

# New Insights

Science-based evidence of  
water quality improvements,  
challenges, and opportunities  
in the Chesapeake



# Acknowledgements

**BACKGROUND:** Over the past several decades, scientists, natural resource managers, and the general public have become increasingly aware of, and concerned for the impaired health of the Chesapeake Bay. The degradation of water quality and habitat conditions throughout the Chesapeake Bay led to the development of the U.S. Environmental Protection Agency's Chesapeake Bay Total Maximum Daily Load (TMDL) for nitrogen, phosphorus, and sediment—also known as a 'pollution diet.' The watershed jurisdictions' implementation of their watershed implementation plans has reinforced the need to understand the effectiveness of best management practices to ensure compliance with local and regional water quality load allocations and targets.

**CITATION:** Lyerly, C.M., A.L. Hernández Cordero, K.L. Foreman, S.W. Phillips, W.C. Dennison (eds.). 2014. *New Insights: Science-based evidence of water quality improvements, challenges, and opportunities in the Chesapeake.*

**AUTHORS:** Christina M. Lyerly, Ana L. Hernández Cordero, Katherine L. Foreman, Scott W. Phillips, William C. Dennison

**CONTRIBUTORS:** Peter Groffman from the **Cary Institute of Ecosystem Studies.**

Ashlee Harvey and Lea J. Rubin from the **Chesapeake Research Consortium, Chesapeake Bay Program.**

John McCoy from the **Columbia Association.**

Claire Buchanan from the **Interstate Commission on the Potomac River Basin.**

Ben Cole, Sherm Garrison, and Renee Kharr from the **Maryland Department of Natural Resources.**

Tad Aburn, Quentin Forrest, Priya Papali and Michael Woodman from the **Maryland Department of the Environment.**

Melanie Harrison from the **National Oceanic and Atmospheric Administration.**

Thomas E. Jordan from the **Smithsonian Environmental Research Center.**

Keith Eshleman from the **University of Maryland Center for Environmental Science Appalachian Laboratory.**

Walter R. Boynton and Jeremy Testa from the **University of Maryland Center for Environmental Science Chesapeake Biological Laboratory.**

Jeff Cornwell and Tom Fisher from the **University of Maryland Center for Environmental Science Horn Point Laboratory.**

Caroline Wicks from the **Integration & Application Network, University of Maryland Center for Environmental Science.**

Sarah Lane from the **University of Maryland Center for Environmental Science, Maryland Department of Natural Resources.**

Kenneth W. Staver from the **University of Maryland Wye Research and Education Center.**

Peter Claggett, Kenneth E. Hyer, Laura Medalie, Nancy Rybicki, Peter Tango, and John Wolf from the **U.S. Geological Survey.**

Gary Shenk from the **U.S. Environmental Protection Agency, Chesapeake Bay Program.**

Carlton H. Hershner Jr. from the **Virginia Institute of Marine Sciences, The College of William & Mary.**

Ning Zhou from the **Virginia Polytechnic Institute and State University, Chesapeake Bay Program.**

Members of the **Tidal Monitoring and Analysis Workgroup and Nontidal Water Quality Workgroup, Chesapeake Bay Program.**

**ONLINE AVAILABILITY:** This publication is also available electronically at: [ian.umces.edu](http://ian.umces.edu) and [chesapeakebay.net](http://chesapeakebay.net)

**SCIENCE COMMUNICATION, DESIGN, & LAYOUT:** Brianne Walsh, Integration & Application Network, University of Maryland Center for Environmental Science ([ian.umces.edu](http://ian.umces.edu)).

**ON THE COVER:** Photo © Chesapeake Bay Program.



# Contents

Purpose .....	1
Synopsis .....	2
Part I: What's working.....	4
<i>Lesson 1: Upgrades in both nitrogen and phosphorus wastewater treatment result in rapid local water quality improvements.....</i>	4
<i>Lesson 2: Improvements in air quality lead to reductions in atmospheric nitrogen deposition .....</i>	10
<i>Lesson 3: Reductions of agricultural nutrient sources result in improved stream quality.....</i>	14
Part II: Challenges .....	18
<i>Lesson 4: Many practices provide initial water quality improvements in runoff; however, full benefits to stream conditions can be delayed.....</i>	18
<i>Lesson 5: Improvements in water quality can be counteracted by changes in nutrient sources and land-use practices .....</i>	22
Part III: Opportunities.....	28
<i>Lesson 6: Observable water quality responses are more likely to occur if A) location-specific sources of pollution are identified and B) targeted practices are implemented.....</i>	28
<i>Lesson 7: An array of practices to promote stormwater infiltration and retention are needed in urban and suburban areas .....</i>	34
Conclusions.....	38
<i>New Insights: case study locations .....</i>	40
Additional case study locations.....	41
Glossary.....	42
References .....	44

# Chesapeake Bay Watershed



## Purpose

The population in the Chesapeake Bay watershed has grown three-fold during the past century, reaching 17.5 million people in 2011.<sup>1</sup> Increasing anthropogenic pressures from urban and suburban development and intensified agriculture have negatively affected water quality. Excess nutrient and sediment loads to the Bay have led to decreased water clarity, increased occurrences of harmful algal blooms, an increase in the occurrences and magnitude of widespread low to no dissolved oxygen events, the reduced coverage of underwater bay grasses, and reduced population levels and overall health of biological communities.

Over the past several decades, scientists, natural resource managers, and the general public have become increasingly aware of, and concerned for the impaired health of the Chesapeake Bay. The degradation of water quality and habitat conditions throughout the Bay led to the development, and subsequent publication of the U.S. Environmental Protection Agency (U.S. EPA) Chesapeake Bay Total Maximum Daily Load (TMDL) for nitrogen, phosphorus, and sediment—also known as a ‘pollution diet.’ The resultant implementation of the jurisdictions’ watershed implementation plans has reinforced the need to understand the effectiveness of best management practices (BMPs) to ensure compliance with local and regional water quality load allocations and targets.

Historically, the Chesapeake Bay scientific and management community’s understanding of the effectiveness of these BMPs has largely relied on estimates derived from panels of experts. Given the performance-driven structure of the TMDL, water quality managers are interested in understanding the connection between BMP operations and real-world water quality monitoring data. The Tidal Monitoring and Analysis Workgroup in conjunction with the Nontidal Water Quality Workgroup of the Chesapeake Bay Program Partnership took on the task of synthesizing information from existing watershed studies of BMP effectiveness at improving water quality across the Chesapeake Bay and its watershed. This report is a resource for water quality managers involved in identifying water quality problems, determining the sources of nutrient loads, creating nutrient management plans, choosing and implementing appropriate BMPs, and monitoring subsequent changes in water quality.



*A plaque mounted on a stormwater drain in Annapolis, Maryland reminds people that water flowing into these grates drains into the Chesapeake Bay. Photo © Jane Thomas, IAN Image Library.*

# Synopsis

This report summarizes results from more than 40 case studies in the Chesapeake Bay watershed where water quality monitoring was conducted to detect benefits from implementation of best management practices (BMPs). Three themes emerged from this data:

- Several groups of practices are proven effective;
- Certain challenges can impede water quality improvements; and
- Practices that target the impacts of intensified agriculture and rapid population growth are needed to enhance progress toward improving water quality.

Each theme consists of lessons that managers can use in their decision-making processes, and the public can use to help raise awareness of and support for restoration efforts. Within each of the seven lessons, several case studies are highlighted to provide a detailed look at the knowledge acquired from water quality monitoring related to BMP implementation.

## What's Working



Blue Plains wastewater treatment facility in Washington, D.C. Photo © Chesapeake Bay Program.

Three major groups of BMPs are demonstrably effective in improving water quality:

- Upgrades to wastewater treatment plants (WWTPs);
- Decreases in atmospheric nitrogen deposition; and
- Reductions in agricultural nutrient inputs.

Advanced WWTP technology reduces excess nitrogen (N) and phosphorus (P) from wastewater prior to being discharged into local waterways. Upgrades to WWTPs across the Bay and its watershed have decreased concentrations of total nitrogen (TN), total phosphorus (TP) and chlorophyll, and in some cases, increased the occurrence of submerged aquatic vegetation (SAV). Research has also directly linked decreased NO<sub>x</sub> atmospheric emissions with improved surface water quality within the watershed. Decreased N emissions associated with greater power plant emission controls and improved vehicle emissions efficiency reduced atmospheric N deposition to the Bay. Finally, the reduction of agricultural nutrient inputs has led to water quality improvements. Data have demonstrated that planting cover crops, managing fertilizer and manure applications, and limiting livestock access to streams reduced nutrient concentrations, and in some instances, decreased sediment loads.

## Challenges



Stormwater runoff. Photo © Chesapeake Bay Program.

Two major challenges have impeded progress despite the implementation of BMPs:

- Delays between BMP implementation and observable water quality improvements; and
- Counteracting influences of population growth and intensified agriculture.

Delays in water quality improvements, or 'lag times,' can occur for several reasons. Groundwater—and the nutrients that have leached into groundwater—discharge into the Bay and its tributaries. However, groundwater ages range from less than a year to more than 100 years. As a result, N can remain in the groundwater system for very long periods of time, delaying water quality responses to BMP implementation. Lag times will also result from sediment storage of P. Sediments will gradually release stored P, particularly under low to no dissolved oxygen conditions, which are common in the Bay during the summer months. Despite the reduction of P loads, water quality responses may be delayed as existing sediment in the Bay continues to release P. The second challenge presents when a nutrient source not targeted by a BMP overwhelms any improvements that would have occurred after BMP implementation. Intensified agriculture

(increased use of fertilizers and greater livestock densities) and land use conversion from forests to agriculture and urban development are driving forces of declining water quality in the Chesapeake Bay watershed. Better understanding these challenges to restoring local and Bay water quality conditions leads directly to opportunities to better manage pollutant sources.

## Opportunities



*A newly planted rain garden at a church in Annapolis, Maryland. Photo © Chesapeake Bay Program.*

Monitoring water quality during and after BMP implementation has exposed the challenges that impede progress and revealed practices that enhance measurable improvements in water quality and habitat conditions:

- Identification of all sources of nutrients and targeting BMPs accordingly; and
- Improvements to stormwater management to accommodate the watershed's population growth.

Targeted BMPs will lead to improvements in water quality and habitat conditions. If agricultural activities are the dominant source of nutrients in a river, upgrading WWTPs alone will not produce the desired water quality outcomes. Agricultural BMPs will be required to reach water quality goals. As agricultural land uses are converted to highly-populated urban and suburban development, stormwater management becomes increasingly important to improving water quality. Stormwater BMPs that reduce sediment runoff, increase the time available for nutrient infiltration, and expand permeable surfaces will help reduce the impact of spreading development.

## Implications

The examination of research based on water quality monitoring data associated with BMP implementation in the Chesapeake Bay watershed reveals multiple implications for continued efforts in Bay restoration:

1. Following implementation of the Clean Water Act and the National Pollutant Discharge Elimination System permits, upgrades to WWTPs have led to many instances of improved water quality. Greater investment in improved WWTP technology will lead to further water quality improvements and help offset the additional pressures of a growing urban and suburban population.
2. Improved air quality in the Chesapeake Bay watershed after the implementation of the Clean Air Act has decreased atmospheric nitrogen reaching the land and waters. As more people live in the watershed—driving more cars further distances—greater fuel efficiency combined with continued installation of improved technology at power plants will be needed to further improve air quality and Bay health.
3. Several agricultural practices that reduced nutrient loads have led to improvements in water quality. Supporting the expansion of these practices in similar areas throughout the watershed is needed to make continued progress in improving water quality and restoring Bay health.
4. Delays between implementing nutrient-reducing activities and observing water quality improvements require patience and persistence. Long-term water quality monitoring is essential to evaluating BMP effectiveness and to adjust management actions as new information is collected.
5. Pressures from increased fertilizer use, livestock densities, stormwater runoff, and WWTP effluent associated with greater numbers of people living in the watershed can overwhelm efforts to improve water quality. Better land-use planning and reducing both point and nonpoint sources of nutrients are needed to sustainably manage the Bay's resources.
6. The Chesapeake Bay watershed is a diverse region consisting of a variety of land-uses and watershed characteristics. Targeting specific BMPs based on local attributes, monitoring changes in water quality, and engaging in adaptive management are needed to attain water quality goals.
7. The number of people living in the Chesapeake Bay watershed continues to grow and more land is being converted to urban and suburban uses. Proven and innovative practices are required to manage the resulting stormwater runoff, and testing is needed to rigorously evaluate water quality benefits.

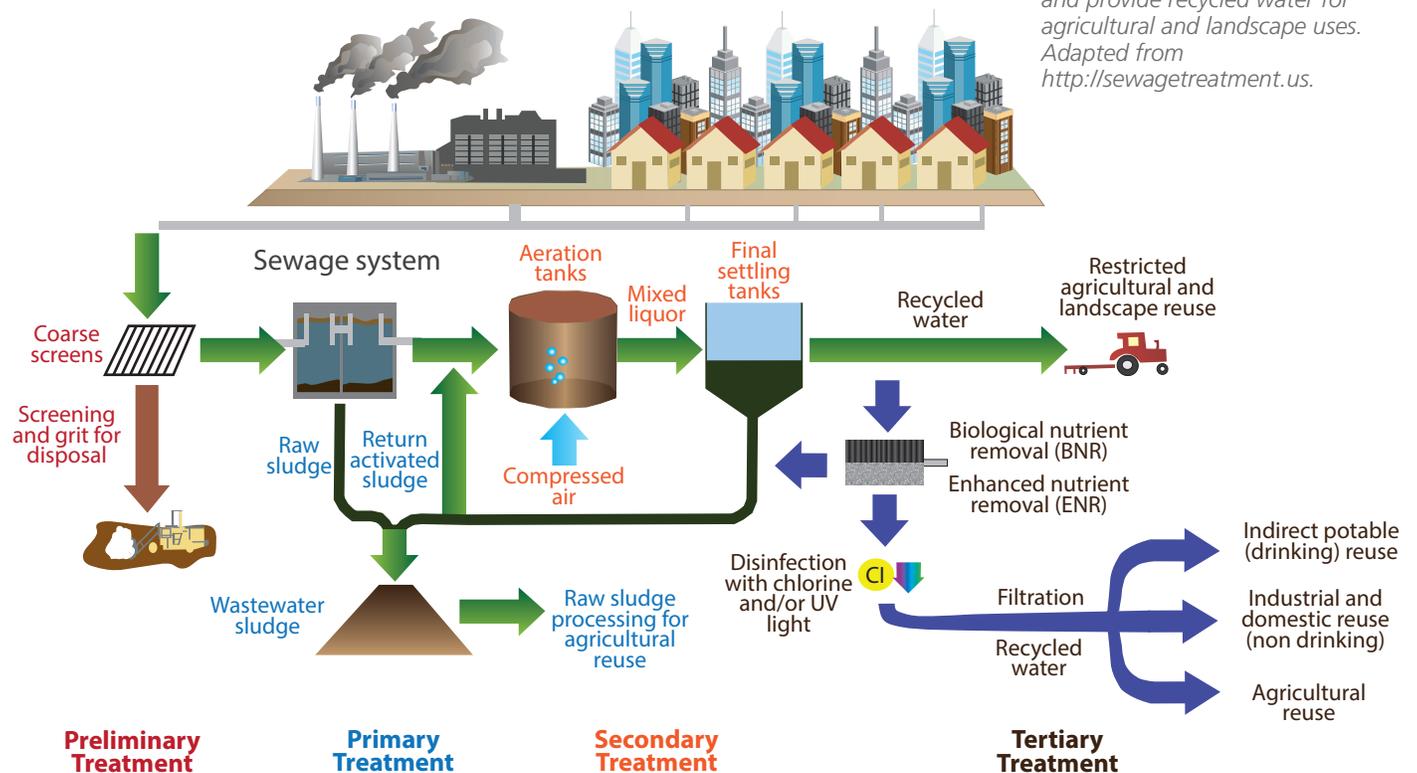


## Upgrades in both nitrogen and phosphorus wastewater treatment result in rapid local water quality improvements

- Upgrades to wastewater treatment plants are effective restoration practices.
- Wastewater treatment plant upgrades result in decreased nitrogen and phosphorus loadings to the Chesapeake Bay.
- Reduced nitrogen and phosphorus loads lead to improved water quality and in some cases increased submerged aquatic vegetation.

The Chesapeake Bay watershed's population growth and urban and suburban development have led to increased volumes of wastewater and sewage. Nitrogen (N) and phosphorus (P) in effluent have contributed to excessive organic production leading to decreased water quality in the Bay—greater turbidity, higher chlorophyll a concentrations, and reduced submerged aquatic vegetation (SAV). The following case studies provide clear examples of the significant water quality improvements that can result from upgrades to wastewater treatment plant (WWTP) technology even as the population continues to grow.

*A central collection and wastewater treatment plant can remove nutrients from wastewater to very low levels (i.e., tertiary treatment) and provide recycled water for agricultural and landscape uses. Adapted from <http://sewagetreatment.us>.*



**Wastewater treatment plant upgrades in the Baltimore, Maryland metropolitan area resulted in estuarine water quality improvements in Back River within three years.**

Wastewater from the Baltimore region is treated at the Back River WWTP, which has been in operation approximately 100 years. Management actions can be traced back to 1912, though as technology has advanced, the upgrades made in recent years appear to have been the most effective at reducing pollutant discharges. As WWTP nutrient loads decreased, N concentrations in Back River also decreased, leading to significant water quality improvements within approximately three years as measured by changes in chlorophyll *a*. P reductions were a less important factor in water quality response, possibly due to sediment storage and delayed release of P, creating a lag time between management actions and the biological estuarine response.<sup>2</sup>

**Wastewater treatment plant upgrades in the metropolitan Washington, D.C. area resulted in reductions in phosphorus and nitrogen concentrations and toxic cyanobacteria and led to the recovery of submerged aquatic vegetation in the tidal Potomac River.**

The Blue Plains WWTP—the largest WWTP servicing the D.C. metro area—began operations in 1938 as a primary treatment facility. It was later upgraded to secondary treatment in 1958, but effluent remained very nutrient enriched.<sup>3</sup> Human illness associated with unclassified cyanobacteria toxins in the Potomac River were documented in the 1930s.<sup>4</sup> Toxic cyanobacteria blooms continued to occur over the following decades, including a particularly severe bloom of *Microcystis aeruginosa*, a toxic form of blue green algae, in 1983.<sup>5</sup> Phosphorus concentrations began to decrease in the 1970s when P removal from sewage was implemented in the Potomac River.<sup>6</sup> Phosphate was banned from laundry detergents in Maryland in 1985 and in Virginia and D.C. in 1986, further decreasing total phosphorus (TP) loads to the estuary. Nitrogen loads, however, still negatively affected water quality. Nitrate concentrations in the upper tidal fresh Potomac River were as much as 30 times greater than concentrations at which algal growth would be considered healthy and controlled. Progress was made when Blue Plains WWTP implemented partial biological nutrient removal (BNR) in October 1996 and then full BNR in



Blue Plains wastewater treatment plant (WWTP) is the largest WWTP servicing the Washington, D.C. metropolitan area. Photo © Chesapeake Bay Program.

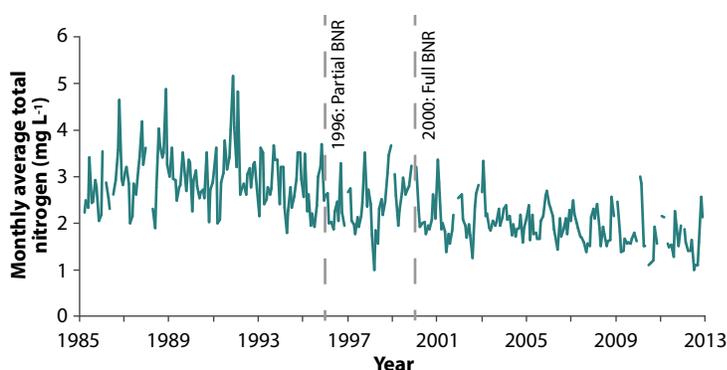


Figure 1.1. Mean monthly surface total nitrogen (TN) concentrations in the Potomac River upper tidal fresh monitoring station off Piscataway Creek (1985–2013). Blue plains wastewater treatment plant (WWTP) is the largest WWTP discharging into the upper Potomac River. The implementation of partial biological nutrient removal (BNR) followed by full BNR was associated with declines in TN concentrations.<sup>7</sup>

February 2000. Nitrogen concentrations significantly decreased in the upper and middle Potomac River, and the duration and bloom intensity of *M. aeruginosa* significantly decreased in the upper estuary (Figure 1.1).<sup>7,8</sup>

Blue Plains WWTP upgrades are also associated with the resurgence of SAV. Research examining SAV abundance in the upper tidal Potomac River found that decreases in total nitrogen (TN) inputs from WWTP discharge, and TN, TP, and total suspended sediment concentrations in the river were highly correlated with increases in total SAV abundance (Figure 1.2).<sup>9</sup> Although WWTP upgrades appear to have reduced N concentrations in the lower estuary as well, this reduction has not been significant enough to control excess algal growth and improve bottom water dissolved oxygen levels.<sup>8</sup> The effects that WWTP upgrades have on water quality fluctuate seasonally with intra-annual variations in precipitation. Decreased nutrient loads will have the greatest effect during low-flow summer months. During seasons with higher freshwater flows, WWTP nutrient loads have a smaller impact on the estuary than nonpoint sources.<sup>8</sup>

**After wastewater treatment upgrades, phosphorus and nitrogen reductions in effluent originating from Fairfax County, Virginia (a suburb of Washington, D.C.) significantly decreased, leading to lower chlorophyll a concentrations in Gunston Cove, an embayment of the Potomac River.**

Fairfax County, VA has been proactive in decreasing nutrient loading since the late 1970s when the county first upgraded the Noman M. Cole Jr. Pollution Control Plant. Phosphorus loading into Gunston Cove was greatly reduced beginning in the early 1980s; however, measurable reductions in TP concentrations were not observed until nearly 20 years later. Beginning in 1989, chlorophyll a and ammonia N concentrations substantially decreased.<sup>10</sup> However, declines in nitrates, organic N, and nitrites did not occur until 1983, early 1990s, and 2000, respectively.<sup>11</sup> In 2003, the WWTP was also equipped with BNR technologies, which led to additional significant reductions in N loading.<sup>11,12</sup> The decreases in nutrient concentrations contributed to markedly increased water clarity beginning in the mid-1990s, which led to pronounced increases in SAV colonization since 2000.<sup>10</sup> The development of extensive beds of SAV in the cove during the last decade has provided favorable habitat for important



*Vallisneria americana*, or wild celery, a common submerged aquatic vegetation species present in tidal and non-tidal waterways throughout the Chesapeake Bay watershed. Photo © Cassie Gurbisz, UMCES.

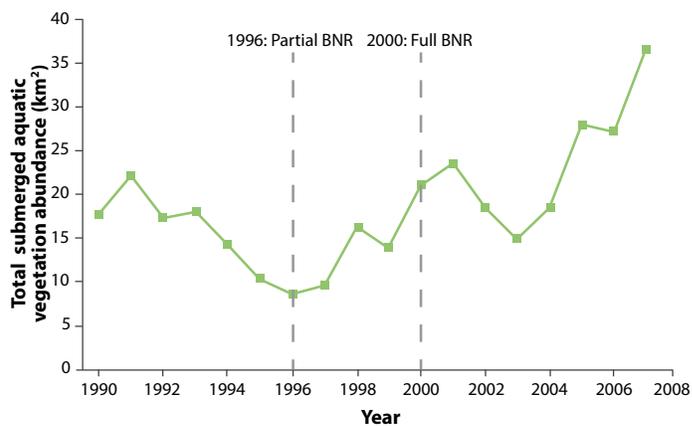


Figure 1.2. Total submerged aquatic vegetation (SAV) abundance in the upper Potomac River (1990–2007). Partial biological nutrient removal (BNR) and full BNR were implemented at the Blue Plains wastewater treatment plant in 1996 and 2000, respectively. The subsequent decreases in total nitrogen, total phosphorus, and total suspended sediment concentrations were highly correlated with increases in SAV abundance.<sup>9</sup>

ecological and fishery species. Gunston Cove exemplifies how major improvements in water quality resulting from reductions in point source loading can also yield enormous benefits to the living resources of tidal waters. Previous research provided a scientific basis for expecting water quality improvements in Gunston Cove, which were ultimately realized. However, the delayed water quality improvements strengthen the argument for using long-term water quality monitoring data to evaluate BMPs and subsequently using these results to inform future BMP planning efforts.

**Nutrient removal upgrades at wastewater treatment plants in the upper Patuxent River watershed led to improved water quality and reestablishment of submerged aquatic vegetation in the upper tidal Patuxent River.**

In the Patuxent River watershed, point source P loads decreased sharply in 1986 in response to a statewide ban on P-based laundry detergents. However, underwater bay grasses did not begin to rebound until 1991 when the WWTPs were equipped with BNR technology, reducing N loads to the estuary (Figures 1.3 and 1.4). In the upper and middle regions of the tidal Patuxent River, declines in nutrient and phytoplankton concentrations were reflective of the WWTP upgrades. The lower tidal river also experienced a decline in nutrient concentrations; however, the effects on phytoplankton concentrations were minimal.<sup>13,14,15,16</sup> The relative importance of P and N as the primary culprit for stimulating poor water quality and habitat conditions can vary regionally. In the case of the upper tidal Patuxent River, after sustained reductions in P, additional reductions in N were

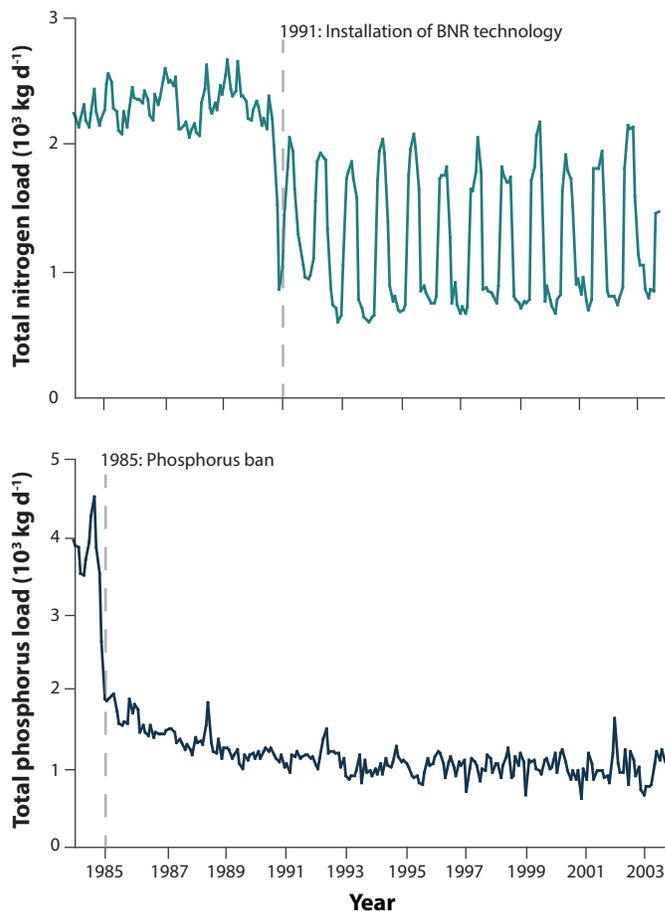


Figure 1.3. Inputs of total nitrogen and total phosphorus (TP) from the wastewater treatment plant (WWTP) in the upper Patuxent River watershed (1984–2003). In 1985, the WWTP TP loads decreased after phosphorus was banned in detergents. In 1991, nitrogen loads decreased when biological nutrient removal (BNR) technology was implemented (data from Chesapeake Bay Program Point Source Nutrient Database).<sup>16</sup>

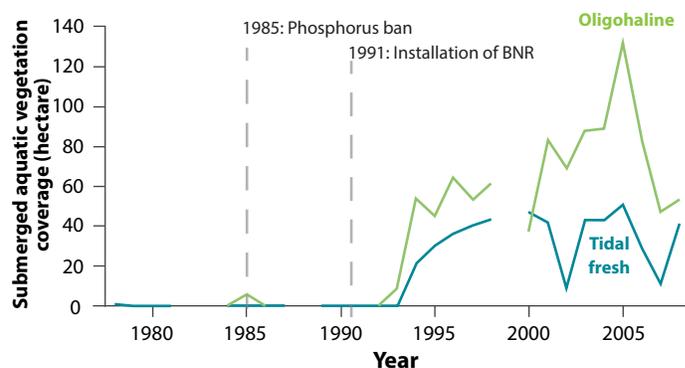


Figure 1.4. Submerged aquatic vegetation (SAV) coverage in the Patuxent River (1978–2008). Total phosphorus loads were reduced in 1985, but SAV did not begin to rebound until total nitrogen loads were reduced in 1991, when biological nutrient removal (BNR) technology was implemented at the wastewater treatment plant (data from W. Boynton, UMCES).

**Salinity** is a measure of the amount of dissolved salts in the water. Within the Chesapeake Bay, salinity gradually decreases as you move north towards the Susquehanna River, and increases as you move south towards the mouth of the Bay, where it meets the Atlantic Ocean. The salinity of waters within the Chesapeake Bay can be described as a percentage of full strength seawater:

- Oligohaline: 1% to 15% of full strength seawater (Northern Bay).
- Mesohaline: 16% to 49% of full strength seawater (Mid-Bay).
- Polyhaline: More than 50% of full strength seawater (Southern Bay).

necessary for sufficient water quality improvement to support the reestablishment of SAV. Understanding the local relationships between nutrients and biological communities can help in making better decisions on selecting which BMPs are needed in the watershed.

**Reductions of nutrient loads into Mattawoman Creek, a small Maryland tidal tributary of the Potomac River, resulted in water quality improvements, including reduced chlorophyll *a* and increased water clarity and submerged aquatic vegetation.**

In the mid-1990s, WWTP effluent discharge was substantially reduced in Mattawoman Creek, which led to a three-fold reduction in nutrient loading. Chlorophyll *a* concentrations significantly declined, leading to large improvements in water clarity and increases in SAV coverage. Monitoring data collected since the early 1970s suggest that prior to the reduction of effluent discharge, Mattawoman Creek was very eutrophic and experienced large algal blooms. SAV was absent from the system from 1977 to 1989, and only covered approximately 5% of the creek bottom from 1989 to 1997. It was not until 1997 that SAV began to rapidly increase and by 2002, 40–50% of the creek bottom was covered in SAV.<sup>17</sup> The improvements in water quality that resulted from the significant reduction of effluent clearly exemplify the magnitude of success that could be achieved when nutrient loads are substantially reduced.



*Mattawoman Creek, a 30-mile long tributary of the Potomac River, flows through Prince Georges and Charles Counties, Maryland. In the mid-1990s, wastewater treatment plant effluent draining into Mattawoman Creek was reduced, leading to a significant decline in chlorophyll *a* concentrations, and improvements in water clarity and submerged aquatic vegetation coverage. Photo © Joel Kinison.*

**Major nitrogen reductions have occurred near large and small urban centers in the Chesapeake Bay watershed.**

Upgrades to WWTPs represent many of the success stories within the watershed, but point sources continue to contribute approximately 20% of the nutrient loads.<sup>18</sup> Figure 1.5 illustrates progress from the late 1980s to 2012. Total nitrogen at some WWTPs—particularly those in highly populated areas—decreased as upgrades were implemented. However, other areas are experiencing increases in TN, partly resulting from WWTPs that have yet to be upgraded due to long implementation times or lack of funding.<sup>18</sup> The map reveals that much work is yet to be done while simultaneously demonstrating promising opportunities for significant and relatively rapid improvements. In particular, the James, Potomac, and Back Rivers represent areas that would likely see continuing improvements as WWTPs undergo enhanced nutrient removal upgrades.

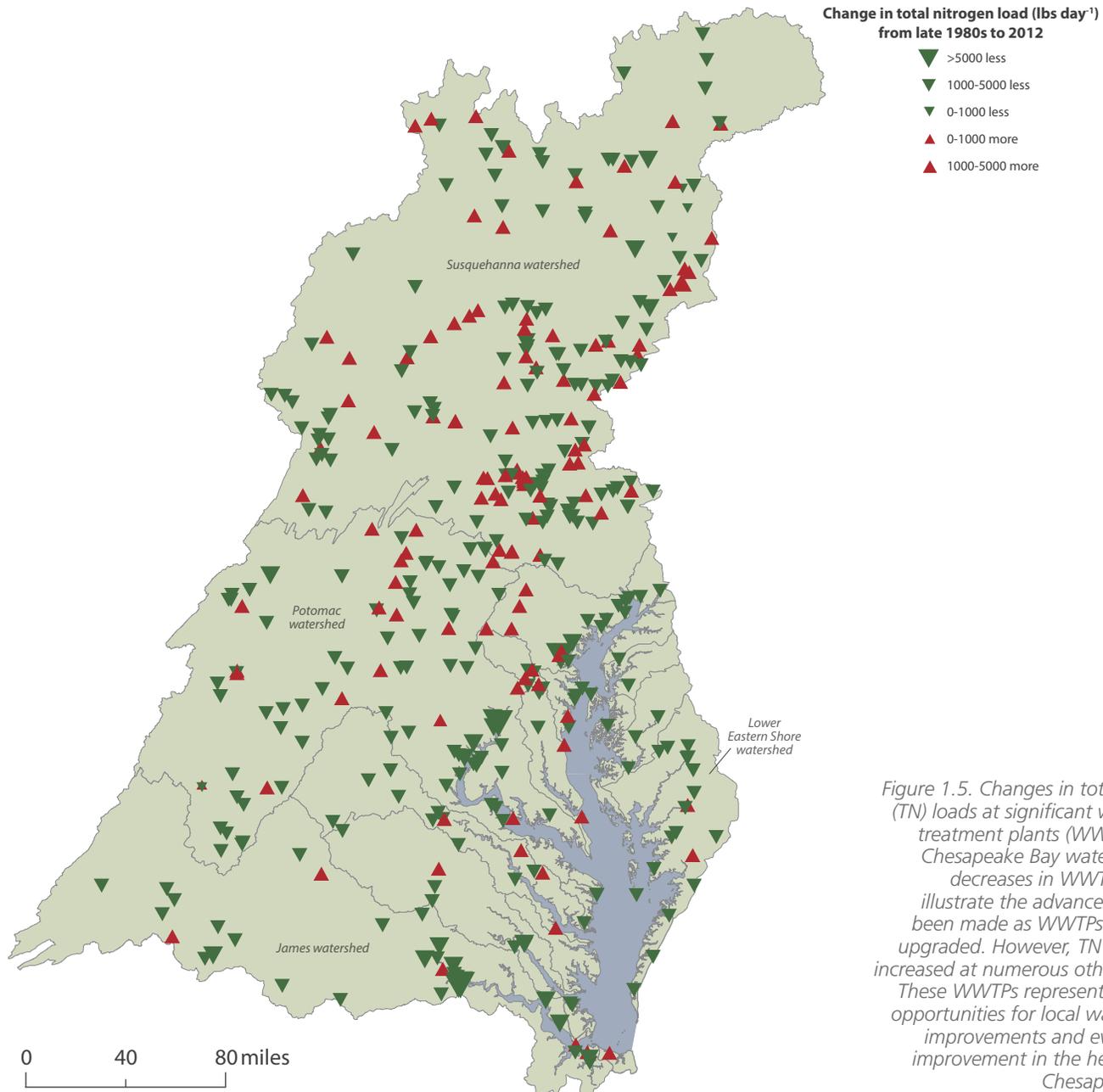


Figure 1.5. Changes in total nitrogen (TN) loads at significant wastewater treatment plants (WWTPs) in the Chesapeake Bay watershed. The decreases in WWTP TN loads illustrate the advances that have been made as WWTPs have been upgraded. However, TN loads have increased at numerous other WWTPs. These WWTPs represent significant opportunities for local water quality improvements and even greater improvement in the health of the Chesapeake Bay.<sup>18</sup>

## Improvements in air quality lead to reductions in atmospheric nitrogen deposition

- **Almost one-third of the nitrogen load to the Chesapeake Bay comes from atmospheric deposition.**
- **Atmospheric nitrogen originates from point sources such as power plants, industrial facilities, and diffuse sources such as vehicle emissions and the volatilization of ammonia from animal waste and ammonia-based fertilizers.**
- **Reductions in atmospheric nitrogen deposition are directly linked to improvements in water quality.**

Technological advances have made great strides in reducing atmospheric nitrogen (N) deposition to the Bay. Atmospheric point sources and vehicle emissions controls have decreased the levels of nitrogen oxides ( $\text{NO}_x$ ) in the air. However, population growth, increased use of vehicles, and intensified agriculture have slowed progress. The following case studies detail success stories achieved over the past 30 years, and highlight the actions needed to continue to observe decreases in atmospheric N deposition.

**During a 20-year period of point source air emission reductions, particularly from power plants, nitrate loads from atmospheric deposition to the Bay watershed have decreased by about 30%.**

Within the National Atmospheric Deposition Program (NADP), the United States Geological Survey (USGS) leads the wet atmospheric deposition monitoring efforts and performs scientific research to examine the effects of deposition on aquatic and terrestrial ecosystems. U.S. Environmental Protection Agency modeling has suggested that  $\text{NO}_x$  emissions affecting the Bay originate from an atmospheric area (airshed) of about 570,000 square miles—equivalent to seven times the size of the watershed.<sup>19</sup> Ammonia ( $\text{NH}_3$ ),  $\text{NO}_x$  and other reactive N compounds are deposited to the Earth's surface via rain, sleet, snow, and fog. Atmospheric N is also deposited onto land and water through a constant daily rate of dry deposition.<sup>19</sup> Wet and dry atmospheric N deposition can saturate terrestrial ecosystems with N, including forested mountain regions in the Northeast, and can be discharged into waterways through groundwater and surface water runoff. Atmospheric N is also deposited directly onto water bodies like the Chesapeake Bay.<sup>20</sup> Although annual mean wet inorganic N deposition across the watershed has been greatly reduced since the early 1990s, opportunities to improve water quality by reducing N loads to the Bay remain and may be achieved by continuing to reduce emissions (Figure 2.1).

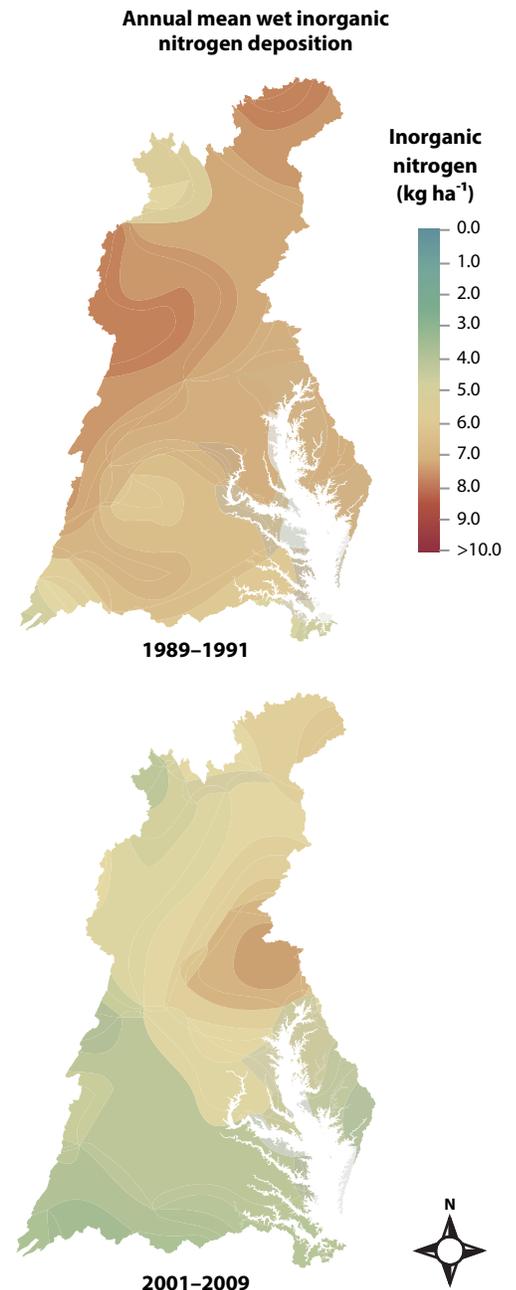


Figure 2.1. Inorganic nitrogen (N) in wet deposition has decreased in the Chesapeake Bay watershed between the periods 1989–1991 and 2001–2009. Significant progress has been made in reducing airborne loads of N as power plant and car emission technology has advanced. The remaining atmospheric deposition loads of N above natural background levels represents an opportunity for greater improvements in water quality (data from NADP 2010).<sup>21</sup>

**Reductions in atmospheric deposition resulting from stricter nitrogen oxides emissions control programs are directly linked to improvements in surface water quality in the Chesapeake Bay watershed.**

A large portion of the Chesapeake Bay watershed is still forested, and therefore, studying the role of forests in atmospheric N deposition and surface water quality changes leads to a more robust understanding of watershed nutrient dynamics. The relationships between wet atmospheric N deposition, nitrate-N loads originating from forested watersheds, and nitrate-N concentrations in streams were examined in nine mostly-forested sub-watersheds in the Appalachian Mountains of Maryland, Pennsylvania, and Virginia. In all nine locations, wet atmospheric N deposition and nitrate-N concentrations significantly decreased and atmospheric deposition strongly predicted observed annual nitrate-N loads to streams. Decreases in nitrate-N loads also occurred in all locations, five of which were statistically significant. The results suggest that decreasing atmospheric N deposition will have positive effects on water quality throughout the entire watershed, independent of sub-watershed size. The decreases in nitrate-N loads occurred rapidly after the passage of the 1990 Clean Air Act Amendment's Acid Rain Program that mandated reductions in NO<sub>x</sub> emissions, primarily originating from power plants (Figures 2.2 and 2.3).<sup>22</sup>

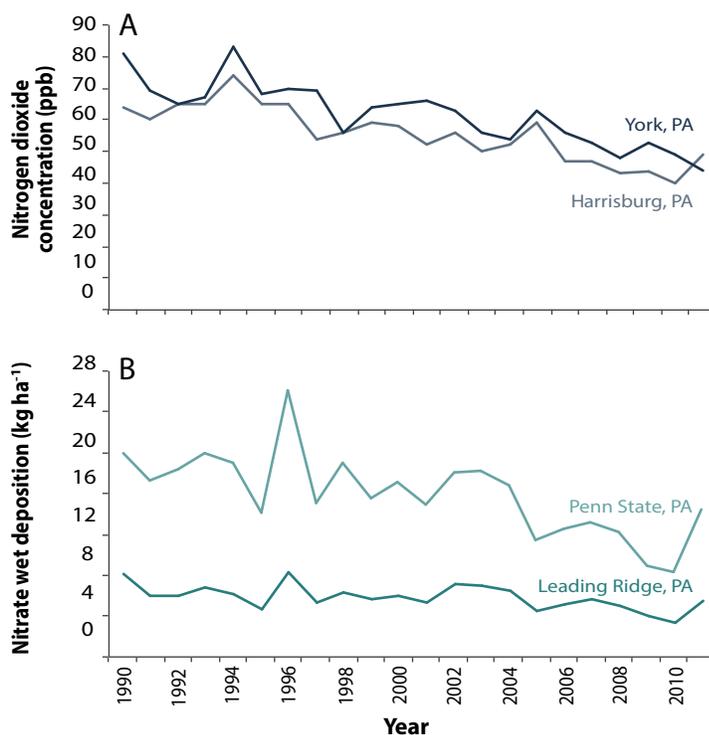


Figure 2.2. Trends in nitrogen dioxide (NO<sub>2</sub>) emissions and wet atmospheric nitrate deposition (1990-2011). Point source emissions began to decrease relatively rapidly after the passage of the 1990 Clean Air Act (A), contributing to a decrease in wet atmospheric nitrate deposition loads (B) (data from U.S. EPA NO<sub>2</sub> Monitoring Program and the National Atmospheric Deposition Program).

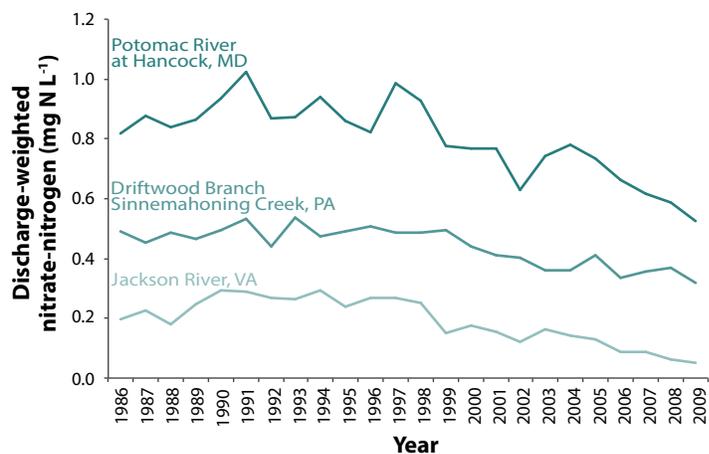


Figure 2.3. Nitrate-nitrogen concentrations in surface water at Potomac River at Hancock (MD), Driftwood Branch Sinnemahoning Creek (PA), and Jackson River (VA) monitoring stations (1986-2009). Research directly linked decreases in atmospheric deposition to reductions in nitrate yields and concentrations in surface water (data from K. Eshleman, UMCES).<sup>22</sup>

**Mobile sources of air emissions are major contributors to atmospheric deposition and nutrient loading to the Chesapeake Bay.**

National  $\text{NO}_x$  air emissions are dominated by mobile sources (vehicles), which represent 58% of the total, whereas fuel combustion (electric utilities and industrial processes) contributes only 35%, indicating that atmospheric diffuse sources contribute more  $\text{NO}_x$  than atmospheric point sources (Figure 2.4). The greatest contributions of  $\text{NO}_x$  emissions from mobile sources originate from cars and light trucks (27%) and semi-trucks and buses (28%) (Figure 2.5).<sup>23</sup> Combustion engines produce  $\text{NO}_x$  when N and oxygen (O) atoms react under high pressure and temperatures. Exhaust emissions contain a mixture of pollutants within which hydrocarbons, naturally found in fuel, are present. Hydrocarbons are highly susceptible to reacting with  $\text{NO}_x$  and sunlight to produce harmful ground-level ozone.  $\text{NO}_x$  is also associated with acid rain and atmospheric N deposition.<sup>24</sup> Reducing vehicle  $\text{NO}_x$  emissions is essential to decreasing atmospheric N and ultimately, improving water quality in local streams and rivers and the Chesapeake Bay.

**Technological advances have decreased vehicle emissions, but progress has been impeded by population growth and urban and suburban development.**

Since 1975, when manufacturers began installing the first generation of catalytic converters on most cars and trucks to control hydrocarbon and carbon monoxide ( $\text{CO}$ ) emissions, significant progress has been made in reducing vehicle emissions. Technological advancements made in the early 1980s resulted in even more sophisticated emission control systems. Presently, the new generation of catalytic converters acts as a three-way catalyst that converts  $\text{CO}$  to carbon dioxide ( $\text{CO}_2$ ), hydrocarbons to water, and reduces  $\text{NO}_x$  to N and O. On-board computers and O sensors have optimized catalytic converter efficiency. The 1990 Clean Air Act instigated even further progress with tighter tailpipe standards, computer diagnostic systems, and greater control of evaporative emissions. Despite these regulatory changes and technological advances, large amounts of emissions continue to pollute the air because vehicle miles driven are increasing.<sup>24</sup> From 1990 to 2010, vehicle miles traveled rose by 34% due to expanding populations, economic growth, sprawling development, and relatively low fuel costs.<sup>25</sup> In order to see lasting progress, emissions standards will need to be tightened even further and infrastructure design will need to accommodate alternative modes of transportation.

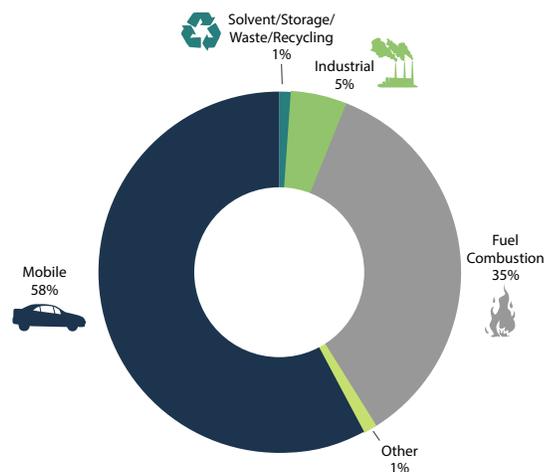


Figure 2.4. U.S. nitrogen oxide ( $\text{NO}_x$ ) emissions by category, 2006. Mobile sources are the greatest contributors to  $\text{NO}_x$  emissions (fuel combustion: electric utility, industrial; Other: chemical and allied manufacturing, petroleum and related industries). Targeting diffuse emissions is required to further reduce atmospheric deposition of nitrogen to the Chesapeake Bay (adapted from U.S. EPA Vehicle Compliance Report, 2007).<sup>23</sup>

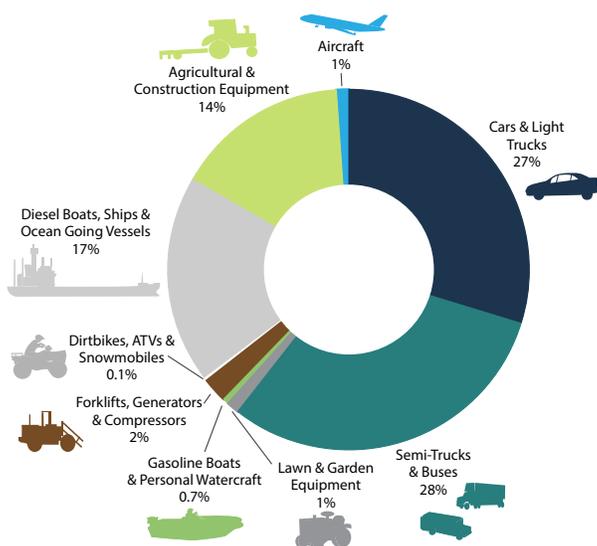


Figure 2.5. U.S. mobile sources of nitrogen oxide ( $\text{NO}_x$ ) emissions by sector, 2007. Cars, light trucks, semi-trucks and buses represent the greatest source of mobile  $\text{NO}_x$  emissions. Increasing vehicle emissions efficiency will further decrease atmospheric deposition of nitrogen (adapted from U.S. EPA Vehicle Compliance Report, 2007).<sup>23</sup>

Figure 2.6. Catalytic converter technology has advanced significantly since its introduction in 1975, significantly decreasing vehicle nitrogen oxide emissions.



**Pre 1970s.** Over concern from early smog studies in Los Angeles, CA, the catalytic converter was invented in the 1950s by Eugene Houdry, a French mechanical engineer living in the United States. Catalytic converters were further developed by John J. Mooney and Carl D. Keith, creating the first production catalytic converter in 1973.

**1975.** The U.S. EPA requires that all new cars be equipped with catalytic converters. These two-way converters combine carbon monoxide ( $\text{CO}$ ) and unburned hydrocarbons ( $\text{HC}$ ) to produce carbon dioxide ( $\text{CO}_2$ ) and water ( $\text{H}_2\text{O}$ ).

**1981.** To keep up with the Clean Air Act of 1970, a new generation of catalytic converters acts as a three-way catalyst, converting carbon monoxide ( $\text{CO}$ ) and hydrocarbons ( $\text{HC}$ ) to water ( $\text{H}_2\text{O}$ ) and carbon dioxide ( $\text{CO}_2$ ), and reducing nitrogen oxides ( $\text{NO}_x$ ) to nitrogen ( $\text{N}$ ) and oxygen ( $\text{O}$ ).

**Vehicle ammonia emissions are an expanding source of atmospheric nitrogen deposition that can be further reduced.**

Sulfur (S) contained in vehicle fuel can impair three-way catalytic converter efficiency and contribute to acid rain, and is therefore being reduced in fuel mixtures. However, research has shown that lower levels of S in fuel can actually increase ammonia (NH<sub>3</sub>) emissions—a compound that contributes to acidification, fine particle mass, and visibility problems, has the potential to worsen air quality, and can contribute to atmospheric N deposition.<sup>26,27</sup> Decreases in vehicle emissions of CO, hydrocarbons, NO<sub>x</sub>, and NH<sub>3</sub> are all imperative to protect human health and prevent environmental degradation. Catalytic converters must be adjusted precisely to ensure balanced reductions in all harmful gases. Despite advances in vehicle emissions technology, NH<sub>3</sub> vehicle emissions are not currently regulated by the U.S. Environmental Protection Agency and have increased 100-fold in the past 30 years.<sup>27</sup>

**Technological upgrades to poultry house ventilation systems may reduce ammonia emissions originating from animal waste.**

Geographic areas that support high densities of animals can receive significant amounts of N through atmospheric deposition, leading to over-enriched lands and water. Livestock and poultry are often given high-protein diets containing surplus N to fulfill nutritional requirements. Some of the N is metabolized into animal protein and the remainder is excreted in animal waste. As the manure decomposes, microbial processes release NH<sub>3</sub> into the air.<sup>28</sup> Ammonia emissions resulting from high densities of livestock may have significant implications for the Delmarva Peninsula—home to 570 million broilers (i.e., chickens raised for meat). Levels of NH<sub>3</sub>-N emitted from the Delmarva Peninsula was estimated to be 18.2 million kg yr<sup>-1</sup>, excluding emissions related to spreading poultry litter over fields.<sup>29</sup> This estimate was extrapolated from emissions data collected at two 11,150-broiler side-wall ventilated poultry houses. However, poultry houses vary in both construction and capacity and the true level of NH<sub>3</sub>-N

emitted via animal waste is unknown. A study of an 18,600-broiler tunnel-ventilated poultry house on the Delmarva Peninsula revealed lower NH<sub>3</sub> emissions than the previously-studied side-wall chicken houses, suggesting technological upgrades to poultry house ventilation systems could impact the levels of atmospheric N deposition affecting the Bay.<sup>30</sup> Despite uncertainty in the true level of emitted NH<sub>3</sub>-N on the Delmarva Peninsula, the magnitude of the initial estimate suggests that NH<sub>3</sub> emissions from animal waste is likely a major contributor of atmospheric N.

**Changes in the nutrient composition of animal feed may lead to reduced ammonia emissions by altering the levels of nitrogen in livestock waste.**

Protein containing N is a necessary component of a cow's diet, but the un-metabolized N that is discharged in manure leads to NH<sub>3</sub> emissions. Altering the levels of protein in animal feed may lessen the levels of N in manure, thereby decreasing potential NH<sub>3</sub> emissions. In Pennsylvania, the dietary crude protein concentration was manipulated in the feed given to dairy cows. The NH<sub>3</sub>-emitting potential was calculated using composition and emissions data associated with the resulting manure. The calculated NH<sub>3</sub>-emitting potential was significantly lower in the manure from cows fed lower protein diets.<sup>31</sup> The level of crude protein in the low-protein diets was lower than the 2001 standards required by the National Research Council (NRC), causing some concern for negative impacts on dairy function. However, research has suggested that the NRC requirements may overestimate dietary requirements of cows, reducing this concern. Furthermore, the addition of multiple rumen-protected amino acids to a protein-deficient diet returned milk fat yield and dry matter intake back to levels consistent with a higher protein diet.<sup>32</sup> Other strategies to reduce excess intake of protein include feeding large herds in smaller groups based on nutritional needs to ensure that cows are not given feed with higher-than-necessary N and P levels.<sup>33</sup> Although additional research is needed to better understand the level of impact animal feed may have on NH<sub>3</sub> emissions, the data suggest that a relationship exists and should be further explored.



Due to the addition and subsequent upgrades of catalytic converters in vehicles, significant progress has been made in reducing vehicle emissions. Photo © Ben Schumin.



On the Delmarva Peninsula, ammonia emissions from animal waste could be a major source of emissions within the Chesapeake Bay watershed. Photo © Chesapeake Bay Program.



## Reductions of agricultural nutrient sources result in improved stream quality

- **Reducing agricultural nutrient input onto the land and in streams may lead to significant water quality and aquatic habitat improvements in as little as one to six years.**
- **Winter cover crops can successfully decrease the levels of nutrient inputs into shallow groundwater, thereby reducing nutrients discharged into streams.**
- **Appropriate manure and fertilizer management can reduce nitrogen, phosphorus, and suspended sediment loads.**
- **Controlling livestock access to streams is an effective way to decrease sediment, nutrients, and bacteria in streams, and prevent stream bank erosion.**

Reducing agricultural nonpoint nutrient sources has presented a challenge due to the complex nature of diverse agricultural practices throughout a watershed characterized by varied landscapes and geology. Despite this difficulty, a number of best management practices (BMPs) have been proven effective in reducing nutrient loads from agricultural lands and improving local water quality. The following case studies provide specific examples of observed water quality improvements resulting from the implementation of agricultural BMPs.

### Cover crops

The implementation of cover crops in the Wye River basin in Queen Anne's County, Maryland decreased leachate nitrate concentrations in shallow groundwater and subsurface nitrate discharge into the river.

Cover crops have been highly effective at reducing nitrate concentrations in groundwater on several farms in the Wye River watershed—a sub-tidal estuary of the Chesapeake Bay. Beginning in 1988, cereal grain winter cover crops planted on two agricultural fields demonstrated that over time, nitrogen (N)

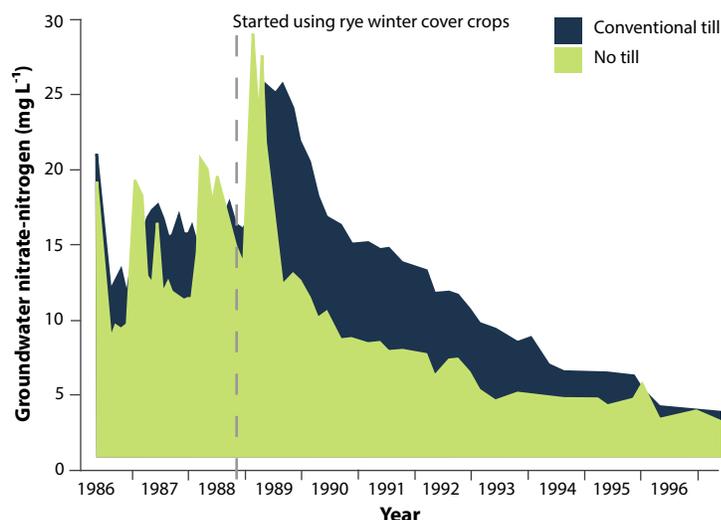


Figure 3.1. Change in groundwater nitrate-nitrogen in two agricultural fields within the Wye River watershed (1986–1997). Winter cover crops were planted in 1988 on two adjacent agricultural fields, resulting in significant decreases in average groundwater nitrate-nitrogen.<sup>34</sup>

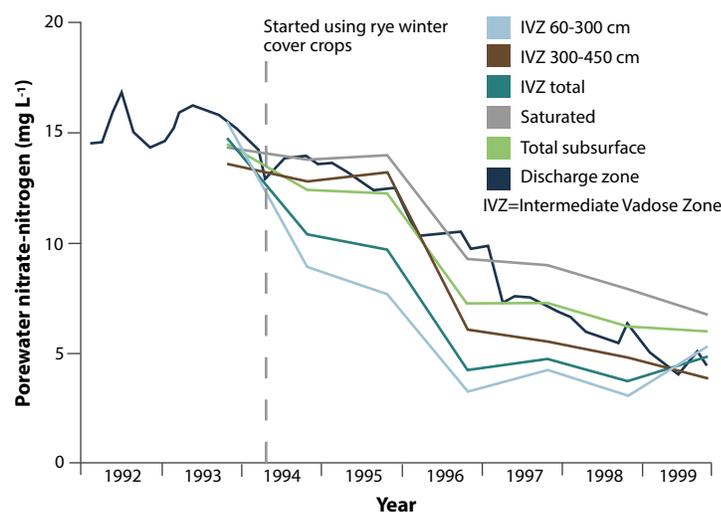


Figure 3.2. Changes in nitrate-nitrogen in different subsurface zones on an agricultural field in the Wye River watershed (1992–1999). Rye was planted as a winter cover crop, resulting in significant decreases in fall nitrate-nitrogen concentrations in multiple regions of the subsurface flow system.<sup>35</sup>

transport can be reduced by 40% in the major Coastal Plain agricultural systems (Figure 3.1).<sup>34</sup> On a different farm from 1993 to 1998, rye was planted as a winter cover crop in the fall, immediately following grain harvest. Prior to cover crop implementation, a corn-soybean crop rotation was practiced and the field remained fallow during the winter months, allowing nutrients to leach into the groundwater. Although annual rates of nitrate discharge into the river varied greatly depending on precipitation and groundwater recharge, implementing the winter cover crops successfully improved water quality. Decreases in nitrate were observed in shallow soil during the first two years, at which point nitrate began to decrease in deeper soil and in subsurface discharge into the estuary. Total nitrate in cover crop fields decreased approximately 75% in the root zone and 45% in the underlying aquifer when the water table was at its lowest elevation (Figure 3.2).<sup>35</sup> Nitrate leaching from the root zone of cover crop fields was approximately 80% less than plots that remained fallow during the winter. These significant results reveal the relatively rapid improvements that can occur when nutrient management is considered during the development of farming practices.

### Manure and fertilizer management

**The export of all poultry litter and the full implementation of cover crops on all available cropland in the upper Pocomoke River, a small watershed on Maryland's eastern shore, significantly reduced total nitrogen concentrations.**

Maryland's eastern shore is known for high volumes of poultry production, creating large amounts of litter and associated nutrient loads. In order to improve water quality in the Upper Pocomoke River watershed, BMPs were implemented between 1998 and 2003. The 1,779-acre area is comprised of 54% cropland and 46% woodland and has a 1.4 million annual broiler (chicken) production capacity and a density of 1,450 broiler chickens per cropland acre. Following litter export and cover crop implementation, nutrient surpluses of both N and phosphorus (P) decreased by 92% and 120%, respectively. Total nitrogen (TN) concentrations declined by 30% while total phosphorus (TP) concentrations remained steady, possibly due to changes in ditch maintenance practices (Figure 3.3).<sup>36,37,38</sup>



Poultry litter is a source of nutrients that can negatively affect water quality by entering streams, rivers, and the Bay through runoff and groundwater. Photo © Chesapeake Bay Program.

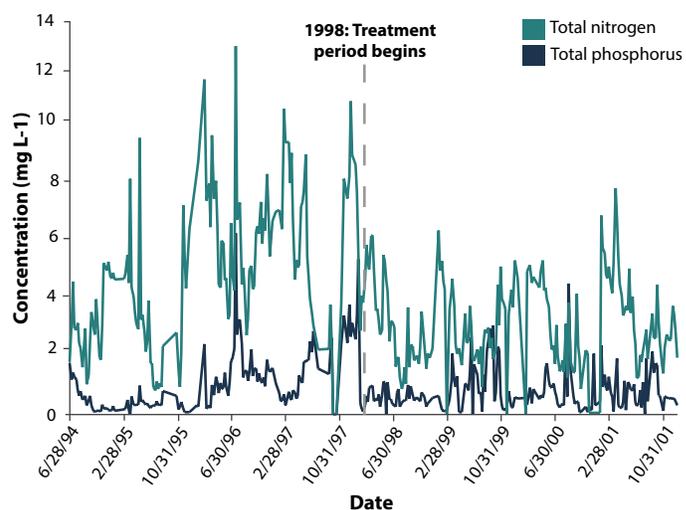


Figure 3.3. Total nitrogen (TN) and total phosphorus (TP) in the treatment watershed within the upper Pocomoke River, Maryland (1994-2001). Following the export of all poultry litter and the implementation of cover crops on all available cropland, TN decreased while TP remained steady.<sup>36</sup>

**Reducing the application of phosphorus in commercial and manure fertilizer led to significant water quality improvements in Brush Run Creek, a small watershed in the lower Susquehanna River basin, Pennsylvania.**

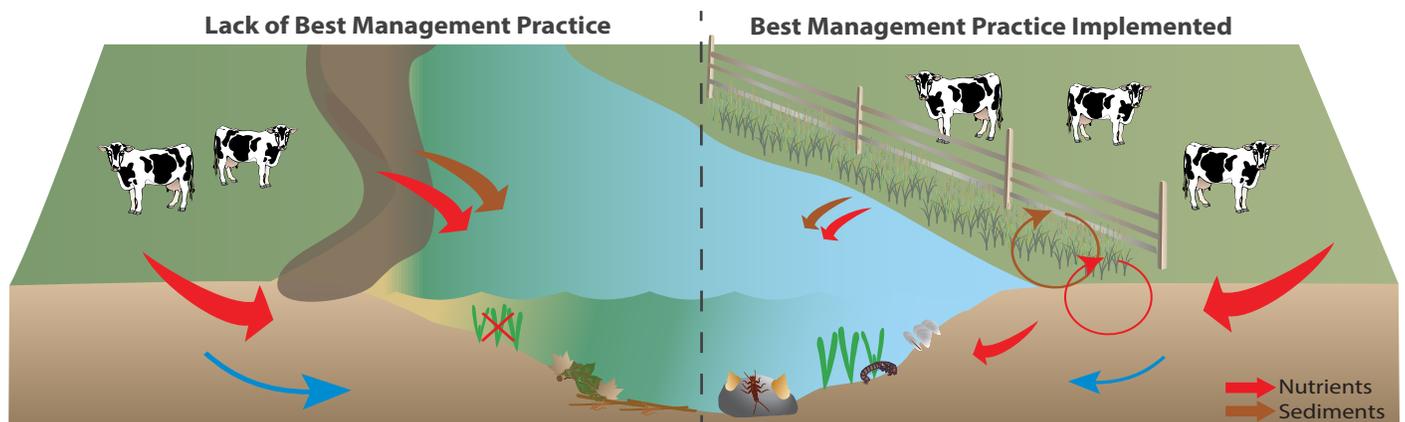
The 0.63 square-mile Brush Run Creek watershed in south-central PA is dominated by agriculture—64% cropland and 14% pasture. Reducing commercial and manure fertilizer applications decreased P and N loads by 57% and 14%, respectively. Total phosphorus and suspended sediment concentrations decreased at the three water quality monitoring sites—two of which were significant—while TN concentrations decreased slightly, though not significantly. The slight TN reductions that did occur were likely due to dry annual precipitation throughout the entire sampling period. Several factors may have prevented significant decreases in N: 1) greater than expected soil depth provided more soil available to receive N leachate; 2) 99% of N in the soil was in an organic form that most plants will not take up, leaving more N in the soil that could potentially leach into groundwater; and 3) N appeared to leach into the soil easily, where it may move through soil water or groundwater and discharge into streams. At two of the sampling sites, the volatilization of ammonia from livestock manure likely added additional nutrient loads through atmospheric deposition. The reductions in P concentrations demonstrate the effectiveness of nutrient management, but the insignificant decreases in N reveal the need for long-term monitoring, likely extended beyond three years post-BMP implementation, to observe changes in N concentrations.<sup>39</sup>

**Livestock grazing management**

**Cattle exclusion resulted in riparian vegetation growth, reduced suspended sediment loads, improved in-stream habitat, reduced nutrients, and improved aquatic life in multiple locations throughout the Chesapeake Bay watershed.**

Limiting livestock access to streams as well as improving riparian zones and vegetation will reduce direct cow manure input into the system, alleviate streambank erosion, and improve aquatic habitat.<sup>40</sup> Within the Chesapeake Bay watershed, several studies in Pennsylvania, Maryland, and Virginia demonstrated that after cattle were excluded from streams and streambanks and the streambanks were replanted, the response time in riparian vegetation growth was rapid, usually on the order of one year. Additional benefits observed within the first five years post-BMP implementation in several of the case studies included decreased suspended sediment loads and

*Streambank fencing is a best management practice that has been utilized successfully to exclude cattle from streambanks, leading to improved stream bank stability, water quality, in-stream habitat, and populations of fish and benthic macroinvertebrates.*



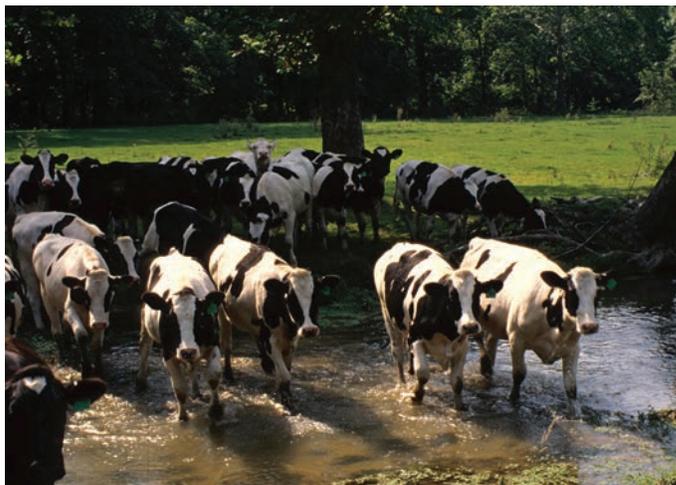
Streambank areas that lack best management practices such as streambank fencing and riparian buffers are prone to erosion , and have greater nutrient  and sediment  inputs into the system. In the absence of riparian buffers, sub-surface nutrients are not taken up prior to entering the stream within groundwater . The excess nutrient runoff will result in poor water quality, which can be detrimental to submerged aquatic vegetation  and other aquatic organisms.

Streambank fencing  removes cows  from the area around streams, as well as improves the riparian zone and its vegetation. Riparian buffers  stabilize stream banks by reducing erosion and reducing nutrient  and sediment  inputs into streams. These practices decrease the direct cow manure input into the system. Sub-surface nutrients are taken up by the roots of the riparian vegetation , reducing the nutrients that enter the stream with groundwater  to a small amount. Additionally, fencing is highly effective at improving bank conditions and restoring in-stream and side stream habitat for aquatic life .

nutrient concentrations, as well as improved in-stream habitat, streambank stability, and streambank vegetation.<sup>41,42,43</sup> Furthermore, improved water quality and in-stream habitat in a variety of the case studies led to rapid and favorable biological responses, particularly in populations of fish and benthic macroinvertebrates.<sup>40,41,42</sup> Collectively, the observed outcomes from each case study are indicative of the effectiveness of a relatively simple and cost-effective practice.

### **Rotational grazing may provide some benefits to water quality and stream habitat.**

Unrestricted continuous grazing near streams negatively affects water quality and stream habitat. Multiple studies in the Midwestern United States demonstrated an association between rotational grazing and healthier macroinvertebrate communities, reduced soil compaction, greater bank stability, less exposed soil, and reduced stream fecal coliform and turbidity.<sup>44,45,46</sup> Rotational grazing has also been examined within the Chesapeake Bay watershed. Water quality conditions on two dairy farms practicing management intensive grazing (MIG) were compared with a farm practicing confined feeding. Management intensive grazing is a form of rotational grazing where herds are rotated through small paddocks every 12 to 24 hours; most of the herds' dietary requirements are met through forage grazing instead of concentrated feeding practices. Except during two high-flow seasons that resulted from high levels of precipitation, groundwater nitrate concentrations were consistently below the U.S. Environmental Protection Agency drinking water maximum contaminant level (MCL) on the MIG farms, whereas the groundwater concentrations on the confined feeding farm exceeded the MCL on ten occasions. Additionally, nitrate and total dissolved nitrogen (TDN) concentrations did not increase in the surface water of two sampled streams as they flowed through one of the MIG farms. These results suggest that the level of inputs attributable to manure on rotationally-grazed farms do not have a significant effect on surface water quality as measured by nitrate and TDN. An N surplus on each farm was a far greater factor influencing stream water TDN and nitrate concentrations. However, dissolved organic nitrogen (DON) was detected in very high concentrations in shallow groundwater on all three farms, likely influencing in-stream water quality conditions.<sup>47</sup> Although data suggest rotational grazing has some benefits, the high concentrations of DON even in the farms practicing MIG illustrate the continuing need to understand the effects of management practices on underlying ecosystem processes, as well as the limitations and need for adaptability of the management practices being applied. Rotational grazing may be a less expensive alternative than the complete exclusion of livestock, and warrants continued study relative to its influence on water quality.



*Cows in pasture walking across an unfenced stream. This can cause streambank erosion as well as sedimentation further downstream. Photo © Chesapeake Bay Program.*



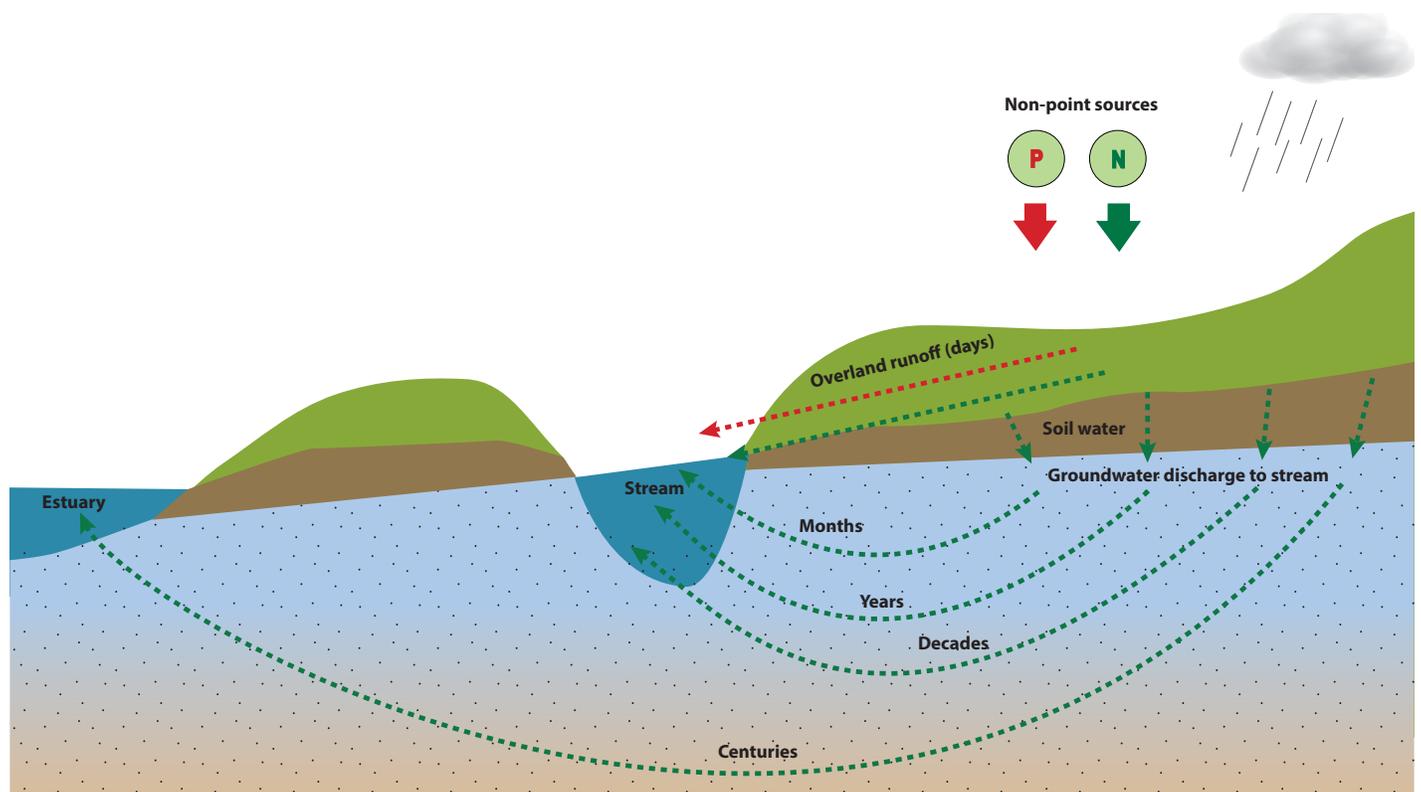
*Rotational grazing along the Creeper Trail, South Fork of the Holston River Project, Virginia. Photo © Jeff Vanuga, USDA Natural Resources Conservation Service.*



## Many practices provide initial water quality improvements in runoff; however, full benefits to stream conditions can be delayed

- 'Lag time' is a delayed response time between implementing best management practices and observing full water quality improvements.
- Lag times are affected by groundwater age, sediment movement, phosphorus storage in sediments, and riparian buffer age.
- The effect of lag times will vary depending on the types of best management practices and where they are implemented.

Research has identified many effective best management practices (BMPs), but numerous factors can impede expected water quality improvements. The Chesapeake Bay watershed is a complex system, which introduces many variables that may influence BMP outcomes. The highlighted case studies describe ecosystem characteristics that may slow or prevent water quality improvements, as well as promising practices that may counteract these challenges.



*Simplified conceptual diagram of the water cycle and major sources of nitrogen, phosphorus, and sediment pollution to the Chesapeake Bay. Once in groundwater, nitrogen can take from months to years to be transported to rivers and then to the Chesapeake Bay which, combined with variable water quality and precipitation, can make detecting improvements difficult (adapted from Ator 2013).*

**Best management practices that reduce nitrogen loads are necessary for improvements in water quality, but the time between groundwater recharge and groundwater discharge into streams will affect water quality response time.**

On average, 50% of the total in-stream water volume in the Chesapeake Bay watershed reaches streams through groundwater, although this estimate may vary between 16% and 92% depending on regional characteristics (Figure 4.1).<sup>48</sup> Approximately half of the nitrogen (N) associated with land use runs off in surface water and soil water—water contained in soil that is discharged into streams during periods of elevated rainfall. The remaining half moves through the groundwater system.<sup>48,49</sup> The age of shallow groundwater that is discharged into streams is variable; in the Coastal Plain it ranges from modern (< 1 year) to more than 100 years.<sup>50</sup> In small watersheds, groundwater ages vary from 2 to 30 years in the Piedmont region (e.g., Polecat Creek, VA), 10 to 20 years in areas dominated by carbonate rocks (e.g., Muddy Creek, VA), and modern to 50 years in areas dominated by siliciclastic rocks (e.g., Mahantango Creek, PA).<sup>51</sup> Management practices designed to reduce nutrient concentrations in surface runoff will lead to initial rapid improvements in water quality. However, N that has infiltrated aged groundwater can remain in the system for very long periods of time, delaying observable benefits of BMPs. (Figure 4.2). BMPs, such as cover crops, will help to reduce N leaching into groundwater, but long-term water quality monitoring is necessary to track reductions in N over time and to accurately assess the effectiveness of implemented BMPs.

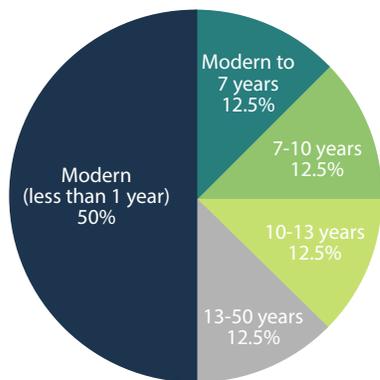


Figure 4.1. Groundwater age widely varies dependent upon regional characteristics. On average, half of all water discharged to a stream originates from runoff or shallow soil. The other half moves through the groundwater system. The majority of water discharging into the stream is less than 13 years old.<sup>48</sup>



Cover crops effectively reduce nitrogen (N) loads leaching into groundwater, but if high concentrations of N have already entered the groundwater system, improvements in water quality may be delayed. Photo © Chesapeake Bay Program.

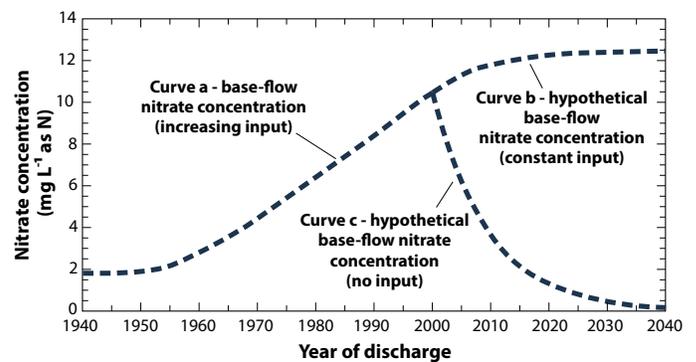


Figure 4.2. Predicted nitrate concentrations of base flow to a stream in the East Mahantango Creek watershed in Pennsylvania. **Curve a** represents increasing base-flow nitrate concentrations due to increasing nutrient loads. **Curve b** represents increases in base-flow nitrate concentrations despite constant nutrient loads. **Curve c** depicts decreases in base-flow nitrate concentrations assuming a 50% reduction in nutrient loads. Initial water quality improvements will be observed within five years due to the rapid response time of surface runoff. Improvements will slow as nitrate remains in the groundwater system for greater lengths of time (adapted from Phillips (ed.) 2007).<sup>48</sup>

### Understanding lag times in different watershed settings may help identify locations where water quality responses to best management practices could occur more quickly.

The multitudes of lag times related to groundwater discharge that may exist within a single region can present a challenge to effective BMP implementation. Understanding the factors contributing to lag times across a region is important to estimating water quality response times after nutrient reduction activities. An example of an area with considerable variation in lag times is the Delmarva Peninsula. The Delmarva Peninsula is an agriculturally dominated area that serves as a large source of excess nutrients to the Bay through groundwater delivery. Sanford et al.'s simulation model of Delmarva's groundwater return time from its point of recharge to its discharge location illustrates the considerable variation in estimated lag times within an agriculturally dominated landscape (Figure 4.3).<sup>47</sup> Implementing BMPs near a stream that receives modern-aged groundwater will result in quicker water quality improvements. Conversely, implementing BMPs in areas where groundwater return times exceed 100 years will not yield rapid water quality improvements. However, reducing nutrient loads in areas with aged groundwater should not be ignored since BMP implementation across the entire watershed is necessary to ultimately achieve Bay-wide water quality improvements. Understanding groundwater movement is crucial in forming realistic expectations, and may contribute to the appropriate prioritization of BMP locations under conditions of scarce resources.

### Best management practices that intercept phosphorus and sediment runoff will lead to water quality improvements, but lag times resulting from long-term phosphorus storage in sediments may delay observable water quality responses.

Phosphorus (P) may be retained in sediments for long periods of time and gradually released, particularly under hypoxic, anoxic, and elevated pH conditions.<sup>5,52</sup> Sediments containing P are transported to streams and floodplains during storm events via agricultural and urban surface runoff and stream bank erosion. Sediments can be stored in upland areas and stream corridors for varying lengths of time based on the movement of water, climate characteristics, and land uses. Sediment residence times will likely affect BMP response time, which can range from days to decades.<sup>53</sup> The full downstream benefit of BMPs will depend on the length of time it takes those sediments to travel through upland streams and tributaries and ultimately discharge into the Bay. Although riparian buffers and other BMPs that prevent additional sediment loadings may have a positive impact on water quality as less P-enriched sediment enters the system, sediments already enriched with P will continue to contribute to P concentrations, delaying measurable water quality improvements.

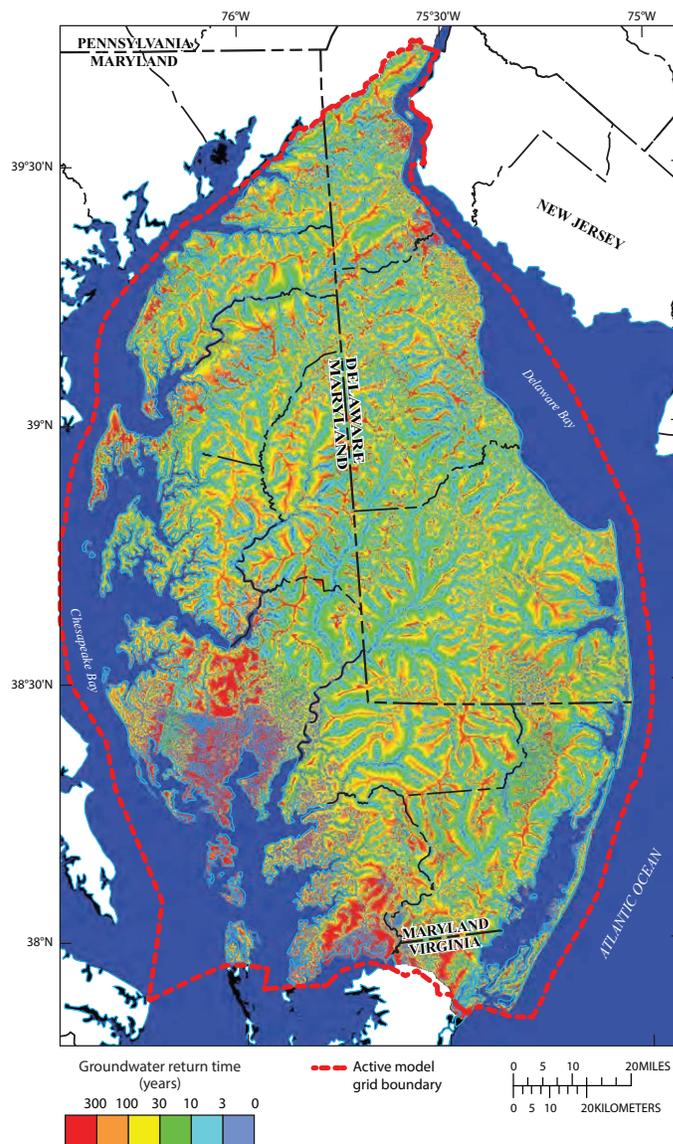


Figure 4.3. Simulated return time of groundwater traveling from the water table to its discharge location. Observable water quality improvements resulting from best management practices implemented in orange and red areas (groundwater return times of >100 years) may be delayed.<sup>50</sup>

However, the sediment storage of nutrients in tidal sediments appears to be less pronounced, leading to quicker improvements in water quality and habitat conditions in tidal waters after BMP implementation. Improvements in water quality and increases in SAV abundance can be observed within the same year nutrient discharges were reduced.<sup>49</sup>

**Nutrient concentrations in the Little Conestoga Creek, a tributary of the Susquehanna River, Pennsylvania, remained constant after manure and fertilizer management actions were implemented while nutrient concentrations in surrounding areas increased, suggesting that the full benefits of best management practices may not be realized for several years after implementation.**

The Little Conestoga Creek's headwaters provide multiple local benefits—recreational activities, fish and wildlife habitat, livestock watering, and public water supply. Agricultural practices that include excess manure and commercial fertilizer use, extensive cropland, and sediment erosion, contributed to degraded water quality. The U.S. Department of Agriculture's Rural Clean Water Program designated the Conestoga River headwaters as a site for remedial actions to improve and monitor surface and groundwater. As part of this project, nutrient and animal waste management BMPs and pipe terracing were implemented in a 1.42 square-mile nutrient management sub-basin in the Little Conestoga Creek watershed. Appropriate N application rates were determined for eleven farms by factoring crop acreage, the quantity and nutrient content of collected manure and commercial fertilizers, soil-nutrient reserve estimates, and data on past nutrient applications. Animal waste was managed through increasing storage times of manure and scheduling manure applications.<sup>54</sup> After manure and commercial fertilizer BMPs were implemented, an average of 32% less N and 35% less P were applied to the land. Although nutrient concentrations did not significantly change in the nutrient management sub-basin between pre-BMP and post-BMP monitoring, nitrate did significantly increase in the rest of the watershed. Nutrient use efficiency practices have not resulted in improved water quality, but they may have prevented nutrient concentration increases that would have otherwise occurred.<sup>55</sup> If this is the case, lag times may be delaying observable water quality improvements, and continued implementation of these BMPs may ultimately improve water quality. Long-term water quality monitoring will be required to assess the full extent of BMP effectiveness.



*A manure storage tank as part of the conservation plan for a dairy farm in Pennsylvania. During the growing season, stored manure can be applied as fertilizer to soil and used by crops. Photo © Bob Nichols, USDA Natural Resources Conservation Service.*



*Riparian buffers reduce sediment loadings to streams, decreasing the availability of sediment-stored phosphorus that may delay observable water quality improvements. Photo © Ben Fertig, IAN Image Library.*



## Improvements in water quality can be counteracted by changes in nutrient sources and land-use practices

- Although best management practices can be effective at decreasing nutrient loading, unaddressed sources may increasingly discharge nutrients into the Chesapeake Bay watershed.
- Nutrient sources not targeted by best management practices could counteract the positive effects of the implemented nutrient reducing practices.
- Increases in point and nonpoint sources associated with population growth and intensified agriculture are the principle causes for offsetting pollutant load reducing best management practices.

Despite implementation of best management practices (BMPs), several case studies are illustrated which have fallen short of expected outcomes. Although each case study is unique in its influencing variables and ecosystem processes, a commonality among many cases is that increased nutrient loads from stormwater and intensified agriculture (increased fertilizer use and animal densities) overwhelmed the positive effects of the implemented practices. Additional influences include geology, nutrient exchanges between tributaries, and incomplete BMP implementation. The highlighted case studies represent a wide range of factors that may counteract pollutant reducing BMPs.

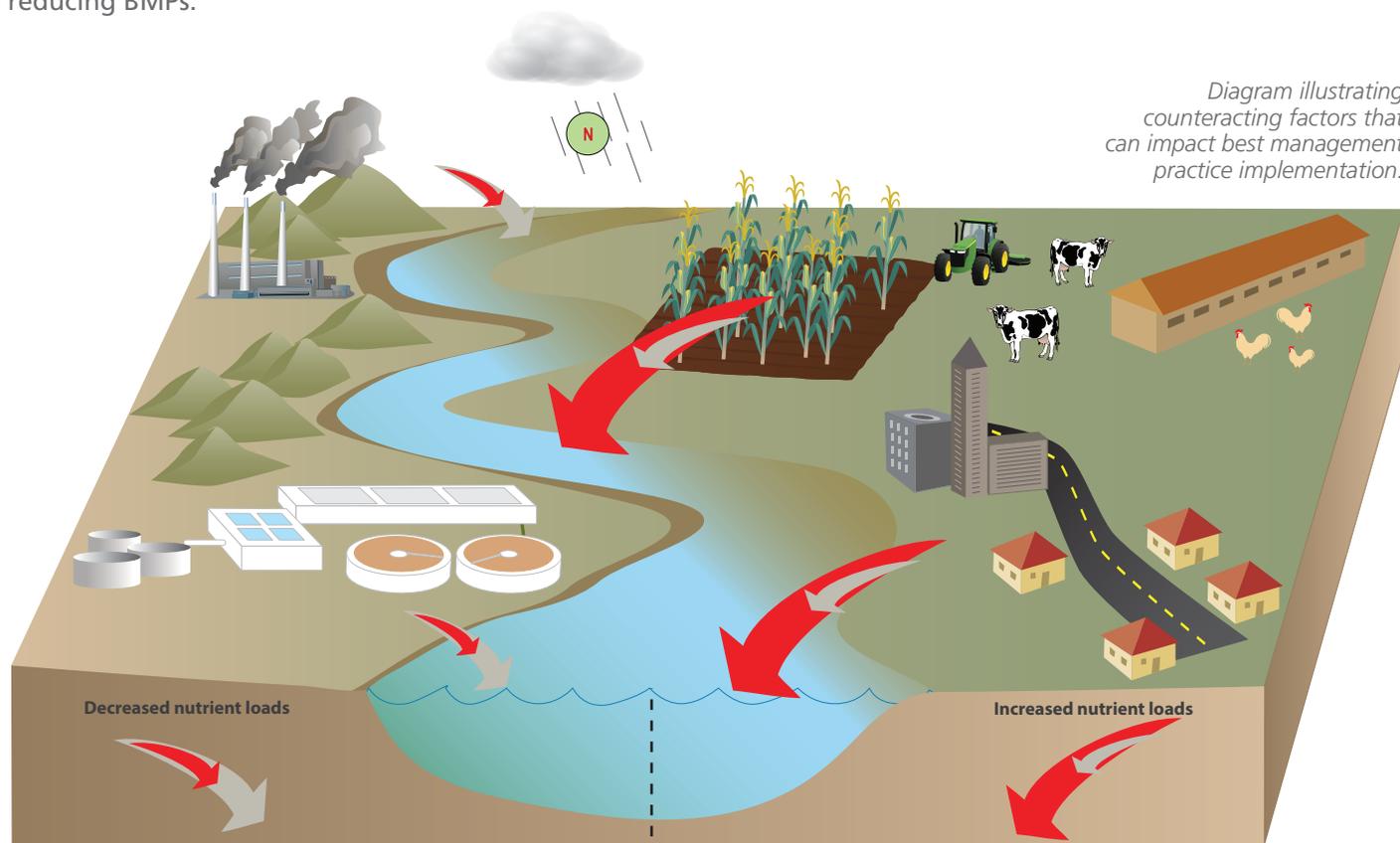


Diagram illustrating counteracting factors that can impact best management practice implementation.

Best management practices (BMPs) such as wastewater treatment plant upgrades and reduced power plant  $\text{No}_x$  emissions are proven practices that reduce nutrient loads to the Chesapeake Bay watershed.

Increases in other pressures, such as intensified agriculture and greater stormwater runoff from expanding development can increase nutrient loads, counteracting water quality improvements that would have resulted from effective BMP implementation.

**Fertilizer rates and changes in farming practices counteracted water quality improvements expected from decreases in livestock in Bald Eagle Creek, located in Pennsylvania’s lower Susquehanna River basin.**

Bald Eagle Creek, located in York County, PA, represents problems that can arise when unaccounted-for nutrient sources prevent water quality improvements despite large reductions in nutrient loads. Cropland and pasture cover 87% of the land. From October 1985 to September 1990, water quality was monitored to assess changes in nutrient concentrations resulting from a reduction in animal units. During the three nutrient management years (1988–1990), the animal population was reduced by 49%. As a result, applications of nitrogen (N) and phosphorus (P) in manure decreased by 40% and 15% and commercial applications of N and P were also reduced by 77% and 65%, respectively. Despite reduced nutrient loads, no changes in P concentrations were observed and total nitrogen (TN) and dissolved nitrate significantly increased in baseflow throughout the entire study period. Multiple factors could be responsible for the declining water quality. Although N loads decreased, more N was applied than was needed by crops during all five years. The number of acres planted with corn—a crop that takes up high levels of nitrogen—was reduced by 34% and acres devoted to legumes increased by 37%. Precipitation increased by 7% between the two non-nutrient management years and the rest of the study period. Lastly, a landowner that did not participate in the study made some land modifications that deepened the stream channel, added fill material soil to stream banks, and allowed a small number of livestock to graze near the stream above the water sampling site.<sup>56</sup>

**Increases in nonpoint sources, as well as nutrient exchanges between the mouth of the Patuxent River and the Chesapeake Bay have impeded water quality improvements in the lower Patuxent River estuary.**

Eight of the nine major Patuxent River wastewater treatment plants (WWTP) are located in the upper Patuxent River watershed, above the tidal river. Although upgrades have significantly reduced P and N loads and water quality improvements have been observed in the upper tidal Patuxent River, nonpoint sources have hindered water quality improvements in the lower tidal Patuxent River.<sup>13,15,57</sup> Expanding population growth, land use changes, and cropland appear to be major nonpoint sources of nutrients.<sup>13,57</sup> Prior to implementing WWTP biological nutrient removal (BNR), 51% of TN and 48% of total phosphorus (TP) inputs originated from nonpoint sources. After BNR implementation, these proportions increased to 70% of TN and 77% of TP, revealing the need to focus future management efforts on diffuse sources. Water exchange between the Chesapeake Bay and the mouth of the Patuxent River is also affecting



*Bald Eagle Creek (West Branch Susquehanna River) located in York County, Pennsylvania. Photo © Ruhrfish.*



*The Patuxent River, a tributary of the Chesapeake Bay. Nonpoint nutrient sources have hindered water quality improvements in the lower Patuxent Estuary. Photo © Chesapeake Bay Program.*

water quality. TN is consistently exported from the Patuxent River to the Chesapeake Bay. However, the lower Patuxent River estuary imports dissolved inorganic N from the Bay, which could be acting as an additional nutrient load. Low dissolved oxygen bottom water from the Bay also enters the lower portion of the tidal Patuxent River, further impairing water quality.<sup>15</sup> Water quality improvements will not be observed in the lower tidal river if nonpoint sources are not addressed.

**Agricultural nutrient inputs and stormwater runoff resulting from an expanding population in the Choptank River watershed on Maryland’s Eastern Shore have impeded water quality improvements.**

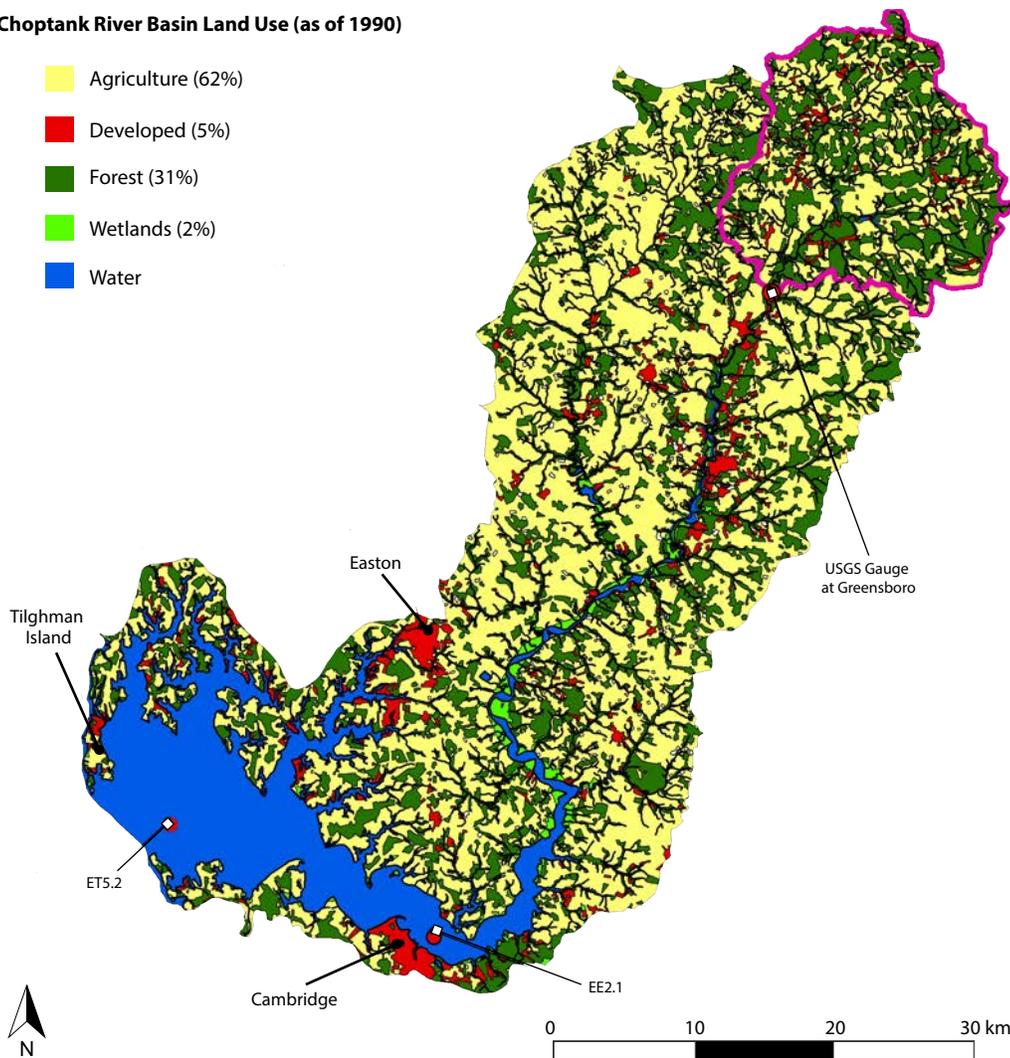
The Choptank River watershed spans portions of four Maryland counties and the river originates in Kent County, DE. As of 2010, more than half of the basin is agricultural (57%) (Figure 5.1). Urban land-use has been expanding, and currently represents 14% of the Choptank River watershed area.<sup>58</sup> The two greatest sources of nutrient loads to the Choptank River are agricultural activities and increased stormwater and



*Harris Creek, a tributary of the Choptank River as it enters the river. As of 2010, more than half of the land-use within the Choptank River basin is agricultural. Photo © Jane Thomas, IAN Image Library.*

**Choptank River Basin Land Use (as of 1990)**

- Agriculture (62%)
- Developed (5%)
- Forest (31%)
- Wetlands (2%)
- Water



*Figure 5.1. Map of land-use in the Choptank River watershed (1990). Agriculture represents the primary land-use in the watershed, and high levels of fertilizer use and manure applications contribute to poor water quality (map provided by T. Fisher, UMCES).<sup>14</sup>*

wastewater from urban growth.<sup>59</sup> Upgrades have been implemented at several WWTPs discharging into the tidal Choptank River. In 1987, an overland-flow tertiary treatment system was added to a WWTP that services Easton, MD, decreasing nutrient loads. Over the past 20 years however, wastewater flows in Easton have slowly increased due to an expanding population and associated urban development, counteracting the benefits of WWTP upgrades.<sup>14,58,59</sup> Construction of BNR and enhanced nutrient removal (ENR) was completed in 2007, resulting in additional load reductions. The largest WWTP in the basin services Cambridge, MD, at which BNR and ENR were implemented in 2003 and 2012, respectively (Figure 5.2).<sup>58</sup> Despite these nutrient load reductions from the two largest WWTPs in the basin, water quality remains poor in the upper and middle tidal Choptank River as measured by TN and TP concentrations and water clarity.<sup>58</sup> Chlorophyll *a* and turbidity have increased while summer dissolved oxygen in bottom waters has decreased.<sup>14</sup>

Agricultural fertilizer and manure inputs are the primary driver of declining water quality trends in the nontidal portions of the Choptank River (Figure 5.3).<sup>14,59</sup> Wheat and corn yields have increased over the past century, likely in part due to increased fertilizer use and new genetic strains of plants.<sup>14</sup> The water quality monitoring station in upper Choptank River near Greensboro, MD has revealed continuing increases in TN and TP concentrations (Figure 5.4).<sup>59</sup> Additional factors may complicate system dynamics, such as the import of P from the Chesapeake Bay into the Choptank River.<sup>14</sup> The lack of water quality

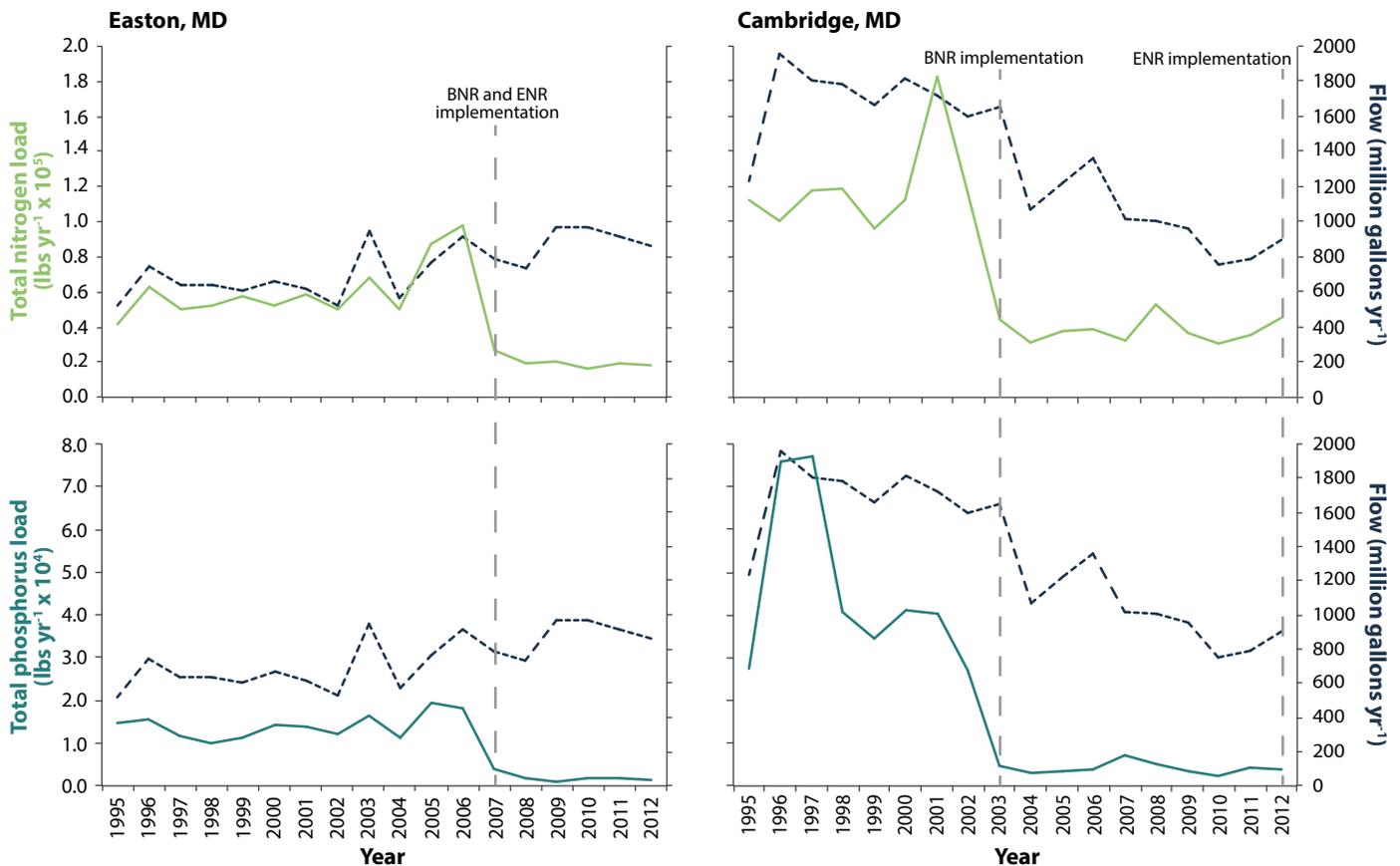


Figure 5.2. Total annual effluent flow, and annual total nitrogen (TN) and total phosphorus (TP) loads at two wastewater treatment plants (WWTPs) draining into the Choptank River (1995–2012). An overland-flow tertiary treatment system was installed at the Easton WWTP in 1987. As the population increased, effluent flow also increased, likely preventing a decrease in TN and TP loads. Biological nutrient removal (BNR) has been implemented within the past decade at both the Easton and Cambridge WWTPs. Long-term monitoring is needed to observe whether the decreased loads will be offset by increased effluent as the population continues to expand, and to assess if the load reductions will have a measurable effect on water quality (data provided by the Maryland Department of the Environment).<sup>58</sup>

improvements points to a need for BMPs that target all nutrient sources. These efforts are underway in the Choptank River watershed—30,700 acres of cover crops were planted, stream fencing was installed on almost 300 acres of farmland, stream buffers covered more than 16,000 acres, and over 250 animal waste containment structures were built to more effectively manage manure applications.<sup>58</sup> These BMPs were implemented in 2010, necessitating continued monitoring to evaluate BMP effectiveness.

**Subsurface geology influenced the effectiveness of stream bank fencing in the Big Spring Run watershed in Lancaster County, Pennsylvania.**

Although streambank fencing has been proven effective at improving water quality, local geographic attributes can influence observed water quality improvements. In Big Spring Run, two miles of fencing was installed along a stream adjacent to pastures. Shallow ground water was monitored for several years pre- and post-fence installation. Water quality measurements were taken from shallow wells at two sites within the fenced area of the stream—one site in an upstream tributary and one site at a downstream outlet—and then compared to water quality at an unfenced stream to control for changes in climate. Relative to the unfenced stream, N species concentrations decreased at the fenced tributary wells, but increased at the fenced outlet wells. The differences in water quality changes between the two monitoring sites within the fenced reach of the stream may be due to differences in bedrock geology that affects groundwater flow. Shallow groundwater flowed from the surrounding groundwater system into the stream in the tributary, benefiting from the reduced manure loads immediately adjacent to the stream. In the basin outlet, however, water flowed in the opposite direction—from the stream into the shallow groundwater system, averting any benefits from the decreased manure inputs on the surrounding land.<sup>41</sup> BMP outcomes can be better predicted with an understanding of subsurface dynamics in an area experiencing poor water quality.

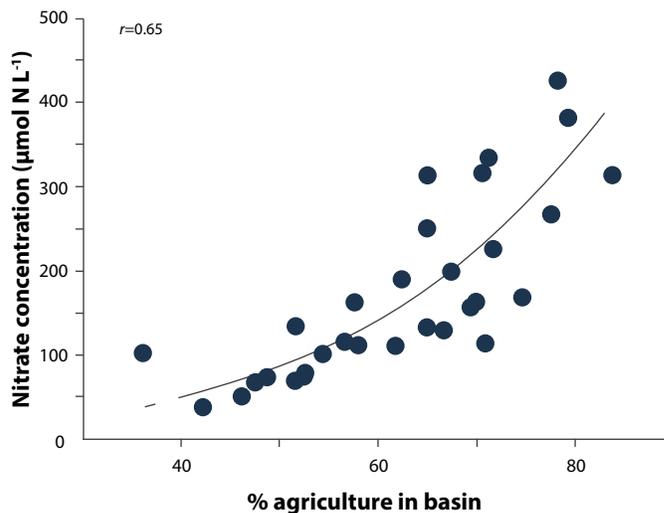


Figure 5.3. The relationship between agricultural land-use and annual average nitrate concentrations in headwater streams in the Choptank River watershed. Greater agriculture land-use is associated with increased nitrate concentrations, driven by both increased fertilizer use and the clearing of natural forests and wetlands that protect local waters.<sup>14</sup>

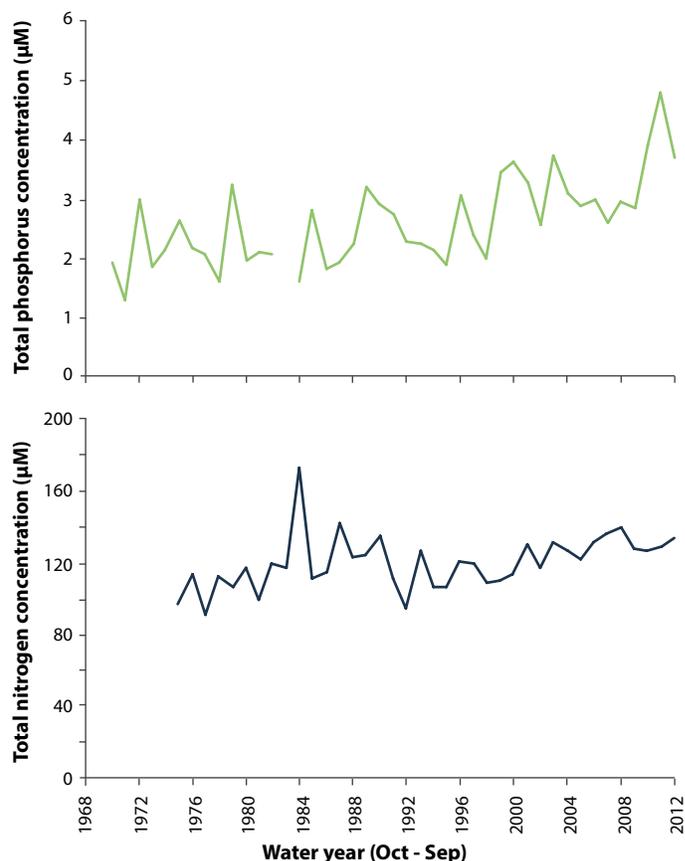
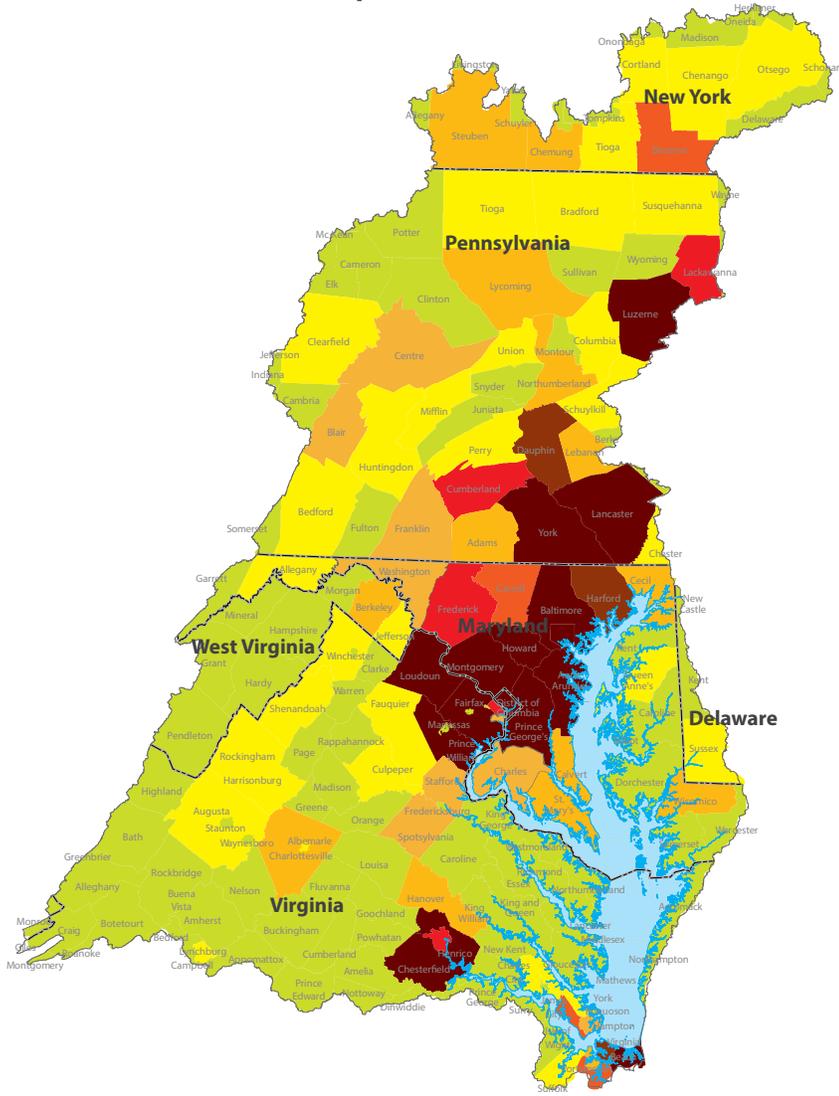


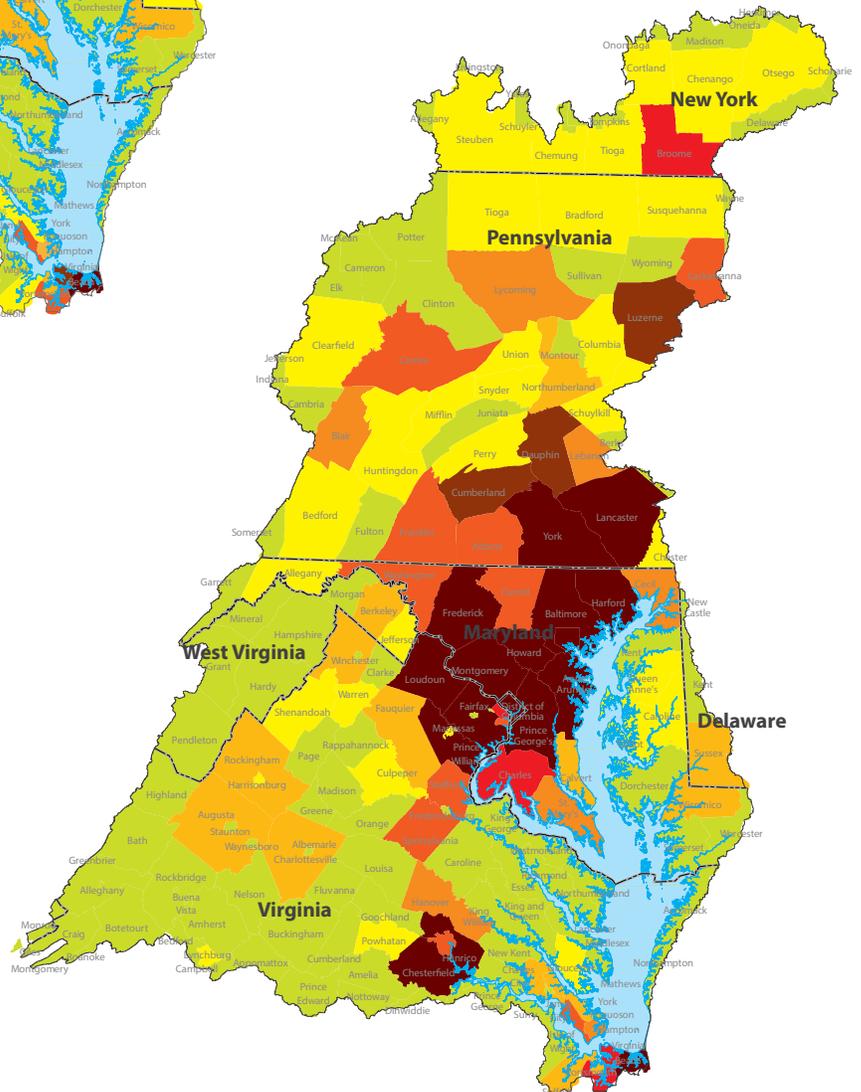
Figure 5.4. Increases annual average total nitrogen and total phosphorus concentrations at the USGS Greensboro, MD monitoring station (1968-2012) (USGS data provided by T. Fisher, UMCES).<sup>58</sup>

## Population 2010



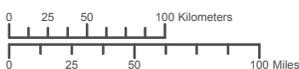
The Chesapeake Bay watershed's population is growing quickly. The watershed is currently home to 17.5 million people, and this number is projected to reach 20 million by 2030.<sup>1</sup> As the population grows, development will expand and with it, impervious surfaces, stormwater runoff, wastewater treatment effluent volume, vehicle use, and lawn fertilizer applications. These development-related pressures will degrade water quality within the watershed unless they are mitigated by effective best management practices (BMPs). A multitude of BMPs are in place, but increasing development may counteract the water quality benefits that would have otherwise been observed. All nutrient sources must be targeted to avoid these counteracting influences and improve the health of the Chesapeake Bay.

## Projected Population 2030



### Population

- 0 - 40,000
- 40,001 - 80,000
- 80,001 - 120,000
- 120,001 - 160,000
- 160,001 - 200,000
- 200,001 - 240,000
- 240,001 - 280,000
- > 280,000



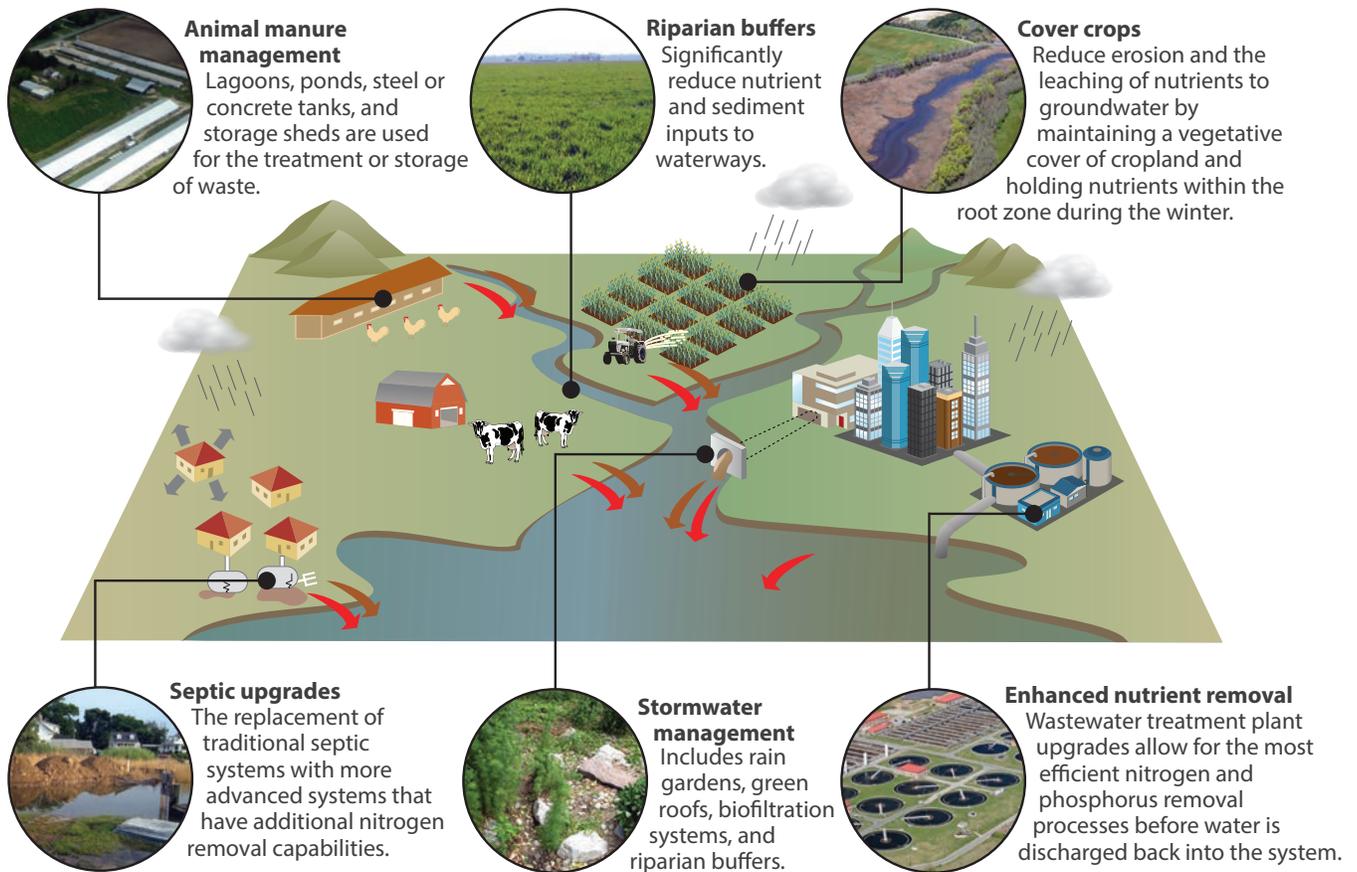


## Observable water quality responses are more likely to occur if A) location-specific sources of pollution are identified, and B) targeted practices are implemented

- A variety of point and nonpoint sources contribute excess nutrients to the Chesapeake Bay.
- Nutrient and sediment management must be targeted to match local ecosystem processes and sources of pollution.
- Factors that may affect best management practice effectiveness include stream location within the watershed, dominant land use, and physiographic provinces.

Excess nutrients in the Chesapeake Bay originate from multiple point and nonpoint sources, including wastewater treatment plants (WWTPs), excess crop fertilizer, livestock manure, urban stormwater runoff, and atmospheric nitrogen (N) deposition. Each best management practice (BMP) is designed to target a specific nutrient source and delivery pathway to the Bay. The local sources of nutrients in any area must be identified in order to ascertain the appropriate BMP that will most likely result in water quality improvements. A suite of BMPs may be required to generate significant change in areas that receive nutrients from numerous sources. The following case studies highlight outcomes of localized efforts, as well as the influence of broad regional characteristics.

*An array of best management practices are required to target the numerous sources and delivery pathways of excess nutrient loads.*



**Water quality in the non-tidal streams of the Corsica River watershed have begun to improve after the aggressive implementation of multiple nutrient reduction practices targeting both point and nonpoint sources of pollution.**

In response to the Maryland Department of the Environment designating the Corsica River as an impaired water body, the Town of Centreville and its partners developed a Watershed Restoration Action Strategy (WRAS) in 2004.<sup>60</sup> A Corsica Implementation Committee—consisting of a diverse group of stakeholders—was subsequently formed and led the efforts in understanding the water quality problems, developing solutions, and tracking progress. BMPs were intensively implemented to target both point and nonpoint sources.<sup>38,61</sup> The Centerville WWTP was upgraded to biological nutrient removal (BNR) in 2010 and the treated wastewater was sprayed onto agricultural fields, greatly reducing a major point source of excess nutrients discharging into the river. However, agriculture represents 60% of the surrounding land-use and contributes the majority of nutrient loads.<sup>62</sup> To target nonpoint sources, cover crops, forested and grassed buffers, manure and fertilizer management, stormwater wetland ponds, bio-retention structures, septic system retrofits, and wetland restorations were implemented. Water quality monitoring began in 2005, but improvements were not observed until 2007. From 2007 to 2011, N and phosphorus (P) concentrations significantly decreased in two of the three monitored non-tidal tributaries of the Corsica River (Three Bridges Branch and Gravel Run) (Figure 6.1).<sup>61</sup> The delay in water quality response points to the need for long-term monitoring data. Furthermore, identifying all nutrient sources, understanding that nonpoint sources dominated the nutrient loads, and implementing BMPs accordingly likely contributed to the observed water quality improvements.

Although N and P concentrations decreased in two non-tidal tributaries, water clarity in the tidal portions of the Corsica River has not yet improved.<sup>38,61,62</sup> Nutrient and chlorophyll a concentrations are high and vary throughout the year. The system continues to experience hypoxic events during the summer months. Reductions in nutrient loads may need to reach a minimum level before water quality will significantly improve. A nutrient budget was developed that included an expansive set of ecosystem

After the aggressive implementation of nutrient reduction strategies in the Corsica River watershed, nutrient concentrations significantly decreased in two non-tidal tributaries of the Corsica River, Three Bridges Branch (top), and Gravel Run (bottom).

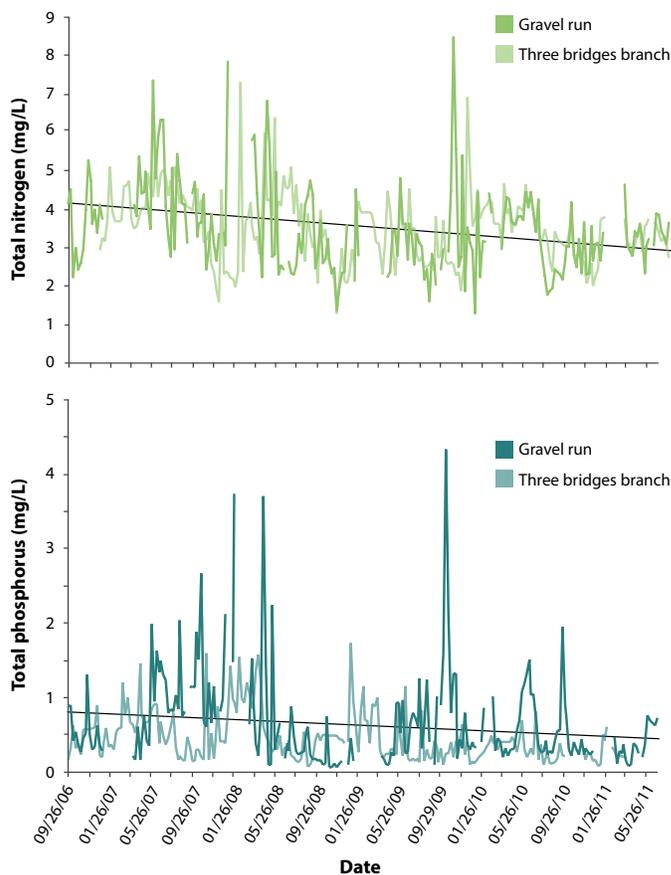
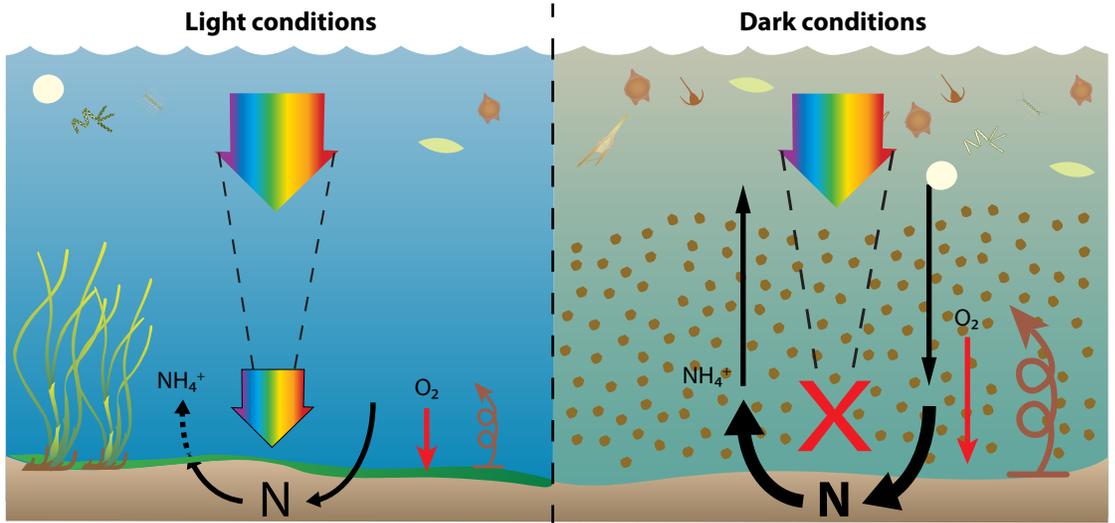


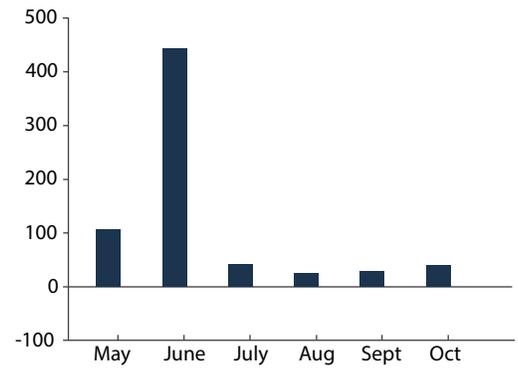
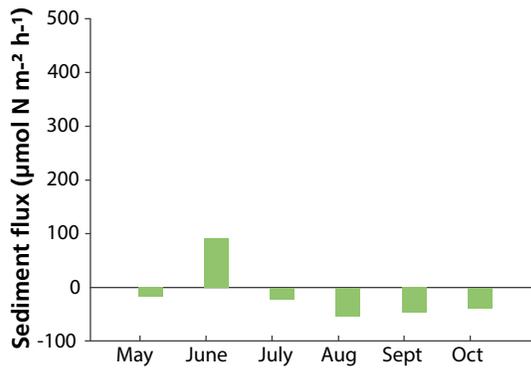
Figure 6.1. Changes in total nitrogen (TN) and total phosphorus (TP) in Three Bridges Branch and Gravel Run (2006–2011). Aggressive best management practice implementation began in 2005 in the Corsica River watershed. In 2007, TN and TP began to decrease in two non-tidal tributaries.<sup>61</sup>

Figure 6.2. Excess nutrients will result in increased chlorophyll and turbidity, limiting the amount of light that reaches benthic sediment. Light is essential for healthy submerged aquatic vegetation (SAV) growth.<sup>63</sup>

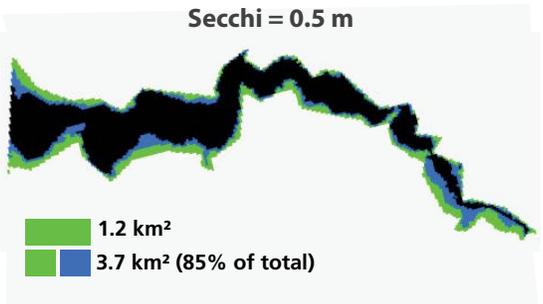
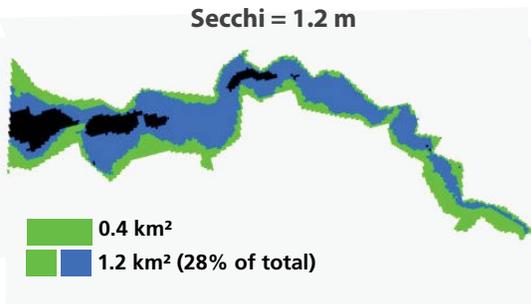


Sediments that receive light through the water column trap nutrients, decreasing excess nutrient concentrations that lead to phytoplankton blooms and depleted oxygen levels. Improved water clarity allows for submerged aquatic vegetation growth, which can aid in trapping suspended sediments and reduce sediment resuspension.

Increased light may inhibit the release of nitrogen from sediment, resulting in less ammonium ( $\text{NH}_4$ ) flux, and a less nutrient-rich aquatic environment (data provided by W. Boynton, J. Testa, W. Kemp, J. Cornwell, M. Brooks, UMCES).



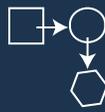
A secchi depth of 0.5 m (very turbid water) will result in less SAV growth than a secchi depth of 1.2 m (less turbid water) (data provided by W. Boynton, J. Testa, W. Kemp, J. Cornwell, M. Brooks, UMCES).



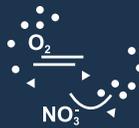
Corsica River (~4.5 km<sup>2</sup>) 0 0.5 1 2Km ■ < 1% Light ■ 1% - 15% Light ■ > 15% Light

processes that may affect nutrient, algae, and dissolved oxygen conditions, including the influx of nonpoint sources of N, losses of N to the atmosphere, and the burial of N in sediments. Scientists were able to quantify a tipping point—the level of reduction in nutrient pollutant loads at which significant water quality improvements are expected to occur. The budget estimated that a 50% reduction of N loading is a tipping point at which water quality will drastically improve. Once this reduction is attained, the river should experience a 70% decline in chlorophyll *a*, 75% improvement in water clarity, and 60% increase in estuarine area capable of supporting healthy submerged aquatic vegetation (SAV) growth.<sup>62</sup> However, groundwater lag time—estimated at 18 years—may delay a tidal system response. Furthermore, most BMPs have not been fully implemented.<sup>61</sup> Even when BMPs are appropriately targeted, full implementation of these BMPs is an important condition for success (see Figure 6.2).

## What does the Corsica River tell us about assessment science and adaptive management?



**DEVELOP A CONCEPTUAL MODEL.** Models can help identify the major nutrient sources, choose the most appropriate BMPs, and predict resulting ecosystem responses. The Corsica River is largely affected by agricultural nutrient sources, necessitating agricultural BMPs.



**CREATE A NUTRIENT BUDGET.** A nutrient budget can predict the minimum load reductions required for observable water quality improvements. A 50% reduction in N loading in the Corsica River should result in dramatic ecosystem improvements.



**MONITOR AND MEASURE.** Monitoring is critical to obtain quantitative data needed to evaluate results and make corrections. Measuring influential processes, such as denitrification and nutrient burial that occurs in the Corsica River, will provide a more accurate picture of system dynamics.



**MEASURE EARLY AND OFTEN.** Baselines are essential in evaluating the impacts of BMPs; monitoring throughout the entire year is required to capture seasonal differences. In the Corsica River, algae vary temporally, which will affect water clarity and hypoxic events within a single year.



**STICK WITH IT.** Water quality responses can take time, particularly when load reductions are delayed by groundwater age and sediment storage of P. Monitoring must be a multi-year effort. Monitoring began in the Corsica River in 2005, but non-tidal responses were not observed until 2007.



**COLLABORATE.** Agencies and organizations can bring different skills to the table. A wide variety of BMPs were implemented in the Corsica River, necessitating an extensive range of expertise.



**UTILIZE STRONG LEADERSHIP.** Analyzing and interpreting the data requires clear goals and strong leadership to guide a long-term restoration project. Supported by many partners, the Town of Centreville developed Corsica's Watershed Restoration Action Strategy, and a Corsica Implementation Committee to lead efforts to identify problems and develop solutions.<sup>64</sup>

Adapted from Boynton et al. 2010.<sup>63</sup>

**Stream location and flow regime affected restoration effectiveness in Anne Arundel County, Maryland, a highly populated region near Baltimore, Maryland and Washington, D.C.**

Stream restoration is a BMP sometimes used in urban areas to reduce stormwater and nutrient runoff. Six restored streams in Anne Arundel County, MD provide insight into factors that can affect restoration outcomes. Three of the streams were located in headwater areas (upland) and the remaining three were near the tidal boundary (lowland). Water quality did not improve in either base flow or storm flow conditions in the upland streams, but the lowland streams experienced partial success. Baseflow N concentrations were significantly reduced in two lowland streams, and stormflow N concentrations were significantly reduced in one lowland stream. Several variables may be the cause of outcome disparities between the two locations. Nutrients were discharged into streams via different pathways, which may have affected water quality responses to the stream restorations. In the two streams that experienced decreased N concentrations, nutrients originated from sources above the restored reaches of the stream. The entire length of the stream was available for in-stream N processing. In the three unsuccessful upland streams, nutrients entered the streams in groundwater and bank seepage throughout the span of the reach, limiting the amount of time that the water could benefit from in-stream N processing. Streams also contained diverse forms of N, each influenced by specific nutrient-reducing practices.<sup>64</sup> The results suggest that the dominant attributes of a stream such as location, groundwater dynamics, flow conditions, and N species may influence restoration outcomes (Figures 6.3 and 6.4).

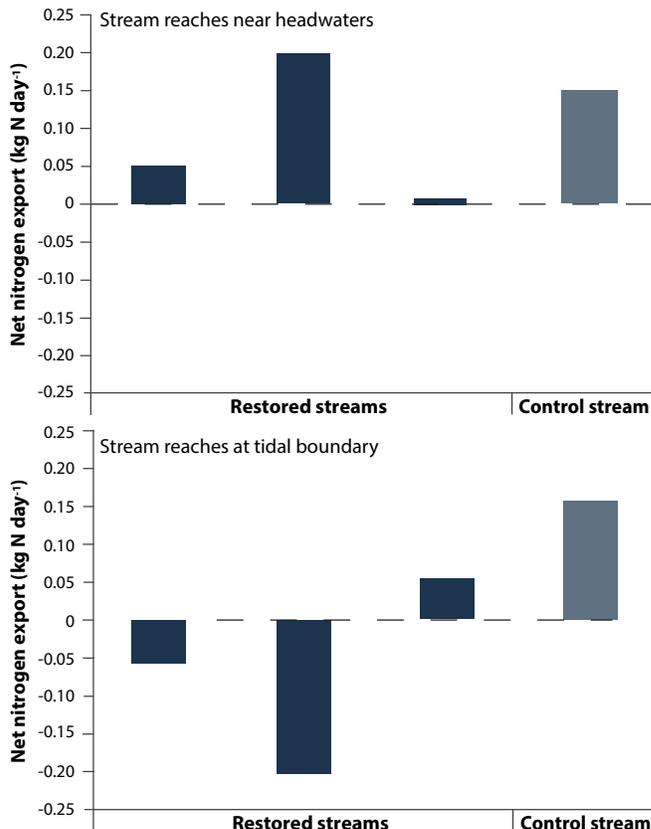


Figure 6.3 Net export of nitrogen (N) in eight streams in Anne Arundel County, Maryland, six of which were restored. Two of the three restored lowland streams retained N—suggesting successful nutrient removal—while all of the upland streams exported N. Stream location may influence the effectiveness of stream restoration as a best management practice intended to improve water quality.<sup>65</sup>

	Annual discharge (L)	Total nitrogen (kg N yr <sup>-1</sup> )	Total suspended sediment (kg N yr <sup>-1</sup> )
Downstream sampling site	608,522,942	417	15,879
Upstream sampling site	563,986,208	507	38,187
<b>Net export</b>	<b>44,536,734</b>	<b>-90</b>	<b>-22,308</b>

Figure 6.4. Total nitrogen (TN), total suspended sediment (TSS), and annual water discharge in one stream located near the tidal boundary in Anne Arundel County, Maryland. A restored lowland stream exhibited a net retention of TN and TSS. The net water discharge in this stream increased only slightly in comparison to the upland streams. Conversely, the upland streams showed a net export of TN and TSS, suggesting stream location may affect best management practice effectiveness.<sup>65</sup>

**Broad regional differences between the physiographic provinces of the Chesapeake Bay watershed may influence water quality responses to best management practices.**

The Chesapeake Bay watershed is characterized by a diverse landscape, and has been partitioned into regions based on rock type and physiography (See Figure 6.5). As the physiographies of regions vary, so may water quality responses to nutrient reducing practices. Wetland and forest buffers along water flow paths that connect cropland to streams may take up excess nutrients from farms, decreasing the nutrient loads being discharged into streams. In order to estimate potential differences in nutrient removal between regions, nitrate concentration data were collected in 321 rural watersheds throughout the Coastal Plain, Piedmont and Appalachian Mountain regions. A statistical modeling framework quantified nitrate loads discharged from cropland and the levels of nitrate removed by buffers. Among the three provinces, the Coastal Plain had the greatest proportion of buffered cropland and the lowest average stream nitrate concentrations. Buffers in the Coastal Plain absorbed nutrients very efficiently and continued buffer restoration is predicted to positively affect water quality. The Piedmont province contained the greatest average proportions of cropland and the highest average stream nitrate concentrations. Buffers along cropland in the Piedmont had the highest potential for absolute nitrate removal. These results suggest that although buffers may improve water quality in multiple regions, large-scale buffer restorations throughout the entire Piedmont region would have the greatest aggregate effect on nutrient loads to the Bay when compared to the Coastal Plain and Appalachian Mountain regions.<sup>66</sup> Understanding regional differences in the watershed will help water quality managers make more informed decisions during the development of BMP plans. Research that targeted the Piedmont region—an area consisting of agriculture, forests, and suburban land uses—has been conducted to evaluate riparian buffers. Data suggest that the age of riparian buffer zones can have a direct influence on benthic macroinvertebrate communities. As buffer age increased, habitat quality, water quality, and macroinvertebrate diversity generally improved within 5–10 years. Although full buffer functionality generally occurs 15–20 years after initial implementation, some water quality improvements can be detected as early as 1–2 years.<sup>67</sup>

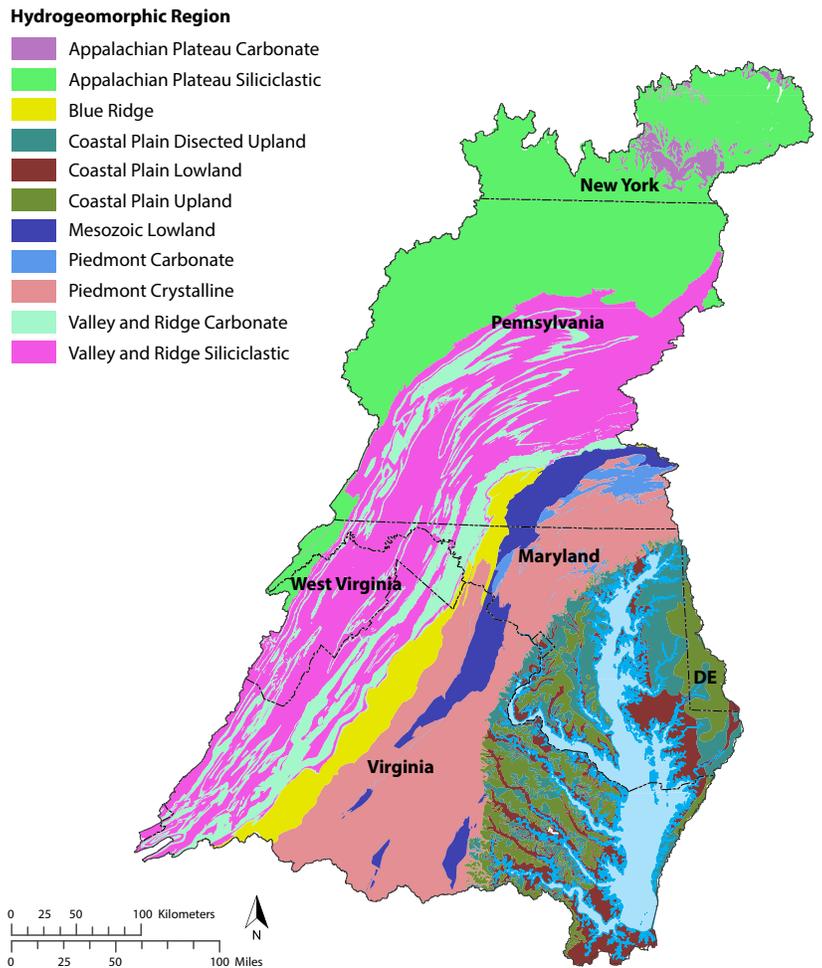


Figure 6.5. U.S. Geological Survey developed a map of hydrogeomorphic regions for the Chesapeake Bay watershed based on rock type and physiography to aid in assessing the relationship between groundwater discharge and nutrient loads to the Bay. Regional physiographic differences may influence the magnitude and timing of improvements in water quality (USGS 2000; Map provided by the Chesapeake Bay Program).



## An array of practices to promote stormwater infiltration and retention are needed in urban and suburban areas

- **Urban and suburban development will continue to expand as the Chesapeake Bay watershed's population grows, necessitating intensified best management practices.**
- **Development is associated with increased impervious surfaces, lawn fertilizer applications, vehicle emissions, septic systems, gas-powered lawn tools, pet waste, and construction.**
- **Resulting increases in nutrients and sediment will reach the Bay through stormwater runoff.**
- **Best management practices that reduce stormwater nutrient and sediment loads include above-ground retention ponds, rain gardens, and sand filters.<sup>69</sup>**



*A stormwater drainage basin in a residential backyard directs excess, untreated runoff to the subsurface soil where it can filter naturally through the soil. Photos © Tim Auer, USGS.<sup>68</sup>*

A recurring theme throughout this report has been the effects of population growth and sprawling development. Growth will continue in the Chesapeake Bay watershed, necessitating best management practices (BMPs) that address the associated water quality problems. As described in the following case studies, several counties have implemented promising stormwater mitigation practices, which may aid other localities as they plan for increased development.

**Sophisticated stormwater best management practices implemented in Fairfax County, Virginia have removed and retained greater soil phosphorus and sediments than traditional stormwater basins.**

Stormwater management activities in Fairfax County—a suburban county located west of Washington, D.C.—illustrate the effectiveness of sophisticated stormwater BMPs. Stormwater management practices have largely been limited to flood control. However, sophisticated BMPs, including saturated or shallow flooded vegetated areas, are designed to slow water flow, distribute water throughout the basin, and increase the time during which stormwater is in contact with soil to allow adequate infiltration before stormwater discharges into streams. Traditional detention basins retain excess stormwater during rain events for only a few hours or days before draining directly into local streams. Although these basins may filter large debris, they are not designed to reduce nutrient and toxin inputs



*An infiltration trench is a rock-filled trench with no outlet that receives stormwater runoff. Stormwater runoff passes through a combination of pretreatment measures before infiltrating through the soil matrix. Photo © Jane Hawkey, IAN Image Library.*

into waterways. Sophisticated BMPs were compared with traditional stormwater practices and were found to be more effective in the removal of soil phosphorus and sediments. Fairfax County's population currently supports over one million residents and is projected to grow more than 0.7% per year through 2025, forecasting the need for widespread implementation of advanced stormwater BMPs.<sup>69</sup>

**Multiple redundant stormwater best management practices and combinations of different best management practices were more effective than a single practice implemented in Montgomery County, Maryland.**

As water runs off building roofs, parking lots, roads, and driveways, it picks up nutrients, sediments, and other harmful substances. Traditional stormwater management may temporarily retain water during storm events, but provides no infiltration to remove pollutants. Creating pervious surfaces using porous concrete or asphalt and installing grid pavers that provide spaces for water to penetrate the surface in urban environments allows soil and vegetation to act as natural filters.<sup>68</sup>

Montgomery County, MD has made progress toward more effective stormwater and development management in a highly populated and sub-urbanized area. Clarksburg, Piney Branch, Upper Paint Branch, and Upper Rock Creek are designated as Special Protection Areas (SPAs), geographic areas characterized by high quality or highly sensitive water resources that are also under threat of degradation by proposed land uses. Developers in these sites worked with county agencies in planning impervious surfaces, creating environmental buffers, conserving forests, controlling sediment and erosion, and managing stormwater. During construction, sediment and erosion control measures included basins with forebays, filter fence baffles, floating skimmers, series of dual basins, and greater storage volumes. These practices were also used in combinations as 'treatment trains'. After construction, stormwater management BMPs were implemented, which included natural and constructed filtering systems, storage for excess water during storm events, and adequate recharge volume. Stormwater BMPs—particularly when implemented in redundant trains—reduced stormwater runoff and decreased pollution loads. The success in Montgomery County emphasizes the need for careful planning prior to development. However, the health of the biological aquatic communities within the SPAs did not always rebound with improvements in water quality and may require more time to respond to decreased pollution loads.<sup>70</sup> This delay in response highlights the urgent need for effective BMPs as development rapidly expands.



Modular paver blocks serve as a pervious paving system in a parking lot. Pavers fit together like tiles and are set with small gaps between them, creating grooves for water to infiltrate the soil beneath. This practice allows for stormwater to infiltrate into limestone and underlying soils instead of directly into storm sewers. Photo © Jane Hawkey, IAN Image Library.



Impervious surfaces such as cement, asphalt and roofing prevent the infiltration of stormwater, increasing the volume and velocity of surface runoff which carries nutrients and sediments with it. Pervious surfaces, such as pervious pavement or pavers  , allow for stormwater to filter through the surface and into the ground  , rather than into nearby streams and storm drains  .

Built landscapes create impervious surfaces that change the hydrology of the environment and prevent natural processes from removing pollutants from water before reaching streams.

**Constructed wetlands in an urban environment in Baltimore, Maryland can reduce nitrate entering streams through stormwater runoff.**

Baltimore is a highly populated urban/suburban environment subject to large volumes of stormwater runoff. Constructed wetlands are promising practices that may be used to mitigate the water quality problems associated with development. Wetlands can permanently remove nitrogen (N) from aquatic systems through a denitrification process that reduces nitrate-N and nitrite into gaseous forms of N that are not bioavailable (bioavailability is the ability to support the growth of phytoplankton). Wetland plants and phytoplankton can also take up bioavailable N and produce forms of N that are less bioavailable. Some of this N is ultimately buried in wetland sediments, removing from the system excess N that would have traveled to the Bay and contributed to algal growth. Three constructed wetlands (Stony Run in north central Baltimore), two U-shaped (oxbow) wetlands created incidentally during a stream restoration project (Minebank Run in Baltimore’s Gunpowder River watershed), and two semi-natural forested wetlands (Baisman Run in Baltimore County) were compared to assess whether constructed wetlands could be as effective at reducing nitrate-N as incidental oxbow and natural forested wetlands. The constructed wetlands were created to directly receive water from stormwater outflows. The other wetlands received water when nearby streams overflowed during periods of high precipitation. The denitrification rates of urban constructed wetlands were not significantly different than other wetlands, suggesting that they are just as effective at decreasing stream concentrations of nitrate. Data demonstrated a positive relationship between denitrification rate and nitrate concentration across all wetland sites. When each site was examined individually, one of the three constructed wetland sites had the highest denitrification rates and groundwater nitrate-N concentrations, suggesting that if denitrification in constructed wetlands increases as nitrate increases, denitrification can be an important factor reducing nitrate delivery to the Chesapeake Bay.<sup>72</sup> As urbanization rapidly spreads throughout the Chesapeake Bay watershed, assessing the degree to which urban constructed wetlands effectively reduce nitrate concentrations in streams is highly relevant and can reveal a potentially effective BMP (Figure 7.1).



A constructed wetland site at Stony Run in north central Baltimore was used to assess whether constructed wetlands could be effective at reducing nitrate-nitrogen. Photo © Melanie Harrison, NOAA.

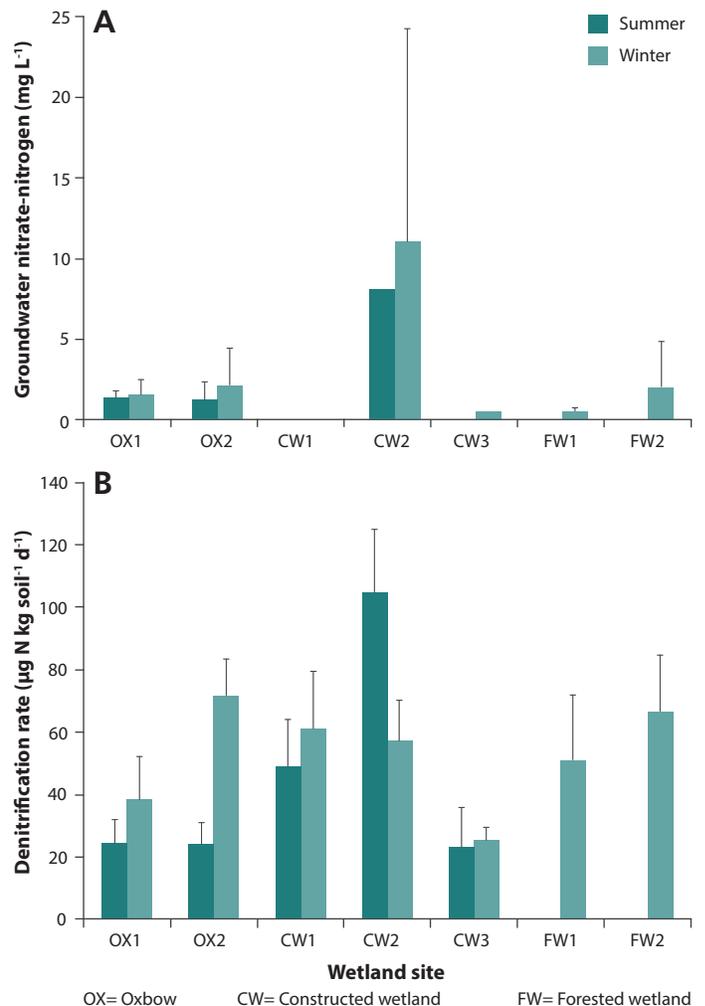
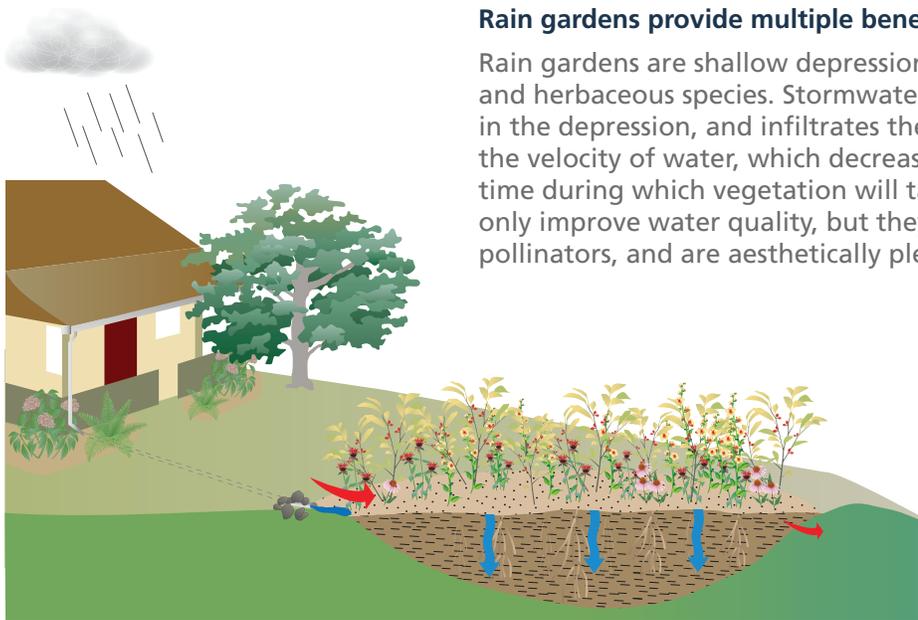


Figure 7.1. Mean groundwater nitrate-nitrogen concentrations (A) and denitrification rates (B) did not differ significantly by type of wetland (constructed, oxbow, and forested). Comparing each site individually revealed that one of the constructed wetlands (CW2) exhibited the highest denitrification rates and groundwater nitrate-nitrogen concentrations. Urban constructed wetlands can potentially serve as effective best management practices targeting nitrates in stormwater runoff.<sup>72</sup>

## Additional initiatives being conducted within the Chesapeake Bay watershed

### Rain gardens provide multiple benefits in developed areas.

Rain gardens are shallow depressions planted with evergreen, deciduous, and herbaceous species. Stormwater runs off impervious surfaces, collects in the depression, and infiltrates the soil. Surrounding vegetation reduces the velocity of water, which decreases soil erosion and extends residence time during which vegetation will take up nutrients. Rain gardens not only improve water quality, but they also provide wildlife habitat, attract pollinators, and are aesthetically pleasing.<sup>71</sup>



Gutters and downspouts installed onto buildings and in lawns help assist in directing rain water from the roof to the garden. A landscape of native, drought resistant plants is well adapted to local conditions and easily maintained. Plants with deep root systems encourage stormwater infiltration and help absorb excess nutrient runoff. Additionally, a berm on the downward slope of a rain garden will help hold water in the garden during heavy rains, further improving its filtering capacity.

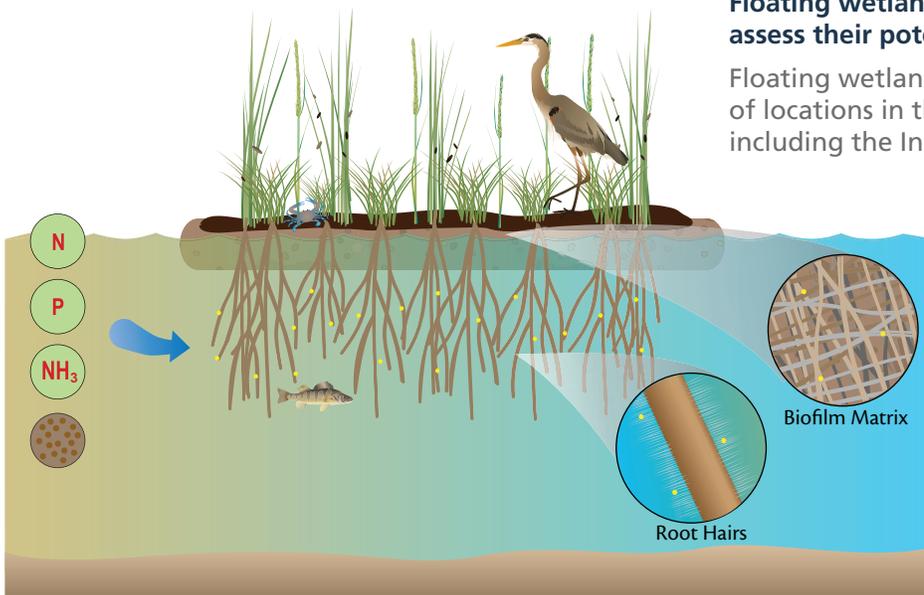


A rain garden and rain barrel used simultaneously for collection and filtration of stormwater runoff. Photo © Alexandra Fries, IAN Image Library.

### Floating wetlands are currently being studied to assess their potential to improve water quality.

Floating wetlands have been constructed in a number of locations in the Chesapeake Bay watershed, including the Inner Harbor of Baltimore, Maryland.

Continuing research is needed to assess the magnitude of impact that floating wetlands may have on water quality, as well as any potential to serve as effective stormwater BMPs.<sup>73</sup>



Emergent wetland plants such as rushes, reeds and sedges are planted on a buoyant matrix or mat that floats at the water surface. The plants grow through the matrix with their roots suspended in the water, and the lack of soil necessitates the plants to take required nutrients directly from the water, potentially decreasing nutrient concentrations. A biofilm matrix covers the floating island and roots, providing a means of biochemical transformation of contaminants as well as particle filtering and entrapment. Root hairs provide extra surface area for nutrient uptake and particle filtering. During storm events, floating wetlands move with the water level, avoiding the damage that can occur to flooded wetlands rooted in soil. Additionally, crabs, mussels and other aquatic species can colonize floating wetlands, while fish and migratory birds use them for refuge.



Floating wetlands being deployed in Baltimore's Inner Harbor, Maryland. Photo © Caroline Wicks, IAN Image Library.

# Conclusions

We have learned that our long-term efforts to reduce pollution have led to local improvements in water quality. We need to expand the improvements in air and water quality that are realized when sewage treatment is upgraded, air emission controls are implemented, and agricultural nutrient management is improved. We also have learned that our progress can be overwhelmed by unsustainable transformations to the landscape. The challenges of groundwater lag times and changes in land-use that can delay or subvert improvements in water quality are ongoing issues. We need to be diligent about how and where we use both proven and innovative practices to reduce pollution, and in monitoring how well they work. Using an adaptive management approach in which monitoring and assessment—followed by evaluations of effectiveness—are incorporated into planning and protocols can lead to better environmental outcomes.

***Our long-term efforts to reduce pollution have led to local improvements in our air, land, and water.***



## **Investments in sewage treatment plants provide rapid water quality improvements.**

The National Pollutant Discharge Elimination System permits—part of the Clean Water Act—has allowed for the development of effluent pollution standards. Wastewater treatment plant (WWTP) technology has advanced, decreasing nutrient loads to receiving bodies of water. As verified by research highlighted in this report, WWTP upgrades have led to reductions in nutrient loads and concentrations, as well as the resurgence of submerged aquatic vegetation.

*Implication: Biological nutrient removal and enhanced nutrient removal promoted by the Clean Water Act have been proven effective, however many WWTPs in the watershed are still discharging increasing loads of nutrients. Further investments in WWTPs are needed to reduce nutrient loading associated with an increasing number of people living in the Chesapeake Bay watershed.*



Regular vehicle emissions inspections and maintenance lead to cleaner air, a healthier public, and improved water quality in the Chesapeake Bay watershed.

Photo © Wendy House.

## **National requirements of the Clean Air Act are benefitting the Bay.**

The Clean Air Act allowed the U.S. Environmental Protection Agency to set National Ambient Air Quality Standards, regulating emissions of nitrogen oxides and sulfur dioxide. Emissions have significantly declined with the installation of power plant scrubbers, as well as the use of catalytic converters in vehicles, leading to decreasing atmospheric nitrogen deposition. These decreases in deposition have been linked to surface water quality improvements in the mostly-forested Appalachian region of the Chesapeake Bay watershed.

*Implication: Decreases in stationary and mobile air emissions will be required to maintain and further improve air quality and contribute to nitrogen reductions in streams.*

## **Some agricultural practices are providing local benefits to streams.**

Several agricultural practices—including cover crops, manure and fertilizer waste management, and livestock exclusion from streams—have been demonstrated to be effective best management practices. Nutrient-reducing agricultural practices have been linked to local stream improvements in multiple locations in the watershed, including the Wye River, Upper Pocomoke River, and Brush Run Creek.

*Implication: The success stories span multiple states, and exemplify practices that may work in a variety of locations under similar conditions. Enhanced implementation of conservation practices, such as carried out under the Chesapeake Bay Initiative of the Farm Bill, are needed to expand water quality benefits in more areas of the watershed.*



***Our progress is affected by 'lag times' and can be overwhelmed by unsustainable transformations to the landscape.***

**Lag times that delay improvements mean patience and persistence are needed.**

Although many best management practices have decreased nutrient loads and improved water and habitat quality, the full benefit is often delayed. The delays for nitrogen result from the wide range of times (years to decades or more) that groundwater can take to travel from under a farm field or suburban lawn and into a stream. Gradual releases of phosphorus from soils or stored in a streambed may delay observable decreases in phosphorus loading in streams and into the Chesapeake Bay.

*Implication: The lag times between implementing management practices and observing the full benefit to water quality conditions in the Chesapeake Bay watershed and its tributaries necessitate patience and persistence of water quality managers.*



*Due to the expanding population and continued development within the Chesapeake Bay watershed, major pressures on water quality must be identified. Photo © Chesapeake Bay Program.*

**Expanding population may counteract water quality improvements.**

The growing number of people in the Chesapeake Bay watershed leads to expanding development and impervious surfaces, and greater wastewater treatment plant effluent. The resources that people require result in increasing amounts of fertilizer for higher crop yields and increasing livestock densities. These are among the major pressures influencing water quality in the Bay and its watershed. Each of these pressures is important in varying degrees throughout the watershed and particular tributaries may respond differently.

*Implication: The growing number of people in the Chesapeake Bay watershed, and the resources we consume, will benefit from land-use planning that anticipates future reductions needed in both point and nonpoint sources of nutrients.*

***We need to be diligent about how and where we use both proven and innovative practices to reduce pollution, and in monitoring how well they work.***



**Enhanced targeting is needed to guide restoration and monitoring to evaluate effectiveness.**

Research has suggested that each nutrient source must be identified so that best management practices can be both targeted and comprehensive. Each location suffering from poor water quality can have a different mixture of pressures, watershed characteristics, and nutrient sources.

*Implication: Understanding the nutrient sources and watershed characteristics of an area will help water quality managers choose the types and locations of practices that will most benefit water quality. Once these are implemented, continuous and long-term monitoring is needed to evaluate outcomes, which will then allow managers to engage in adaptive management, altering course as new data are available.*

**Innovative practices and testing are needed.**

As the current population of the Chesapeake Bay watershed grows, the pressures from urban and suburban development will increase. Stormwater runoff can contribute excess nutrient and sediment loads to the Chesapeake Bay and its tributaries. Innovative practices are needed to prevent these pollution problems. Practices that are being implemented in many locations include rain gardens, pervious surfaces, and urban wetlands.

*Implication: As urban and stormwater practices are implemented and new practices are designed, testing will be needed to evaluate their water quality benefits.*



*Rain gardens are an innovative practice that allow targeted restoration on a local scale. Photo © Chesapeake Bay Program.*

# New Insights: Case Study Locations



## Additional Case Study Locations

*For further examples of science-based evidence of water quality improvements, challenges, and opportunities in the Chesapeake Bay watershed, please refer to the following case studies. Full citations available in reference section (beginning on page 44).*

Cullers Run, West Virginia<sup>74</sup>

German Branch of the Choptank River, Maryland<sup>75,76,77</sup>

Lake Linganore, Maryland<sup>43</sup>

Lower Dry River, Virginia<sup>43</sup>

Lower Gunpowder Falls, Maryland<sup>43</sup>

Lower Monocacy River, Maryland<sup>43</sup>

Mill Creek, Pennsylvania<sup>41</sup>

Minebank Run, Maryland<sup>78</sup>

Nomini Creek, Virginia<sup>79</sup>

North Fork of the Potomac River, West Virginia<sup>41</sup>

Owl Run watershed, Virginia<sup>80</sup>

Sawmill Creek, Maryland<sup>81</sup>

Sligo Creek, Maryland<sup>41</sup>

Spring Branch, Maryland<sup>43</sup>

Stephen Foster Lake, Pennsylvania<sup>43</sup>

Trap Pond, Delaware<sup>43</sup>

Upper Monocacy River, Maryland<sup>82</sup>

Willis River, Virginia<sup>43</sup>

# Glossary

**Animal unit** – 1,000 pounds of animal weight.<sup>35</sup>

**Anoxia** – a condition where no oxygen is present in the water. Also called a ‘dead zone.’

**Anthropogenic** – caused by humans.

**Aquifer** – underground soil or rock through which groundwater can easily move. Aquifers typically consist of gravel, sand, sandstone, or fractured rock such as limestone.

**Atmospheric deposition** – the process through which airborne pollutants settle onto land or water. ‘Wet deposition’ refers to pollutants that fall to the earth while attached to rain or snow. ‘Dry deposition’ refers to pollutants that fall without precipitation.

**Baseflow** – the portion of river flow that comes from groundwater, rather than runoff.

**Basin** – an area of land that drains into a particular river, lake, bay, or other body of water. Also called a watershed.

**Benthic** – bottom-dwelling. Benthic organisms spend at least part of their lives in, on, or near the bottom of streams, rivers, lakes, or the Chesapeake Bay.

**Best management practice (BMP)** – the most effective and practical restoration practice used to control pollutants and meet environmental quality goals. BMPs include wastewater treatment upgrades, agricultural practices (e.g., cover crops, manure storage and management), and stormwater management (e.g., rain gardens).

**Biological nutrient removal (BNR)** – technology that removes nitrogen and phosphorus during wastewater treatment.

**Chlorophyll a** – the predominant type of chlorophyll found in algae (tiny, single-celled planktonic plants that are the primary producers of food and oxygen in the Bay food web). Chlorophyll a is used as an indicator of nutrient pollution in the Chesapeake Bay and its tributaries.

**Coastal Plain** – the level land downstream of the Piedmont and fall line, where soils are generally finer and fertile and rivers are influenced by the tide.

**Conservation tillage** – a soil tillage practice that leaves one-third or more of a farm field covered with crop residue or vegetation throughout the year. When tillage is reduced and soil is left undisturbed, a field is less prone to erosion.

**Cover crops** – crops that are grown to provide soil cover and prevent erosion. Planting cover crops uses living plants to fill in bare soil in a field. This can occur when a main crop has been harvested, when there is a niche in a season’s crop rotation or when there is a need to interplant a cover crop with a cash crop.

**Cyanobacteria** – blue-green algae that are toxic to wildlife and animals and can grow into large blooms under conditions of excess nutrients.

**Denitrification** – a process that reduces nitrate-nitrogen and nitrite into gaseous forms of nitrogen that do not support the growth of phytoplankton.<sup>78</sup>

**Dissolved inorganic nitrogen (DIN)** – nitrogen that is readily usable by plants.

**Dissolved oxygen (DO)** – the amount of oxygen that is present in the water. It is measured in units of milligrams per liter (mg/L), or the milligrams of oxygen dissolved in a liter of water.

**Effluent** – discharge of liquid waste from a wastewater treatment facility, factory, or industry to a local water body.

**Eutrophic** – an aquatic system with high nutrient concentrations, which fuels algal growth. This algae eventually dies and decomposes in a process that reduces the amount of dissolved oxygen in the water.

**Fall line** – the boundary between the Piedmont Plateau and the Coastal Plain, ranging from 15 to 90 miles west of the Chesapeake Bay. Waterfalls and rapids clearly mark this line.

**Groundwater** – water that is stored underground in cracks and spaces in rock and soil.

**Groundwater age** – the time it takes for groundwater to move through an aquifer from the area of recharge (i.e., where water permeates the soil and enters the groundwater aquifer) to the area of discharge (e.g., a stream).

**Hydrogeomorphic regions** – regions characterized by rock type and physiography based on geologic formations. These regions are used to advance the understanding of the role groundwater discharge has in nutrient loading to the Chesapeake Bay watershed.

**Hypoxia** – a condition in which oxygen levels in water are very low.

**Impervious** – a surface or area that is hardened and does not allow water to pass through (e.g., roads, rooftops, driveways, sidewalks, pools, patios, and parking lots).

**Infiltration** – the movement of water that falls as rain and snow into the subsurface soil and rock. Some water that infiltrates will remain in the shallow soil layer, where it will gradually move vertically and horizontally through the soil and subsurface material. Eventually, it might enter a stream by seepage into the stream bank. Some of the water may infiltrate deeper, recharging groundwater aquifers.

**Intensified agriculture** – agricultural practices associated with an increased use of fertilizers and greater animal densities.

**Lag time** – the amount of time between the implementation of a management practice and measurable improvements in water quality in the Chesapeake Bay.

**Leachate** – a contaminated liquid that results when water collects contaminants as it trickles through wastes, agricultural pesticides, or fertilizers. Leaching may occur in farming areas and landfills and may be a means of the entry of hazardous substances into soil, surface water, or groundwater.

**Macroinvertebrates** – large, generally soft-bodied organisms that lack backbones.

**Mesohaline** – moderately salty waters with salinities that range from 5 to 18 parts per thousand (ppt).

**Nonpoint source** – a source of pollution that cannot be attributed to a clearly identifiable, specific physical location or a defined discharge channel (e.g., nutrients that run off croplands, feedlots, lawns, parking lots, and streets). It also includes nutrients that enter waterways via air pollution, groundwater, or septic systems.

**Nutrient concentration** – the amount of a nutrient present in a given volume of water (e.g., milligrams per liter).

**Nutrient load** – the amount of a nutrient that the Chesapeake Bay and its tributaries receive.

**Oligohaline** – brackish waters with low salinities that range from 0.5 to 5 parts per thousand (ppt).

**Piedmont** – uplands or hill country located above the fall line. Rivers and streams in the Piedmont region are not influenced by the tide.

**Physiographic provinces** – regions of the Chesapeake Bay defined by rock type, terrain texture, and geologic structure and history.

**Point source** – a source of pollution that can be attributed to a specific physical location—an identifiable, end-of-pipe ‘point.’ The vast majority of point source discharges of nutrients are from wastewater treatment plants, although some come from industries.

**Polyhaline** – salty waters with salinities that range from 18 to 30 parts per thousand (ppt).

**Recharge** – rainfall and snowmelt that percolate through the soil zone and enter the groundwater system.

**Riparian buffers** – trees and/or other vegetation located along the edge of streams, rivers, and other waterways that filter pollution, prevent erosion, and provide wildlife habitat.

**Riparian zone** – the area of land next to a body of water. Riparian areas form the transition between aquatic and land environments.

**Sediment residence times** – Length of time that sediment remains within a section of a stream or river before being moved further downstream and into the Chesapeake Bay during periods of elevated precipitation.

**Stormflow** – the portion of river flow that comes from runoff during times of elevated precipitation.

**Submerged aquatic vegetation (SAV)** – technical term for underwater bay grasses. SAV help improve water quality and provide important food and habitat for fish, shellfish, invertebrates, and waterfowl.

**Suspended sediments** – tiny particles of clay and silt that become suspended in the water, reducing water clarity and the amount of sunlight that can reach underwater bay grasses.

**Total Maximum Daily Load (TMDL)** – defines the pollutant load that a water body can acquire without violating water quality standards, and allocates the pollutant loading between contributing point sources and nonpoint sources.

**Turbidity** – decreased clarity in a body of water due to excess suspended sediments.

**Volatilization of ammonia** – a process by which the nitrogen contained in animal waste is released into the air in the form of ammonia as the manure decomposes.<sup>25</sup>

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