Determining Nutrient and Sediment Loads and Trends in the Chesapeake Bay Watershed by Using an Enhanced Statistical Technique

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Effects of Nutrients and Sediment on Chesapeake Bay

As the largest and most productive estuary in North America, Chesapeake Bay is a vital ecological and economic resource. In recent decades, however, the bay and its tributaries have been degraded by excessive inputs of nutrients (nitrogen and phosphorus) and sediment from contributing watersheds, and in 1998, the Chesapeake Bay and its tidal tributaries were listed as "impaired" under the Clean Water Act. Consequently, a Chesapeake Bay Total Maximum Daily Load (TMDL) was established for nitrogen, phosphorus, and sediment in 2010 (U.S. Environmental Protection Agency, 2010). The TMDL requires that the seven watershed jurisdictions implement management practices to reduce inputs of nutrients and sediment to meet water-quality standards for dissolved oxygen, chlorophyll, and water clarity in the bay. Additional information on the TMDL can be found at *http://www.epa.gov/chesapeakebaytmdl/*.

The Chesapeake Bay Program (CBP) is a Federal-jurisdictional partnership that is working to meet water-quality standards in the bay. The CBP partners are pursuing an integrated approach to assess and communicate progress in water-quality improvements as the bay TMDL is implemented. This approach includes--

- tracking the implementation of management practices to meet the TMDL allocations for the bay;
- documenting trends in in-stream nitrogen, phosphorus, and sediment concentrations as well as loads of these constituents entering the bay from all parts of the watershed; and
- reporting on progress toward achieving the jurisdictions' water-quality standards for dissolved oxygen, chlorophyll, and water clarity/submerged aquatic vegetation in the bay.

This science summary focuses on results of a U.S. Geological Survey (USGS) study (Moyer and others, 2012) in which an enhanced statistical technique was used to estimate loads of nutrients and sediment to the bay and assess changes in those loads over time. Possible causes of the observed loads and trends are discussed, and ongoing and planned next steps are described.

Use of Two Complementary Approaches to Assess Changes in Nutrient and Sediment Loads in the Chesapeake Bay Watershed

Documenting trends in nitrogen, phosphorus, and sediment concentrations in the Chesapeake Bay watershed as well as loads of these constituents entering the bay will help assess progress in water-quality improvements associated with the TMDL. The USGS uses existing techniques to determine changes in *concentration*, which have been described most recently by Langland and others (2012). Because the bay TMDL is focused on changes in *loads* of nitrogen, phosphorus, and sediment to Chesapeake Bay, the USGS has developed an enhanced statistical technique to describe long-term changes in nutrient and sediment loads. This newer technique was first applied in a USGS study of nutrient concentrations and loads in tributaries to Chesapeake Bay (Hirsch and others, 2010). The technique, known as the "Weighted Regression on Time, Discharge, and Season" (WRTDS) method, is designed to analyze nontidal river-monitoring nutrient and sediment data to assess changes in the loads of these constituents that are delivered to Chesapeake Bay. It has recently been applied in other areas, including the Mississippi River Basin. By adding a second trend-analysis technique, the USGS can now assess changes in water-quality conditions with respect to trends in both concentration and load. The two different approaches to trends are defined as follows:

Trend in concentration: The trend in concentration is a useful measure of the quality of water in a river at a given location. It provides information about temporal changes in the quality of water encountered by aquatic organisms in the river, withdrawn at drinking-water intakes along the river, and experienced by people who use the river for recreation. The trend in concentration is "flow-adjusted," which means that the variability in concentration resulting from the day-to-day variations in streamflow is taken into account. This adjustment prevents the reported trend from being an artifact of the particular sequence of wet and dry years over the period of record and enables the results to be more sensitive to changes in the watershed related to land use, land-use practices, and point-source controls. Trends in concentration reflect the time-averaged conditions in the river, and all days have equal weight in the analysis, regardless of whether they are low-flow days or high-flow days.

Trend in load: The WRTDS computation tracks the annual loads of nutrients and sediment moving past the river-monitoring station and quantifies the trends in these loads. This computation also removes the effect of variations in streamflow by using a statistical technique called “flow normalization.” Both flow adjustment and flow normalization are designed to prevent the trend measure from being an artifact of the sequence of wet and dry years so that it can be more sensitive to changes in the watershed related to land use and (or) implementation of management practices. The primary difference between this new load trend estimate and the concentration trend estimate is that the WRTDS technique does not treat every day as being of equal importance. Because it considers the total load, which is influenced much more by conditions on high-flow days than by those on low-flow days, it is more sensitive to changes on high-flow days.

Trends determined by using both techniques: These two types of trend indicators (concentration and load) serve different purposes: the former describes changes in conditions in the river concentrations over all days of the year, whereas the latter describes changes in the amount of nutrients or sediment (load) that is transported past the station and delivered to the tidal waters of the bay. The two techniques can, in some cases, lead to different conclusions--that is, results obtained by using one technique may show degrading conditions whereas those obtained by using the other technique show improving conditions. Typically, sources of contamination that are relatively constant over a wide range of flow conditions, such as wastewater-treatment plants (WWTPs) or groundwater contributions to streamflow, have a large effect on concentration trends but a smaller effect on load trends. In contrast, sources of contamination that respond to wet-weather conditions, such as stormwater runoff from urban or agricultural land or erosion of soil from construction sites, farms, river channels, or floodplains, have a large effect on load trends but a smaller effect on concentration trends.

The USGS report “Comparison of two regression-based approaches for determining nutrient and sediment fluxes and trends in the Chesapeake Bay watershed” by Moyer and others (2012) documents the enhancements made to the WRTDS method (including new computations for total nitrogen, orthophosphorus, and sediment); compares the results to those obtained by using previously available methods; and presents trend results for loads of total nitrogen, nitrate, orthophosphorus, total phosphorus, and suspended sediment at the nine USGS River Input Monitoring (RIM) stations in the Chesapeake Bay watershed (fig. 1). These nine stations are located on the three largest tributaries to Chesapeake Bay--the Susquehanna, Potomac, and James Rivers; the Choptank River on the eastern shore and the Patuxent River on the western shore of Maryland; and the Rappahannock, Mattaponi, Pamunkey, and Appomattox Rivers in Virginia. The nine RIM stations are part of the CBP nontidal water-quality monitoring network, which consists of 125 stations. Collectively, the drainage basins upstream from the RIM sites account for about 78 percent of the land area of the bay watershed. A large portion of the point- and nonpoint-source loads from the Washington, D.C., Baltimore, Maryland, and Richmond, Virginia, metropolitan areas, however, originates in the 22 percent of the watershed (shown in white in figure 1) from which runoff and effluents do not flow past the RIM sites on their way to the bay. Consequently, practices that are implemented in this area to reduce loadings from these major metropolitan areas, as well as from a number of smaller communities and areas of other land-use types located near the bay, are not reflected in the RIM results. Additional information about the loadings from the parts of watershed that are not monitored by the RIM sites also must be considered in any analysis of the causes of water-quality trends in the bay.

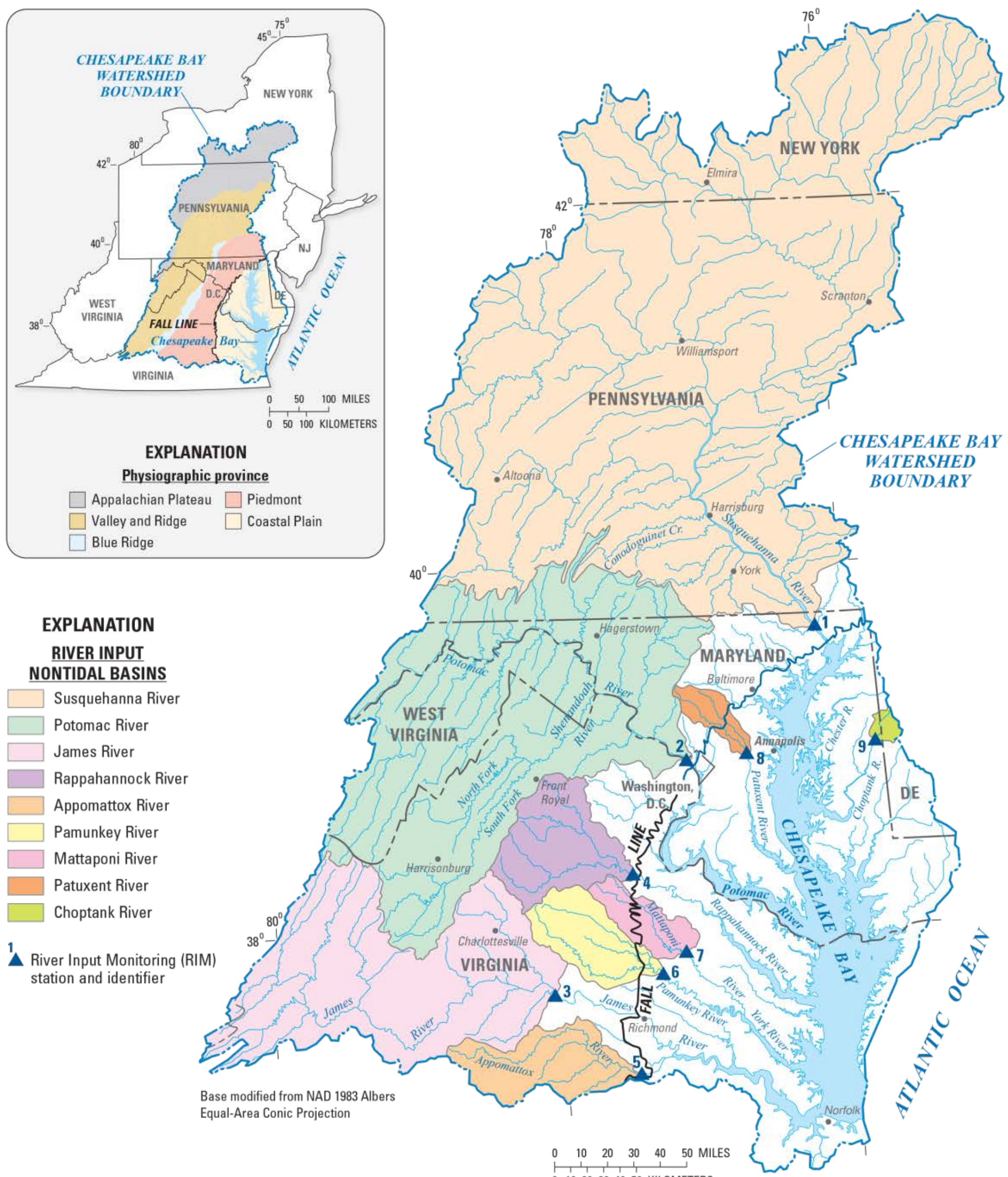

Figure 1. Location of the nine U.S. Geological Survey River Input Monitoring (RIM) stations at which the new load and trend computation method (Weighted Regression on Time, Discharge, and Season, or WRTDS) was applied: (1) Susquehanna River, (2) Potomac River, (3) James River, (4) Rappahannock River, (5) Appomattox River, (6) Pamunkey River, (7) Mattaponi River, (8) Patuxent River, and (9) Choptank River. (Modified from Moyer and others, 2012, fig. 1).

Key Results

Moyer and others (2012) provide results for trends in load and yield (load per unit area) for total nitrogen, nitrate, orthophosphorus, total phosphorus, and suspended sediment. Because loads (expressed in units of pounds per day) are strongly dependent on watershed size, loads of nitrogen, phosphorus, and sediment are higher in the largest rivers (Susquehanna, Potomac, and James) than in the five smaller rivers. Examining yields rather than loads facilitates comparisons among the nine monitored rivers. Trends in yields of the five constituents listed above (expressed in units of pounds per day per square mile) are shown in figures 2 to 5. Because the percent change over time in load and yield are identical, only trends in yield are presented here. Trends in watershed yields at the nine RIM stations are discussed for two time periods: a long-term period (1985—2010) and a short-term period (2001—10). Constituent yields that showed downward trends greater than 10 percent over the period are called “improving,” those that showed upward trends greater than 10 percent over the period are called “degrading,” and those that changed less than 10 percent over the period are called “minimal change.”

Nitrogen Trends

Over the long-term period (1985—2010), nitrate yields improved at most of the RIM sites but total nitrogen yields improved at only three sites (table 1). Over the short-term period (2001—10), nitrate yields improved at five sites and showed minimal change at four sites, whereas total nitrogen yields exhibited minimal change at all sites except the Patuxent River site, where they improved.

Table 1. Changes in yields of nitrate and total nitrogen at the nine U.S. Geological Survey River Input Monitoring (RIM) stations during two time periods, long-term (1985–2010) and short-term (2001–10).

RIM STATION	LONG-TERM TREND IN YIELD (1985–2010)		SHORT-TERM TREND IN YIELD (2001–10)	
	NITRATE	TOTAL NITROGEN	NITRATE	TOTAL NITROGEN
SUSQUEHANNA	IMPROVING	IMPROVING	IMPROVING	MINIMAL CHANGE
POTOMAC	IMPROVING	IMPROVING	IMPROVING	MINIMAL CHANGE
JAMES	IMPROVING	MINIMAL CHANGE	MINIMAL CHANGE	MINIMAL CHANGE
RAPPAHANNOCK	IMPROVING	MINIMAL CHANGE	IMPROVING	MINIMAL CHANGE
APPOMATTOX	IMPROVING	MINIMAL CHANGE	MINIMAL CHANGE	MINIMAL CHANGE
PAMUNKEY	MINIMAL CHANGE	MINIMAL CHANGE	IMPROVING	MINIMAL CHANGE
MATTAPONI	MINIMAL CHANGE	MINIMAL CHANGE	MINIMAL CHANGE	MINIMAL CHANGE
PATUXENT	IMPROVING	IMPROVING	IMPROVING	IMPROVING
CHOPTANK	DEGRADING	MINIMAL CHANGE	MINIMAL CHANGE	MINIMAL CHANGE

- *Long-term:* Long-term improvements in nitrate yields were observed at most of the RIM sites (including those at the three largest rivers—the Susquehanna, Potomac, and James); only one site (Choptank River) showed degrading conditions. Total nitrogen yields improved at only three sites--those on the two largest rivers (the Susquehanna and Potomac) and the Patuxent—and exhibited only minimal change at the remaining six sites (see figure 2).

- *Short-term:* Nitrate yields improved at five sites (including those at the two largest rivers—the Susquehanna and Potomac) and showed minimal change at four sites. Total nitrogen yields exhibited minimal change at all sites except the Patuxent River, where they improved.

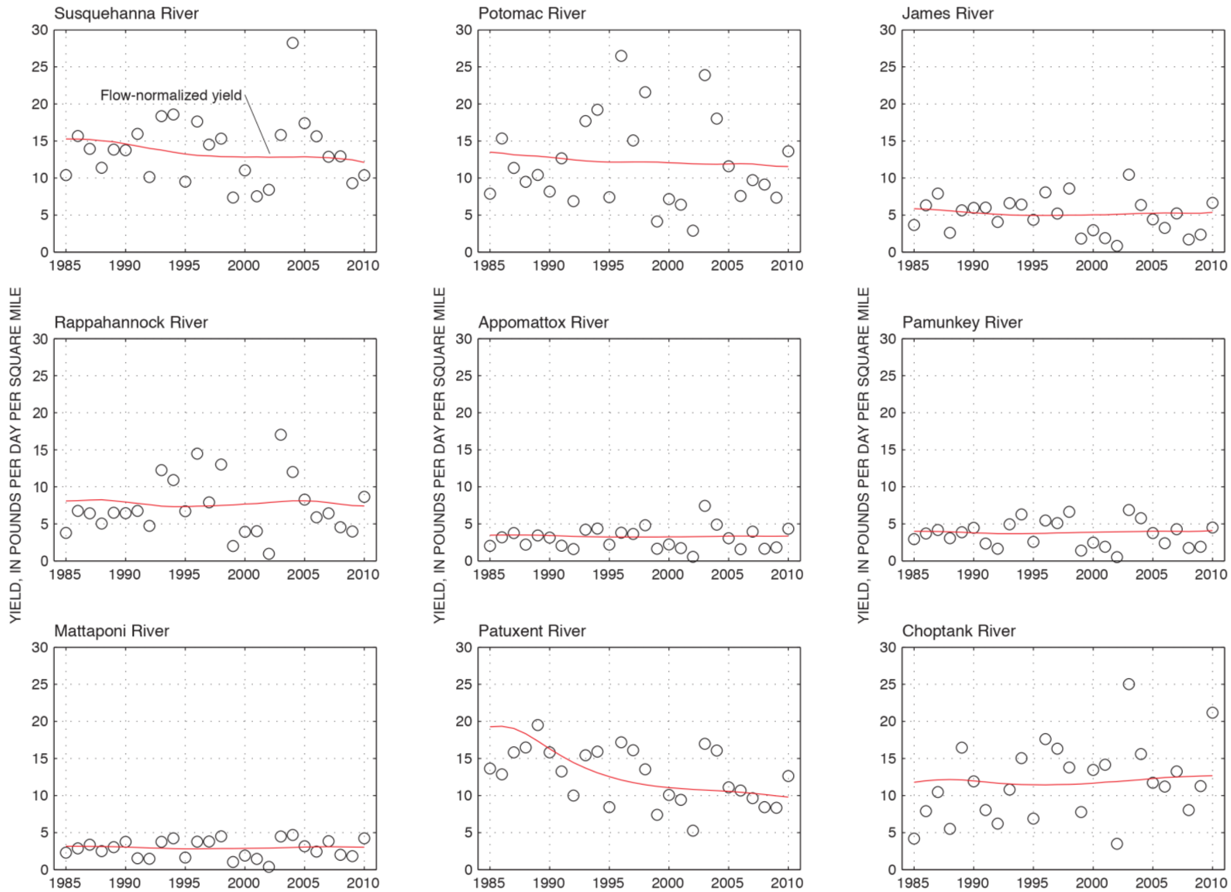

Figure 2. Estimated annual yields of total nitrogen at the nine U.S. Geological Survey River Input Monitoring (RIM) stations, Maryland and Virginia. (Trends in yield are computed on the basis of differences in flow-normalized yields over a given period of time; axes are scaled identically to permit comparisons of watershed yields over time. Modified from Moyer and others, 2012, fig. 18).

Phosphorus Trends

Yields of orthophosphorus (the principle form of dissolved phosphorus) improved during both the long- and short-term periods at most of the RIM sites except at the Choptank River, which showed degrading conditions (table 2). Over the long-term period, yields of total phosphorus (which is associated primarily with sediment) improved at only two sites, showed minimal change at three sites, and were indicative of degrading conditions at four sites, whereas short-term trends showed degrading conditions at six of the nine RIM sites.

Table 2. Changes in yields of orthophosphorus and total phosphorus at the nine U.S. Geological Survey River Input Monitoring (RIM) stations during two time periods, long-term (1985–2010) and short-term (2001–10).

RIM STATION	LONG-TERM TREND IN YIELD (1985–2010)		SHORT-TERM TREND IN YIELD (2001–10)	
	ORTHOPHOSPHORUS	TOTAL PHOSPHORUS	ORTHOPHOSPHORUS	TOTAL PHOSPHORUS
SUSQUEHANNA	IMPROVING	MINIMAL CHANGE	MINIMAL CHANGE	DEGRADING
POTOMAC	IMPROVING	IMPROVING	IMPROVING	MINIMAL CHANGE
JAMES	IMPROVING	MINIMAL CHANGE	IMPROVING	DEGRADING
RAPPAHANNOCK	IMPROVING	DEGRADING	MINIMAL CHANGE	DEGRADING
APPOMATTOX	IMPROVING	DEGRADING	IMPROVING	DEGRADING
PAMUNKEY	IMPROVING	DEGRADING	IMPROVING	DEGRADING
MATTAPONI	IMPROVING	MINIMAL CHANGE	IMPROVING	MINIMAL CHANGE
PATUXENT	IMPROVING	IMPROVING	IMPROVING	MINIMAL CHANGE
CHOPTANK	DEGRADING	DEGRADING	DEGRADING	DEGRADING

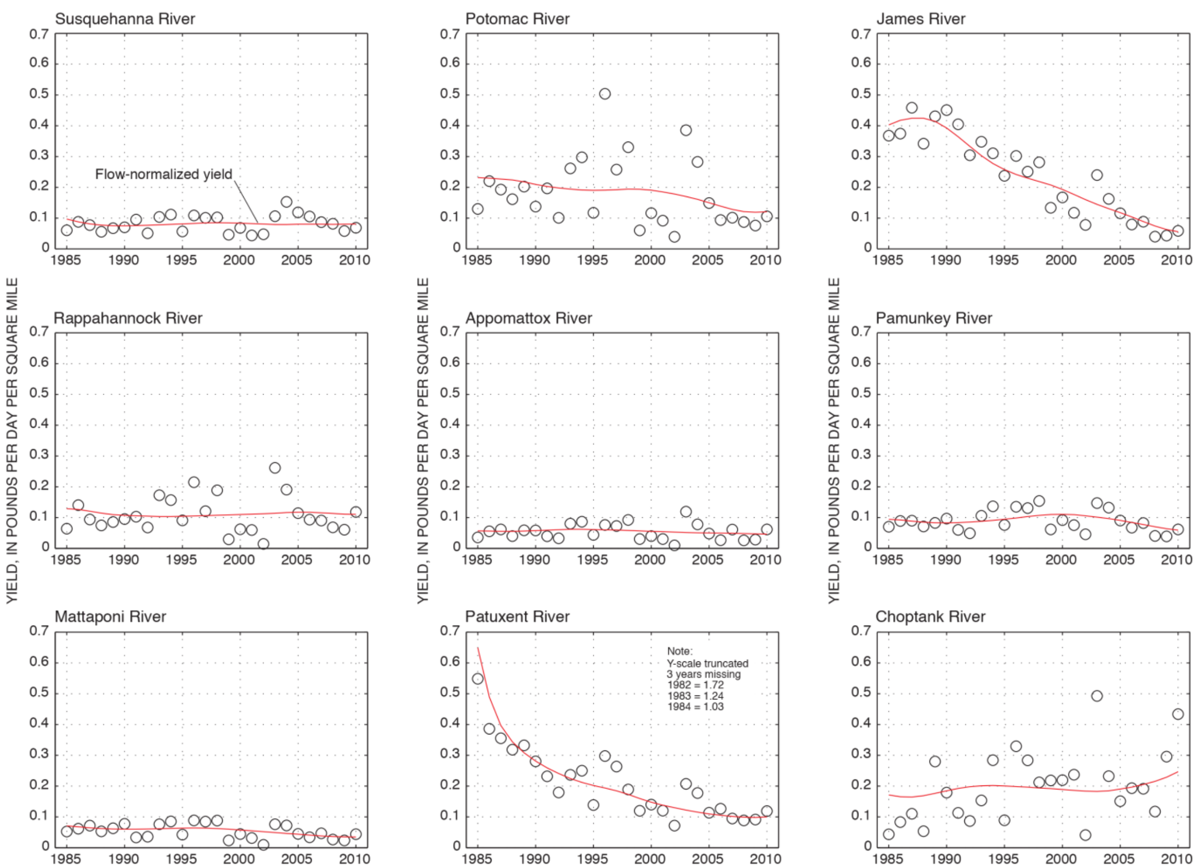

Figure 3. Estimated annual yields of orthophosphorus at the nine U.S. Geological Survey River Input Monitoring (RIM) stations, Maryland and Virginia. (Trends in yield are computed on the basis of differences in flow-normalized yields over a given period of time; axes are scaled identically to permit comparisons of watershed yields over time. Modified from Moyer and others, 2012, fig. 21).

- *Long-term*: Orthophosphorus yields indicated improving conditions at all sites except the Choptank River (where they showed degrading conditions). Orthophosphorus yields showed the largest improvements at the James, Potomac, and Patuxent River sites (fig. 3). In contrast, total phosphorus yields improved at only two sites (Patuxent and Potomac Rivers), degraded at four sites (particularly at the Rappahannock River site--see figure 4), and showed minimal changes at the three remaining sites.

- *Short-term:* Orthophosphorus yields indicated improving conditions at six of the sites and degrading conditions at one site (Choptank River). For total phosphorus yields, however, degrading conditions were observed at six sites and minimal change was observed at the three remaining sites. Increases in total phosphorus yield were largest (in percent) at the Rappahannock, James, and Pamunkey Rivers (see figure 4); at these three sites, the average rate of increase was greater over the short-term period than over the long-term period.

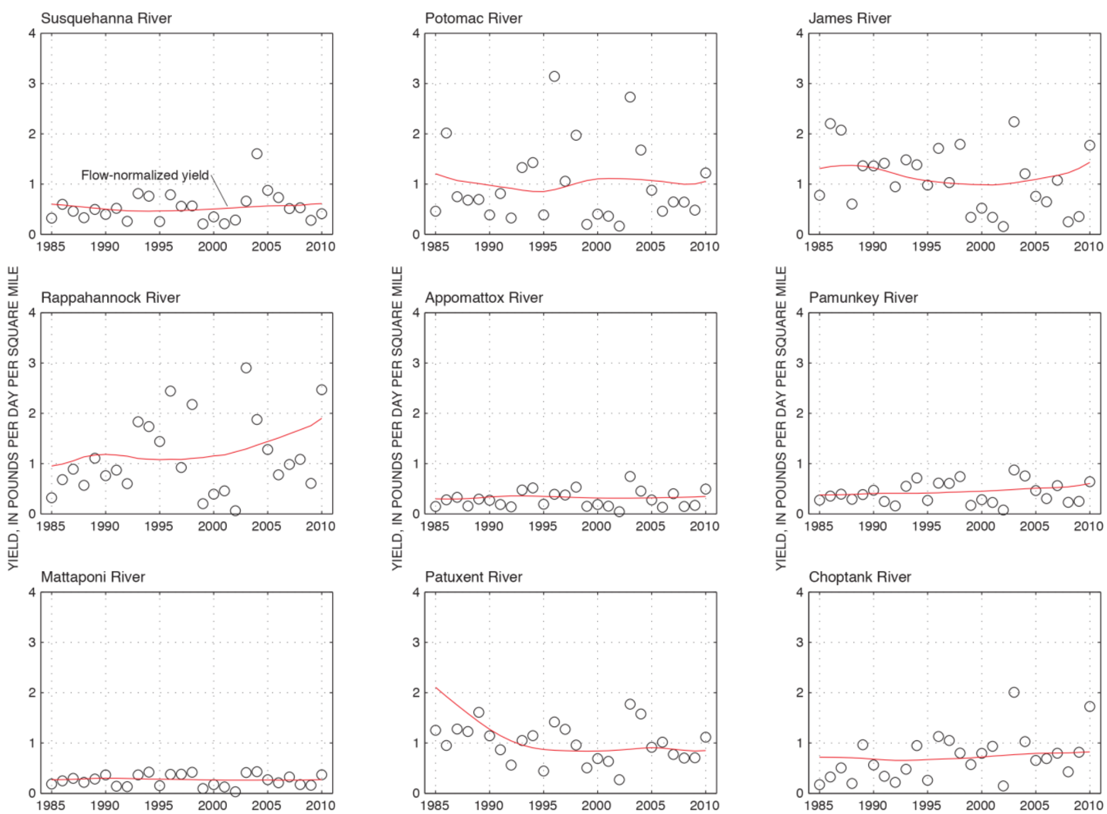

Figure 4. Estimated annual yields of total phosphorus at the nine U.S. Geological Survey River Input Monitoring (RIM) stations, Maryland and Virginia. (Trends in yield are computed on the basis of differences in flow-normalized yields over a given period of time; axes are scaled identically to permit comparisons of watershed yields over time. Modified from Moyer and others, 2012, fig. 20).

Sediment Trends

Long-term trends in suspended-sediment yield are available only for the four Maryland sites, two of which showed improving conditions and two of which showed degrading conditions (table 3). Short-term trends in suspended-sediment yield at all nine RIM sites were similar to the trends in total phosphorus yield, with six sites exhibiting degrading conditions, one site exhibiting improving conditions, and two sites exhibiting minimal change.

Table 3. Changes in yields of suspended sediment at the nine U.S. Geological Survey River Input Monitoring (RIM) stations during two time periods, long-term (1985–2010) and short-term (2001–10). [NA, not available]

RIM STATION	LONG-TERM TREND IN YIELD (1985–2010)	SHORT-TERM TREND IN YIELD (2001–10)
SUSQUEHANNA	DEGRADING	DEGRADING
POTOMAC	DEGRADING	DEGRADING
JAMES	NA	DEGRADING
RAPPAHANNOCK	NA	MINIMAL CHANGE
APPOMATTOX	NA	MINIMAL CHANGE
PAMUNKEY	NA	DEGRADING
MATTAPONI	NA	IMPROVING
PATUXENT	IMPROVING	DEGRADING
CHOPTANK	IMPROVING	DEGRADING

- *Long-term*: Among the four Maryland RIM sites, sediment yields improved at the Patuxent and Choptank Rivers and degraded at the Susquehanna and Potomac Rivers; the latter two rivers also showed the greatest change (see figure 5). Trends in sediment yield could not be computed for the Virginia sites because the number of long-term suspended-sediment data was insufficient.

- *Short-term:* Sediment yields improved only at the Mattaponi River, where they are historically very low. Degrading conditions were observed at six sites, with the largest percentage increases in yield observed for the Potomac and Susquehanna Rivers (see figure 5).

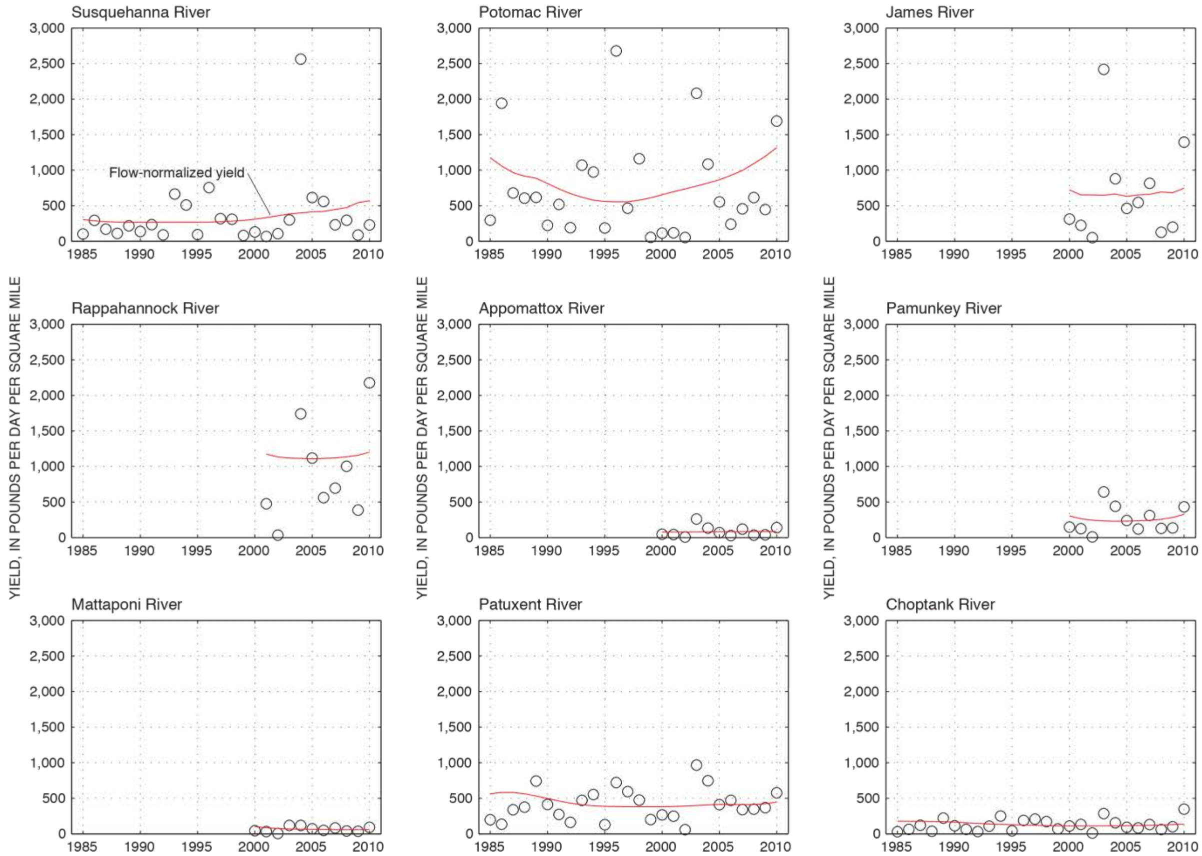

Figure 5. Estimated annual yields of suspended sediment at the nine U.S. Geological Survey River Input Monitoring (RIM) stations, Maryland and Virginia. (Trends in yield are computed on the basis of differences in flow-normalized yields over a given period of time; axes are scaled identically to permit comparisons of watershed yields over time. Modified from Moyer and others, 2012, fig. 22).

Possible Reasons for Trends

Trends in nutrient and sediment yields are affected by several factors, including implementation of practices to reduce sources, changes in land use, and response time between implementation of practices and water-quality improvements. Although Moyer and others (2012) did not examine these factors, some of the possible causes of trends that will be explored in future studies are discussed below.

Nitrogen: Some possible reasons for the changes in nitrogen yield that will be explored include upgrades made to WWTPs, practices designed to reduce the effects of fertilizer and manure, and reductions in air emissions. Additionally, more information is needed to examine the changes in land use that affect the amount of nitrogen entering the rivers. Response time for water-quality improvements (time between implementing practices and observation of measurable effects on water quality) also could affect the trends. Water-quality improvements resulting from WWTP upgrades or from practices that reduce the runoff of nitrogen to streams can be relatively rapid (Phillips and Lindsey, 2003) and are possible reasons for the improvement in nitrate yields at the majority of the RIM sites. Some of the nitrogen applied in the watershed, however, travels through groundwater and can take years to decades to reach the streams (Sanford and others, 2012; Lindsey and others, 2003). Additionally, some of the nitrogen load (typically less than 50 percent) is attached to sediment. Decades or more may be required for this sediment to travel through the watershed to the bay (Langland and Cronin, 2003). Therefore, the improvement associated with water-quality-management practices can be much slower for the portion of nitrogen that is transported by groundwater or associated with sediment. These are some of the possible reasons for the minimal changes in total nitrogen yield observed at the majority of the RIM sites.

Phosphorus: Possible causes of trends in phosphorus yield (both orthophosphorus and total phosphorus) that will be explored include implementation of water-quality-management practices, response times, and changes in land use.

- Practices that will be examined include upgrades to WWTPs, the phosphorus detergent ban, practices to reduce fertilizer and manure in agricultural areas, and practices to reduce fertilizer and stormwater in urban/suburban areas. A combination of these practices is most likely responsible for the observed improvement in orthophosphorus yield at a majority of the RIM sites.
- The mixed results for observed changes in total phosphorus yield at the RIM sites could be the result of the locations where practices are being implemented. For example, upgrades to WWTPs most likely contributed to improvements in the phosphorus load in the Patuxent River. In other river basins, however, upgrades to WWTPs take place primarily in the areas downstream from the RIM stations, which could be one reason for the lack of observed improvements at the majority of the sites. Response times of the phosphorus load in rivers to implementation of water-quality-management practices are also affected by the amount of phosphorus attached to sediment. More than half the phosphorus load is typically attached to sediment, and decades or more may be required for this sediment to travel through the watershed to the bay. Because this sediment (and associated phosphorus) is commonly stored in streams and their floodplains, it is sometimes referred to as "legacy sediment." During storms, this stored material is resuspended, transported some distance downstream, and redeposited; therefore, improvements in yield are delayed.
- Land-use changes can affect phosphorus trends. For example, as a watershed undergoes urban development, the increase in impervious surface area can cause an increase in runoff, leading to erosion of sediment (and associated phosphorus) stored in streams and ultimately causing degrading conditions. Additionally, an increase in the amount of animal manure and chemical fertilizer being applied in agricultural and suburban areas can lead to degrading conditions with respect to phosphorus.

Sediment: Less is known about the possible factors affecting trends in sediment yield. Sediment and associated phosphorus can be trapped in reservoirs, which affect their movement. In a recent USGS study, Hirsch (2012) reported that loads of sediment and phosphorus from the Susquehanna River to the bay have increased since 1996 because Conowingo Dam is filling with sediment. Consequently, the reservoir has lost some of its capacity to trap sediment and associated phosphorus. As mentioned in the phosphorus discussion above, when a watershed undergoes urban development, the increase in impervious surface area can cause an increase in runoff, leading to erosion of sediment and, ultimately, degrading water-quality conditions. The sediment can be stored in streams and subsequently eroded and transported during storm events. The time required for sediment to travel through the watershed to the RIM stations can be decades or longer, however, depending on the size of the basin and the proportion of floodplains and wetlands it contains. The long travel time can lead to a slow response between the implementation of water-quality-management practices and the detection of water-quality improvements.

Next Steps

- The CBP partners are pursuing an integrated approach to assess and communicate progress in water-quality improvements as the bay TMDL is implemented. This approach includes (1) tracking the implementation of management practices to meet the TMDL allocations for the bay; (2) documenting trends in in-stream nitrogen, phosphorus, and sediment concentrations as well as loads of these constituents entering the bay from all parts of the watershed; and (3) reporting on progress toward achieving the jurisdictions' water-quality standards for dissolved oxygen, chlorophyll, and water clarity/submerged aquatic vegetation in the bay. The enhanced technique (WRTDS) to determine trends in loads, together with existing techniques to determine trends in concentration, will both be used in the future.
- Trend in concentrations of nutrients and sediment is a useful measure of the quality of water in a river at a given location. The USGS will continue to apply this measure to the data collected in the CBP nontidal network, which includes the RIM sites. The CBP network consists of 125 sites throughout the watershed; sites that are closest to areas where water-quality-management practices are implemented are more likely to be the first in the network to reflect water-quality improvements. For example, Langland and others (2012) reported improvements in long-term trends for total nitrogen and total phosphorus at the majority of sites in the network that are upstream from the RIM stations. Because evaluating trends in load (yield) is essential to tracking progress toward load-reduction goals, future USGS updates of water-quality trends at the nine RIM sites will include information on trends in load in addition to information on trends in concentration. Because the RIM sites are at the farthest downstream nontidal locations in major river basins, improvements at these sites are likely to be observed later than those at other sites in the CBP network.
- The USGS and CBP partners are updating communication products to present the results of these two complementary measures (trends in concentration and trends in load), and both will be available on the CBP Web site *(www.chesapeakebay.net*) and the USGS Web site for Chesapeake Bay Activities *(http://chesapeake.usgs.gov/*).
- The USGS is working with partners to help explain the trends described in Moyer and others (2012). The initial areas of focus are the Eastern Shore and the Potomac River Basin. Studies are also underway to continue to evaluate the ongoing changes in the trapping efficiency and sediment-scour thresholds of the lower Susquehanna River reservoirs as they approach their sediment-storage capacity. These studies will examine the relations between the observed trends in water quality and various characteristics of the watersheds, including changes in land-use and land-management practices, changes in atmospheric deposition, changes in WWTPs, and geologic and soil conditions. In order to develop these relations, water-quality data from not only the RIM sites but also other surface-water, precipitation, and groundwater monitoring sites in the watersheds will be analyzed. The goal of these studies is to improve the understanding of water-quality changes in the Chesapeake Bay watershed as a means to help inform Chesapeake Bay restoration efforts.

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