thereby decreasing deposition. Approximately 8 percent remains of the original 146,000 acre-feet of sediment storage capacity (table 6). As the capacity is reduced, sediment concentrations and loads to the upper Chesapeake Bay may increase, owing to an increase in velocity through the reservoirs. Hirsch (2012) indicates that increases in sediment concentrations and loads are occurring and suggests the increases are occurring at streamflows less than 400,000 ft^3/s.

In four previous USGS reports (Hainly and others, 1995; Reed and Hoffman, 1996; Langland and Hainly, 1997; and Langland, 2009) estimates of time for Conowingo Reservoir to reach the “dynamic equilibrium” phase were based upon the documented rate and pattern of filling in the most upstream reservoir, Lake Clarke. Reed and Hoffman (1996) discuss the data in terms of loss of water storage. In this report, the rate of change in sediment storage capacity (percent full) is based on the change in water-storage capacity (fig. 10). The rate of sediment deposition was approximately 20 million tons every 5 years starting in 1931 such that Lake Clark has been in dynamic equilibrium since approximately 1950. Subsequent surveys have confirmed the reservoir no longer effectively traps sediment except for short periods of time. In

Table 6. Storage capacity change in Conowingo Reservoir from bathymetric surveys since construction.

[--, not applicable]

Year	Reservoir capacity (acre-feet)	Change in reservoir capacity (acre-feet)	Sediment deposition (acre-feet)	Total sediment deposition (tons)	Net gain/loss between bathymetric surveys[1] (tons)	Percent full
1929	280,000	--	0	0	--	0
1959	215,000	65,000	65,000	96,000,000	96,000,000	49
1990	175,000	40,000	105,000	155,000,000	60,000,000	78
1993	169,000	6,000	111,000	164,000,000	9,000,000	83
1996	171,000	-2,000	109,000	161,000,000	-3,000,000	81
2008	162,000	9,000	118,000	174,000,000	13,000,000	88
2011	157,000	5,000	123,000	181,000,000	7,000,000	92
Equilibrium	[2]146,000	11,000	134,000	198,000,000	17,000,000	100

[1]Numbers in black represent deposition; numbers in red represent scour.

[2]Note the equilibrium capacity previously has been reported at 142,000 acre-feet. The volume was adjusted after the 2011 bathymetry survey when more detailed information near the dam became available.

1996, approximately 2.5 million tons were scoured from Lake Clarke and the resulting bathymetry data indicated a slight reduction in total sediment deposition and resulting increase in capacity (fig. 10). Reasons for different patterns in the rate of filling in Lake Clark (linear through 1950, fig. 10) compared to Conowingo Reservoir (non-linear, fig. 9) probably are due to the fact that Conowingo Reservoir encompasses a longer reach length, a larger surface area, and has about twice the capacity.

Since construction of Conowingo Dam in 1929 until 2012, approximately 470 million tons of sediment was estimated to be transported by the Susquehanna River into the reservoir system, approximately 280 million tons were trapped (with Conowingo Reservoir trapping about 62 percent), and approximately 190 million tons of sediment was transported to Chesapeake Bay, indicating a trapping efficiency over the 85 years of approximately 60 percent for the reservoir system. Using the average estimated scour to total load of 30 percent (table 5), approximately 57 million tons was predicted to be from scour in the reservoirs. Twenty of the storms for which scour is estimated account for 50 million tons or 90 percent of the predicted total scour.

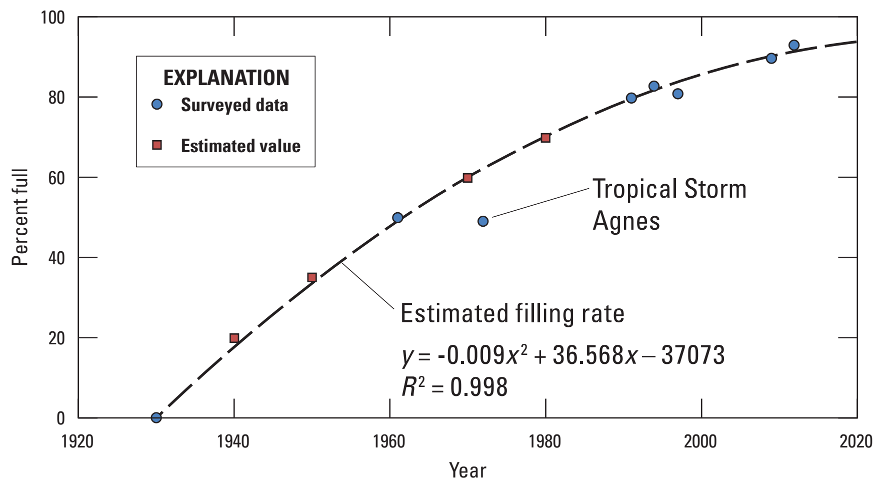


Figure 9. Trend in sediment storage capacity change (percent full) in the Conowingo Reservoir; Lower Susquehanna River Basin, Pennsylvania and Maryland, since construction, 1929–2012. Values are estimated from a combination of methods and assume a gradual reduction in long-term trapping efficiency from 75 to 55 percent.

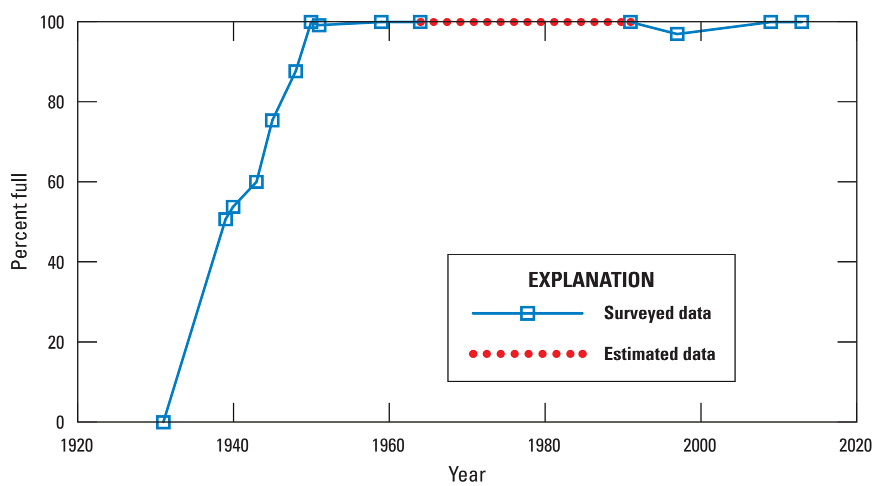


Figure 10. Trend in sediment storage capacity change (percent full) in Lake Clarke, Lower Susquehanna River basin, Pennsylvania, since construction in 1931 to 2013. (Modified from Reed and Hoffman, 1996, based on change in water-storage capacity [1931 through 1990].)

Sediment Cores and Spatial Distribution of Sediment in Conowingo Reservoir

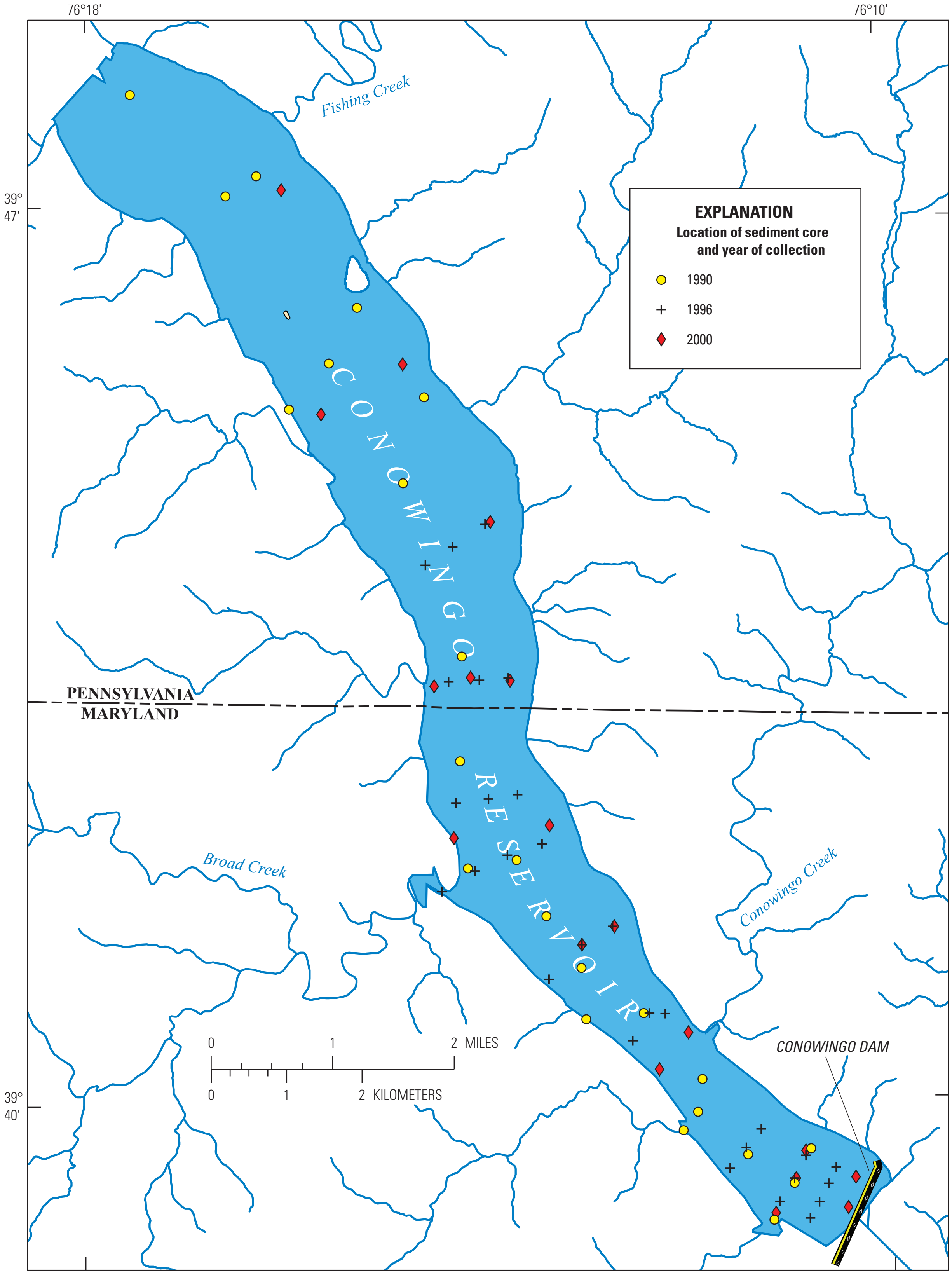
A natural consequence of any reservoir is a change in the sediment carrying capacity of the inflowing water; velocity is reduced, thereby enhancing the deposition of sand. A certain amount of alluvial material, primarily sands, is beneficial to areas downstream. The heavier sands help support underwater grasses, which protect young fish from predators, and transport nutrients essential to life in the upper Chesapeake Bay. To aid in the identification of spatial distribution of sediment by grain-size class (sand, silt, and clay), the locations of 70 USGS cores collected over three periods are presented in figure 11. Beginning with the 1990–91 collection (23 locations; Hainly and others, 1995), efforts were made to sample as closely to previous sampling points as possible so comparisons could be made over multiple time intervals. For the 1996 sampling (Langland and Hainly, 1997), 29 cores were collected, and for the 2000 sampling (Edwards, 2006), 18 cores were collected. Particle-size results have been compiled and are available in Cerco (2012).

The Conowingo Reservoir was divided into three sections (upper, middle, and lower) to examine sediment deposition and particle size fractions (fig. 12; Langland, 2009). This partitioning is based on common conveyances, depositional areas, and state of equilibrium. In general, sediment storage capacity in the upper and middle sections is considered to be in a state of dynamic equilibrium; over the long term, the sections are neither net scour nor deposit areas. The upper section accounts for about 19 percent of the total area of the Conowingo Reservoir, of which about two-thirds is considered to contain very little sediment as a result of steep channel slopes, high water velocities, and the effects of the Muddy Run hydroelectric water-storage facility near the top of the pool (Hainly and others, 1995). The middle and lower sections of the reservoir account for approximately 50 and 31 percent of the total area, respectively.

Changes in average total sediment deposition and in total sand deposition in the Conowingo Reservoir from the three sediment coring studies (1990–91, 1996, and 2000) are presented in table 7. Projections to the year 2012, based on the historical changes, are also included in table 7. The average percentage of sand/silt/clay is based predominantly on the uppermost 1 foot of the sediment cores, areas most prone to bed scour and movement. Results of evaluations of the sediment cores indicate the highest percentages of sands are in the upper section of the reservoir. This is an area where sands are deposited as a result of the loss of streamflow velocity upon entering the top of the impounded reservoir with a general downgradient distribution of sands to fines. Results also indicate minor changes in the percentage of sands in the upper section. Sand increased in the middle section from approximately 39 to 45 percent (1990–2012) as a result of continual displacement (scour) of fines and transport of sand during high-flow events. The middle section had the greatest amount of sand deposition. The lower section is the active area for sediment deposition and had the greatest increase in sand, from 5 to 20 percent (1990–2012). Silt was the dominant class of grain size in the lower section of Conowingo Reservoir and the dominant class transported in and out of the reservoirs. Clay fractions in the lower section have been reduced from approximately 35 percent in 1990 to 12 percent in 2000, indicating this is also an active area for scouring of fines.

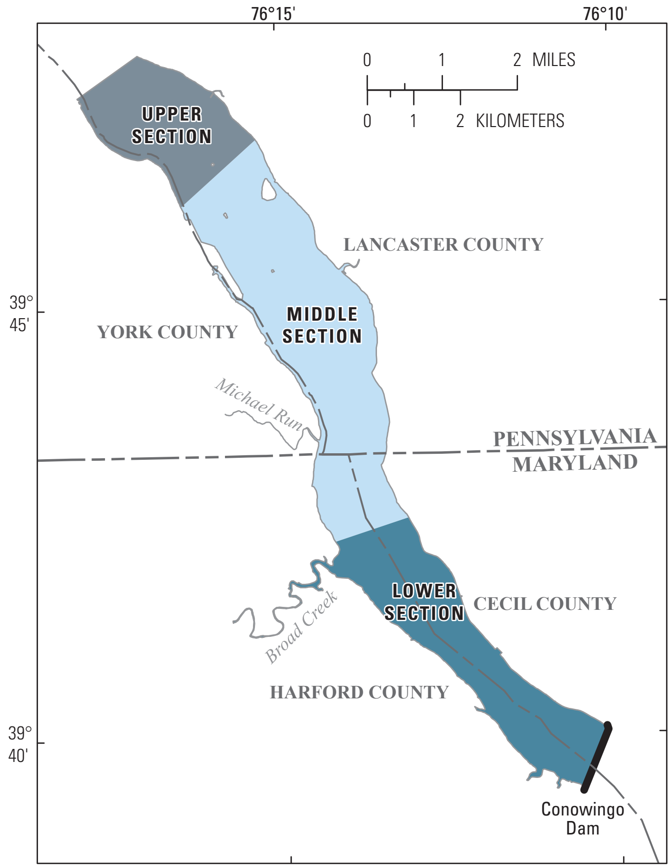
Table 7. Change in grain-size distribution and deposition for three sediment coring studies and projected to 2012 for Conowingo Reservoir, Lower Susquehanna River Basin.

Location	Total sediment deposition (tons)	Average sand/silt/clay (percent)	Total sand deposition (tons)
1990 study			
Upper	11,000,000	80/13/7	8,800,000
Middle	64,000,000	39/41/20	24,000,000
Lower	80,500,000	5/60/35	4,000,000
1996 study			
Upper	11,200,000	82/12/6	9,200,000
Middle	62,000,000	42/39/19	26,000,000
Lower	89,800,000	8/56/36	7,200,000
2000 study			
Upper	11,500,000	83/12/15	9,500,000
Middle	63,000,000	43/40/17	26,000,000
Lower	103,000,000	15/73/12	15,500,000
2012 (projected)			
Upper	11,500,000	84/12/14	9,660,000
Middle	64,000,000	45/39/12	27,500,000
Lower	108,000,000	20/70/10	21,600,000



Base from U.S. Geological Survey 1:24,000-scale digital data, Universal Transverse Mercator Projection: Zone 18, NAD 1983

Figure 11. Locations and year for 70 sediment cores collected from Conowingo Reservoir, Lower Susquehanna River Basin, Pennsylvania and Maryland.



Base from U.S. Geological Survey 1:24,000-scale digital data,
Universal Transverse Mercator Projection: Zone 18, NAD 1983

Figure 12. Locations of the upper, middle, and lower sections of Conowingo Reservoir, Pennsylvania and Maryland. (From Langland, 2009)

Summary

The Susquehanna River is the largest tributary to Chesapeake Bay and transports about one-half of the total freshwater input and substantial amounts of sediment, nitrogen, and phosphorus to the bay The loads transported by the Susquehanna River to the bay are substantially affected by the deposition of sediment and nutrients behind three hydroelectric dams on the Lower Susquehanna River near its mouth. The three consecutive reservoirs (Lake Clarke, Lake Aldred, and Conowingo Reservoir) that formed behind the three dams (Safe Harbor, Holtwood, and Conowingo) involve nearly 32 miles of the river and have a combined design storage capacity of 510,000 acre-feet (acre-ft) at normal pool elevations. The District of Columbia, the six states with water draining into Chesapeake Bay (Maryland, Pennsylvania, Virginia, New York, West Virginia, and Delaware), the Chesapeake Bay Commission, and the U.S. Environmental Protection Agency (EPA) have agreed to a plan to reduce nutrient loads to Chesapeake Bay in an attempt to restore and protect the estuarine environment of the bay. The EPA has established a Total Maximum Daily Load (TMDL), which mandates sediment and nutrient (nitrogen and phosphorus) allocation goals. The six states and the District of Columbia have written Watershed Implementation Plans to reduce loads to the bay and to meet load allocation goals for the TMDL.

The U.S. Geological Survey (USGS) has conducted numerous sediment transport studies in the Susquehanna River and in particular in three reservoirs in the Lower Susquehanna River Basin. Results from these studies were used to determine sediment transport rates over the past century (1900–2012) and to document changes in sediment and water storage capacity in the three reservoirs. When storage capacity is reached, a dynamic-equilibrium condition exists between incoming and outgoing sediment and nutrient loads discharged through the reservoir system to Chesapeake Bay. In the dynamic-equilibrium condition, constituent loads may increase because of short-term high-flow scour events, thereby potentially contributing to non-attainment of the sediment and nutrient allocation TMDL goals set by EPA and the State of Maryland water-quality standards for dissolved oxygen, water-clarity, and chlorophyll A. However, also in this dynamic equilibrium condition, loads may decrease for a short duration owing to increased deposition as a result of, and related to, the length of time since a preceding scour event.

The USGS has been estimating annual sediment loads at Susquehanna River at Marietta, Pennsylvania, and Susquehanna River at Conowingo, Maryland, locations since the mid-1980s to predict the mass balance of sediment transport through the reservoir system. Using streamflow and sediment data from the Susquehanna River at Harrisburg, Pa., prior to the mid-1980s, a decadal total of sediment loads was generated from 1900 to 1910. Loads were greatest in the early to mid-1900s when land disturbance activities from coal production and agriculture were at the peak. Sediment loads indicate a major decline (approximately 87 to 60 million tons) in the 1950s with the introduction of agricultural soil conservation practices. Loads were dominated by climatic factors in the 1960s (drought) and 1970s (very wet) and have been declining from the 1980s until 2012. Sediment input from two monitored tributaries flowing below Susquehanna River at Marietta into the reservoir system (Conestoga River at Conestoga and Pequea Creek at Martic Forge) were estimated to account for most of the sediment load entering the reservoirs from the Susquehanna River and tributaries. In general, sediment loads from Conestoga and Pequea contributed about 5–10 percent of the total riverine load entering the reservoirs at the scour threshold streamflow of 400,000 cubic feet per second (ft^3/s).

The number of days with streamflow greater than 400,000 ft^3/s ranged from 1 to 5; the average was about 3 days. The 1972 event (Tropical Storm Agnes) was the largest flood in the Susquehanna River Basin since 1889, when recording of streamflow began at Harrisburg, Pa. The second largest

recorded flood event using daily mean streamflow data in the Susquehanna River Basin since 1972 was in 2011 (Tropical Storm Lee). An examination of daily duration streamflow events indicated the highest number of daily mean streamflow events greater than 300,000 ft^3/s occurred in spring (March–May), whereas the greatest daily mean streamflows per storm event occurred in fall (September–November).

Since 1972, there have been 11 storms with daily mean streamflows greater than 400,000 ft^3/s (5-year recurrence interval), which is the streamflow when an average mass wasting event (when large areas of the bed begin to move) begins scouring the sediment in the reservoirs. The USGS developed a regression equation that is based on streamflow and sediment-load data from 11 storms to predict the sediment scour load for daily mean streamflows greater than 300,000 ft^3/s for the Lower Susquehanna River reservoirs. A compilation of data from various sources produced a range in total sediment transported through the reservoir system and allowed an apportioning to source (total watershed or scour) for various streamflows. The percent scour to total watershed load, based on frequency of streamflow events, ranges from 20 to 44 percent (average 30 percent) for streamflows of 400,000–800,000 ft^3/s. In general, for streamflows greater than 400,000 ft^3/s, the average incoming sediment load from the Susquehanna River Basin contributes approximately 70 percent of the load transported to the upper Chesapeake Bay.

As of 2011, approximately 8 percent remained of the original 146,000 acre-feet of sediment storage capacity. Since construction of Conowingo Dam in 1929 through 2012, approximately 470 million tons of sediment was transported down the Susquehanna River into the reservoir system, approximately 280 million tons were trapped, and approximately 190 million tons were transported to Chesapeake Bay. Using the estimated scour to total load percentage of 30 percent, approximately 57 million tons of the 190 million tons was estimated to be from scour in the reservoirs. Combining findings from this analysis and Bob Hirsch's (2012) report, increasing sediment concentrations and loads are due to the loss of storage capacity and a possible decrease in the scour threshold of 400,000 ft^3/s. Reasons for the increase are not certain but likely involve changes in particle-falling velocities owing to increased water velocity, transport capacities, and bed shear.

A total of 70 cores were collected over three time periods (1990–91, 1996, and 2000) to help describe location and distribution differences of grain size. The occurrence of sand had become more widespread and moved downgradient in Conowingo Reservoir. At the same time, finer sediment particles (silts and clays) were being displaced, resulting in lesser amounts of fines in the bottom sediments near the dam due to scour.

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