Flux of Nitrogen, Phosphorus, and Suspended Sediment from the Susquehanna River Basin to the Chesapeake Bay during Tropical Storm Lee, September 2011, as an Indicator of the Effects of Reservoir Sedimentation on Water Quality

Scientific Investigations Report 2012–5185

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

Cover. View of the Conowingo Dam on the Susquehanna River in the aftermath of Tropical Storm Lee. Photo taken at 4:30 p.m., September 12, 2011. Discharge at time of the photo was 220,000 cubic feet per second. Peak discharge for the flood was 778,000 cubic feet per second at 4:00 a.m. on September 9, 2011. Photograph by Wendy McPherson, U.S. Geological Survey.

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By Robert M. Hirsch

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KEN SALAZAR, Secretary

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Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047.0	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per day (gal/d)	3.785	liter per day (L/d)
	Mass	
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per day (ton/d)	0.9072	metric ton per day
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
ton per year (ton/yr)	0.9072	metric ton per year

A water year is the period from October 1st to September 30th. It is designated by the calendar year in which it ends.

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Abstract

Concentrations of nitrogen, phosphorus, and suspended sediment are measured at the U.S. Geological Survey streamgage at Conowingo Dam at the downstream end of the Susquehanna River Basin in Maryland, where the river flows into the Chesapeake Bay. During the period September 7–15, 2011, in the aftermath of Tropical Storm Lee, concentrations of these three constituents were among the highest ever measured at this site. These measurements indicate that sediment-storage processes behind the three dams on the lower Susquehanna River are evolving. In particular, they indicate that scouring of sediment (and the nitrogen and phosphorus attached to that sediment) may be increasing with time. Trends in flow-normalized fluxes at the Susquehanna River at Conowingo, Maryland, streamgage during 1996–2011 indicate a 3.2-percent decrease in total nitrogen, but a 55-percent increase in total phosphorus and a 97-percent increase in suspended sediment. These large increases in the flux of phosphorus and sediment from the Susquehanna River to the Chesapeake Bay have occurred despite reductions in the fluxes of these constituents from the Susquehanna River watershed upstream from the reservoirs. Although the Tropical Storm Lee flood event contributed about 1.8 percent of the total streamflow from the Susquehanna River to the Chesapeake Bay over the past decade (water years 2002–11), it contributed about 5 percent of the nitrogen, 22 percent of the phosphorus, and 39 percent of the suspended sediment during the same period. These results highlight the importance of brief high-flow events in releasing nitrogen, phosphorus, and sediment derived from the Susquehanna River watershed and stored in the Conowingo Reservoir to the Chesapeake Bay.

Introduction

The water and the nitrogen, phosphorus, and suspended sediment—the three constituents for which there are watershed-specific goals under the Chesapeake Bay Total Maximum Daily Load (TMDL) requirements (U.S. Environmental Protection Agency, 2012)—that are derived from the Susquehanna River Basin and flow past Conowingo Dam are critically important to the ecological condition of the Chesapeake Bay. Reductions in nutrients are needed to limit algae blooms that die and sink to the bottom of the Chesapeake Bay and consume oxygen, resulting in hypoxic zones where fish and shellfish cannot survive. In addition, suspended sediments and these algae blooms limit the penetration of light that is important to grasses and other aquatic life on the bottom of the Chesapeake Bay. Estimates indicate that, on average, the Susquehanna River contributed nearly 47 percent of the freshwater and 41 percent of the nitrogen, 25 percent of the phosphorus, and 27 percent of the sediment load to the Chesapeake Bay during 1991–2000 (Gary Shenk, U.S. Environmental Protection Agency, written commun., 2012). In September 2011, Tropical Storm Lee produced an estimated 4 to 7 inches of rainfall throughout much of the Susquehanna River Basin, with precipitation in some areas exceeding 12 inches. This storm produced very large, although not unprecedented, flooding in various parts of the basin. It was widely noted in the media that the outflows from the Susquehanna River past Conowingo Dam produced a large plume of sediment that was visible in satellite photographs for several days after the flood peak. The visible plume extended at least as far as the mouth of the Potomac River, approximately 100 miles downstream from Conowingo Dam. A satellite image from September 13, 2011 (4 days after the peak streamflow at Conowingo Dam), is shown in figure 1. It was widely recognized that a volume of water and sediment of this magnitude would have transported large amounts of nitrogen and phosphorus to the Chesapeake Bay (Blankenship, 2011).

The U.S. Geological Survey (USGS) streamgage on the Susquehanna River at Conowingo, Maryland (hereafter referred to in this report as “Susquehanna River at Conowingo”), has a 44-year streamflow record (1968–2011). The maximum daily discharge during the flood of September 2011, associated with Tropical Storm Lee, was 709,000 cubic feet per second (ft^3/s) on September 9, 2011; this value was the second largest annual maximum daily discharge recorded for water years 1968–2011. The largest occurred during the flood of June 1972, a result of Hurricane Agnes, with a maximum daily-mean discharge of 1,120,000 ft^3/s. The third and fourth largest events in the period were 662,000 ft^3/s in 1975 and 622,000 in 1996, respectively. Therefore, the Tropical Storm Lee flood event, although large, was of a magnitude that can be expected to occur about once every 20 years as determined from the data recorded at this streamgage.

Figure 1. National Aeronautics and Space Administration Moderate Resolution Imaging Spectroradiometer (MODIS) photograph from the Terra satellite, September 13, 2011, showing sediment plume extending to near the mouth of the Potomac River, a distance of about 100 miles (modified from National Aeronautics and Space Administration, 2012).

An analysis of the transport of sediment and nutrients during a flood event can benefit from an examination of discharge over a period of several days, rather than the peak discharge alone. The 2011 flood, when measured as an average of the highest 7 consecutive days of flow, was the third largest in the period of record (387,000 ft^3/s, compared to 712,000 ft^3/s in 1972 and 391,000 ft^3/s in 1993). Seven-day average maximum flows for 8 of the 44 years of record exceeded 300,000 ft^3/s. By this measure, the Tropical Storm Lee flood falls well within a range that can be expected to occur once every 10 to 15 years.

Purpose and Scope

This report examines the flow and water-quality data measured at the Susquehanna River at Conowingo streamgage during the Tropical Storm Lee event (September 7–15, 2011) in the context of the historical water-quality record at this site in order to (1) provide the best possible estimate of the flux of sediment, total nitrogen, and total phosphorus from the Susquehanna River to the Chesapeake Bay during the event; (2) evaluate these quantities in the context of long-term average fluxes from the Susquehanna River; (3) use the information from Tropical Storm Lee along with the prior years of record to re-evaluate the trends in fluxes of these materials to the bay, and (4) explore a hypothesis about the extent to which the system of three reservoirs on the lower Susquehanna River have begun a transition from a period of high trapping efficiency to one of approximate equilibrium.

Lower Susquehanna River Reservoirs

The three dams on the lower Susquehanna River (in downstream order, Safe Harbor, Holtwood, and Conowingo Dams) and their associated reservoirs (Lake Clarke, Lake Aldred, and Conowingo Reservoir, respectively) are described by Langland (2009) and shown in figure 2. The history of sediment storage in the lower Susquehanna River has been the topic of a number of studies (Langland, 2009; Langland, 1998; Langland and Hainly, 1997), all of which generally conclude that the pools behind the dams (in total) are on a long-term trajectory to becoming filled. In a description of the history of deposition in Lakes Clarke and Aldred, Langland (2009) concludes that both are in “long-term equilibrium”—that is, on average over several years, no net change has occurred in the volume of sediment stored in these two reservoirs. Although individual flood events have caused sediment scour, the subsequent low to moderate flows have resulted in deposition, so little net change in sediment storage has occurred. Repeated bathymetric surveys of Conowingo Reservoir show that the portion of the reservoir that is more than about 6 miles above Conowingo Dam has been at equilibrium at least since 1959.

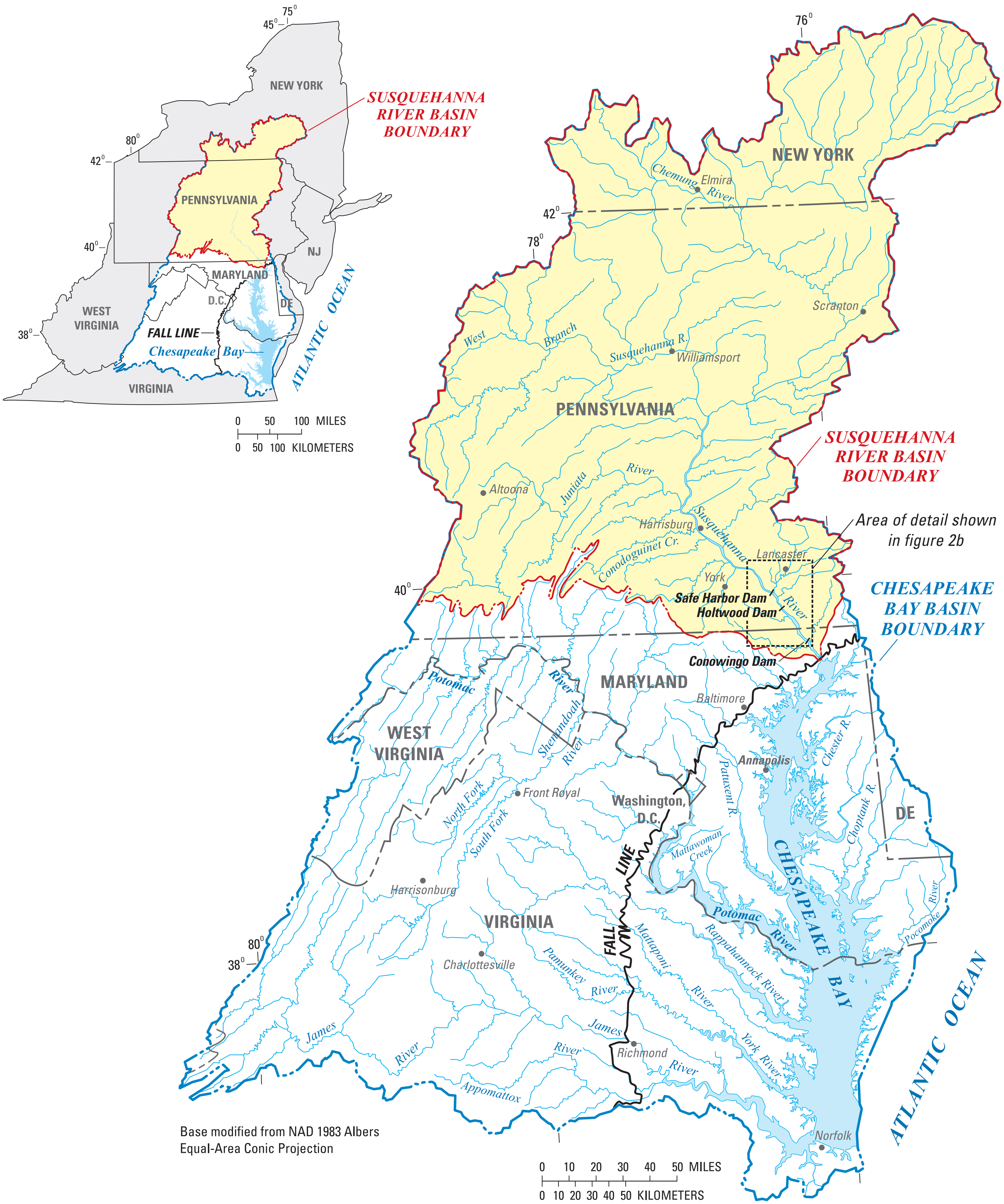

Figure 2a. Location of the Susquehanna River Basin within the Chesapeake Bay Basin and the three dams on the lower Susquehanna River (Safe Harbor Dam, Holtwood Dam, and Conowingo Dam).

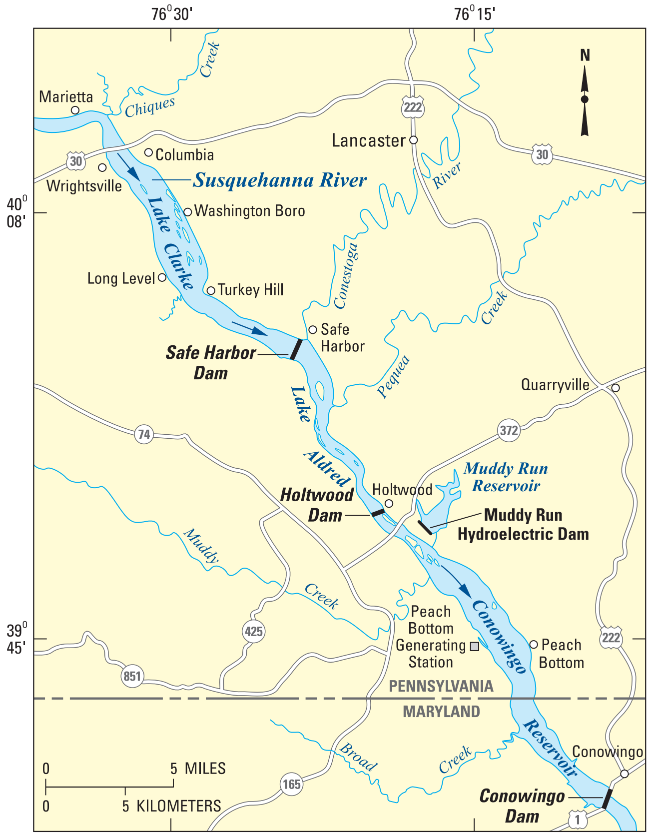

Figure 2b. Location of Safe Harbor Dam, Holtwood Dam, and Conowingo Dam and their associated reservoirs, Lake Clarke, Lake Aldred, and Conowingo Reservoir (modified from Langland, 2009, fig. 1).

Deposition in the lower 11.5 miles of the reservoir from 1929, when the dam was constructed, to the most recent bathymetric survey in 2008, is shown in figure 3 (Langland, 2009). The equilibrium sediment capacity of this part of the reservoir is estimated to be 138,000 acre-feet; as of 2008, 118,000 acre-feet of storage (86 percent of capacity) had been lost to sediment deposition. Results of the several surveys of the major portion of the reservoir (the lower 11.5 miles) show that deposition is asymptotically approaching this estimated capacity (fig. 3).

According to Langland (2009):

> “Once the sediment-storage capacity is reached, sediments will no longer be effectively trapped and loads transported out of the reservoir will approach the loads transported into the reservoir. However, the reservoirs will not be constantly filled to capacity with sediments because of short-term changes from storms that cause scour and a subsequent reduction in exported sediments until the scoured amount is refilled. Therefore, the amount of sediment transported out of the reservoirs will not always be in equilibrium with the amount of sediment transported into the reservoirs.”

Hypothesis Regarding the Changing Role of the Reservoirs

The data analysis in this report is designed to explore the hypothesis that, as the reservoir moves toward this equilibrium condition, the extent of scour resulting from each high-flow event is greater than it would have been in the past, when the volume of sediment storage was smaller than it currently is. It is assumed in this analysis that the transition from the situation in which the reservoirs trapped a large fraction of the sediment that enters them to the equilibrium condition is likely to be gradual. The working hypothesis of this analysis is that deposition of sediment and its attached nitrogen and phosphorus diminishes gradually, although the gradual decrease may be punctuated by episodic scour events.

Langland and Hainly (1997) described the conditions of the mid 1990s and also made a projection of the equilibrium condition. In the mid 1990s, the reservoirs were trapping about 2 percent of the nitrogen, 40 percent of the phosphorus, and 70 percent of the suspended sediment that would have entered the Chesapeake Bay from the Susquehanna River if the three reservoirs did not exist (Langland and Hainly, 1997). If it is assumed that no change occurs in the average annual inputs of nitrogen, phosphorus, and sediment to the reservoir system, the average annual flux out of each of the reservoirs will increase as they fill. The changes projected by Langland and Hainly (1997) were a 2-percent increase in total nitrogen, a 70-percent increase in total phosphorus, and a 250-percent increase in suspended sediment. In 1997, the time required to fill the reservoirs (in the absence of additional scour-producing floods) was estimated to be 17 to 20 years (Langland and Hainly, 1997). In this report, the data collected at the Susquehanna River at Conowingo streamgage are analyzed to explore the extent to which a transition to this equilibrium state is underway.

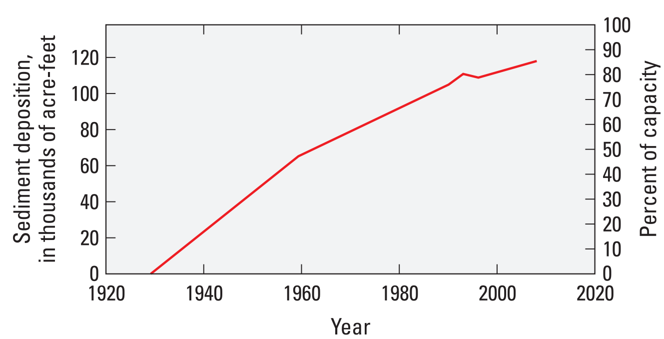

Figure 3. Sediment deposition in the lower 11.5 miles of Conowingo Reservoir from the time of dam construction (1929) to the most recent survey (2008), in acre-feet and as a percentage of the estimated capacity of 138,000 acre-feet (data from Langland, 2009, table 3).

In the past, the discharge at which flows through the reservoirs initiate substantial scour of stored sediment and the attached nitrogen and phosphorus was thought to be about 390,000 ft^3/s (Lang, 1982). This discharge is commonly referred to as the "scour threshold." The physical mechanism that would bring about the gradual changes hypothesized is the following: For any given discharge of water through the reservoirs, the velocity and water-surface slope are likely to increase as the reservoirs fill with sediment as a result of the decrease in reservoir cross-sectional area through which the water can flow. As velocities increase, rates of settling decrease, decreasing sediment deposition and increasing the shear stress on the reservoir bed. The increase in shear stress would cause scour to occur at a lower discharge than in the past, and would increase the extent of scour at discharges that exceed the scour threshold.

This report describes the evolving "behavior" of water quality for the Susquehanna River Basin as measured at Conowingo Dam but does not discuss the hydrodyamics of the specific scour or deposition processes. The behavior can be thought of as a characterization of the response of the watershed (including the reservoirs) to the full range of hydrologic conditions. The response is quantified by the concentrations of nitrogen, phosphorus, or sediment at the Susquehanna at Conowingo streamgage. The hydrologic condition is quantified by the streamflow at the streamgage. The statistical methods used in this study are designed to describe this evolving behavior by characterizing the changing relation between concentration and discharge over the period of record. This report examines total nitrogen, total phosphorus, and suspended sediment; however, because nitrogen transport is less related to the presence of particulates than is phosphorus transport, the hypothesized changes can be expected to be smallest for nitrogen, larger for phosphorus, and greatest for suspended sediment.

The report explores changes in the behavior of the Susquehanna River to search for evidence that the changes in flux predicted by Langland and Hainly (1997) have begun. Knowing the status of this transition from the reservoirs being a trap for these materials to being at steady state is crucial to the ongoing adjustment of actions needed to meet Chesapeake Bay restoration goals.

Nitrogen

The USGS National Water Information System (NWIS) database contains data for 988 samples that were analyzed for total nitrogen (hereafter in this report, the term "nitrogen" without a qualifier represents total nitrogen) from August 3, 1978, through September 29, 2011. The average concentration in the 981 samples collected before September 2011 was 1.75 milligrams per liter (mg/L). Five samples were collected during the September 2011 flood event; concentrations in these samples ranged from a maximum of 10.4 mg/L on September 8, the day before the maximum flow, to a minimum of 1.4 mg/L 5 days after the peak flow. The average concentration in these five samples was 3.9 mg/L, more than twice the long-term mean. Nitrogen concentrations in all 988 samples collected over the period of record are shown in figure 4. Concentrations from 2011 stand out as high values, but the highest value, 20.1 mg/L, was measured on September 20, 2004 (during the flood associated with Hurricane Ivan), at a discharge nearly equal to the discharge of September 8, 2011 (the date of the highest nitrogen concentration during Tropical Storm Lee). Nitrogen concentrations associated with the particulates are very high in these extreme high-flow samples. In the four samples with the highest concentrations (all from 2004 and 2011), the particulate fraction of the total nitrogen ranged from 65 to 98 percent of the total. In contrast, the average for all the samples collected during the 2002–11 time period was 12 percent (Joel Blomquist, U.S. Geological Survey, written commun., 2012). The biogeochemical processes by which the dissolved and suspended fractions of nitrogen enter the food web of the bay differ in that the suspended fraction may become available more slowly than the dissolved fraction. The nutrient-reduction goals for the bay are stated in terms of total nitrogen, however, and high-flow events with their associated large particulate fractions are highly relevant to the efforts to achieve the water-quality goals for the bay; therefore, the analysis presented here is in terms of total nitrogen.

In order to evaluate the history of nitrogen concentrations and flux, a statistical model of nitrogen concentration as a function of discharge and season over the 34-year period of record was constructed. In this study, the method used to construct the model is known as "Weighted Regressions on Time, Discharge, and Season" (WRTDS), which is described by Hirsch and others (2010). In that publication, WRTDS was applied to concentrations of nitrate and total phosphorus at all nine of the Chesapeake Bay River Input Monitoring stations (a set of nine monitoring locations just above the head of tide on major tributaries to the Chesapeake Bay) for the 31-year period ending with water year 2008. The statistical smoothing methods used are designed for large (more than 200 observations) water-quality datasets more than 20 years long and

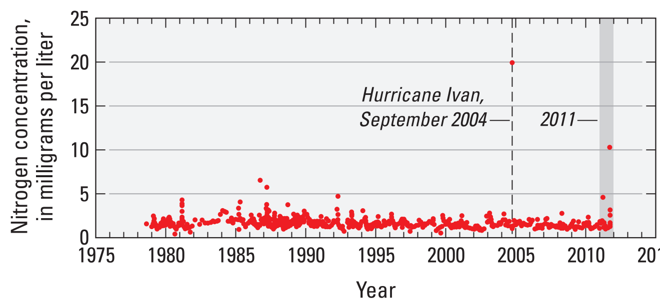

Figure 4. Total-nitrogen concentration as a function of time for the Susquehanna River at Conowingo, Maryland.

for which complete daily streamflow records are available. The method creates a statistical model that can be used to determine the expected value of concentration for each day in the period of record, and from that value it determines the expected value of flux for each day. Estimates of flux for the period of record are shown in figure 5 and summarized in table 1.

The record includes no estimated daily flux values greater than 4,000 tons per day (tons/d) prior to 2004 (fig. 5). Since that time, two events (a total of 5 days) have had estimated flux values ranging from about 7,000 to 18,000 tons/d. Whether this marked change in the last decade is a result of a few days of high streamflow or a result of a change in the response of the Susquehanna River at Conowingo Dam to high streamflow cannot be determined from figure 5 alone. Daily discharge values for the same period are shown in figure 6. Although the September 2011 high flow was the highest discharge in the record, no general tendency toward an increase in the frequency of extreme high flows (for example, above thresholds such as 200,000 or 400,000 ft^3/s) is observed.

The Mann-Kendall test (Mann, 1945; Kendall, 1938) was used to evaluate the possible presence of a monotonic trend in the annual number of exceedances of a 400,000-ft^3/s threshold at the Susquehanna at Conowingo. The null hypothesis is that the expected number of exceedances per year is unchanged over the record. The 400,000-ft^3/s threshold was used in this test because it is approximately the discharge that has been considered to be required to generate substantial scour in the reservoir. The value of Kendall's tau for this dataset is 0.06, which is near zero, the expected value of tau (which can range from -1 to +1) if there were no trend. The p-value for rejecting the null hypothesis was 0.6. These results indicate that there has been no statistically significant change in the frequency of flood events that exceed 400,000 ft^3/s. Results of a Mann-Kendall test of exceedances of 400,000 ft^3/s in the 122-year-long streamgage record for the Susquehanna River at Harrisburg, Pennsylvania (PA), also indicate no change in the frequency of large streamflow events. Therefore, it is unlikely that the predominance of high fluxes in the last decade is solely an artifact of the streamflow pattern.

Two other hypotheses could explain this substantial increase in the number of high-flux days and the magnitude of fluxes: an increase in inputs to the reservoirs from upstream, and an increase in scouring of nitrogen-rich sediments within the system of reservoirs. The first hypothesis appears to be unlikely, as recent analyses of the long-term water-quality records for the Susquehanna River at Marietta, PA, and the Conestoga River at Conestoga, PA, show significant improvements (decreases) in total nitrogen during the 1985–2010 and 2001–10 periods (Langland and others, 2012). The drainage basins of these two monitoring sites cover about 98 percent of the total drainage area of the Susquehanna River at Conowingo streamgage. The absence of similar changes at these sites indicates that a hypothesis that the high concentrations at the Susquehanna River at Conowingo result from changes occurring upstream from the reservoirs is not a reasonable explanation for the changes observed. The same hypothesis was considered for the total-phosphorus and suspended-sediment results (discussed farther on in this report). Langland and others (2012) document improvements (decreases) in total-phosphorus concentrations for the periods 1985–2010 and 2001–10 at both the Susquehanna River at Marietta, PA, and the Conestoga River at Conestoga, PA. The suspended-sediment concentrations show significant improvements, although the changes for the 2001–10 period at the

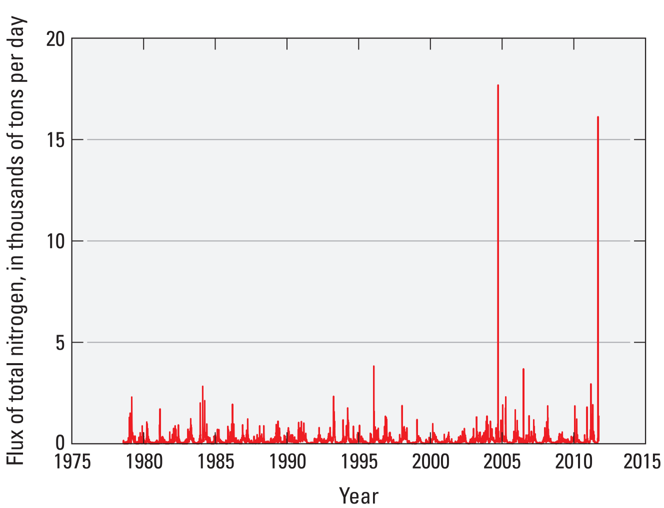

Figure 5. Estimated daily flux of total nitrogen for water years 1978–2011, Susquehanna River at Conowingo, Maryland.

Table 1. Estimated flux of total nitrogen, total phosphorus, and suspended sediment for Tropical Storm Lee and water year 2011; and average annual flux for water years 2002–11 and 1978–2011.

Flux	Total nitrogen	Total phosphorus	Suspended sediment
Tropical Storm Lee, in tons	42,000	10,600	19,000,000
Water year 2011, in tons	135,000	17,400	24,300,000
Highest for any water year prior to 2011, in tons	135,000	8,200	11,700,000
Average annual, water years 2002–11, in tons per year	79,000	4,800	4,800,000
Average annual, water years 1978–2011, in tons per year	71,000	3,300	2,500,000

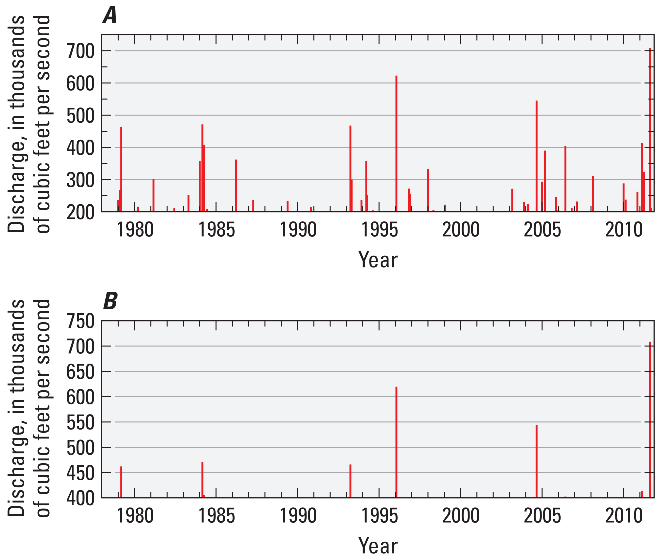

Figure 6. Daily discharge values for the Susquehanna River at Conowingo, Maryland, showing only discharges that exceeded *(A)* 200,000 cubic feet per second, and *(B)* 400,000 cubic feet per second.

Susquehanna River at Marietta, PA, were not significant. Therefore, the scour hypothesis is the most likely explanation for the increased flux of nitrogen (and the other two constituents considered in this report) at high flow.

The changing relation between streamflow and total-nitrogen concentration at the Susquehanna River at Conowingo is shown in figure 7. Concentrations in samples collected at discharges greater than 100,000 ft^3/s are separated into two groups—those prior to 2000 and those from 2000 to the present. For discharges less than about 300,000 ft^3/s, the two datasets are similar, but at discharges greater than about 300,000 ft^3/s, the post-2000 concentrations are distinctly higher than those for the previous 24 years. An analysis of covariance (Helsel and Hirsch, 2002, p. 316–318) was performed on the data shown in figure 7. The null hypothesis was that for discharges greater than 100,000 ft^3/s, the logarithm of the concentration followed a single model with the explanatory variables of log(Q) and $(\log(Q))^2$, where Q is discharge. The alternative hypothesis was that the relation between concentration and discharge for the period prior to 2000 was significantly different from that for the period beginning in 2000. The null hypothesis was rejected ($p < 0.0001$)—that is, the relation between log total-nitrogen concentration and log discharge is significantly different for these two periods.

The WRTDS smoothing procedure was used to evaluate the relation between discharge and concentration around the midpoints of the two periods depicted in figure 7 (1978–99 and 2000–11). The dates assigned to the two curves in the graph define the midpoints used in this smoothing procedure. Data from a range of as much as 10 years before and after those dates were used, but more weight was placed on the data collected near those dates and less on those collected several years from those dates. Similarly, data from all seasons were used but more weight was placed on the time of year specified (September 1). This time of year was selected because it is in the middle of the tropical storm season, a time when many (but not all) of the highest streamflow events have occurred. For the pre-2000 period, concentrations vary little across the range of discharges shown (5,000–500,000 ft^3/s) (fig. 8). For 2000 and later (which includes the high flows of 2004 and 2011), concentrations at discharges less than about 100,000 ft^3/s are slightly lower than those for the previous decades. For discharges greater than about 175,000 ft^3/s, however, concentrations rise steeply. For example, at 500,000 ft^3/s, estimated concentrations are three to four times those for the same discharge in the previous decades, indicating that the relation between discharge and nitrogen concentration has changed.

Concentrations at the highest discharges have been substantially higher since 2000 than they were prior to 2000 (figs. 7 and 8). Because relatively few observations are available at discharges greater than about 200,000 ft^3/s, the curve shown in figure 8 is only a rough approximation; nevertheless, it clearly shows the pattern of lower concentrations since 2000 at the lower discharges (less than about 100,000 ft^3/s) and higher concentrations since 2000 at higher discharges (especially above about 300,000 ft^3/s).

The nitrate fraction of the total-nitrogen flux (not described in this report) likely has not undergone a similar marked increase in flux at high discharges; in fact, for virtually all flows and seasons of the year, nitrate concentrations have been decreasing. The observed increase in total nitrogen at extreme high discharges in recent years is a result of the increase in the particulate fraction of the total nitrogen. This increase would be expected if the frequency and intensity of scouring of the reservoir sediments has increased and deposition rates have declined as the reservoirs fill with sediment.

The annual flux of total nitrogen by water year is shown in figure 9 together with a curve that represents the "flow-normalized flux" of total nitrogen. Using the flow-normalized flux removes the effect of year-to-year variations in streamflow but preserves the effect of the normal seasonal and random

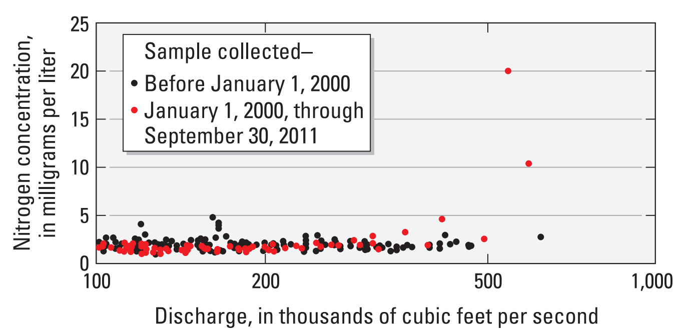

Figure 7. Observed concentration of total nitrogen as a function of discharge for the Susquehanna River at Conowingo, Maryland.

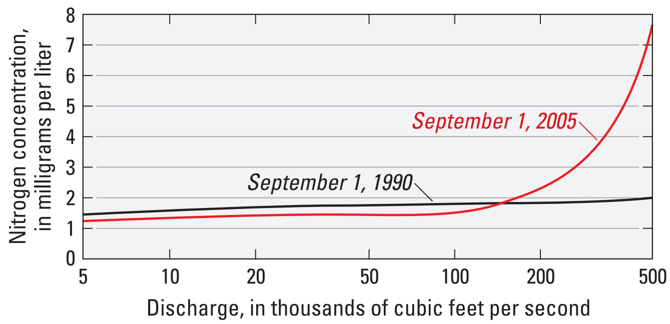

Figure 8. Estimated concentration of total nitrogen as a function of discharge for the Susquehanna River at Conowingo, Maryland, based on smoothing centered on September 1, 1990, or on September 1, 2005.

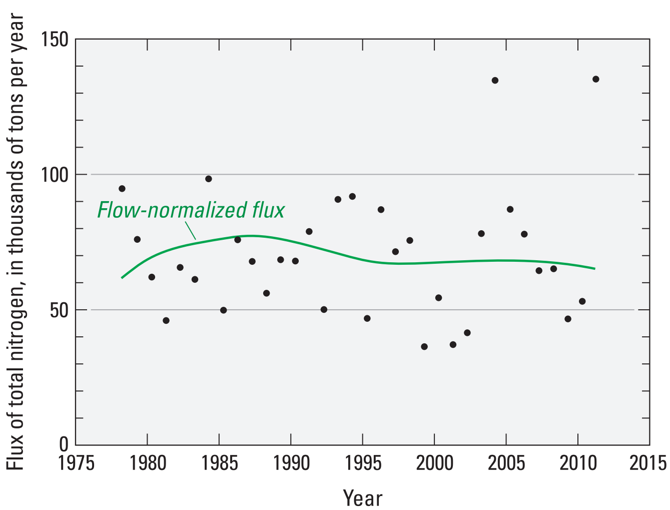

Figure 9. Estimated annual flux of total nitrogen by water year for the Susquehanna River at Conowingo, Maryland (data are listed in appendix 1).

components of the streamflow record. The flow-normalization method is described by Hirsch and others (2010).

The flow-normalized flux results indicate that after removing the year-to-year variations that result from variations in streamflow, the overall trend has been a decline in the flux of total nitrogen since the late 1980s. The flow-normalized results indicate an average rate of change in total-nitrogen transport of about -0.5 tons per year per year (tons/yr/yr), or -0.6 percent per year, from 1990 through 2011.

In general, because the dominant form of nitrogen (about 70 percent of the average annual flux) is nitrate, which is relatively unaffected by scour or deposition processes, the filling of the reservoirs appears to have little or no detrimental effect on the progress toward decreasing the total-nitrogen flux to the bay; however, the filling of the reservoirs does appear to be affecting the variability of the annual nitrogen flux to the bay.

Total Phosphorus

The USGS NWIS database contains data for 951 samples that were analyzed for total phosphorus (hereafter in this report, the term “phosphorus” without a qualifier represents total phosphorus) collected from August 3, 1978, through October 4, 2011. The average concentration in the 943 samples collected before September 2011 was 0.067 mg/L. In the five samples collected over the course of the flood associated with Tropical Storm Lee, concentrations ranged from a maximum of 2.31 mg/L on September 8, the day before the maximum flow day, to a minimum of 0.11 mg/L 5 days after the peak flow. The average concentration in these five samples was 0.88 mg/L, about 13 times the long-term mean up to the time of Tropical Storm Lee. Phosphorus concentrations in all 951 samples collected over the period of record are shown in figure 10. All of the values in the 34-year record that are higher than 0.4 mg/L occurred during 2004–11. The first of these was a value of 1.17 mg/L, which was measured on September 20, 2004, when the mean daily discharge was 545,000 ft^3/s. The second was a value of 0.87 mg/L, measured on March 12, 2011, when the mean daily discharge was 414,000 ft^3/s. The other three values greater than 0.4 mg/L were associated with Tropical Storm Lee—2.30, 0.73, and 0.88 mg/L on September 8, 10, and 11, respectively, when discharges were 592,000, 493,000, and 365,000 ft^3/s, respectively. The 365,000-ft^3/s discharge on September 11 was the 22nd highest daily discharge for a sampled day in the 34-year record, yet it resulted in the third highest concentration in the record, indicating that for discharge values in the range of a few hundred thousand cubic feet per second, phosphorus concentrations associated with a given discharge have been considerably higher in recent years than in the earlier part of the record.

For all samples collected from 2000 to 2011, an average of 71 percent of the total phosphorus was in the particulate phase (compared to 12 percent for total nitrogen). During the high-flow events of 2004 and 2011, however, the particulate phase constituted 98 to 99 percent of the total-phosphorus concentration (Joel Blomquist, U.S. Geological Survey, written commun., 2012). The biogeochemical processes by which the dissolved and suspended fractions of phosphorus, like those of nitrogen, enter the food web of the bay differ—that is, the suspended fraction may become available more slowly than the dissolved fraction. The nutrient-reduction goals for the bay are stated in terms of total phosphorus, however, and high-flow events with their associated large particulate fractions are highly relevant to the effort to achieve the water-quality goals for the bay. Therefore, the analysis presented here is in terms of total phosphorus.

Total-phosphorus concentration and associated discharge data for the periods before and after 2000 are shown in figure 11. At a discharge greater than about 300,000 ft^3/s, the concentrations for a given discharge are substantially higher in the later period than in the earlier one. An analysis of covariance was performed on these data. The null hypothesis was that for discharges greater than 100,000 ft^3/s, the logarithm of the

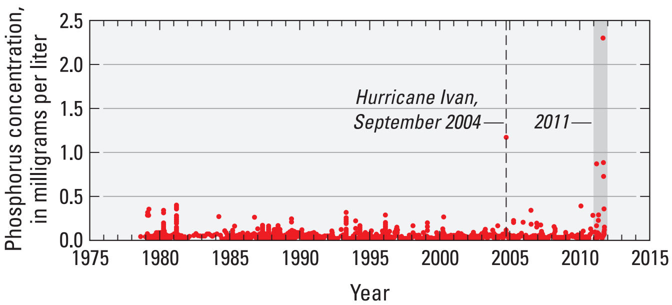

Figure 10. Total-phosphorus concentration as a function of time for the Susquehanna River at Conowingo, Maryland.

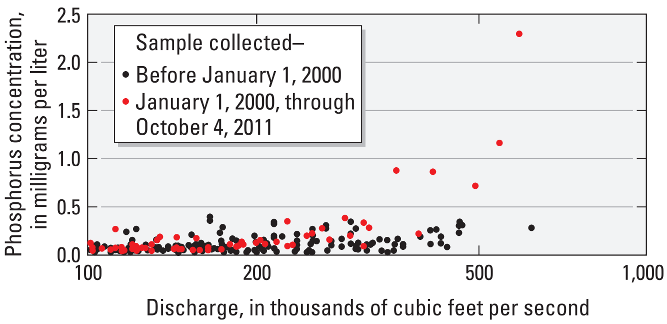

Figure 11. Observed concentration of total phosphorus as a function of discharge for the Susquehanna River at Conowingo, Maryland.

concentration followed a single model with the explanatory variables of log(Q) and $(\log(Q))^2$, where Q is discharge. The alternative hypothesis was that the relation between concentration and discharge for the period prior to 2000 was significantly different from that for the period beginning in 2000. The null hypothesis was rejected ($p < 0.0001$)—that is, the relation between log total-phosphorus concentration and log discharge is different for these two periods.

The WRTDS model presents this same information through smooth curves that describe the relation between concentration and discharge in the different time periods (fig. 12). In the past decade (2001–11), for discharge values less than about 75,000 ft^3/s, concentrations generally were the same as or slightly less than they were in the earlier two decades. For discharges greater than about 150,000 ft^3/s, however, concentrations for any given discharge were much higher during the past decade than they were previously.

The hypothesized shift in the behavior of the system such that the discharge threshold for scour within the reservoirs has decreased in recent years and (or) deposition in the reservoirs has decreased is strongly supported by the data in figures 11 and 12. The overall history of total-phosphorus flux from the Susquehanna River to the Chesapeake Bay (fig. 13, table 1) illustrates the high degree of year-to-year variability in phosphorus flux. This variability appears to be increasing as a result of the large increase in phosphorus concentrations at extreme high discharges from prior decades to the past decade.

Although the annual flux of total phosphorus appears to have declined from 2004 to 2009, the decline is simply a result of the decrease in annual discharge over those years. The daily-mean discharge for those 6 years was 66,600, 50,900, 46,600, 40,400, 40,800, and 31,200 ft^3/s, respectively. The large increase in 2011 was an outcome of the random occurrence of a year of extreme high discharge (66,000 ft^3/s), although 2011 was not the highest discharge year in the record. The flow-normalized record (fig. 13) is more indicative of the long-term change in the behavior of the system; it shows a period of decreased flow-normalized flux through about 1993, and an increase since that time from about 2,500 to about 3,900 tons/yr. The rate of change over that period has been steady at about +3.3 percent per year. The estimate of the change in flow-normalized flux of total phosphorus for the period 2000–08, reported by Hirsch and others (2010), was +1.9 percent per year, with a change in flux over the period of 390 tons/yr; figure 13 shows a change of 740 tons/yr for the same period. There are two reasons for this difference: The first is that the high concentration of 1.17 mg/L in 2004 was considered to be suspect because it was about three times the maximum value of any observed concentration in the previous 26 years. Therefore, it was not used in the analysis by Hirsch and others (2010). The observation of four additional concentrations above 0.4 mg/L at high discharges in 2011 lent credibility to the 2004 value, which consequently was included in the current analysis. Second, the availability of an additional 3 years of data (for water years 2009, 2010, and 2011) provides stronger evidence of the upward trend. Therefore, the current analysis confirms the upward trend reported previously and increases the estimate of the rate of change during that period.

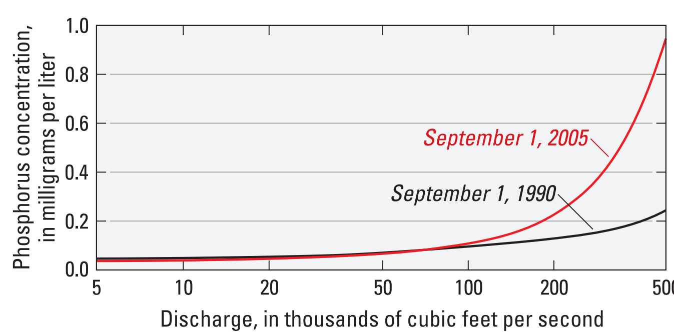

Figure 12. Estimated concentration of total phosphorus as a function of discharge for the Susquehanna River at Conowingo, Maryland, based on smoothing centered on September 1, 1990, or on September 1, 2005.

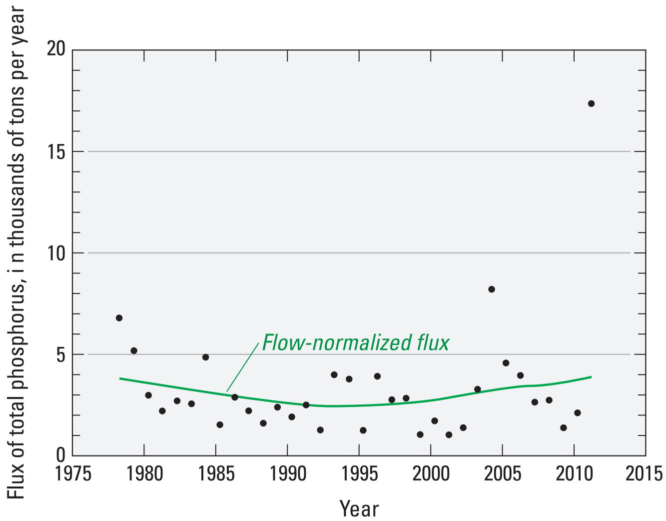

Figure 13. Estimated annual flux of total phosphorus by water year for the Susquehanna River at Conowingo, Maryland (data are listed in appendix 2).

The steady increase in the flux of total phosphorus reflects the fact that the concentrations associated with the highest discharge values have been rising sharply over time. Given the hypothesis that this rise is caused by the filling of the reservoir, resulting in a decrease in deposition at moderate flows and a decrease in the threshold of flow required to cause scour of the reservoir sediments, there is no reason to expect a reversal of this trend in the absence of changes that would cause the sediment that is vulnerable to scour to either be removed or be made less vulnerable to scour.

Suspended Sediment

The USGS NWIS database contains data for 985 samples that were analyzed for suspended sediment collected from January 29, 1978, through September 12, 2011. The average concentration in the 981 samples collected before September 2011 was 45 mg/L. Four samples were collected over the course of the September 2011 flood event; concentrations in these samples ranged from a maximum of 2,980 mg/L on September 8, the day before the maximum flow, to a minimum of 332 mg/L 3 days after the peak flow. The average concentration in these five samples was 1,300 mg/L, more than seven times the long-term mean for the period prior to Tropical Storm Lee. Suspended-sediment concentrations in all 985 samples collected over the period of record are shown in figure 14. Those from 2011 stand out as high values, but the highest concentration, 3,685 mg/L, was measured on September 20, 2004, at a discharge nearly equal to the discharge on September 8, 2011. Also among the highest values were 937 mg/L on March 12, 2011, and four values ranging from 533 to 1,200 mg/L during 2 days of flooding, January 21–22, 1996.

Suspended-sediment concentrations as a function of discharge are shown in figure 15. At discharges greater than about 300,000 ft^3/s, the concentrations for a given discharge are substantially higher in the period before 2000 than in the period beginning in 2000. This pattern is similar to that observed for total phosphorus (fig. 11) because most of the total phosphorus is in the particulate phase when suspended-sediment concentrations are high. An analysis of covariance was performed on the data. The null hypothesis was that for discharges greater than 100,000 ft^3/s, the logarithm of the concentration followed a single model with the explanatory variables of log(Q) and $(\log(Q))^2$, where Q is discharge. The alternative hypothesis was that the relation between suspended-sediment concentration and discharge was significantly different prior to 2000 than during the period beginning in 2000. The null hypothesis was rejected ($p < 0.0001$)—that is, the relation between log suspended-sediment concentration and log discharge is different between these two periods.

The WRTDS representation of the estimated value of concentration as a function of discharge (fig. 16) uses a smoothed estimate centered around September 1, both for the period centered around 1990 and for the period centered around 2005. At discharges greater than about 175,000 ft^3/s, the concentrations during the more recent period were much higher than those measured at similar discharges before 2000. In contrast, the concentrations at discharges less than 100,000 ft^3/s during the more recent period have been slightly lower than those measured at similar discharges before 2000. These results indicate that some of the actions taken to improve water quality in the Susquehanna River Basin may be having a beneficial effect at low to moderate flows.

The flux of suspended sediment from the Susquehanna River to the Chesapeake Bay (fig. 17, table 1) follows a pattern that is similar to that for total phosphorus (fig. 13), except that the highest fluxes (in 2004 and 2011) are even more extreme. For example, the flux for 2011 is estimated to be 60 times the 2009 flux, even though the discharge in 2011 was only two times the 2009 discharge. In contrast, the total-phosphorus flux for 2011 was about 12 times the flux for 2009 because, although both total phosphorus and suspended sediment are nonlinearly related to streamflow, the relation for suspended sediment is much more nonlinear than the relation for total phosphorus. The flow-normalized flux of suspended sediment decreased through about 1993, and since that time it has increased from about 1.5 million to about 3.1 million tons/yr, slightly more than doubling the annual flow-normalized flux over that 18-year period. The rate of increase has been steady at about 85,000 tons/yr/yr, or an average rate of change of about 3.7 percent per year over the period 2000–11. Additionally, the highly nonlinear nature of the relation between suspended-sediment flux and streamflow results in greatly increased year-to-year variability.

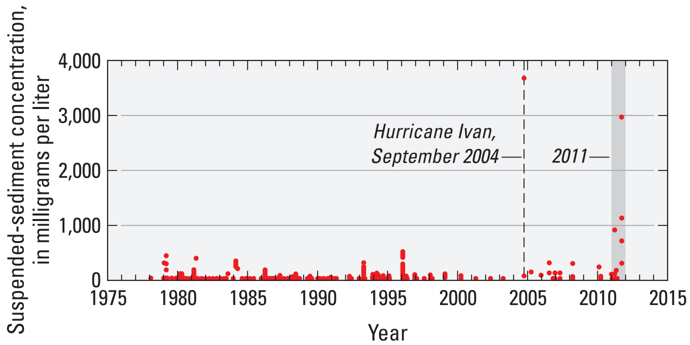

Figure 14. Suspended-sediment concentration as a function of time for the Susquehanna River at Conowingo, Maryland.

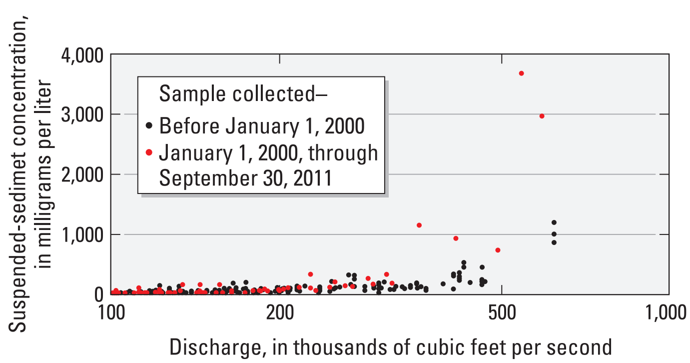

Figure 15. Observed concentration of suspended sediment as a function of discharge for the Susquehanna River at Conowingo, Maryland.

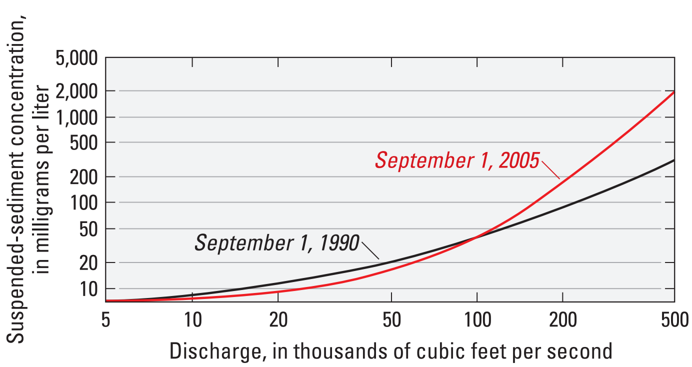

Figure 16. Estimated concentration of suspended sediment as a function of discharge for the Susquehanna River at Conowingo, Maryland, based on smoothing centered on September 1, 1990, or on September 1, 2005 (note that, in contrast to figures 8 and 12, the vertical scale is a logarithmic scale in order to show the separation between the two curves at the lower discharges).

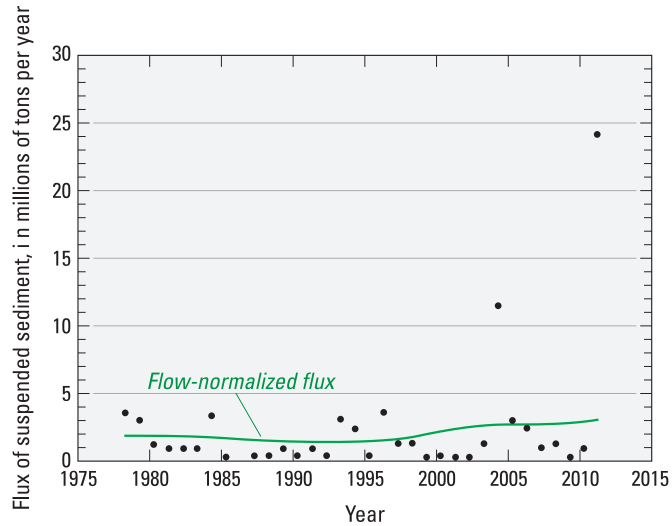

Figure 17. Estimated annual flux of suspended sediment by water year for the Susquehanna River at Conowingo, Maryland (data are listed in appendix 3).

Overview of Tropical Storm Lee Fluxes for the Susquehanna River at Conowingo, Maryland

The contribution of the flood resulting from Tropical Storm Lee on the Susquehanna River constituted a considerable fraction of the flux of total nitrogen, total phosphorus, and suspended sediment to the Chesapeake Bay in water year 2011. The relative contribution of this event was greatest for suspended sediment and least for total nitrogen; this observation also is true for the relation between the Tropical Storm Lee flux and the total flux during the last decade (2002–11) or the entire 34-year period (table 2), because the long-term total fluxes of total phosphorus and particularly suspended sediment are largely determined by the fluxes that occur during brief high-flow events.

Concentrations and fluxes of all three constituents at high streamflows have increased over the past approximately 10 years (2002–11). Because the period 1997 through 2003 was virtually devoid of high-flow events (there were no days with average flows greater than 400,000 ft^3/s during this 7-year period), the timing of this change cannot be identified with any precision; however, the change began to become apparent between the high flows of January 1996 and those associated with Hurricane Ivan in 2004—although analysis results are available for only one water-quality sample collected in this extreme high-discharge range. The concentration data from the extreme high flow in March 2011 followed by those for September 2011 strongly support this interpretation. The

Table 2. Time, streamflow, and flux of total nitrogen, total phosphorus, and suspended sediment associated with Tropical Storm Lee as a percentage of total values for water year 2011, water years 2002–11, and water years 1978–2011.

Storm total	Water year 2011	Water years 2002–11	Water years 1978–2011
Time	2	0.2	0.06
Streamflow	12	1.8	0.6
Flux			
Total nitrogen	31	5	1.8
Total phosphorus	61	22	9
Suspended sediment	78	39	22

discharge at which the increase occurs also is impossible to identify with precision, though it lies in the range of about 175,000 to 300,000 ft^3/s. Furthermore, the relative roles of the two processes that likely are occurring—decreased deposition and increased scour—cannot be determined from this analysis.

Implications for the Chesapeake Bay

Future changes in flux are tied to the spatially and temporally complex processes of scour and deposition and the many changes in the watershed that are driven by economic, demographic, and agricultural conditions, as well as management actions designed to move the watershed toward the water-quality goals associated with the Chesapeake Bay restoration. The hypothesized changes in scour and deposition processes that appear to be underway can be expected to be a major impediment to progress toward meeting those goals, especially for phosphorus and suspended sediment. The net result of changes upstream in the watershed and within the reservoirs has been a trend of generally increasing fluxes of phosphorus and suspended sediment of slightly more than 3 percent per year since 2000, and a decrease of about 0.3 percent per year for nitrogen. The results of this analysis are consistent with the hypothesis that the fluxes from the Susquehanna River to the Chesapeake Bay are already on a trajectory toward a new steady-state condition of average annual fluxes such as those predicted by Langland and Hainly (1997), with large increases in the flux of phosphorus and suspended sediment (table 3). (The year 1996 was used as a base year for this estimate of change because it is approximately the time of Langland and Hainly's estimates, and also because 1996 is approximately when the flow-normalized flux values for phosphorus and suspended sediment began to increase.)

The filling of the reservoirs is not a simple process in which filling occurs up to a specific time after which the reservoirs, once full, remain at steady state. Rather, filling is an asymptotic process in which average rates of deposition gradually decrease and average rates of scour gradually increase until they become equal (on average). The approach to full-reservoir status also is highly stochastic, with an alternation of short scour events balanced by longer depositional periods. The analyses in this report indicate that the final stages of this asymptotic filling process are already (2012) well underway, and not a projection of a future occurrence.

Additional monitoring and ongoing evaluation of the changes that are currently occurring in the reservoirs will be crucial to the evolution of plans to meet the load-reduction goals for the Susquehanna River watershed and the Chesapeake Bay. The results presented here highlight the need to consider the management of the sediment in these reservoirs as a part of future strategies for reducing loads of total phosphorus and suspended sediment to the bay. Some of these issues are currently under consideration as part of the Lower Susquehanna River Watershed Assessment (see *http://mddnr.chesapeakebay.net/LSRWA/index.cfm*). Accurate predictions of the future evolution of these changes in the system will depend on (1) continuing to collect water-quality and flow data (especially during storm events) at Conowingo Dam and at sites upstream from the reservoirs; (2) supplementing analyses of these standard samples with *in situ* measurement of characteristics such as turbidity to improve estimates of inputs to and outputs from the reservoirs; (3) conducting a detailed analysis of the mass balance of sediment and nutrients for the reservoir reach, using data from multiple monitoring sites; and (4) simulating the spatially and temporally variable deposition and scour processes within the reservoir system through the use of physically based representations together with empirically based parameter-estimation techniques.

Understanding the changes that are taking place in these reservoirs is crucial to effective implementation of the Chesapeake Bay Total Maximum Daily Load (TMDL) requirement. Success in reducing fluxes of nitrogen, phosphorus, and sediment from the parts of the Susquehanna River Basin upstream from the reservoirs may be counterbalanced by changes in deposition and scour in the reservoirs, with a potential resulting net increase in the average fluxes of nitrogen, phosphorus, and sediment to the bay. These increases

Table 3. Predicted change in average flux of total nitrogen, total phosphorus, and suspended sediment from the mid 1990s to the time when reservoir sediment-storage capacity is reached (Langland and Hainly, 1997), and observed change in flow-normalized flux, water years 1996–2011.

Constituent	Predicted change in average flux (Langland and Hainly, 1997) (percent)	Observed change in flow-normalized flux, water years 1996–2011 (percent)
Total nitrogen	+2	-3.2
Total phosphorus	+70	+55
Suspended sediment	+250	+97

would be even larger if upstream reductions were not successful. Strategies for reducing contaminant inputs to the bay must be evaluated and adjusted as new information regarding recent and future changes in the watershed and the reservoirs becomes available, and as engineering solutions that could be undertaken in the reservoirs are considered .

The results of this study highlight the importance of ongoing monitoring of river inputs to the bay and of frequent reanalysis of the data that are being collected. The phenomenon described in this report was revealed primarily through analysis of a relatively small number of samples collected during high-flow conditions. Determining and interpreting future changes in water quality during high-flow conditions will be crucial to the development of effective water-quality management plans for the Susquehanna River and the Chesapeake Bay.

Summary and Conclusions

The three dams at the downstream end of the Susquehanna River are important in mitigating the downstream transport of nitrogen, phosphorus, and suspended sediment from the Susquehanna River watershed to the Chesapeake Bay. The reservoirs are known to be more than 80 percent filled with sediment. A consequence of that filling is that they are no longer a major sink for the nitrogen, phosphorus, and sediment coming from the watershed, but rather are approaching steady state, with an approximately equal balance between the fluxes of these materials that enter the reservoir and those that leave the reservoir and enter the Chesapeake Bay. Water-quality measurements made during the large flood in the aftermath of Tropical Storm Lee (September 2011), as well as high flows that occurred in March 2011 and after Hurricane Ivan (September 2004), indicate that this decrease in the effectiveness of the watershed/reservoir system at trapping nitrogen, phosphorus, and sediment is well underway. Results of analyses of samples for total nitrogen, total phosphorus, and suspended sediment all demonstrate that the relation between concentration and discharge has changed substantially over the past 10 to 15 years (from some time between 1996 and 2004 to 2012). The concentrations of total nitrogen, total phosphorus, and suspended sediment measured in samples collected at discharges greater than about 100,000 or 200,000 cubic feet per second currently (2012) are substantially higher than they were 10 to 15 years ago.

Trends in the flow-normalized flux of total nitrogen, total phosphorus, and suspended sediment were estimated by using all of the water-quality data collected at the Susquehanna River at Conowingo, Maryland, streamgage since 1978. The results indicate that, over the period 1996–2011, the flow-normalized flux of total nitrogen, total phosphorus, and suspended sediment has decreased 3.2 percent, increased 55 percent, and increased 97 percent, respectively. These changes represent the combined effects of changes in the fluxes of these constituents from the watershed upstream from the reservoirs and of changes in deposition and scour within the reservoirs. It has long been predicted that, given no change in upstream inputs to the reservoirs, the filling of the reservoirs would cause only modest changes in nitrogen flux (because sediment has a limited role in nitrogen transport), large increases in phosphorus fluxes, and even larger increases in suspended-sediment fluxes. The evidence presented in this report indicates that the predicted changes are not just a theoretical issue for future consideration, but are already underway. These changes in the reservoirs are already overwhelming the progress being made to reduce constituent loads from the Susquehanna River watershed. Therefore, efforts to reduce nutrient and sediment inputs to the Chesapeake Bay will need to include consideration of changes in the trapping of sediment entering, and scouring of sediment in, the reservoirs along with the management actions implemented upstream in the watershed. Continued analysis of water-quality and discharge data that help to improve understanding of the future trajectory of these changes (with and without engineered modifications of the reservoirs) will be crucial to planning for the achievement of restoration goals for the Chesapeake Bay.

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Appendixes 1–3

Appendix 1. Daily-mean discharge, average flux, and flow-normalized annual flux values from the Weighted Regressions on Time, Discharge, and Season (WRTDS) model for total nitrogen in the Susquehanna River at Conowingo, Maryland, water years 1978–2011.

[ft^3/s, cubic feet per second; tons/yr, tons per year]

Water year	Discharge (10^3 ft^3/s)	Flux (10^3 tons/yr)	Flow-normalized flux (10^3 tons/yr)
1978	61.1	95	62
1979	45.3	76	66
1980	37.5	62	69
1981	26.6	46	72
1982	37.8	66	73
1983	35.1	61	74
1984	53.4	99	75
1985	26.9	50	76
1986	40.3	76	77
1987	36.1	68	77
1988	29.9	56	77
1989	38.0	69	77
1990	37.5	68	75
1991	43.1	79	74
1992	29.0	50	72
1993	52.2	91	71
1994	54.1	92	69
1995	27.9	47	68
1996	51.9	87	67
1997	42.9	72	67
1998	46.2	76	67
1999	22.8	36	67
2000	35.6	55	67
2001	24.5	37	68
2002	28.2	42	68
2003	51.1	78	68
2004	66.6	135	68
2005	50.9	87	69
2006	46.6	78	68
2007	40.4	65	68
2008	40.8	65	67
2009	31.2	47	67
2010	34.0	53	66
2011	65.7	135	65

Appendix 2. Daily-mean discharge, average flux, and flow-normalized annual flux values from the Weighted Regressions on Time, Discharge, and Season (WRTDS) model for total phosphorus in the Susquehanna River at Conowingo, Maryland, water years 1978 –2011.

[ft^3/s, cubic feet per second; tons/yr, tons per year]

Water year	Discharge (10^3 ft^3/s)	Flux (10^3 tons/yr)	Flow-normalized flux (10^3 tons/yr)
1978	61.1	6.8	3.8
1979	45.3	5.1	3.7
1980	37.5	3.0	3.6
1981	26.6	2.2	3.5
1982	37.8	2.7	3.4
1983	35.1	2.5	3.3
1984	53.4	4.9	3.1
1985	26.9	1.5	3.1
1986	40.3	2.9	3.0
1987	36.1	2.2	2.9
1988	29.9	1.6	2.8
1989	38.0	2.4	2.7
1990	37.5	1.9	2.6
1991	43.1	2.5	2.5
1992	29.0	1.3	2.5
1993	52.2	4.0	2.5
1994	54.1	3.8	2.5
1995	27.9	1.3	2.5
1996	51.9	3.9	2.5
1997	42.9	2.8	2.6
1998	46.2	2.8	2.7
1999	22.8	1.0	2.7
2000	35.6	1.7	2.8
2001	24.5	1.0	2.9
2002	28.2	1.4	3.0
2003	51.1	3.3	3.1
2004	66.6	8.2	3.2
2005	50.9	4.6	3.4
2006	46.6	4.0	3.4
2007	40.4	2.7	3.5
2008	40.8	2.8	3.6
2009	31.2	1.4	3.7
2010	34.0	2.1	3.8
2011	65.7	17.4	3.9

Appendix 3. Daily-mean discharge, average flux, and flow-normalized annual flux values from the Weighted Regressions on Time, Discharge, and Season (WRTDS) model for suspended sediment in the Susquehanna River at Conowingo, Maryland, water years 1978–2011.

[ft^3/s, cubic feet per second; tons/yr, tons per year]

Water year	Discharge (10^3 ft^3/s)	Flux (10^6 tons/yr)	Flow-normalized flux (10^6 tons/yr)
1978	61.1	3.6	1.9
1979	45.3	3.0	1.9
1980	37.5	1.4	2.0
1981	26.6	1.1	2.0
1982	37.8	1.2	1.9
1983	35.1	1.2	1.9
1984	53.4	3.5	1.8
1985	26.9	0.5	1.7
1986	40.3	1.5	1.6
1987	36.1	0.9	1.6
1988	29.9	0.5	1.5
1989	38.0	1.1	1.5
1990	37.5	0.7	1.5
1991	43.1	1.2	1.5
1992	29.0	0.4	1.5
1993	52.2	3.3	1.5
1994	54.1	2.6	1.5
1995	27.9	0.5	1.5
1996	51.9	3.8	1.6
1997	42.9	1.6	1.7
1998	46.2	1.5	1.8
1999	22.8	0.4	2.0
2000	35.6	0.7	2.2
2001	24.5	0.3	2.4
2002	28.2	0.5	2.6
2003	51.1	1.5	2.8
2004	66.6	11.7	2.8
2005	50.9	3.2	2.9
2006	46.6	2.7	2.8
2007	40.4	1.2	2.8
2008	40.8	1.5	2.8
2009	31.2	0.4	2.9
2010	34.0	1.1	3.0
2011	65.7	24.3	3.1

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