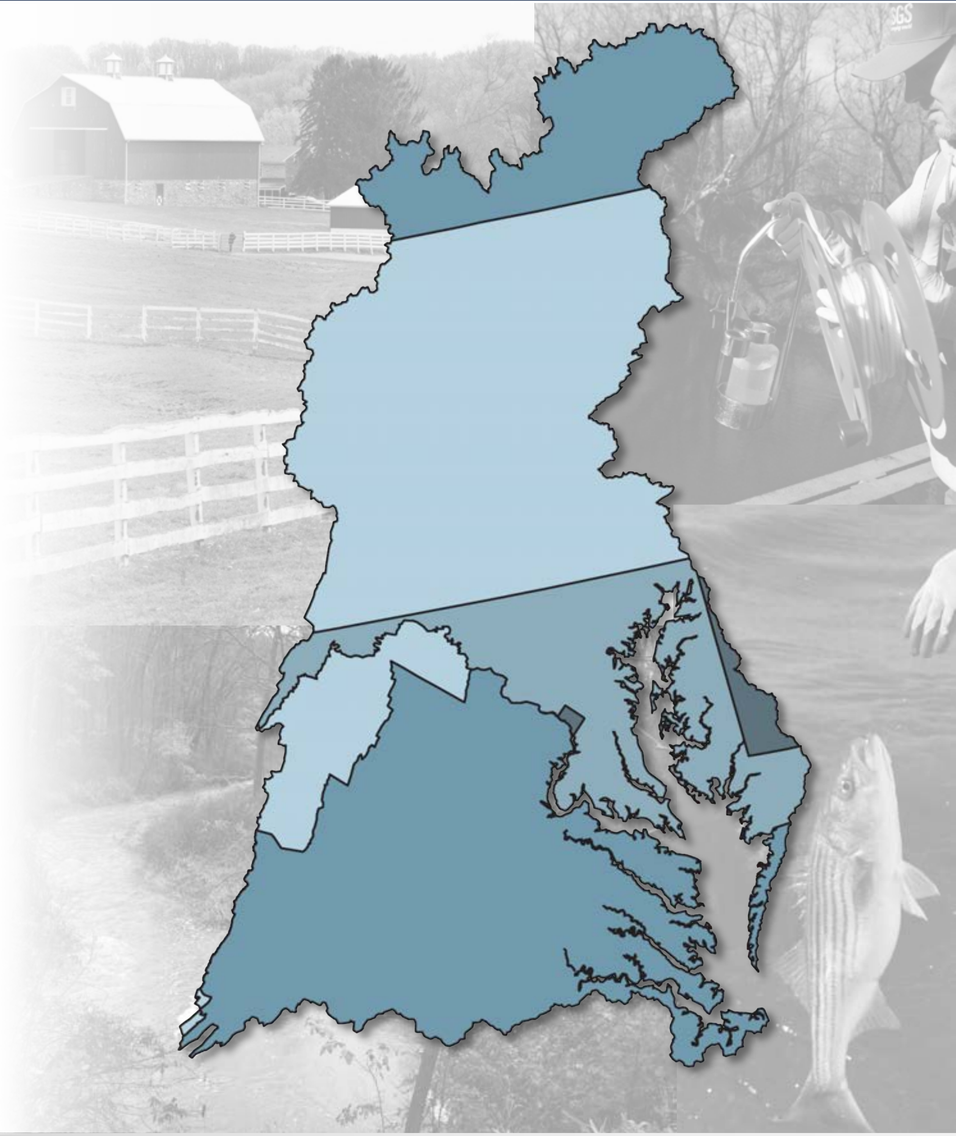
Summarizing Scientific Findings for Common Stakeholder Questions to Inform Nutrient and Sediment Management Activities in the Chesapeake Bay Watershed

The United States Geological Survey (USGS) worked with Chesapeake Bay stakeholders to identify priority questions where scientific findings can inform nontidal nutrient and sediment management activities.

This presentation summarizes scientific findings for selected stakeholder questions, organized into nine important decision making "themes".

Click the "forward" button to advance to the next slide and learn more about the use of this presentation.



Photos courtesy of Chesapeake Bay Program

This presentation is designed for the reader to choose the themes and level of detail they want to explore

Each theme contains 3-4 summary statements about major findings followed by additional details supported by peer-reviewed publications and online resources, which can be accessed for additional information.

Citations are listed throughout the presentation using superscript numbers, which correspond to numbered references on slides 91-105.

On the next slide, readers can click on a theme to jump directly to the major findings, selected stakeholder questions, and detailed content.

This presentation contains a large amount of information but can be explored over time as a resource to support ongoing and future management activities.

This presentation is best experienced using a single page or full screen view in your PDF reader

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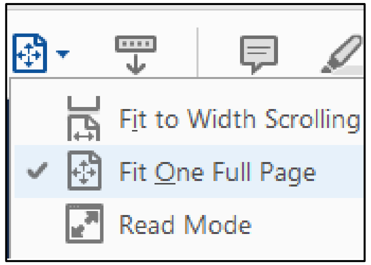

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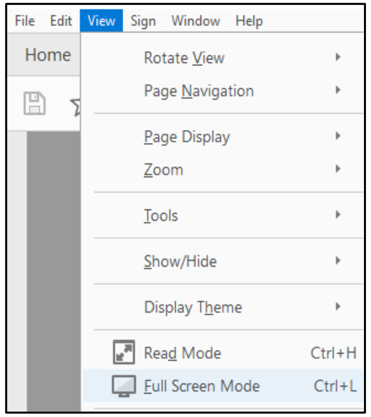

Navigation controls are listed on each slide to help explore the presentation.

Click the “home” button to return to a list of themes, presented on the next slide.

Click the “back” button to return to the previous slide.

Click the “forward” button to advance to the next slide.

Click the “dictionary” button to view definitions of common terms.

Click the “information” button to view a list of contacts and references.

There are common themes across the watershed where scientific insights can inform management activities.

- Strengthening Decision Making with Modeling and Monitoring
- Practices to Reduce Nutrients and Sediment: Placement, Changes, and Implications for Targeting
- Water-Quality Benefits to Biological Conditions and Human Health
- Nutrient and Sediment Responses in Nontidal Streams
- Legacy Nutrients and Lag Times
- Sediment Dynamics and Reservoir Infilling
- Drivers of Nutrient Responses in Nontidal Streams
- Nontidal Influences on Estuarine Response and Standards Attainment
- Climatic Influences on Water Quality

Begin exploring the themes by clicking the “forward” button or a banner above.

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Strengthening Decision Making with Modeling and Monitoring

Management Implications

1. The Chesapeake Bay Program's modeling tools are used to plan implementation of nutrient and sediment reduction activities and forecast responses.

2. However, monitoring data offer the most accurate representation of how water-quality conditions are responding in the watershed and Bay.

3. Therefore, monitoring data can help inform future implementation by assessing the effectiveness of practices and the primary drivers of changing water-quality condition.

4. Scientific support and online resources can help apply modeling tools, monitoring data, and new insights to strengthen management strategies.

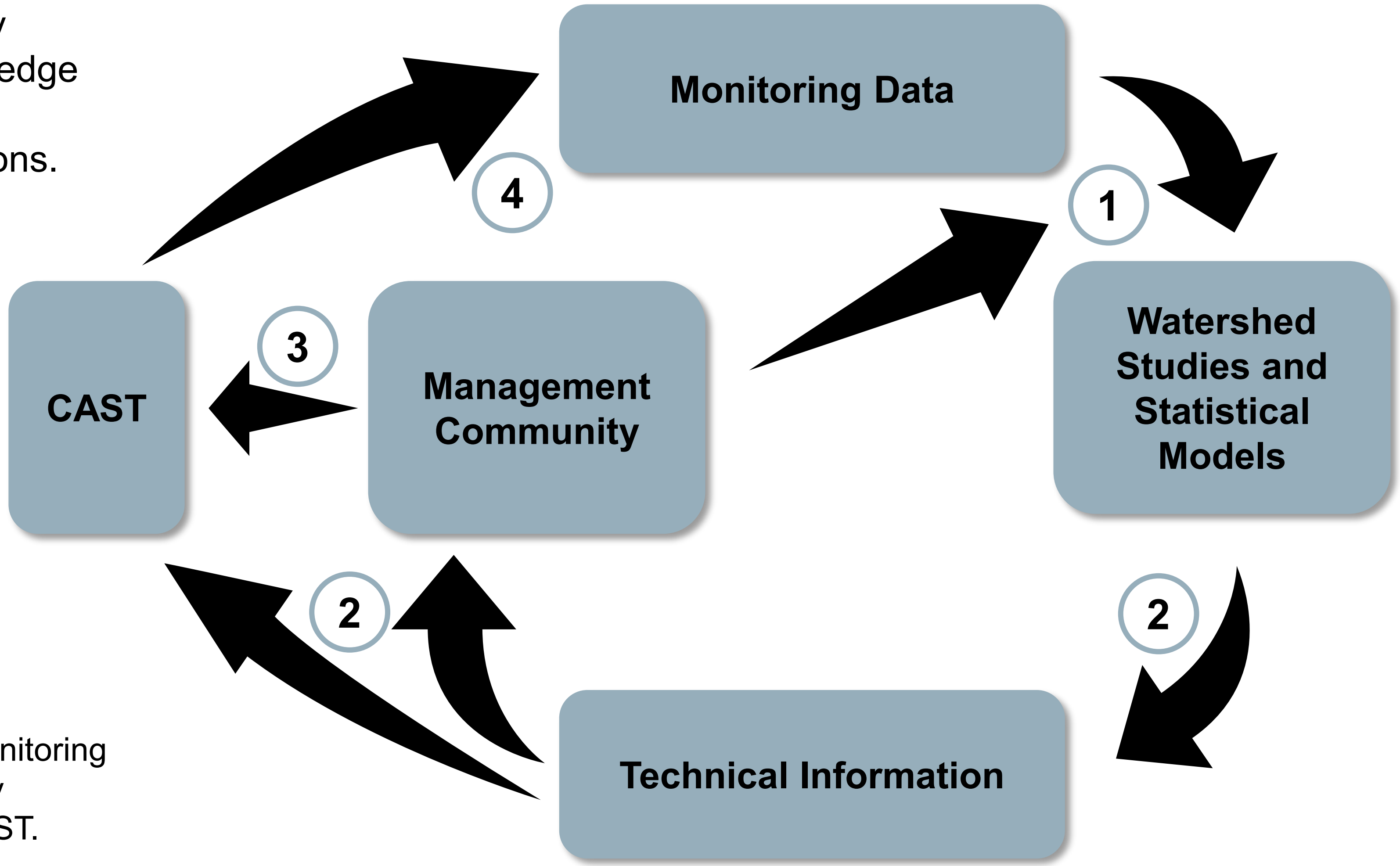
This use of monitoring data will be critical to inform the Chesapeake Bay Program of progress towards attaining water-quality standards in coming years, as all nutrient and sediment reducing practices are scheduled to be implemented by 2025.

Background photo courtesy of Chesapeake Bay Program

The Chesapeake Bay Program's modeling tools are used to plan implementation of nutrient and sediment reduction activities and forecast responses

CAST, the online version of the Chesapeake Bay Program's watershed model, incorporates knowledge across the scientific community and is used plan management strategies and predict load reductions.

1. Watershed studies and statistical models analyze and interpret monitored water-quality data to address priority concerns identified by the management community.
2. Watershed studies and statistical models provide technical information that is communicated to the management community and used to inform and improve CAST.
3. The management community uses CAST to develop management strategies.
4. Estimates from CAST are compared against monitoring data to develop new insights about water-quality conditions and to improve future versions of CAST.



However, monitoring data offer the most accurate representation of how water-quality conditions are responding in the watershed and Bay

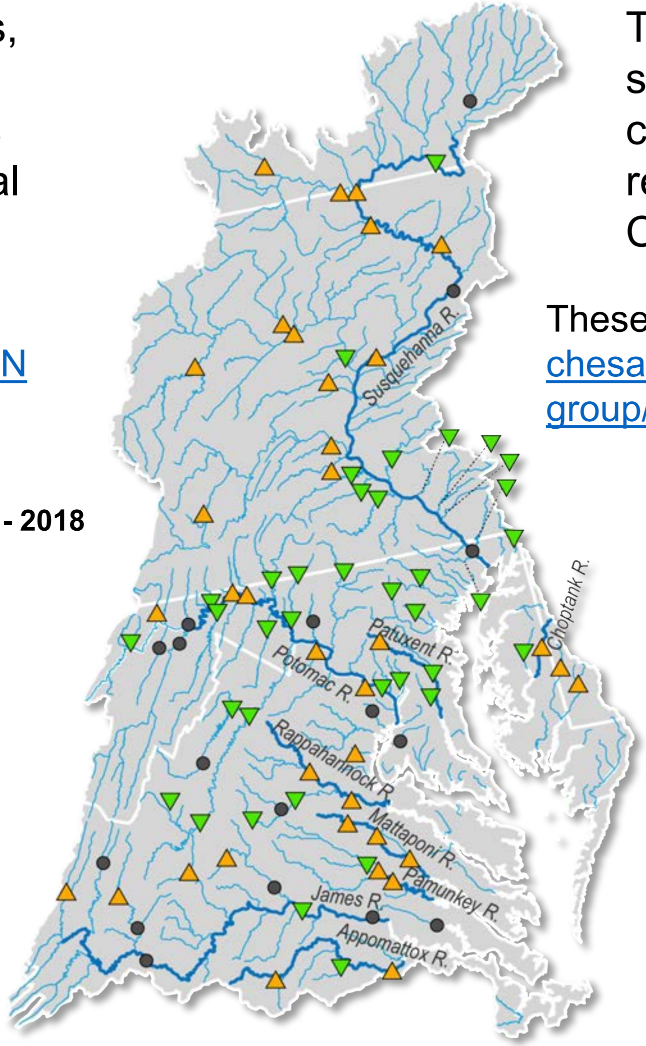
Trends in nitrogen, phosphorus, and sediment loads are reported for streams and rivers in the Chesapeake Bay nontidal monitoring network.[1]

These data can be explored online:

- va.water.usgs.gov/storymap/NTN
- cbrim.er.usgs.gov

TN load trends at NTN stations, from 2009 - 2018

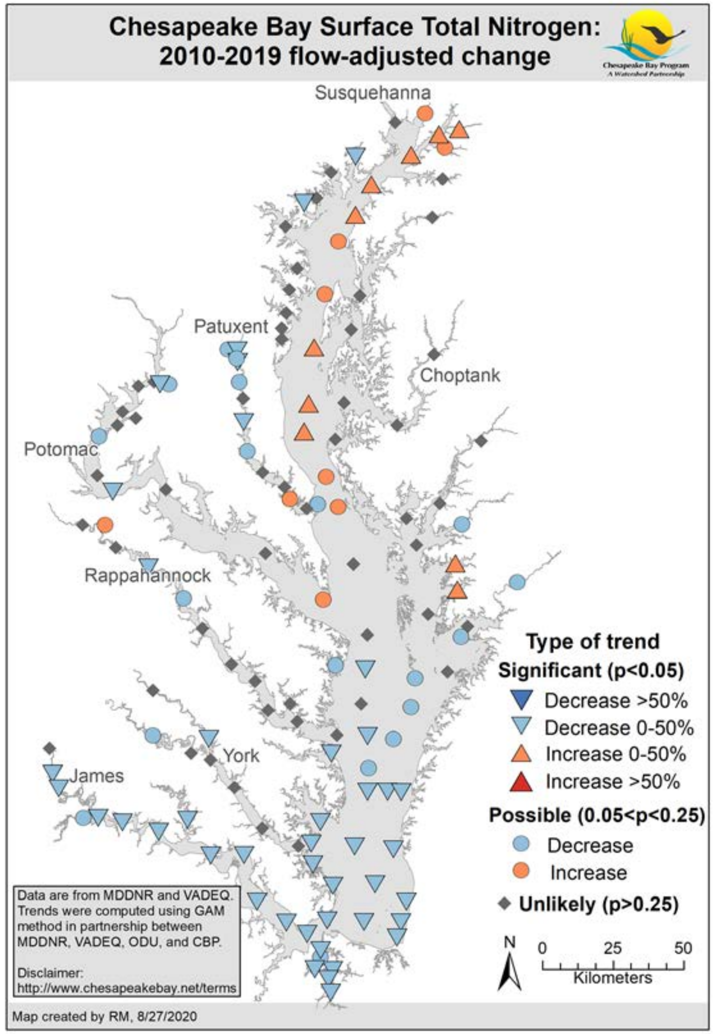
- Improving Trend
- Degrading Trend
- No Trend



__Right__: flow-normalized total nitrogen (TN) load trends from 2009 – 2018 from the Chesapeake Bay nontidal monitoring network.

Trends in nitrogen, phosphorus, sediment, dissolved oxygen, chlorophyll-a, and clarity are reported for tidal stations in the Chesapeake Bay.[2]

These data can be explored online:
chesapeakebay.net/who/group/integrated_trends_analysis_team



__Right:__ flow-adjusted surface total nitrogen concentration trends from 2010 – 2019 from the Chesapeake Bay tidal monitoring network.

Therefore, monitoring data can help inform future implementation by assessing the effectiveness of practices and the primary drivers of changing water-quality condition

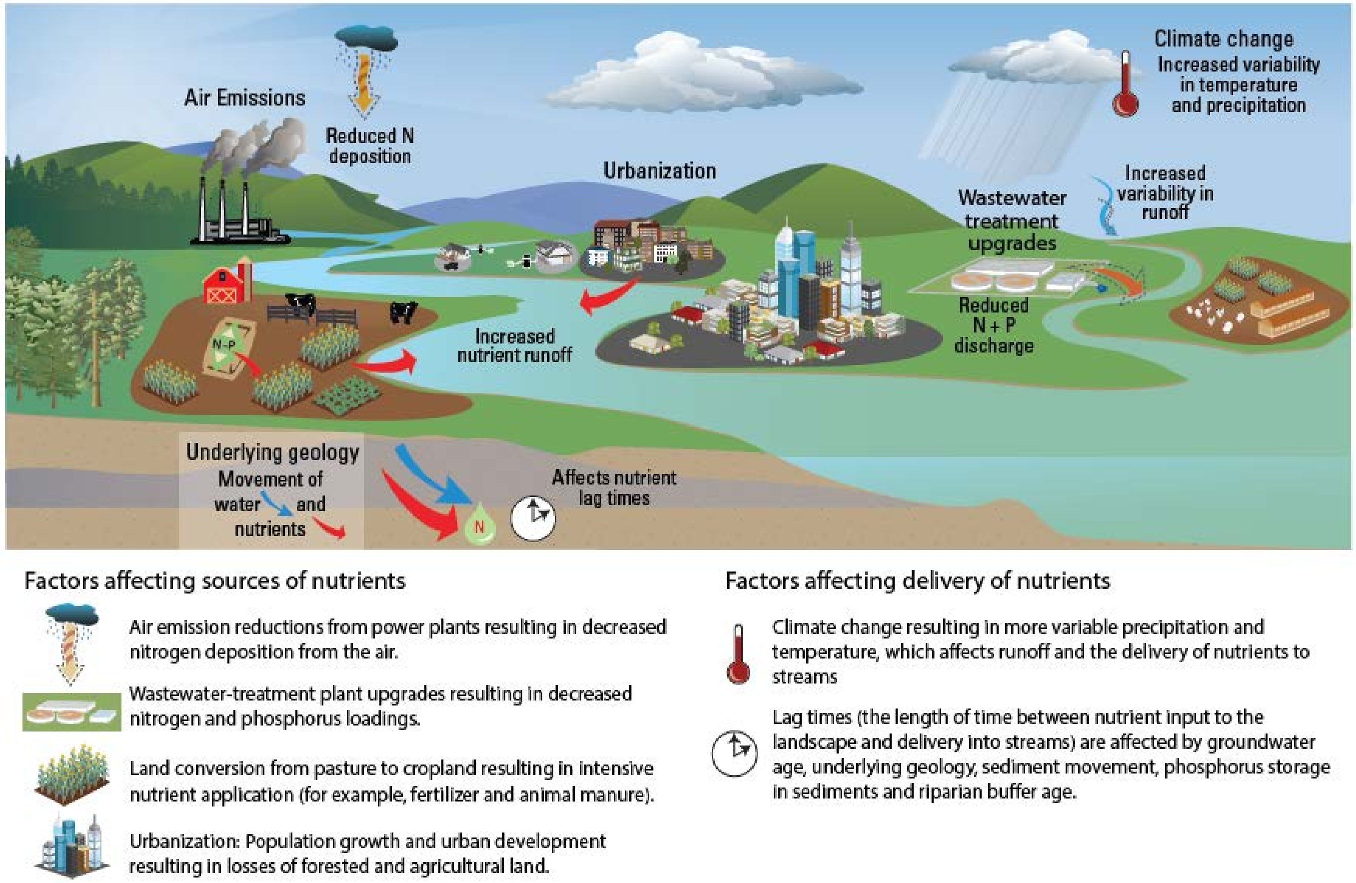
Nitrogen, phosphorus, and sediment trends are primarily affected by changes in sources and changes in factors affecting their delivery from the landscape to streams.[3,4]

Nitrogen and phosphorus sources include a combination of point sources and urban, agricultural, and atmospheric nonpoint sources.[3]

Sediment sources include upland and streambank erosion, which differ by watershed size and setting.[4]

For nitrogen and phosphorus, management practices that directly reduce inputs to the landscape may be more effective at reducing nitrogen and phosphorus loads than those that attempt to control their transport.[5]

For sediment, management practices that prevent bank erosion are likely to be effective in headwater streams and those associated with floodplain protections are important in larger streams.[4]



***Above**: Conceptual diagram illustrating some of the complex factors affecting nitrogen and phosphorus trends in the Chesapeake Bay watershed.[3]*

Scientific support and online resources can help apply modeling tools, monitoring data, and new insights to strengthen management strategies

The United States Geological Survey (USGS) provides scientific support for Chesapeake Bay management.

Primary USGS Points of Contact by Jurisdiction

Virginia and West Virginia

Jimmy Webber
jwebber@usgs.gov
804-261-2621

Pennsylvania and New York

John Clune
jclune@usgs.gov
570-327-3171

Maryland, Delaware, and D.C.

Alex Soroka
asoroka@usgs.gov
443-498-5529

Online tools that explore local conditions and water-quality responses can develop effective management strategies.

The Chesapeake Assessment Scenario Tool (CAST) is a free, online nitrogen, phosphorus and sediment load estimator tool that streamlines environmental planning: cast.chesapeakebay.net

The **Chesapeake Bay Phase 6 Land Use Viewer** can be used to explore land use patterns throughout the watershed: chesapeake.usgs.gov/phase6/map

The **Nontidal Monitoring Network Storymap** describes and explores water-quality monitoring results for nontidal streams in the Chesapeake Bay watershed: va.water.usgs.gov/storymap/NTN

The **Chesapeake Bay Program's Watershed Model Phase 6 Map Viewer** includes a variety of data to guide management, including nutrient inputs, healthy watersheds, and aquatic resources: gis.chesapeakebay.net/mpa/scenarioviewer

A **SPAtially Referenced Regression On Watershed** attributes (SPARROW) model can be used to explore estimated nutrient and sediment loads: sparrow.wim.usgs.gov/sparrow-northeast-2012

The **Chesapeake Bay Watershed Data Dashboard** provides accessibility and visualization of data and technical information that can help guide water quality and watershed planning efforts: gis.chesapeakebay.net/wip/dashboard

Nutrient and Sediment Responses in Nontidal Streams

Management Implications

1. Total nitrogen loads decreased in 41% of nontidal monitoring network stations in recent years and a similar percent show increasing conditions. Decreases occurred in some of the highest loading areas of the watershed, but drivers of such changes are unresolved.

2. Total phosphorus loads decreased in 44% of nontidal monitoring network stations in recent years and increased at 32% of stations. The direction of phosphorus trends differs from nitrogen trends in some stations, highlighting that nitrogen and phosphorus often require different management strategies.

3. Suspended sediment loads have only decreased at 20% of nontidal monitoring network stations in recent years. As sediment carries particulate nutrients and most nutrient loads are delivered during high flow conditions, these changes have important implications for nitrogen and phosphorus loads.

Background photo courtesy of Chesapeake Bay Program

Nutrient and Sediment Responses in Nontidal Streams

Priority Stakeholder Questions

How have nitrogen, phosphorus, and sediment loads changed throughout the watershed?

Do nitrogen and phosphorus loads and trends vary by flow or season?

Are nitrogen and phosphorus loads and trends driven by changes in dissolved or particulate material?

Clicking a “launch” button will jump to content for a specific priority question.

A “return” button is included throughout this theme that will return you to this slide.

How have nitrogen loads changed throughout the watershed?

From 2009 – 2018, total nitrogen (TN) loads decreased at 41%, increased at 40%, and had no trend at 19% of 90 NTN stations.[1]

TN loads decreased at most sites with the largest per area loads, including agricultural areas of the lower Susquehanna and Potomac River watersheds.

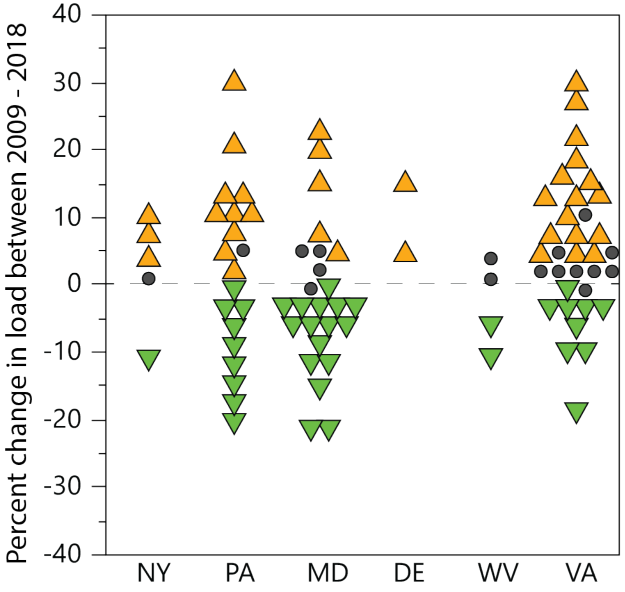
Most TN loads decreased on Maryland's Western Shore, but most loads on the Delmarva Peninsula increased.

TN loads in the upper Susquehanna and Virginia watersheds have a mixture of decreasing and increasing trends.

Since 1985, TN loads decreased at 56%, increased at 31%, and had no trend at 13% of 45 NTN stations.[1]

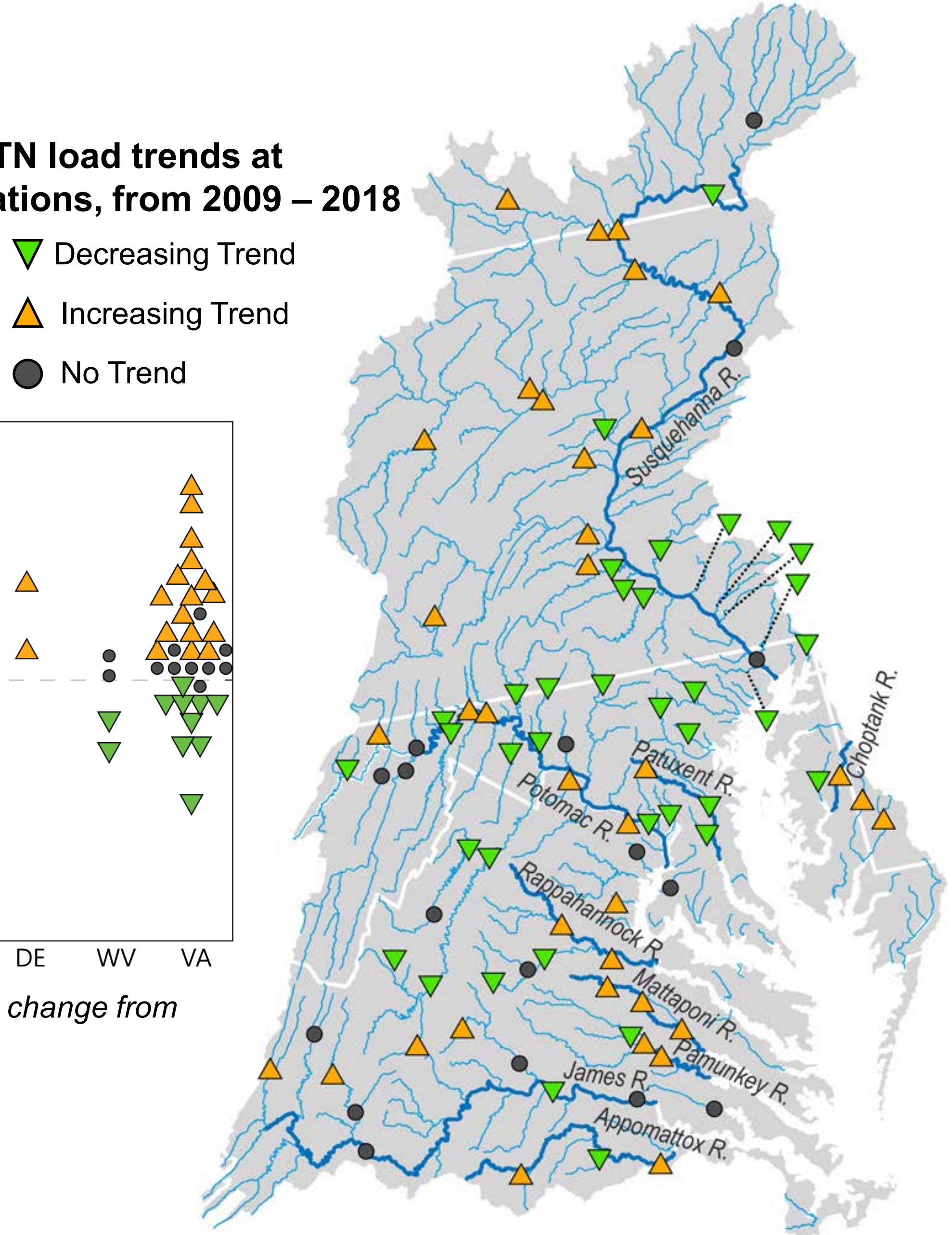
Learn more about the nontidal monitoring network (NTN) and explore load and trend results:

- va.water.usgs.gov/storymap/NTN
- cbrim.er.usgs.gov



Above: *TN load percent change from 2009 – 2018, by state.[1]*

TN load trends at NTN stations, from 2009 – 2018



Above: *Trends in TN load from 2009 – 2018 at 90 NTN stations.[1]*

How have phosphorus loads changed throughout the watershed?

From 2009 – 2018, total phosphorus (TP) loads decreased at 32%, increased at 44%, and had no trend at 24% of 66 NTN stations.[1]

Increasing TP trends were common in agricultural watersheds in the lower Susquehanna and on the Delmarva Peninsula.

TP loads on Maryland's Western Shore, in the upper Susquehanna, and in Virginia watersheds have a mixture of trends.

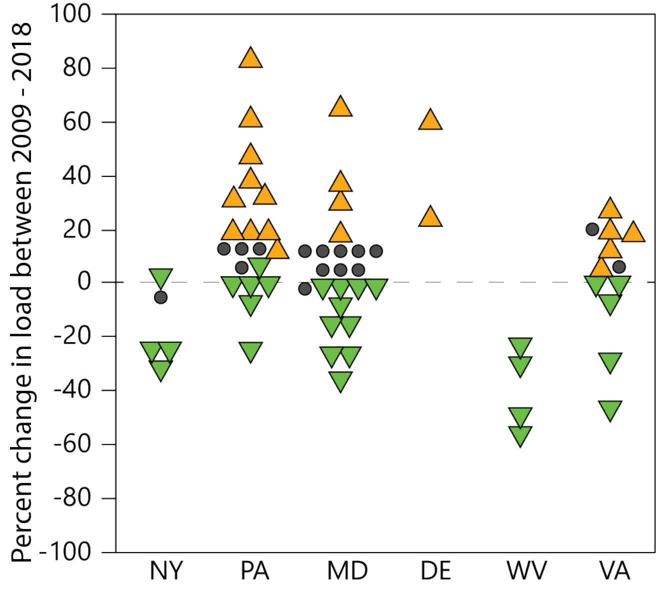
No TP loads in the Potomac watershed increased.

The direction of TP trends differs from TN trends in some stations, most notably in the Susquehanna River watershed, highlighting that nitrogen and phosphorus often require different management strategies.

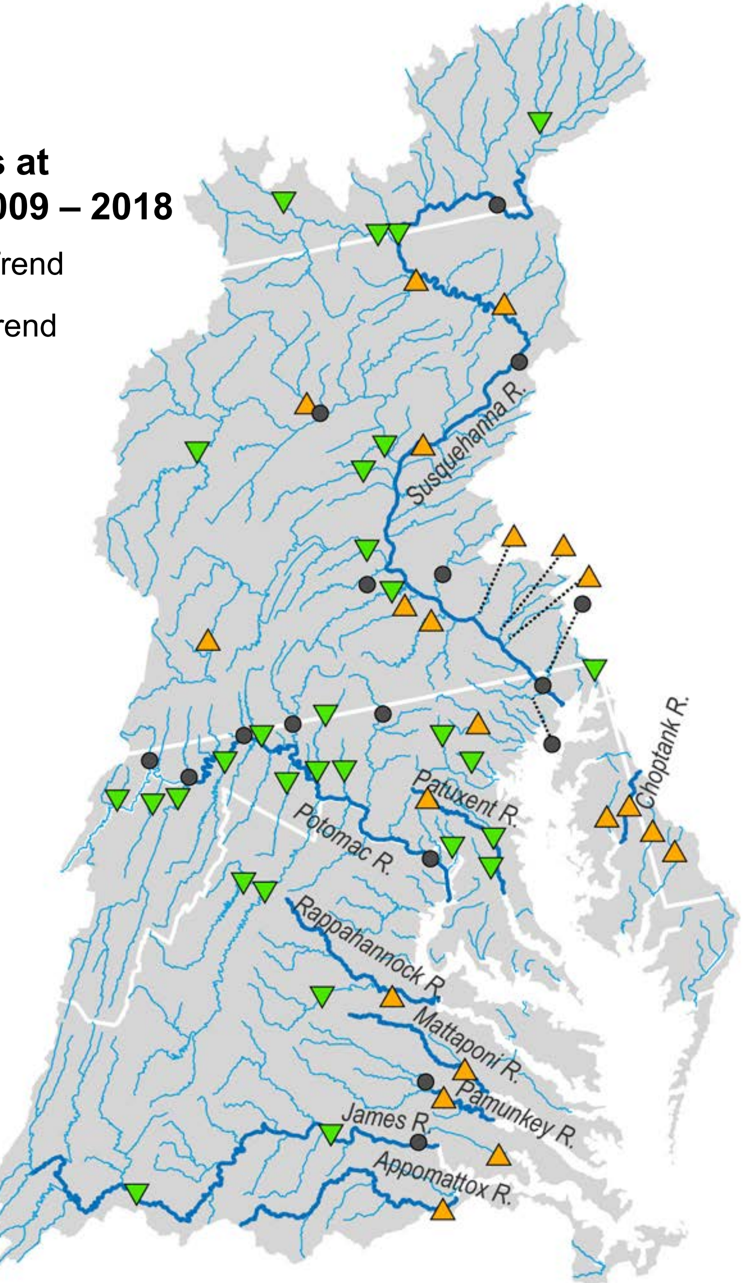
Since 1985, TP loads decreased at 61% and increased at 39% of 18 NTN stations.[1]

Learn more about the nontidal monitoring network (NTN) and explore load and trend results:

- va.water.usgs.gov/storymap/NTN
- cbrim.er.usgs.gov



***Above**: TP load percent change from 2009 – 2018, by state.[1]*



***Above**: Trends in TP load from 2009 – 2018 at 66 NTN stations.[1]*

USGS science for a changing world

Question continues on the next slide.

How have sediment loads changed throughout the watershed?

From 2009 – 2018, suspended sediment (SS) loads decreased at 20%, increased at 42%, and had no trend at 38% of 66 NTN stations.[1]

Increasing SS trends were common on the Delmarva Peninsula and throughout the Susquehanna River watershed.

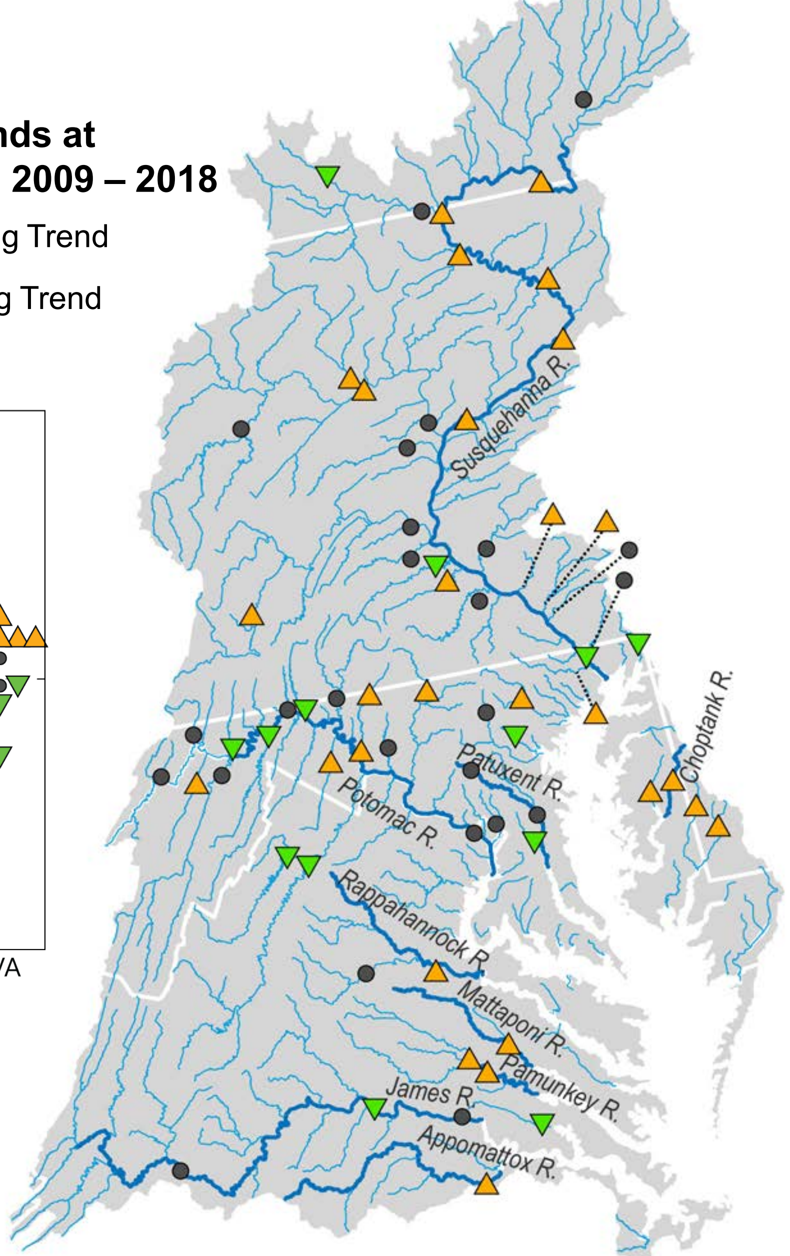
SS loads in Virginia watersheds have a mixture of increasing and decreasing trends.

SS loads in the Potomac watershed have a mixture of decreasing and increasing trends, unlike total phosphorus loads which mostly decreased.

Since 1985, SS loads decreased at 39%, increased at 28%, and had no trend at 33% of 18 NTN stations.[1]

***Above**: SS load percent change from 2009 – 2018, by state.[1]*

SS load trends at NTN stations, from 2009 – 2018



***Above**: Trends in SS load from 2009 – 2018 at 66 NTN stations.[1]*

Learn more about the nontidal monitoring network (NTN) and explore load and trend results:

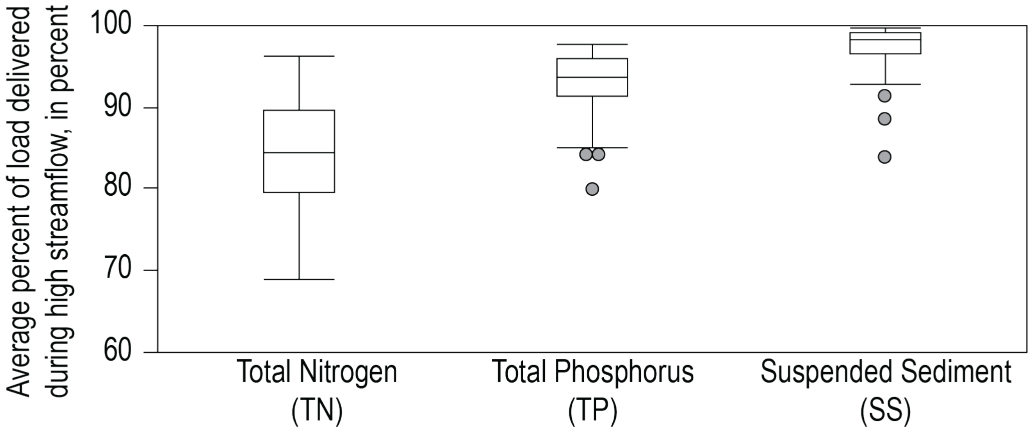
- va.water.usgs.gov/storymap/NTN
- cbrim.er.usgs.gov

Do nitrogen and phosphorus loads and trends vary by streamflow?

Most nitrogen, phosphorus, and sediment loads are delivered to streams and rivers during high streamflow conditions.

In most NTN stations, more than 90% of annual TP and SS loads and about 85% of annual TN loads are contributed during high streamflow conditions, defined as above average daily streamflow.[6]

High streamflow conditions typically represent a lower percent of TN loads in NTN stations where groundwater nitrogen concentrations and per-area TN loads are high.[6]

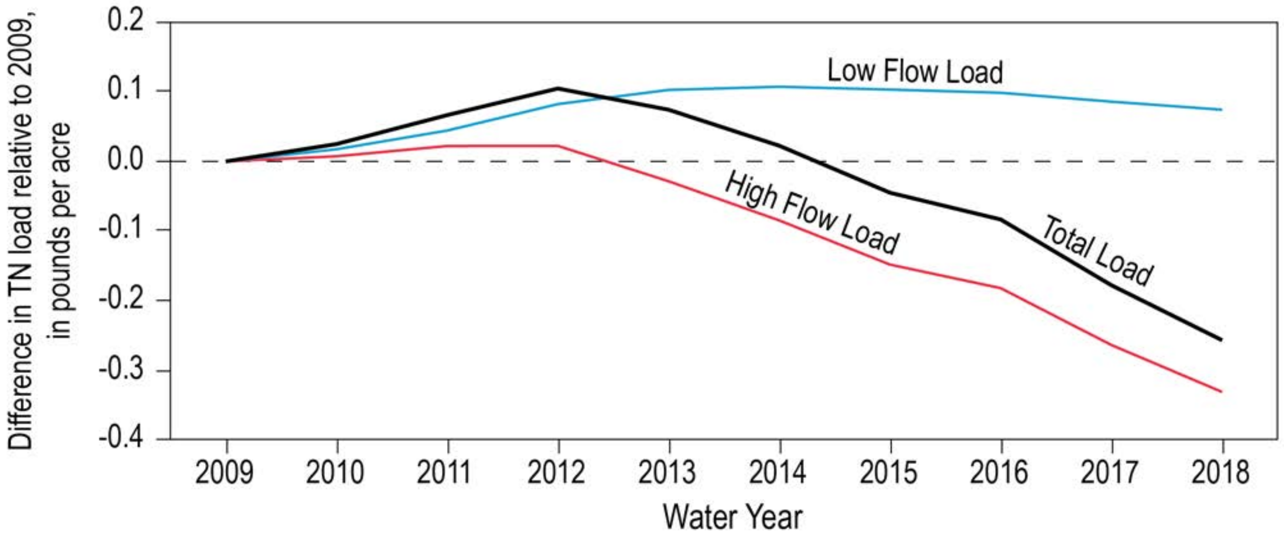


***Above**: Average annual percent TN, TP, and SS loads contributed during high streamflow conditions at NTN stations.*[6]

Trends in nitrogen, phosphorus, and sediment load are influenced by changes during all streamflow conditions, but often reflect changes in load during high streamflow.[6]

Management practices that control nutrient and sediment sources and delivery to streams during high streamflow conditions may effectively reduce loads in some watershed settings.

Nutrient load reductions associated with declining point sources have been observed during low streamflow conditions but can be offset by load increases during high streamflow.[7,8]



***Above**: The flow normalized load of TN improved at the NF Shenandoah River near Strasburg, VA (USGS station ID 01634000) by about 0.26 pounds per acre. Load reductions during high streamflow conditions were greater than load increases during low streamflow conditions.*[6]

Data on this slide represent data from water years 2009 – 2018.

Question continues on the next slide.

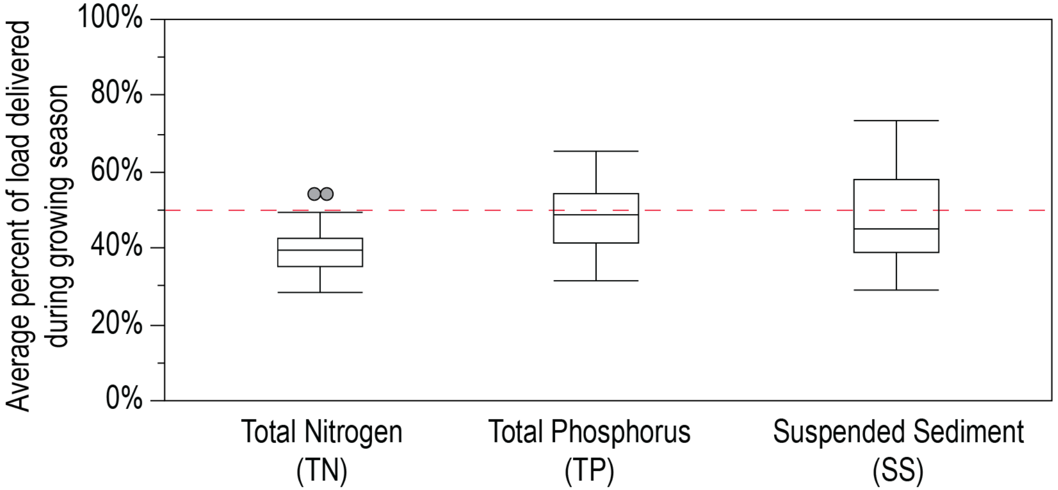
Do nitrogen and phosphorus loads and trends vary by season?

Across the NTN, most annual nitrogen load is contributed during the non-growing season; seasonal phosphorus and sediment load differences are less pronounced.[6]

NTN stations typically contribute more TN load during the non-growing (Oct 1 – Mar 31) than the growing (Apr 1 – Sep 30) season.[6]

Seasonal TN patterns reflect the influences of higher streamflow, groundwater recharge, and nitrogen concentrations (likely because of less biotic uptake and denitrification) in the non-growing season.

Seasonal TP patterns vary. Warmer growing season temperatures promote enhanced biological release of dissolved phosphorus.[9] Elevated non-growing season streamflow mobilizes more particulate phosphorus.[10]



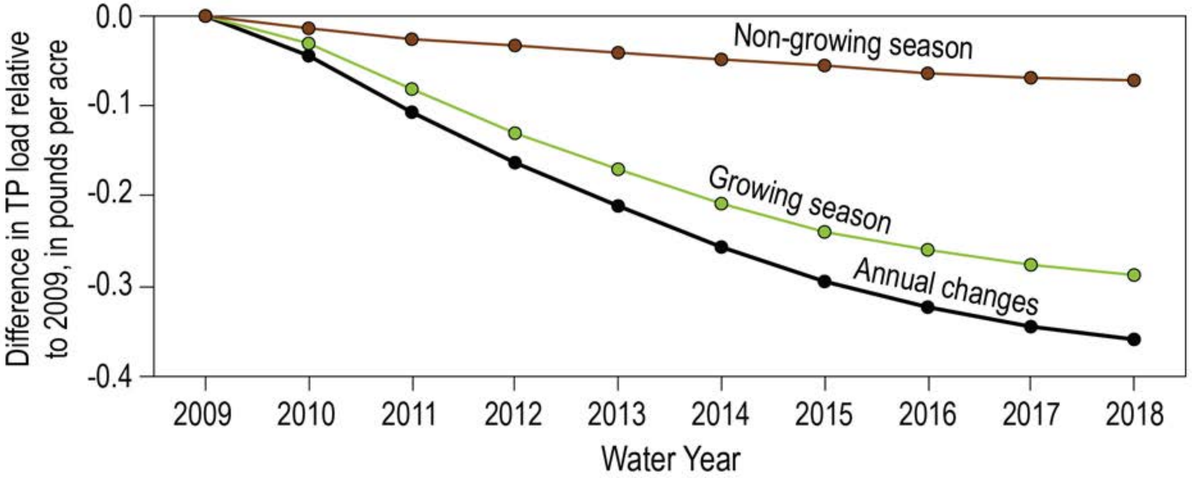
***Above**: The percent average annual TN, TP, and SS loads contributed during the growing season (Apr 1 – Sep 30) at NTN stations.[6]*

Changes in nitrogen and phosphorus loads can vary seasonally.

In most NTN stations, more TN load change occurred during the non-growing season than the growing season,[6] consistent with the time of year when TN loads are often highest.

Phosphorus changes in Chesapeake Bay watersheds can be large during the growing season.[8] Decreasing loads during the growing season accounted for most of TP load change in 23 of 29 NTN stations with improving trends.[6]

Data on this slide represent data from water years 2009 – 2018.



***Above**: The flow normalized load of TP improved at the NF Shenandoah River near Strasburg, VA (USGS station ID 01634000) by about 0.36 pounds per acre. Load reductions during the growing season were larger than the non-growing season.[6]*

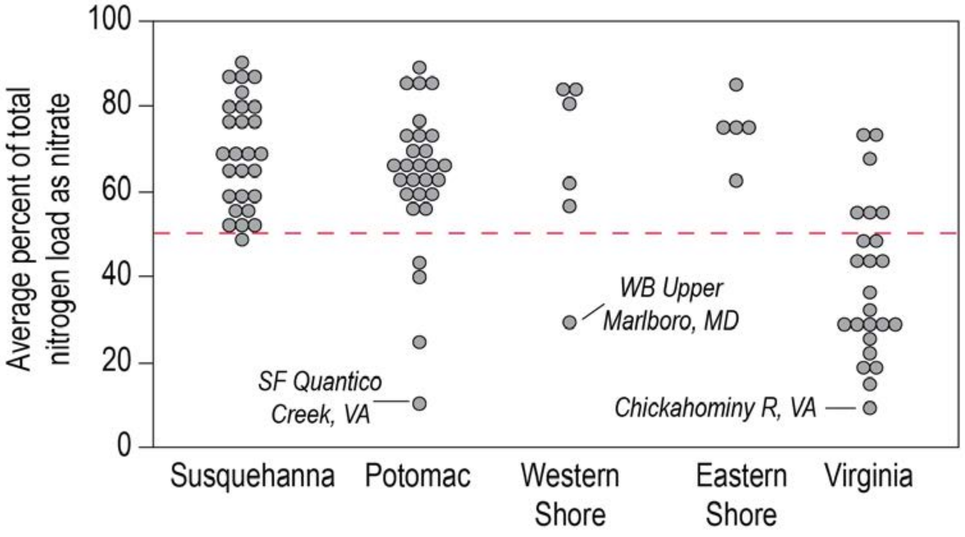
Are nitrogen loads and trends driven by changes in dissolved or particulate material?

Most TN load measured in NTN streams is in the dissolved form as nitrate.[1]

Nitrate is primarily delivered to Chesapeake Bay streams through groundwater flow paths.[11] Delivery of bioavailable nutrients, such as nitrate, to streams and rivers poses significant challenges to achieving water-quality standards in the Bay.[12]

The ratio of nitrate to TN varies across major river basins, with most TN as nitrate in watersheds where per-area TN loads are highest.[1]

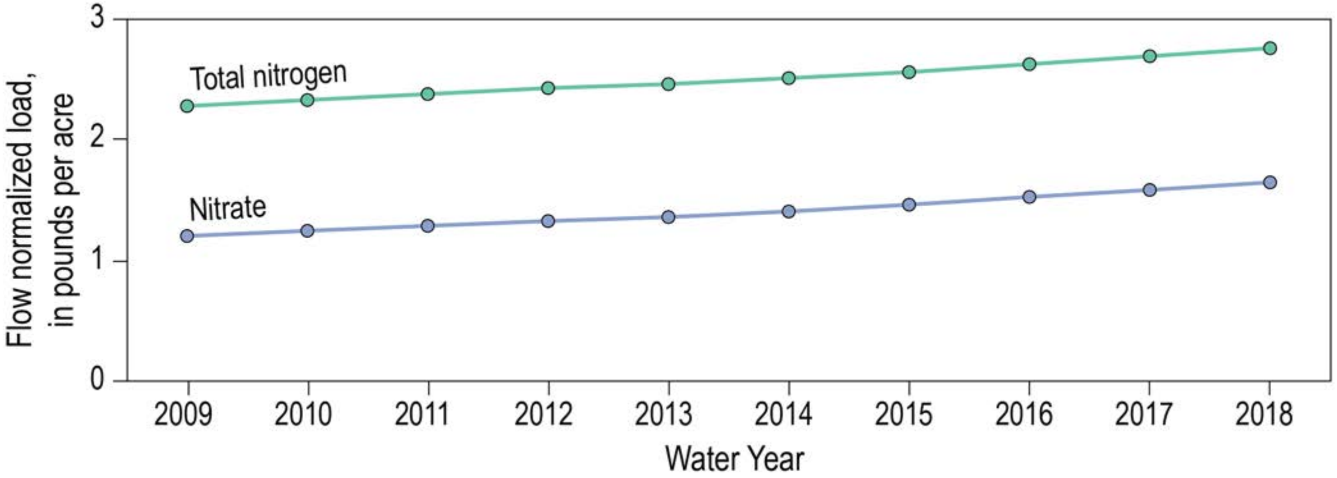
- The nitrate : TN ratio is lower in most Virginia watersheds than elsewhere in the watershed.[1]
- On the Eastern Shore, groundwater contributions of nitrate result in high TN loads.[13]



***Above**: The 2009 – 2018 average percent of TN load as nitrate in NTN stations, by major river basin.[1]*

Nitrate loads decreased at 38%, increased at 40%, and had no trend at 22% of 90 NTN stations from 2009 – 2018.[1]

Changes in nitrate load affect TN trends. TN and nitrate loads both decreased or both increased at about 75% of NTN streams from 2009 – 2018.[1]



***Above**: Flow normalized loads of TN and nitrate at Pine Creek near Waterville, PA (USGS station ID 01549700) from 2009 – 2018. Nitrate represents about 60% of the annual TN load and both measures of nitrogen increased over the ten-year period.[1]*

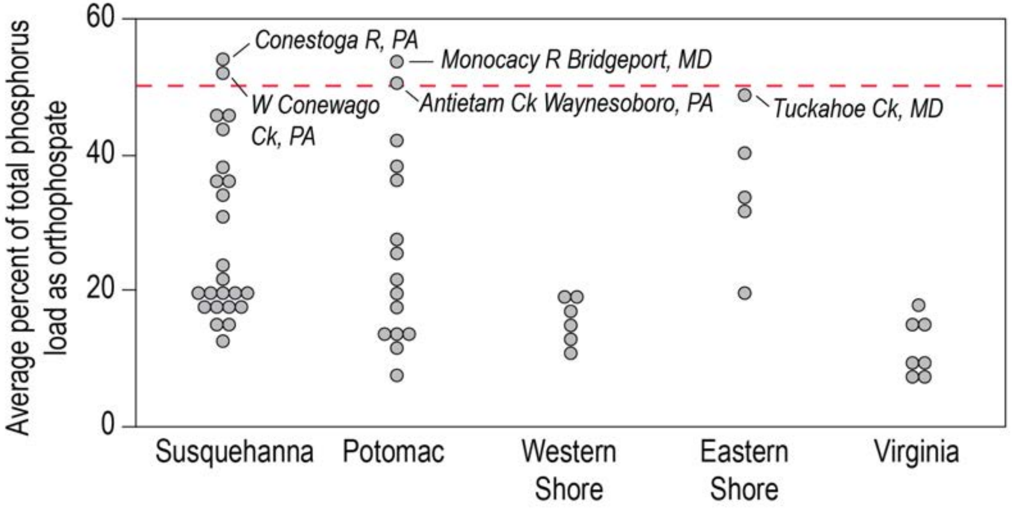
Question continues on the next slide.

Are phosphorus loads and trends driven by changes in dissolved or particulate material?

Phosphorus is primarily delivered to Chesapeake Bay streams as particulate material attached to sediment.[12]

Orthophosphate, the most bioavailable form of phosphorus in streams, typically represents less than 50% of TP loads.[1]

The ratio of orthophosphate to TP is typically highest in agricultural watersheds.[8] These soils may have reached or are reaching phosphorus saturation from years of excessive phosphorus inputs, a condition that increases dissolved phosphorus export to streams[14] and can take decades to reverse.[15]

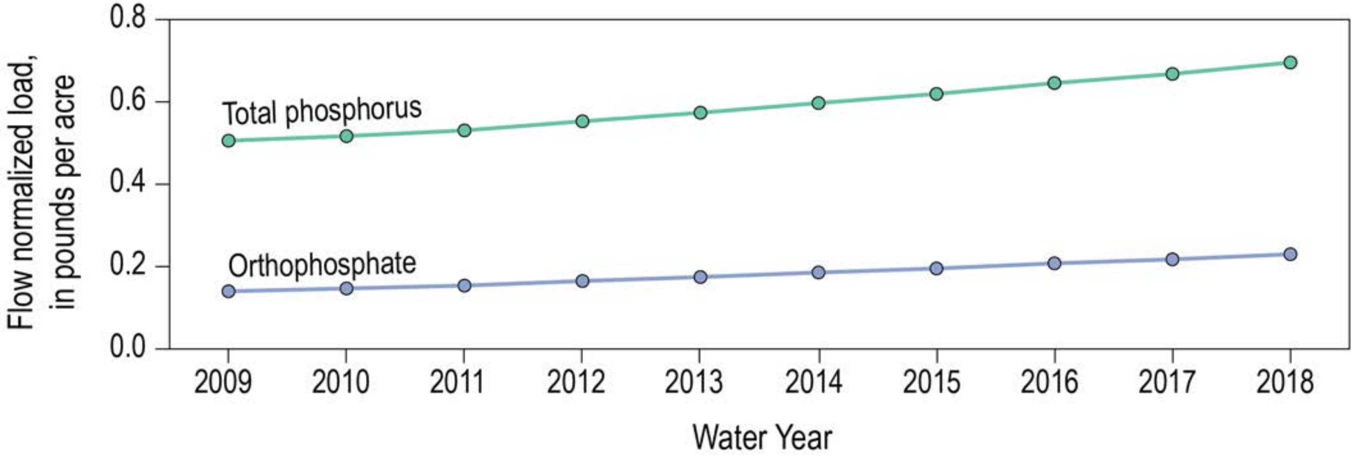


***Above**: The 2009 – 2018 average percent of TP load as orthophosphate by basin in NTN streams.[1]*

Orthophosphate loads decreased at 56%, increased at 33%, and had no trend at 11% of 57 NTN stations from 2009 – 2018.[1]

Changes in orthophosphate load affect TP trends. TP and orthophosphate loads both decreased or both increased at about 75% of NTN streams from 2009 – 2018.[1]

The proportion of phosphorus load as orthophosphate is increasing in some areas of the watershed,[1] with the largest increases typically occurring in agricultural watersheds.[8]



***Above**: Flow normalized loads of TP and orthophosphate at Choptank River near Greensboro, MD (USGS station ID 01491000) from 2009 – 2018. Orthophosphate represents about 32% of the annual TP load and both measures of phosphorus degraded over the ten-year period.[1]*

Question continues on the next slide.

Are nitrogen and phosphorus loads and trends driven by changes in dissolved or particulate material?

Sediments are important vectors for nitrogen, phosphorus, and other pollutants in Chesapeake Bay streams.[4]

73% of the TP loads and **18%** of TN loads delivered to the Bay are typically attached to sediment.[16]

Sediment-bound phosphorus entering streams and rivers can contribute to dissolved phosphorus loads, as changes in chemical and biological conditions can detach phosphorus from sediment and increase orthophosphate.[4]

Similarities in SS and nutrient trends highlight the importance of understanding the drivers of particulate material to manage TN and TP loads in Chesapeake Bay streams.

From 2009 – 2018 in the NTN…

62% of stations (8/13) with a decreasing SS trend also had a decreasing TN trend.[1]

54% of stations (15/28) with an increasing SS trend also had an increasing TN trend.[1]

77% of stations (10/13) with a decreasing SS trend also had a decreasing TP trend.[1]

61% of stations (17/28) with an increasing SS trend also had an increasing TP trend.[1]

Above: *Elevated streamflow through a watershed after a storm event, where the visible turbidity is mostly caused by suspended sediment. Sediment carries attached nitrogen and phosphorus and can deliver a large amount of nutrients to streams and the Bay during stormflow conditions (Photo courtesy of Chesapeake Bay Program).*

Drivers of Nutrient Responses in Nontidal Streams

Management Implications

1. There are numerous factors affecting nutrient responses in the watershed that have complex interactive effects. In general, these include changes in nutrient sources and processes affecting the delivery of nutrients from the landscape to streams.

2. Point source reductions are responsible for substantial water-quality improvements and, for nitrogen, reductions in atmospheric deposition have been linked to nitrogen improvements.

3. Agricultural inputs of manure and fertilizer contribute the most nitrogen and a large fraction of phosphorus to the Bay, but despite some varying local changes, total agricultural inputs to the watershed have remained unchanged in recent years, as manure increases have offset fertilizer reductions.

4. Water-quality improvements have occurred in response to management practices in some agricultural and urban watersheds, but anticipated nutrient and sediment reductions do not consistently align with monitored observations.

Background photo courtesy of Chesapeake Bay Program

Drivers of Nutrient Responses in Nontidal Streams

Priority Stakeholder Questions

What are the major nutrient sources in the Bay watershed?

How have nutrient sources changed over time?

Have nutrient responses been influenced by changes in sources?

Are we seeing evidence of water-quality responses to management practices?

Clicking a "launch" button will jump to content for a specific priority question.

A "return" button is included throughout this theme that will return you to this slide.

Background photo courtesy of Chesapeake Bay Program

What are the major nutrient sources in the Bay watershed?

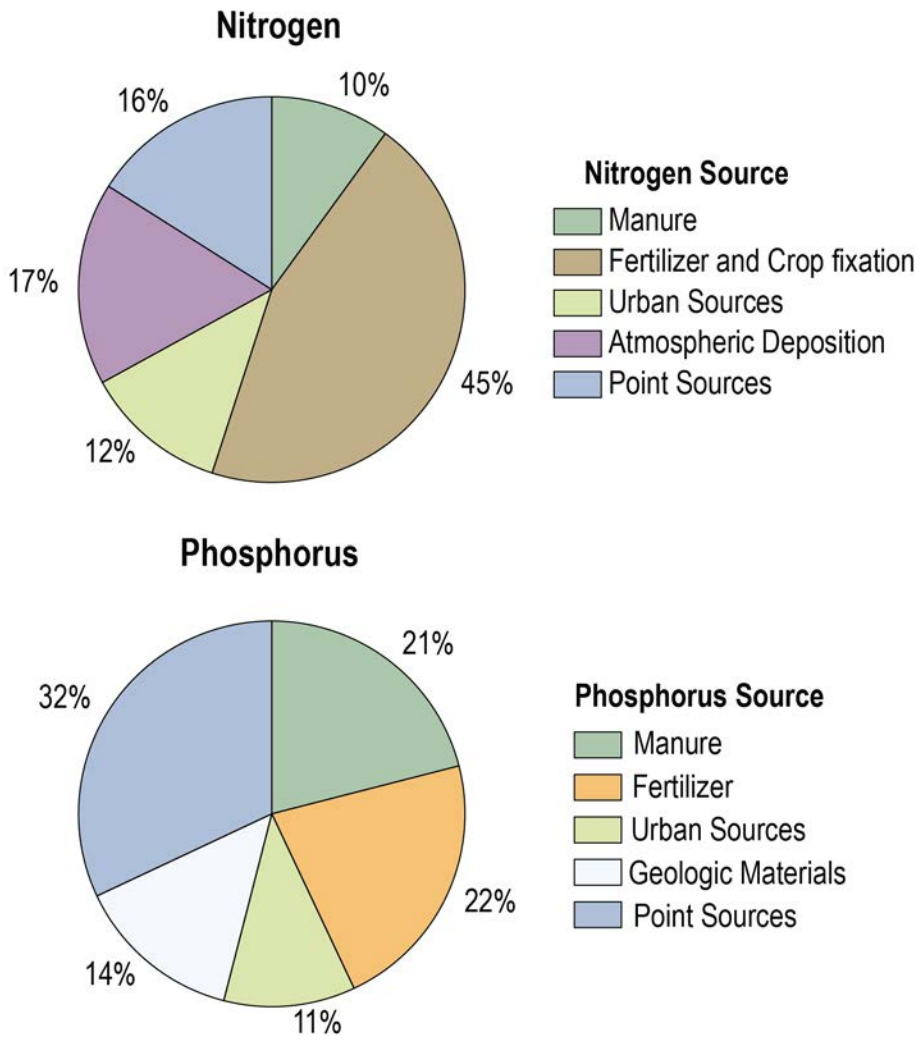
Agricultural inputs of fertilizer and manure contribute about half of the nitrogen and phosphorus reaching the Bay, with remaining loads primarily attributable to point sources, various urban inputs, atmospheric deposition (for nitrogen) and geologic materials (for phosphorus).[5]

Major nonpoint nutrient sources include:

Agricultural inputs of manure and fertilizer are the largest sources of nutrients to the watershed.[5] Manure inputs are largest in areas with large livestock and poultry populations and fertilizer inputs tend to be largest in areas with intensive row crop agriculture.[17,18]

Urban inputs include a variety of diffuse sources, such as roadway runoff, septic systems, leaking sewer lines, pet waste, lawn fertilizer, and local nitrogen deposition sources.[5]

Atmospheric deposition of nitrogen primarily originates from power plants, transportation, and industrial sources and is a significant nitrogen source in forested watersheds.[5]



***Above**: Percent of nitrogen and phosphorus load delivered to the Bay from various sources in 2002.*[17]

How have nutrient sources changed over time?

Point and nonpoint nutrient inputs have declined in the watershed, with the largest nonpoint nitrogen reductions driven by atmospheric inputs and the largest nonpoint phosphorus reductions driven by agricultural fertilizer usage.[19]

Point source inputs of nitrogen and phosphorus have declined, largely because of upgrades to wastewater treatment plants.[3]

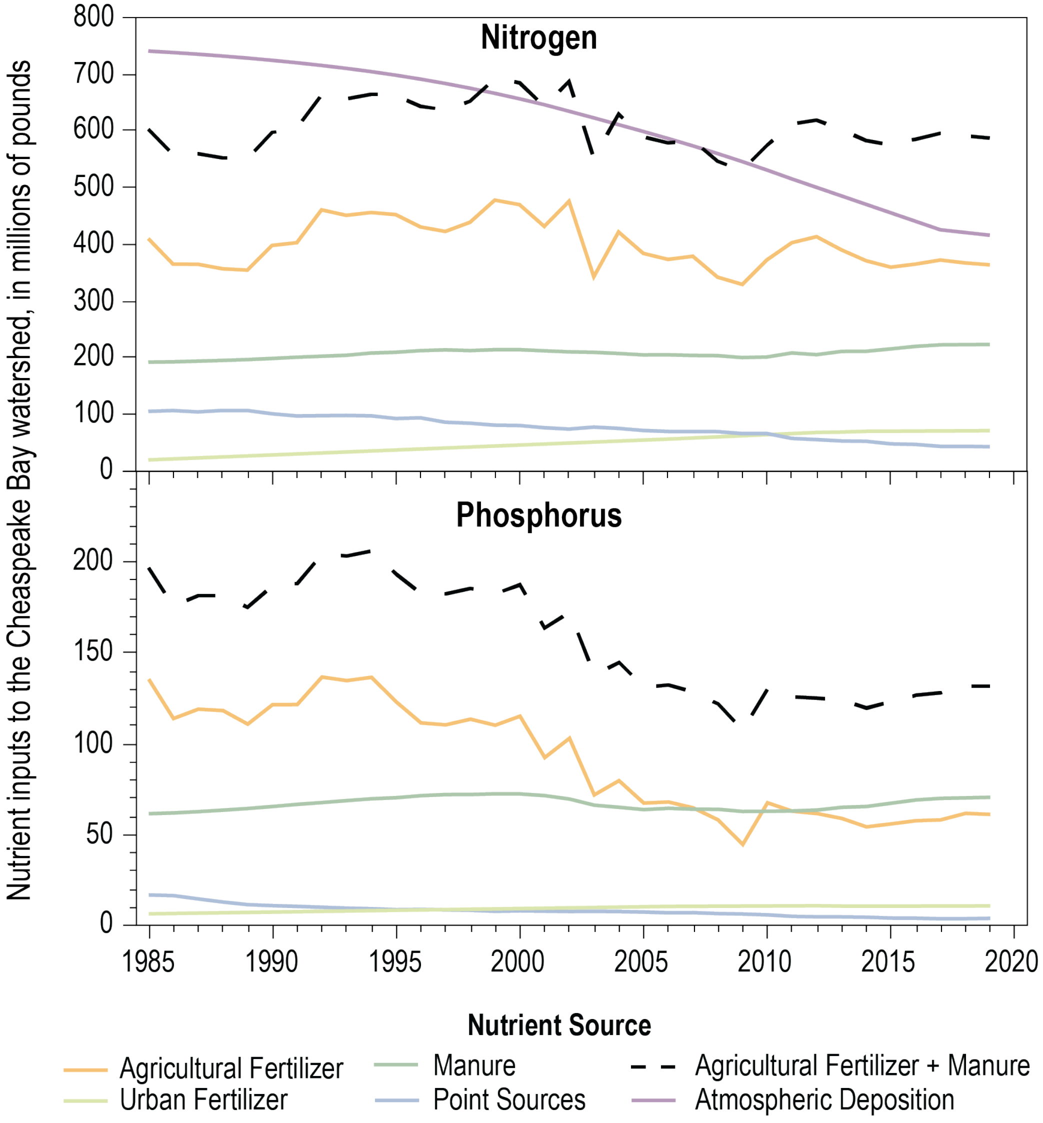
Atmospheric nitrogen deposition declined throughout the Bay watershed over the past 40 years,[19] with the largest reductions occurring after the 1990s as a result of Clean Air Act amendments.[20]

Agricultural fertilizer inputs of have declined since 1985 and in recent years, with reductions in phosphorus fertilizer use being larger and more consistent than that that of nitrogen.[19]

Manure inputs of nitrogen and phosphorus have increased since 1985, with most changes occurring in the past ten years, reflecting increased livestock and poultry populations in the Bay watershed.[19]

Total agricultural inputs (manure + agricultural fertilizer) of nitrogen and phosphorus have been relatively unchanged in recent years, with manure increases generally offsetting fertilizer reductions.[19]

Urban inputs, including urban fertilizer, have increased, as urban land increased by about 50% since 1985.[19]



***Above**: Sum of nitrogen and phosphorus inputs for 197 Chesapeake Bay counties from 1985 – 2019.[19]*

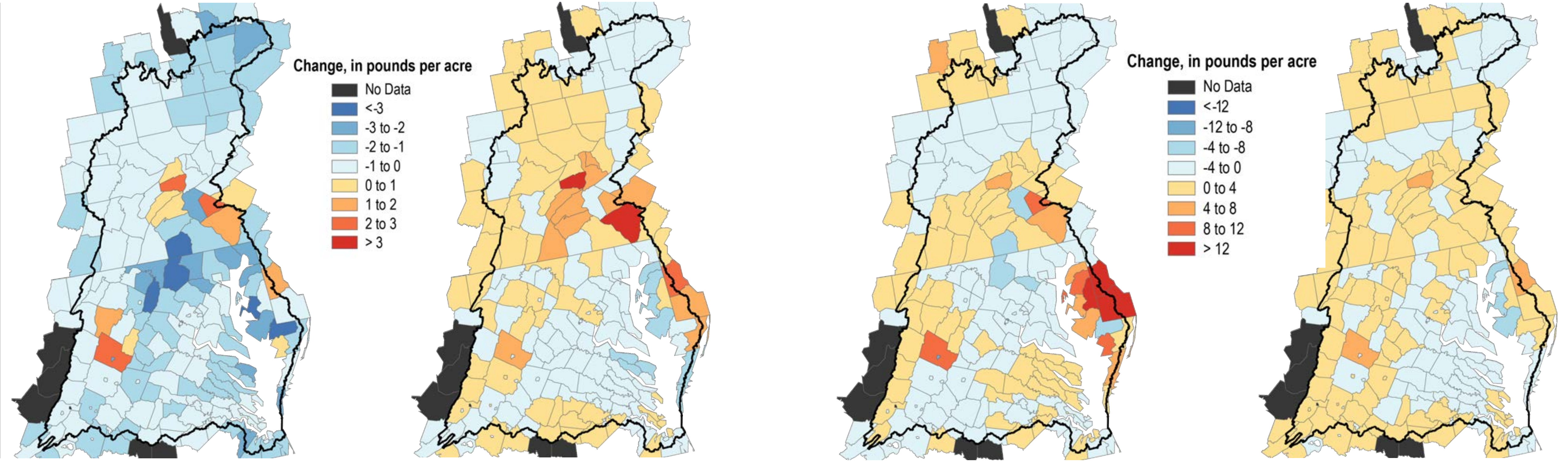
How have nutrient sources changed over time?

Nutrient inputs from agricultural fertilizer and manure have increased in some of the most intensive agricultural regions since 1985 and in recent years, despite a decrease in agricultural land area.[19]

Agricultural inputs of **phosphorus** have declined in most areas since 1985, largely because of fertilizer reductions. These improvements have been reversed in some areas since 2009, typically because of increased poultry manure inputs, reflecting increased animal populations and intensification of cropping practices.[19]

Agricultural inputs of **nitrogen** have increased in some of the most intensive agricultural regions since 1985 and over recent years. Like phosphorus, these increases are typically driven by increased poultry manure inputs.[19]

Phosphorus, long-term change | **Phosphorus, short-term change** | **Nitrogen, long-term change** | **Nitrogen, short-term change**



Above: *Changes in agricultural nutrient inputs in Chesapeake Bay counties from ‘85 – ‘87 to ‘17 – ‘19 (long term) and ‘09 – ‘11 to ‘17 – ‘19 (short term).*[19]

Question continues on the next slide.

How have nutrient sources changed over time?

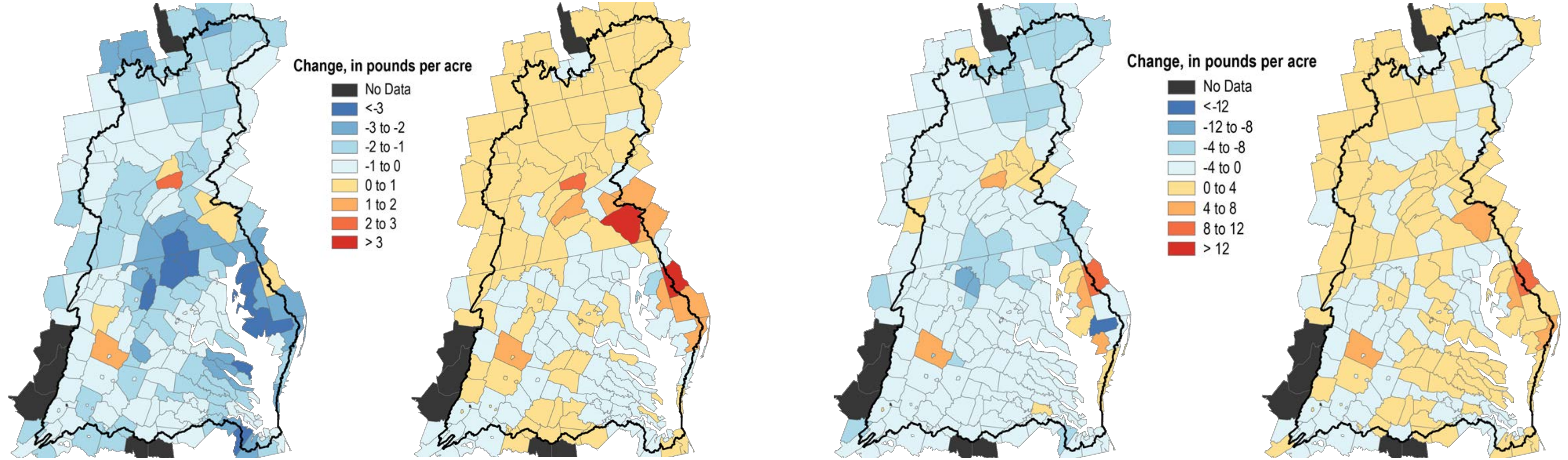
Nutrient inputs to agricultural land exceed crop removal rates in nearly all areas of the Bay watershed. In most areas, this surplus amount of nitrogen and phosphorus is lower in recent years compared to 1985 but has increased over the past 10 years.[19]

Agricultural surplus = Nutrient inputs to agricultural land – nutrients removed by crops

Over the long term, reduced fertilizer and atmospheric deposition (nitrogen only) inputs along with increased crop uptake have lowered nitrogen and phosphorus surplus inputs in most agricultural areas.[19]

In recent years, agricultural surplus inputs have increased in many areas because of increased manure inputs and changing crop demand.[19]

Phosphorus, long-term change **Phosphorus, short-term change** **Nitrogen, long-term change** **Nitrogen, short-term change**



***Above:** Changes in agricultural surplus nutrient inputs in Chesapeake Bay counties from '85 – '87 to '17 – '19 (long term) and '09 – '11 to '17 – '19 (short term).[19]*

Have nutrient responses been influenced by changes in sources?

While nutrient reductions have been attributed to wastewater improvements throughout the Bay watershed,[3] changes in nonpoint source inputs have also been associated with water-quality responses.

Reductions to nutrients in streams and in groundwater have been observed in response to reduced **fertilizer and manure agricultural inputs**.[21,9]

Sanitary sewer overflows have been associated with increased nitrogen loads in urban watersheds.[22]

Declines in **atmospheric deposition** have been linked to reductions in streams draining forested and mixed land uses[23,24] and explain about 13-14% of declines since the early 1990s in overall flow-normalized nitrogen load from the watershed to the Bay.[25,26]

Water-quality responses to nonpoint source changes are affected by storage of nitrogen and phosphorus in the landscape, though such legacy effects are uncertain and vary throughout the Bay watershed.[5]

Legacy nitrogen effects can delay expected water-quality improvements and be locally significant[27] but may have a smaller influence on load trends throughout the watershed over a multidecadal time scale.[26]

Soil phosphorus concentrations are high in many agricultural watersheds, may remain high for decades after applications are reduced, and can result in increased loading in streams.[14,15]

Continued research is needed to better understand the role of changing nonpoint sources and legacy nutrients. While nitrogen load reductions have been observed in some agricultural watersheds with high nonpoint source inputs and loads, the drivers of these changes are unresolved.[5]

***Above**: Streams in some forested watersheds have experienced nitrogen declines because of reduced atmospheric nitrogen deposition.*[23,24] *(Photo courtesy of Chesapeake Bay Program)*

Question continues on the next slide.

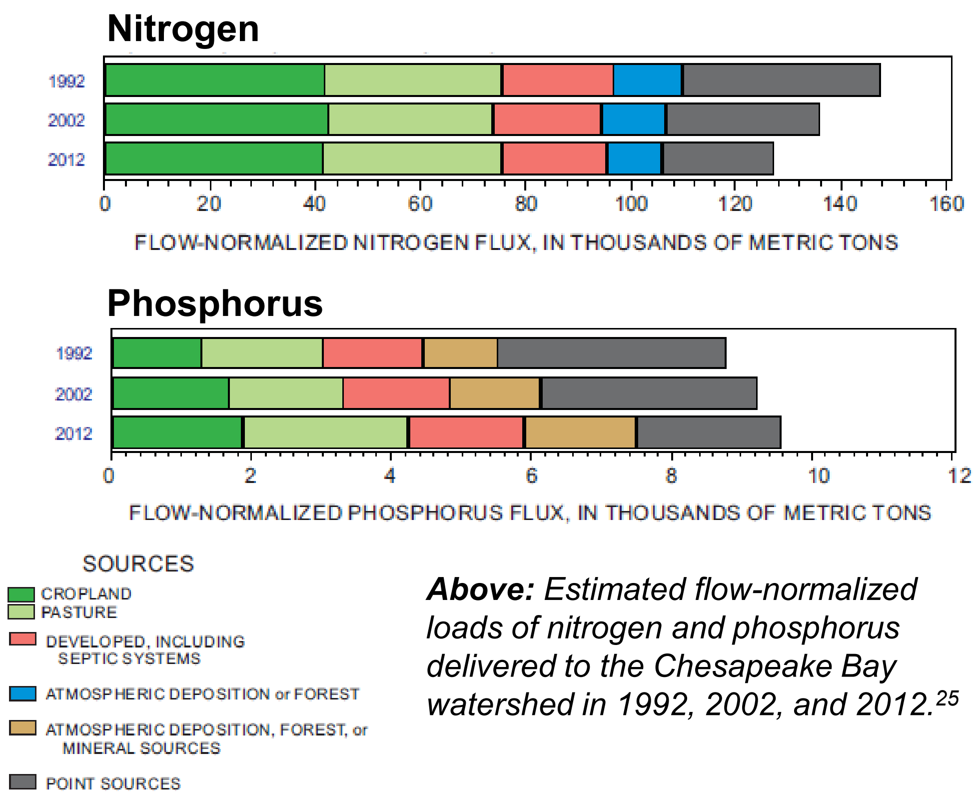
Have nutrient responses been influenced by changes in sources?

Although changes in nitrogen and phosphorus loads vary in agricultural and urban streams across the watershed, watershed-wide average patterns can inform management.

On average across the watershed from the early 1990s to 2010s…

…nonpoint agricultural sources did not contribute to large changes in nitrogen or phosphorus loads delivered to streams or the Bay.[25]

…nitrogen loads delivered to the Bay from urban areas declined while urban phosphorus loads were relatively unchanged.[25]



***Above:** Estimated flow-normalized loads of nitrogen and phosphorus delivered to the Chesapeake Bay watershed in 1992, 2002, and 2012.*[25]

The estimated nitrogen load delivered to the Bay declined between the early 1990s and 2010s while phosphorus loads increased.[25]

The estimated nitrogen load delivered to the Bay declined during this period, primarily because of reductions in point source loads (representing at least 50% of the decline) and atmospheric deposition (representing about 13-14% of the decline).[25]

Although point source phosphorus loads from wastewater declined and nonpoint phosphorus inputs were relatively unchanged, the load of phosphorus delivered to the Bay increased during this period because of changes in phosphorus load retention in the Susquehanna River at Conowingo Reservoir.[25]

Continued research is needed to understand the effects of changing nutrient inputs, land use, climate change, and other influences on water-quality response.[5] The importance of these factors likely varies between regional and local scales. For example, nitrogen load reductions have been observed in some agricultural watersheds and though some of these changes may be related to management of manure and fertilizer inputs, such estimated effects are relatively small across the entire Bay watershed.

Are we seeing evidence of water-quality responses to management practices?

Management practices have achieved positive water-quality outcomes in a variety of source sectors and watershed settings.

Water-quality improvements in response to management practices have been documented in **agricultural watershed settings**.[28,29]

Cover crops decreased nitrate losses to shallow groundwater in an agricultural watershed on Maryland's Eastern Shore.[14]

Riparian forest buffers have achieved positive water-quality outcomes in agricultural watersheds, commonly through the control of sediment in runoff.[30]

Combined effects of **tillage management, filter strips, and nutrient management** resulted in reductions in particulate nitrogen and phosphorus in an agricultural watershed on Maryland's Eastern Shore.[31]

Water-quality improvements in response to management practices have been documented in **urban watershed settings**.[32]

Infiltration-based stormwater practices reduced storm sediment export in a suburban watershed in Montgomery County, MD.[33]

Stream restoration reduced baseflow and stormflow nitrogen conditions in some streams in Anne Arundel County, MD.[34]

Stormwater detention basins designed to provide a water-quality improvement had greater soil phosphorus removal and retention rates than basins designed for flood control in Fairfax County, VA.[35]

***Above**: Cover crops and tillage management practices on an agricultural field. (Photo courtesy of Chesapeake Bay Program)*

***Above**: An infiltration-based stormwater practice designed to intercept impervious surface runoff. (Photo courtesy of Chesapeake Bay Program)*

Question continues on the next slide.

Are we seeing evidence of water-quality responses to management practices?

Anticipated nutrient and sediment reductions from management practices do not consistently align with observed responses,[5] are often not found in field monitoring studies,[36] and are particularly difficult to quantify at watershed scales[37] for the following reasons:

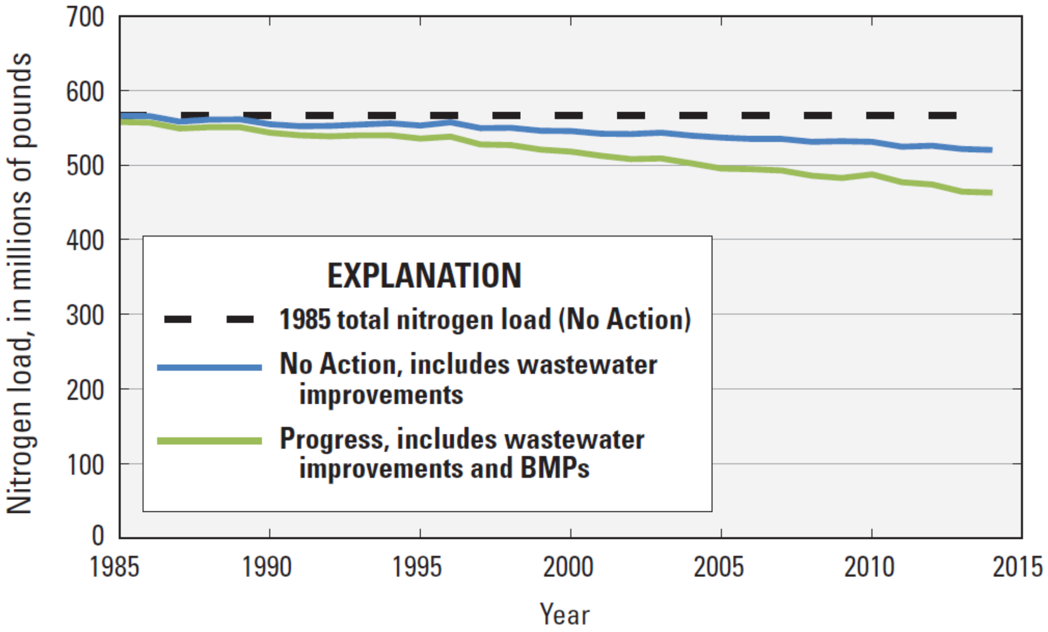
Unrealistic expectations: Expectations about management practice performance are often extrapolated from limited field studies and may not generalize well across diverse landscape settings.

Travel time: nitrogen and phosphorus may be delivered to water bodies relatively quickly through surface pathways or over many years through groundwater flow paths, which may influence when management practice effects may be recognized.

Insufficient monitoring: long-term monitoring of small watersheds and/or shallow groundwater networks may provide the better evidence of water-quality responses and management practice effects than most surface water studies.

Competing factors: management practice effects may be quickly overwhelmed by offsetting increases in nutrient sources, changes in climatic patterns, or other adverse water-quality conditions.

Continued research is needed to better understand the role of agricultural and urban/suburban management practices on observed water-quality responses.



***Above:** Estimated total nitrogen load delivered to Chesapeake Bay streams from 1985 – 2014 for Chesapeake Bay Program watershed model scenarios with management practices (green line), with only wastewater improvements (blue line), and with no management practices (black dotted line).[38] While management practices are expected to reduce total nitrogen loads, these changes are not consistently observed in monitored water-quality data.*

Practices to Reduce Nutrients and Sediment: Placement, Changes, and Implications for Targeting

Management Implications

1. Targeting management practices to areas with high nutrient and sediment loads can improve their effectiveness and reduce costs.

2. The most effective management practices are those that target dominant sources, are located in critical source areas, and are customized to local transport pathways.

3. In general, management practices that reduce nutrient sources are more effective than those that attempt to control their transport.

4. There are tools and resources available to explore local conditions and identify management practices that would likely be most effective in your watershed or area of interest.

Practices to Reduce Nutrients and Sediment: Placement, Changes, and Implications for Targeting

Priority Stakeholder Questions

Clicking a "launch" button will jump to content for a specific priority question.

What are the most commonly used types of management practices?

How has management practice implementation changed over time?

Are most management practices being implemented in the highest loading areas of the watershed?

What characteristics affect the benefits of management practices?

A "return" button is included throughout this theme that will return you to this slide.

What are the most commonly used types of agricultural management practices?*

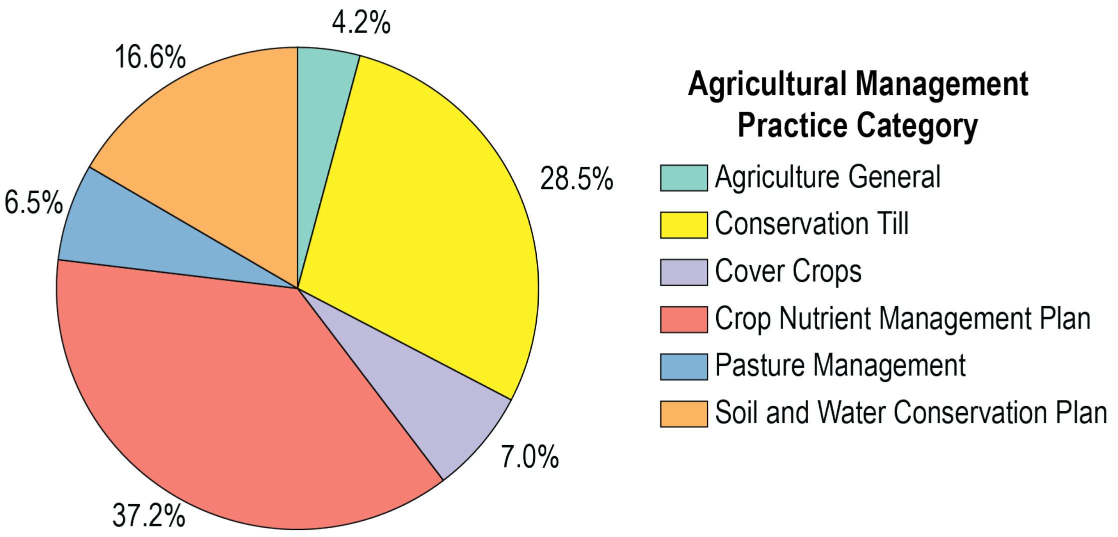
Crop nutrient management plans, conservation tillage practices, and soil and water conservation plans represented about 80% of the total reported agricultural management practice acres in the Bay watershed.[19]

These practices represent most reported agricultural management practice acres in each state.

Crop nutrient management plans implement a site-specific combination of nutrient source, rate, timing, and placement into a strategy that seeks to optimize nitrogen and phosphorus use.

Conservation tillage involves the planting, growing, and harvesting of crops with minimal soil disturbance, thereby reducing soil erosion and the loss of associated nutrients.

Soil and water conservation plans utilize practices that control soil erosion and manage runoff.



***Above:** The percent of reported agricultural management practices acres in the Chesapeake Bay watershed represented by management practices categories.*[19]

Most agricultural management practices targeted toward directly addressing animal waste in the Bay watershed are animal waste management systems.[19]

Animal waste management systems are any structures designed for collection, transfer, and storage of manures and associated wastes from confined portions of animal operations.

Explore management practice patterns by source sector or geography: cast.chesapeakebay.net/TrendsOverTime/BMPs

***Data on this slide represent average values from years 2010 – 2019.**

Question continues on the next slide.

What are the most commonly used types of urban/suburban management practices?*

Urban nutrient management plans and stormwater retrofits classified as runoff reduction or stormwater treatment practices represented about 96% of the total reported urban/suburban management practice acres in the Bay watershed.[19]

The distribution of these practices varies by state.

- An **urban nutrient management plan** regulation only exists in Maryland and is the most abundant urban/suburban management practice in the state.
- **Runoff reduction** and **stormwater treatment practices** are used in all states and are the most abundant urban/suburban management practice in all states except Maryland.

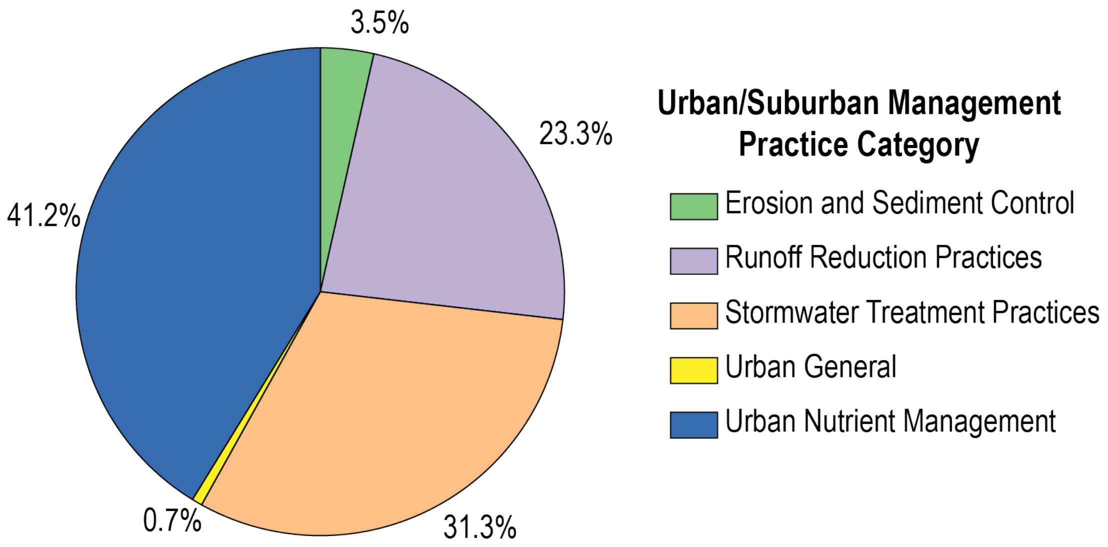
Urban nutrient management plans implement a site-specific plan to address how nitrogen and phosphorus are to be managed for turf and landscape plants.

Runoff reduction and **stormwater treatment practices** achieve nitrogen, phosphorus, and sediment reductions through practices that capture and/or treat stormwater runoff.

Stormwater treatment practices (wetlands, detention ponds, etc.) reduce loads through filtration or settling mechanisms.

Runoff reduction practices (bioretention cells, green roofs, etc.) function similarly, but have higher pollutant removal expectations.[19]

***Data on this slide represent average values from years 2010 – 2019.**



Above: *The percent of reported urban/suburban management practice acres in the Chesapeake Bay watershed represented by management practice categories.[19]*

Explore management practice patterns by source sector or geography: cast.chesapeakebay.net/TrendsOverTime/BMPs

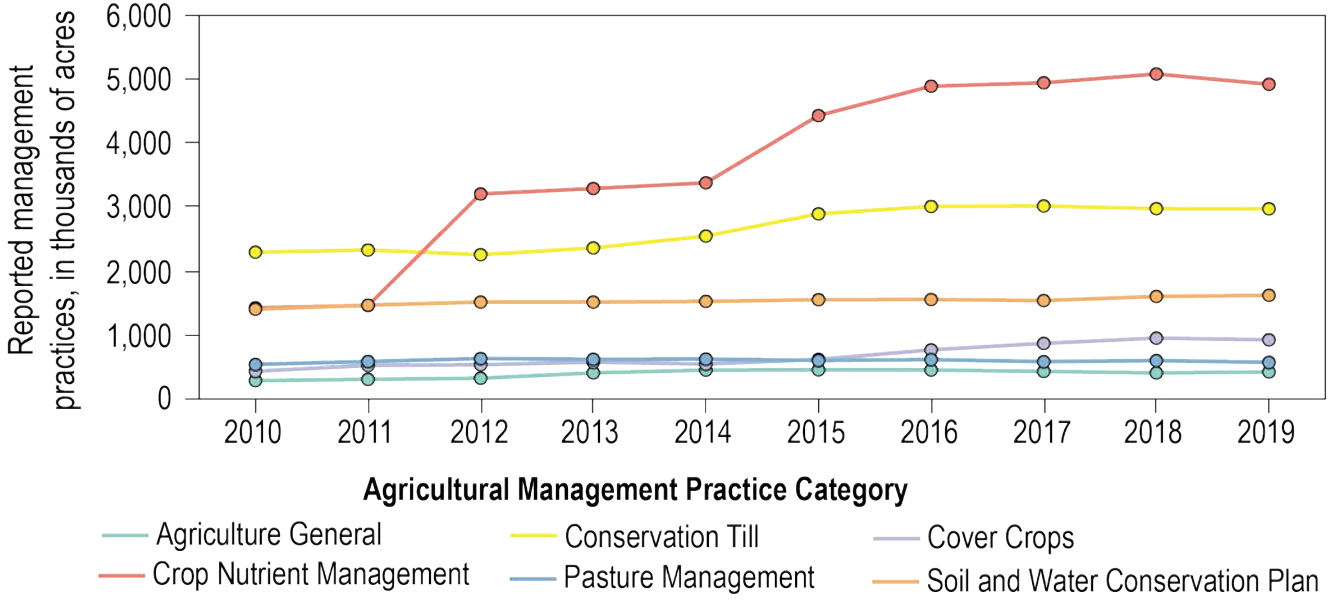
How has agricultural management practice implementation changed over time?*^

Reported agricultural management practice acres increased throughout the Bay watershed by 79% since 2010, from about 6.4 million to 11.4 million acres.[19]

Crop nutrient management plans increased by nearly 250% and represented most (69%) of the increase in agricultural management practice acres.

Conservation tillage, increased by 30% and represented about 13% of the increase in agricultural management practice acres.

Cover crops more than doubled their acreage by 2019 (114%) but represented only about 8% of total agricultural management practice acres in 2019.



***Above:** Reported acres of agricultural management practice categories in the Chesapeake Bay watershed, from 2010 – 2019.*[19]

Increases in reported agricultural management practice acres occurred in all states.[19]

Crop nutrient management plan acres more than doubled by 2019 in all states except PA, where there was a 25% reduction in such practices.

Conservation tillage increased in all states except VA, with most increases in PA.

Cover crops increased in all states, with most increases in MD.

***Data on this slide represent changes from years 2010 – 2019.**
^Multiple management practices can be installed on the same land area.

Explore management practice patterns by source sector or geography: cast.chesapeakebay.net/TrendsOverTime/BMPs

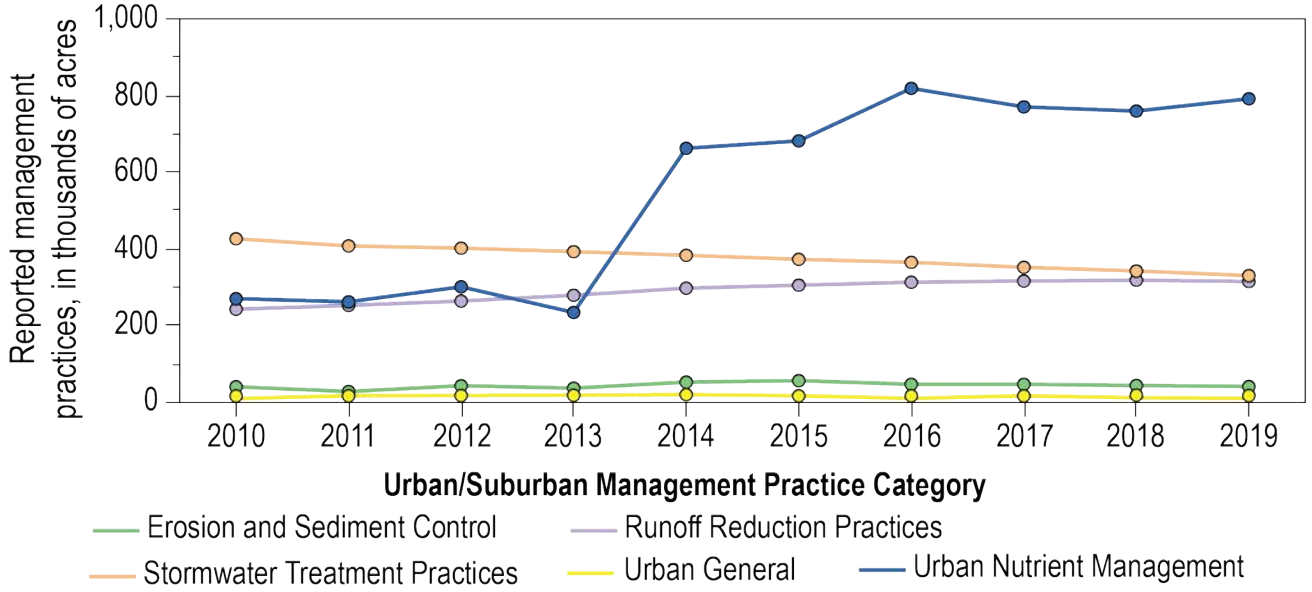
How has urban/suburban management practice implementation changed over time?*^

Reported urban/suburban management practice acres increased throughout the Bay watershed by 51% since 2010, from about 1.0 to 1.5 million acres.[19]

Urban nutrient management plans increased by nearly 200% and represented most of the increased urban management practice acres.

Runoff reduction practices increased by about 30% while **stormwater treatment practices** decreased by about 23%.

Increased use of runoff reduction practices is expected to positively impact water-quality, as these practices have larger expected load reductions than stormwater treatment practices.[19]



Above: *Reported acres of urban/suburban management practice categories in the Chesapeake Bay watershed, from 2010 – 2019.*[19]

Increases in reported urban/suburban management practice acres occurred in all states.[19]

Nearly all of the increase in **urban nutrient management plans** occurred in MD, where acres increased by over 200%.

Increases in **runoff reduction practices** occurred in all jurisdictions except MD, with most increases in PA.

Stormwater treatment practice acres increased in DE, NY, VA, WV, and DC, but declined in PA and MD.

Explore management practice patterns by source sector or geography: cast.chesapeakebay.net/TrendsOverTime/BMPs

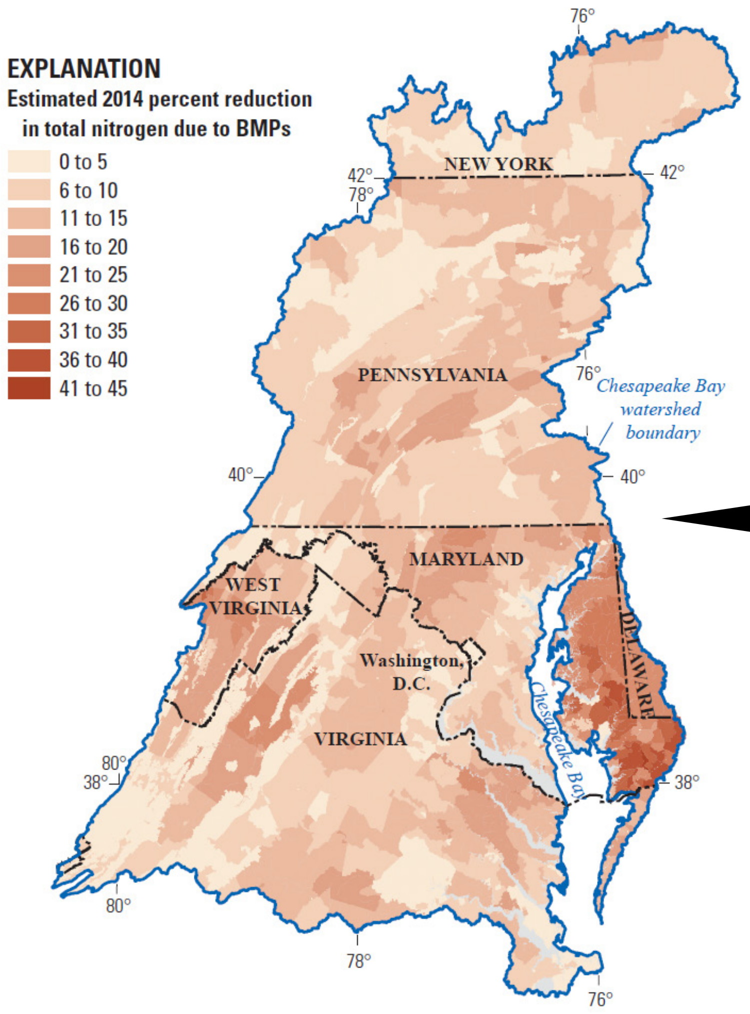
***Data on this slide represent changes from years 2010 – 2019.**
^Multiple management practices can be installed on the same land area.

Are most management practices being implemented in the highest loading areas of the watershed?

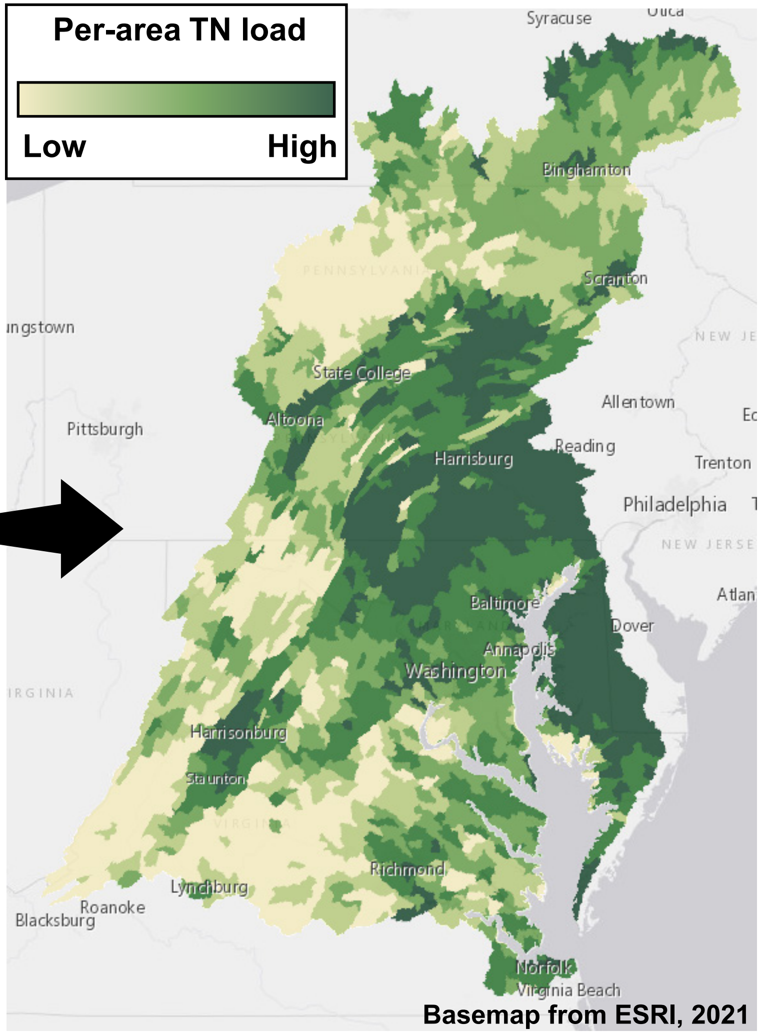
Targeting management practices in areas with high nutrient and sediment loads can improve their effectiveness and reduce costs.[39]

Between 5-20% of the watershed area generates 50-90% or more of runoff and nonpoint source loads.[39]

Researchers are currently working to inform future management practice targeting strategies by relating spatial management practice implementation patterns with estimated water-quality conditions on the landscape, as shown in the maps to the right.



__Above:__ Estimated 2014 percent reduction of total nitrogen attributed to management practices.[38]



__Above__: Estimated 2012 per-area total nitrogen loads.[40] Explore these data online: sparrow.wim.usgs.gov/sparrow-northeast-2012

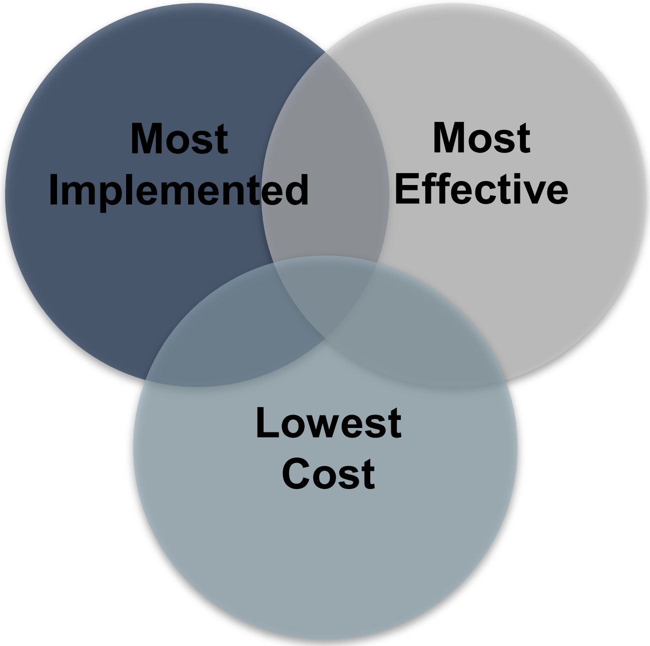
Question continues on the next slide.

Are most management practices being implemented in the highest loading areas of the watershed?

In addition to targeting management practices in high loading areas, practices can be targeted that offer the largest nutrient and sediment reductions at the lowest cost.

CAST provides estimates of management practice costs and expected nutrient/sediment reductions, customized by geography, that can be used to target cost effective practices: cast.chesapeakebay.net/Documentation/CostProfiles

The most commonly used management practices are not always the most cost effective. Understanding local conditions, practice co-benefits, and cost effectiveness are some of the considerations that make up an effective management strategy.



***Below:** Average cost effectiveness of nitrogen and phosphorus management practices by source sector, as estimated by CAST.*[19]

Source Sector	Average Cost Effectiveness ($/lb reduced)	
	Nitrogen	**Phosphorus**
Agriculture	$108	$10,100
Developed	$7,724	$80,349
Septic	$1,006	$0
Natural*	$548	$2,461

*Management practices in the natural sector include practices such as wetland enhancements, forest harvesting practices, oyster practices, and non-urban shoreline management and stream restoration.

Learn more about these data and developing management plans by viewing CAST training videos: cast.chesapeakebay.net/Learning/FreeTrainingVideos

What characteristics affect the benefits of management practices?

The most effective nutrient and sediment management practices are those that target dominant sources, are located in critical source areas, and are customized to local transport pathways.[5,36,28]

Source: Effective management practices target the largest nutrient and sediment sources in a watershed.

Location: Effective management practices are placed in critical source areas, those locations that generate the highest loads or have high connectivity to receiving waters.

Transport: Effective management practices address primary nutrient and sediment delivery pathways to prevent loads from entering receiving waters.

In Smith Creek, an agricultural watershed in Virginia's Shenandoah Valley, nitrogen load reductions may be achieved through management practices that target manure application reductions in karst headwaters where sinkholes allow nitrogen applications to quickly reach the groundwater.[41]

In many urban watersheds, sediment load reductions may be achieved through management practices that reduce streambank erosion and through stormwater infiltration practices that mitigate peak streamflow.[4]

For **nitrogen and phosphorus**, management practices that directly reduce inputs to the landscape may be the more effective at reducing nitrogen and phosphorus loads than those that attempt to control their transport.[5]

For **sediment**, management practices that prevent streambank erosion are likely to be effective in headwater streams and those associated with floodplain protections are important in larger streams.[4]

Management practices designed to reduce nitrogen, phosphorus, and sediment can also help achieve additional environmental or economic goals.[42] Adopting a management strategy that maximizes these co-benefits offers an opportunity to improve water-quality conditions as well as local outcomes and priorities. Learn more about management practice co-benefits: cast.chesapeakebay.net/Documentation/DevelopPlans

What characteristics affect the benefits of management practices?

There are online tools available to explore local conditions and develop customized management strategies.

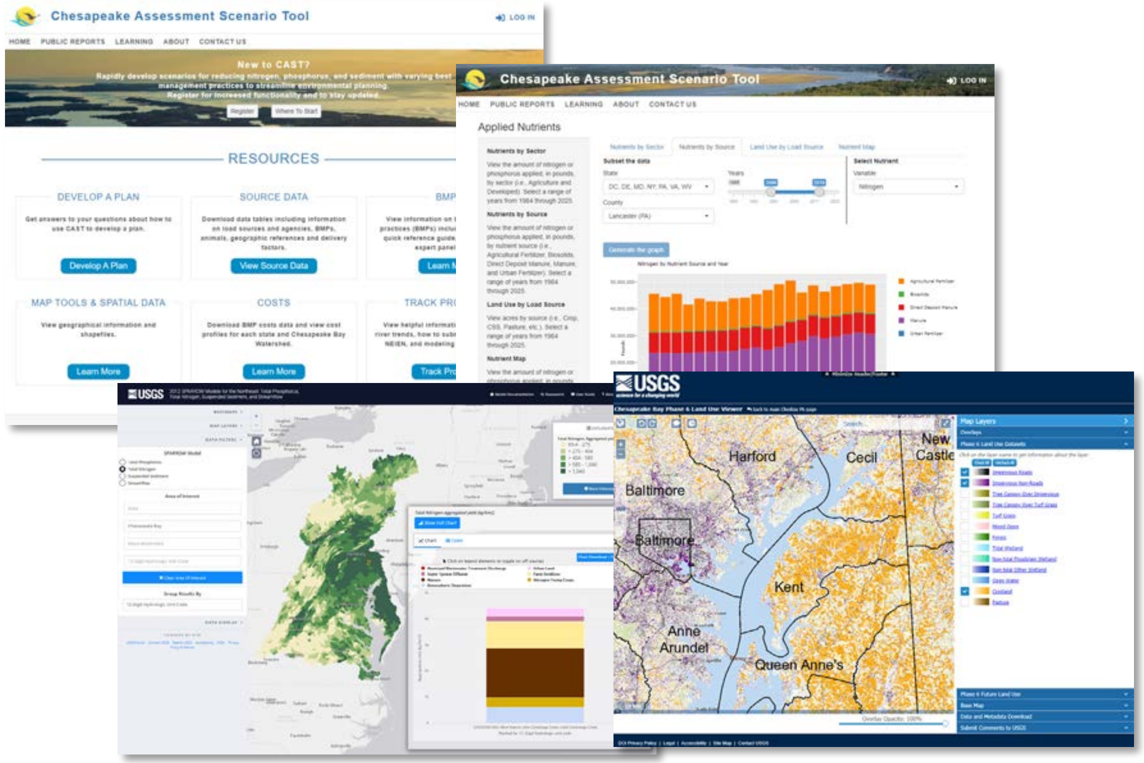
The **Chesapeake Assessment Scenario Tool** (CAST) is a free, online nitrogen, phosphorus and sediment load estimator tool that streamlines environmental planning: cast.chesapeakebay.net

- Explore nutrient sources, application rates, and land use patterns: cast.chesapeakebay.net/TrendsOverTime/NutrientsApplied
- Explore management practice implementation patterns by source sector and geography: cast.chesapeakebay.net/TrendsOverTime/BMPs
- Explore management practice cost profiles: cast.chesapeakebay.net/Documentation/CostProfiles

The **Chesapeake Bay Program's Watershed Model Phase 6 Map Viewer** includes a variety of data to guide management, including nutrient inputs, healthy watersheds, and aquatic resources: gis.chesapeakebay.net/mpa/scenarioviewer

The **Chesapeake Bay Phase 6 Land Use Viewer** can be used to explore land use patterns throughout the watershed: chesapeake.usgs.gov/phase6/map

A **SPAtially Referenced Regression On Watershed** attributes (SPARROW) model can be used to explore estimated nutrient and sediment loads: sparrow.wim.usgs.gov/sparrow-northeast-2012



***Above**: Screenshots of online tools and resources that can help guide effective watershed management.*

The **Nontidal Monitoring Network Storymap** describes and explores water-quality monitoring results for nontidal streams in the Chesapeake Bay watershed: va.water.usgs.gov/storymap/NTN

The **Chesapeake Bay Watershed Data Dashboard** provides accessibility and visualization of data and technical information that can help guide water quality and watershed planning efforts: gis.chesapeakebay.net/wip/dashboard

Legacy Nutrients and Lag Times

Management Implications

1. Water-quality responses are affected by the storage of nitrogen and phosphorus in the landscape, though such legacy effects are uncertain and vary throughout the watershed.

2. Environmental storage of nitrogen and phosphorus is affected by geologic and hydrologic properties, but is likely to be high in areas of the watershed with surplus nutrient applications. In recent years, surplus agricultural nutrient applications have increased.

3. The most effective management strategies to reduce environmental storage of nitrogen and phosphorus include long-term nutrient application reductions.

Background photo courtesy of Chesapeake Bay Program

Legacy Nutrients and Lag Times

Priority Stakeholder Questions

Clicking a "launch" button will jump to content for a specific priority question.

Where does legacy nitrogen and phosphorus come from?

How do legacy effects and lag times of nitrogen and phosphorus vary across the watershed?

Has the contribution of legacy nitrogen and phosphorus to streams changed in recent years?

How strongly do lag times and legacy effects influence trends in load?

A "return" button is included throughout this theme that will return you to this slide.

Where does legacy nitrogen and legacy phosphorus come from?

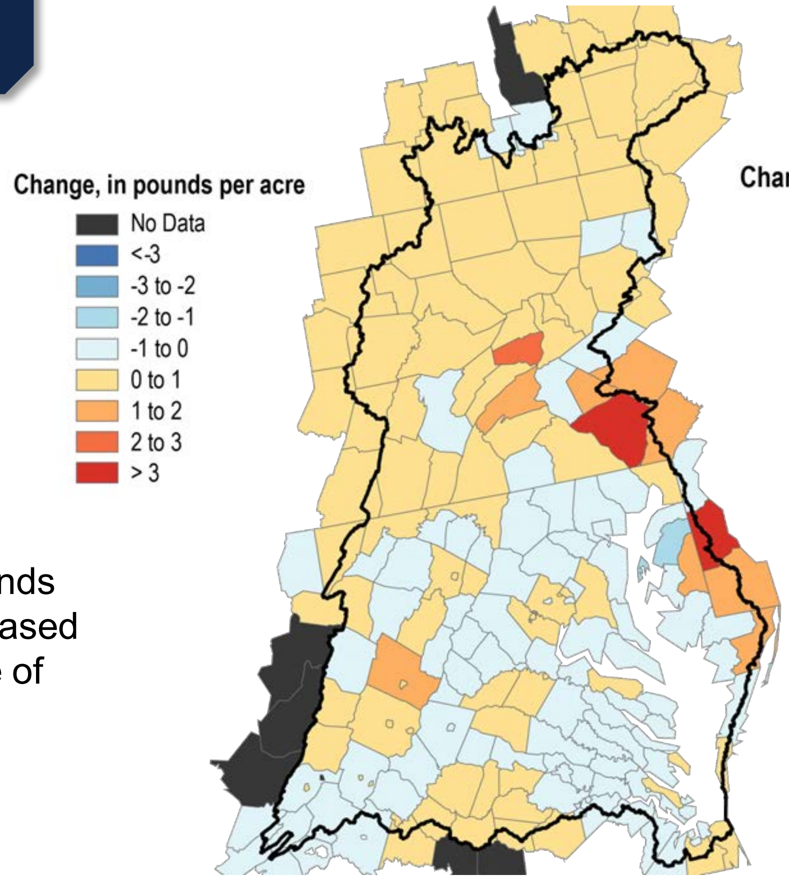
Environmental storage of nitrogen and phosphorus can increase in areas with surplus nutrient inputs where application rates exceed removal rates.[43]

Nutrients applied to the landscape that are not removed by vegetation, agricultural products, or biochemical processes (denitrification, for nitrogen only) are either exported to streams or stored in the environment.

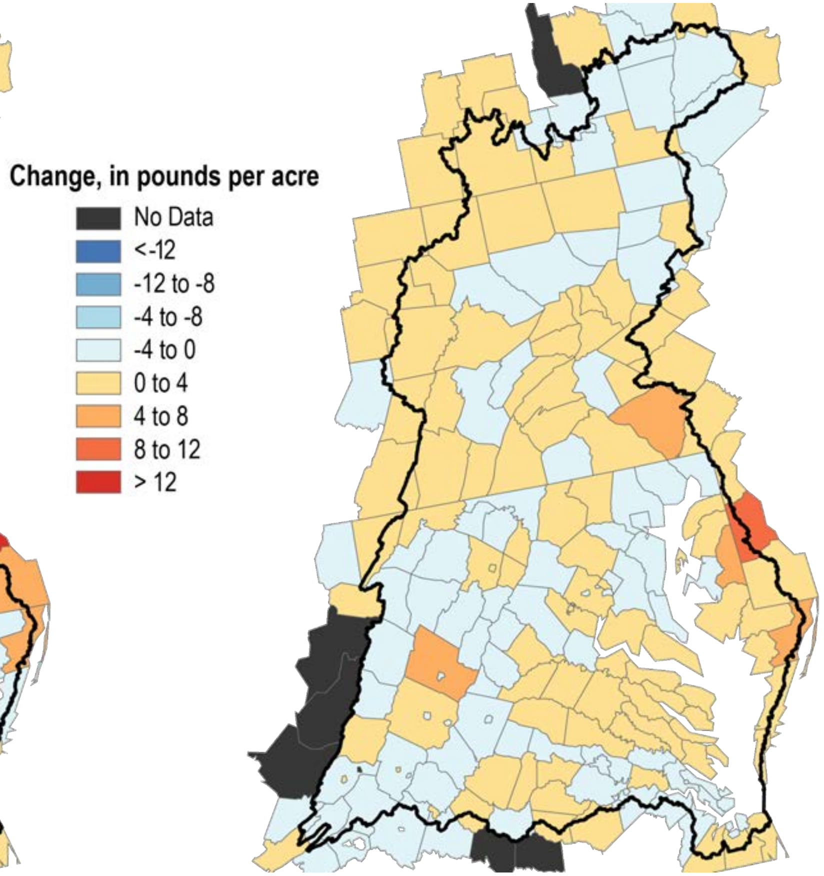
Surplus nutrient applications may be important drivers of loads and contribute to lag times between management actions and water-quality response.[27]

Surplus inputs of nitrogen and phosphorus to agricultural lands generally decreased from conditions in 1985 but have increased in most areas of the watershed since 2009, mostly because of increased manure inputs.[19]

Phosphorus, short-term change in agricultural surplus inputs



Nitrogen, short-term change in agricultural surplus inputs



Above: *Changes in agricultural surplus nutrient applications in Chesapeake Bay counties from ‘09 – ‘11 to ‘17 – ‘19 (short term).*[19]

Nitrogen: How do legacy effects and lag times vary across the watershed?

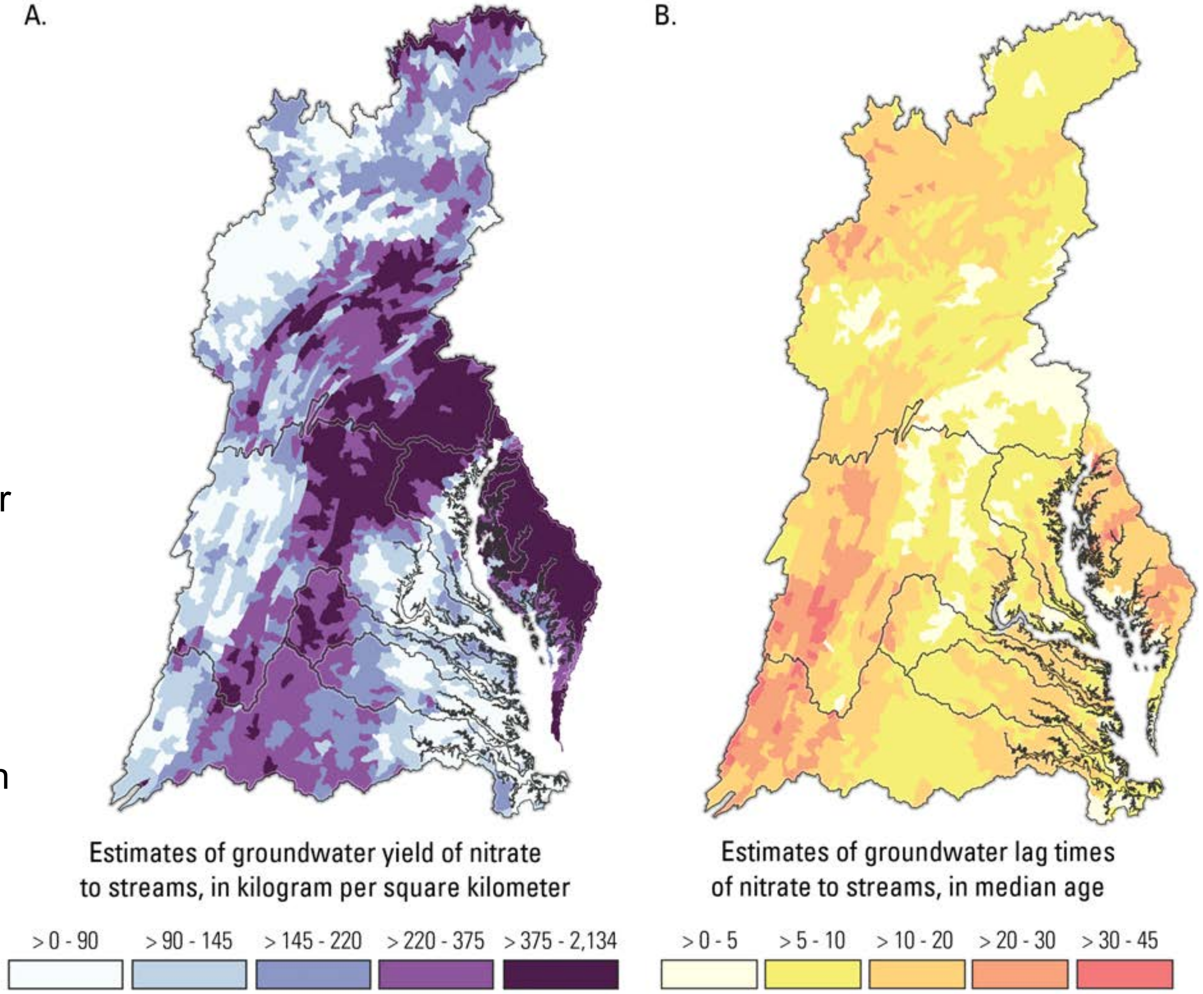
Legacy nitrogen, stored in groundwater and soils, can be a significant portion of annual nitrogen delivered to streams.[43,44]

After application, nitrogen is accumulated in soil organic matter or is converted to nitrate, both forms that can be transported to groundwater and contribute to stream nitrogen loads for years, even with no additional nitrogen application.

On average, just over 50 percent of the total volume of water in streams is from groundwater, with a range of 16 to 92 percent for different streams.[44] Estimates of the amount of nitrogen delivered to a stream through groundwater range from 17 to 80 percent, with an average of 48 percent.[44]

Modeling within the Bay watershed shows elevated concentrations of groundwater nitrate in several regions, with residence times ranging from less than a day to several decades based on aquifer type and geology. High concentrations are associated with intensive agricultural land use, especially in areas of carbonate geology.[45] Other contributing factors include riparian vegetation and characteristics that limit denitrification at the subsurface.[45,46]

Patterns of soil nitrogen reservoirs and residence times are less certain. Studies suggest it may take decades to reduce soil organic nitrogen accumulated in agricultural soils and stream valley sediments.[47,48]



***Above**: Estimates of (A) groundwater yield of nitrate to streams[49] and (B) median age of groundwater lag times of nitrate to streams[50] at the subwatershed scale.*

Question continues on the next slide.

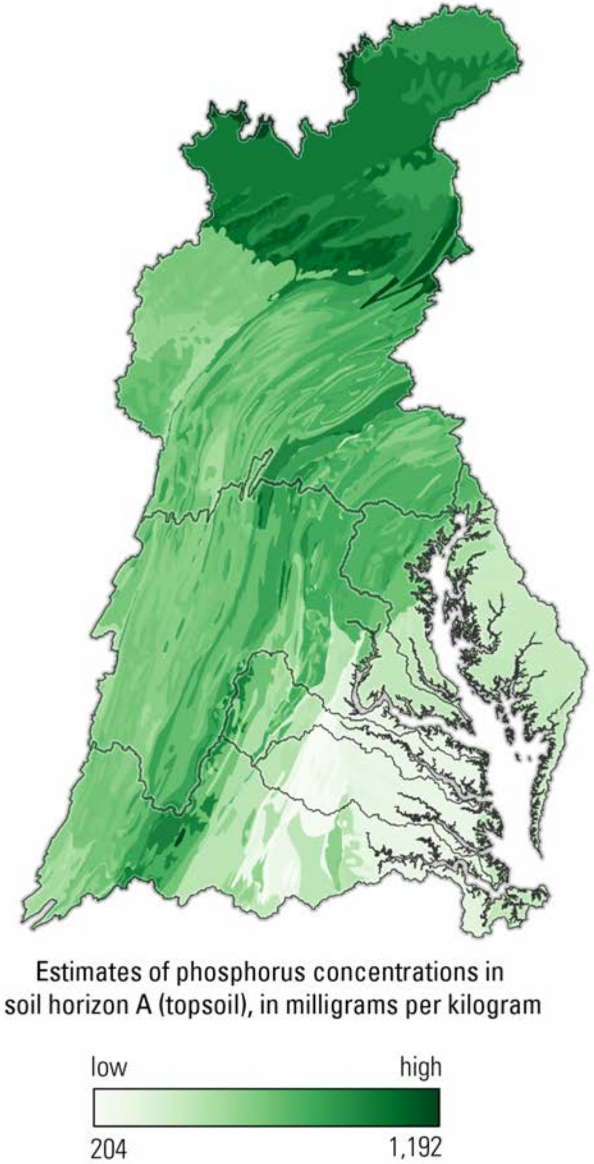
Phosphorus: How do legacy effects and lag times vary across the watershed?

Legacy phosphorus, stored primarily in soils, presents a persistent challenge to water quality management.

In contrast to nitrogen, there are no natural processes that remove phosphorus from the terrestrial environment. Consequently, continued releases of legacy phosphorus can occur where phosphorus is applied in excess of plant uptake and accumulates in soils. This is common in areas where animal manures are applied to the landscape as fertilizer.

Phosphorus can be transported from soils to streams in particulate (sediment-bound, from surface runoff) or dissolved forms (from surface runoff and subsurface flows).[8,51] Phosphorus that erodes from the landscape can further accumulate and contribute to continued phosphorus releases in downstream floodplains, uplands, and/or stream channels. Legacy phosphorus can persist for decades both in uplands and in legacy sediment, especially where accumulated concentrations are high.[15,52]

Phosphorus transport to streams varies spatially within the watershed based on the erodibility, hydrological activity, and connectivity of soils (e.g., permeability, precipitation).[17,53] These factors influence the transfer of phosphorus to runoff, with most transport occurring episodically during and after large storm events.[54]



Above: *Estimates of soil phosphorus concentrations in soil horizon A (topsoil) interpolated from discrete soil sampling events occurring from 2007 – 2010.*[55]

Has the contribution of legacy nitrogen and phosphorus to streams changed in recent years?

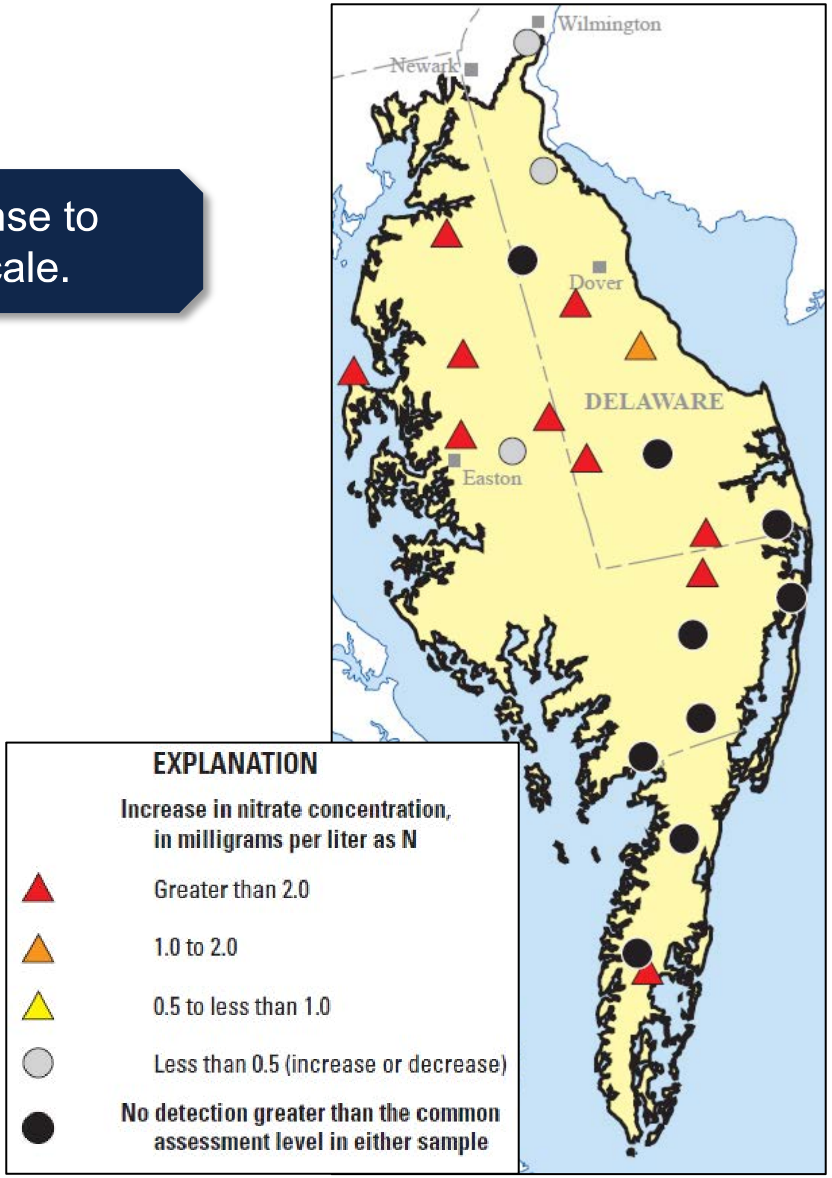
Assessing how groundwater nitrogen and soil phosphorus levels are changing in response to management strategies requires long-term monitoring at both the site and watershed scale.

Groundwater nitrate concentrations have not declined in recent decades in the Potomac River watershed and on the Delmarva Peninsula.[56,57]

Groundwater nitrate concentrations increased or had no trends in the Potomac River watershed or on the Delmarva Peninsula from the late 1980s to the 2010s, with trends varying by decade, dominant landuse, and physiographic setting.[56,57]

It may take decades for concentrations of soil phosphorus to decline after inputs are reduced, especially where accumulated phosphorus levels are high.[15,53]

No changes in groundwater orthophosphate concentrations were observed in Potomac River carbonate aquifers or on the Delmarva Peninsula from 1993 – 2002 or 1988 – 2001, respectively.[56] In the mid-Atlantic coastal plain, phosphorus-saturated sites may take 18 – 44 years to reach optimal agronomic levels, assuming no additional phosphorus applications.[58]



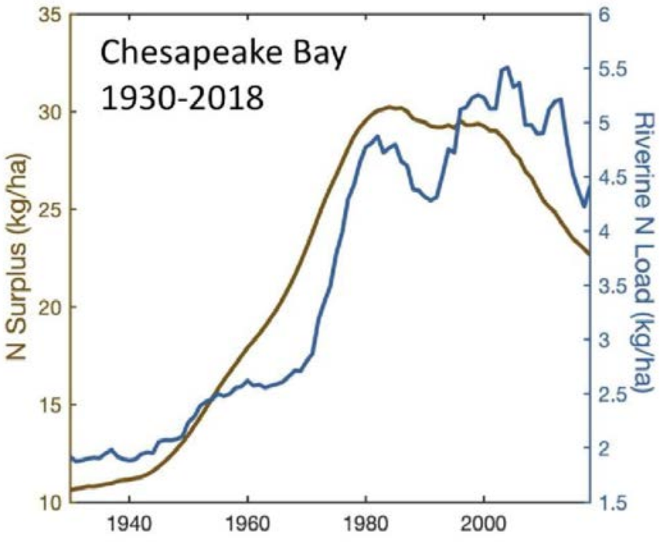
***Above**: Trends in groundwater nitrate concentration from 1988 – 2010 from wells on the Delmarva Peninsula.*[56]

How strongly do lag times and legacy effects influence trends in load?

The time between management action and water-quality response varies based on the movement of nutrients from soils and groundwater to surface waters and such legacy effects may delay attainment of Bay water-quality goals.[59]

Nitrogen

Legacy nitrogen effects can delay expected water-quality improvements and can be locally significant, with time-lags that vary considerably between watersheds.[27] However, over a multidecadal timescale throughout the Bay, the average effects of legacy nitrogen may not outweigh the importance of contemporaneous changes in inputs and climatic effects.[26]



***Above**: Nitrogen surplus inputs and estimated nitrogen load delivered to watershed streams, which suggests that that response of river load lags the trend in surplus inputs.*[27]

Phosphorus

Watersheds with phosphorus-saturated soils may export more total phosphorus as dissolved phosphorus, typically in the form of orthophosphate.[51] While some phosphorus losses via erosion can be controlled through conventional soil conservation techniques, these practices do not address orthophosphate losses at the subsurface.[51]

Orthophosphate makes up nearly 50% of the exported total phosphorus load in some agriculturally intensive NTN watersheds.[8] The proportion of phosphorus load as orthophosphate is increasing in some areas of the watershed,[12] with the largest changes occurring in agricultural watersheds associated with total phosphorus load increases.[8]

Continued research is needed to better understand the role of legacy phosphorus and legacy nitrogen. Orthophosphate loads have increased in the Susquehanna River[1] and understanding these changes is critical, as the Susquehanna River greatly influences phosphorus conditions in the Bay.[51] Nitrogen loads have declined in some watersheds underlain by carbonate rocks, but the drivers of these changes are unresolved.[5]

Nontidal Influences on Estuarine Response and Standards Attainment

Management Implications

1. Water quality in the Bay has improved slightly over the past 30 years, with 33% of tidal water segments meeting attainment thresholds of their criteria for the 2017 – 2019 assessment period compared to 27% attainment in the mid-1980's.

2. Attainment levels vary over time, with the highest value of 42% observed in 2015 – 2017, and lower values occurring during times of high river flow when more nutrients are delivered to the Bay.

3. Dissolved oxygen (DO) attainment varies throughout the Bay and generally gets worse with depth, with most segments meeting DO standards for open water and migratory fish spawning designated uses, but not meeting DO standards for deep water and deep channel designated uses in the 2017 – 2019 assessment period.

4. There are numerous physical, chemical, and biological factors influencing Bay water quality, including impacts from extreme weather events, but overall attainment has been statistically associated with nitrogen inputs to the Bay.

Background photo courtesy of Chesapeake Bay Program

Nontidal Influences on Estuarine Response and Standards Attainment

Priority Stakeholder Questions

What is the current attainment of water-quality standards in the Bay?

How have attainment patterns and water-quality parameters changed over time?

What factors are affecting water-quality responses in the Bay?

Clicking a “launch” button will jump to content for a specific priority question.

A “return” button is included throughout this theme that will return you to this slide.

What is the current attainment of water-quality standards in the Bay?

In 2017 – 2019, **33%** of tidal water segments met attainment thresholds of their water-quality criteria.[60]

This score represents a surface-area-weighted estimate of water-quality standards attainment, quantifying the fraction of tidal waters that meet season-specific criteria for each applicable standard.[61]

Criterion	Designated Use	Abbreviation
Dissolved Oxygen	Migratory fish spawning and nursery	MSN-DO
	Open-water fish and shellfish	OW-DO
	Deep-water seasonal fish and shellfish	DW-DO
	Deep-channel seasonal refuge	DC-DO
Chlorophyll-a	Open-water fish and shellfish	OW-CHLA
Submerged aquatic vegetation and/or Water Clarity	Shallow-water bay grass	SW-Clarity/SAV

***Above**: The six criterion-designated use combinations listed in the Chesapeake Bay total maximum daily load (TMDL) used in the water-quality standards attainment indicator.*

The 2017 – 2019 total attainment score was composed of:[60]

63% attainment of OW-DO, which applies to all 92 tidal segments.

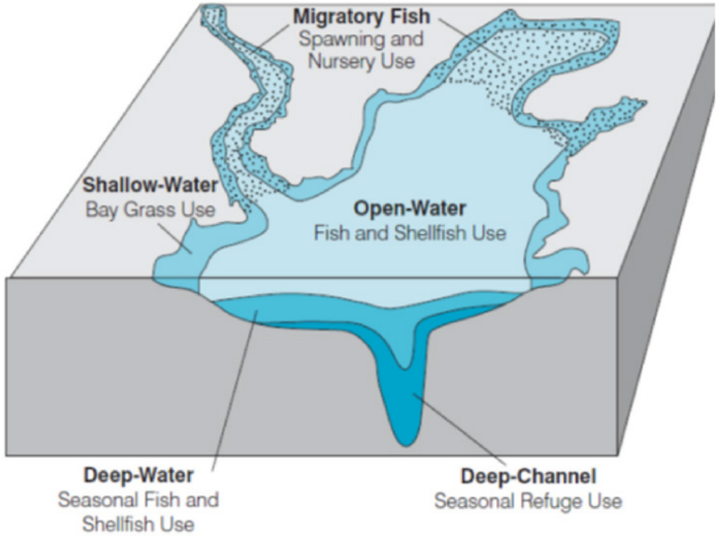
65% attainment of MSN-DO, which applies to 73 tidal segments.

12% attainment of DW-DO, which applies to 18 tidal segments.

0.5% attainment of DC-DO, which applies to 10 tidal segments.

15% attainment of OW-CHLA, which applies to 7 Potomac and James River tidal segments.

16% attainment of SW-Clarity/SAV, which applies to 79 tidal segments.



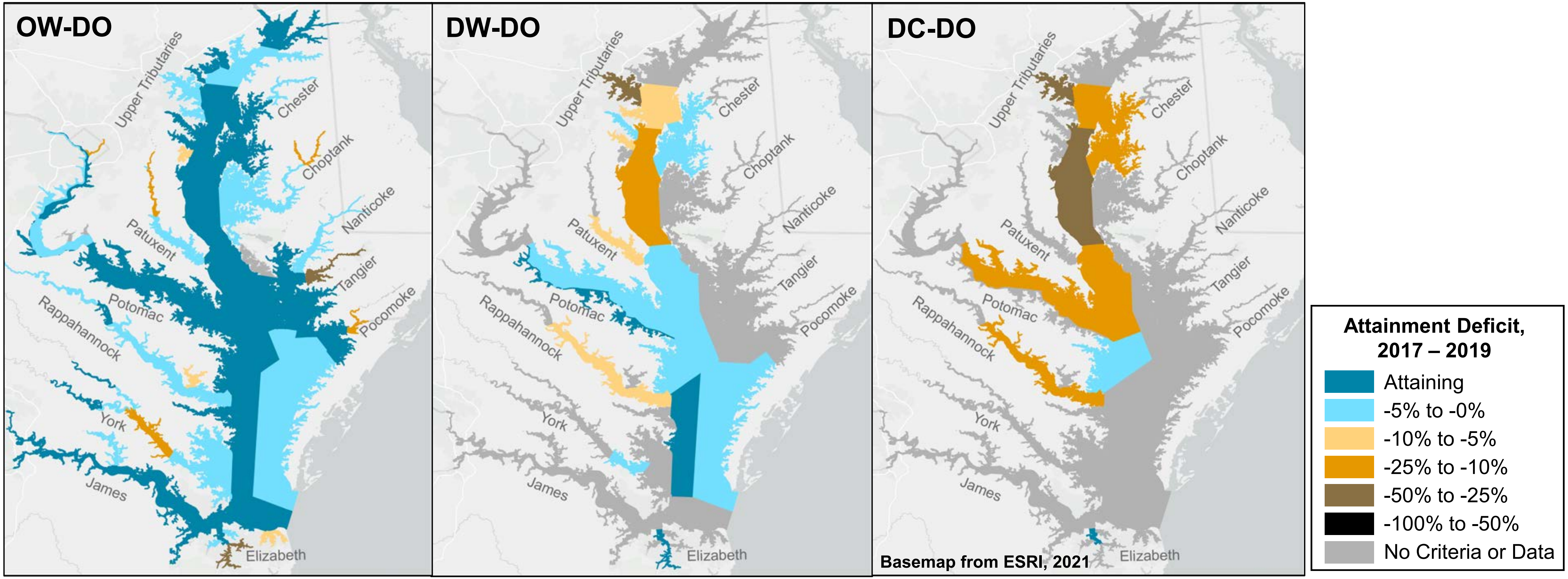
***Above**: Conceptual illustration of the five designed uses in the Chesapeake Bay water quality standards assessment.*[61]

Learn more about water-quality standards attainment in the Bay:
chesapeakeprogress.com/clean-water/water-quality

What is the current attainment of water-quality standards in the Bay?

Attainment of dissolved oxygen (DO) standards generally gets worse with depth, as designated uses go from open water (OW) to deep water (DW) to deep channel (DC).[60]

Attainment deficit measures how close each tidal segment is to meeting minimum water-quality requirements, where 0% is the best possible condition and implies attainment and values of -100% are the worst possible condition and implies complete non-attainment.[62]



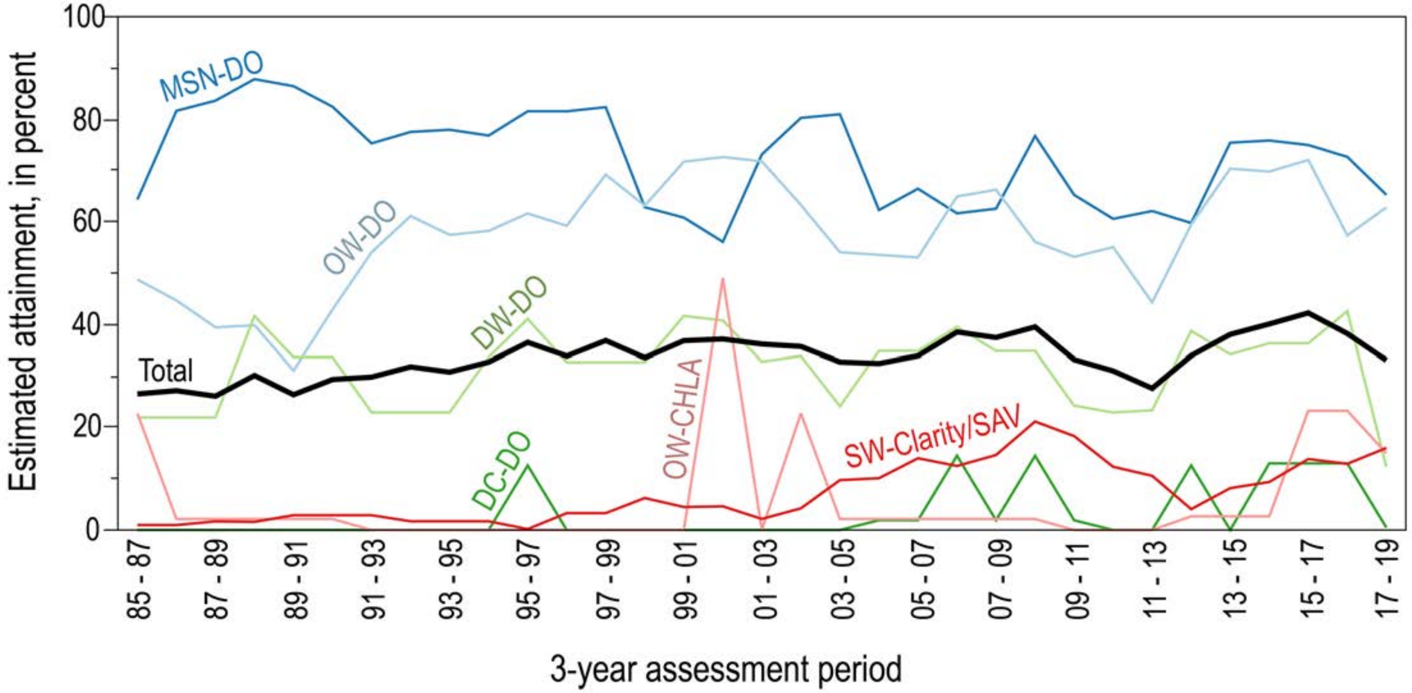
***Above**: The 2017 – 2019 attainment deficit for Chesapeake Bay dissolved oxygen (DO) criterion in open water (OW), deep water (DW), and deep channel (DC) designated uses.[62]*

How have attainment patterns and water-quality parameters changed over time?

Water quality in the Bay has improved slightly since 1985, with improvements occurring in OW-DO, DC-DO, and SW-Clarity/SAV.[61]

33% total attainment in 2017 – 2019 is lower than the highest observed attainment of **42%**, which was observed in 2015 – 2017.[60]

27% total attainment in 1985 – 1987 was among the lowest indictor score on record, which coincides with the start of Bay restoration efforts.[60]



***Above**: Time series of designated use-specific attainment scores and multimetric indicator score between 1985 – 1987 and 2017 – 2019.[60]*

Despite improvements, water-quality measures remain far below the 100% attainment necessary to support full survival, growth, and reproduction of its living resources.

The Chesapeake Bay total maximum daily load (TMDL) is not designed to reach 100% standards attainment by 2025, rather, the regulations call for all management practices to be implemented in the watershed by 2025 to eventually reach this goal.

Learn more about water-quality standards attainment in the Bay: chesapeakeprogress.com/clean-water/water-quality

Question continues on the next slide.

How have attainment patterns and water-quality parameters changed over time?

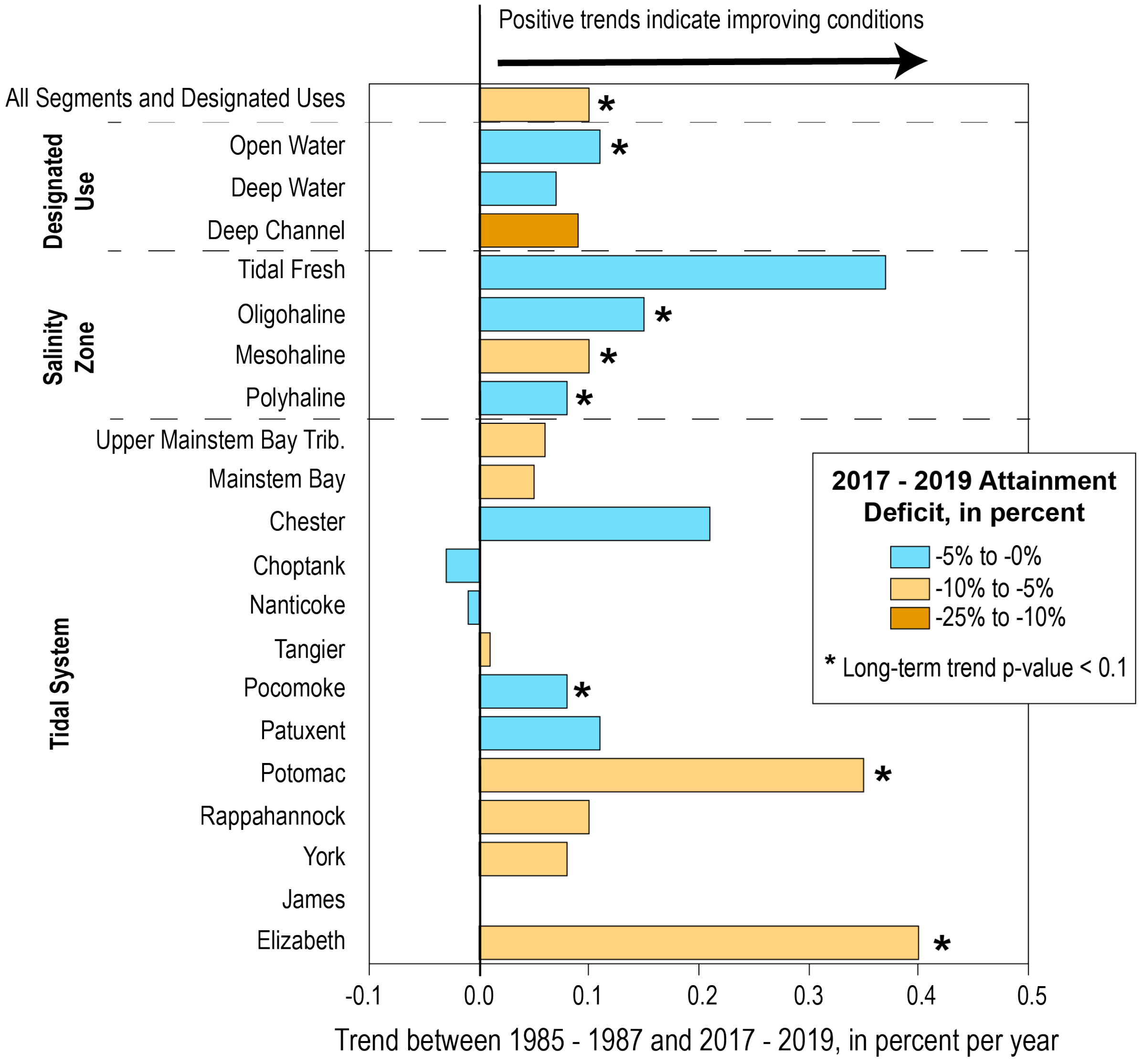
DO attainment improved between 1985 – 1987 and 2017 – 2019 for all combined segments and designated uses.[60]

DO attainment levels improved for the open water designated use and have no statistically significant trend for deep water or deep channel. Deep channel segments continue to have poorer conditions than open water or deep-water segments.

DO attainment levels improved for all salinity zones, with higher levels of attainment in tidal fresh, polyhaline, and oligohaline zones compared to the mesohaline.

DO attainment levels improved in the Pocomoke, Potomac, and Elizabeth tidal segments and have no statistically significant trends in all other tidal systems.

Continued management actions will likely be necessary to reach full attainment of DO in all designated uses, salinity zones, and tidal systems.[61]

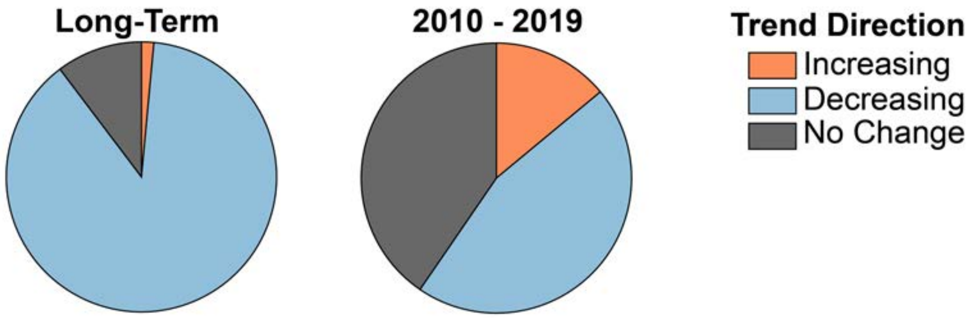


Above: *DO attainment deficit patterns and changes between earliest and most recent assessment periods for tidal systems, salinity zones, and designated uses.[60]*

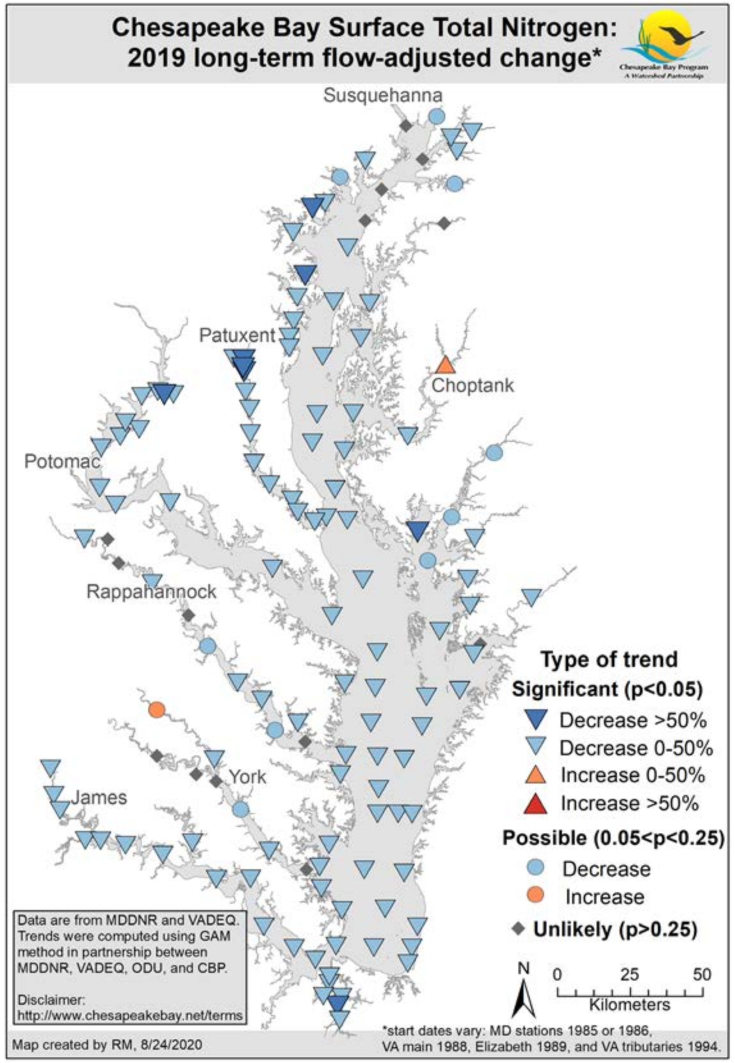
How have attainment patterns and water-quality parameters changed over time?

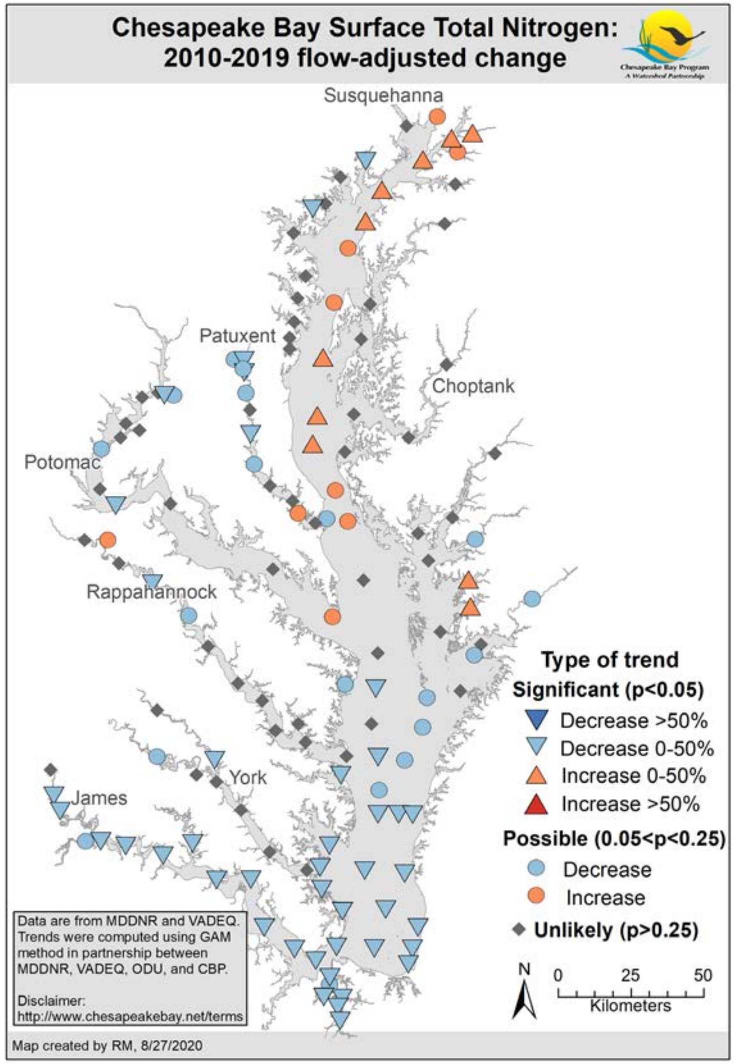
Samples have been collected from 136 stations in the Chesapeake Bay for more than 30 years and are used to assess water-quality trends.

At most stations, flow-adjusted surface total nitrogen concentrations decreased over the long-term monitoring period and decreased or had no change from 2010 – 2019.[2]



***Above**: Trends in flow-adjusted surface total nitrogen concentration over a long-term monitoring period and from 2010 – 2019.[2]*





***Above**: 1985 – 2019 and 2010 – 2019 flow-adjusted surface total nitrogen concentration trends throughout the Chesapeake Bay.[2]*

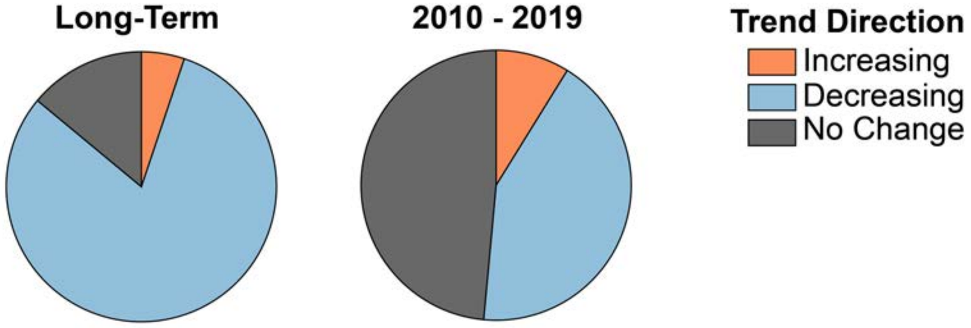
Learn more about water-quality trends in the Bay:
chesapeakebay.net/who/group/integrated_trends_analysis_team

Question continues on the next slide.

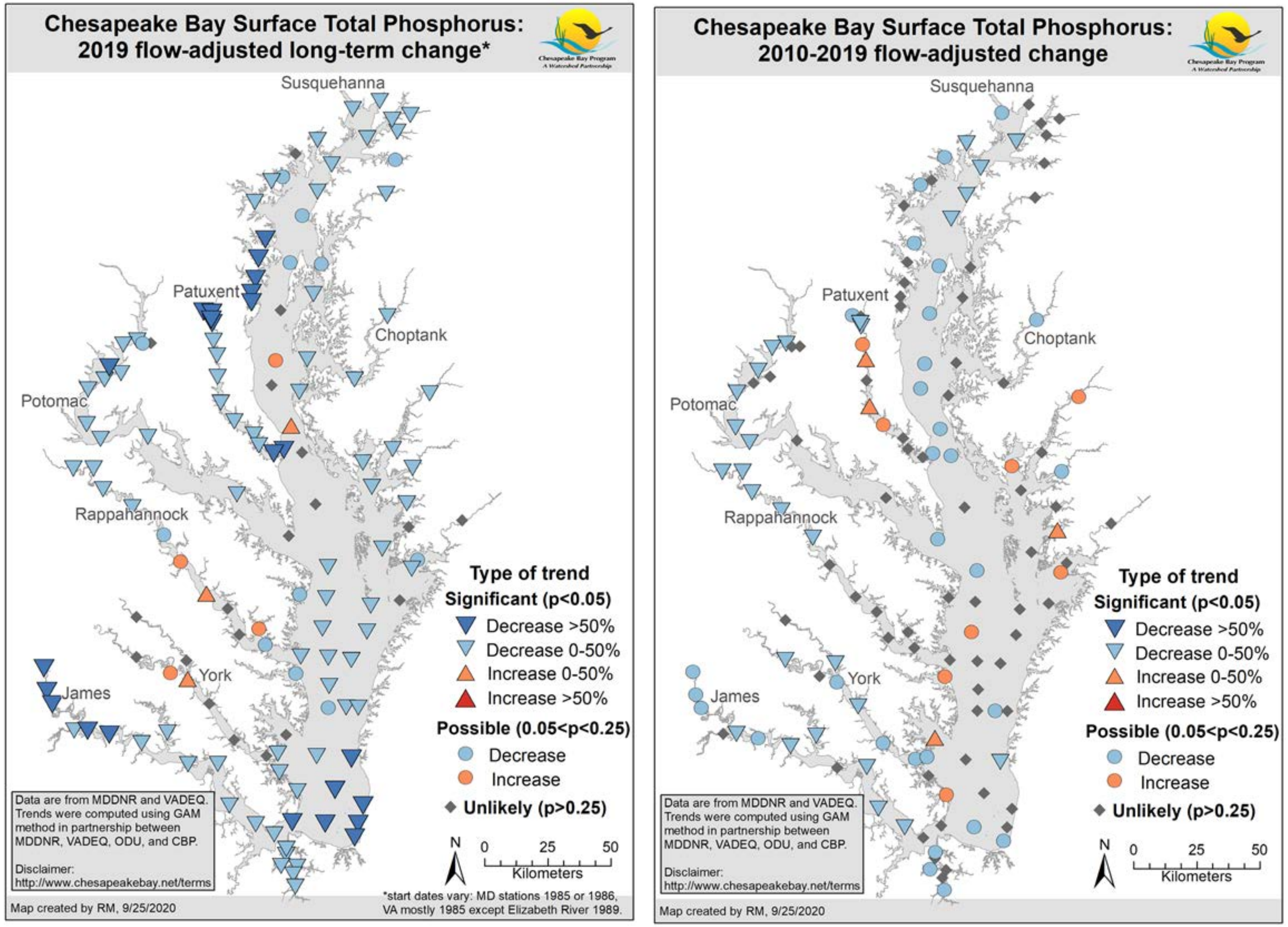
How have attainment patterns and water-quality parameters changed over time?

Samples have been collected from 136 stations in the Chesapeake Bay for more than 30 years and are used to assess water-quality trends.

At most stations, flow-adjusted surface total phosphorus concentrations decreased over the long-term monitoring period and decreased or had no change from 2010 – 2019.[2]



***Above**: Trends in flow-adjusted surface total phosphorus concentration over a long-term monitoring period and from 2010 – 2019.*[2]



***Above**: 1985 – 2019 and 2010 – 2019 flow-adjusted surface total phosphorus concentration trends throughout the Chesapeake Bay.*[2]

Learn more about water-quality trends in the Bay:
chesapeakebay.net/who/group/integrated_trends_analysis_team

What factors are affecting water-quality responses in the Bay?

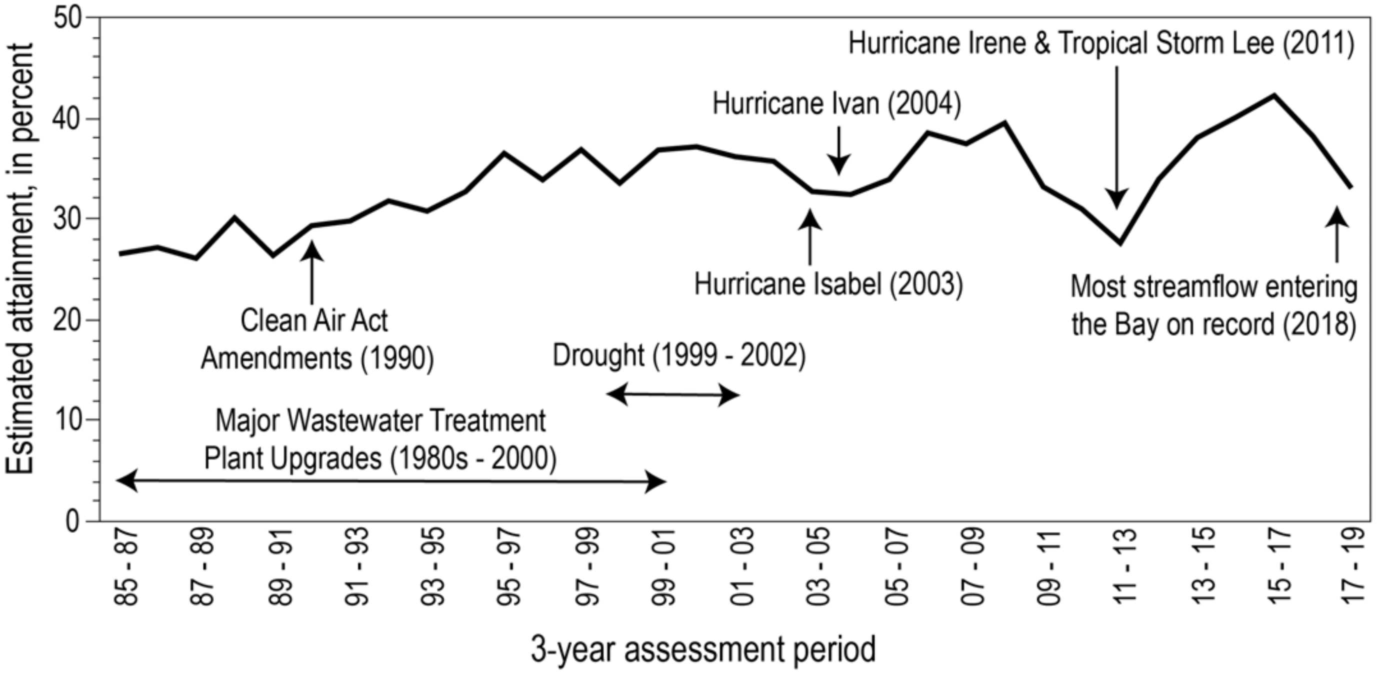
Interannual variability in Baywide water-quality attainment shows impacts of and recovery from extreme weather events.[61]

The Baywide attainment indicator represents a surface-area-weighted estimate of water-quality standards attainment, quantifying the fraction of tidal waters that meet season-specific criteria for each applicable standard.[61]

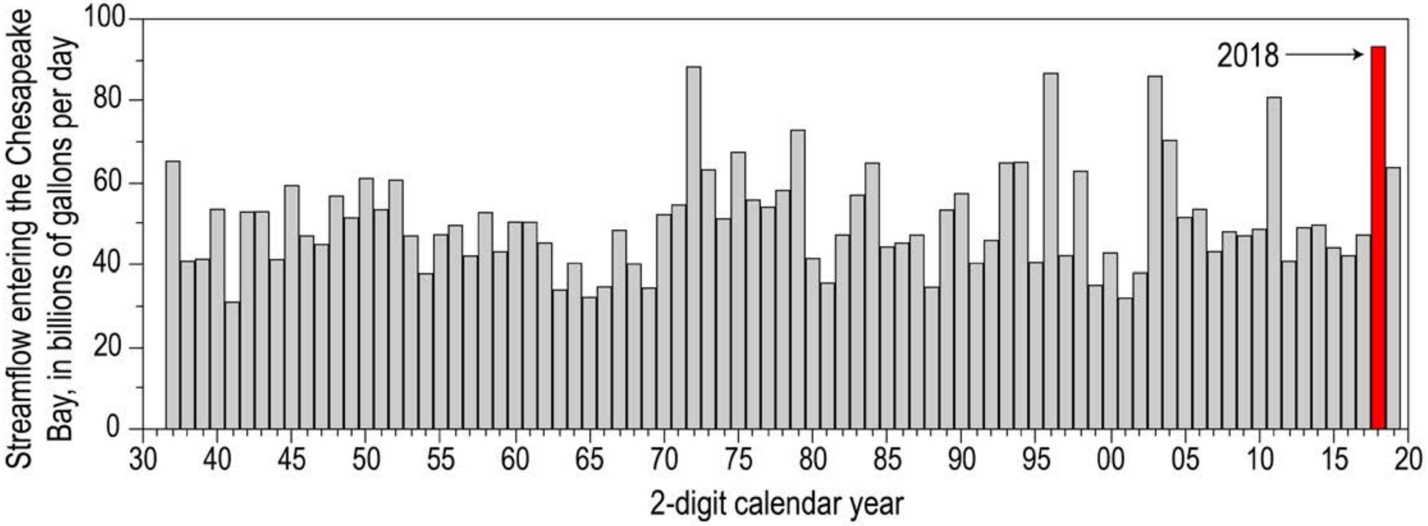
Low-points in the Baywide indicator occurred in 2003, 2004, and 2011, followed by periods of improvement. These changes coincide with Hurricane Isabel, Hurricane Ivan, and Tropical Storm Lee and Hurricane Irene, respectively.[61]

A recent low-point in the Baywide indicator in 2017 – 2019 coincides with the highest amount of streamflow delivered the Chesapeake Bay in more than 80 years of record.[63]

While chlorophyll-a attainment has been near zero for most years, the highest levels of attainment (2000 – 2002 and 2002 – 2004) are associated with an extended period of drought.[61]



***Above:** Baywide attainment indicator and highlighted events, from 1985 – 2019.[61]*



***Above**: Annual streamflow entering the Chesapeake Bay, from 1936 – 2019.[63]*

What factors are affecting water-quality responses in the Bay?

Nitrogen, phosphorus, and sediment loads, uptake, and transformation are among the many processes influencing water-quality conditions in the Chesapeake Bay.

Nitrogen delivered from the watershed strongly influences hypoxic conditions[64,65,66] and attainment of multiple water-quality standards in the Bay.[61]

Submerged aquatic vegetation (SAV) abundance has been associated with lower nitrogen concentrations and loads throughout the Bay[67] and, in some tidal areas, phosphorus and/or total suspended solids have also been identified as factors influencing SAV recovery.[67,68,69]

Local water-quality improvements have occurred in response to reduced nutrient inputs, most commonly from wastewater treatment plant upgrades.[70,71,72,73,74]

Reducing nonpoint nutrient sources is critical to achieving sustained water-quality improvements,[71] as effects of wastewater treatment plant upgrades vary seasonally with streamflow[28] and can be offset by inputs from agricultural and urban activities.[70]

Learn more about factors influencing water-quality standards attainment: chesapeakeprogress.com/clean-water/water-quality

***Above**: The Blue Plains Advanced Wastewater Treatment Plant, where upgrades have resulted in reduced nutrient loads discharged to the Potomac River (Photo courtesy of Chesapeake Bay Program).*[28]

***Above**: SAV in the Chesapeake Bay, which is heavily influenced by nitrogen delivered from the watershed (Photo courtesy of Chesapeake Bay Program).*[67]

What factors are affecting water-quality responses in the Bay?

Patterns in open water dissolved oxygen (OW-DO) attainment vary spatially throughout the Bay.[75]

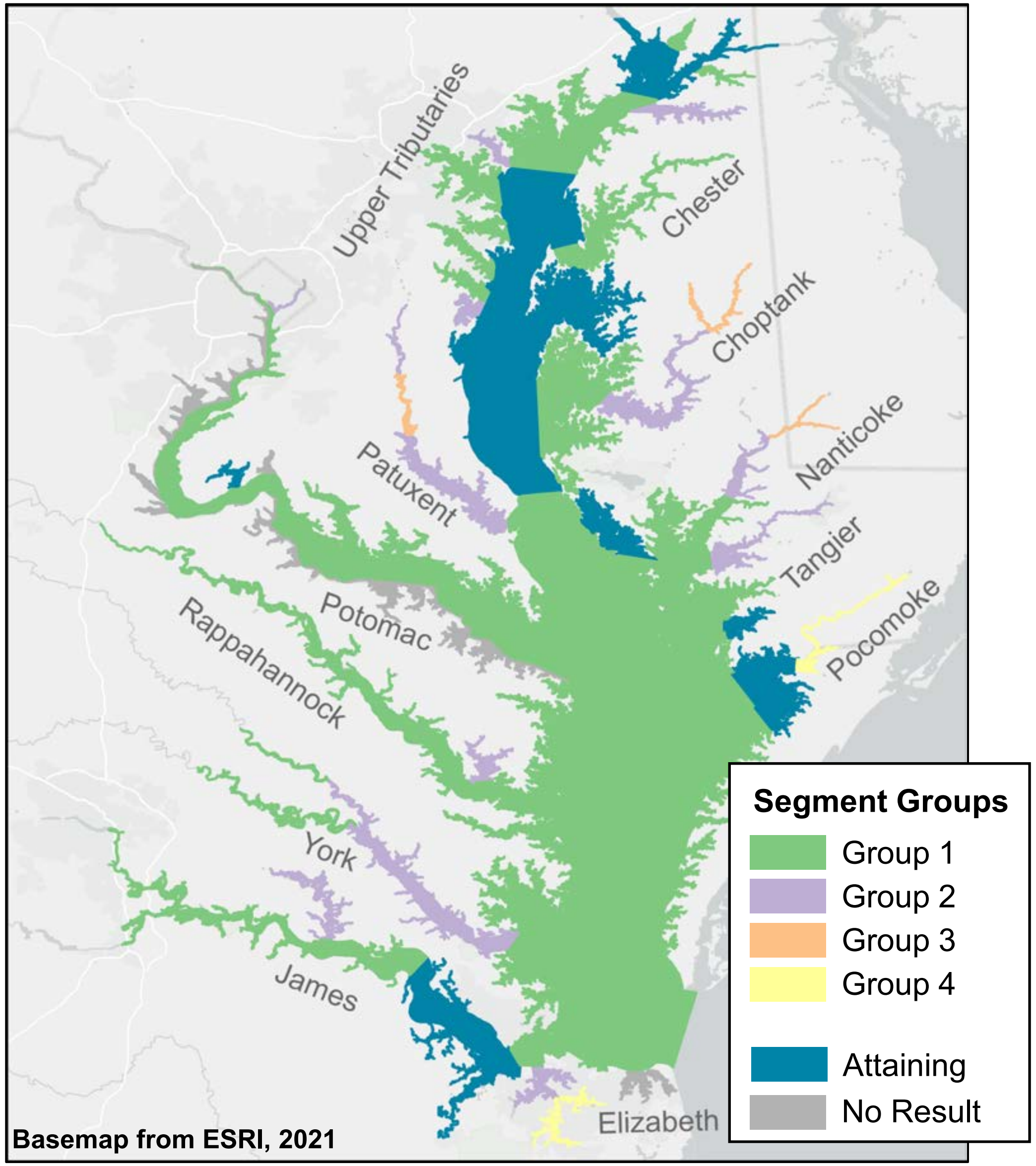
In general, mainstem segments (**group 1**) or downstream tidal segments (**group 2**) met or nearly met OW-DO criteria from 1985 – 2016, whereas attainment deficit was larger and more variable in upstream reaches surrounded by land in low-salinity (**group 3**) and high-salinity (**group 4**) regions.[75]

Freshwater inputs, and associated nutrient and sediment loads, have large impacts on dissolved oxygen attainment, but these effects vary seasonally and spatially throughout the Bay.[75]

Summer freshwater and sediment inputs reduced OW-DO attainment in landward regions, but elevated attainment in open, mainstem waters.[75]

Algal biomass was often positively associated with DO attainment in surface waters, in contrast to deep waters where algae are well-understood to cause lower oxygen levels.[75]

The complexity of water-quality responses and drivers in the Bay highlight the need for continued collection of spatially explicit, long-term monitoring data to identify effective management strategies.[75]



***Above**: Tidal segments colored by group, where 1985 – 2016 OW-DO attainment deficit patterns have statistically different patterns between groups. “Attaining” segments met OW-DO criteria during the entire period.[75]*

Question continues on the next slide.

What factors are affecting water-quality responses in the Bay?

The amount of nitrogen, phosphorus, and sediment delivered to the Bay is affected by streamflow and management activities.

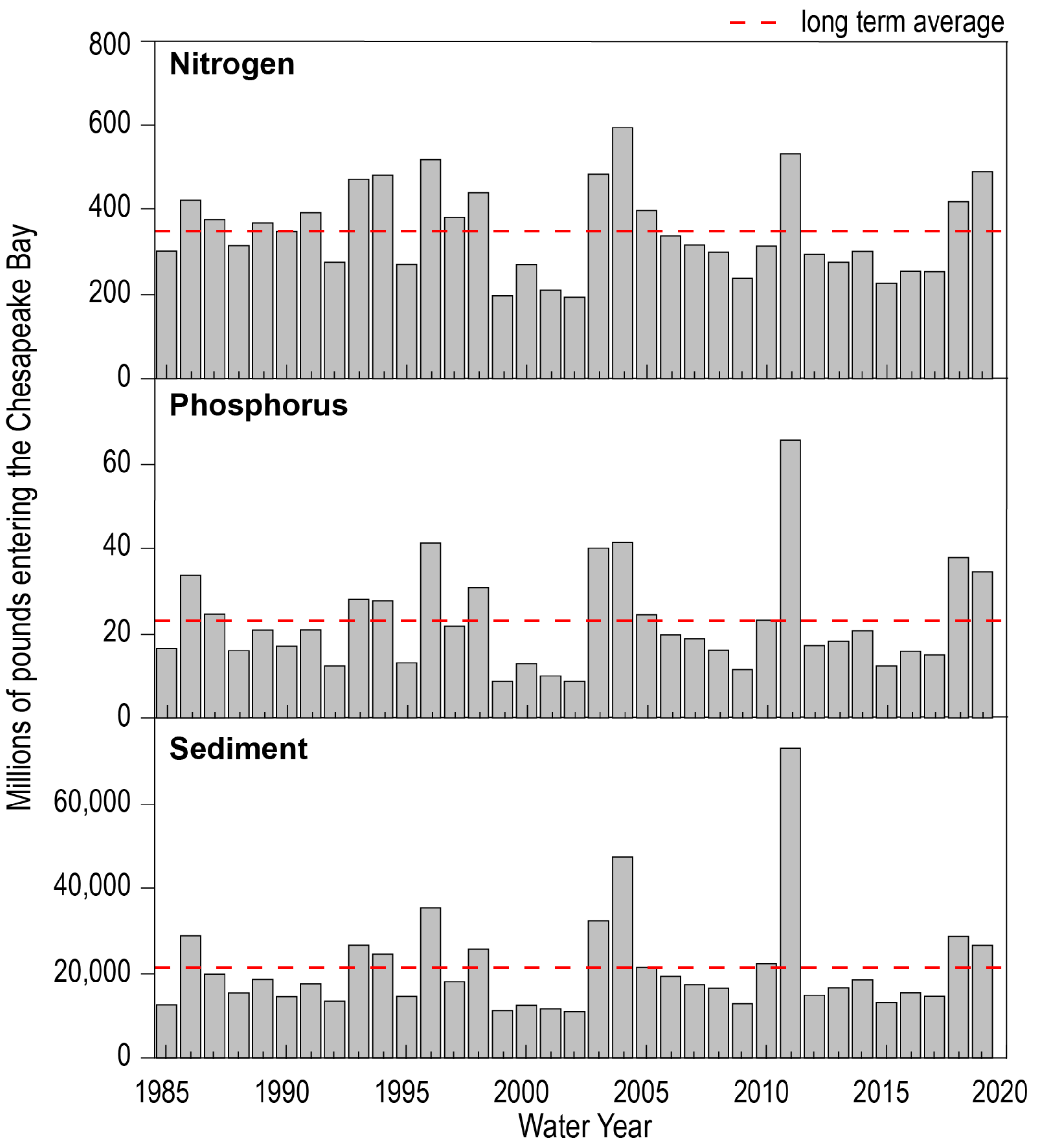
Nitrogen, phosphorus, and sediment loads reaching the Bay in water years 2018 and 2019 were higher than their long-term averages because of exceptionally high amounts of streamflow.[60]

Most nitrogen, phosphorus and sediment delivered to the Bay is from nontidal watershed areas, a load source that has no statistical change over time from 1985 – 2019.[60]

Management efforts throughout the Bay watershed can result in local water-quality improvements,[28] but the estimated effect of nutrient reductions on Bay water-quality varies throughout the watershed based on (1) the delivery of nutrients from landscape to streams, (2) the fraction of river loads that reach tidal waters, and (3) estuarine circulation patterns and biogeochemical transformations in the Bay.[19]

In general, nitrogen and phosphorus reductions in the Shenandoah Valley, lower to middle Susquehanna River watershed, Piedmont suburban and urban watersheds, and Delmarva Peninsula are estimated to result in the largest dissolved oxygen improvements in the Bay.[19]

Learn more about factors influencing water-quality standards attainment: chesapeakeprogress.com/clean-water/water-quality



Above: *Total load of nitrogen, phosphorus, and sediment entering the Chesapeake Bay, from 1985 – 2019.*[60]

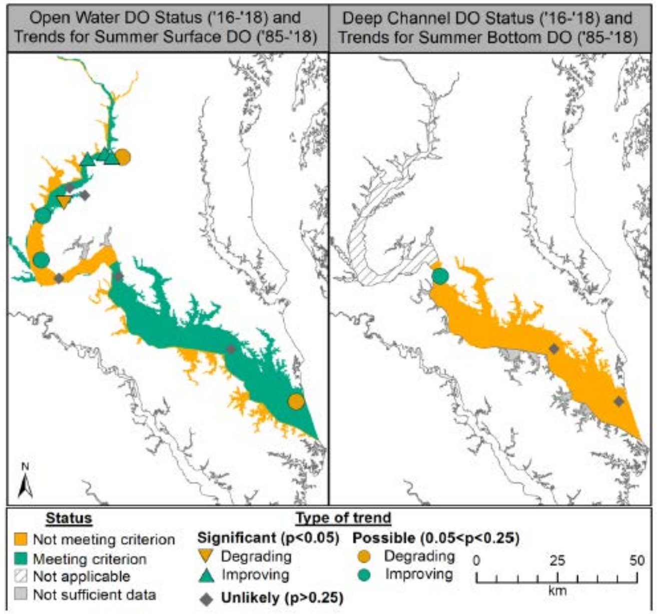
Question continues on the next slide.

What factors are affecting water-quality responses in the Bay?

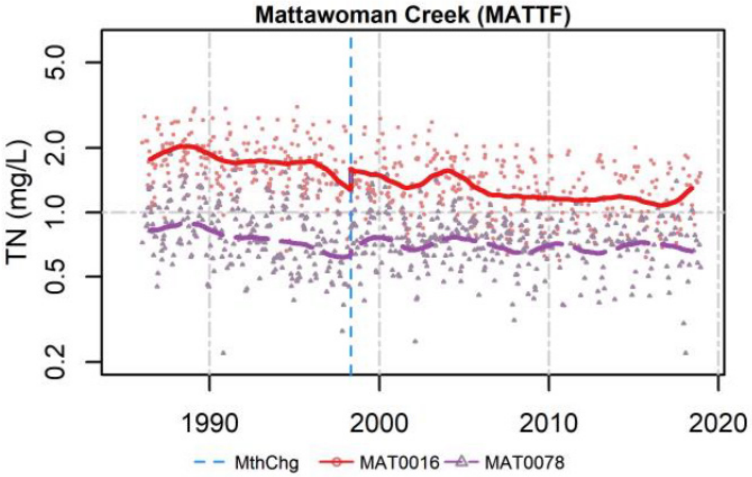
Tributary basin summaries were recently assembled for 12 major tributaries or tributary groups in the Chesapeake Bay watershed. Each document summarizes how tidal water quality and factors influencing tidal water quality have changed over time and can be used to develop local management strategies.

For example, in the tidal portion of the Potomac River…

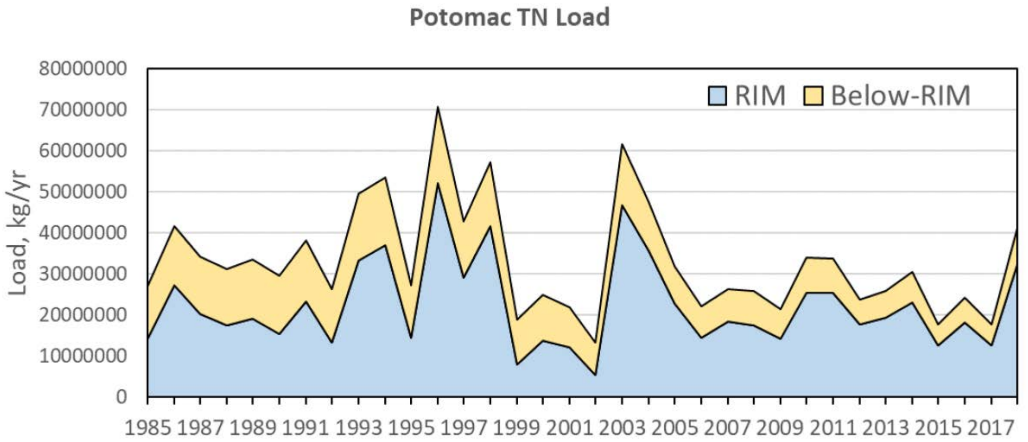
…most segments are meeting open water dissolved oxygen designated use criteria but are not meeting the deep channel criteria.[76]



…nutrient trends vary but have mostly improved over the long-term.[76]



…the delivered load of total nitrogen has declined over the long-term and is heavily influenced by annual streamflow variability.[76]



Explore the tidal tributary summaries:
cast.chesapeakebay.net/Home/TMDLTracking

***Above**: Graphics from the Potomac tidal tributary summary used to characterize water-quality changes.*[76]

Water-Quality Benefits to Biological Conditions and Human Health

Management Implications

1. While proper amounts of nitrogen, phosphorus, and sediment are required to support healthy aquatic communities, excess nitrogen, phosphorus, and sediment (and associated toxic contaminants) harms benthic macroinvertebrate and fish populations in the Bay and across the watershed.

2. Nitrogen and phosphorus management can address human health concerns, specifically, by improving the quality of drinking water and mitigating risks associated with toxic contaminants and harmful algal blooms.

3. The many co-benefits associated with nutrient and sediment reducing practices mean that management strategies can be tailored to address multiple priorities, such as improving local stream conditions, restoring fish habitat, reducing toxic contaminants, providing safe drinking water, and protecting healthy lands.

4. Existing water-quality monitoring networks can help inform state-impaired waters and be customized to address new areas of interest.

Background photo courtesy of Chesapeake Bay Program

Water-Quality Benefits to Biological Conditions and Human Health

Priority Stakeholder Questions

What are the risks to fish and other aquatic communities from nutrients and sediment?

What are the human health benefits of nitrogen, phosphorus, and sediment reductions?

How can monitoring, analysis, and modeling data better integrate states' water-quality initiatives?

Clicking a "launch" button will jump to content for a specific priority question.

A "return" button is included throughout this theme that will return you to this slide.

Background photo courtesy of Chesapeake Bay Program

What are the risks to fish and other aquatic communities from nutrients and sediment?

Proper amounts of nitrogen, phosphorus, and sediment are necessary to support healthy aquatic communities, but excess amounts can cause a range of negative outcomes in local streams and in the Bay.

Excess **nutrient loads** are a leading cause of eutrophication in the Chesapeake Bay watershed[77] and may interfere with hormone production,[78] collectively resulting in conditions that are deadly to aquatic life.

Sediment can be a vector for nutrients and contaminants; therefore, ecological impacts may also occur through exposure to elevated nitrogen, phosphorus, metals, pesticides, and other contaminants.[4] However, deposition of new 'clean' sediment may, in some cases, bury legacy-contaminated sediment present at a site.[79]

Sediment can directly impact biota through siltation degrading stream bed habitats, or suspended sediment altering light availability and causing physical damage to tissues and gills.[4]

Nitrogen, phosphorus, and sediment have been identified as important stressors to aquatic communities[4,80], but stressor-specific impacts vary by watershed setting,[81] climatic conditions,[82] trophic level,[83,84] study scale,[85] and often have complex interacting effects that lead to unexpected effects on stream health.[86]

In general, **nitrogen and phosphorus** are often identified as biotic community stressors,[80.85] with impacts detected more frequently in benthic macroinvertebrate communities than fish communities.[83,84] However, these effects may be obscured by larger land use effects.[81,87]

In general, **sediment** has been shown to impact a range of biota, from algae to aquatic vegetation, and native oysters to sport fish. Suspended sediment concentration alone is typically a poor predictor of ecological impacts, but the timing and duration of sediment impacts are important to understand negative ecological outcomes.[4]

What are the risks to fish and other aquatic communities from nutrients and sediment?

Many management practices designed to reduce nitrogen, phosphorus, and sediment may also benefit fish habitat and health.[42]

Management practices that benefit fish habitat include practices that protect natural shorelines, maintain riparian tree canopies, and slow surface water runoff.[42]

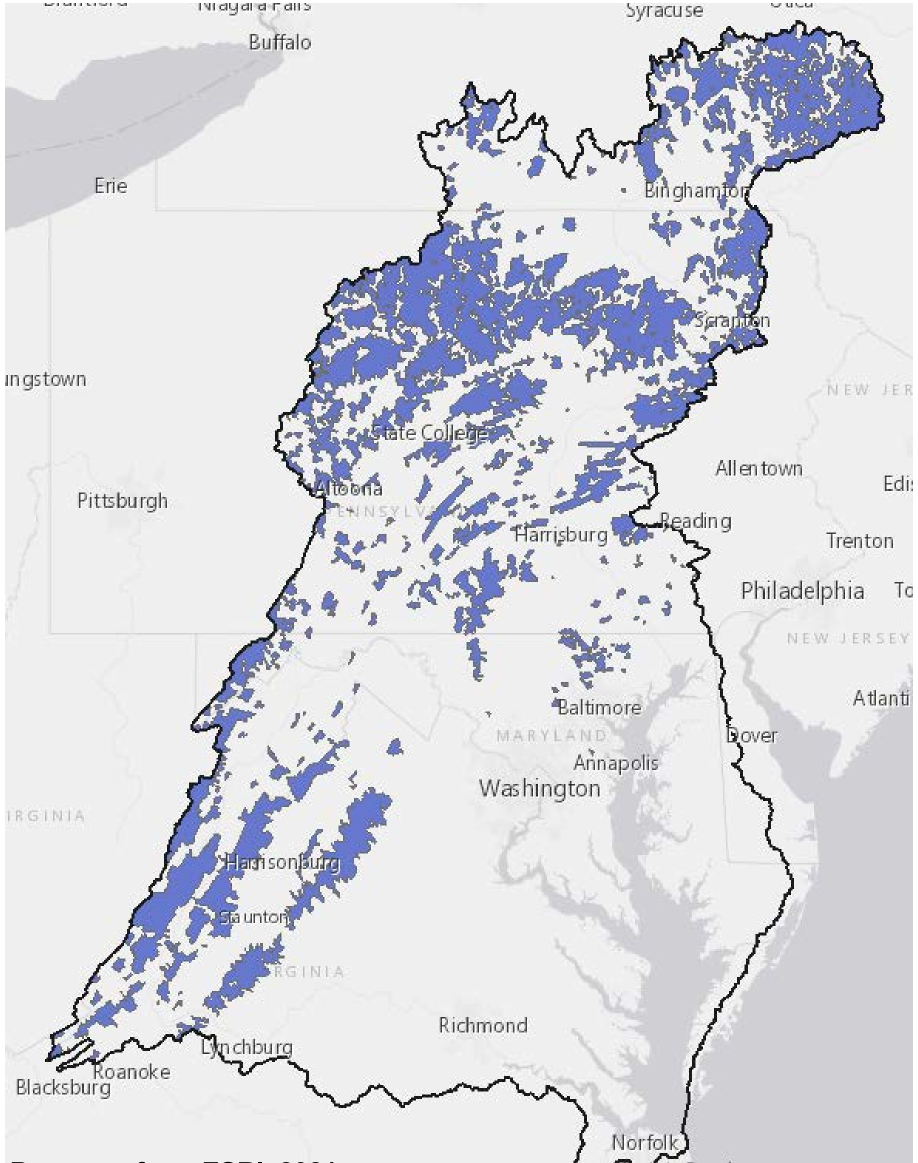
For brook trout, the most beneficial management practices are those that protect groundwater resources; avoid, mitigate, or reverse stream temperature increases; reduce high-velocity streamflow events, and consider passage requirements.[42]

***Above**: A brook trout caught in Pendleton County, WV. Many nutrient and sediment management practices offer co-benefits for fish health and habitat (Photo courtesy of Chesapeake Bay Program).*

Learn more about brook trout habitat in the Chesapeake Bay watershed: chesapeakeprogress.com/abundant-life/brook-trout

Learn more about brook trout and fish habitat management practice co-benefits:

- chesapeakebay.net/channel_files/26661/brooktrout_wiptemp_feb13.2018.pdf
- chesapeakebay.net/channel_files/26661/fish_habitat_wiptemp_2.12.18_v13.pdf



Basemap from ESRI, 2021

***Above:** Brook trout habitat in the Chesapeake Bay watershed.[88]*

What are the human health benefits of nitrogen, phosphorus, and sediment reductions?

Toxic contaminants are a health risk to people, fish, and wildlife and can co-occur with nutrients and sediment because they are delivered to agricultural and urban streams in the Chesapeake Bay watershed through similar runoff and erosion processes.[89,90]

Toxic contaminants such as polychlorinated biphenyls (PCBs), mercury, polycyclic aromatic hydrocarbons (PAHs) lead to fish consumption advisories, can increase cancer risks, and cause developmental damage in humans.[89,90]

In **urban areas**, toxic contaminants are often associated with industrial, commercial, and residential sources.[90.91]

In **agricultural areas**, toxic contaminants are often associated with chemicals used for livestock (biogenic hormones and antibiotics) and crop (herbicides and pesticides) production.[89]

Many water-quality management practices designed to reduce nitrogen, phosphorus, or sediment may also reduce toxic contaminants.[42,92]

Management practices may most effectively reduce toxic contaminants if they are targeted in areas with known legacy contaminants, trap sediments, target wastewater treatment plant upgrades, or interrupt land to water delivery pathways through buffers or stormwater retrofits.[42]

Learn more about toxic contaminant research and management practice co-benefits:

- chesapeakebay.net/what/goals/toxic_contaminants
- d3upxwu13a0qpr.cloudfront.net/documents/CoBenefits/CoBeneToxics_draft%202-14-18_Clean.pdf

Question continues on the next slide.

What are the human health benefits of nitrogen, phosphorus, and sediment reductions?

Groundwater used as a drinking water supply often comes into contact with what's on the land and/or underground before making it to your faucet.

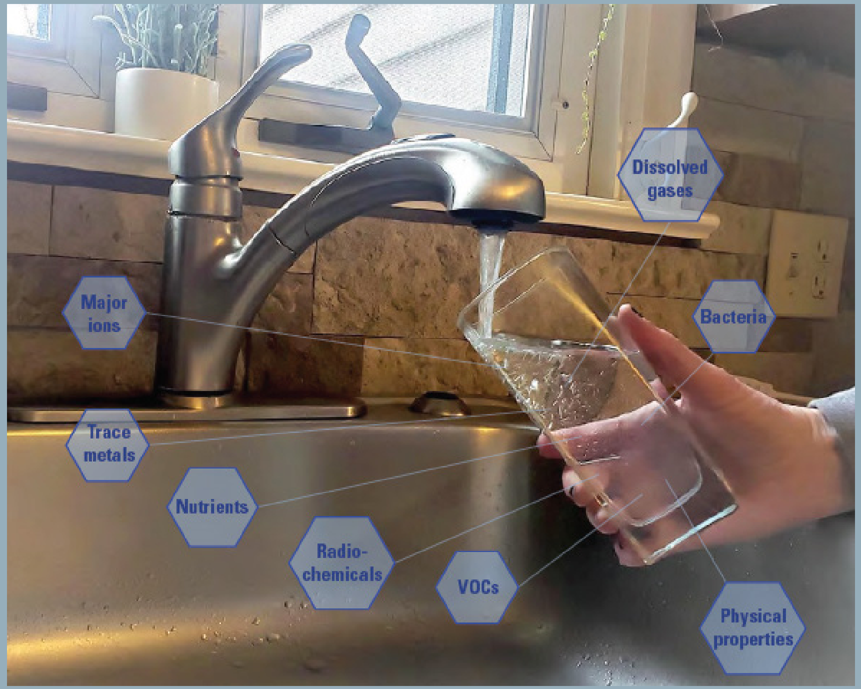
The quality of groundwater used as a drinking water supply is influenced by the regional and local setting, including the surrounding soil, geology, and land use, piping/plumbing, treatment, and well construction.[93,94,95]

Drinking water may be delivered through regulated public water-supply systems or private domestic-supply wells that are solely the responsibility of the homeowner. About 14% of the US population uses private wells for their primary residential water supply.[96]

Excessive nitrate in drinking water is a health risk and is often associated with other harmful contaminants, such as bacteria.[97]

High concentrations of nitrate in drinking water causes "blue baby syndrome" (*infant methemoglobinemia*) and may be associated with birth defects and certain cancers.[96,98]

A regulatory upper limit on nitrate in public drinking water supplies is set at 10 milligrams per liter as nitrate-nitrogen to guard against these risks.[99]



***Above**: Common constituents found in private well water are influenced by local geology, land use, well construction, and plumbing. (Photo courtesy of John W. Clune, USGS)*

Question continues on the next slide.

What are the human health benefits of nitrogen, phosphorus, and sediment reductions?

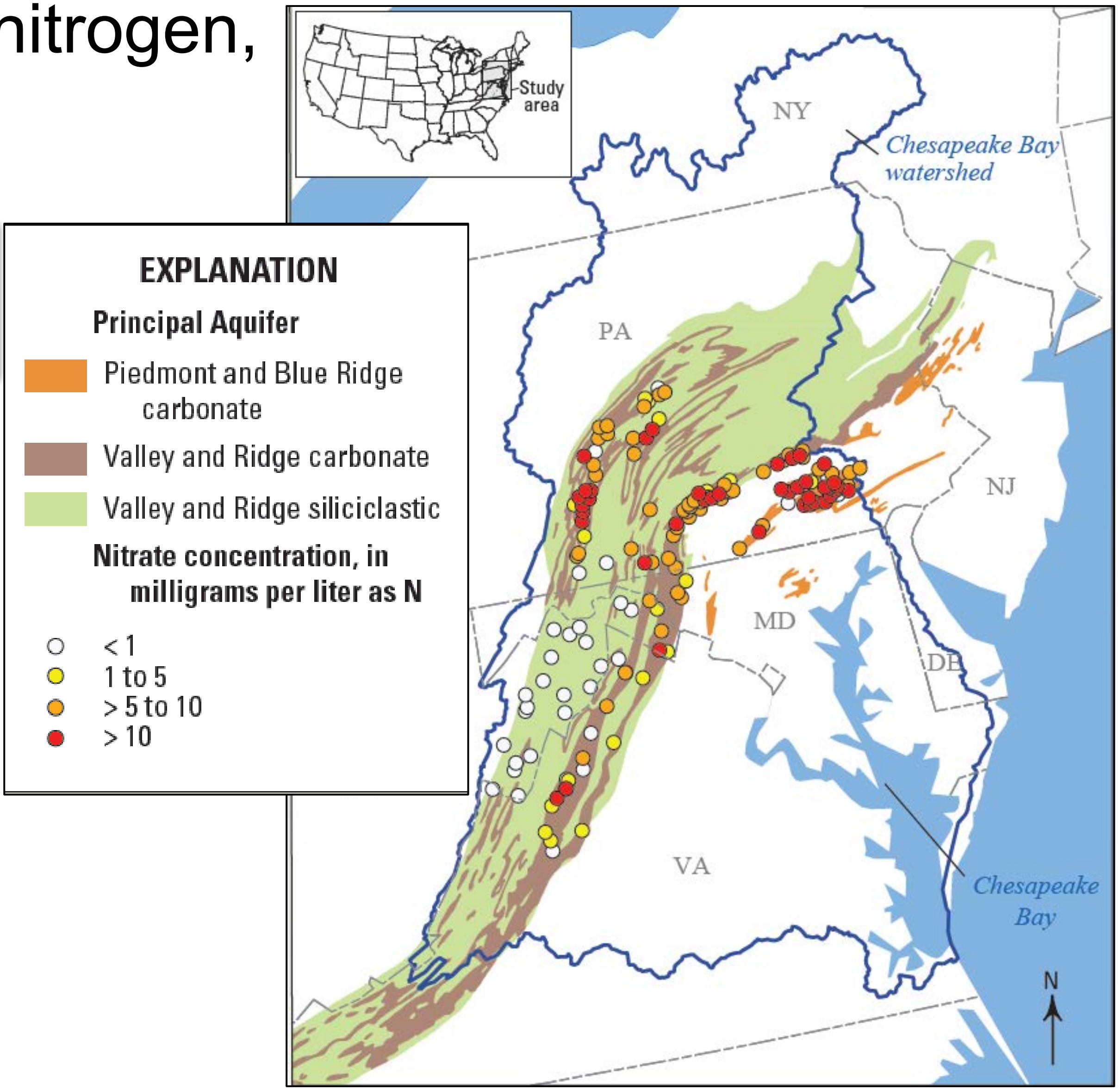
While concentrations of nitrate in groundwater are commonly below regulatory limits, elevated concentrations are found in some settings where transmissive bedrock can facilitate groundwater contamination by human activities at the land surface.[97]

Nitrate concentrations in groundwater beneath agricultural lands can be elevated because of manure and fertilizer applications[100] and, in some aquifers, these concentrations have increased in recent decades.[56]

Sinkholes and fractures allow water to quickly enter some carbonate rock aquifers, resulting in elevated nitrate concentrations. Some of the highest nitrate concentrations in the nation are measured in shallow groundwater in agricultural carbonate areas of the Chesapeake Bay watershed.[101]

Agricultural land use and soil conditions promote elevated nitrate groundwater concentrations on the Delmarva Peninsula[13], where nitrate concentrations were found to exceed upper regulatory limits in about one third of groundwater samples.[102]

Learn more about the water quality of our nation's aquifers: pubs.er.usgs.gov/publication/cir1360



***Above**: Nitrate concentrations sampled from groundwater wells in selected Valley and Ridge, Piedmont, and Blue Ridge aquifers.[101]*

Question continues on the next slide.

What are the human health benefits of nitrogen, phosphorus, and sediment reductions?

Harmful algal blooms (HABs) have been observed in a broad range of habitat conditions in the Bay watershed and its tributaries and are associated with widespread harmful impacts to humans, aquatic living resources, and aquatic ecosystems.[103,104,105]

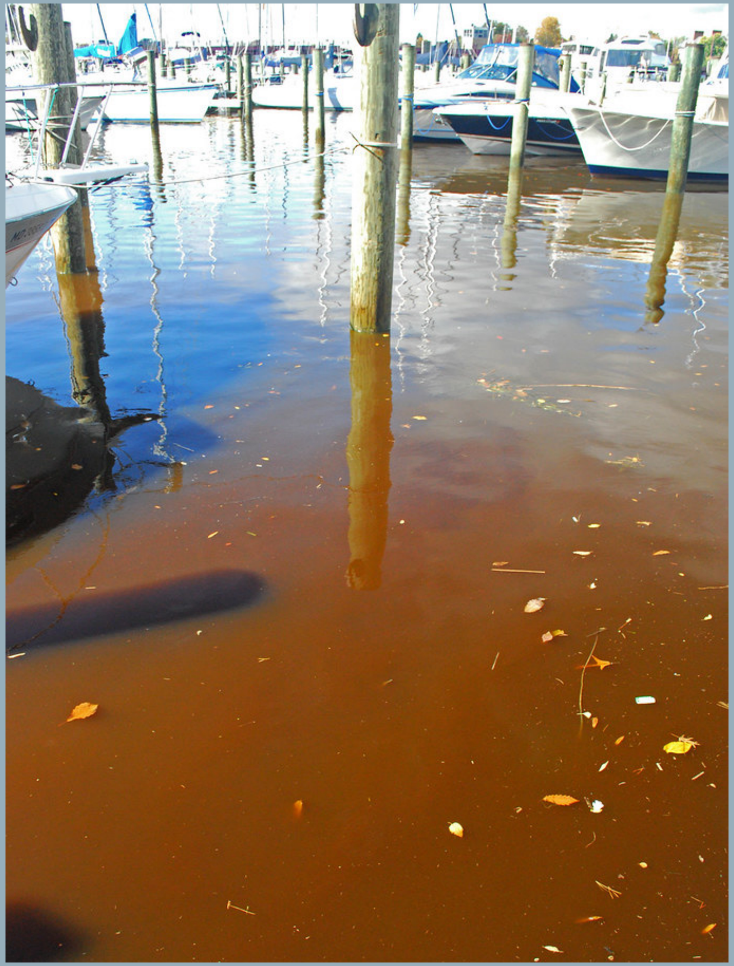
Large algal blooms can cause negative ecosystem impacts, but when some blooms produce toxins, a range of harmful effects on fish, wildlife, and people can occur. Both toxin and non-toxin producing blooms can be harmful and are defined as HABs.

Exposure to HABs, typically through ingestion of contaminated food, inhalation, or direct skin contact, can result in a suite of human health issues that range from respiratory irritations to fatalities.[106]

Nutrient over-enrichment and climate-related changes are key contributors to HAB outbreaks and are among a complex mix of physical-biological interactions that cause certain algal communities to produce harmful toxins.[107,108,109,110]

HAB occurrences have increased in the Chesapeake Bay in recent decades and warmer water temperatures may increase blooms in future years.[111,112]

Management of nutrient inputs to the watershed can lead to significant reduction in HABs.[110]



***Above**: An algae bloom in a Chesapeake Bay tributary. Not all algae blooms produce harmful toxins, and while factors affecting the production of harmful toxins are complex, nutrient reductions can lead to significant reduction in HABs.[110] (Photo courtesy of Chesapeake Bay Program)*

How can monitoring, analysis, and modeling data better integrate states' water-quality initiatives?

Monitoring networks, assessments, and management strategies can be adapted to meet local and state water-quality concerns.

Sediment/turbidity and nutrients are common causes of impairment on the Environmental Protection Agency (EPA) 303d list of impaired waters in the Chesapeake Bay watershed.[113] Water-quality management strategies that target these areas can address state and regional requirements.

Pathogens like E. *coli* and other fecal coliforms are a significant water-quality concern in many local waterways because of their harm to human and aquatic health and impacts on recreational uses.

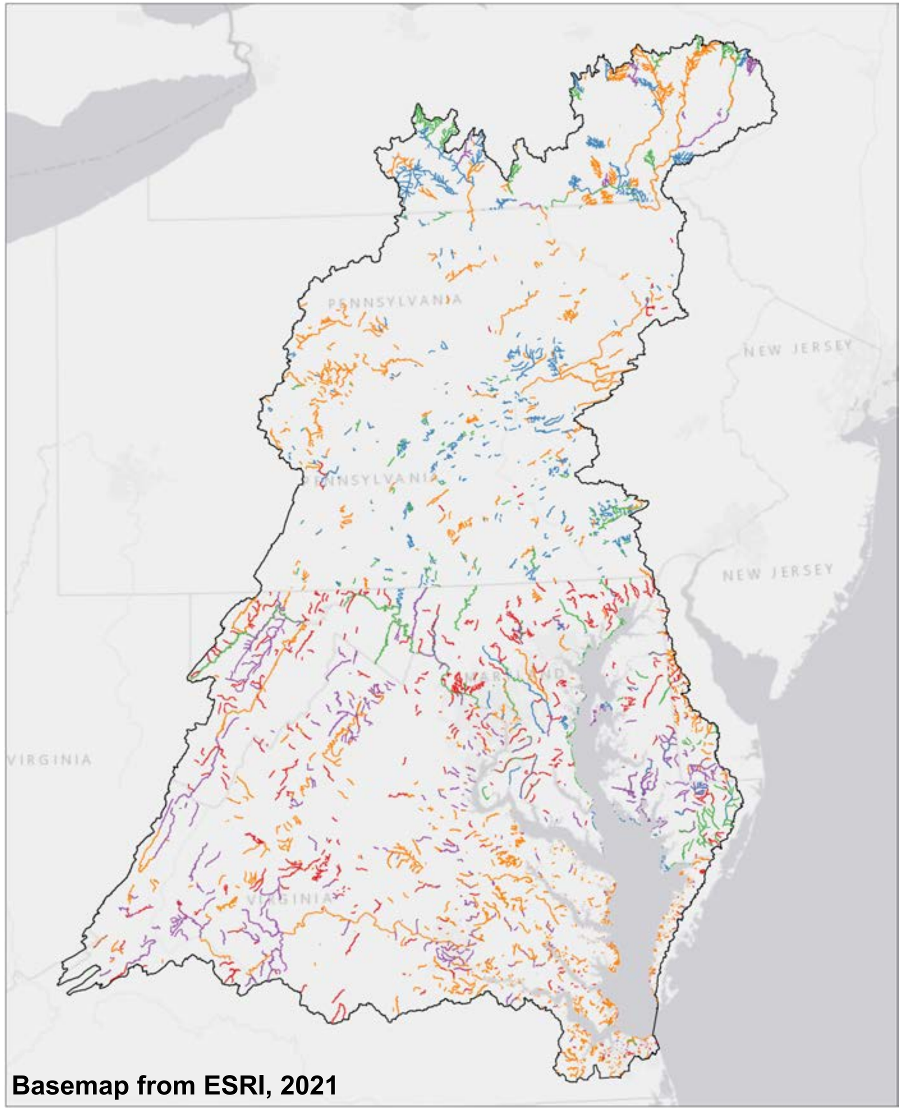
Through partnerships with state and local agencies, existing water-quality monitoring networks can be expanded to collect bacteria samples or other constituents of concern.

Through partnership with Virginia Department of Environmental Quality, bacteria samples are collected at some NTN stations along with nutrient and sediment samples.

Above: *A hydrologic technician collects a water-quality sample from the Chesapeake Bay nontidal monitoring network (NTN) following a large storm, conditions often transport elevated bacteria counts.*

Probable Source of Impairment

- Nutrients
- Sediment or Turbidity
- Pathogens
- Other Source
- Cause Unknown



Above: *Impaired waters with established TMDLs in the Chesapeake Bay watershed that appeared on a state's 303(d) list to EPA, as of 2015.*[113] *These data do not include all impaired waters in the watershed.*

Question continues on the next slide.

How can monitoring, analysis, and modeling data better integrate states' water-quality initiatives?

Existing water-quality data can be better leveraged to address state and local concerns through interagency collaborative efforts.

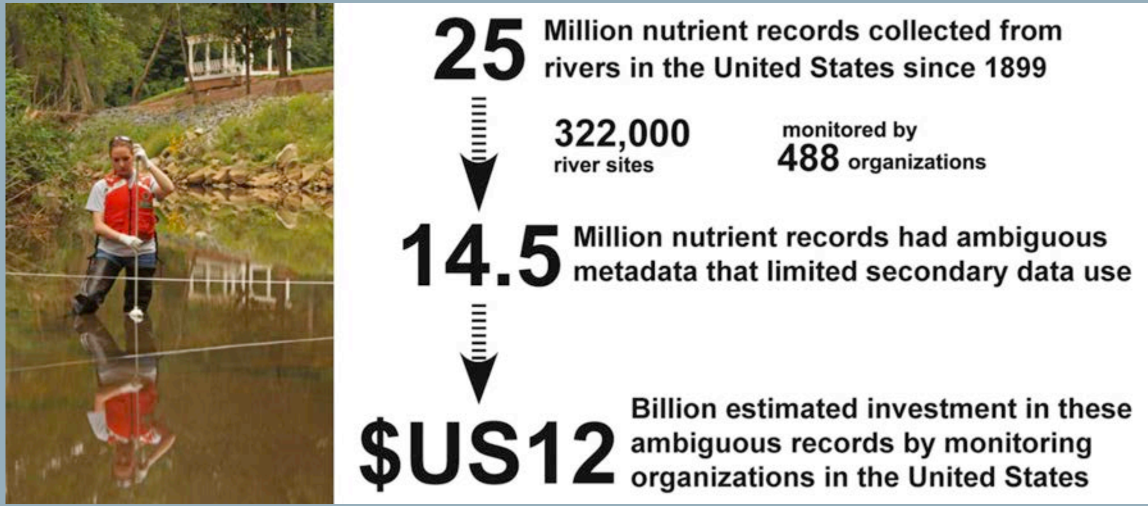
Ambiguous water-quality data records are defined as those missing key pieces of information that limit use of the data beyond original intent.[114]

Nationally, the economic loss of ambiguous legacy data is estimated to be $12 billion.[114]

Collaborative efforts toward shared and reliable datasets across agencies can help reduce ambiguous data and have the potential to improve the scientific basis for decision making.[115]

Reliable datasets would help regional, state, and local efforts in shared development of status/trends, modeling, nutrient criteria, impaired water designations, conservation planning, etc. For example, multi-agency datasets were used to determine thresholds for reference conditions and compare nutrient criteria values in Pennsylvania.[116]

These goals may be best achieved through interagency committees that bring together stakeholders and serve an advisory role for sharing recommended sampling and metadata protocols and develop a plan to resolve issues for better secondary use of data.[115]



***Above**: Water-quality records with that are missing key pieces of information can often not be used across agencies or for secondary uses, use of the data beyond original intent.[114]*

How can monitoring, analysis, and modeling data better integrate states' water-quality initiatives?

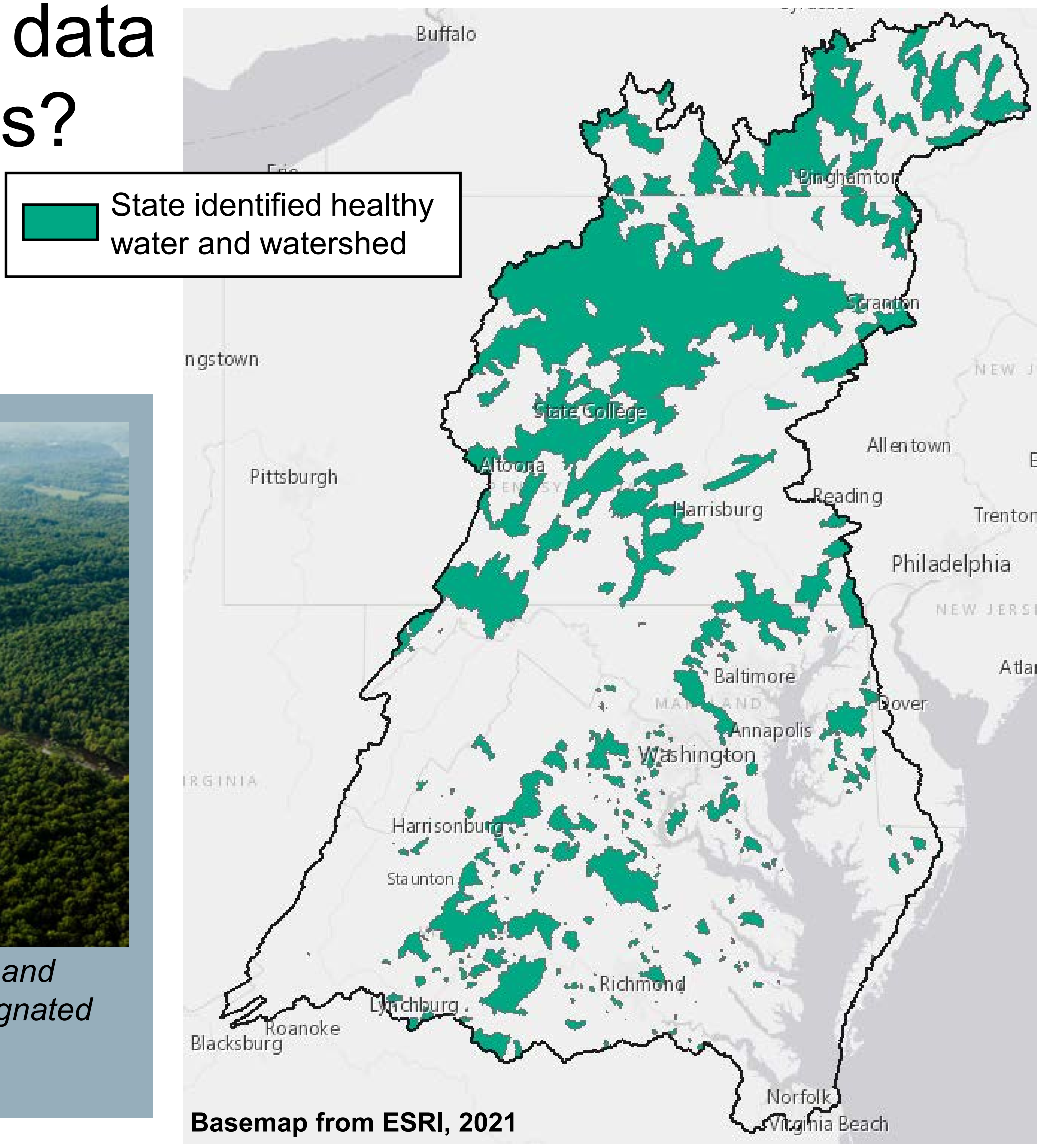
Meeting Chesapeake Bay water-quality goals can help protect state-identified healthy waters and watersheds.

Each Chesapeake Bay jurisdiction has its own definition of healthy waters and watersheds, generally based on six key ecological attributes[117]:

1. Landscape Condition
2. Geomorphology
3. Habitat
4. Water Quality
5. Hydrology
6. Biological Condition

Management activities to restore water-quality are often more expensive than those designed to protect the quality of healthy waters and watersheds.

Above: *The confluence of the Rapidan and Rappahannock Rivers in VA, state designated healthy watersheds (Photo courtesy of Chesapeake Bay Program).*



Above: *Map of healthy waters and watersheds, as defined by Chesapeake Bay states.*[88]

Explore state Chesapeake Bay healthy watersheds and their various health indices: gis.chesapeakebay.net/healthywatersheds/assessment

Sediment Dynamics and Reservoir Infilling

Management Implications

1. Sediment loads are typically highest in agricultural and urban watersheds and in the Piedmont physiographic province. Streambank erosion processes typically dominate in headwater streams and floodplain trapping can reduce sediment loads in larger rivers.

2. Consider management practices that reduce streambank erosion in headwater streams and urban areas, that control upland erosion in agricultural areas, and that increase floodplain connectivity in larger rivers.

3. Reservoirs in the Lower Susquehanna River watershed affect particulate and, to a lesser extent, dissolved water-quality constituents. Effective nutrient and sediment management in the Susquehanna River is critical to attaining water-quality standards in the Bay and would consider such reservoir effects.

Sediment Dynamics and Reservoir Infilling

Priority Stakeholder Questions

Clicking a “launch” button will jump to content for a specific priority question.

What is legacy sediment and how can it be addressed?

What are the sources of suspended sediment and how is it transported?

What are sources and mechanisms driving water-quality changes in the lower Susquehanna River reservoirs?

A “return” button is included throughout this theme that will return you to this slide.

What is legacy sediment and how can it be addressed?

Changes to the landscape that occurred centuries ago continue to impact stream sediment dynamics, including the effect of current watershed management efforts.[4]

Legacy sediment is "…sediment stored in upland and lowland portions of the Bay's tributary watersheds as a byproduct of accelerated erosion caused by landscape disturbance following European settlement, most prominently in Piedmont and Coastal Plain provinces."[118]

Land clearing and other activities associated with early colonization altered relatively stable sedimentation rates, transported large amounts of sediment to streams, and resulted in increased floodplain sediment storage.[4]

This accumulated stream valley and floodplain sediment – often resulting in tall streambanks – continues to be mobilized to streams, with increased sediment erosion exacerbated through urbanization.[4]

***Above**: A historic plank road buried under floodplain sediments in Fairfax County, VA highlights the impact of land use history on present-day sediment dynamics.*

Legacy sediment management is a priority for reducing sediment loads in the Bay watershed because it represents a long-term supply that will continue to be eroded and supply sediment to streams and rivers.[4]

Multiple management strategies exist to address legacy sediment along stream channels. The appropriateness of these strategies are influenced by watershed-specific contexts and continued research is needed to evaluate their effectiveness.[4]

What are the sources of suspended sediment and how is it transported?

Understanding sources and transport of sediment is critical to evaluating watershed impairment and management strategies.

Suspended sediment can be derived from erosion of upland or channel sources. These two sources require different management strategies.[4]

Headwater streams can have erosive streambanks or head cuts. Consider management practices that prevent bank erosion or control runoff.[4]

Larger streams and rivers can trap large amounts of sediment eroded upstream. Consider management practices that conserve and restore hydrologic connectivity to the floodplain.[4]

Urban areas experience high sediment loads, primarily from streambank erosion. Consider management practices that offer upland stormwater controls and prevent bank erosion.[4]

Agricultural areas can experience high sediment loads from bank and upland erosion. Consider management practices that address both sources.[4]

Above: *Riparian buffers and cover crops, which primarily reduce sediment from streambank and upland erosion, respectively (Photos courtesy of Chesapeake Bay Program).*

Question continues on the next slide.

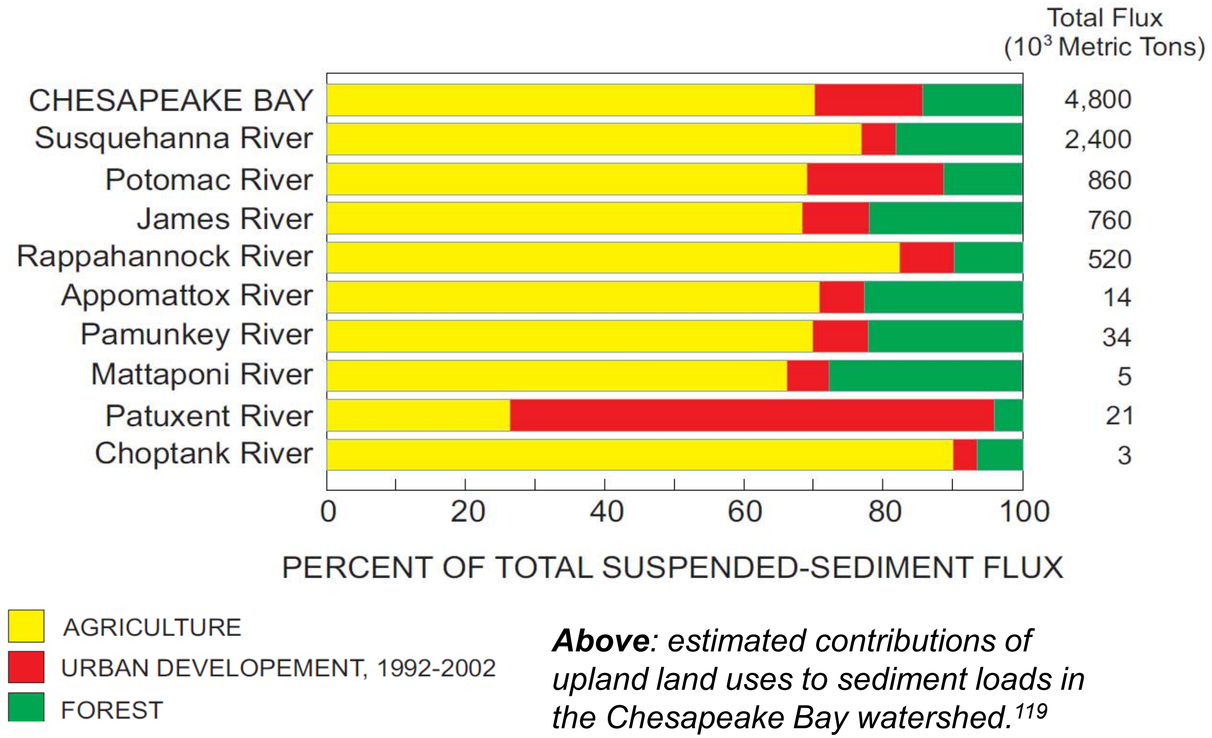
What are the sources of suspended sediment and how is it transported?

Important sources of sediment in the Bay watershed include agricultural and urban land uses and the Piedmont physiographic province.[4]

Agricultural land use contributes about 69% of sediment delivered to the Bay.[119]

On a per-area basis, **urban lands** contribute about 70 times more sediment than agricultural, but, because there is more agricultural land in the watershed, urban areas deliver less sediment to the Bay than agriculture.[119]

Piedmont watersheds typically have elevated sediment yields because of unique geologic features that contribute to erosive soils.[4]



***Above**: estimated contributions of upland land uses to sediment loads in the Chesapeake Bay watershed.[119]*

View the estimated spatial distribution of suspended sediment loads in the Chesapeake Bay watershed: sparrow.wim.usgs.gov/sparrow-northeast-2012

In smaller watersheds, sediment sources can be identified through "sediment fingerprinting". This data collection and analysis technique can quantify specific sediment sources in a watershed and can be used to assess and target management practices.[120]

What are the sources of suspended sediment and how is it transported?

Sediment enters streams from upland or streambank erosion, with rates of streambank erosion exceeding upland erosion in many Chesapeake stream networks.[4]

Streambank erosion rates are highly variable in space and time and are difficult to predict. Factors that influence streambank erosion include watershed area, streambank vegetation, stream-valley geomorphology, freeze-thaw cycles, and flood frequency.[4]

Not all eroded sediment is delivered to streams or to downstream receiving waters; floodplains can trap large amounts of sediment.[4]

Floodplains can trap large amounts of sediment through storing material during overbank flooding and by buffering eroded sediment from entering stream channels.[4]

While rates of sediment erosion and deposition can theoretically balance one another, most Chesapeake stream networks are dominated by one of these processes.[4]

Headwaters are primarily dominated by bank erosion, while floodplains along larger streams can trap large amounts of sediment.[4]

Most suspended sediment is delivered to the Bay as fine-grained material (silt or clay).[4]

***Above**: Stormflow and streambank erosion, processes that represent a common source of sediment delivered to urban streams.*

Question continues on the next slide.

What are the sources of suspended sediment and how is it transported?

Sediment "hops and rests" in and out of different storage zones as it is transported downstream, with storage time that can range for days to millenia.[4]

In-channel bed sediment is mobilized frequently and often has an average age of less than a year.[4]

Sediment stored within in-channel deposits, such as point bars or fine channel margin deposits, are assumed to be mobilized downstream on yearly to decadal timescales.[4]

Above: *Example storage zones of sediment with a description of average residence times.*

Floodplain sediment storage can range from decades to millenia and is commonly reintroduced to stream channels through bank erosion.[4]

Sediment storage and residence times affect watershed responses to management.[4]

What are the sources and mechanisms driving water-quality changes in the lower Susquehanna River reservoirs?

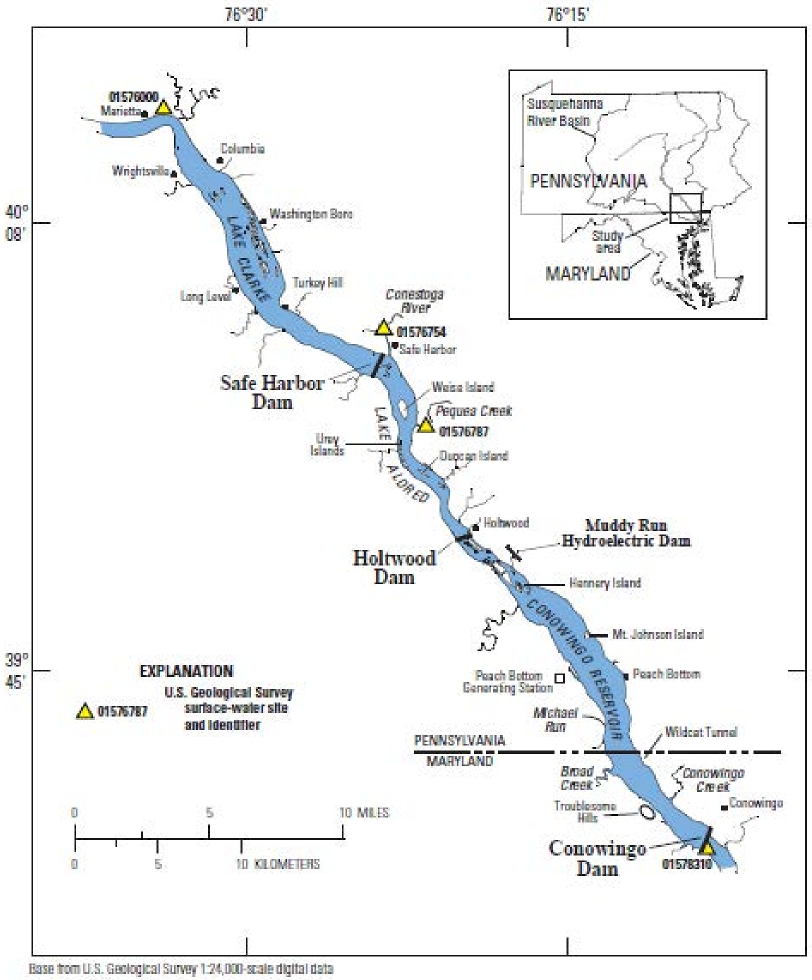
The delivery of sediment and associated nutrients from the Susquehanna River to the Bay has increased since the late 1990s because of sediment infill of the Conowingo Reservoir.[121,122,123]

Historically, the three reservoirs on the Lower Susquehanna River functioned as sediment traps. Over the past 80 years, approximately 60% of sediment transported into the reservoirs was retained.[121]

This trapping capacity is reduced as sediment fills within the reservoirs. Lake Clarke and Lake Aldred reached sediment equilibrium decades ago while the Conowingo Reservoir has recently entered this state. The Conowingo Reservoir is at about 92% capacity for sediment storage.[121]

Decreased reservoir trapping allows more sediment and nutrients to enter the Bay, posing new challenges towards meeting water-quality attainment goals.

Understanding these reservoir dynamics is critical to the overall health of the Bay, as the Susquehanna River delivers the largest amounts of nutrients and sediment to the Bay and directly impacts standard attainment in the Upper Bay.[121]



***Above**: Location of the Lake Clarke, Lake Aldred, and Conowingo Reservoirs in the Lower Susquehanna River Basin.[121]*

Question continues on the next slide.

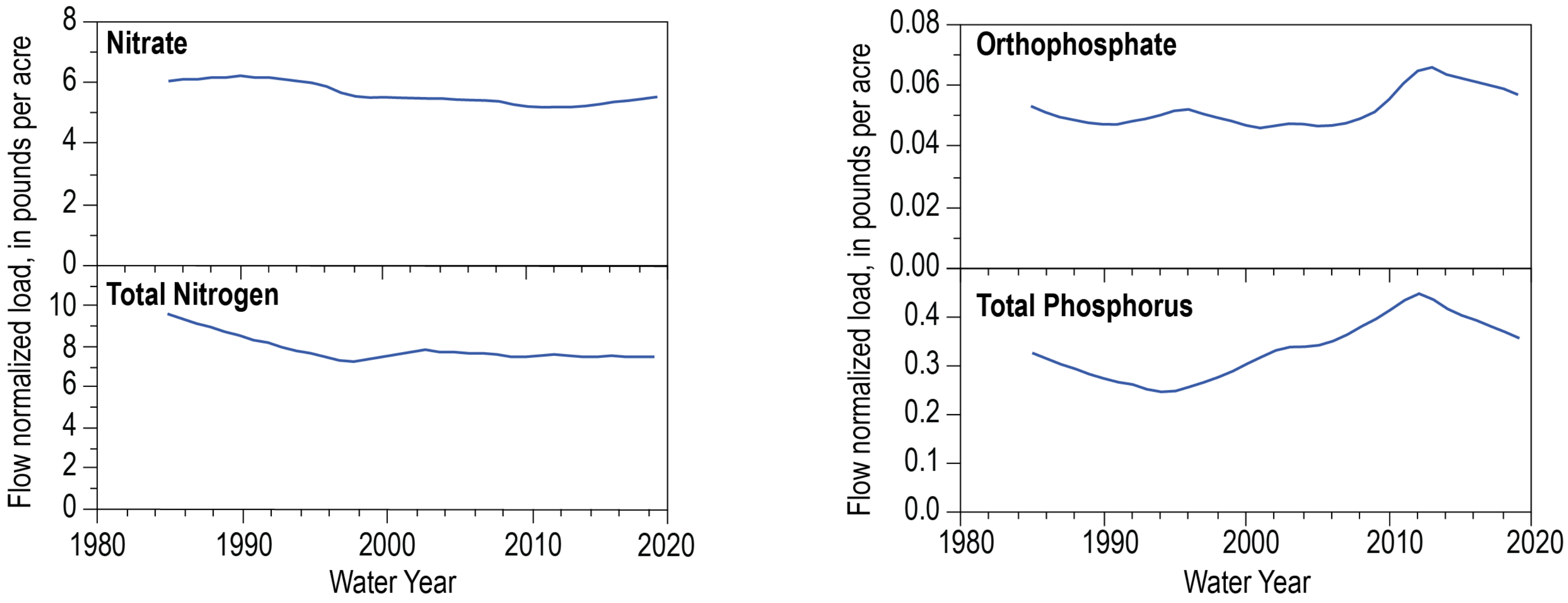
What are the sources and mechanisms driving water-quality changes in the lower Susquehanna River reservoirs?

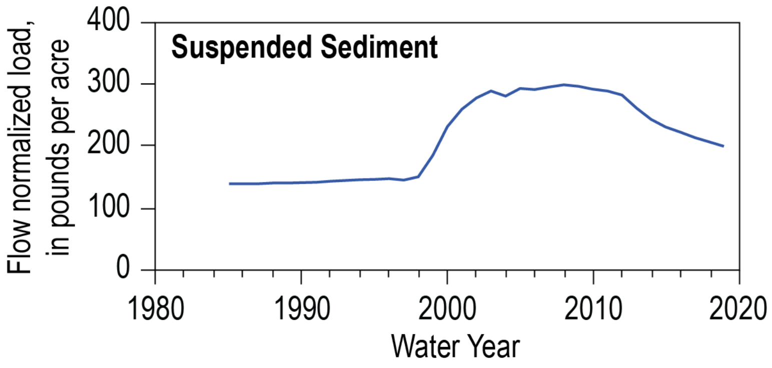
Water-quality trends measured from a Susquehanna River monitoring station immediately downstream of the Conowingo Reservoir (USGS station ID: 01578310) can help quantify how conditions entering the Bay are changing over time.

Long-term nitrate and TN loads have **declined**, but short-term nitrate loads have **increased** while TN has **no trend**.[124]

Long-term TP loads have **no trend** and have **declined** in the short term. Orthophosphate loads have **no trend** during either trend period.[124]

Long-term SS loads have **increased** and have **declined** during the short-term.[124]





***Above and left**: Flow normalized nutrient and sediment loads at Susquehanna River Conowingo, MD (USGS station ID: 01578310) from 1985 – 2019.*[124]

Water-quality changes below the Conowingo Reservoir can differ from patterns upstream in the Susquehanna River watershed.[1]

What are the sources and mechanisms driving water-quality changes in the lower Susquehanna River reservoirs?

Phosphorus loads in the lower Susquehanna River may be influenced by internal sources within the reservoir system and dynamics in upstream areas.

Submerged aquatic vegetation may scavenge phosphorus from reservoir sediments and release dissolved phosphorus during seasonal senescence.[125]

Biogeochemical changes such as warming temperatures or increasing pH may promote phosphorus release from sediments.[9]

Increased orthophosphate loads in some lower Susquehanna River watersheds have been associated with increased manure applications and use of conservation tillage.[8]

While changes in sediment and particulate nutrients throughout the mainstem of the lower Susquehanna River are generally influenced by reservoir dynamics, changes in dissolved nutrients are less well understood and can directly impact water-quality in the Upper Bay.

While factors limiting algal growth in the Bay (commonly a combination of nutrient, light, and temperature conditions) vary seasonally and spatially, phytoplankton communities in the upper Bay are phosphorus limited during most of the year.[126]

Increased phytoplankton biomass, and associated chlorophyll-a concentrations in the upper Bay, while not definitely understood, may be associated with phosphorus export from the Susquehanna River.[127]

Continued research and additional monitoring data is needed to better understand the internal dynamics in the lower Susquehanna River reservoirs, including processes affecting nutrient exchange and mobilization.

Climatic Influences on Water Quality

Management Implications

1. Air and stream-water temperatures and the volume and intensity of precipitation have increased in the Bay in recent decades and these trends are expected to continue.

2. Climate change is expected to alter nutrient and sediment loads to the Bay. Most hypothesized impacts are related to changes in streamflow, terrestrial runoff and erosion, or biogeochemical processes, and these may sometimes result in complicated interacting effects on trends.

3. Climate change is expected to alter the effectiveness of some management practices. The Chesapeake Bay Program's watershed model recently incorporated climate change projections to understand potential effects on water quality.

Background photo courtesy of Chesapeake Bay Program

Climatic Influences on Water Quality

Priority Stakeholder Questions

Clicking a “launch” button will jump to content for a specific priority question.

How are temperature and precipitation patterns changing and expected to change in future years?

How are streamflow patterns changing?

How are climatic changes expected to influence water quality in the Bay and its watershed?

How do climatic changes affect management practices?

A “return” button is included throughout this theme that will return you to this slide.

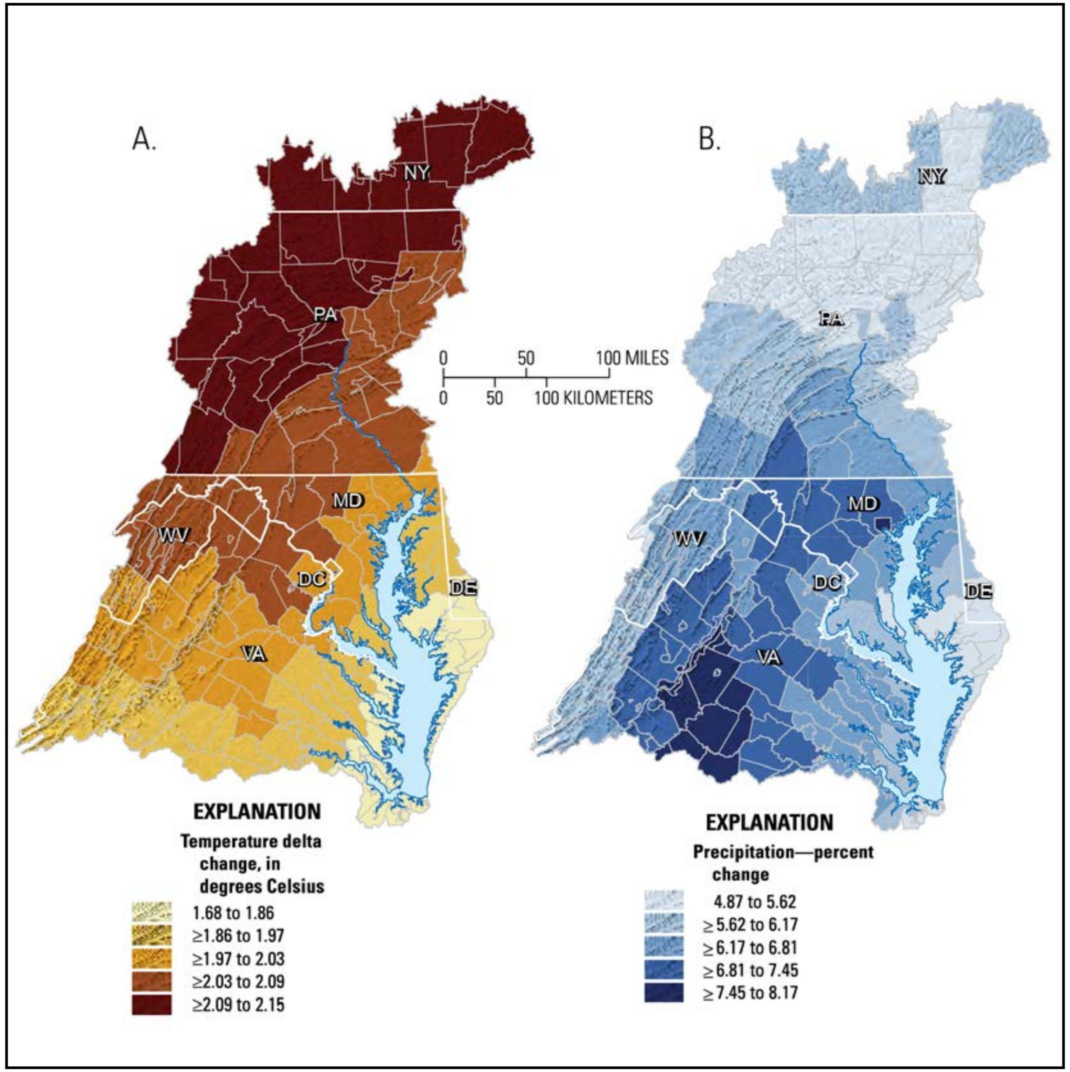
How are temperature and precipitation patterns changing and expected to change in future years?

Air and stream-water temperatures and the volume and intensity of precipitation have increased in the Bay in recent decades and these trends are expected to continue.

Precipitation: The magnitude and frequency of extreme precipitation events has increased more in the Northeast than any other region of the U.S.[128] Average annual precipitation volume has increased through the Chesapeake Bay watershed (1927 – 2014), with greater increases observed in northern watersheds than in southern watersheds.[129]

Temperature: Air and water temperatures have increased through 2010 in the Mid-Atlantic by approximately 0.02 and 0.03 °C per year, respectively.[130]

Projections: Water temperatures are forecasted to increase by 2-6 °C by the year 2100 and annual mean air temperatures are expected to increase by 2 °C by 2050.[131] Annual precipitation is forecasted to increase in most areas of the watershed on average by 6.3%, along with increases in precipitation intensity and patterns of drought followed by intense rainfalls.[131,132]



***Above**: Spatial variability in predicted change from 1995 – 2050 in (A) mean annual air temperature and (B) precipitation.*[133]

How are streamflow patterns changing?

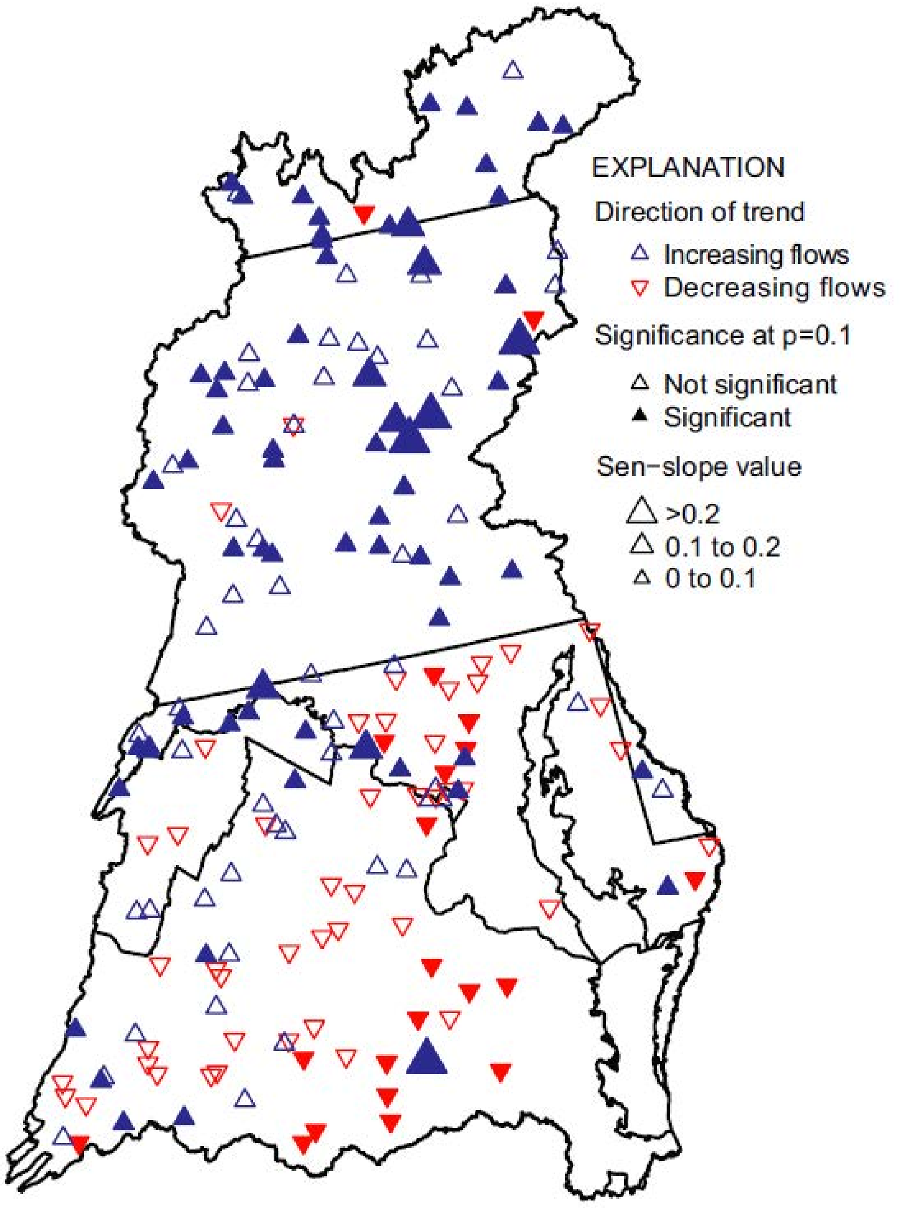
Streamflow changes over time have shown a mixture of responses, with trends varying spatially, over different time periods, and during high and low flow conditions.[129,134,135]

Average monthly streamflow generally increased from 1927 – 2014, with larger and more significant changes in the northern part of the watershed and few significant changes in southern part of the watershed.[129]

Low-flow conditions are important indicators for water management and ecological conditions and have generally increased in the northern part of the watershed and decreased in the southern part of the watershed from 1939 – 2013.[134]

Trends in a variety of streamflow conditions were non-significant throughout most of the watershed in recent years (2000 – 2018), with previous time periods showing larger and more significant changes (1940 – 1969 and 1970 – 1999).[135]

Although precipitation is an important driver of streamflow and has also increased throughout the Bay watershed, total precipitation does not explain all streamflow variability, highlighting the complexity of regional water budgets and the role of seasonal climatic patterns.[129,134]



Above: *Spatial distribution of trend results for annual seven-day minimum streamflow from 1939 – 2013.*[134]

How are climatic changes expected to influence water quality in the Bay and its watershed?

Climate change is expected to affect nutrient fate and transport in multiple ways. Most hypothesized impacts are related to changes in streamflow, terrestrial runoff and erosion, or biogeochemical processes, and these may sometimes result in complicated interacting effects on trends.[5] In general, increasing intensity of precipitation is expected to drive increases in sediment and phosphorus loads. Impacts on nitrogen may vary across the watershed.

Precipitation effects
(wetter, more storm events)

Studies across the watershed generally support a direct 1:1 relation between changes in streamflow and total nitrogen load, particularly in developed and agricultural watersheds. Forested watersheds may be more sensitive to changes in flow due to increased atmospheric nitrogen deposition in high precipitation years.[136]

Changes in rainfall volume and intensity have been linked to corresponding increases in phosphorus and sediment loads from the landscape because of increased erosion and sediment transport, resulting increased flux of sediment-associated phosphorus.[36,131,137]

Increased precipitation may overwhelm combined sewer overflow design capacities, resulting in more frequent overflow events and increased nutrient loads from these sources.[138]

Aggregate effects
(warmer and wetter)

Aggregate effects may decrease nitrogen loads through increased biochemical reaction rates, resulting in loss of nitrogen to the atmosphere through denitrification or biotic uptake.[139] Reductions in flow-normalized total nitrogen loads in the Bay between 1990 and 2010 were closely linked to regionally warmer and wetter conditions. These climatic effects were greater than the combined effects of anthropogenic sources and were consistent with the effects of terrestrial denitrification.[26]

In low-lying coastal areas, legacy phosphorus may be mobilized in agricultural soils in areas of saltwater intrusion resulting from drought or sea level rise.[140]

Temperature effects
(warmer)

Warmer temperatures may increase nitrogen and phosphorus release from organic matter and mobilization into waterways.[36]

- Dry periods may slow plant growth, resulting in increased erosion of sediment and nutrients, particularly if followed by intense rain events.[141]
- Soil enzymatic activities may increase with increasing temperature, increasing nitrogen and phosphorus mobilization.[142]

How are climatic changes expected to influence water quality in the Bay and its watershed?

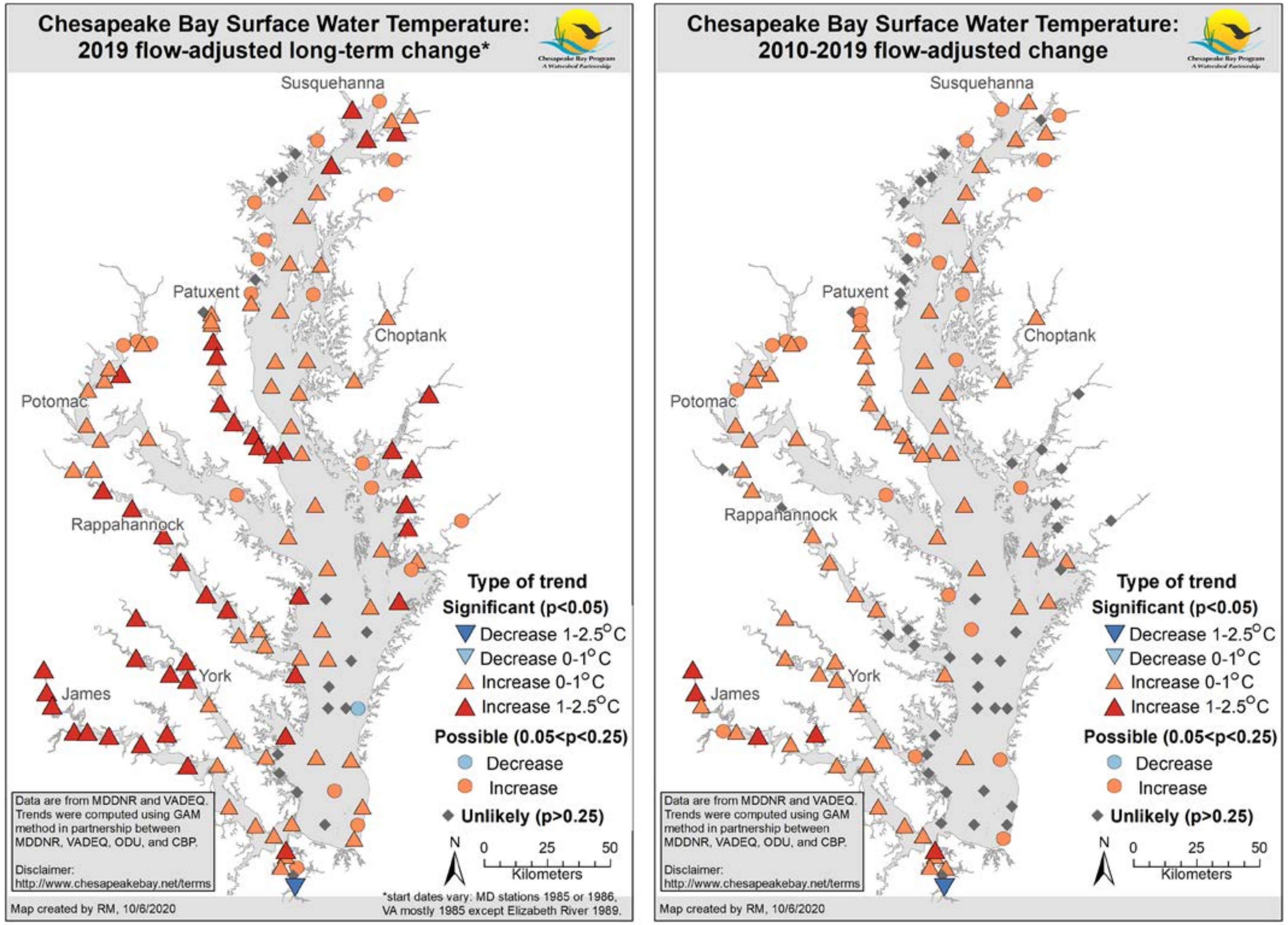
Climatic impacts of rising sea levels, increasing freshwater flows, and warming Bay waters may negatively impact attainment of Bay water-quality standards.[143]

Rising sea levels are expected to increase estuarine circulation and stratification, which may increase or decrease dissolved oxygen (DO) concentrations at various depths.[143]

Increased freshwater flows are expected to increase nutrient and sediment delivery from the watershed, likely decreasing DO concentrations throughout the Bay.[143]

Increased water temperatures, which have been observed throughout most Bay waters, are expected to have the largest climatic impact on DO and will likely decrease DO concentrations in the Bay.[143]

Despite these challenges, DO attainment has generally improved over time[62] and achieving nutrient reductions required by the Bay Total Maximum Daily Load is expected to outweigh the negative effects of climatic change and result in improved DO conditions.[143]



***Above**: Flow-adjusted surface water temperature trends throughout the Chesapeake Bay from 1985 – 2019 and 2010 – 2019.*[2]

How do climatic changes affect management practices?

Some climatic changes are expected to alter the effectiveness of certain management practices[36] – particularly those that control sediment and nutrients by controlling flow. This has implications for future management practice siting, design, and maintenance strategies and may pose a challenge for meeting Bay nutrient and sediment reduction targets.

The Chesapeake Bay Program's watershed model recently incorporated temperature and precipitation change projections to simulate the potential effects of climatic changes on water quality. This work is intended to help develop a robust response to climate change risk and will be refined for a 2025 decision based on improving understanding of: (1) the impacts of climate change, and (2) climate-resilient management practices that address climate change conditions (e.g., increased storm intensity).

Examples of potential effects of climatic changes on management practices:

Increased streamflow may reduce the ability of urban and agricultural practices to trap and remove nutrients,[36] requiring resizing, redesign, or the need for additional practices in these areas to meet water quality goals.[138,144]

Total annual precipitation is a major driver of total phosphorus loads in the Bay and climatic changes may offset management actions through increased phosphorus loadings from runoff.[10] Although estimated changes in phosphorus loads vary throughout the watershed under differing climatic projections, there is general agreement that more efficient and additional practices will be needed to maintain phosphorus loading targets under dynamic climatic conditions.[51]

Continued research is needed to improve comprehensive understanding of management practice performance under varying climatic changes.

Dictionary of Commonly Used Terms and Acronyms

Co-benefits: Management practices have a variety of benefits beyond their primary intended outcome. Many practices designed to reduce nitrogen, phosphorus, and sediment loads also have positive ecological, economic, and recreational effects. Adopting a management strategy that maximizes these co-benefits offers an opportunity to improve water-quality conditions and other local priorities.

Chesapeake Assessment Scenario Tool (CAST): a free, online nitrogen, phosphorus and sediment load estimator tool that streamlines environmental planning: cast.chesapeakebay.net

Designated Uses: zones of aquatic habitats within the Chesapeake Bay that represent the seasonal nature of water column structure and the life history needs of living resources. Water-quality standards/criteria vary between the five designated uses, which include: **migratory spawning and nursery habitats (MSN), shallow water (SW), open water (OW), deep water (DW),** and **deep channel (DC)**

Harmful Algal Bloom (HAB): algae communities that grow excessively large and are associated with negative ecosystem impacts, some producing toxins that have harmful effects to humans and aquatic resources.

Legacy Effects and Lag Time: refers to processes in the Chesapeake Bay watershed that result in environmental storage of nitrogen, phosphorus, and/or sediment. Many of these processes are affected by underlying watershed geology or other natural features and complicate relations between landscape changes and in-stream response, specifically water-quality responses that may occur after management practice implementation.

Load and Trend: Load refers to the amount of material transported downstream, typically reported as an annual total. Trend refers to the changes in conditions between start and end years. Loads of nitrogen, phosphorus, and suspended sediment are heavily influenced by streamflow and reflect a combination of natural processes and human activities. Therefore, trends reflect changes in **flow-normalized loads**, which have removed most interannual streamflow variability.

Dictionary continues on the next slide.

Dictionary of Commonly Used Terms and Acronyms

Nontidal Monitoring Network (NTN): a monitoring network of 123 stations located on nontidal rivers in each Chesapeake Bay state. The NTN consists of coordinated data collection by local, state, and federal partners that, since 1985, has been used to quantify the load and trend of nitrogen, phosphorus, and sediment generated throughout the Chesapeake Bay watershed.

Total Maximum Daily Load (TMDL): the Chesapeake Bay TMDL is a regulatory framework established by the U.S. Environmental Protection Agency in 2010 that requires management practices to be implemented by 2025 to limit nitrogen, phosphorus, and sediment loads in the Bay.

Total Nitrogen (TN): a measure of all dissolved and particulate nitrogen species commonly occurring in water bodies, including nitrate, ammonia, and organic forms.

Total Phosphorus (TP): a measure of all dissolved and particulate phosphorus species commonly occurring in water bodies, including orthophosphate and organic forms.

Suspended Sediment (SS): a measure of particulate material suspended in the water column, which represents the sediment fraction transported in water.

Water Quality Criteria: Standards developed by the Chesapeake Bay Program partnership that vary by tidal segment, season, and designated use. Full attainment of these water quality criteria is necessary to fully support the survival, growth, and reproduction of the Bay's living resources. Water quality criteria have been developed for: **Chlorophyll-a (CHLA), dissolved oxygen (DO), and water clarity / submerged aquatic vegetation (SAV)**.

Summarizing Scientific Findings for Common Stakeholder Questions to Inform Nutrient and Sediment Management Activities in the Chesapeake Bay Watershed

Primary United States Geological Survey (USGS) Points of Contact by Jurisdiction

Pennsylvania and New York

John Clune
jclune@usgs.gov
570-327-3171

Maryland, Delaware, and D.C.

Alex Soroka
asoroka@usgs.gov
443-498-5529

Virginia and West Virginia

Jimmy Webber
jwebber@usgs.gov
804-261-2621

Contributing Scientists

Matthew Cashman[1], John Clune[1], Olivia Devereux[2], Rosemary Fanelli[1], Kaycee Faunce[1], Kristina Hopkins[1], Jennifer Keisman[1], Ryan Langendorf[3], Christopher Mason[1], Rebecca Murphy[4], Mark Nardi[1], Robert Sabo[5], Gary Shenk[1], Alex Soroka[1], Peter Tango[1], Jeremy Testa[6], Jimmy Webber[1], Qian Zhang[4]

[1]US Geological Survey; [2]Devereux Consulting, Inc.; [3]University of Colorado; [4]Chesapeake Bay Program / University of Maryland Center for Environmental Science; [5]U.S. Environmental Protection Agency; [6]Chesapeake Bay Biological Laboratory / University of Maryland Center for Environmental Science

Learn more about USGS Chesapeake Bay science activities: usgs.gov/centers/cba

References

1. Moyer, D.L., and Langland, M.J., 2020, Nitrogen, phosphorus, and suspended-sediment loads and trends measured at the Chesapeake Bay Nontidal Network stations: Water years 1985-2018 (ver. 2.0, May 2020): U.S. Geological Survey data release, https://doi.org/10.5066/P931M7FT.

2. Chesapeake Bay Program, 2021, Tidal Water Quality Change, accessed July 21, 2021, at https://www.chesapeakebay.net/who/group/integrated_trends_analysis_team.

3. Hyer, K.E., Phillips, S.W., Ator, S.W., Moyer, D.L., Webber, J.S., Felver, R., Keisman, J.L., McDonnell, L.A., Murphy, R., Trentacoste, E.M., Zhang, Q., Dennison, W.C., Swanson, S., Walsh, B., and others, 2021, Nutrient trends and drivers in the Chesapeake Bay Watershed: Fact Sheet 2020–3069, 4 p, http://pubs.er.usgs.gov/publication/fs20203069.

4. Noe, G.B., Cashman, M.J., Skalak, K., Gellis, A., Hopkins, K.G., Moyer, D., Webber, J., Benthem, A., Maloney, K., Brakebill, J., Sekellick, A., Langland, M., Zhang, Q., Shenk, G., and others, 2020, Sediment dynamics and implications for management: State of the science from long-term research in the Chesapeake Bay watershed, USA: WIREs Water, v. 7, no. 4, p. e1454, https://doi.org/10.1002/wat2.1454.

5. Ator, S.W., Blomquist, J.D., Webber, J.S., and Chanat, J.G., 2020, Factors driving nutrient trends in streams of the Chesapeake Bay watershed: Journal of Environmental Quality, v. 49, no. 4, p. 812–834, https://doi.org/10.1002/jeq2.20101.

6. Webber, J.S., and Zhang, Q., 2020, Chesapeake Bay Nontidal Network 1985 - 2018: Daily High-Flow and Low-Flow Concentration and Load Estimates: U.S. Geological Survey data release, https://doi.org/10.5066/P9LBJEY1.

7. Zhang, Q., Webber, J.S., Moyer, D.L., and Chanat, J.G., 2020, An approach for decomposing river water-quality trends into different flow classes: Science of The Total Environment, p. 143562, https://doi.org/10.1016/j.scitotenv.2020.143562.

8. Fanelli, R.M., Blomquist, J.D., and Hirsch, R.M., 2019, Point sources and agricultural practices control spatial-temporal patterns of orthophosphate in tributaries to Chesapeake Bay: Science of The Total Environment, v. 652, p. 422–433, https://doi.org/10.1016/j.scitotenv.2018.10.062.

9. Denver, J.M., Cravotta III, C.A., Ator, S.W., and Lindsey, B.D., 2010, Contributions of Phosphorus from Groundwater to Streams in the Piedmont, Blue Ridge, and Valley and Ridge Physiographic Provinces, Eastern United States: U.S. Geological Survey Scientific Investigations Report 2010–5176, p. 38, https://doi.org/10.3133/sir20105176.

10. Ryberg, K.R., Blomquist, J.D., Sprague, L.A., Sekellick, A.J., and Keisman, J., 2018, Modeling drivers of phosphorus loads in Chesapeake Bay tributaries and inferences about long-term change: Science of The Total Environment, v. 616–617, p. 1423–1430, https://doi.org/10.1016/j.scitotenv.2017.10.173.

References

11. Terziotti, S., Capel, P., Tesoriero, A., Hopple, J., and Kronholm, S., 2017, Estimates of nitrate loads and yields from groundwater to streams in the Chesapeake Bay watershed based on land use and geology: U.S. Geological Survey Scientific Investigations Report 2017–5160, p. 20, https://doi.org/10.3133/sir20175160.

12. Shenk, G., Wainger, L., Wu, C., Capel, P., Friedrichs, M., Hubbart, J., Iho, A., Kleinman, P., Sellner, K., and Stephenson, K., 2020, Assessing the environment in outcome units: STAC Publication Number 20-003, p. 34, https://www.chesapeake.org/stac/wp-content/uploads/2020/06/FINAL_STAC-Report_AEIOU.pdf.

13. Ator, S.W., and Denver, J.M., 2015, Understanding Nutrients in the Chesapeake Bay Watershed and Implications for Management and Restoration— the Eastern Shore: U.S. Geological Survey Circular 1406, p. 72, https://doi.org/10.3133/cir1406.

14. Staver, K.W., and Brinsfield, R.B., 2001, Agriculture and Water Quality on the Maryland Eastern Shore: Where Do We Go from Here? Long-term solutions to accelerated eutrophication must provide mechanisms for redistributing nutrients flowing into concentrated animal-producing regions: BioScience, v. 51, no. 10, p. 859–868, https://doi.org/10.1641/0006-3568(2001)051[0859:AAWQOT]2.0.CO;2.

15. Kleinman, P.J.A., Sharpley, A.N., Buda, A.R., McDowell, R.W., and Allen, A.L., 2011, Soil controls of phosphorus in runoff: Management barriers and opportunities: Canadian Journal of Soil Science, v. 91, no. 3, p. 329–338, https://doi.org/10.4141/cjss09106.

16. Zhang, Q., Brady, D.C., Boynton, W.R., and Ball, W.P., 2015, Long-Term Trends of Nutrients and Sediment from the Nontidal Chesapeake Watershed: An Assessment of Progress by River and Season: JAWRA Journal of the American Water Resources Association, v. 51, no. 6, p. 1534–1555, https://doi.org/10.1111/1752-1688.12327.

17. Ator, S.W., Brakebill, J.W., and Blomquist, J.D., 2011, Sources, fate, and transport of nitrogen and phosphorus in the Chesapeake Bay watershed: An empirical model: U.S. Geological Survey Scientific Investigations Report 2011–5167, p. 27, http://pubs.usgs.gov/sir/2011/5167/.

18. Keisman, J.L.D., Devereux, O.H., LaMotte, A.E., Sekellick, A.J., and Blomquist, J.D., 2018, Manure and fertilizer inputs to land in the Chesapeake Bay watershed, 1950–2012: U.S. Geological Survey Scientific Investigations Report 2018-5022, p. 37, https://doi.org/10.3133/sir20185022.

19. Chesapeake Bay Program, 2020, Chesapeake Assessment and Scenario Tool (CAST) Version 2019, accessed July 1, 2021, at cast.chesapeakebay.net.

20. Burns, D.A., Bhatt, G., Linker, L.C., Bash, J.O., Capel, P.D., and Shenk, G.W., 2021, Atmospheric nitrogen deposition in the Chesapeake Bay watershed: A history of change: Atmospheric Environment, v. 251, p. 118277, https://doi.org/10.3133/sir20185022.

21. McCoy, J., Sigrist, M., and Jaber, J., 2010, Upper Pocomoke agricultural best management practice evaluation project: In 2010 Trust Fund Water Quality Monitoring Strategy, University of Maryland Center for Environmental Science, p. 13-16.

References

22. Majcher, E.H., Woytowitz, E.L., Alexander, R.J., and Groffman, P.M., 2018, Factors affecting long-term trends in surface-water quality in the Gwynns Falls watershed, Baltimore City and County, Maryland, 1998–2016: U.S. Geological Survey Open-File Report 2018-1038, p. 27, https://doi.org/10.3133/ofr20181038.

23. Eshleman, K.N., Sabo, R.D., and Kline, K.M., 2013, Surface Water Quality Is Improving due to Declining Atmospheric N Deposition: Environmental Science & Technology, v. 47, no. 21, p. 12193–12200, https://doi.org/10.1021/es4028748.

24. Eshleman, K.N., and Sabo, R.D., 2016, Declining nitrate-N yields in the Upper Potomac River Basin: What is really driving progress under the Chesapeake Bay restoration? Atmospheric Environment, v. 146, p. 280–289, https://doi.org/10.1016/j.atmosenv.2016.07.004.

25. Ator, S.W., García, A.M., Schwarz, G.E., Blomquist, J.D., and Sekellick, A.J., 2019, Toward Explaining Nitrogen and Phosphorus Trends in Chesapeake Bay Tributaries, 1992–2012: JAWRA Journal of the American Water Resources Association, v. 55, no. 5, p. 1149–1168, https://doi.org/10.1111/1752-1688.12756.

26. Chanat, J.G., and Yang, G., 2018, Exploring Drivers of Regional Water-Quality Change Using Differential Spatially Referenced Regression—A Pilot Study in the Chesapeake Bay Watershed: Water Resources Research, v. 54, no. 10, p. 8120–8145, https://doi.org/10.1029/2017WR022403.

27. Chang, S.Y., Zhang, Q., Byrnes, D.K., Basu, N.B., and VanMeter, K.J., 2021, Chesapeake legacies: The importance of legacy nitrogen to improving Chesapeake Bay water quality: Environmental Research Letters, https://doi.org/10.1088/1748-9326/ac0d7b.

28. Lyerly, C.M., Hernandez Cordero, A.L., Foreman, K.L., Phillips, S.W., and Dennison, W.C. (eds.), 2014, New Insights: Science-based evidence of water quality improvements, challenges, and opportunities in the Chesapeake. University of Maryland, http://ian.umces.edu/pdfs/ian_report_438.pdf.

29. Moriasi, D.N., Duriancik, L.F., Sadler, E.J., Tsegaye, T., Steiner, J.L., Locke, M.A., Strickland, T.C., and Osmond, D.L., 2020, Quantifying the impacts of the Conservation Effects Assessment Project watershed assessments: The first fifteen years: Journal of Soil and Water Conservation, v. 75, no. 3, p. 57A, https://doi.org/10.2489/jswc.75.3.57A.

30. Lowrance, R., Altier, L.S., Newbold, J.D., Schnabel, R.R., Groffman, P.M., Denver, J.M., Correll, D.L., Gilliam, J.W., Robinson, J.L., Brinsfield, R.B., Staver, K.W., Lucas, W., and Todd, A.H., 1997, Water quality functions of riparian forest buffers in Chesapeake Bay watersheds: Environmental Management, v. 21, no. 5, p. 687–712, https://doi.org/10.1007/s002679900060.

31. Inamdar, S., Mostaghimi, S., Mcclellan, P., and Brannan, K., 2001, BMP impacts on sediment and nutrient yields from an agricultural watershed in the coastal plain region: Transactions of the ASABE, v. 44, p. 1191–1200, http://hdl.handle.net/10919/48214.

References

32. Jefferson, A.J., Bhaskar, A.S., Hopkins, K.G., Fanelli, R., Avellaneda, P.M., and McMillan, S.K., 2017, Stormwater management network effectiveness and implications for urban watershed function: A critical review: Hydrological Processes, v. 31, no. 23, p. 4056–4080, https://doi.org/10.1002/hyp.11347.

33. Hopkins, K.G., Loperfido, J.V., Craig, L.S., Noe, G.B., and Hogan, D.M., 2017, Comparison of sediment and nutrient export and runoff characteristics from watersheds with centralized versus distributed stormwater management: Journal of Environmental Management, v. 203, p. 286–298, https://doi.org/10.1016/j.jenvman.2017.07.067.

34. Filoso, S., and Palmer, M., 2011, Assessing Stream Restoration Effectiveness at Reducing Nitrogen Export to Downstream Waters: Ecological applications: a publication of the Ecological Society of America, v. 21, p. 1989–2006, http://dx.doi.org/10.2307/41416633.

35. Hogan, D.M., and Walbridge, M.R., 2007, Best Management Practices for Nutrient and Sediment Retention in Urban Stormwater Runoff: Journal of Environmental Quality, v. 36, no. 2, p. 386–395, https://doi.org/10.2134/jeq2006.0142.

36. Lintern, A., McPhillips, L., Winfrey, B., Duncan, J., and Grady, C., 2020, Best Management Practices for Diffuse Nutrient Pollution: Wicked Problems Across Urban and Agricultural Watersheds: Environmental Science & Technology, v. 54, no. 15, p. 9159–9174, https://doi.org/10.1021/acs.est.9b07511.

37. Tomer, M.D., and Locke, M.A., 2011, The challenge of documenting water quality benefits of conservation practices: a review of USDA-ARS's conservation effects assessment project watershed studies: Water Science and Technology, v. 64, no. 1, p. 300–310, https://doi.org/10.2166/wst.2011.555.

38. Sekellick, A.J., Devereux, O.H., Keisman, J.L.D., Sweeney, J.S., and Blomquist, J.D., 2019, Spatial and Temporal Patterns of Best Management Practice Implementation in the Chesapeake Bay Watershed, 1985–2014: Scientific Investigations Report 2018–5171, p. 37, http://pubs.er.usgs.gov/publication/sir20185171.

39. Easton, Z., Stephenson, K., Collick, A., Fleming, P., Kellner, E., Martin, J., Ribaudo, M., and Shenk, G., 2020, Increasing Effectiveness and Reducing the Cost of Nonpoint Source Best Management Practice (BMP) Implementation: Is Targeting the Answer? STAC Publication Number 20-002, p. 53, https://www.chesapeake.org/stac/wp-content/uploads/2020/02/FINAL_STAC-Report_BMP-Targeting.pdf.

40. Ator, S.W., 2019, Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the northeastern United States: Scientific Investigations Report 2019–5118, http://pubs.er.usgs.gov/publication/sir20195118.

References

41. Hyer, K.E., Denver, J.M., Langland, M.J., Webber, J.S., Böhlke, J.K., Hively, W.D., and Clune, J.W., 2016, Spatial and Temporal Variation of Stream Chemistry Associated With Contrasting Geology and Land-Use Patterns in the Chesapeake Bay Watershed: Summary of Results from Smith Creek, Virginia; Upper Chester River, Maryland; Conewago Creek, Pennsylvania; and Difficult Run, Virginia, 2010–2013: U.S. Geological Survey Scientific Investigations Report 2016–5093, p. 211, http://dx.doi.org/10.3133/sir20165093.

42. Tetra Tech, Inc., 2017, Estimation of BMP Impact on Chesapeake Bay Program Management Strategies:, accessed July 1, 2021, at https://www.chesapeakebay.net/channel_files/25159/draft_bmp_impact_scoring_report_-_20170421.pdf.

43. Van Meter, K.J., Basu, N.B., and Van Cappellen, P., 2017, Two centuries of nitrogen dynamics: Legacy sources and sinks in the Mississippi and Susquehanna River Basins: Global Biogeochemical Cycles, v. 31, no. 1, p. 2–23, https://doi.org/10.1002/2016GB005498.

44. Bachman, L.J., Lindsey, B.D., Brakebill, J.W., and Powars, D.S., 1998, Ground-water discharge and base-flow nitrate loads of nontidal streams, and their relation to a hydrogeomorphic classification of the Chesapeake Bay Watershed, middle Atlantic Coast: Water-Resources Investigations Report 98–4059, http://pubs.er.usgs.gov/publication/wri984059.

45. Wherry, S.A., Tesoriero, A.J., and Terziotti, S., 2020, Factors Affecting Nitrate Concentrations in Stream Base Flow: Environmental Science & Technology, v. 55, no. 2, p. 902-911, https://doi.org/10.1021/acs.est.0c02495.

46. Sanford, W.E., and Pope, J.P., 2013, Quantifying Groundwater’s Role in Delaying Improvements to Chesapeake Bay Water Quality: Environmental Science & Technology, v. 47, no. 23, p. 13330–13338, https://doi.org/10.1021/es401334k.

47. Sebilo, M., Mayer, B., Nicolardot, B., Pinay, G., and Mariotti, A., 2013, Long-term fate of nitrate fertilizer in agricultural soils: Proceedings of the National Academy of Sciences, v. 110, no. 45, p. 18185, https://doi.org/10.1073/pnas.1305372110.

48. Van Meter, K.J., Basu, N.B., Veenstra, J.J., and Burras, C.L., 2016, The nitrogen legacy: emerging evidence of nitrogen accumulation in anthropogenic landscapes: Environmental Research Letters, v. 11, no. 3, p. 035014, https://doi.org/10.1088/1748-9326/11/3/035014.

49. Terziotti, S., and Hopple, J., 2018, Datasets and Metadata for Estimates of Nitrate Loads and Yields from Groundwater to Streams in the Chesapeake Bay Watershed Based on Land Use and Geology: U.S. Geological Survey data release, https://doi.org/10.5066/F79G5KP4.

References

50. Bhatt, G., Sommerlot, A., Shenk, G., and Sanford, W., 2017, Groundwater Lag-Time Estimates, accessed July 1, 2021, at https://www.chesapeakebay.net/channel_files/24719/20170404_-_bhatt_-_cbp_-_mqrm_-_gw_lag_times.pdf.

51. Kleinman, P.J.A., Fanelli, R.M., Hirsch, R.M., Buda, A.R., Easton, Z.M., Wainger, L.A., Brosch, C., Lowenfish, M., Collick, A.S., Shirmohammadi, A., Boomer, K., Hubbart, J.A., Bryant, R.B., and Shenk, G.W., 2019, Phosphorus and the Chesapeake Bay: Lingering Issues and Emerging Concerns for Agriculture: Journal of Environmental Quality, v. 48, p. 1191-1203, https://doi.org/10.2134/jeq2019.03.0112.

52. Sharpley, A., Jarvie, H.P., Buda, A., May, L., Spears, B., and Kleinman, P., 2013, Phosphorus legacy: overcoming the effects of past management practices to mitigate future water quality impairment: Journal of Environmental Quality, v. 42, no. 5, p. 1308–1326, https://doi.org/10.2134/jeq2013.03.0098.

53. Kleinman, P.J.A., 2017, The Persistent Environmental Relevance of Soil Phosphorus Sorption Saturation: Current Pollution Reports, v. 3, no. 2, p. 141–150, https://doi.org/10.1007/s40726-017-0058-4.

54. Edwards, W.M., and Owens, L.B., 1991, Large storm effects on total soil erosion: Journal of Soil and Water Conservation, v. 46, no. 1, p. 75–78, https://www.jswconline.org/content/46/1/75.

55. Terziotti, S., 2019, Distribution of Phosphorus in Soils and Aggregated Within Geologic Mapping Units, Conterminous United States: U.S. Geological Survey data release, https://doi.org/10.5066/P918DF1E.

56. Lindsey, B., D., andv Rupert, M., G., 2012, Methods for Evaluating Temporal Groundwater Quality Data and Results of Decadal-Scale Changes in Chloride, Dissolved Solids, and Nitrate Concentrations in Groundwater in the United States, 1988–2010: U.S. Geological Survey Scientific Investigations Report 5049, p. 46, https://pubs.usgs.gov/sir/2012/5049/support/sir2012-5049.pdf.

57. Lindsey, B.D., Levitt, J.P., and Johnson, T.D., 2020, Data from Decadal Change in Groundwater Quality Web Site, 1988-2018: U.S. Geological Survey data release, https://doi.org/10.5066/P9AE19F9

58. Fiorellino, N., Kratochvil, R., and Coale, F., 2017, Long-Term Agronomic Drawdown of Soil Phosphorus in Mid-Atlantic Coastal Plain Soils: Agronomy Journal, v. 109, no. 2, p. 455–461, https://doi.org/10.2134/agronj2016.07.0409.

59. National Research Council, 2001, Assessing the TMDL Approach to Water Quality Management: The National Academies Press, Washington, DC., accessed July 1, 2021 at https://www.nap.edu/catalog/10146/assessing-the-tmdl-approach-to-water-quality-management.

References

60. Chesapeake Progress Water Quality Standards Attainment and Monitoring, accessed July 1, 2021, at https://www.chesapeakeprogress.com/clean-water/water-quality.

61. Zhang, Q., Murphy, R.R., Tian, R., Forsyth, M.K., Trentacoste, E.M., Keisman, J., and Tango, P.J., 2018a, Chesapeake Bay's water quality condition has been recovering: Insights from a multimetric indicator assessment of thirty years of tidal monitoring data: Science of The Total Environment, v. 637–638, p. 1617–1625, https://doi.org/10.1016/j.scitotenv.2018.05.025.

62. Zhang, Q., Tango, P.J., Murphy, R.R., Forsyth, M.K., Tian, R., Keisman, J., and Trentacoste, E.M., 2018b, Chesapeake Bay Dissolved Oxygen Criterion Attainment Deficit: Three Decades of Temporal and Spatial Patterns: Frontiers in Marine Science, v. 5, p. 422, https://doi.org/10.3389/fmars.2018.00422.

63. United States Geological Survey Freshwater Flow into Chesapeake Bay, accessed July 1, 2021, at https://www.usgs.gov/centers/cba/science/freshwater-flow-chesapeake-bay.

64. Murphy, R.R., Kemp, W.M., and Ball, W.P., 2011, Long-Term Trends in Chesapeake Bay Seasonal Hypoxia, Stratification, and Nutrient Loading: Estuaries and Coasts, v. 34, no. 6, p. 1293–1309, https://doi.org/10.1007/s12237-011-9413-7.

65. Testa, J.M., Li, Y., Lee, Y.J., Li, M., Brady, D.C., Di Toro, D.M., Kemp, W.M., and Fitzpatrick, J.J., 2014, Quantifying the effects of nutrient loading on dissolved O2 cycling and hypoxia in Chesapeake Bay using a coupled hydrodynamic–biogeochemical model: Journal of Marine Systems, v. 139, p. 139–158, https://doi.org/10.1016/j.jmarsys.2014.05.018.

66. Hagy, J.D., Boynton, W.R., Keefe, C.W., and Wood, K.V., 2004, Hypoxia in Chesapeake Bay, 1950–2001: Long-term change in relation to nutrient loading and river flow: Estuaries, v. 27, no. 4, p. 634–658, http://dx.doi.org/10.1007/BF02907650.

67. Orth, R.J., Williams, M.R., Marion, S.R., Wilcox, D.J., Carruthers, T.J.B., Moore, K.A., Kemp, W.M., Dennison, W.C., Rybicki, N., Bergstrom, P., and Batiuk, R.A., 2010, Long-Term Trends in Submersed Aquatic Vegetation (SAV) in Chesapeake Bay, USA, Related to Water Quality: Estuaries and Coasts, v. 33, no. 5, p. 1144–1163, https://doi.org/10.1007/s12237-010-9311-4.

68. Ruhl, H.A., and Rybicki, N.B., 2010, Long-term reductions in anthropogenic nutrients link to improvements in Chesapeake Bay habitat: Proceedings of the National Academy of Sciences, v. 107, no. 38, p. 16566, https://doi.org/10.1073/pnas.1003590107.

References

69. Lefcheck, J.S., Orth, R.J., Dennison, W.C., Wilcox, D.J., Murphy, R.R., Keisman, J., Gurbisz, C., Hannam, M., Landry, J.B., Moore, K.A., Patrick, C.J., Testa, J., Weller, D.E., and Batiuk, R.A., 2018, Long-term nutrient reductions lead to the unprecedented recovery of a temperate coastal region: Proceedings of the National Academy of Sciences, v. 115, no. 14, p. 3658, https://doi.org/10.1073/pnas.1715798115.

70. Boynton, W.R., Hagy, J.D., Cornwell, J.C., Kemp, W.M., Greene, S.M., Owens, M.S., Baker, J.E., and Larsen, R.K., 2008, Nutrient Budgets and Management Actions in the Patuxent River Estuary, Maryland: Estuaries and Coasts, v. 31, no. 4, p. 623–651, https://doi.org/10.1007/s12237-008-9052-9.

71. Boynton, W.R., Testa, J.M., and Kemp, W.M., 2009, An ecological assessment of the Corsica River estuary and watershed: Scientific advice for future water quality management. Final Report to Maryland Department of Natural Resources: University of Maryland Center for Environmental Science Technical Report TS-587-09, p. 54, accessed July 1, 2021 at https://gonzo.cbl.umces.edu/documents/Publications/FULL%20CORSICA%20TEXT%20FINAL%2023OCT09.pdf.

72. Fisher, T.R., Fox, R.J., Gustafson, A.B., Koontz, E., Lepori-Bui, M., and Lewis, J., 2021, Localized Water Quality Improvement in the Choptank Estuary, a Tributary of Chesapeake Bay: Estuaries and Coasts, v. 44, no. 5, p. 1274–1293, https://doi.org/10.1007/s12237-020-00872-4.

73. Jones, R.C., 2020, Recovery of a Tidal Freshwater Embayment from Eutrophication: a Multidecadal Study: Estuaries and Coasts, v. 43, no. 6, p. 1318–1334, https://doi.org/10.1007/s12237-020-00730-3.

74. Boynton, W.R., Hodgkins, C.L.S., O'Leary, C.A., Bailey, E.M., Bayard, A.R., and Wainger, L.A., 2014, Multi-decade Responses of a Tidal Creek System to Nutrient Load Reductions: Mattawoman Creek, Maryland USA: Estuaries and Coasts, v. 37, no. 1, p. 111–127, http://dx.doi.org/10.1007/s12237-013-9690-4.

75. Langendorf, R.E., Lyubchich, V., Testa, J.M., and Zhang, Q., 2021, Inferring Controls on Dissolved Oxygen Criterion Attainment in the Chesapeake Bay: ACS ES&T Water, v. 1, no. 8, p. 1665-1675, https://doi.org/10.1021/acsestwater.0c00307.

76. Keisman, J.L., Murphy, R., Devereux, O.H., Harcum, J., Karrh, R., Lane, M., Perry, E., Zhang, Q., Wei, Z., Webber, J.S., and Petenbrink, M.N., 2020, Potomac tributary report: A summary of trends in tidal water quality and associated factors: Chesapeake Bay Program Office, accessed July 21, 2021, at http://pubs.er.usgs.gov/publication/70216971.

77. Boesch, D.F., Brinsfield, R.B., and Magnien, R.E., 2001a, Chesapeake Bay Eutrophication: Journal of Environmental Quality, v. 30, no. 2, p. 303–320, https://doi.org/10.2134/jeq2001.302303x.

References

78. Poulsen, R., Cedergreen, N., Hayes, T., and Hansen, M., 2018, Nitrate: An Environmental Endocrine Disruptor? A Review of Evidence and Research Needs: Environmental Science & Technology, v. 52, no. 7, p. 3869–3887, https://doi.org/10.1021/acs.est.7b06419.

79. Connolly, J.P., Zahakos, H.A., Benaman, J., Ziegler, C.K., Rhea, J.R., and Russell, K., 2000, A Model of PCB Fate in the Upper Hudson River: Environmental Science & Technology, v. 34, no. 19, p. 4076–4087, https://doi.org/10.1021/es001046v.

80. Yuan, L.L., and Norton, S.B., 2003, Comparing responses of macroinvertebrate metrics to increasing stress: Journal of the North American Benthological Society, v. 22, no. 2, p. 308–322, http://dx.doi.org/10.2307/1468000.

81. Maloney, K.O., and Weller, D.E., 2011, Anthropogenic disturbance and streams: land use and land-use change affect stream ecosystems via multiple pathways: Freshwater Biology, v. 56, no. 3, p. 611–626, https://doi.org/10.1111/j.1365-2427.2010.02522.x.

82. Carline, R.F., and Walsh, M.C., 2007, Responses to Riparian Restoration in the Spring Creek Watershed, Central Pennsylvania: Restoration Ecology, v. 15, no. 4, p. 731–742, https://doi.org/10.1111/j.1526-100X.2007.00285.x.

83. Schmidt, T.S., Van Metre, P.C., and Carlisle, D.M., 2019, Linking the Agricultural Landscape of the Midwest to Stream Health with Structural Equation Modeling: Environmental Science & Technology, v. 53, no. 1, p. 452–462, https://doi.org/10.1021/acs.est.8b04381.

84. Waite, I.R., Pan, Y., and Edwards, P.M., 2020, Assessment of multi-stressors on compositional turnover of diatom, invertebrate and fish assemblages along an urban gradient in Pacific Northwest streams (USA): Ecological Indicators, v. 112, p. 106047, https://doi.org/10.1016/j.ecolind.2019.106047.

85. Waite, I.R., 2014, Agricultural disturbance response models for invertebrate and algal metrics from streams at two spatial scales within the U.S.: Hydrobiologia, v. 726, no. 1, p. 285–303, https://doi.org/10.1007/s10750-013-1774-4.

86. Piggott, J.J., Lange, K., Townsend, C.R., and Matthaei, C.D., 2012, Multiple Stressors in Agricultural Streams: A Mesocosm Study of Interactions among Raised Water Temperature, Sediment Addition and Nutrient Enrichment: PLOS ONE, v. 7, no. 11, p. e49873, https://doi.org/10.1371/journal.pone.0049873.

87. Bazinet, N.L., Gilbert, B.M., and Wallace, A.M., 2010, A Comparison of Urbanization Effects on Stream Benthic Macroinvertebrates and Water Chemistry in an Urban and an Urbanizing Basin in Southern Ontario, Canada: Water Quality Research Journal, v. 45, no. 3, p. 327–341, https://doi.org/10.2166/wqrj.2010.035.

88. Chesapeake Bay Program, 2017, Chesapeake Bay Watershed Model Phase 6 Map Viewer, accessed July 1, 2021, at gis.chesapeakebay.net/mpa/scenarioviewer.

References

89. Smalling, K.L., Devereux, O.H., Gordon, S.E., Phillips, P.J., Blazer, V.S., Hladik, M.L., Kolpin, D.W., Meyer, M.T., Sperry, A.J., and Wagner, T., 2021, Environmental and anthropogenic drivers of contaminants in agricultural watersheds with implications for land management: Science of The Total Environment, v. 774, p. 145687, https://doi.org/10.1016/j.scitotenv.2021.145687.

90. Schueler, T., and Youngk, A., 2015, Potential benefits of nutrient and sediment practices to reduce toxic contaminants in the Chesapeake Bay watershed: Part 1: removal of urban toxic contaminants. Final Report to the CBP Toxic Contaminants Work Group. Chesapeake Stormwater Network, accessed July 1, 2021 at https://cbtrust.org/wp-content/uploads/FY14-Potential-Benefits-of-Nutrient-and-Sediment-Practices-to-Reduce-Toxic-Contaminants-in-CBW.pdf.

91. Nowell, L.H., Moran, P.W., Bexfield, L.M., Mahler, B.J., Van Metre, P.C., Bradley, P.M., Schmidt, T.S., Button, D.T., and Qi, S.L., 2021, Is there an urban pesticide signature? Urban streams in five U.S. regions share common dissolved-phase pesticides but differ in predicted aquatic toxicity: Science of The Total Environment, v. 793, p. 148453, https://doi.org/10.1016/j.scitotenv.2021.148453.

92. Majcher, E., Smalling, K., Blaney, L., Harvey, A., Phillips, S., Blazer, V., Pickney, A., Brosch, C., and Allen, G., 2020, Integrating Science and Developing Approaches to Inform Management for Contaminants of Concern in Agricultural and Urban Settings: STAC Publication Number 20-001, 51 p, accessed July 1, 2021 at https://www.chesapeake.org/stac/wp-content/uploads/2020/01/FINAL_STAC-Report_Contaminants-of-Concern.pdf.

93. Zimmerman, T.M., Zimmerman, M.L., and Lindsey, B.D., 2001, Relation between selected well-construction characteristics and occurrence of bacteria in private household-supply wells, south-central and southeastern Pennsylvania: Water-Resources Investigations Report 2001–4206, http://pubs.er.usgs.gov/publication/wri014206.

94. Simpson, H., 2004, Promoting the Management and Protection of Private Water Wells: Journal of Toxicology and Environmental Health, Part A, v. 67, no. 20–22, p. 1679–1704, https://doi.org/10.1080/15287390490492296.

95. Swistock, B.R., and Sharpe, W.E., 2005, The influence of well construction on bacterial contamination of private water wells in Pennsylvania: Journal of environmental health, v. 68, no. 2, p. 17–22, https://pubmed.ncbi.nlm.nih.gov/16220718/.

96. Ward, M.H., Jones, R.R., Brender, J.D., De Kok, T.M., Weyer, P.J., Nolan, B.T., Villanueva, C.M., and Van Breda, S.G., 2018, Drinking Water Nitrate and Human Health: An Updated Review: International Journal of Environmental Research and Public Health, v. 15, no. 7, https://dx.doi.org/10.3390%2Fijerph15071557.

97. Clune, J.W., and Cravotta III, C.A., 2020, Groundwater quality in relation to drinking water health standards and geochemical characteristics for 54 domestic wells in Clinton County, Pennsylvania, 2017 (ver 1.1, July 2020): U.S. Geological Survey Scientific Investigations Report 2020–5022, p. 72, https://doi.org/10.3133/sir20205022.

References

98. Thorpe, N., and Shirmohammadi, A., 2005, Herbicides and Nitrates in Groundwater of Maryland and Childhood Cancers: A Geographic Information Systems Approach: Journal of Environmental Science and Health, Part C, v. 23, no. 2, p. 261–278, https://doi.org/10.1080/10590500500235001.

99. United States Environmental Protection Agency National Primary Drinking Water Regulations, accessed July 1, 2021, at https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations.

100. Greene, E.A., LaMotte, A.E., and Cullinan, K.-A., 2005, Ground-water vulnerability to nitrate contamination at multiple thresholds in the Mid-Atlantic region using spatial probability models: U.S. Geological Survey Scientific Investigations Report 2004-5118, p. 24, https://doi.org/10.3133/sir20045118.

101. DeSimone, L.A., McMahon, P.B., and Rosen, M.R., 2014, The quality of our Nation's waters—Water quality in Principal Aquifers of the United States, 1991–2010: U.S. Geological Survey Circular 1360, p. 151, https://doi.org/10.3133/cir1360.

102. Denver, J.M., Ator, S.W., Fischer, J.M., Harned, D.C., Schubert, C., and Szabo, Z., 2014, The quality of our Nation's waters—Water quality in the Northern Atlantic Coastal Plain surficial aquifer system, Delaware, Maryland, New Jersey, New York, North Carolina, and Virginia, 1988–2009: U.S. Geological Survey Circular 1353, p. 88, https://doi.org/10.3133/cir1353.

103. Kemp, W., Boynton, W., Adolf, J., Boesch, D., Boicourt, W., Brush, G., Cornwell, J., Fisher, T., Glibert, P., Hagy, J., Harding, L., Houde, E., Kimmel, D., Miller, W., and others, 2005, Eutrophication of Chesapeake Bay: historical trends and ecological interactions: Marine Ecology Progress Series, v. 303, p. 1–29, 10.3354/meps303001.

104. Pan, S., Bian, Z., Tian, H., Yao, Y., Najjar, R.G., Friedrichs, M.A.M., Hofmann, E.E., Xu, R., and Zhang, B., 2021, Impacts of Multiple Environmental Changes on Long-Term Nitrogen Loading From the Chesapeake Bay Watershed: Journal of Geophysical Research: Biogeosciences, v. 126, no. 5, https://doi.org/10.1029/2020JG005826.

105. Tango, P.J., Magnien, R., Butler, W., Luckett, C., Luckenbach, M., Lacouture, R., and Poukish, C., 2005, Impacts and potential effects due to Prorocentrum minimum blooms in Chesapeake Bay: Harmful Algae, v. 4, no. 3, p. 525–531, http://dx.doi.org/10.1016/j.hal.2004.08.014.

106. Young, N., Sharpe, R.A., Barciela, R., Nichols, G., Davidson, K., Berdalet, E., and Fleming, L.E., 2020, Marine harmful algal blooms and human health: A systematic scoping review: Harmful Algae, v. 98, p. 101901, https://doi.org/10.1016/j.hal.2020.101901.

107. Anderson, D.M., Glibert, P.M., and Burkholder, J.M., 2002, Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences: Estuaries, v. 25, no. 4, p. 704–726, https://doi.org/10.1007/BF02804901.

References

108. Boesch, D.F., Brinsfield, R.B., and Magnien, R.E., 2001b, Chesapeake Bay Eutrophication: Scientific Understanding, Ecosystem Restoration, and Challenges for Agriculture: Journal of Environmental Quality, v. 30, no. 2, p. 303–320, https://doi.org/10.2134/jeq2001.302303x.

109. Hofmann, E.E., Klinck, J.M., Filippino, K.C., Egerton, T., Davis, L.B., Echevarría, M., Pérez-Vega, E., and Mulholland, M.R., 2021, Understanding controls on Margalefidinium polykrikoides blooms in the lower Chesapeake Bay: Harmful Algae, v. 107, p. 102064, https://doi.org/10.1016/j.hal.2021.102064.

110. Heisler, J., Glibert, P.M., Burkholder, J.M., Anderson, D.M., Cochlan, W., Dennison, W.C., Dortch, Q., Gobler, C.J., Heil, C.A., Humphries, E., Lewitus, A., Magnien, R., Marshall, H.G., Sellner, K., and others, 2008, Eutrophication and harmful algal blooms: A scientific consensus: HABs and Eutrophication, v. 8, no. 1, p. 3–13, https://doi.org/10.1016/j.hal.2008.08.006.

111. Li, J., Glibert, P.M., and Gao, Y., 2015, Temporal and spatial changes in Chesapeake Bay water quality and relationships to Prorocentrum minimum, Karlodinium veneficum, and CyanoHAB events, 1991–2008: Harmful Algae, v. 42, p. 1–14, https://doi.org/10.1016/j.hal.2014.11.003.

112. Li, M., Ni, W., Zhang, F., Glibert, P.M., and Lin, C.-H. (Michelle), 2020, Climate-induced interannual variability and projected change of two harmful algal bloom taxa in Chesapeake Bay, USA: Science of The Total Environment, v. 744, p. 140947, https://doi.org/10.1016/j.scitotenv.2020.140947.

113. United States Environmental Protection Agency, 2015, EPA Office of Water (OW): 303(d) Listed Impaired Waters NHDPlus Indexed Dataset, accessed July 1, 2021, at https://www.epa.gov/waterdata/waters-geospatial-data-downloads.

114. Sprague, L.A., Oelsner, G.P., and Argue, D.M., 2017, Challenges with secondary use of multi-source water-quality data in the United States: Water Research, v. 110, p. 252–261, https://doi.org/10.1016/j.watres.2016.12.024.

115. Clune, J.W., Crawford, J.K., Chappell, W.T., and Boyer, E.W., 2020b, Differential effects of land use on nutrient concentrations in streams of Pennsylvania: Environmental Research Communications, v. 2, no. 11, p. 14, https://ui.adsabs.harvard.edu/link_gateway/2020ERCom...2k5003C/doi:10.1088/2515-7620/abc97a.

116. Clune, J.W., Crawford, J.K., and Boyer, E.W., 2020a, Nitrogen and Phosphorus Concentration Thresholds toward Establishing Water Quality Criteria for Pennsylvania, USA: Water, v. 12, no. 12, https://doi.org/10.3390/w12123550.

117. Velkoverh, J., 2021, Chesapeake Healthy Watersheds Assessment, accessed July 1, 2021, at storymaps.arcgis.com/stories/294d8042dac542888bbd7c72ac66e5e3.

118. Miller, A., Baker, M., Boomer, K., Merritts, D., Prestegaard, K., and Smith, S., 2019, Legacy Sediment, Riparian Corridors, and Total Maximum Daily Loads: STAC Publication Number 19-001, p. 64, accessed July 1, 2021 at http://www.chesapeake.org/pubs/399_Miller2019.pdf.

References

119. Brakebill, J., Ator, S., and Sekellick, A., 2019, Input and predictions from a suspended-sediment SPARROW model CBSS_V2 in the Chesapeake Bay watershed: U.S. Geological Survey data release, https://doi.org/10.5066/P9Q2YQY6.

120. Gellis, A.C., and Gorman Sanisaca, L., 2018, Sediment Fingerprinting to Delineate Sources of Sediment in the Agricultural and Forested Smith Creek Watershed, Virginia, USA: JAWRA Journal of the American Water Resources Association, v. 54, no. 6, p. 1197-1221, https://doi.org/10.1111/1752-1688.1268.

121. Langland, M.J., 2015, Sediment transport and capacity change in three reservoirs, Lower Susquehanna River Basin, Pennsylvania and Maryland, 1900-2012: Open-File Report 2014–1235, p. 28, http://pubs.er.usgs.gov/publication/ofr20141235.

122. Cerco, C.F., 2016, Conowingo Reservoir Sedimentation and Chesapeake Bay: State of the Science: Journal of Environmental Quality, v. 45, no. 3, p. 882–886, http://dx.doi.org/10.2134/jeq2015.05.0230.

123. Zhang, Q., Ball, W.P., and Moyer, D.L., 2016, Decadal-scale export of nitrogen, phosphorus, and sediment from the Susquehanna River basin, USA: Analysis and synthesis of temporal and spatial patterns: Science of The Total Environment, v. 563–564, p. 1016–1029, https://doi.org/10.1016/j.scitotenv.2016.03.104.

124. Moyer, D.L., and Blomquist, J.D., 2020, Nitrogen, phosphorus, and suspended-sediment loads and trends measured at the Chesapeake Bay River Input Monitoring stations: Water years 1985-2019: U.S. Geological Survey data release, https://doi.org/10.5066/P9VG459V.

125. Knight, R.L., Gu, B., Clarke, R.A., and Newman, J.M., 2003, Long-term phosphorus removal in Florida aquatic systems dominated by submerged aquatic vegetation: Ecological Engineering, v. 20, no. 1, p. 45–63, https://doi.org/10.1016/S0925-8574(03)00003-X.

126. Zhang, Q., Fisher, T.R., Trentacoste, E.M., Buchanan, C., Gustafson, A.B., Karrh, R., Murphy, R.R., Keisman, J., Wu, C., Tian, R., Testa, J.M., and Tango, P.J., 2021, Nutrient limitation of phytoplankton in Chesapeake Bay: Development of an empirical approach for water-quality management: Water Research, v. 188, p. 116407, https://doi.org/10.1016/j.watres.2020.116407.

127. Testa, J.M., Murphy, R.R., Brady, D.C., and Kemp, W.M., 2018, Nutrient- and Climate-Induced Shifts in the Phenology of Linked Biogeochemical Cycles in a Temperate Estuary: Frontiers in Marine Science, v. 5, p. 114, https://doi.org/10.3389/fmars.2018.00114.

128. United States Global Change Research Program Climate Science Special Report: Fourth National Climate Assessment, v. 1, p. 470, 10.7930/J0J964J6.

129. Rice, K.C., Moyer, D.L., and Mills, A.L., 2017, Riverine discharges to Chesapeake Bay: Analysis of long-term (1927–2014) records and implications for future flows in the Chesapeake Bay basin: Journal of Environmental Management, v. 204, p. 246–254, https://doi.org/10.1016/j.jenvman.2017.08.057.

References

130. Rice, K. C.; Jastram, J. D. Rising Air and Stream-Water Temperatures in Chesapeake Bay Region, USA. Climatic Change 2014, 1–12, https://doi.org/10.1007/s10584-014-1295-9.

131. Najjar, R.G., Pyke, C.R., Adams, M.B., Breitburg, D., Hershner, C., Kemp, M., Howarth, R., Mulholland, M.R., Paolisso, M., Secor, D., Sellner, K., Wardrop, D., and Wood, R., 2010, Potential climate-change impacts on the Chesapeake Bay: Estuarine, Coastal and Shelf Science, v. 86, no. 1, p. 1–20, https://doi.org/10.1016/j.ecss.2009.09.026.

132. Reclamation, 2013, Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado, accessed July 1, 2021 at https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html.

133. PRISM Climate Group, 2017, PRISM climate data: Oregon State University web page, accessed July 1, 2021, at https://www.prism.oregonstate.edu.

134. Fleming, B.J., Archfield, S.A., Hirsch, R.M., Kiang, J.E., and Wolock, D.M., 2021, Spatial and Temporal Patterns of Low Streamflow and Precipitation Changes in the Chesapeake Bay Watershed: JAWRA Journal of the American Water Resources Association, v. 57, no. 1, p. 96–108, https://doi.org/10.1111/1752-1688.12892.

135. Mason, C.A., Chanat, J.G., and Rapp, J.L., 2021, Multidecadal Streamflow Trends and Ecological Flow Statistics at USGS Monitoring Stations within the Chesapeake Bay Watershed (1940-2018): U.S. Geological Survey data release, https://doi.org/10.5066/P99OOTED.

136. Shenk, G., Bhatt, G., Tian, R., Cerco, C., Bertani, I., and Linker, L., 2021, Modeling Climate Change Effects on Chesapeake Water Quality Standards and Development of 2025 Planning Targets to Address Climate Change: CBPO Publication Number 328-21, accessed July 1, 2021 at https://www.chesapeakebay.net/channel_files/42671/p6modeldocumentation_climatechangedocumentation_(5).pdf.

137. Vidon, P., Karwan, D.L., Andres, A.S., Inamdar, S., Kaushal, S., Morrison, J., Mullaney, J., Ross, D.S., Schroth, A.W., Shanley, J.B., and Yoon, B., 2018, In the path of the Hurricane: impact of Hurricane Irene and Tropical Storm Lee on watershed hydrology and biogeochemistry from North Carolina to Maine, USA: Biogeochemistry, v. 141, no. 3, p. 351–364, https://doi.org/10.1007/s10533-018-0423-4.

138. United States Environmental Protection Agency, 2008, A Screening Assessment of the Potential Impacts of Climate Change on Combined Sewer Overflow (CSO) Mitigation in the Great Lakes and New England Regions (Final Report) EPA/600/R-07/033F, p. 52, accessed Jule 1, 2021 at https://ofmpub.epa.gov/eims/eimscomm.getfile?p_download_id=472009.

139. Pilegaard Kim, 2013, Processes regulating nitric oxide emissions from soils: Philosophical Transactions of the Royal Society B: Biological Sciences, v. 368, no. 1621, p. 20130126, https://dx.doi.org/10.1098%2Frstb.2013.0126.

References

140. Tully, K.L., Weissman, D., Wyner, W.J., Miller, J., and Jordan, T., 2019, Soils in transition: saltwater intrusion alters soil chemistry in agricultural fields: Biogeochemistry, v. 142, no. 3, p. 339–356, https://dx.doi.org/10.1098%2Frstb.2013.0126.

141. Li, Y., Chen, B.-M., Wang, Z.-G., and Peng, S.-L., 2011, Effects of temperature change on water discharge, and sediment and nutrient loading in the lower Pearl River basin based on SWAT modelling: Hydrological Sciences Journal, v. 56, no. 1, p. 68–83, https://doi.org/10.1080/02626667.2010.538396.

142. van Vliet, M.T.H., and Zwolsman, J.J.G., 2008, Impact of summer droughts on the water quality of the Meuse river: Journal of Hydrology, v. 353, no. 1, p. 1–17, https://doi.org/10.1016/j.jhydrol.2008.01.001.

143. Irby, I.D., Friedrichs, M.A.M., Da, F., and Hinson, K.E., 2018, The competing impacts of climate change and nutrient reductions on dissolved oxygen in Chesapeake Bay: Biogeosciences, v. 15, no. 9, p. 2649–2668, https://doi.org/10.5194/bg-15-2649-2018.

144. Wagena, M., 2018, Agricultural conservation practices can help mitigate the impact of climate change: The Science of the total environment, v. 635, http://dx.doi.org/10.1016/j.scitotenv.2018.04.110.