NCHRP 25-25 Task 85
Nutrient (Nitrogen/ Phosphorus) Management and Source Control

Final Report

Requested by:

American Association of State Highway andTransportation Officials (AASHTO)

Standing Committee on the Environment

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August 2014

The information contained in this report was prepared as part of NCHRP Project 25-25, Task 85, National Cooperative Highway Research Program, Transportation Research Board.

ACKNOWLEDGMENTS

This study was conducted for the AASHTO Standing Committee on Environment, with funding provided through National Cooperative Highway Research Program (NCHRP) Project 25-25. The NCHRP is supported by annual voluntary contributions from the state Departments of Transportation. Project 25-25 is intended to fund quick response studies on behalf of the AASHTO Standing Committee on Environment.

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AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
BMP	Best Management Practice
BMPDB	International Stormwater BMP Database
CAFO	Concentrated Animal Feeding Operation
Caltrans	California Department of Transportation
CASQA	California Stormwater Quality Association
CDOT	Colorado Department of Transportation
CEC	Cation Exchange Capacity
CWA	Clean Water Act
CWP	Center for Watershed Protection
DCP	Dicalcium Phosphate
DO	Dissolved Oxygen
DOT	Department of Transportation
DP	Dissolved Phosphorus
EMC	Event Mean Concentration
ETN	Environmental Trading Network
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GI	Green Industry
GIS	Geographic Information System
HRDB	Highway Runoff Database
HRT	Hydraulic Residence Time
ILF	In-Lieu Fee
IQR	Interquartile Range
LADPW	Los Angeles County Department of Public Works
LID	Low Impact Development
LIDC	Low Impact Development Center
MCL	Maximum Contaminant Level
MDA	Maryland Department of Agriculture
MDE	Maryland Department of the Environment
MDSHA	Maryland State Highway Administration
MEP	Maximum Extent Possible
MINT	Missouri Innovative Nutrient Trading
MPCA	Minnesota Pollution Control Agency
MS4	Municipal Separate Storm Sewer System
N_2	Molecular Nitrogen
NAE	National Academy of Engineering
NC DENR	North Carolina Department of Environment and Natural Resources
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NH_3	Ammonia
NH_3-N	Ammonia as Nitrogen
NH_4^+	Ammonium
NHDOT	New Hampshire Department of Transportation
NITG	Nutrient Innovations Task Group
NMP	Nutrient Management Plan
NO_2	Nitrite

NO_3	Nitrate
NO_3-N	Nitrate as Nitrogen
NO_x	NO and NO_2 in atmosphere
NPDES	National Pollutant Discharge Elimination System
NPS	Nonpoint Source
NRC	National Research Council
NSQD	National Stormwater Quality Database
NYSDEC	New York State Department of Environmental Conservation
OP	Orthophosphate
OR DEQ	Oregon Department of Environmental Quality
ORP	Oxidation-Reduction Potential
PFC	Permeable Friction Course
PS	Point Source
ROW	Right-of-way
SAB	Scientific Advisory Board
SELDM	Stochastic Empirical Loading and Dilution Model
SEMCOG	Southeast Michigan Council of Governments
SRDEM	State of Rhode Island Department of Environmental Management
SRP	Soluble Reactive Phosphorus
SUP	Soluble Unreactive Phosphorus
TKN	Total Kjeldahl Nitrogen
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
TxDOT	Texas Department of Transportation
USGS	United States Geological Survey
U.S. EPA	United States Environmental Protection Agency
VA DCR	Virginia Department of Conservation and Recreation
VA DEQ	Virginia Department of Environmental Quality
VT ANR	Vermont Agency of Natural Resources
WERF	Water Environment Research Foundation
WIP	Watershed Implementation Plan
WisDOT	Wisconsin Department of Transportation
WLA	Wasteload Allocation
WRE	Water Resource Elements
WSDOE	Washington State Department of Ecology
WSDOT	Washington Department of Transportation
WTR	Water Treatment Residual
WWTP	Wastewater Treatment Plants

Executive Summary

As the U.S. Environmental Protection Agency (U.S. EPA) continues to press for development of numeric nutrient criteria for state waters and incorporation of nutrient Total Maximum Daily Loads (TMDLs) into National Pollutant Discharge Elimination System (NPDES) permits, it has become increasingly important for NPDES permit holders to have effective, flexible, and low-cost implementation alternatives for nutrient management. Some state Departments of Transportation (DOTs) are already stakeholders in TMDL allocations for NPDES stormwater discharges. Nutrients in runoff are a concern because they contribute to eutrophication, which is caused by over-enrichment of waters by primarily nitrogen and phosphorus in both particulate and dissolved form. Eutrophication can be accelerated as a result of human activities (anthropogenic eutrophication). Consequences of eutrophication include harmful algal blooms, depleted oxygen levels, impairment of aquatic life uses, and reduced aesthetics. Two of the most notable eutrophication impacts to U.S. waters include the Gulf of Mexico and the Chesapeake Bay.

This report was developed to address the growing need for a better understanding of nutrient cycling, fate and transport, and removal mechanisms to improve the control of nutrient sources and runoff concentrations from DOT facilities. It was developed based on the latest research and focused data analysis to provide DOTs an understanding of highway nutrient contributions and how they can be cost-effectively managed, if required, via best management practices (BMPs). Key report findings include:

- Particulate bound phosphorus makes up as much as 70 percent or more of the total phosphorus in stormwater and has limited bioavailability; the remaining dissolved fraction is mostly bioavailable as inorganic orthophosphates.
- Nitrogenous solids associated with plant debris and nitrates are typically the dominant nitrogen species in stormwater, with ammonia and nitrite also being common in runoff.
- Nutrient concentrations in highway runoff and traffic levels were found to be weakly correlated, but most studies suggest that the primary sources of nutrients in highway runoff are atmospheric deposition, soil erosion, decomposing organic debris, animal waste, and fertilizer applications. Therefore, land use, vegetation, and soils within or near the right-of-way are likely the most important factors influencing nutrient concentrations in highway runoff.
- Controllable or partially controllable nutrient-containing materials used or present within the right-of-way include roadside fertilizer, sediment, animal waste, plant material, roadside compost, road sands, deicing chemicals, and crumb rubber asphalt.
- Source controls and gross solids removal BMPs have not been shown to consistently control nutrients in stormwater, but are critical for the long-term performance of runoff control BMPs.
- Cost-effective nutrient source control BMPs include animal waste control (via dedicated pet areas at rest stops, wildlife crossings, and bird roosting deterrents) and management of fertilizer application, winter road materials, and roadside vegetation maintenance and selection.
- Catch basin inserts, sumps, and nutrient baffles are cost-effective gross solids removal BMPs that can aid in nutrient reduction, but require frequent maintenance.
- Nutrient removal in runoff control BMPs can be enhanced by using filter media additives such as iron filings, water treatment residuals or carbon-based materials (e.g., wood chips, newspaper, biochar, activated carbon, etc.); a saturated anaerobic zone for denitrification; dense vegetation, and increased hydraulic residence time.
- Infiltration is the most effective strategy for nutrient control where feasible. Wet ponds and wetland basins can be effective for all forms of nutrients. Sand filters and detention basins can be effective for phosphorus concentration reduction while vegetated filter strips and swales can be partially effective for nitrate concentration reduction.
- Watershed-based approaches (i.e., banking and trading) are increasingly gaining acceptance nationwide; DOTs can also use these strategies as part of nutrient mitigation efforts.

1.0 Introduction

As the population of the U.S. has grown, with its accompanying rise in agricultural and industrial production, the mass of nutrients (particularly nitrogen and phosphorus) discharged to receiving waters has increased. The National Academy of Engineering (NAE, 2008) identifies that human activity has doubled the amount of fixed nitrogen over the levels present during pre-industrial times. Carpenter and Bennett (2011) indicate that, although the global distribution of phosphorus is uneven, the release of phosphorus in industrialized areas is causing widespread eutrophication of surface freshwaters. The United States Environmental Protection Agency (U.S. EPA) predicts that this trend will continue for many years to come. The National Pollutant Discharge Elimination System (NPDES) was created to help address discharges of nutrients and other pollutants to receiving waters in the U.S. A major challenge facing those entities seeking NPDES permits, including State Departments of Transportation (DOTs), is how to cost-effectively, flexibly, and equitably address nutrient pollution problems resulting from development and facility management operations. These challenges will continue to grow as more states develop nutrient targets, including Total Maximum Daily Loads (TMDLs), numeric discharge criteria or benchmarks, and/or restrict the use of certain forms of nutrients (e.g. bans or restrictions on phosphorus fertilizers and detergents).

NCHRP 25-25 Task 85: Nutrient (Nitrogen/Phosphorus) Management and Source Control research presented herein was developed to support DOTs by providing guidance on how to assess and best control nutrient sources, loads, and concentrations in stormwater discharged from DOT facilities. This report is a compilation and summary of the significant research to date regarding the control of nutrients in stormwater, particularly in the highway environment. Nutrient management recommendations are made regarding source controllability, policies and programs, project and watershed-based approaches, and appropriate Best Management Practices (BMPs) and tools.

1.1 Goals and Objectives

The objectives of this report are to summarize the characteristics of nutrients in the environment and in highway runoff, current regulations and trends for nutrients, and key research findings related to nutrient control factors and BMP design as a means of providing comprehensive, technically-based recommendations for nutrient management strategies for DOTs. The research team focused its efforts on identifying successfully implemented DOT strategies for reducing nutrients from highway runoff and included previous experience and study findings, applicable former NCHRP work, nutrient databases, and other key nutrient focused project work. The team also performed searches of state DOT websites and state DOT online library searches to identify DOT nutrient management and source control policies, programs, and procedures. Targeted interviews with state DOTs were used to gain insight into the extent and focus of current nutrient management efforts and their effectiveness. The results of these tasks have been compiled into this report that can be used by DOTs to strategize and prioritize nutrient management efforts.

1.2 Document Organization

Following this introductory section, this document is organized into the following sections:

Section 2.0 Nutrient Regulations and Trends – This section provides a summary of impaired water bodies and current U.S. EPA and state water quality policies and programs affecting nutrient management.

Section 3.0 Nutrients in the Environment – This section provides an overview of nutrient sources and forms and their fate and transport mechanisms.

Section 4.0 Highway Contribution Analysis – This section summarizes DOT studies and data analyses focused on evaluating nutrient contributions from highway runoff.

Section 5.0 Removal Processes – This section summarizes the treatment processes that effectively remove nutrients from stormwater and the role of BMPs in nutrient removal.

Section 6.0 Assessment Tools and BMPs – This section summarizes current DOT source control and runoff management strategies as well as DOT organizational efforts for nutrient control.

Section 7.0 Summary and Recommendations – This section summarizes the major findings and provides DOT-specific recommendations for nutrient management based on the research.

Cited references are provided at the end of the report.

2.0 Nutrient Regulations and Trends

Nutrients in stormwater and other discharges to receiving water bodies are regulated and controlled by federal and state agencies, and in some areas, local governments. The Clean Water Act requires all major point source discharges to be regulated under the National Pollutant Discharge Elimination System (NPDES), including stormwater runoff from roadways and road maintenance facilities. State DOTs may be required to control nutrients if they discharge to an impaired waterbody or to a regulated Municipal Separate Storm Sewer System (MS4), which includes both municipally and DOT-owned stormwater conveyance systems. Nutrients are controlled by source control, which eliminates or reduces the entrainment of nutrients into runoff, and runoff management, which typically entails volume control and treatment. This section covers current federal and state regulatory nutrient source control and runoff management policies and programs to provide a framework that State DOTs can use to assess and compare their regulations and procedures. Developing trends in nutrient regulations (e.g., adoption of new water quality criteria and development of TMDLs) and enforcement are also discussed. Specific State DOT management policies and programs are discussed in Section 2.3.

2.1 Summary of Impaired Water Bodies

The U.S. EPA has identified over 100,000 miles of rivers and streams, almost 2.5 million acres of lakes, reservoirs, and ponds, and over 800 square miles of bays and estuaries in the United States with poor water quality due to nutrient pollution (U.S. EPA, 2013a). Elevated levels of nitrate in groundwater are also a concern; 64% of shallow monitoring wells sampled in a U.S. Geological Survey (USGS) study exceeded background nitrate concentrations in agriculture and urban areas, and U.S. EPA's drinking water Maximum Contaminant Level (MCL) for nitrate was exceeded in 2,388 domestic wells (USGS, 2010).

Section 303(d) of the 1972 Clean Water Act requires states to develop lists of impaired waters that do not meet water quality standards, even after point sources have implemented pollution control technology (U.S. EPA, 2013b). Priority ranking and Total Maximum Daily Loads (TMDLs) must then be established for these waters. The TMDL is developed from the loading capacity of the water body, and the pollutant load is allocated to the different pollutant sources. These sources are point and nonpoint sources and may include stormwater discharge from municipalities and roadways, wastewater discharge, etc. If a roadway is discharging to impaired waters with TMDL(s), DOTs may need to reduce pollution discharges to meet a load allocation. The following sections describe Chesapeake Bay and Northern Gulf of Mexico, two 303(d) waters that are of particular national concern.

2.1.1 Chesapeake Bay

Nutrient loads have caused algal blooms, hypoxic zones, and other signs of water quality degradation in Chesapeake Bay since the 1970s (Chesapeake Bay Foundation, 2012). These loads have been attributed to rapid population growth and development in the region. The Chesapeake Bay Program was developed in 1983 to address water quality and restore Chesapeake Bay and its watershed. The program is a regional partnership that includes the states of Delaware, Maryland, New York, Pennsylvania, Virginia, and West Virginia, the District of Columbia, the Chesapeake Bay Commission, U.S. EPA, advisory groups, and the scientific community (Chesapeake Bay Program, 2013).

The TMDL developed for Chesapeake Bay covers approximately 166,000 km^2 (64,000 mi^2) and identifies pollution reductions from major sources of nitrogen and phosphorus, with an overall reduction in nitrogen and phosphorus loads of 25% and 24%, respectively. States are currently working to develop nutrient management plans and reductions strategies to reach this requirement (discussed in Section 3.3).

2.1.2 Mississippi River and Gulf of Mexico

Covering an area of approximately 14,250 km^2 (5,500 mi^2) the hypoxic zone in the Gulf of Mexico is currently the largest hypoxic zone in the United States (Schleifstein, 2013). The hypoxic zone harms the ecosystem as well as commercial and recreational fishing in the Gulf of Mexico. The hypoxic area can largely be attributed to nutrient loads from the Mississippi-Atchafalaya River basin, which has caused algal blooms and subsequent oxygen depletion after die-off (U.S. EPA, 2007a). Studies suggest that climate change will increase impacts of nutrient loads on the hypoxic zone (Jha et al, 2006; Justic et al, 1996). The scientific advisory board (SAB) recommends at least a 45% reduction in total nitrogen and phosphorus load to the river to eliminate the hypoxic zone in the Gulf of Mexico.

Many states within the Mississippi-Atchafalaya River basin are working towards developing nutrient reduction strategies and TMDLs, including BMPs for agricultural areas (discussed in Section 2.3).

2.2 U.S. EPA Water Quality Policies and Programs

The overall goal of the U.S. EPA water quality policies and programs is to help states improve water quality, particularly in regions with impaired water bodies. U.S. EPA is increasing controls on stormwater discharges to impaired bodies of water through NPDES construction activity and Municipal Separate Storm Sewer System (MS4) permits. To start, U.S. EPA is requiring the District of Columbia as part of its NPDES permit renewal to drastically reduce stormwater runoff to the Chesapeake Bay (Shaw and Bell, 2011). Currently, U.S. EPA and some members of Congress are proposing similar restoration efforts in the Gulf of Mexico, Columbia River, San Francisco Bay, Great Lakes, Puget Sounds, and Long Island Sound watershed (Quinlan, 2011). Below is a brief description of the programs U.S. EPA currently has in place to help states, including next steps.

2.2.1 Ecoregions

Ecoregions were developed by U.S. EPA to serve as a spatial framework for assessment and monitoring of ecosystems (Omernik, 1987; Bryce et al., 1999). Ecoregions are areas that have similar geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology. These ecoregions provide structure for collaboration of federal, state, and other agencies to implement ecosystem management strategies and are used for U.S. EPA's ambient water quality criteria recommendations and national nutrient strategy. Ecoregions have been applied for various natural resource assessments, including development of recommended nutrient criteria to water bodies.

2.2.2 National Nutrient Strategy Program

Several national nutrient strategies and programs are in place to provide water quality management guidance, including the following:

National Nutrient Strategy. The National Nutrient Strategy was developed by U.S. EPA in 1998 to help states adopt numeric water quality standards and build scientific and technical knowledge for developing new nutrient criteria through:

- direct assistance;
- identification of state progress;
- construction of a science-based foundation; and
- public education.

Some state programs, including those in connection with Chesapeake Bay and Tennessee streams, have made significant progress in establishing numeric nutrient standards (U.S. EPA, 2007b).

National Water Program. The National Water Program, established to provide safe and reliable sources of water, was developed as a result of the four general themes that were identified (U.S. EPA, 2009). This program has three goals:

- Protect human health with clean, safe water
- Protect and restore aquatic ecosystems at the watershed and local scale
- Protect and restore water quality for the health of aquatic ecosystems

To achieve these goals, the program includes four main areas:

- Drinking water, groundwater, source water, and water security protection programs
- Wastewater management for water quality protection programs
- Wetland, ocean, watershed, and local protection and restoration programs
- Aquatic life and human health protection programs

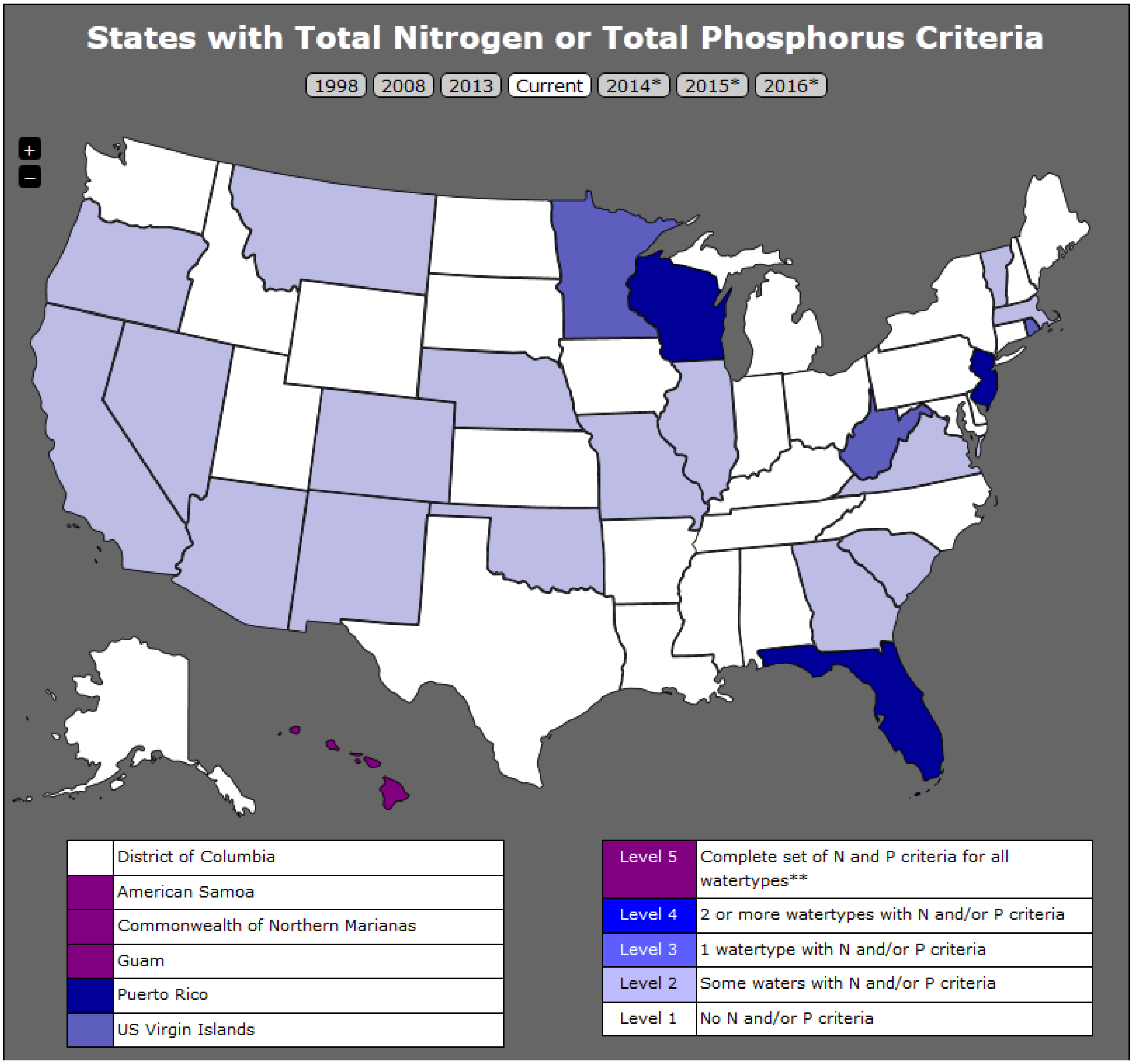
Framework for State Nutrient Reductions. The U.S. EPA issued a comprehensive framework in March 2011 to assist states in reducing nutrient exports (U.S. EPA, 2011). Region-specific and locally appropriate water quality criteria will be developed as the final step of this framework. The framework is intended to be a planning tool to initiate dialogue with states, tribes, and other partners and stakeholders on achieving reduction in nitrogen and phosphorus in the nation's waters, and to develop and implement effective state management strategies. The recommended framework for a state nutrient management strategy includes:

- Prioritize watersheds for nitrogen and phosphorus reductions
- Set reduction goals on a watershed scale based on best available information
- Ensure point source permit efficacy in priority watersheds
- Develop watershed-scale plans to develop conservation practices in agricultural areas
- Create load reduction programs for stormwater and septic systems not covered by MS4 program
- Develop accountability and verification measures
- Provide an annual public report on implementation activities and report load reductions and environmental impacts of each management activity in priority watersheds biannually
- Develop a plan and schedule for numeric criteria development

2.2.3 Ambient Water Quality Criteria Recommendations

As part of the National Nutrient Strategy and the Clean Water Act section 304(a), the U.S. EPA published a series of ecoregional nutrient documents for reservoirs, lakes, rivers, and streams to develop and establish numeric nutrient criteria to reduce and prevent eutrophication at the national scale. There are 14 distinct ecoregions used for national nutrient strategy (U.S. EPA, 2002). Ecoregional nutrient criteria reflect surface waters that are minimally impacted by human activity, and can be used as a baseline to identify areas with impaired water quality, develop state water quality criteria, and evaluate efficacy of projects intended to reduce nutrient load and eutrophication. These criteria are not laws or regulations; they are guidelines for states to use when developing criteria for water quality standards (U.S. EPA, 2000a). The U.S. EPA has published a total of 26 ecoregional nutrient criteria documents: 13 for lakes/reservoirs, 12 for rivers/streams, and 1 for wetland, as well as technical guidance manuals describing methods for determining nutrient conditions in four main water body types; lakes and reservoirs (U.S. EPA, 2000b), rivers and streams (U.S. EPA, 2000c), estuarine and coastal areas (U.S. EPA, 2001), and wetlands (U.S. EPA, 2008). State DOTs should be aware of these ecoregional nutrient criteria and how they may be used by states to develop regulations on stormwater discharges from highways.

Figure 2-1 shows the progress of states towards adopted numeric nutrient criteria. Currently, Hawaii, American Samoa, Commonwealth of Northern Marianas, and Guam have a complete set of nutrient criteria for all water types, Wisconsin, New Jersey, and Puerto Rico have nutrient criteria for 2 or more water types, Florida, Minnesota, West Virginia, and Rhode Island have nutrient criteria for 1 water type, and 16 states and 1 territory have nutrient criteria for some waters.



Source: http://cfpub.epa.gov/wqsits/nnc-development/

Figure 2-1. Current progress of States adopting numeric nutrient criteria.

2.3 State Water Quality Policies and Programs

In addition to the U.S. EPA water quality policies and programs, states have also developed policies and programs for reducing nutrient pollution, often in response to a TMDL. For example, eight (8) states in which DOTs are currently named a stakeholder for nutrient TMDLs include California, Delaware, Florida, Michigan, Minnesota, New York, North Carolina, and Washington. Some issues that have arisen as a result of nutrient TMDLs include (AASHTO, 2011a, Abbasi and Koskelo, 2013):

- heightened design requirements
- inconsistent enforcement

- limited financial resources for successful implementation
- lack of flexibility or availability of BMPs for linear highway applications
- increased methods for compliance demonstration
- increased discussion on responsibility if no demonstrated scientific nexus exists between the load in the DOT discharge of the constituent and the receiving water impairment.

Washington State Department of Ecology (WSDOE) modifies the DOT MS4 permit and/or issues a new administrative order every eighteen months to implement any new, EPA-approved TMDL-related permit requirements for discharges from WSDOT facilities and encourages WSDOT to participate in the TMDL development process (AASHTO, 2011a). For Big Bear Lake, California, where eutrophication has been found to mainly be a result of air pollution and sewage disposal, and Caltrans property is only 0.3% of the watershed, no BMPs are being planned by the agency (Jones, 2013).

The sections below discuss some example state policies and programs that have been developed to limit nutrient pollution.

2.3.1 Nutrient Reduction Strategies and Management Plans

Nutrient Reduction Strategies similar to the National Strategy are being developed by some states (e.g., Kansas, Wisconsin, and Missouri). Kansas adopted a nutrient reduction plan in 2005 that included watershed restoration action plans, over 40 nutrient TMDLs, point source nutrient reductions, agriculture nutrient reductions, funding mechanisms, and a timeline for restoration (Kansas Department of Health and Environment Bureau of Water, 2004; Kansas Department of Health and Environment, 2013). Wisconsin developed a nutrient reduction strategy in response to the action plan outlined by the U.S. EPA (U.S. EPA, 2007b). Wisconsin is using adaptive management and water quality trading to reduce nutrient loads on a 15-year schedule (Wisconsin Department of Natural Resources, 2013). Missouri is currently developing a strategy with over 90 stakeholders (Missouri Department of Natural Resources, 2013). Iowa has a Nutrient Reduction Strategy that focuses on reducing nutrient loads from the state’s largest wastewater treatment plants, in combination with targeted practices to reduce loads from nonpoint sources, prioritize watersheds, and improve the effectiveness of current state programs (Iowa State University, 2012).

Maryland developed an overall TMDL implementation framework that includes plans and operational procedures to reduce excessive pollutants, procedures for off-setting new sources of pollutants, and an anti-degradation policy for protecting high quality waters (Maryland Department of Environment, 2010). The implementation portion addresses geography, types of water bodies, and types of pollutants in addition to TMDL. The Maryland Department of the Environment (MDE) informs responsible parties of TMDLs and notifies state agencies and others, who are encouraged to ensure that their future actions are consistent with the TMDL and strive to routinely incorporate these considerations into their planning, decision-making and budgeting processes. State and local agencies that conduct permit reviews are required to add “TMDL consistency review” to their review checklists.

MDE institutionalizes TMDLs by adjusting permit limits to reflect waste load allocations, and by considering TMDL implementation needs when setting funding priorities through various loan and grant procedures as well as guidance for local governments. Chesapeake Bay TMDL Watershed Implementation Plans (WIPs) establish an accountability framework and Water Resource Elements (WREs) of local land use plans and NPDES Stormwater Permits, which have included a watershed assessment requirement for Phase I jurisdictions that identify opportunities for restoration projects. Maryland State Highway Authority (MDSHA) sometimes partners in these. Recently MDE has begun including in NPDES permits a requirement to develop TMDL Implementation Plans within one year of issuing the permit. Because these plans must be developed for many areas, many pollutants, and in a short period of time, they will likely build upon the previous watershed assessments. Many existing forums are used to coordinate these implementation efforts.

In Virginia, all state agencies are required to have Nutrient Management Plans (NMPs), including Virginia DOT. Nutrient Management Plans (NMPs) are site-specific and used as planning tools to optimize plant uptake of nutrients and minimize impacts of nutrients to water quality (Virginia Joint Legislative Audit and Review Commission, 2005). The Virginia DOT, which is responsible for approximately 300,000 acres of land, proposed to fully implement the NMP and educate personnel on appropriate application levels of fertilizer. The state is also trying to encourage farmers to voluntarily develop and implement NMPs before it becomes a requirement. The Department of Conservation and Recreation has developed a global positioning database to better account for efforts to curb nutrient and sediment loss in addition to providing soil nitrate tests as part of their own nutrient accounting framework.

Virginia has reduced phosphorus in fertilizers statewide and is also encouraging the voluntary adoption of more NMPs by enhancing or augmenting current incentive programs, one of the options suggested by the 2005 Audit (Virginia Joint Legislative Audit and Review Commission, 2005).

2.3.2 Nutrient Trading

Nutrient trading has been explored in North Carolina, Missouri, Oregon, Virginia, and other states. Trading is based on the fact that sources in a watershed can face very different costs to control the same pollutant. Trading programs allow facilities with higher pollution control costs to meet their regulatory obligations by purchasing environmentally equivalent (or superior) pollution reduction credits from another source at lower cost, thus achieving the same or greater water quality improvement at lower overall cost.

Out-of-kind mitigation refers to a mitigation measure that is not directly associated with the negative impact it is intended to address. Off-site mitigation is removed from the source of the impact. These terms are commonly used in reference to mitigation for wetland impacts, where the ability to adequately replace lost functions or acreage on-site and of a similar type can be limited. A challenge for using an out-of-kind approach is to establish a clear path, including standard protocols for measuring either ecosystem services or water quality credits, including measuring the beneficial effect of implementing water quality projects (an approved form of credit exchange/currency). Trading programs must also generate a demonstrable benefit (economic, ecologic, or both). Where state programs support the application and use of water quality credit trading markets, state departments of transportation can build upon this framework to achieve significant efficiencies in water quality mitigation.

A water quality offset occurs where a project proponent implements or finances the implementation of controls for point or nonpoint sources to reduce the levels of pollution for the purpose of creating sufficient assimilative capacity to allow new or expanded discharges. The purpose of water quality offsets is to sufficiently reduce the pollution levels of a water body so that a proponent's actions do not cause or contribute to a violation, but result in a net environmental benefit. Water quality offsets may be used to assist a project in meeting load allocations targeted under a pollution reduction analysis (such as a Total Maximum Daily Load). Successful water quality trading programs include the Chesapeake Bay Basin and the Ohio River Basin. Virginia, North Carolina, California, Oregon, and Washington are leaders in wetland mitigation and conservation banking.

As part of a simulated nutrient trading exercise which is part of the Missouri Innovative Nutrient Trading project (MINT), Geosyntec and ERC (2013) evaluated economic and regulatory factors that could influence the environmental and economic benefits associated with trading in Missouri. The project developed a comprehensive guide that provides a clear understanding of nutrient sources and loading as well as control. The MINT project research showed that many factors were involved, including land use, geographic location, soils, and precipitation.

2.3.3 State Water Quality Laws

Various states have enacted laws to control sources of nutrients, particularly with regards to fertilizer use and commercially available products containing phosphorus (Table 2-1).

Table 2-1. States with laws limiting nutrient use.

Law	Banned P in Dishwashing Detergent	Bannned P Fertilizer Use or Sale
States	Illinois, Indiana, Maryland, Massachusetts, Michigan, Minnesota, Montana, New Hampshire, Ohio, Oregon, Pennsylvania, Utah, Vermont, Virginia, Washington, Wisconsin	Illinois, Maine, Maryland, Michigan, Minnesota, New Jersey, New York, Vermont, Virginia, Washington, Wisconsin

In 2010, phosphorus in dishwashing detergent was banned in 16 states (Table 2-1). In Minnesota, prior to the dishwashing detergent ban, approximately 1.9% of the total phosphorus loading was from residential dishwashing detergent for an average flow water year (Barr Engineering Company, 2004). Before that, in 1994, the laundry detergent industry voluntarily agreed to remove phosphates from their products because the number of states with P laundry detergent bans was high enough it became cost-effective for them to do so, so P is no longer found in any legal laundry detergents in any state. (Litke, 1999).

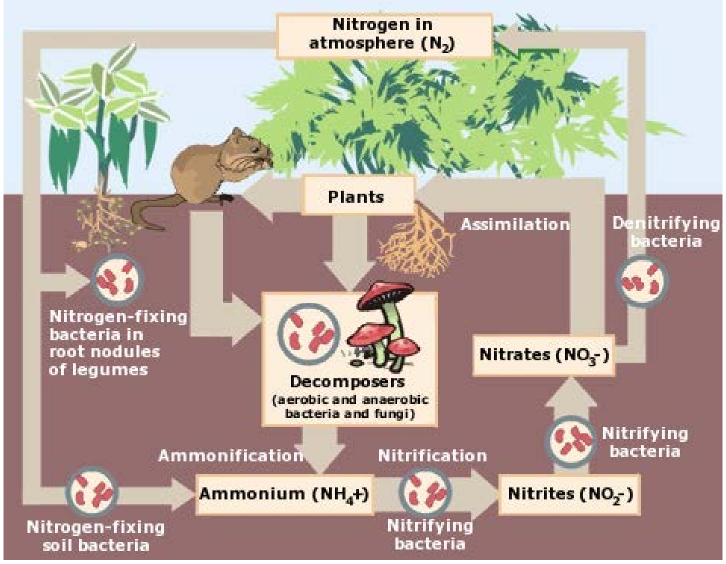
As of 2012, 11 states ban phosphorus fertilizer use or sale (Miller, 2012), which mostly affects yard maintenance for homeowners and renters. In general, agricultural uses, commercial or sod farms, gardening, and golf courses are exempt, and fertilizer can be used by property owners if plants are stressed due to lack of phosphorus or establishing/repairing turf. Florida restricts fertilizer use and bans fertilizer application during specific time periods in nutrient-impaired watersheds (agricultural use is exempt).

Many local and state governments have made a concerted effort to limit residential fertilizer use (e.g., Maryland and Florida). DOTs have undertaken training of staff that will be applying fertilizer, or require such training of contractors. For example, Maryland’s Fertilizer Use Act of 2011 required that by October 1, 2013, more than 1,500 urban land managers statewide be trained and certified by Maryland Department of Agriculture (MDA) before they can apply nutrients to non-agricultural properties. In addition, both lawn care professionals and private residents will be required to obey fertilizer application restrictions, observe fertilizer blackout dates, employ best management practices, and follow University of Maryland recommendations when fertilizing lawns (Maryland Department of Agriculture, 2013). In Florida by January 2014, all personnel applying fertilizer will be trained and certified through the Green Industry (GI) BMP Program. Florida DOT is also implementing requirements that any contracts for fertilizer application use only commercial applicators of fertilizer who have been trained through the GI-BMP Program and have obtained a limited certification for urban landscape commercial fertilizer application under Florida state statute (Florida DOT, 2012).

3.0 Nutrients in the Environment

Nutrients are chemical compounds containing elements that are required by all living organisms. Many nutrients are needed by organisms in relatively small quantities including Magnesium (Mg), Calcium (Ca), Iron (Fe), Zinc (Zn), and Manganese (Mn), among other trace elements, readily available in the environment. However, compounds containing nitrogen and phosphorus are often limited in water bodies. Therefore, these two nutrients, either individually or in tandem, often control the productivity of aquatic ecosystems. Thus, in the field of water resources management the term nutrient commonly refers to nitrogen and phosphorus containing compounds.

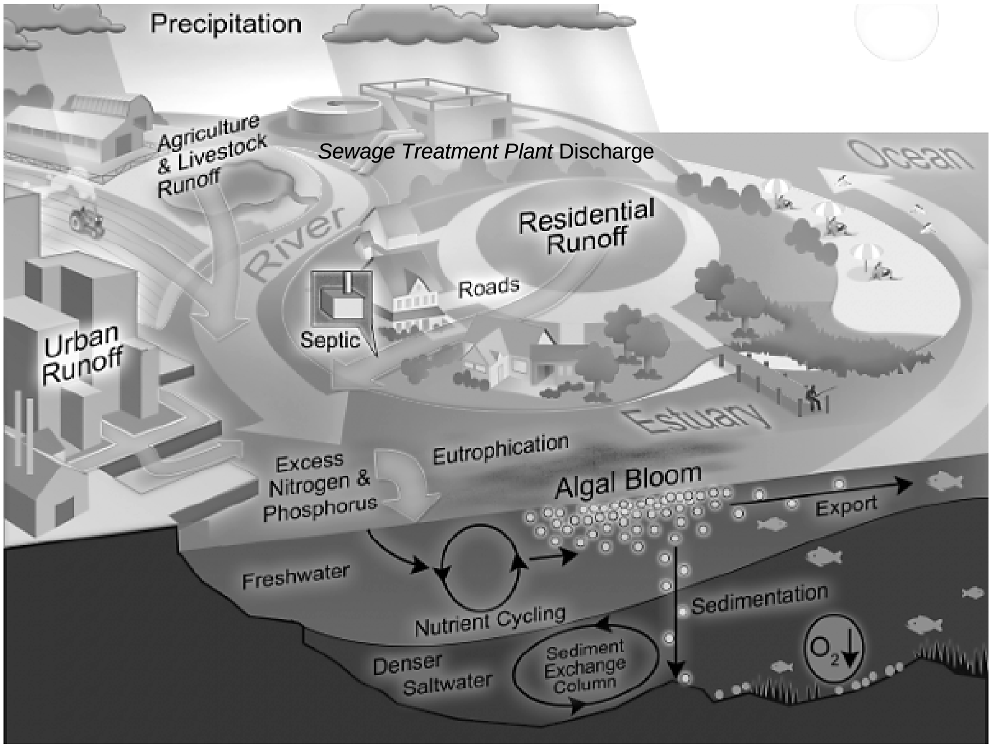
Nutrients cycle between molecular form (i.e., N_2), organically bound forms (e.g., plant and animal tissue, leaf litter etc.) and inorganic forms such as orthophosphate or nitrate that are generated by the decomposition of organic matter by microbes or generated from mineral or chemical sources. Figure 3-1 depicts a simplified version of the nitrogen cycle where nitrogen is recycled through the environment via "natural" pathways. Many natural processes and pathways facilitate the cycling of nutrients throughout the environment, including the uptake and assimilation of nutrients by plants and animals, and the subsequent decomposition of living things by bacteria and fungi.



Source: U.S. EPA. http://www.epa.gov/caddis/ssr_amm_nitrogen_cycle_popup.html.
Figure 3-1. Simplified illustration of the nitrogen cycle.

In addition to natural pathways, nutrient cycling through the environment can include pathways significantly influenced by human activities. For example, manmade stormwater drainage features or wastewater discharges can provide pathways for large masses of nutrients to reach water bodies in a relatively short period of time.

Nutrients associated with anthropogenic activities may be directly or diffusely discharged to waterways. An example of a direct discharge (termed point source) is a municipal wastewater treatment plant. Point sources can be a major manmade source of nutrients to water bodies if nutrients are not removed through treatment. However, in many lakes, rivers, and streams, a significant portion of nutrients from manmade sources are transported along more diffuse pathways. Diffuse inputs are termed 'nonpoint' sources and include such pathways as surface runoff from urban and agricultural areas, subsurface seepage from drainage tiles or conveyance lines, leaking septic systems, atmospheric deposition, and precipitation. Figure 3-2 depicts several common nutrient sources and transport pathways.



Source: Modified from Paerl et al., 2006.
Figure 3-2. Common nutrient sources, transport pathways, and effects.

All ecosystems and surface waters require nutrients to support life, but the introduction of excessive nutrients to an ecosystem can cause various problems such as toxicity (e.g., from ammonia) and eutrophication. Eutrophication is the process whereby lakes, streams, and rivers accumulate and process nutrients and sediment (Wetzel, 2001). Under natural conditions, this process occurs very slowly, however, when nutrients are introduced at an escalated rate, eutrophication can greatly accelerate and waterways can become over-enriched much sooner than would otherwise occur naturally. Waters suffering from anthropogenic over-enrichment are at greater risk of harmful or unsightly algal blooms, impairment of aquatic life uses, and reduced aesthetics (U.S. EPA, 2000b). The U.S. EPA realizes these risks, recognizing more than 6,000 waters in the U.S. as impaired due to excessive nutrient inputs (U.S. EPA, 2013a).

Impacts to surface waters in rural areas are often caused by agricultural runoff, which can be very high in nutrients. In comparison to agricultural runoff, waterways near more urbanized areas are more likely to be influenced by point sources (e.g., wastewater treatment plant discharges), leaky septic systems, combined sewer overflows, and urban stormwater. Nutrients in urban stormwater have been linked to numerous aquatic life impairments (U.S. EPA, 2013a). Nutrient contributions from DOT facilities are frequently categorized as either point sources or urban stormwater in regulatory contexts, including watershed management plans and Total Maximum Daily Loads (TMDLs). Such categorization arises from the fact that many facilities and roadways managed by DOTs in urban areas are permitted under the Municipal Separate Storm Sewer Systems (MS4) program. However, DOTs differ from most other MS4 permittees (e.g., cities and towns) in the following ways:

- Roadways that span several miles will cross a diverse set of waterways, watersheds, land uses, and administrative jurisdictions;

- Stormwater conveyance systems are likely to transmit pollutants (i.e., nutrients) from a diverse set of sources that are generated beyond the transportation right-of-way;
- Transportation systems serve a transient population; and
- Implementation and enforcement of ordinances is challenged by limited authority and the logistics of transient populations.

Realistic consideration of these differences is critical to the success of nutrient management in a highway setting. A broad discussion of nutrient sources and common forms in the environment is provided in Section 3.1 to inform a comprehensive view of potential nutrient risks in and around highways and other DOT facilities. Eutrophication risks and treatment of nutrients is influenced by several factors including nutrient fate and transport mechanisms, which are discussed in Section 3.2.

3.1 Nutrient Sources and Forms

3.1.1 Sources

Nitrogen and phosphorus containing compounds can be found throughout the environment as these nutrients cycle through the air, water, soil as well as plant and animal biomass. For this reason, background concentrations of nutrients are expected in stormwater runoff from any land use or cover type. Activities to support a growing human population have increased the number of pathways and the rate at which nutrient inputs can enter fresh and saltwater systems. Because nutrients are ubiquitous and continually cycle throughout the environment, defining the nutrient's *source*, i.e. its point of origin, is dependent upon context and setting, as both N and P are elements and are not created or destroyed. The source, then, in this context, does not refer to where N or P were created, but rather the place and form they took in order to become pollutants in stormwater. In the context of pollution control, a source of nutrients refers to the point in time and space (i.e. setting) where a management action might be applied to control the chemical form and transport of nitrogen and phosphorus. A nutrient source is further defined by the name of the object or product containing nitrogen and/or phosphorus at the time and setting a management action is proposed. For example, in an agricultural setting, farm managers may elect to control nutrient pollution by ensuring that chemical fertilizers are applied at agronomic rates to maximum crop uptake and growth. In this context the chemical fertilizer is identified as the nutrient source since a management action is controlling its application. As another example, a phosphate mining facility and fertilizer manufacturer are not identified as a nutrient source because a management action is not applied to control the production of fertilizer. It is important to note that the definition of a nutrient source is context sensitive and, hence, there is no universally accepted listing as to whether a nutrient containing compound qualifies as a source.

Human activities associated with nutrient over-enrichment include agricultural and urban/residential fertilization, manure application, treated sewage effluent, detergents, septic systems, combined sewer overflows, sediment mobilization, animal waste, flame-retardants, lubricants, corrosion inhibitors, and plasticizers (Leisenring et al., 2010). Human activities can also affect natural processes such as atmospheric deposition (e.g., fuel combustion resulting in NOx emissions), internal nutrient recycling from sediment and detritus, and stream channel erosion.

For the purposes of regulatory convenience, nutrient sources are sometimes described along with the predominant transport mechanism. For example, 'urban stormwater' is not a nutrient source per se, but rather a suite of sources (e.g., lawn fertilizers, pet and wildlife waste, leaf litter, etc.) mobilized by surface runoff processes in response to a precipitation event. An informed distinction between the source and transport mechanism is needed to effectively develop source control and pollution reduction strategies (NRC, 2000). Table 3-1 lists nutrient sources in agricultural, urban, highway (subset of urban), and undeveloped settings. Note that there are many sources of nutrients that discharge to surface waters that have nothing to do with highway runoff (e.g., WWTP discharges, leaching from septic systems, animal waste, fertilizers, agricultural runoff, etc.). In addition, highways and highway drainage systems often receive inputs (i.e., runoff and deposition) from many of these land uses and thus many nutrient sources in Table 3-1 could contribute to the load observed in highway runoff, even though the highway was not the source. Specific sources in highway runoff include soil erosion from highway construction activities, traction and deicing materials, fertilizers applied within the right of way, and plant litter from the right of way.

Table 3-1. Potential or known nutrient sources in agriculture, urban, DOT, and undeveloped settings.

Land Use	Nutrient Source	Description
Agriculture	Chemical Fertilizers	Excess nutrients are lost through volatilization, surface runoff, leaching to groundwater, or subsurface drainage. Phosphorus, which binds to the soil, is generally lost through soil erosion from agricultural lands.
	Livestock Manure	Animal production is intensifying, and the density of animals in livestock operations is increasing, causing large amounts of manure in concentrated areas. The manure is typically captured in lagoons or dried/composted before being applied to crops and pastures as fertilizer.
	Aquaculture Wastes	Marine fish and shrimp farming often occur in net pens or cages situated in enclosed bays. These farms generate concentrated amounts of nitrogen and phosphorus from excrement, uneaten food, and other organic waste.
	Excessive Soil Erosion	Underprotected cropland and eroded streambanks facilitate nutrient transport, particularly phosphorus bound to soil particles.
Urban or Developed (* Potential contributor to nutrients in highway runoff)	Lawn Fertilizers	Excess nutrients are primarily lost through surface runoff, leaching to groundwater, or subsurface conveyance lines.
	Plant Stabilization Fertilizers*	Fast and slow release chemical fertilizers that promote or maintain road and streamside plant communities for erosion control and are delivered to receiving waters through surface runoff processes.
	Detergents	High-phosphorus cleaning detergents are discharged to sanitary wastewater lines and contribute to increased influent loads at wastewater treatment facilities.
	Human Waste	Nitrogen and phosphorus in human waste may be delivered to waterways following treatment at wastewater reclamation facilities, discharged from combined sewer overflows, leaked from failing septic tanks, or lost as exfiltration from wastewater conveyance lines.
	Pet Waste	Organically bound nutrients are primarily transported through surface runoff or subsurface conveyance lines.
	Attracted Wildlife*	Some urbanized setting concentrate or attract wildlife such as deer and birds resulting in concentrated nutrient loads from wildlife wastes. Organically bound nutrients are primarily lost through surface runoff or subsurface conveyance lines.
	Fossil Fuels*	When fossil fuels are burned, they release nitrogen oxides (NOx) into the atmosphere. NOx contributes to the formation of smog and acid rain. NOx is re-deposited to land and water through rain and snow (wet deposition), or can settle out of the air (dry deposition). Coal-fired power plants and exhaust from cars, buses, and trucks are primary sources of NOx.
	Machine Lubricants*	Ammonium phosphates and other nutrient chemistries in lubricants are primarily delivered through surface runoff processes.
	Construction Materials*	Consideration of nutrient content of base, fill, or other construction materials such as the use of phosphogypsum as a base material.
	Traction/Deicing Compounds*	Corrosion inhibitors, biologically-based compounds, functional groups, or urea delivered through runoff and snowmelt processes.
	Land Disturbance and Streambank Erosion*	Sediment bound phosphorus transported during or as the result of road and facility construction via surface runoff processes.
	Herbicides and Pesticides*	Degradation of some herbicides such as glyphosate to bioavailable phosphates.

	Leaf and Grass Litter*	Organically bound nutrients from mowing, brush clearing, or other landscaping activities. Transported via surface runoff or direct fall.
Undeveloped	Fish and Wildlife Wastes	Organically bound nutrients from fish and wildlife wastes transported via surface runoff processes.
	Minerals	Dissolution of phosphorus in soil and geologic materials such as apatite and organic acids. Leached through soil horizon towards stream network or erosion of stream banks.
	Plant Litter	Organically bound nutrients made bioavailable through microbial decomposition. Transported via surface runoff, groundwater seeps, or direct fall.
	Wildfires and Land Disturbance	Release of bioavailable nutrients from incineration of plant and animal nutrient stores. Transported by surface runoff.

Sources: Barrett et al. (1995), Millennium Ecosystem Assessment (2005), NITG (2009), Strain and Hargave (2005), World Resources Institute (2013) at: http://www.wri.org/project/eutrophication/about/sources#agriculture

The majority of nutrient loads in runoff are from fertilizer application in agricultural or residential land uses. According to the Virginia Department of Conservation and Recreation (VA DCR) 2002 Biennial Nonpoint Source Pollution Water Quality Assessment Report, a state watershed model indicates that about 70 percent of the state's total nonpoint source nitrogen load and 60 percent of the state's total nonpoint source phosphorus loads come from agricultural land uses (Virginia Joint Legislative Audit and Review Commission, 2005). In Maryland, an overall model of nutrient loading to the Chesapeake Bay showed that lawn fertilizer is a considerable problem and that considerable excess is applied (Maryland Department of Agriculture, 2013). Overall, nutrient loading from DOTs has been found to be a small fraction of total nutrient loads to receiving waters. A 2004 study conducted in Minnesota indicated that, on average, 1.1% of all total phosphorus loading (including both point and nonpoint sources) to state receiving waters is from roadway and sidewalk deicing and the majority (29%) is from agriculture (crop and pasture runoff, agriculture tile drainage and feedlots). Urban runoff and non-agricultural runoff accounted for 4.8% and 5.7%, respectively. (Barr Engineering Company, 2004).

3.1.2 Forms

Nitrogen. Nitrogen is present in runoff and natural waters in one or more forms, depending on the source and the environmental conditions. Common forms include organic nitrogen, which can be either dissolved or particulate, and the inorganic ions ammonium/ammonia (NH_4^+/NH_3), nitrite (NO_2), and nitrate (NO_3). The nitrogen cycle is a series of biologically-catalyzed reactions by which one form of nitrogen is transformed into another (USGS, 2010). Nitrite (NO_2) is a short-lived intermediate state, whereas nitrate (NO_3) tends to be more mobile and persistent (WERF, 2005). The dominant forms of nitrogen found in typical highway stormwater can generally be characterized as (listed from highest concentration to lowest concentration):

- Nitrogenous organic solids
- Nitrate (NO_3)
- Ammonia/Ammonium (NH_3/NH_4^+)
- Nitrite (NO_2)

Nitrate is readily available for biological uptake and, when present with sufficient amounts of phosphorus, which is often the case for estuaries and coastal environments, can cause eutrophication. Ammonia is of concern due to its fairly rapid transformation to nitrate, but also because it can be toxic to some aquatic species at relatively low concentrations. Although nitrate and ammonia in typical stormwater runoff are generally below applicable drinking water and aquatic toxicity standards, respectively, U.S. EPA nutrient criteria may result in a total nitrogen limit for stormwater discharges to levels below those often found in urban runoff, perhaps even after implementation of effective source controls.

Phosphorus. Phosphorus occurs in natural waters almost solely as phosphates. These are classified as orthophosphates (OP), condensed phosphates (pyro-, meta-, and other polyphosphates), and organically-bound phosphates. The vast majority of dissolved phosphorus occurs as orthosphosphate. Orthophosphates also exist in solution, bound to particles or detritus, or in the bodies of aquatic organisms. In rainfall-runoff, the predominant (> 30%) phosphate forms are HPO_4^{2-} and $H_2PO_4^-$ and to a lesser degree (10%) $MgHPO_4$(aq) and $CaHPO_4$(aq) (WERF, 2005). Inorganic phosphorus forms in soils are typically composed of hydrous sesquioxides, amorphous and crystalline Al and Fe compounds in acidic, noncalcareous soils and by Ca compounds in alkaline, calcareous soils. Organic P forms in soils include relatively labile phospholipids and fulvic acids.

In laboratory analysis, total phosphorus is usually first separated into dissolved and particulate portions. The dissolved portion is then typically divided into soluble reactive phosphorus (SRP) and soluble unreactive phosphorus (SUP). SRP is primarily composed of inorganic orthophosphates and is readily available for plants, algae, and microorganisms. SUP is primarily composed of polyphosphates and various organic compounds. Particulate phosphorus is primarily composed of bacteria, algae, detritus, zooplankton, and inorganic particulates such as silt and clay. Organic particulate phosphorus in water can be broken down and eventually converted to orthophosphates by bacteria (Tchobanoglous and Schroeder, 1985).

Because phosphorus is typically the limiting nutrient in most freshwater systems, stormwater discharge of phosphorus, especially SRP, has the potential to cause significant water quality impairment to receiving waters. Most dissolved phosphorus is readily bioavailable. Among particulate-bound forms of phosphorus, some forms are more readily converted to bioavailable forms. Generally, as complexity (molecular weight) of forms increases, phosphorus species become less readily bioavailable (WERF, 2005).

3.2 Fate and Transport Mechanisms

3.2.1 Nitrogen

The fate and transport of N can be considered a dynamic interplay between the anthropogenic and natural sources and sinks of N, transport mechanisms, and the biogeochemical processes of the N-cycle (Atlas and Bartha, 1993).

The Nitrogen Cycle. The major processes in the N-cycle include fixation, nitrification, denitrification, and ammonification (Figure 3-1). Each of these is described in Table 3-2 below. The biochemical reactions for each of these processes are mediated or facilitated primarily by microbial taxa including bacteria, archaea, and fungi. Although immobilization via conversion of ammonia and nitrate to organic N via microbes, and plant uptake are not included in Table 3-2, they are also important parts of the N-cycle.

Table 3-2. Major biological/chemical processes in the nitrogen cycle.

Process	Simplified Reactions	Requirements	Description
Fixation	$N_2 + 8\,H^+ + 8\,e^- \Rightarrow 2NH_3 + H_2$	Microbes or legumes with nitrogenase enzyme, typically low O_2 environments	Converts gaseous N_2 into biologically available ammonia
Nitrification	$NH_3 + O_2 + 2H^+ + 2e^- \Rightarrow NH_2OH + H_2O$ $NH_2OH + H_2O \Rightarrow NO_2{}^- + 5H^+ + 4\,e^-$ $NO_2{}^- + \frac{1}{2}\,O_2 \Rightarrow NO_3{}^-$	Microbes with ammonia monooxygenase, hydroxylamine oxidoreductase enzmes, O_2	Converts ammonia to nitrite and then to nitrate
Denitrification	$2NO_3^- + 10e^- + 12H^+ \Rightarrow N_2 + 6\,H_2O$	Denitrifying bacteria, anoxic conditions	Converts nitrate into N_2
Ammonification	$R - NH_2 + H_2O \Rightarrow NH_3 + R - OH$	Microbes with synthetase, 2-oxoglutarate aminotransferase, dehydrogenase enzymes	Converts organic N in organic matter into ammonia/ammonium

Nitrogen Transport Processes. Nitrogen is principally transported at the catchment scale by four physical processes (Follet, 1995) listed in Table 3-3 below.

Table 3-3. Major transport processes for nitrogen.

Process	Description and Importance
Surface Runoff	Runoff of N is influenced by the amount and timing of rainfall, soil properties, and the timing and type of fertilizer application. Nitrogen that degrades surface water is primarily transported in soil organic matter, as ammonia in fertilizer runoff or untreated sewage, and as nitrate in runoff or interflow.
Soil Erosion	Erosion is important to the movement of N in surface waters. A portion of the N as ammonium (NH4+) is sorbed to the negatively charged surfaces of clays and finer sediments or to the soil organic matter as organic-N forms.
Leaching	Nitrate is negatively charged, is repelled by negatively charged clay minerals, and is therefore very soluble and susceptible to leaching into and through the vadose zone. Nitrate is also a very stable and requires anaerobic conditions to denitrify. For these reasons, nitrate is the primary form of N leached into groundwater (Jury and Nielson, 1989).

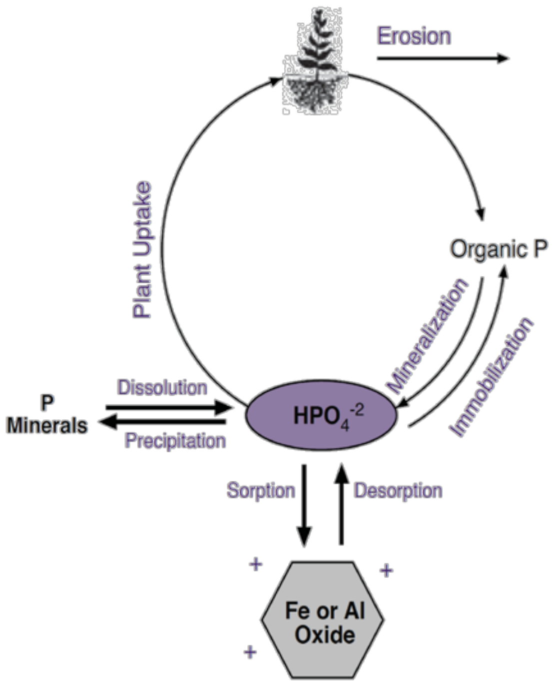
Process	Description and Importance
Atmospheric Deposition	Deposition of nitrogen has been recognized as a major factor in the over-fertilization of forest ecosystems in the northeast United States and eutrophication to larger water bodies including the Gulf of Mexico (Lawrence et al., 1999). Atmospheric nitrogen can be transported and deposited in precipitation (wet deposition) or dry deposition (attached to particles or as vapor) in the forms of nitrate, ammonium, and nitric acid vapor. The numerous atmospheric reactions responsible for N deposition are beyond the scope of this review. However, additional information can be obtained from the National Atmospheric Deposition Program at http://nadp.sws.uiuc.edu/.

3.2.2 Phosphorus

As with nitrogen, phosphorus (P) is an essential element for plant growth and amendments as fertilizers are often needed to achieve optimum agricultural crop yields and residential lawn maintenance. The fate and transport of P can be considered a dynamic interplay between the anthropogenic and natural sources and sinks of P, transport mechanisms, and the biogeochemical processes of the P-cycle.

The Phosphorus Cycle. The major processes in the P-cycle include mineralization, immobilization, sorption to solids, dissolution of P minerals, and biotic uptake by terrestrial and aquatic vegetation (Figure 3). Organic P is converted to inorganic phosphate through the process of mineralization as mediated by various microbial taxa. Primary organic P forms subject to mineralization include phytin, nucleic acids, and phospholipids. Immobilization is the reverse of mineralization where microbes convert inorganic P forms to organic phosphate as microbial biomass (Atlas and Bartha, 1993). The rates of mineralization and immobilization reactions are affected by temperature, moisture, and oxygen levels. Phosphorus-containing minerals, such as apatite, are slowly dissolved through weathering processes termed dissolution that contributes to bioavailable dissolved phosphate. In neutral-to-calcareous soils, P retention is dominated by precipitation reactions (Lindsay et al., 1989), although P can also be sorbed to surface of calcium carbonate and clay minerals. Phosphate can precipitate with calcium (Ca), generating dicalcium phosphate (DCP) that is available to plants.

Factors affecting plant uptake of P from any source, soil or fertilizer include temperature, soil moisture, oxygen, clay content or composition, and pH. When soil temperatures are low during early plant growth, P uptake is reduced. Soil compaction reduces pore space and consequently water and oxygen, which in turn reduces P uptake. Soil pH greatly affects the availability of P to plants, with P being tied up by Ca at high pH and by Fe and aluminum (Al) at low pH (Figure 3). Soils with high clay content tend to fix (adsorb) more P than sandy soils with a low clay content.



Source: Extracted from Jones and Jacobsen (2005)
Figure 3-3. Simplified illustration of the phosphorus cycle.

Phosphorus Transport Processes. Phosphorus can be transported in either dissolved or particulate (attached to soil or incorporated into biomass) form. P in developed land uses is primarily transported in the particulate form due to the large number of eroded soil particles and organic material. P in runoff from grass or forest land carries little sediment because it causes less erosion and more particles are filtered. Therefore, P is generally present primarily in the dissolved form in runoff from grass or forest land. Leaching of P is typically low because of sorption of P to unsaturated subsoils. However, organic matter in peat and acidic soils may facilitate leaching of P in association with organic acids (Miller, 1979).

3.3 Highway Contribution Analysis

Sources of nitrogen in highway runoff include atmospheric deposition (contributed from vehicle exhaust, factory emissions, and natural sources), roadside fertilizer, sediment, plant material, compost, animal feces, deicing materials, petroleum products, motor oil, and detergents in gasoline (U.S. EPA, 1995; Irish et al., 1998; Yonge et al., 2002; Havlik, 2013). Potential sources of phosphorus in highway runoff include road sanding materials, roadside fertilizer, sediment, animal feces, plant material, compost, deicing materials, crumb rubber asphalt, petroleum products, motor oil, and detergents in gasoline (Smith & Granato, 2010; U.S. EPA, 1995; Irish et al., 1998, Yonge et al., 2002; Havlik, 2013). Sources of nutrients can vary by location. For example, the largest source of nitrate is likely from atmospheric deposition, particularly in the northeast due to a higher fossil fuel combustion and fertilizer use in this region (U.S. EPA, 2012) with as much as 70-90% of nitrate loading originating from bulk precipitation (Wu et al., 1998). A USGS study found that road sanding materials were, by far, the most important source of phosphorus in highway runoff in Massachusetts (Smith & Granato, 2010). Barrett et al. (1998) concluded that highway stormwater runoff in Texas likely has a small negative impact on receiving waters. While the impact of highway runoff alone is generally insignificant, degradation of water quality may result when highway runoff is combined with other sources of pollution, such as agricultural and urban (municipal) runoff.

Table 3-4 indicates which nutrient sources are controllable, and located within the highway right-of-way. Both runoff from surrounding land uses and transportation-related sources are included. To limit nutrients in highway runoff, DOTs will need to focus on sources that can be controlled and are located within the highway right-of-way (ROW).

Source control should be focused on roadside management, where DOTs have the ability to control roadside fertilizer application and sediment loading from roadside erosion and construction. Increased pet waste control could include human-behavior modifying measures, such as increased pet waste bags and signage, and education on pet waste contamination issues. A larger, costlier action to reduce roadside deposition of pet waste includes increasing rest stops along the highway, which may be feasible as part of a new or retrofit project to serve other DOT functions. Some sources, including sediment, wildlife waste, and plant material, come from both the highway right-of-way and as runoff from other land uses. Wildlife waste can be partially controllable by constructing wildlife crossings and installing bird roosting exclusion devices on overpasses. Atmospheric deposition, petroleum products, motor oil and gasoline detergents are not controllable at the DOT level; control at the national level through incentives and regulations are necessary to decrease nutrients from these sources. Agricultural runoff may be partially controlled where highway conveyance systems can be designed to minimize the co-mingling of highway runoff with runoff from adjacent land uses. However, while preventing co-mingling reduces the regulatory burden for the DOT, it does not reduce the load to the receiving water. Ultimately, source control should be evaluated on the watershed scale to control runoff from agricultural or urban areas. While DOTs can collaborate on watershed-scale planning and control efforts (Section 6.7), source control from other land uses is generally the responsibility of municipalities or counties who develop stormwater and land-use policy and guidelines as required in their NPDES permits. Source control BMPs for DOT projects are discussed in Section 6.2.

Table 3-4. Controllability of nutrient sources.

Source	Controllable	Partially Controllable	Not Controllable	Located Within the ROW	Located Outside the ROW	Located Within and Outside the ROW
Atmospheric Deposition			X			X
Roadside Fertilizer	X			X		
Sediment		X				X
Pet Waste		X		X		
Wildlife Waste		X				X
Plant Material (including leaf litter)		X				X
Roadside Compost	X			X		
Road Sanding	X			X		
Deicing Materials	X			X		
Crumb Rubber Asphalt	X			X		
Petroleum Products			X	X		
Motor Oil			X	X		
Detergents in Gasoline			X	X		
Agriculture Runoff		X			X	
Urban or Developed Runoff	X				X	
Wildfires and Land Disturbance Runoff			X		X	

Sources in bold= sources that are at least partially controllable and partially located within the ROW.

3.3.1 Runoff Concentrations

Table 3-5 shows typical ranges of event mean concentrations (EMCs) from urban and non-urban highways. These studies are representative of different regions across the United States.

Table 3-5. Typical range of mean pollutant concentrations from urban and non-urban highways.

Source	Reference	Pollutant (mg/L)				
		NH_3-N	NO_3-N	OP	TKN	TP
Non-urban Highway (AADT<30,000)	Kayhanian et al., 2003	2.3	0.6	0.1	2.0	0.2
	Kayhanian et al., 2007	--	0.6	0.1	1.5	0.2
	Driscoll et al., 1990[1]	--	0.46	0.16	0.87	--
	Barrett et al., 1998[1]	--	0.71	--	--	0.11
	Wu et al., 1998[1]	0.42-0.66	0.08-0.38	0.08-0.16	0.95-1.02	0.20-0.37
Urban Highway (AADT>30,000)	Kayhanian et al., 2003	1.0	1.1	0.1	2.1	0.3
	Kayhanian et al., 2007	--	0.8-1.6	0.1	2.1-2.5	0.3
	Driscoll et al., 1990[1]	--	0.76	0.40	1.83	--
	Barrett et al., 1998[1]	--	0.37-1.07	--	--	0.10-0.33
	Flint, 2004[1]	--	0.67	--	2.5	0.46
	Smith & Granato, 2010[1]	--	--	--	--	0.11
Highway (Western Washington)	Herrera, 2007	1.84	0.51-3.0	0.01-0.42	0.38-3.4	0.03-0.57

[1]Reported as median of EMCs

As shown in Table 3-5, pollutant concentrations in highway runoff are relatively consistent in magnitude across studies, indicating that runoff directly generated from transportation activities is very similar across the country.

Many studies have shown that highway sources of nutrients are small compared to non-highway sources (Driscoll et al., 1990; Gupta et al., 1981; Kayhanian et al., 2007; Barrett et al., 1998). In a Washington State Department of Transportation (WSDOT) study, Herrera (2007) identified the primary sources of nutrients in highway runoff as atmospheric deposition and agricultural fertilizer application, and concluded that elevated nutrient concentrations in highway runoff are likely a result of loading from surrounding land uses. Similarly, an FHWA study conducted by Driscoll et al. (1990) found nutrient loading from highways to be lower than loading from urban and agricultural runoff (Table 3-6). Lower nutrient concentrations in highway runoff are likely due to both the lower nutrient loading and the small percentage of the total watershed area that is occupied by highways.

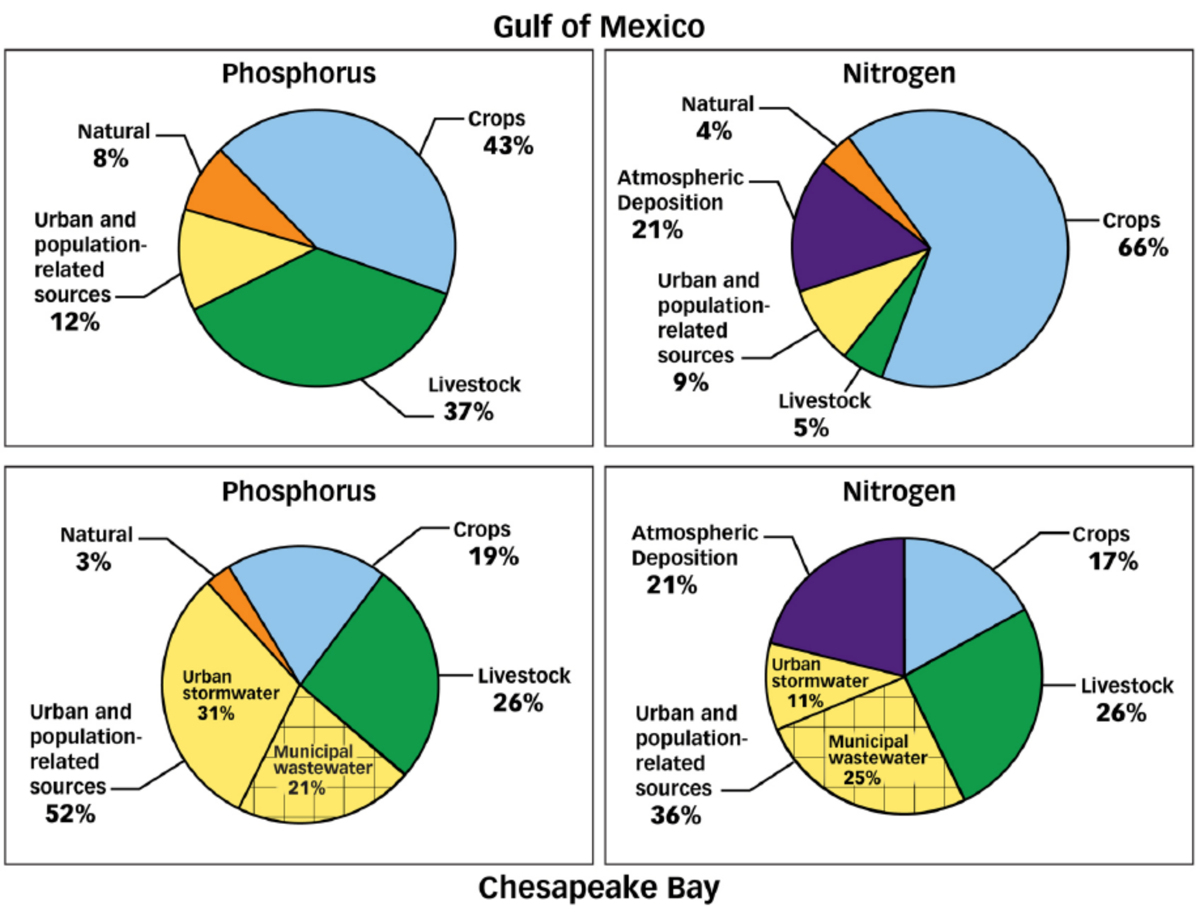
Table 3-6. Representative runoff concentrations for different land uses.

Pollutant	Representative Runoff Concentration (mg/L)			
	Highways		Runoff from other Anthropogenic Sources	
	Rural	Urban	Urban	Agricultural
OP	0.16	0.40	0.33	0.80
NO_3-N	0.46	0.76	0.70	3.00

Source: Driscoll et al. (1990).

Surrounding land uses have a significant impact on highway runoff quality. Highway runoff may combine with runoff from other land uses that contain very high levels of nutrients such as agricultural or urban areas, which can increase the overall nutrient concentrations in runoff. In a study conducted in California (Kayhanian et al., 2007), runoff from highways in agricultural areas had significantly higher concentrations of TP, TKN, and OP ($p<0.05$). TP and TKN were also significantly higher in commercial areas ($p<0.05$). Barrett et al. (1998) observed that pollutants, including nutrients, were highest at sites with urban land use contributing to runoff. This study found that highway runoff characteristics were generally similar to urban runoff characteristics, indicating that the same types of stormwater treatment systems and controls used to treat urban runoff can be used for highway runoff. Runoff control BMPs for DOT projects are discussed in Section 5.3.

While human activity remains the largest overall cause of nutrient pollution to receiving waters throughout the U.S., the importance of individual land uses as nutrient sources varies regionally. For example, the most important nutrient sources for the Gulf of Mexico appear to be agriculture (crops and livestock); however, the most important sources in the Chesapeake Bay are agriculture, municipal wastewater, and urban stormwater (Figure 3-4). A comparison between the two watersheds indicates that crops and livestock dominate the phosphorus (70 percent) and nitrogen (71 percent) sources in the Gulf of Mexico. Phosphorus and nitrogen sources in the Chesapeake Bay are relatively evenly split between agricultural (crops and livestock) and urban (municipal wastewater and urban stormwater) sources.



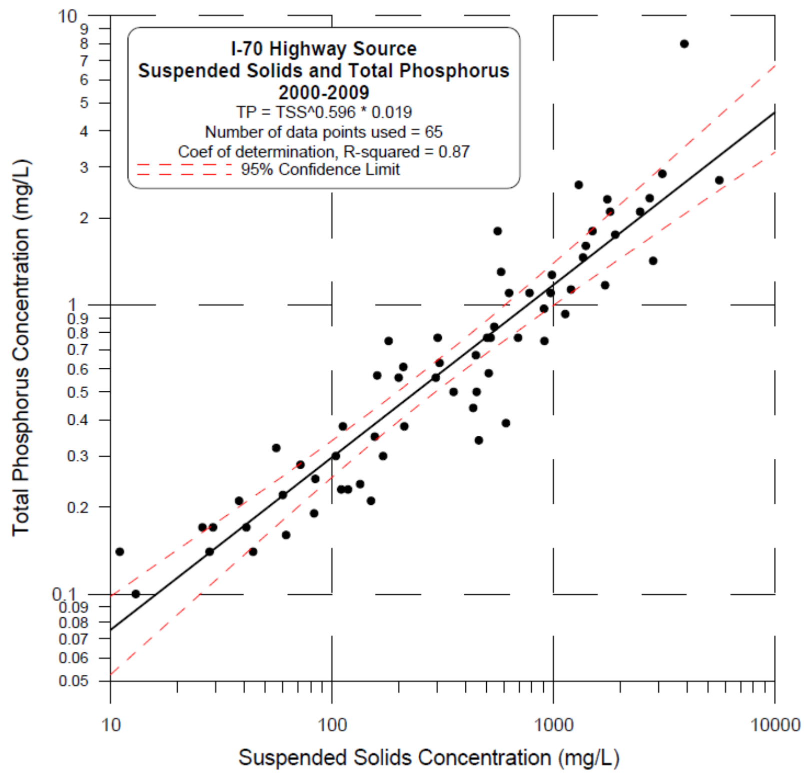
Note: Urban and population-related sources include urban stormwater and municipal treatment.

Source: Nutrient Innovations Task Group (NITG, 2009)

Figure 3-4. Comparison of nitrogen and phosphorus sources in the Chesapeake Bay and Gulf of Mexico watersheds.

3.3.2 DOT Highway Nutrient Contribution Studies

Analyses of highway contributions provide a greater understanding of nutrient levels, interactions and treatability in the highway environment. DOTs have completed several studies that have evaluated nutrient contributions from highway runoff to receiving waters, including nutrient transport and loading rates, the results of which provide data and guidance for nutrient management methodology. CDOT (2013) found a strong positive log-log correlation between total suspended solids (TSS) and TP for several monitoring points, including I-70 (Figure 3.5), indicating TP is associated with particulate solids and that implementation of standard sediment control BMPs would be effective in reducing TP transport.



Source: CDOT (2013).
Figure 3.5. CDOT I-70 Highway TSS concentration versus TP concentration.

North Carolina Department of Transportation (NCDOT) examined loading rates on different facilities, primary routes, and secondary routes and found the following:

- 75% of NCDOT's impervious areas were exporting nutrients at levels of intact forest cover (Huisman, 2012).
- The proximity of concentrated animal feeding operations (CAFOs) could be positively correlated with nutrients found in runoff on nearby roads (Lauffer, 2013). This relationship is potentially due to localized atmospheric deposition and inadvertent animal waste discharges during transport.

These NCDOT findings are aligned with the concentrations shown in Table 3-6 that indicate influence of agricultural sources on highway loading.

3.3.3 Comparison of Highway and Non-Highway Contributions

A trend in increasing vehicular use with population growth has been observed by Kramer (2013), which may results in an increase in pollutant loading from highway runoff. To determine how increasing vehicular traffic affects nutrient concentrations, nutrient concentrations in highway runoff and annual average daily traffic (AADT) were plotted as shown in Figure 3.6 through Figure 3.10. Data was obtained from the Highway Runoff Database (HRDB) (Smith and Granato, 2010) and the National Stormwater Quality Database (NSQD) (Pitt, 2008), and grouped into 4 categories based on AADT levels:

AADT Category 1: 0 – 25K
AADT Category 2: 25-50K
AADT Category 3: 50-100K
AADT Category 4: 100K+

The non-detect results were included in the plots and shown at the method detection limits. To determine the general trend in nutrients with AADT, a Kendall-Theil Robust line (Granato, 2006) was used to fit the data. Because there were several nutrient data points with the same AADT, the median nutrient concentration for each AADT was used for the linear model.

Though nutrient concentrations vary significantly for a given AADT, nutrient concentrations generally increase with increasing AADT. This finding is consistent with the values shown in Table 3-6 from Driscoll et al. (1990) since high traffic can be associated with urban areas. Urban areas are expected to have higher NOx emissions from vehicles and industrial sources. Also, high traffic freeways typically have piped drainage systems thereby providing more opportunities for build-up and transport of organic nutrients, such as plant matter (e.g., leaves) and animal waste. The high variability at all AADT levels indicates that surrounding land uses from outside of the highway ROW also likely play a role in observed runoff concentrations. Highways are long, narrow areas that often cut across other land uses. The co-mingling of highway runoff with adjacent land use runoff may be more prevalent for rural highways where stormwater is conveyed by open ditches and swales. If the main sources of nutrients do not originate within the highway ROW, nutrient concentrations will not be affected by traffic volumes. As previously indicated in Section 3.3.1, surrounding land uses outside of the ROW that are controlled by non-DOT entities are an additional, significant source of nutrients to highway runoff.

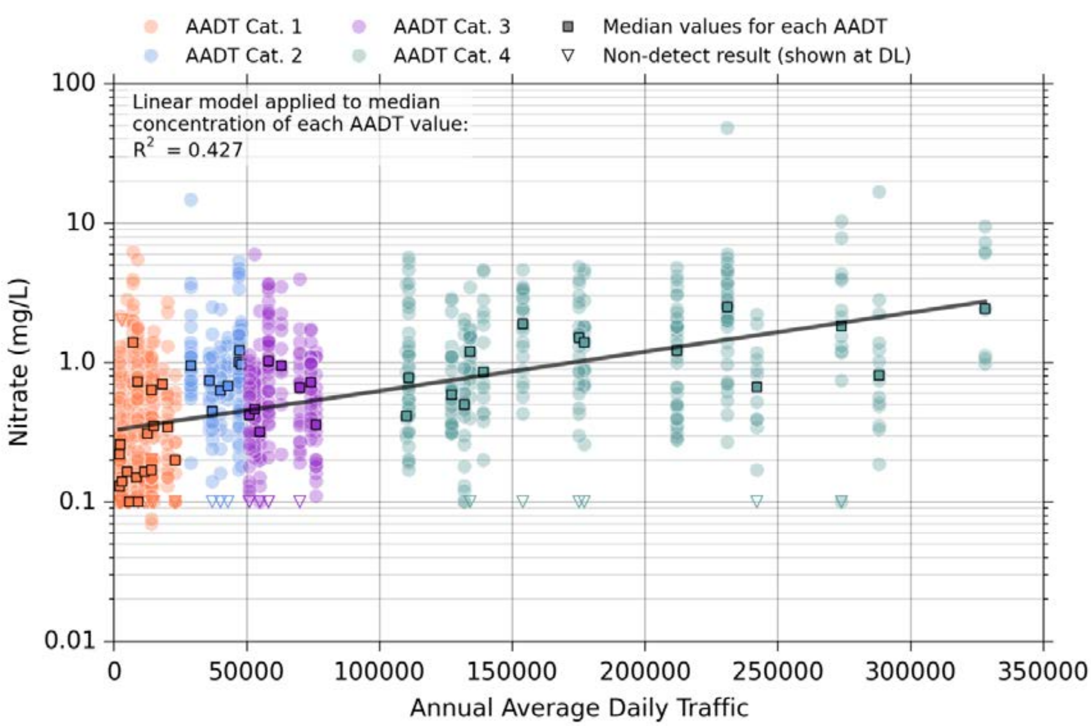


Figure 3.6. Variation in NO_3 concentration with AADT.

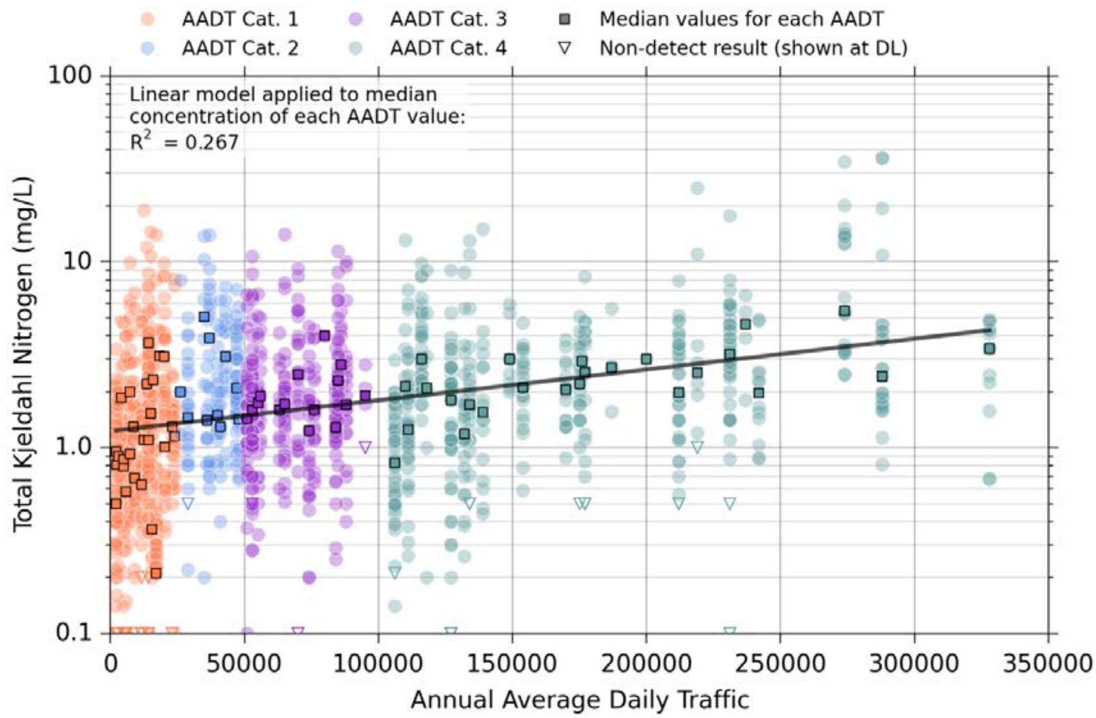


Figure 3.7. Variation in TKN concentration with AADT.

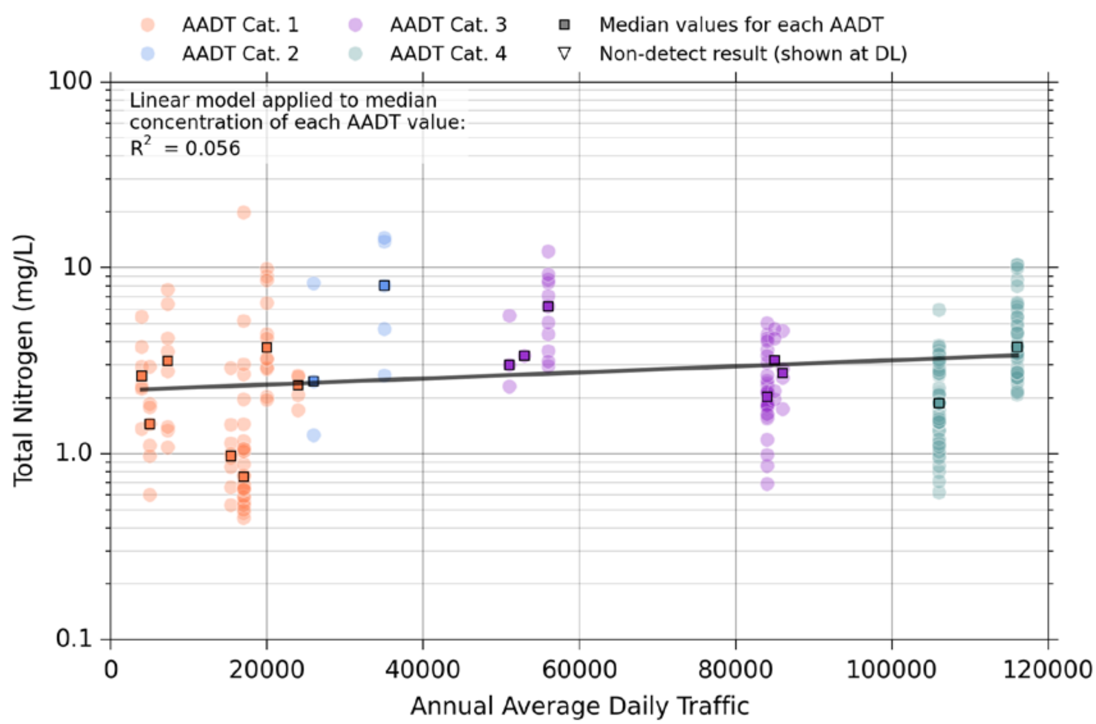


Figure 3.8. Variation in TN concentration with AADT.

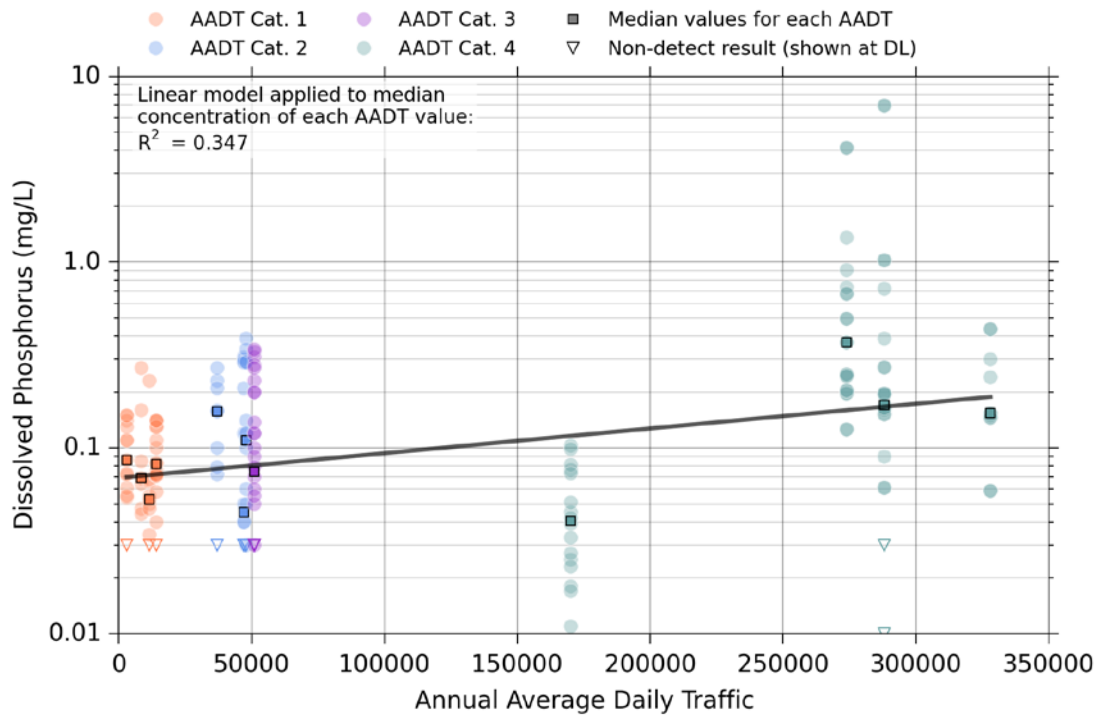


Figure 3.9. Variation in DP concentration with AADT.

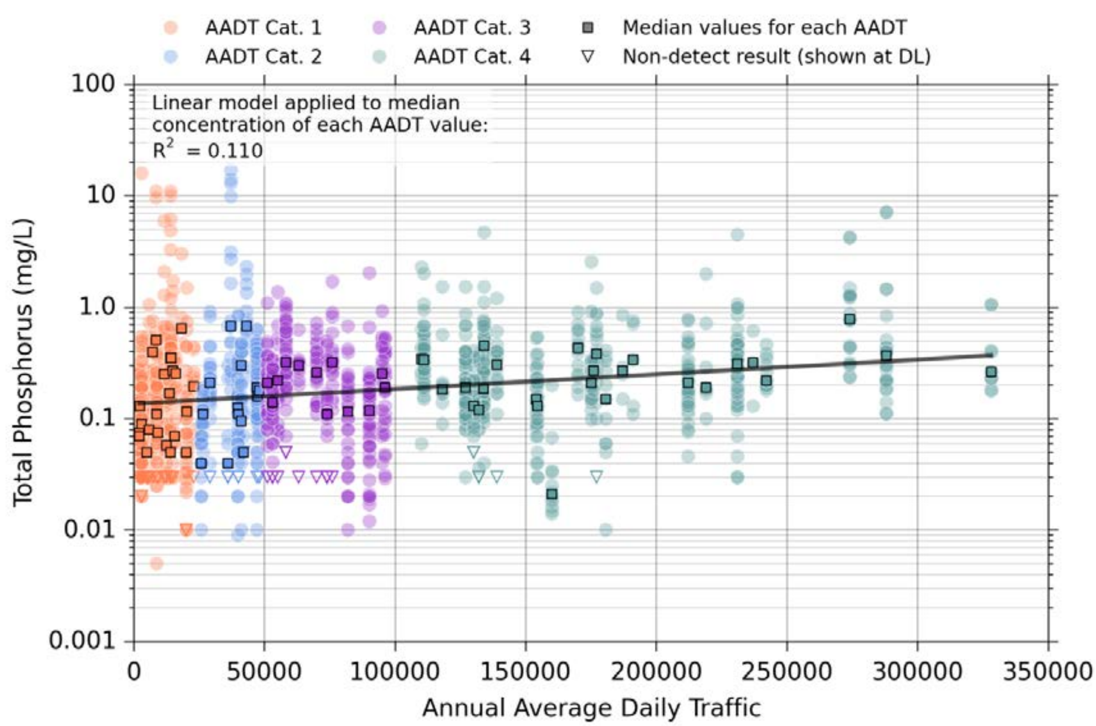


Figure 3.10. Variation in TP concentration with AADT.

National studies relating to highway runoff have found no simple linear correlation between AADT and nutrient concentrations (Driscoll et al., 1990; Barrett et al., 1995; Kayhanian et al., 2003). However, using multiple linear regression Kaynanian et al. (2003) found that AADT is among other factors, such as antecedent dry period, total event rainfall, and seasonal cumulative rainfall that have a statistically significant effect on highway runoff concentrations. Roadway spray to vehicles is likely a significant source of pollutants, and roadway surfaces that minimize spray, such as open-graded friction course and permeable friction course, greatly reduce TSS and phosphorus (Eck et al., 2012). Irish et al. (1998) found that antecedent dry periods help predict the amount of pollutants, which may also be influenced by traffic volumes between storms. Nevertheless, a number of studies maintain that land use is more important. Clary et al. (2013) found positive correlations among TSS, TN, and TP concentrations in commercial and residential areas and strong correlation among TP and TSS concentrations in natural/open space areas. In highway-related areas TP and TN concentrations were not significantly correlated (Clary et al., 2013).

Though discussion of nutrients sources and management responsibilities are ongoing, DOTs have begun to take an active role in nutrient reduction in some states as a collaborative effort to meet water quality requirements. Nutrient management drivers, BMPs, and approaches for addressing nutrients are continually evolving, and thereby influencing the environmental and economic tradeoffs and choices for DOTs. Limited DOTs currently have nutrient reduction goals, and goals may be synonymous with federal and/or state objectives. For example, in accordance with the Chesapeake Bay TMDL (U.S. EPA, 2013c), Maryland State Highway Administration (MDSHA) has a goal of reaching 60% reduction in nitrogen, phosphorus and sediment by 2017. Their nutrient reduction program will treat approximately 1,000 more acres and remove nearly 4,700 pounds of nitrogen and 1,089 pounds of phosphorus from the Chesapeake Bay watershed annually (MDSHA, n.d.).

3.3.4 Impact Assessment

As discussed in Sections 3.3.1 and 3.3.2, nutrient contributions from highway runoff are small relative to other land uses and atmospheric deposition. To show that highway runoff contributions to receiving water is insignificant (de minimis), DOTs can conduct a relative loading analysis. This analysis would evaluate loading from various sources to receiving waters and quantify contributions from highway runoff. A contaminant loading model such as Stochastic Empirical Loading and Dilution Model (SELDM) (Granato, 2013) can be used to assess nutrient impacts to receiving waters from highway runoff. If this assessment indicates that highway runoff may cause a problem, then management approaches may be needed.

Table 3-7 shows the median nutrient effluent concentration for selected BMPs commonly used to treat highway runoff. Compared to highway runoff concentrations in Table 3-5, BMP effluent concentrations are slightly lower for nitrate and approximately equal for total phosphorus, depending on the highway runoff study used. Using data from Kayhanian et al. (2003) for non-urban highways, BMP effluent nitrate concentrations are 15-85% lower and BMP effluent total phosphorus concentrations are 5-60% lower. In urban areas, nutrient concentrations are generally higher in highway runoff than BMP effluent. For some BMPs and highways (rural highways in particular), there may not be a significant difference between contributions from highway runoff and BMPs to receiving waters.

Table 3-7. Median effluent concentrations for BMPs commonly used to treat highway runoff.

BMP Type	Pollutant (mg/L)			
	NO_3-N	**DP**	**TN**	**TP**
Vegetated Filter Strip	0.27	0.25	1.13	*0.18*
Bioretention	0.22	0.13	0.9	0.09
Bioswale	0.25	*0.07*	0.71	*0.19*
Dry Detention Basin	0.36	0.11	*2.37*	0.22
Media Filter	*0.51*	0.08	0.82	0.09
Wet Pond	0.18	0.06	1.28	0.13
Wetland Basin	0.08	0.05	1.19	0.08
Wetland Channel	0.19	0.09	1.33	0.14

Note: Pollutant effluent concentrations in italics indicate nutrient concentrations in effluent were higher than influent.

Source: WERF (2012).

As indicated in Table 3-7, certain BMPs have been shown to export nutrients, which could be attributed to organic matter content intentionally or unintentionally introduced into the BMP (i.e., nitrate export may occur due to ammonification and subsequent nitrification of organic nitrogen). The findings for bioswales (grassed swales), dry detention basins, and wet ponds in Table 3-7 are in line with those found by the Florida Department of Environmental Protection (Harper and Baker, 2007). Grassed swales were effective for total nitrogen (TN) removal from stormwater, but did not lower TP concentrations in comparison to sites using curb and gutter systems. Wet basins decreased TN and TP concentrations more than dry detention basins. While some states credit grass swales for TN and TP reduction, an overall assessment based on nationwide data indicates limited concentration reduction (CWP, 2007; Leisenring et al., 2010). Retrofitting of grass swales into bioretention facilities with carefully selected soil mixes, such as that completed by MDSHA (Pujara and Minami, 2013), can aid in nutrient removal from stormwater.

4.0 Removal Processes

Understanding processes for phosphorus and nitrogen removal from stormwater is critical to the identification of effective nutrient management strategies. Nutrient removal refers to the treatment mechanisms (a.k.a. unit processes) provided by BMPs that physically, biologically, or chemically prevent nutrients from reaching receiving waters. Descriptions of key nutrient removal processes and factors affecting these processes are detailed in the sections below.

4.1 Infiltration

Infiltration is the surficial entry and subsequent percolation of water through soil pore spaces. The majority of nutrients found in stormwater can be effectively removed with this process when site conditions are conducive to infiltration. In urban areas and near highways, the soil is almost always disturbed and compacted, which may inhibit easy movement of water into the ground, even in sandy soils (Huber et al., 2006). Steep slopes, seasonal high water tables, and karst geology and may also reduce the feasibility and desirability of infiltration. Therefore, before relying on infiltration as the primary treatment mechanism, infiltration testing and soil borings are generally recommended.

4.2 Filtration and Sedimentation

Filtration and sedimentation are the two primary treatment mechanisms for particulate phosphorus and nitrogen removal from stormwater. Because settling velocity plays a key role in particulate removal via sedimentation, removal effectiveness is largely dependent on particle size and density. Changes in temperature can influence sedimentation and filtration by impacting water viscosity and settling velocities for sediments, which in turn affect removal rates for particulate bound nutrients. In essence, a decrease in temperature will increase the viscosity of water, which then decreases the rate of sedimentation (NYSDEC, 2010).

Overall, sediment removal mechanisms are relatively effective, but because partitioning between particulate and soluble forms can vary greatly, sediment removal alone is not expected to result in consistently high performance. BMPs may need to address dissolved nutrients in order to achieve high and/or consistent pollutant removal, or to achieve numeric targets that are based on biostimulatory criteria.

4.3 Adsorption and Precipitation

Dissolved phosphorus can be treated via adsorption and precipitation, but nitrogen compounds would not be expected to be significantly removed by this process. The media and/or soil properties used in treatment predominantly determine effectiveness of nutrient removal from stormwater. The oxidation-reduction potential (ORP) in soils is especially important in interactions between phosphorus and iron. Phosphorus may be removed from solution in oxidizing conditions (i.e., high ORP) as iron oxidizes from Fe^{+2} to Fe^{+3}, which binds phosphorus more effectively and causes phosphorus to precipitate. However, this reaction is reversible, with phosphorus being released under reducing (i.e., low ORP) conditions. Studies have shown that anaerobic conditions in BMPs can result in less removal of phosphorus from stormwater (Minton, 2005).

The removal of dissolved phosphorus from stormwater through adsorption and precipitation is dependent on the adsorption capacity of media/soil. Two media/soil properties important for adsorption are cation exchange capacity (CEC) and amount of phosphorus already present. Though there is debate over the most appropriate and accurate method for measuring and specifying the maximum acceptable leachable soil phosphorus, Hunt et al. (2006) suggested the use of soils with a low "P-index" (an index describing the amount of phosphorus in soil) to improve phosphorus adsorption in bioretention cells and prevent leaching. In addition, organic material with high CEC (such as hemic peat) has been shown to provide good phosphorus removal. Conversely, highly decomposed peat (sapric) can release phosphorus. As a result, some BMP design manuals have specified the use of partially decomposed fibric or hemic peat (NYSDEC, 2010). In addition, a variety of mineral substances such as zeolites, iron, aluminum oxide-coated sand, and similar filtration media have been found to promote the adsorption of phosphorus (Strecker et al., 2005).

4.4 Biological Uptake

Plant and microbial uptake can provide significant removal of both nitrogen and phosphorus from stormwater (Huber, et al., 2006). If completed on a regular basis, plant uptake and harvest can provide long-term sequestration of nutrients. Plant uptake varies seasonally as temperature can have a substantial impact on microbial and plant activity. It has been found that during winter months, nitrogen and phosphorus export may occur as a result of decaying of biological matter (NYSDEC, 2010); however, additional study of this phenomenon is needed.

4.5 Factors Affecting Phosphorus Removal

Phosphorus in stormwater runoff may be bound to particulate matter (inorganic or organic) or exist as free (dissolved) orthophosphate. For either form, infiltration is the most effective removal process. When infiltration is insufficient or infeasible, other physical treatment processes are needed to reduce phosphorus loading in stormwater. Dominant treatment processes are influenced by the partitioning of phosphorus between particulate and dissolved forms. If influent phosphorus is predominantly in the bound form, then physical filtration and sedimentation are most effective (Strecker et al., 2005). Conversely, if the influent phosphorus is predominantly in the dissolved state, plant uptake and enhanced adsorption with reactive media are more effective. Table 4-1 contains dominant treatment mechanisms for phosphorus forms and factors that influence process effectiveness.

Table 4-1. Summary of phosphorus forms, treatment mechanisms, and influential factors.

Form	Treatment Mechanism	Factors Influencing Treatment
Particulate	filtration, sedimentation	• partitioning of phosphorus between particulate and soluble forms • particle size distribution • oxidation-reduction potential • pH • bacterial communities that transform phosphorus into soluble forms (microbial transformation) • temperature
Dissolved	adsorption, precipitation	• contact with reactive media/soils • pH • oxidation-reduction potential • presence of calcium, magnesium, iron, aluminum
	biological uptake	• vegetation and root density • presence of nitrogen and other essential nutrients • bacterial communities • periodic harvesting of vegetation • temperature

A study of stormwater treatability found that, on average, approximately 70 percent of TP and phosphate were removed from stormwater through removal of particles with diameter greater than 20 µm using wet ponds (Johnson, 2003). Other studies on phosphorus fractionation (i.e., mass associated with various particle size ranges) in soils and sediment suggest that concentrations are typically greatest on fine particles (clays and silts). However, the particle size distribution also affects where most of the phosphorus mass resides. Therefore, if most of the suspended particles are sands, then most of the particulate-bound phosphorus mass in stormwater will be associated with sand (Dong et al., 2003; Vaze and Chiew, 2004; Tamatamah, 2005).

4.6 Factors Affecting Nitrogen Removal

The transport of nitrogen compounds in surface waters and stormwater runoff, and the transformation and removal of nitrogen in stormwater treatment BMPs is a complex subject. This section provides a technical summary of nitrogen removal processes as a framework for discussing BMP performance. As with phosphorus, an important concept for nitrogen management is long-term sequestration, which can be provided either by infiltration or plant uptake and harvest. In most natural treatment systems, for plant uptake of nitrogen to be truly effective, vegetation must be harvested if nitrogen is not stored in longer-lived woody vegetation (Tchobanoglous and Burton, 1991). Research by Burgoon et al. (1991), Gersberg et al. (1983), Rogers et al. (1991), and Tchobanoglous and Burton (1991) indicates that reeds, in particular bulrush, may be particularly efficient at nitrogen uptake. Table 4-2 provides a brief summary of dominant transformation, treatment mechanisms, and factors important to each of the mechanisms.

Table 4-2. Summary of nitrogen forms, treatment mechanisms, and influential factors.

Form	Treatment Mechanism	Factors Influencing Treatment
Nitrogenous Organic Solids	physical separation (screening, filtration, settling)	• partitioning of nitrogen between particulate and soluble forms
	ammonification (transform via microbial decomposition to NH4)	• temperature • pH • bacterial community
Nitrate (NO_3)	plant uptake	• vegetation density • presence of phosphorus • periodic harvesting of vegetation
	denitrification (transformation via biological reduction to N2 gas)	• bacterial community • oxidation-reduction potential/dissolved oxygen
Ammonium (NH_4^+) Ammonia (NH_3)	volatilization	• temperature • pH • circulation and air flow
	nitrification (transform via biological oxidation to NO3)	• temperature • pH • bacterial community

Temperature. The effectiveness of processes for removal of the two most dominant forms of nitrogen (nitrogenous organic solids, nitrate) found in stormwater have been shown to be temperature dependent (Kadlec and Knight, 1996). In general, higher temperatures have been shown to improve microbially-mediated processes such as ammonification, volatilization, nitrification and denitrification.

pH. Processes for nitrogen removal from stormwater are also highly dependent on pH, with optimal rates of removal processes occurring when the pH is near neutral or slightly higher than neutral.

Bacterial Community. Ammonification, nitrification and denitrification processes rely on bacteria mediation. Therefore, the presence and abundance of specific bacterial communities affects the rates of nitrogen treatment from these processes.

Dissolved Oxygen. For nitrification to occur, dissolved oxygen (DO) must be present. Low DO levels can limit nitrification rates because oxidation processes of nitrification can consume significant amounts of DO. Denitrification, in contrast, only occurs under anaerobic conditions, when little to no DO is present. The process of denitrification requires that nitrate act as an alternative terminal electron acceptor to oxygen.

5.0 BMP Types and Performance

As BMPs have developed and evolved over time to address stormwater management goals, various terminologies have been used to identify the same BMP. To maintain consistency throughout this report, BMPs have been categorized according to source control BMPs, gross solids removal BMPs, and runoff control BMPs. The dividing line between these categories can vary between stormwater authorities and pollutants, but it is established in the stormwater community that BMP implementation is most beneficial in terms of cost-effectiveness for nutrient management when following a sequential BMP selection process that puts source controls ahead of gross solids removal, followed by runoff controls.

5.1 Source Control BMPs

Source control BMPs eliminate or reduce the transport of nutrients by eliminating or reducing the exposure of nutrients to runoff. In general, BMPs categorized as source control provide no or limited treatment processes and require minimal project-specific engineering design. Source control BMPs typically do not require much physical alteration of the existing project site, which makes these BMPs highly suitable for managing nutrients from existing roadways. DOT staff play a key role in right-of-way (ROW) management and operations to limit the availability of nutrients entering stormwater runoff. Table 5-1 describes potential nutrient source controls that could be considered by DOTs.

Table 5-1. Nutrient source control BMP types.

BMP	Other Common Terms	Description
Fertilizer Application Management	Nutrient Management, Fertilizer Management	Management of fertilizer application types, timing, location, rates, and storage to reduce or eliminate nutrients
Permanent Erosion and Sediment Control		Measures to control erosion and sediment after construction including vegetated embankments, check dams, and erosion control blanket
Permeable Friction Course (PFC)	Open Graded Friction Course	Layer of porous asphalt placed on top of existing conventional concrete or asphalt to improve safety and reduce undercarriage washing from road spray
Pet Waste Control	Pet Waste Management	Management strategies for pet waste including education efforts, increased rests stops and signage
Wildlife Waste Control		Constructing wildlife crossings and bird roosting deterrents to reduce the incidence of roadkill and animal droppings on the road surface
Plant Material Management	Roadside Vegetation Management	Management strategies to minimize roadside vegetation and leaf litter from entering roadway, including mowing and grooming practices
Plant Selection and Installation Methods		Selection of plants and trees that will enhance nutrient uptake and installation methods that reduce compaction to promote root growth and infiltration
Planting Medium Selection		Selection of a planting medium that will not leach nutrients
Street Sweeping		Remove the buildup of sediment and detritus that have been deposited along the street or curb, using a vacuum assisted sweeper truck
Winter Road Management	Road Weather Management, Snow and Ice Control	Management of application types, timing, location, rates, and storage to reduce or eliminate nutrients. Includes road sanding and deicing.

5.2 Gross Solids Removal BMPs

Gross solids removal BMPs screen and settle coarse sediment and plant debris from runoff that could further break down to release bound nutrients in downstream runoff control BMPs or the receiving water. By removing organic debris and coarse/larger solids from runoff, these devices provide pretreatment for downstream runoff control BMPs thereby increasing their performance and longevity.

Table 5-2. Gross solids removal BMP types.

BMP	Other Common Terms	Description
Catch Basin Insert	Inlet Filter	Passive devices that are fitted below the grate of a drain inlet to intercept gross solids (e.g., litter and vegetation) and coarse sediment
Catch Basin Sump	Sump, Catch Basin	Inlet structure with enlarged storage capacity used to capture gross solids (e.g., litter and vegetation) and coarse sediment
Hydrodynamic Device	Vortex Settler	Cyclonic trapping of solids, oil/grease, floatables, and other debris
Nutrient Baffle	Nutrient Separating Baffle Box, Baffle Box	Baffle for gross solids (e.g., litter and vegetation) and coarse sediment
Oil/Water/Grit Separator	Oil Water Separator	Device designed to separate oil and suspended solids/grit from runoff

5.3 Runoff Control BMPs

Runoff control BMPs (a.k.a. treatment BMPs) rely on various unit processes to treat nutrients entrained in stormwater runoff and require project-specific engineering design. Runoff control BMPs typically require physical alteration of the project site. Runoff control BMPs are further subdivided by their primary method of nutrient reduction, which is either via runoff volume reduction through infiltration or via concentration reduction through various unit treatment processes (e.g., sedimentation, filtration, sorption, plant uptake, biological transformation, etc.).

Table 5-3. Runoff control BMP types.

BMP	Other Common Terms	Description
Bioretention (no underdrain)	Rain Garden, Bioinfiltration	Vegetated, shallow depressions which may include engineered planting media that temporarily store stormwater prior to infiltration
Bioretention (with underdrain)	Biofiltration	Vegetated, shallow depressions with engineered planting media and an underdrain outlet. Underdrain outlet may be elevated or controlled by an automated valve/controller to provide internal water storage for increased infiltration and the creation of an anaerobic zone for denitrification.
Bioswale	Vegetated swales, grassed swales	Shallow channels designed to remove pollutants through sedimentation, filtration, and infiltration. Check dams (e.g., earthen, gravel) may be installed within the channel to reduce flows, increase settling and infiltration, and provide filtration of low flows through the berm. Soil amendments may be used to increase infiltration and target nutrients.
Dry Detention Basin	Dry Pond, Detention Basin	Grass-lined basins that, while fully drainable between storm events, temporarily detain water through outlet controls to reduce peak stormwater runoff release rates and provide sedimentation treatment
Infiltration Facility		Stormwater management control that provides storage to capture and hold stormwater runoff and allow it to infiltrate into the surrounding native soils; includes infiltration basins, infiltration/exfiltration trenches, and infiltration vaults

BMP	Other Common Terms	Description
Media Filter	Sand Filter, Cartridge Filter	A constructed bed or container (cartridge) with filtration media that provides treatment when inflows percolate through the bed. Outflow from the media filter system can be through underdrains or infiltration
Media Filter Drain	Ecology Embankment, Bioslope	A linear, flow-through treatment system that includes gravel, grass strip, and media filter bed treatment zones and associated conveyance system
Multi- Chambered Treatment Train		Three treatment chambers with grit removal, sedimentation, and filtration through media
Porous Pavement	Pervious Pavement, Permeable Pavement	Pavement that allows for infiltration through surface void spaces into underlying material; includes modular block, pervious concrete, porous aggregate, porous asphalt, and porous turf. Typically used on shoulders, parking spaces, and low traffic areas.
Subsurface Flow Wetland	Gravel Wetland, Submerged Wetland	Engineered system that can include a combination of wetland vegetation, porous media, and the associated microbial and physiological ecosystems
Vegetated Filter Strip	Biofilter, Grass Strip, Filter Strip	Vegetated strips that provide treatment via filtration, sedimentation, infiltration, biochemical processes and plant uptake. Soil amendments may be used to increase infiltration and target nutrients.
Wet Pond	Retention Basin, Retention Pond	Constructed basins that have a permanent pool of water, treats stormwater runoff through settling and biological activity
Wetland Basin	Stormwater Wetland, Constructed Wetland	Constructed naturalistic pond, lake, or wetland that incorporates design elements such as a sedimentation pool (forebay), permanent or seasonal treatment pool, vegetation, and outlet control structure
Wetland Channel	Wetland Swale	Densely vegetated waterways used to treat and convey runoff

5.4 BMP Performance for Nutrient Control

Performance data for nutrient management varies for BMPs depending on the amount of available monitoring information and summarized statistics. For some BMPs, particularly source control BMPs which have not been as widely studied in comparison with runoff control BMPs, available data may be highly localized, with only a limited range of climate, pollutant load or other influencing factors. This section provides a synthesis of the best available BMP performance data for nutrient control to provide insight into BMP effectiveness for the various forms of phosphorus and nitrogen.

5.4.1 Source Control BMP Water Quality Performance

Studies quantifying the efficiency of source control practices for nutrients are limited because these practices are designed to minimize the exposure to rainfall and transport of nutrients in runoff, thereby rendering analytical runoff monitoring an ineffective tool for measuring the effectiveness of source control practices. Additionally, source control BMPs are usually not isolated from other management practices, making it difficult to control variables. The efficiencies can also be very site-specific, so extrapolating values from one project area in to another may be a misrepresentation of the data. A discussion of each of the source control practices and identified performance information is provided below. BMP strategy and design considerations that can improve on nutrient performance are discussed in Section 6.0.

Fertilizer Application Management. Fertilizer has the potential to be a significant source of nutrients in highway environments. However, few DOTs use fertilizers except during initial vegetation establishment or at more manicured landscaped areas (e.g., rest stops). While fertilizer application management can minimize the entrainment of nutrients in runoff, there are very few studies that have quantified the effectiveness of these practices. The Maryland Department of the Environment (MDE) draft wasteload allocation guidance indicates fertilizer application management may reduce total nitrogen and total phosphorus by 17 and 22%, respectively (MDE, 2011). However, these reduction rates are highly dependent upon the current rate of application and may not be representative of highway fertilizer management. To claim these levels of nitrogen and phosphorus reductions, MDE requires that nutrient management plans specify the rate, timing, and application of fertilizer and soil testing be completed to determine appropriate fertilizer quantities (MDE, 2011).

Permanent Erosion and Sediment Control. While some nutrient types are typically transported primarily in particulate phases which can be transported during erosion, no data were found to quantify the efficiency of this source control for nutrient removal.

Permeable Friction Course (PFC) Overlay. PFC overlay (Figure 5-1) is considered a source control because it reduces vehicle undercarriage washing and pollutants that accumulate in the pore spaces can become immobilized. On the surface of a conventionally paved road, splashing created by tires moving through standing water can transport even large particulate matter rapidly to the edge of pavement. However, water velocities within the pore spaces of the PFC are low and likely could only transport the smallest material (Eck et al, 2010). A PFC performance study in Austin, TX found the mean runoff concentrations of total phosphorus from PFC were 64% lower than mean runoff concentrations from an adjacent conventional pavement (Stanard et al., 2008). Mean concentrations of dissolved phosphorus and TKN were also lower for PFC runoff, but not statistically significant. PFC appeared to significantly increase nitrate/nitrite concentrations by approximately 50% presumably due to the oxidation of organic nitrogen that became trapped in the pore spaces.

Source: Copyright Bradley J Eck, used with permission from http://bradeck.net/research
Figure 5-1. PFC overlay.

Pet Waste Control. Elimination of pet waste sources in urban environments has focused on ordinances and programs to encourage and require cleaning up after pets in public places. No data are available about the efficiency of these practices relevant to the highway environment, such as at rest stops where travelers may walk their pets.

Wildlife Waste Control. Wildlife waste deposited on road surfaces can be partially controlled by installing wildlife crossings and bird roosting deterrents. While no data were found regarding the potential effectiveness of these approaches for reducing nutrients in runoff, other benefits include improved motorist safety and reduce wildlife-vehicle collisions.

Plant Material Management, Selection and Installation, and Planting Medium Selection. Plant material management includes: 1) roadside mowing and grooming practices to minimize the deposition of vegetation debris on the roadway, 2) tree maintenance to maintain the benefits of runoff reduction via canopy uptake while minimizing nutrient losses from leaf litter, 3) careful plant selection and installation to maximize nutrient uptake and minimize compaction, and 4) planting medium selection to capture nutrients and avoid leaching. While plant management is suspected to be effective nutrient source control practices, no data are currently available on the efficiency of these practices for nutrient reduction in highway runoff.

Street Sweeping. Although limited, compared to the other source controls, street sweeping has the most data available for nutrient removal from stormwater with total nitrogen and phosphorus removals estimated to range from 3-9% (CWP, 2006; Law et al., 2008; MDE, 2011; Selbig and Bannerman, 2007). The studies indicate that street sweeping can provide minor, but not insignificant reduction in nutrient concentrations. However, there are very few studies that examine the actual reduction in nutrient loads between equivalent watersheds that are swept or unswept, or that measure nutrient concentration before and after sweeping.

Winter Road Management. Management protocols for road sands and deicing materials are typically developed to target sediments and salts in runoff (U.S. EPA, 1995; Venner, 2008). However, some of these materials can also contain nutrients. A highway monitoring study by Smith and Granato (2010) found that phosphorus concentrations in runoff from a Massachusetts highway site where traction sands were applied were significantly higher than a site without traction sand application. Application management to reduce the amount of sands and deicers used may help reduce nutrients in runoff, but no data were available on their efficiency.

5.4.2 Gross Solids Removal BMP Performance

The performance of gross solids removal BMPs for nutrients are limited because these devices by themselves are not expected to significantly reduce nutrient concentrations. Instead, performance studies are often focused on quantifying the bulk removal of coarse sediment, trash, and debris. A summary of the studies identified in the literature on gross solids removal effectives is provided below.

Catch Basin Inserts and Sumps. Catch basin inserts and sumps remove gross solids (sediment, leaf litter, trash, and debris), and because these solids contain nutrients, nutrient concentrations should be reduced in stormwater runoff. However, some studies found inserts to be ineffective for nutrient removal (FHWA, 2002; LADPW, 2005). Removal of nitrogen, in the form of nitrogenous solids (5-10%), can be slightly more effective than phosphorus (1-10%) for catch basin sumps based on studies where catch basins and associated storm drain systems were typically cleaned semi-annually (CWP, 2006; Pitt, 1984; Pitt and Shawley, 1981). A study of a deep-sumped catch basin on the Southeast Expressway in Boston, Massachusetts found that concentrations of TKN and TP decreased by up to 18% and 30%, respectively (Smith, 2002). However, removal efficiencies will be highly variable depending on nutrient content of the solids being removed. If traction sands have high phosphorus content, as described above, phosphorus removal may be more effective for areas where these sands are applied. In general, long-term removal effectiveness is influenced by the timing of cleaning of the inserts or sumps, and the state of breakdown of the gross solids. Leaf litter that is removed immediately and kept out of water is less likely to leach nutrients than leaf litter that is in an advanced state of decomposition (Strynchuk et al., 2001). Finally, the aerobic state of the gross solids can have a substantial effect on the long-term capture of nutrients, which is also related to the frequency of storms and the timing of cleanouts. Phosphorus, which is often highly particulate-bound in stormwater, can become more dissolved and thereby harder to remove if the oxidation state goes anaerobic.

Nutrient Baffles. Nutrient baffles consist of a series of chambers separated by walls, skimmers, and/or screens either in a vault or inserted in a catch basin. The baffles are designed to capture debris and promote settling of coarse solids. Some baffles additionally employ vertical or horizontal screens or filters to provide increased removal of coarse solids. The horizontal screen maybe suspended above the water level in effort to keep debris dry and minimize nutrient leaching from the captured solids into standing water. In a study of four full-scale baffle boxes (two with horizontal screens above the standing water, and two with vertical screens in the standing water) in Florida over two years (GPI Southeast, 2010), baffles boxes containing horizontal screens above the water line were found to be much more effective at nutrient removal (up to 28% reduction for total nitrogen and up to 19% reduction for total phosphorus) than baffle boxes where coarse solids remained in standing water. The results of the study indicate that baffle boxes designed without screens, or submerged screens, have nutrient removal rates similar to other gross solids removal methods, whereas those with skimmers or screens elevated above standing water provide improved nutrient control.

Caltrans has studied a variety of non-proprietary gross solids removal devices, including baffle boxes (Figure 5-2) and vaults with inclined screens and linear radial screens (Caltrans, 2003a, 2003b, 2005a, 2005b). While the focus of the performance monitoring has been on the full capture of solids greater than 5 millimeters, the studies indicate that a significant quantity of organic debris with the potential of contributing to nutrient loads to receiving water may be removed by the use of well-designed gross solids removal devices. Key considerations for the design of these devices includes the particle size targeted, the flow-through hydraulic capacity, the potential for clogging, ability to completely drain between storms, the gross solids storage capacity, and maintenance access (Caltrans, 2003a).

Source: Caltrans, 2003a.
Figure 5-2. Baffle box after installation.

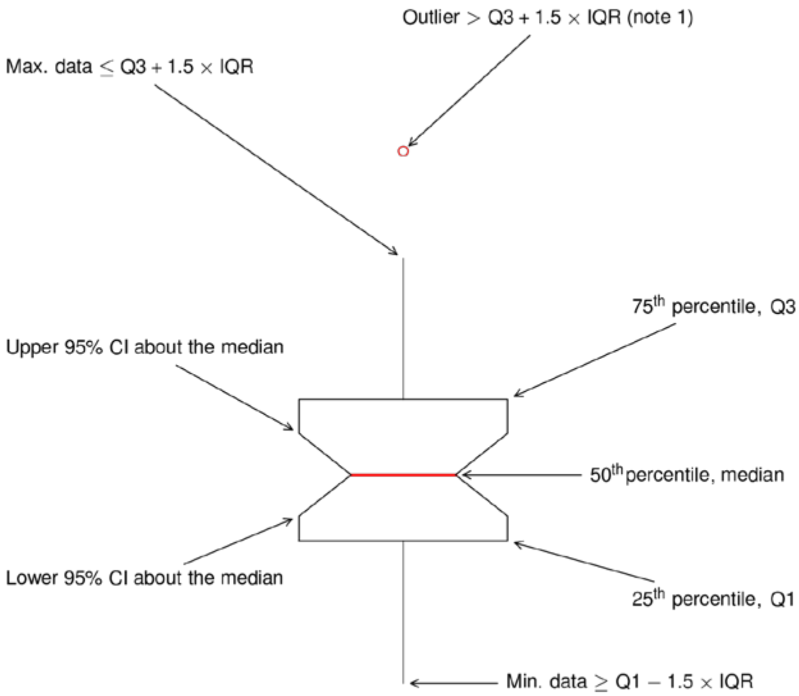
Oil/Water/Grit Separator. Oil/water/grit separators settle suspended sediment and particulates and separates free oil and floating debris from runoff. The number of chambers within an oil-water/grit separator can vary, but usually consists of at least two, with the first chamber designed to trap grit, coarse sediment, trash and debris and the second chamber for further particle settling. Oil is trapped within the chambers via an internal wall or an inverted discharge elbow. Results of a study of three, two-chambered 1,500-gal oil/water/grit separators in Boston, Massachusetts indicated concentration reductions up to 31% for TKN and 19-36% for TP. In general, the first chamber had higher percentages of coarse material, whereas finer particles (less than 0.062 mm) and less dense particles were found in the second chamber (Smith, 2002).

5.4.3 Runoff Control BMP Water Quality Performance

Data from the International Stormwater BMP Database (www.bmpdatabase.org) (BMPDB) version 03 24 2013 were selected and analyzed to assess BMP performance with respect to nutrients. Data were grouped by BMP categories as defined in Table 5-3 and by nutrient. Within each group of data, values of non-detect (i.e., censored) results were estimated using the regression-on-order statistics method (Helsel, 2005). This method is preferred over substituting the detection limit (or a fraction thereof) for the non-detect data as it reduces bias by utilizing the probability distribution of the uncensored data to make reasonable estimates of censored values. Next, the confidence intervals around the medians were computed using the bias-corrected and accelerated (BCa) bootstrap method (Efron, 1987).

BMP performance was primarily assessed by comparing the 95% confidence intervals around the median influent and effluent concentrations. For a given pollutant, a BMP category is classified as reducing nutrient concentrations when the upper bound of the effluent median confidence interval is below the lower bound of the influent median confidence interval. Conversely, if the lower confidence bound of the effluent median is above the upper confidence bound of the influent median, the BMP is exporting the nutrient. Generally, effluent concentrations are less variable (tighter confidence intervals) than influent concentrations, presumably due to flow equalization effects (i.e., smoothing of pollutograph due to reduced turbulence and velocities and increased settling), consistency in achievable effluent concentrations, and the representativeness of collected samples. Influent sampling is prone to higher variability due to a higher likelihood of collecting bedload, particles transported along the bottom of the inlet, in addition to suspended load.

Notched box and whisker plots (Tukey, 1977) graphically demonstrate this procedure. In general, box and whisker plots visually represent some basic statistics of a sample population and the general shape of the statistical distribution of the data. Figure 5.3 below explains how box and whisker plots are represented throughout this document. The horizontal line inside each box represents the median of a given dataset. The notches expanding out from the median represent the 95% confidence intervals around that median.



Note 1: IQR = interquartile range, or 75th minus 25th percentiles.

Figure 5.3. Explanation of box and whisker plots

Figure 5.4 and Figure 5.5 below provide BMP performance results comparisons for nitrogen and phosphorus compounds, respectively, using color-coded box and whisker plots. The figures indicate where median effluent (green) nutrient concentrations are statistically lower than median influent (blue) nutrient concentrations. Box and whisker plot pairs whose effluent median upper confidence bound is below the lower influent median confidence bound indicate reduced concentrations for a given nutrient and are shown in solid colors with black medians. Otherwise, the boxes are left hollow and only the medians are colored. As shown in Figure 5.4, median nitrate (NO3) removals are indicated for vegetated filter strips, wet ponds, and wetland channels; median TKN removals are indicated for bioswales, sand filters, wet ponds, and wetland channels; and median ammonia removals are indicated for bioretention, sand filters, and vegetated filter strips. As shown in Figure 5.5 median total phosphorus (TP) removals are indicated for dry detention basins, sand filters, wet ponds, and wetland basins; only wet ponds and wetland channels are shown to significantly reduce median dissolved phosphorus (DP) and orthophosphate (OP) concentrations. A collection of additional box and whisker plots for each nutrient separately is included as Appendix A.

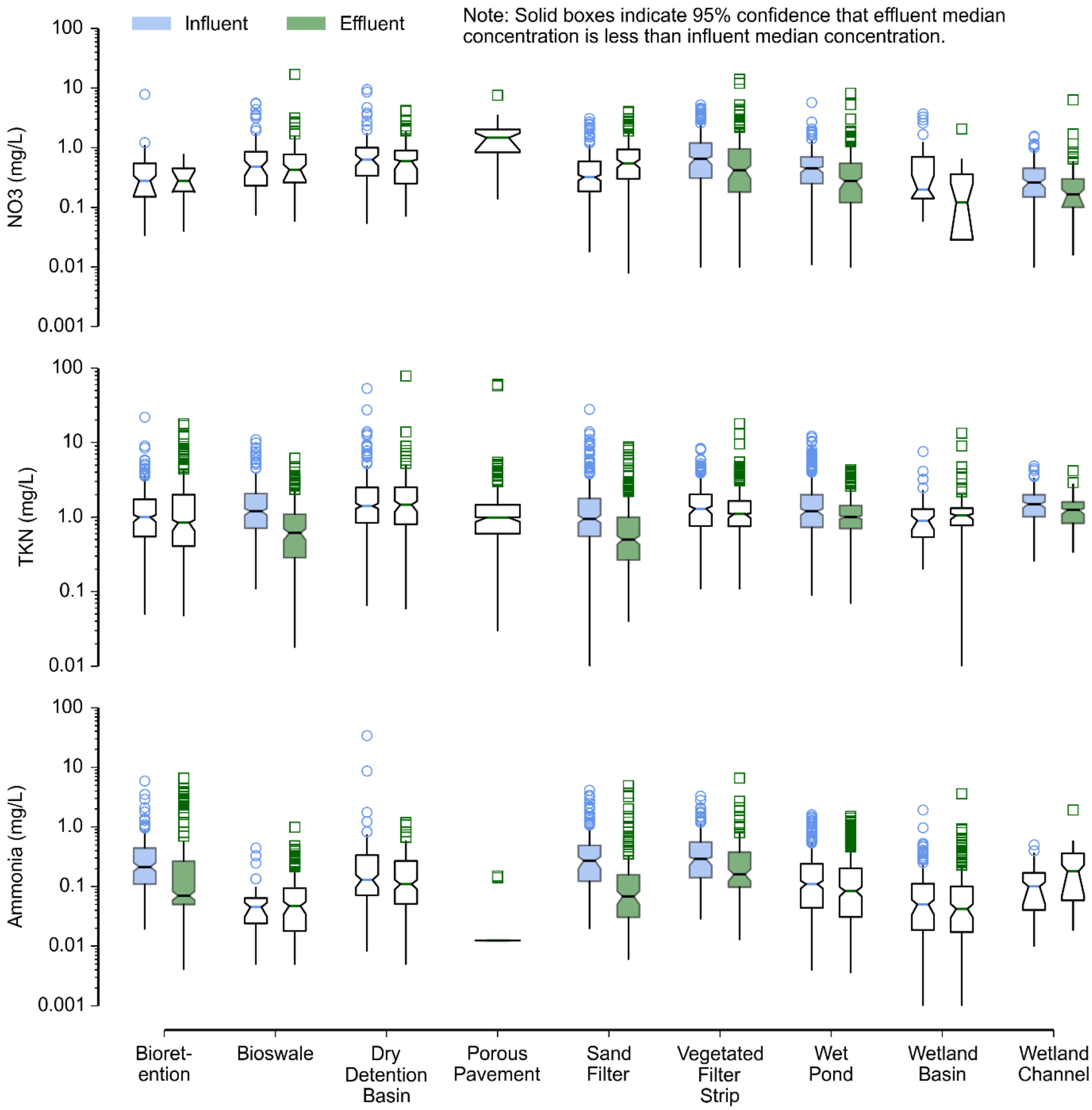


Figure 5.4. Box and whisker plots summarizing BMP performance for reducing nitrogen constituent concentrations.

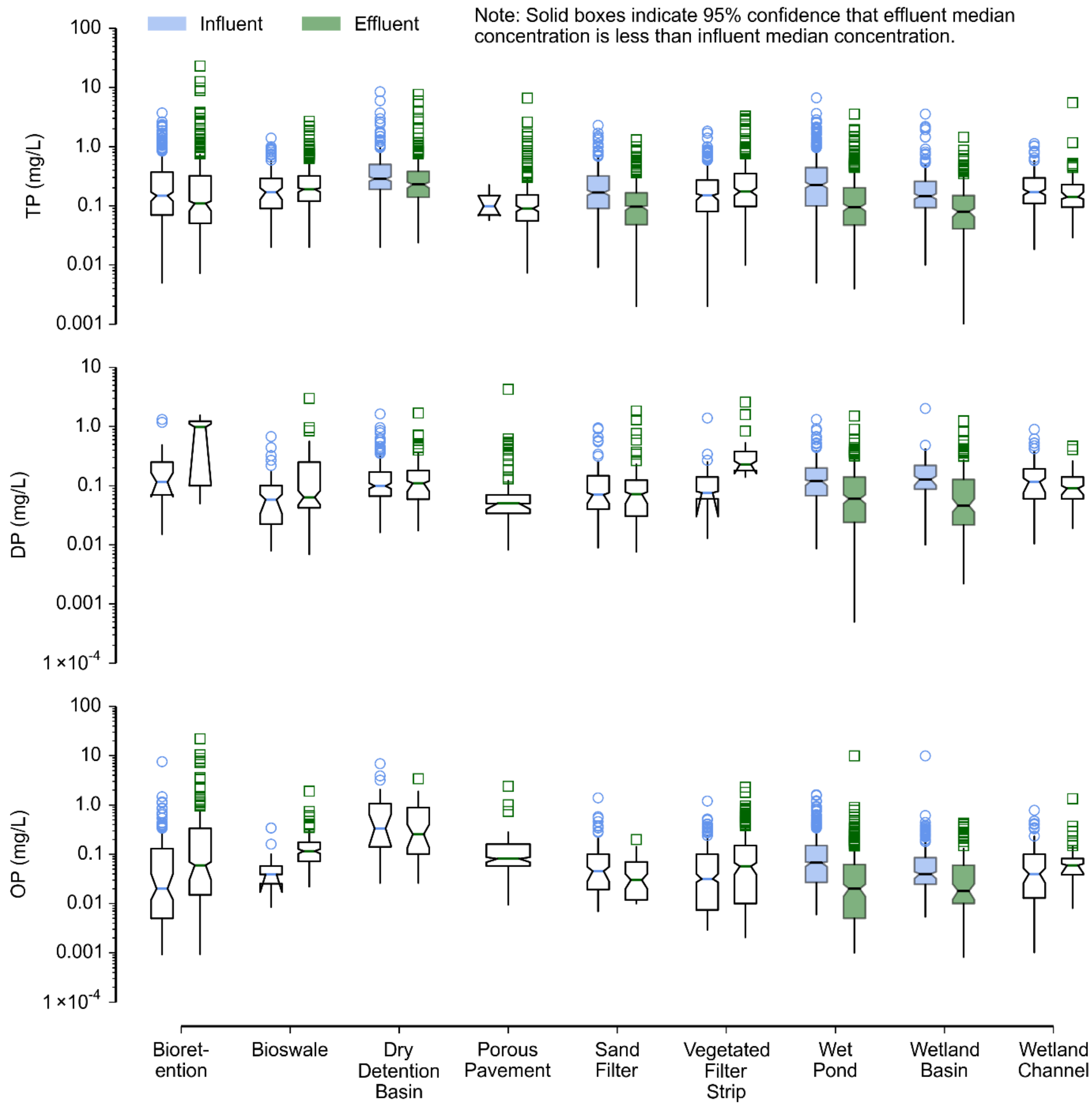


Figure 5.5. Box and whisker plots summarizing BMP performance for reducing phosphorus constituent concentrations.

In addition to the box and whisker plots, two other methods are used to assess BMP efficacy for nutrient removal: the Wilcoxon signed-rank test and the Mann-Whitney rank test. Both methods are non-parametric tests that assess the independence of two sample populations. The Wilcoxon test uses only paired influent/effluent measurements, while the Mann-Whitney test looks at all of the available data regardless if an influent sample does not have a complimentary effluent sample for a given storm (or vice versa). If the resulting p-values for these tests are less than 0.05, then the null hypothesis that the influent and effluent populations are equal can be rejected with 95% confidence.

Table 5-4 shows the results of all three of these assessments with black or grey and empty or solid circles. Black circles are used to represent nutrient reduction between influent and effluent whereas grey circles represent a nutrient export (thus, undesirable). The circles are solid when a statistical assessment suggests a significant difference between influent and effluent concentrations. The first circle shows whether or not the 95% confidence intervals overlap (i.e., a solid circle implies that they do not overall, which is desirable between influent and effluent reductions). The second and third circles show the results of the Wilcoxon and Mann-Whitney tests, respectively (solids circles imply a *p*-values less than 0.05). The key to the individual elements of this symbology is as follows:

● ○ ○ 95% confidence intervals for the medians do not overlap;
○ ● ○ The Wilcoxon test has a p-value less than 0.05; and
○ ○ ● The Mann-Whitney test has a p-value less than 0.05

Table 5-4. Summary of statistically significant nutrient concentration reductions.

BMP Category	NO_3	TKN	NH_4^+	TP	DP	OP
Vegetated Filter Strip	● ● ●	○ ○ ●	● ● ●	○ ● ●	● ○ ●	○ ● ●
Bioswale	○ ● ○	● ○ ●	○ ○ ○	○ ● ●	○ ● ○	● ● ●
Bioretention	○ ● ○	○ ● ○	● ● ●	○ ○ ○	○ ● ○	○ ● ●
Dry Detention Basin	○ ● ○	○ ● ○	○ ● ○	● ● ●	○ ○ ○	○ ○ ○
Sand Filter	● ● ●	● ● ●	● ● ●	● ● ●	○ ● ○	○ ● ○
Porous Pavement	○ ● ●	○ ● ○	○ ● ●	○ ○ ○	○ ○ ○	○ ● ○
Wet Pond	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
Wetland Basin	○ ● ●	○ ○ ●	○ ○ ○	● ○ ●	● ○ ●	● ○ ●
Wetland Channel	● ○ ●	● ● ●	○ ● ●	○ ○ ●	○ ● ○	○ ● ○

In general, the table above demonstrates that a majority of the BMPs included in the analysis can be effective at reducing either phosphorus or nitrogen concentrations, but generally not both except for BMPs with wet pools (e.g., wet ponds). Vegetated filter strips, bioswales, and bioretention systems tend to export or are ineffective for phosphorus concentration reduction. As will be discussed in Section 6.0, the results for bioretention may be due to nutrient leaching from added compost, and therefore it is still considered a viable BMP for nutrient reduction with consideration for volume reduction and proper gross solids pretreatment and planting medium selection. The most effective BMP for all nutrient types is wet ponds. Export of TKN is indicated for dry detention basins and wetland basins. Export of nitrate is indicated for bioretention and sand filters.

A more detailed summary table showing the influent and effluent medians, the 95% confidence bounds around those medians and other basic statistics is included in Appendix B.

6.0 Strategies and Designs for Nutrient Control

There are many factors influencing the selection and design of BMPs to control nutrients, many of which are specific to the highway environment. This section summarizes key considerations for success in nutrient control BMP planning, selection and implementation for new or retrofit DOT projects. Following a summary of general highway environment opportunities and constraints applicable to most BMPs, specific considerations for individual BMP types is discussed along with O&M costs. Organizational efforts and watershed-based approaches that can be implemented in conjunction with BMPs for nutrient management are also discussed.

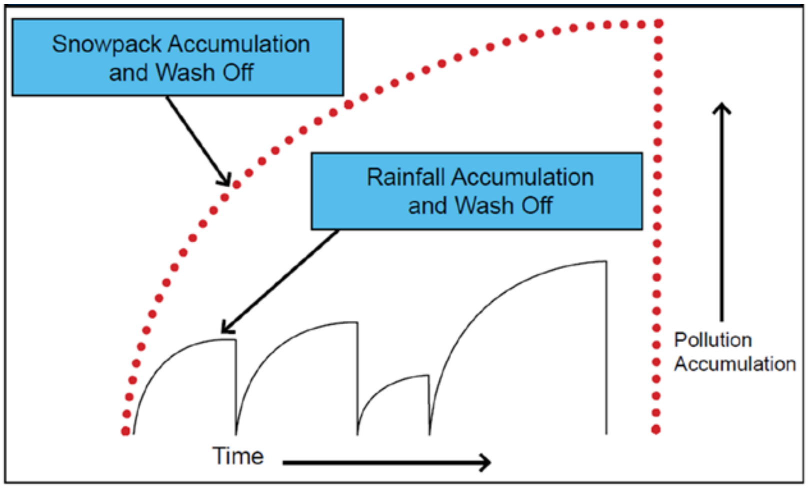
6.1 Opportunities and Constraints in the Highway Environment

6.1.1 Climate

Regional and periodic climatic variations, particularly temperature and precipitation, are factors that play key roles in BMP sizing, location and operational planning. DOT operations can be proactive or reactive to climatic factors, with proactivity generally leading to more control of nutrients. Understanding and appropriately responding to temperature and rainfall and their influence on source and runoff control BMPs will maximize nutrient reduction potential.

The difference between warm and cold regions, or warmer and colder periods alters the performance of some BMPs. Cold weather causes decreased biological activity, which can lead to decreased nutrient uptake and/or reduction by microbes and plants. Freezing temperatures may cause ponds and porewater in BMPs to freeze, and frozen water may block or damage pipes. Snow also changes the performance of BMPs by causing longer periods without drainage to them followed by increased flow from snowmelt. Snowbanks also accumulate nutrients from deicers, road sands, atmospheric deposition, and other sources for longer periods of time, which can lead to higher nutrient loading in snowmelt relative to rainfall runoff (Geosyntec, 2012).

Rainfall patterns affect the seasonality of precipitation volumes and the intensity of storms, which both affect BMP performance. For example, much of the arid west experiences a dry season where little or no rainfall occurs for several months. Nutrients can accumulate during this time leading to high loads of nutrients in the first storm of the wet season or “seasonal first flush” (Stenstrom and Kayhanian, 2005). Climates with more intense rainfall will result in higher runoff rates, which can lead to decreased BMP performance for some BMP types (Caltrans, 2003c). Regions with high intensity rainfall may require equalization storage to help meter flows to a BMP and regions with low intensity, but steady rainfall may have infiltration constraints associated with saturated soil conditions or high water tables. Therefore, consideration of the rainfall patterns in a region must be considered when selecting BMPs. In arid climates, source control BMPs may need to focus on litter and sediment removal just prior to the first storm of the wet season. Wetter climates may need to consider seasonal performance for infiltration BMPs (Stenstrom and Kayhanian, 2005). Cold climates may need to consider snow storage BMPs to minimize the export of nutrients during snowmelt periods, particularly if traction sands have been applied. As shown in Figure 6-1, pollutant accumulation and wash-off occur per storm event, whereas spring snowmelt releases pollutants accumulated in the snow pack throughout the winter. In general, surface filters, including media beds, permeable pavement, and bioretention with underdrain, are not recommended for sanded areas due to clogging concerns (CWP, 1997). However, the effect of winter road maintenance on nutrient removal performance of BMPs is an area of needed research.



Source: http://stormwater.pca.state.mn.us/index.php/Cold_climate_impact_on_runoff_management
Figure 6-1. Snowpack and rainfall pollutant accumulation and washoff as a function of time.

6.1.2 Land Use

Surrounding land use of a highway section, particularly agriculture and urban, has been indicated as the most important factor affecting the loading of nutrients (Driscoll, et al., 1990). Nutrients from agricultural land use are primarily from fertilizer use, tillage practices, and livestock production, whereas nutrients in the urban environment are primarily from deposition of plant material and fine particulates on impervious surfaces. Decreased urban right-of-way for runoff control BMPs in urban areas may limit the types of BMPs available, which, in turn, can limit BMP effectiveness for nutrient control. For example, linear infiltration facilities and channelized BMPs may be more feasible than a wet pond in constrained environments. Urban environments also tend to show a stronger "first flush" phenomenon (where most of the pollutants are discharged in the first part of the storm) than non-urban areas. Thus, designing runoff control BMPs for first-flush treatment may be more effective in urban areas (Meastre et al., 2004).

Decreased right-of-way also tends to coincide with less vegetation in the right of way, which is both beneficial and detrimental to nutrient management. Canopy and vegetative cover can lead to increased leaf litter and grass clippings, which can be a large source of nutrients and cause maintenance issues for some BMPs. Conversely, increased vegetation in the right-of-way can capture and filter more runoff than impervious surfaces. Therefore, careful selection of surrounding vegetative cover and type are key considerations in nutrient BMP selection and design.

6.1.3 Site Hydrology and Terrain

Highway environments are typically characterized by flatter slopes for vehicle safety and higher imperviousness than other areas. Flatter slopes can affect the hydraulic head available for water to flow through the BMP and the capacity for BMP conveyance systems, which may affect which BMP type is most effective for a site and influence the hydraulic design. Highway environments may be located near or within cut/fill areas which can expose soils, have high slopes draining into the right-of-way, or require slope drains for groundwater control, all of which could lead to increased nutrient loads into the highway environment.

6.1.4 Soils

The soil properties in the highway environment can influence BMP selection and design in several ways. The hydraulic conductivity of the soil may determine if infiltration BMPs are feasible by affecting drawdown times and capture volumes. Additionally, soils adjacent to the ROW and into which BMPs are placed may contain high concentrations of nutrients which can be exported to the highway environment via surface or groundwater flow. If nutrients are a concern, testing of in-situ soils for phosphorus and/or nitrogen may be warranted to maximize BMP effectiveness.

6.1.5 Groundwater

Similar to soils, the characteristics of the groundwater underlying a section of highway can greatly affect which BMPs should be selected and the design of these BMPs. For example, locations with high groundwater may render the use of infiltration BMPs impractical or undesirable. Infiltration BMPs in such areas could contaminate groundwater used for drinking water and, depending on the soil type, could lead to greater risks of liquefaction due to more frequent saturation of the soils.

Karst aquifers are characterized by more soluble minerals such as limestone and dolomite that, when dissolved, can cause sinkholes, caves, and depressions that could potentially damage highway infrastructure and lead to unsafe conditions. Karst aquifers also typically have high conductivities that minimize filtration of highway runoff, increasing the possibility for contamination of groundwater drinking water supplies (Donaldson, 2004). Some DOTs have stringent guidelines for dealing with highway runoff above karst aquifers, which may have a significant effect on BMP selection and design. For example, stormwater ponds can introduce unacceptable structural loadings on karst substrata and infiltration without pretreatment should be avoided. Therefore, BMPs may need to be lined and structurally enhanced in such environments.

6.1.6 Nutrient Cycling

Another factor to consider in BMP selection is the role of nutrient cycling. Nitrogen and phosphorus each undergo natural cycles between different forms, and different types of BMPs affect these nutrient cycles in various ways. For example, BMPs which make use of anaerobic conditions, such as wetlands, can cause denitrification leading to a release of N gas into the atmosphere. However, P has no such removal mechanism and can only be reduced from runoff by uptake into biological material. Over time, this uptake can lead to a build-up of P which can be released into outflows as plants die and decay. Phosphorus can become soluble under anaerobic conditions, so efforts to reduce nitrate can result in phosphorus export if the sources of phosphorus are not removed from the system (e.g., removing sediment and harvesting plants). Large storms after dry periods can also flush P back into the environment. For BMPs employing aerobic conditions, ammonia and organic nitrogen is converted to nitrate, which is negatively charged and very soluble. As a result, some BMP types can be net exporters of nitrate, even as they remove other types of N. Selection and design of BMP must consider the local factors affecting nutrient cycling and the needs of receiving waters.

6.1.7 Construction Methods

Construction methods can have a large impact on BMP performance. Construction can compact soils, which decreases infiltration rates and the efficacy of volume reduction. Heavy earth moving equipment can compact native soil, and topsoil can be removed during grading activities, both of which reduces infiltration to the surrounding soils. In Florida, a 70-90% decrease in infiltration rates were measured at urban construction sites (Gregory et al., 2006). These sites were previously undeveloped lots, and construction vehicles were the main cause of compaction. In Alabama, significant reduction in infiltration rates occurred due to compaction at urban sites (Pitt et al., 2008). It is recommended that grading of infiltration areas use low-impact earth moving equipment such as backhoes, small dozers and skid-steers loaders. Construction techniques such as scarifying and tilling the BMP subgrade surface during excavation can minimize effects of compaction (Brown and Hunt, 2009).

6.1.8 Conveyance Infrastructure

Because roadside ditches are more common in rural environments, co-mingling of highway runoff with adjacent agricultural runoff and groundwater is more prevalent in rural highway drainage systems than in urban, piped highway conveyance systems. If nutrient inflows from adjacent land uses to the ROW are a concern, consideration of a closed system to minimize these flows may be warranted to limit nutrient treatment to highway-generated runoff. Since providing treatment of adjacent agricultural runoff would result in a net environmental benefit and may be less costly than installing infrastructure to separate flows, it may be in the best interest of the DOT and the regulator to come to an agreement in such situations that the DOT is not taking ownership of the agricultural discharge. In fact, the DOT may be able to obtain nutrient offset credits for treating this type of discharge (see Section 6.7 for a discussion of watershed based approaches).

Underdrains for BMPs are only typically required when infiltration rates are low, the water table is close to the surface, or the system must be lined to prevent inflow to contaminated soils or aquifers. Underdrain use should be given careful consideration as part of the project site evaluation, and for maximum nutrient removal via infiltration, an underdrain should be omitted if the site evaluation identifies no infiltration constraints.

6.1.9 Maintenance

Runoff control BMPs require maintenance at the appropriate frequency in order to work properly, and the type of maintenance required varies greatly between BMPs to facilitate continued nutrient removal via the BMP unit treatment processes. More information on BMP maintenance considerations is provided in Section 6.5. In many cases, this maintenance is more difficult to conduct in the highway environment than in other environments due to safety concerns for the workers and public and access concerns in the right of way. Therefore some BMPs that require frequent maintenance may not be well suited for the highway environment (Barrett et al., 1995). Planning for BMP implementation should consider ease of maintenance access needs for inspections and cleanout as part of design considerations to prevent unintentional interference with traffic, provide safe passage around BMPs for maintenance equipment and personnel and protect adjacent properties and wildlife habitat.

6.2 Source Control BMP Considerations

As discussed in Section 5.4.1, the efficiency of source controls for nutrient removal varies widely between projects, sites, and conditions, and the limited available performance data show that they can only achieve a modest reduction in nutrient loads to receiving waters. This section provides guidance on choosing and implementing specific source control BMPs to maximize nutrient reduction in highway runoff. In general, many DOTs are already employing many of the practices detailed below, and newer technology is increasingly making pollution prevention methodology easier and more effective, which increases overall nutrient management cost-effectiveness.

6.2.1 Fertilizer Application Management

As previously indicated, fertilizer application management can be an effective source control BMPs for reducing nutrient loads if fertilizers are currently applied. A research study funded by the Florida Department of Transportation (Chopra et al., 2010) found that highway fertilization is needed to establish roadside turf grasses that prevent soil erosion, but the use of a slow release, phosphorus free fertilizer can significantly reduce nutrient discharges.

The main goal of fertilizer application management is to avoid using excess fertilizer and to apply it in a way that minimizes runoff potential. Such practices include (U.S. EPA, 1995; GPI Southeast, 2012; CASQA, 2003; Chopra et al., 2010):

- Using slow release, no phosphorus fertilizers
- Ensuring all personnel using fertilizers are properly trained and certified
- Testing soil to determine fertilizer needs and applying only as much as is required
- Limiting fertilizer application to the initial seeding or turf establishment period
- Working fertilizers into the soil rather than broadcasting them
- Using slow irrigation methods to prevent runoff
- Cleaning pavement if fertilizer spilled
- Timing fertilizer application to maximize plant uptake and avoid application just prior to or during storms
- Reducing or eliminating fertilizer application near edges of water bodies, within BMPs and conveyance swales, or on steep slopes
- Using track-driven or roller wiper application methods rather than spray application

These management practices rely on training personnel to ensure that those who develop protocols are knowledgeable about fertilizer management issues and the staff performing the work is knowledgeable about the developed protocols. Using a more targeted approach for fertilizer use is becoming easier through the use of technology such as Geographic Information System (GIS) and databases to track fertilizer usage, easier and faster methods for testing soil, and real-time forecasting. Many DOTs can develop standard protocols for fertilizer application in their stormwater or nutrient management plans to specify the required training personnel must receive, help personnel determine the method, when, where, and at what rate to apply fertilizer, and determine other relevant controls such as those listed above. As an example, NCDOT employees are required to become state certified and possess a commercial driver license to operate flatbeds, hydroseeders and application equipment before transporting fertilizer products (NCDOT, n.d.).

6.2.2 Permanent Erosion and Sediment Control

Permanent erosion and sediment controls measures that can reduce particulate-bound nutrients include (FDOT, 2012; Keller and Sherar, 2003):

- Use of check dams, filter strips, and sediment traps
- Permanently covering exposed soils in right-of-way with grass seed or mulch with tackifier
- Maintaining vegetation and reducing disruption of native vegetation to the extent possible
- Stabilizing slopes with terraces, retention walls, etc.
- Surface armoring and ground cover netting on steep slopes or erodible surfaces

NCDOT has had success with compost seeding, a vegetative establishment technique that utilizes a mixture of seed, fertilizer and compost applied pneumatically to roadway slopes, and has expanded its use statewide (Sherrod, 2013). As shown in Figure 6-2, TxDOT was able to quickly establish vegetation using compost on a side slope along State Highway 47. Site-specific erosion and sediment control plans should be developed for all projects and should include the type of erosion and sediment control measures to be used, appropriate implementation of these measures, types and sources of seeds and plants, and planting methods to minimize nutrients introduction to runoff via soil loss.

Source: https://www.fhwa.dot.gov/publications/publicroads/04mar/03.cfm
Figure 6-2. Slope erosion before and 2 weeks after erosion control compost on State Highway 47 in College Station, TX.

6.2.3 Permeable Friction Course

Permeable friction course (PFC) is a porous layer constructed on top of conventional impervious pavement that allows for runoff from the highway surface to flow horizontally through the overlay to the roadside. The quality of water discharged from PFC into the environment is of comparable quality to a sand filter (Eck et al., 2012) without requiring additional ROW. Nutrient reductions with PFC treatment is associated with reducing spray and trapping particulates before they become mobilized.

6.2.4 Pet Waste Control

Most pet waste control programs have been implemented in public parks and residential areas where pets are most likely to be present. In the highway environment, control of pet waste should seek to eliminate pet waste left by vehicles on the highway shoulders or rest areas. Because nutrients from pet waste is typically a result of DOT highway and facility users, not DOT-managed material sources, efforts should focus on human behavior modification through instating ordinances against pet waste disposal in the highway right-of-way, providing educational materials about the effects of pet waste on receiving waters, designating specific pet use areas, and providing bags and receptacles at rest areas for proper disposal of pet waste. North Carolina Department of Transportation (NCDOT) has installed pet waste stations at rest areas which provide educational placards about pet waste, along with bags and receptacles (NCDOT, 2008).

6.2.5 Wildlife Waste Control

Two primary approaches to reduce the amount of wildlife waste (e.g., roadkill and feces) deposited on the road surface are installing wildlife crossings and bird roosting deterrents or exclusion devices. Cliff swallows and pigeons often roost under overpasses and their droppings can be a significant source of nutrients and bacteria. Sejkora et al. (2011) found that nesting colonies of cliff swallows on bridges near Austin, Texas are a significant source of E. coli and fecal coliform. Bird spikes and nets strategically placed on the undersides of bridges can be used to deter birds from roosting, but maintenance is required for long-term effectiveness (RBF Consulting et al., 2014a).

6.2.6 Plant Material Management, Selection and Installation, and Planting Medium Selection

Plant material management can have a significant effect on nutrients in highway runoff. Grass in the ROW often requires mowing to maintain site distances and safety in the highway environment, but mowing too frequently can cause grass clippings to enter stormwater runoff, decreases the ability of grassy areas to capture runoff, and can lead to introduction of invasive species. While they can significantly minimize the amount of runoff generated from a site, trees or other large bushes can counterproductively deposit leaves and other nutrient-rich materials to the right-of-way. Nutrients have been shown to leach from some grass and other vegetative clippings fairly rapidly, with the majority of N and P leached within 1 to 22 days (Strynchuk et al., 2001). Therefore, when practical and at locations where nutrient transport is a concern, grass clippings should be removed.

Careful selection of plants can provide uptake for both phosphorus and nitrogen, storing them as organic P and N, respectively, in plant tissue. Plant uptake of nutrients can be a key removal mechanism, but care must be taken that decomposing plants be removed from BMPs and maintained rights-of-way such that nutrients do not leach back into the system as vegetation dies (VT ANR, n.d.). Choosing trees and plants that leach nutrients more slowly can also help decrease the nutrient load to surface waters (Hobbie et al., 2013). Plant material management, selection and installation practices to control nutrients may include (Mn/DOT, 2008):

- Reducing mowing frequency
- Mowing only in areas needed to improve site distance – maintain an unmowed buffer
- Controlling large bushes and trees to minimize leaf fall on the roadway
- Selection of vegetation with limited leaf and debris litter
- Selection of vegetation with less nutrients or nutrient leaching rates from leaves and debris

Planting medium can capture and remove nutrients if selected properly, or can be a source of nutrients if improperly selected. For example, some planting mediums contain high concentrations of P, which can leach into runoff and groundwater. The P-index is increasingly being used to assess suitability of planting mediums for stormwater management. A higher P-index (50-100) medium is more saturated with phosphorus and can leach phosphorus, while a low P-index (0-25) medium has a low level of phosphorus with the potential ability to capture phosphorus (Hunt, 2011). Many agencies now require planting media with a low P concentration (<10-30 mg/kg) (MPCA, 2014; Hunt, 2011; Fassman et al., 2013). Another consideration when selecting planting media is the use of compost. Compost can help provide nutrients for plants growth, but the use of compost in media mixes has been shown to cause leaching of nutrients in bioretention facilities (Fassman et al., 2013; Roseen et al., 2013). If compost is to be used in planting medium, only well-aged compost should be used and it should be managed similar to fertilizer to minimize nutrient losses to runoff.

6.2.7 Street Sweeping

Nutrient masses measured in materials removed from roadway can be quite large. However, as previously shown in Section 5.4.1, most studies indicated nutrient decreases of less than 10%. While not directly pertinent to the highway environment, one study has seen significant reductions with TP (62-82%) from an urban watershed containing multi-family housing and commercial land uses (Sorenson, 2013). An intensive street sweeping study by Selbig and Bannerman (2007) in Madison, Wisconsin found that regenerative-air and vacuum-assisted sweepers significantly reduced street dirt yields by 60-80%, but sweeping was found to have little direct effect on runoff quality regardless of sweeper type. Statistically significant *increases* of ammonia and nitrate+nitrite loads were found with the vacuum-assisted sweeper. The conflicting results from these studies clearly indicate that more research is needed to fully understand street sweeping practices and its direct effects on water quality for optimizing nutrient control.

There are several possible explanations for the very modest reduction of nutrient concentrations in stormwater from street sweeping. One is that not all nutrients removed from streets and gutters are transported in stormwater. For example, one study examining the nutrient content of swept materials found that 40-97% of the N and 87% of the P was associated with coarse (>2 mm) particles, which are less easily washed into receiving waters (Kalinosky et al., 2012). Some studies have suggested that the removal of the coarse solids actually allows more nutrients from the smaller size particles left on the street to be entrained in runoff (Schilling, 2005). In addition, effectiveness of solids removal may depend on the leaching rates of nutrients from leaf litter and other organic materials, which have been shown to vary (Hobbie et al., 2013).

Another explanation for limited nutrient removal via street sweeping is that the bulk of the nutrient load to some storm drains come from sources other than street litter materials. One study estimated that the nutrient contribution from leaf litter was about 2 orders of magnitude smaller than typical nutrient loads in stormwater, so removal made little difference (Allison et al., 1998). Conversely, other studies estimate that between 40-60% of the P that is exported during runoff during the warm season comes from leaf litter (Hobbie et al., 2013). This value is likely to be a function of the fraction of canopy cover of a watershed, which may also play a role in how effective street sweeping is for nutrient removal. In general, canopy cover is likely to be relatively low in the highway environment. Sweeping frequency and sweeper type seem to play very little role in the efficacy of street sweeping for reducing nutrient concentrations (MDE, 2011; Law et al., 2008; CWP, 2006).

While the quantified nutrient removals are typically very low, street sweeping it a useful source control BMP by removing a measurable amount of nutrients from the highway environment, prevents clogging of catch basins and storm sewers by removing sediment and trash, and can improve nutrient removal effectiveness in downstream BMPs. Street sweeping may be more effective in areas with high canopy cover or seasonally to remove leaves or sanding materials, respectively. On a cost per pound of nitrogen and phosphorus removed, Sansalone et al. (2011) found that street sweeping is 1 to 2 orders of magnitude, respectively, less expensive than structural controls such as hydrodynamic separators and media filters.

6.2.8 Winter Road Management

Winter road management can control nutrients in runoff by both 1) limiting impurities in materials used in road sanding or deicing and 2) using management approaches that minimize the use of these materials such that snowmelt laden with nutrients does not flow to receiving waters. As discussed in Section 5.4.1, Smith and Granato (2010) found that sites with traction sand application had significantly higher phosphorus concentrations than those without. Application management of road sanding and deicer materials for nutrient control include (U.S. EPA, 1995; Venner, n.d.; Venner, 2004; Staples et al., 2004)

- Discontinue or minimize the practice of winter sanding to only critical locations
- Training all personnel involved in deicer and sand application
- Selecting materials which contain less nutrients
- Covering sand and salt storage piles and locating them away from surface waters
- Calibrating sand and deicer application rates to consider road temperature, precipitation type, and accumulation
- Using trucks equipped with deicer application calibration devices
- Using alternative deicing materials near sensitive ecosystems
- Using dedicated snow storage areas that promote melt water infiltration rather than runoff
- Prevent dumping of accumulated snow into surface waters
- Applying deicer before snow and ice start
- Remove as much snow as possible before application of deicer
- Develop a strategic plan for precision application to reduce deicer and sand usage
- Targeting street sweeping for sand removal after application

Most of these practices rely on personnel knowledgeable about deicer and traction material application management issues and proper use protocols. Similarly to fertilizer application management, use of a more targeted use of sand and deicers is becoming easier through the use of technology such as GIS and databases to track deicer application and real-time forecasting so that deicer can be applied prior to the storm when possible. More detailed information on winter road management can be found in the online compendium for NCHRP Project 25-25/Task 04 (Venner, n.d.). Additionally, the final draft submitted to NCHRP regarding bridge stormwater runoff analysis and treatment (RBF Consulting et al., 2014a) contains detailed deicer application guidelines for bridges, which are similar as those that could be used to control nutrients from road deicer use.

6.3 Gross Solids Removal BMP Considerations

Gross solids removal BMPs focus on removal of solids, sediments, plant debris, and trash from the highway environment, and are next type of BMP function after pollution prevention measures. Because nutrients in stormwater sorb to gross solids, removal of the solids should remove nutrients from the highway environment. However, as shown in Section 5.4.1, data indicate that these practices may not be effective at significantly reducing nutrient concentrations, but they are expected to reduce bulk sources of nutrients before they breakdown and are measurable in the water column. A highway litter monitoring study conducted by Caltrans (2002) found that greater than 70% of the wet weight of gross solids (> 5 mm) transported in highway runoff in Fresno and Stockton, California could be attributed to vegetation. Consequently, the nutrient performance of gross solids removal BMPs depends on the timing of gross solids clean out and/or whether the design of the device prevents long-term saturation to reduce decomposition rates of captured organic material. More research is needed to understand the complete mass balance of nutrients and the effectiveness of gross solids removal on long-term nutrient control.

6.3.1 Catch Basin Inserts

Catch basin inserts are designed to remove gross solids, trash, and hydrocarbons usually using filter fabrics or other screening devices at the inlet of catch basins. A Caltrans study examined several types of proprietary catch basin inserts for their ability to remove pollutants from highway runoff. They reported frequent clogging and minimal removal of pollutants, even with frequent maintenance, and recommended that this technology not be routinely considered for implementation (Caltrans, 2003c). A study by DelDOT found similar results and determined that catch basin inserts required a very high frequency of cleaning to avoid clogging and that they performed poorly for pollutant removal (Walch, 2004). It is therefore recommended that these devices only be used where need for trash or large debris removal, and they must be maintained frequently in order to avoid clogging in most areas.

6.3.2 Catch Basin Sumps

Catch basin sumps perform about as well as street sweeping for nutrient removal if emptied and cleaned frequently (Section 5.4.2). A concern with catch basin sumps is that large storms can cause the captured material to re-enter runoff causing large flows of trash and debris in large storms (Howard et al., 2011). If catch basins are not cleaned out, long-term removal efficiency for nutrients is decreased even further (~50% decrease after catch basin is 50% full). The study of a deep-sumped catch basin in Boston, Massachusetts indicated in Section 5.4.2 found that 18% of the final retained load of suspended sediment was resuspended (Smith, 2002). However, there are very few studies that evaluate pollution reduction due to catch basin and storm drain cleaning or that examine optimum cleanout frequencies at a catchment scale (CWP, 2006). Additional research is needed to isolate factors affecting catch basin sump efficiency.

6.3.3 Nutrient Baffles

Nutrient baffles are similar to sumps in that they capture sediment and debris in catch basins or vaults and store it for later removal. However, because most designs dissipate energy coming in, large storms tend to not resuspend trash and sediment as easily as in regular sumps, so they are able to achieve better removal (Howard et al., 2011). Baffles can also often have several chambers where one chamber overflows into the next, which enhances removal of smaller particles. Some devices use baffles as well as filters or screens, and these have been shown to remove nutrients much better than other gross solids removal devices, likely due to employing both settling and filtering unit processes for gross solids. As indicated in Section 5.4.2, studies by GPI Southeast (2010) found that nutrient baffles with horizontal screens above the water line to keep organic material in a dry state were much more effective at nutrient removal than those without screens. However, it should be noted that that access to vaults for inspection and cleanout can be very difficult, and devices that utilize filters/screens are prone to clogging.

6.3.4 Oil/Water/Grit Separators

The ability of oil-water-grit separators to target a large range of particles promotes a higher level of nutrient control. Design of oil/water/grit separators for nutrient management should focus on maximizing particle removal, especially fine particles as it has been shown that P sorbs binds more effectively to smaller particles (Section 4.5). As indicated in Section 5.4.2, the study by Smith (2002) indicated that the secondary chamber within the oil/water/grit separator was critical to targeting finer particles, thus maintaining sediment capacity of this second chamber will likely maximize nutrient control effectiveness. Like nutrient baffles, screening of organic material within the first chamber of the oil/water/grit separator will also aid in minimizing nutrient entrainment in runoff.

6.4 Runoff Control BMP Considerations

Runoff control BMPs typically require additional infrastructure, and, in a retrofit situation, may require physical site alteration for implementation. Consequently, BMP capital and operation and maintenance (O&M) costs (Section 6.5) for runoff control BMPs tend to be higher than source control measures. This section discusses general techniques for volume reduction and targeted nutrient treatment BMPs that are applicable for many runoff control BMPs. Runoff control BMPs can take the next step in the functional approach process by providing treatment through inclusion of various physical design strategies to increase nutrient control. The BMP designs detailed in this next section engage the physical, biological, and/or chemical unit processes that improve phosphorus and nitrogen removal in BMPs.

6.4.1 General Runoff Control BMP Considerations

Filter Media and Additives. Filter media like inert sand or other specialized reactive media and/or additives can be incorporated into BMPs to improve nutrient removal. This media can be added to volume control BMPs to provide enhanced treatment prior to infiltration and serve as the primary treatment mechanisms in media filter drains and sand filters. Other treatment BMPs such as bioretention can use specialized filter media in place of traditional bioretention soil mixes to specifically reduce nutrients.

Factors influencing the performance of filter media can include external factors like hydraulic loading rate and retention time, organic and nitrogen loading rates, influent pH and alkalinity, as well as internal factors such as the media's particle size distribution, surface area, redox potential, ligand complexation, and ion exchange capacity. Filter media structure and microbial function will affect the type of denitrification that will occur (autotrophic versus heterotrophic) and the frequency of oxic/anoxic fluctuations that ultimately affect the amount of denitrification. Phosphorus can be removed in either aerobic or anaerobic environments via proper sorption media, but phosphorus removal decreases as sorption sites fill and precipitation becomes the dominant process. More research is needed to understand the competing considerations for nitrogen and phosphorus and if they sorb onto the same filter media sites (Chang et al., 2010; Reddy et al. 2013).

Several studies have found several filter media types and additives that have been shown to reduce nutrients from stormwater. Wanielista and Chang (2008) found that a filter media mixture of sandy loam, limestone, tire crumb and sawdust was found to be cost-effective for nutrient removal, including both nitrogen and phosphorus, within an appropriate detention time via the sorption processes (Chang et al, 2010). Iron-enhanced sand filters, which are sand filtration systems with 5-8% percent elemental iron (such as aggregate or filings) by weight, have been used successfully in Minnesota to remove total phosphorus (TP) and orthophosphate (OP) for discharges from a sand filter basin and a sand filter bench along the perimeter of a wet pond. Based on lab testing results comparing inflow and outflow concentrations, the long-term expected removal of dissolved phosphorus is at least 80% after a 35-year period, equivalent to 200 meters of treated depth. However, the lifespan of the iron material is still unknown, and because iron has the capacity to bind with other stormwater pollutants such as fluoride and sulfide, this could decrease binding capacity for phosphorus. (MPCA, n.d.; Erickson et al., 2011). Similarly, in a batch laboratory study of four types of filter media (calcite, zeolite, sand, and iron filings) Reddy et al. (2013) found that removal of both nitrate and phosphate was the most successful (73-100% removal) when the filter material was iron filings. Iron filings were more effective in removal for the entire range of simulated stormwater concentrations of nitrate and total phosphorus than the other three filter media types.

Other materials that have been added to filter media with good results for phosphorus removal include water treatment residuals (WTRs). WTRs, which can sorb OP to calcium, iron and aluminum sites, are a byproduct of coagulation/flocculation in water treatment processes and are typically widely available (Hunt, 2011; Palmer et al., 2013). Oxide-coated sand, calcite, fly ash, and expanded shale have also been identified as key additives for phosphorus removal (Minton, 2012; VT ANR, n.d.).

Nitrogen removal additives include wood chips and newspaper that promote the denitrification process by adding a carbon food source for microbial processes (VT ANR, n.d., Christianson and Helmers, 2011). These additives can be critical to nutrient removal when plants are being established and are unable to provide nutrient uptake (Palmer et al., 2013). In a laboratory study by Tian et al. (2014), the addition of biochar to sand was shown to be effective for the removal of ammonium, which upon conversion to nitrate was available for plant uptake as part of the nitrogen cycle. Additionally, available biochar pore volume aided in water retention, which may limit the volume of stormwater and associated nutrients released from a BMP.

Saturation Zone. A saturation zone is a permanent volume of water at the bottom of a BMP that creates an anaerobic zone to promote denitrification such that nitrogen is lost to the atmosphere (VT ANR, n.d.). A saturation zone was found to significantly reduce nitrate in effluent water in bioretention media column tests, with results indicating 71% nitrate removal compared to only 33% without a saturation zone (Palmer et al., 2013). This saturation zone can be created via an upturned elbow installed at the downstream end of an underdrain or via an internal weir structure designed to hold back water to a certain design ponding level. For areas where infiltration is prohibited or undesirable, an impermeable liner can be used to create the saturation zone. For areas where infiltration is allowable, but an underdrain is incorporated for drainage needs, the use of internal water storage below the underdrain outlet (Figure 6-3) can significantly reduce the ratio of outflow volume to inflow volume (Brown et al., 2009).

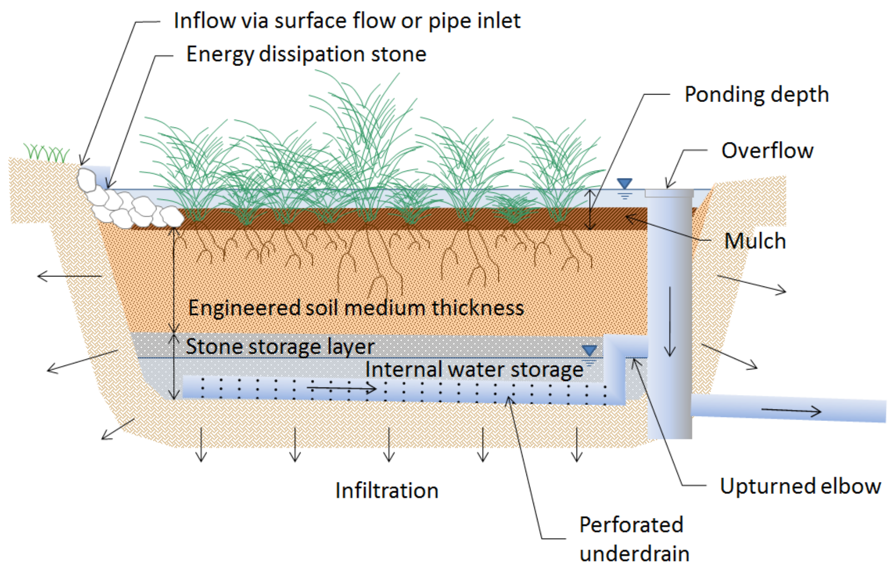


Figure 6-3. Schematic bioretention with underdrain and internal water storage.

Hydraulic Residence Time. A longer hydraulic residence time (HRT) can increase the opportunity for phosphorus and nitrogen uptake by plants, as well as time for sorption of dissolved phosphorus and ammonia and settling of particulate phosphorus (VT ANR, n.d.). A larger length-to-width ratio, longer and more tortuous flow path, and outlet control can help achieve a longer HRT for BMPs to provide greater nutrient removal.

6.4.2 Volume Reduction BMP Considerations

Volume reduction BMPs can reduce nutrient loading to receiving waters by reducing overall runoff volumes (Brown and Hunt, 2009), and can be used upstream of a targeted nutrient treatment BMP to reduce the volume of runoff required to be treated to achieve nutrient effluent limitations. In the highway environment, volume reduction is achieved primarily through BMPs that promote infiltration, though evapotranspiration will also reduce a lesser amount of volume from many BMPs. Assuming uniform mixing, it is estimated that reducing the runoff volume discharged from the BMP will reduce the nutrient load associated with the volume reduction via infiltration.

Bioretention (no underdrain). Bioretention relies on infiltration and a filter bed, which typically has a media mixture of sand, soil, and organic material, and a surface mulch layer. Studies have shown that bioretention can reduce runoff volumes and nutrient loads (Hunt et al., 2006; Davis, 2008). During storms, runoff temporarily ponds a shallow depth of water above the mulch layer, which then is evaporated or filtered through the media bed. Flows through the media bed are consequently infiltrated to the surrounding soils.

Infiltration Facilities. Infiltration facilities that are primarily used by DOTs include infiltration basin and infiltration/exfiltration trenches as well as more rarely used underground infiltration vaults (Venner at al., 2013). Infiltration facilities primarily provide nutrient removal via volume reduction through filling soil pores and secondarily through filtering and other unit processes. Considerations for use in nutrient removal are not greatly different from traditional application, though incorporation of a filter media layer for enhanced nutrient removal is an option for locations where groundwater impacts are a concern. Design considerations include safe bypass of overflow for runoff exceeding the infiltration facility capacity and possible subsurface flows from the facility to adjacent pavement subgrade and/or buildings.

Permeable Shoulders or Parking. Permeable shoulders or parking take flow from the roadway and temporarily store and treat runoff before infiltration into the roadway subgrade soils and/or discharge to other stormwater conveyance and treatment systems (Hein et al., 2013). Nutrient removal is similar in nature to infiltration facilities and porous pavement technologies.

Porous Pavement. Porous pavement is often used for shoulders, parking spaces or other low traffic areas but is not unilaterally accepted for a main driving surface by DOTs. It has been shown to reduce runoff volumes and pollutant loads in several studies (Bean et al., 2007; Collins et al., 2008). Stormwater is stored in the underlying gravel layer, and is either evaporated, infiltrated to the surrounding soils, or transported via underdrains to a stormwater system or outfall. Nutrient leaching to the subsurface has been observed due to decomposition of organic materials on the surface of the porous pavement, residual fertilizer, and leaching from the pavement itself (Roseen et al., 2012; Hogland et al., 1987; Hunt and Collins, 2008). Nutrient removal can be improved by frequent vacuuming of the pavement surface and design components such as a filter media layer between the pavement and the gravel layer.

To improve infiltration to the surrounding soils without losing the ability of the soil to support the pavement, the porous pavement subgrade should be treated with boreholes, ripping, or trenches (Brown and Hunt, 2009). Boreholes filled with coarse sand, excavated trenches backfilled with coarse sand or aggregate, and a subsoil ripper have been shown to increase infiltration rates (Tyner et al., 2009). A subsoil ripper makes rips along the length of the plot, and coarse sand is poured over the ripped surface to fill cracks and fissures.

Vegetative Filter Strip. Vegetative filter strips are simple BMPs can be used prior to discharge to other BMPs or in constrained areas to provide effective filtering of solids and volume reduction. Because they are a flow-through BMP, not a storage-based BMP, they are more flexible for use on steeper slopes or areas where other BMPs may not be feasible or practicable.

6.4.3 Targeted Nutrient Treatment BMP Considerations

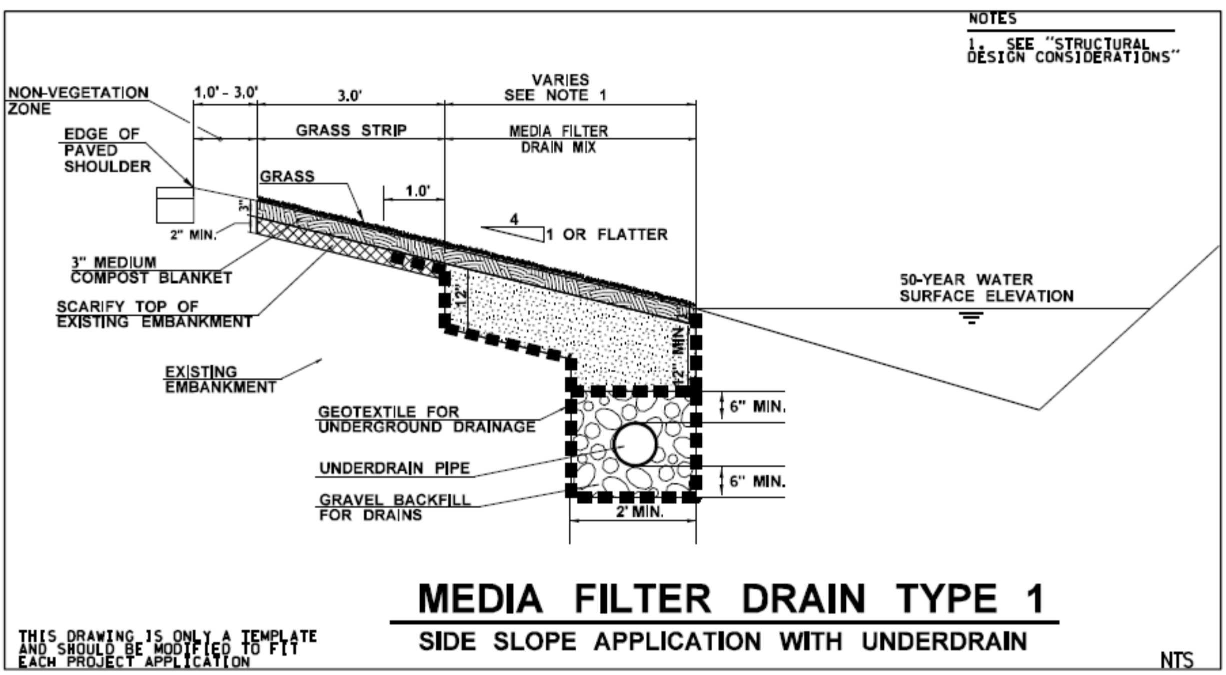
On the spectrum of runoff control BMP designs, targeted nutrient treatment BMPs typically have the most sophisticated designs, and are generally more costly than source control and simple volume control BMPs because they provide a higher degree of nutrient removal. Targeted nutrient treatment BMPs can provide reductions for harder-to-remove fine and dissolved particles, which make them a good choice for placement at the end of a BMP treatment train, after larger particles have been removed and runoff volumes have been reduced to the maximum extent practicable.

Bioretention (with underdrain). An underdrain for bioretention is typically only required when infiltration rates are low or the water table is close to the surface and is typically installed in a bottom gravel layer with connection to a stormwater system or outfall. Leaching of nutrients from compost has been observed in bioretention systems with underdrains (Herrera, 2012), which can be reduced by using media mixes low in organic content or selection of a planting medium with a low P-index, as discussed in Section 6.2.6. A saturation zone can be added to increase nitrate removal.

Dry Detention Basin. Dry detention basins have a reputation that they are not as effective as wet ponds in removing nutrients (U.S. EPA, 1999; CWP, n.d.), but performance data indicates these BMPs can be effective at removing particulate phosphorus and possibly nitrate and ammonia (Section 5.4.3). This dry detention basin performance for nutrient removal can be linked to the HRT provided for adequate gravitational settling time and denitrification opportunity (VA DCR, 2011). Thus, detention basins providing extended drawdown times, usually provided via outlet control design to limit the release rate from the basin, will typically have greater nutrient removal than basins with shorter drawdown times. Estimated mass removal efficiencies for dry detention systems are 0-30% for total nitrogen and 0-40% for total phosphorus depending on the relationship between the pond bottom or underdrain and the groundwater table elevation, and the anticipated settling of pollutants present in a particulate form within the pond (Harper and Baker, 2007; Hussain, 2005).

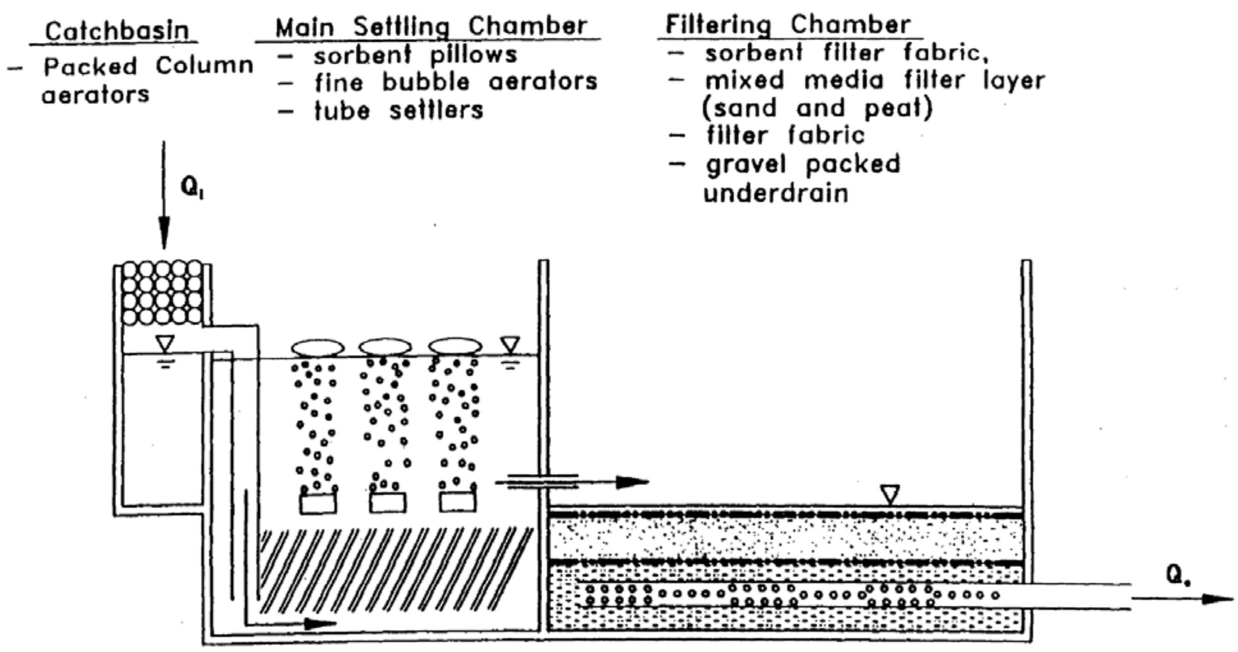
Media Filter. Filter media and additives, previously discussed, can be used independently of other BMPs to provide nutrient treatment. Both proprietary and non-proprietary media mixtures can be used to provide nutrient control, with varying associated costs. Testing of media with anticipated unit flow rates is generally recommended to provide a level of confidence that the nutrients of concern will be removed at the design hydraulic loading rate. Minimum contact times for nutrient removal can vary between various media mixes and should be understood prior to designing the media system hydraulic controls. Pretreatment to remove gross solids is generally required to prevent clogging of the media bed.

Media Filter Drain. Media filter drains (Figure 6-4) are runoff treatment options that are effective for phosphorus reduction and can be sited in most right of way confined situations where conventional treatment is not feasible (WSDOT, 2014). Enhanced nutrient treatment can be achieved with incorporation of specialized filter media similar to the more conventional media bed filters.



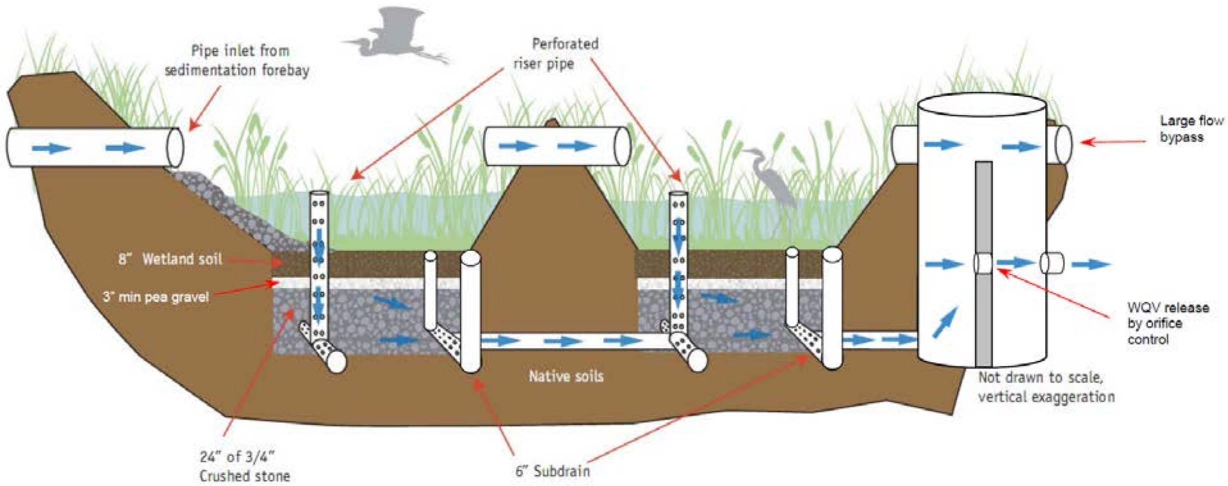
Source: WSDOT (2014)
Figure 6-4. Cross-section schematic of media filter drain.

Multi-Chambered Treatment Train. Multi-Chambered Treatment Trains (MCTT) is an underground vault system that employs screening in the first chamber to remove gross solids, settling in the next for fine particles, and filtration in the last chamber (CWP, 1995; Pitt et al., 1999). Thus, this three chambered approach allows for many unit processes for nutrient reduction. There are also various components that can be incorporated such as wedge-wire screens, baffles, plate settlers and specialized filter media to enhance nutrient removal performance (Figure 6-5).



Source: Pitt et al. (1999)
Figure 6-5. Cross-section schematic of Multi-Chambered Treatment Train.

Subsurface Flow Wetland. Subsurface flow wetlands convey runoff through a gravel (generally limestone or volcanic rock lava stone) or sand substrate and may or may not include surface vegetation. In subsurface flow systems, flows may move either horizontally, parallel to the surface, or vertically, from the planted layer down through the substrate and out (Figure 6-6; Figure 6-7). Subsurface, horizontal-flow wetlands are less of an attraction for mosquitoes and wildlife as there is less frequent open water, and these systems typically require less land area for water treatment in comparison with other runoff control BMPs. Research has demonstrated variable removal of nutrients with this technology (Kiracofe, 2000). Ammonia volatilization losses are negligible in subsurface flow wetland systems and, because of the gravel media typically used, adsorption is minimal. Biological denitrification is the major removal mechanism of nitrogen in subsurface flow wetland systems, with plant uptake accounting for less than 10-15%. It is not necessary for the entire system to be anoxic for denitrification to occur, and anoxic and aerobic microzones often exist adjacent to each other in most natural treatment systems, in the soil, water, and plant interfaces (Titus, 1992). A saturation zone and vegetation will increase nutrient removal in subsurface flow wetland systems.



Source: UNHSC (2009)
Figure 6-6. Schematic of a subsurface flow wetland.

Figure 6-7. Post-construction photo of a subsurface flow wetland installed in Salem, OR.

Wet Pond, Wetland Basins, and Wetland Channels. Wet ponds, wetland basins, and wetland channels have a permanent, open-water pool that provides an environment for pollutant settling, biological uptake and microbial transformations. In Florida, to evaluate wet pond mass removal efficiencies, researchers divided treatment into 7-day and 14-day detention times and found mass removal efficiencies ranging from 20-30% for TN, and 60-70% for TP (Harper and Baker, 2007). Wetland systems (basins and channels) or wet ponds with a portion designed as a wetland by incorporating appropriate aquatic plants, growing medium, and bottom elevations can provide significantly more nutrient uptake (VA DCR, 2011). In a research study sponsored by the Florida Department of Transportation (FDOT), Wanielista et al. (2012) found that the nutrient removal performance of wet ponds could be improved and the occurrence of algal blooms decreased by incorporating mats of floating wetland vegetation (Figure 6-8). Oregon Department of Environmental Quality (OR DEQ) reports that wetlands retaining and treating stormwater for 36 hours can reduce nitrate by 65%, TP by 40-100%, TN by 28-90%, and soluble reactive phosphorus by 75% (Jurries, 2003). Because open water of a wet system can attract wildlife like Canadian geese which can increase nutrients from droppings, BMP design should consider incorporation of dense, tall native plants around ponded areas instead of a more manicured, turf grass approach to discourage animal grazing or resting (SEMCOG, 2007).

Source: Wanielista et al. (2012)
Figure 6-8. Deployment of floating wetland vegetation as a retrofit to an existing wet pond.

6.5 BMP Capital and O&M Costs

Both capital and O&M costs must be considered as part of nutrient BMP strategies and designs in order to fully understand the DOT resources needed for the BMP lifetime. Focusing only on capital or initial costs can lead to design decisions that result in greater lifecycle costs due to increased maintenance activities (Lampe et al. 2005). Stormwater nutrient controls should therefore consider the net costs of using a technology when scoping potential BMPs. Net cost calculations should give consideration to the functional category of the BMP (Section 5.0) and assess the value of source controls over runoff treatment as well as determine the tradeoff between increased gross solids pretreatment and volume control over finer particle treatment. Costs placed towards the initial BMP subfunctions can minimize BMP maintenance and replacement activities, resulting in lower overall costs. This section provides basic information on BMP and project cost factors, relative capital and O&M cost comparisons, and strategies to reduce the cost per pound of nutrients removed.

6.5.1 BMP Cost Factors

Described below are the capital cost, O&M and regional factors that will influence BMP costs summarized from various in-progress NCHRP projects (RBF Consulting et al., 2014a; RBF Consulting et al., 2014b; Geosyntec Consultants, 2014) to provide a framework for nutrient BMP cost comparison.

Capital Cost Factors. Capital costs are fixed value, one-time expenses for purchasing labor, land, materials, or equipment needed to provide operational stormwater BMPs. Capital costs may include:

- Conceptual planning and design
- Land acquisition
- Site investigation and surveying
- Preliminary and final engineering design
- Permitting and recording fees
- Initial construction material and equipment

O&M Cost Factors. O&M costs are needed to preserve a BMP's water quality, volume reduction, and conveyance functions, and, in some cases, its aesthetics. These O&M costs include any labor, equipment, replacement material, and disposal costs over the lifespan of the technology. Both the maintenance frequency and expected lifespan of a BMP will impact the overall O&M costs. Major restorative maintenance or replacement can significantly raise the cost of a BMP if they must be completed frequently.

BMP functional maintenance helps preserve the performance and safety of the BMP, whereas aesthetic maintenance helps provide public acceptance of the technology. These types of maintenance activities are both important to BMP success and can be intertwined. Regularly raking and bagging leaves or other vegetation for aesthetic reasons, for example, may reduce the need for more costly BMP maintenance and improve the long-term nutrient control of the system. Often overlooked O&M considerations are unanticipated conditions that could arise from factors such as inadequate pre-treatment and/or maintenance access, or public safety and/or aesthetic concerns.

Regional Factors. Some regional parameters that influence BMP costs include the following:

- **Soil type and groundwater vulnerability** will determine the type of BMPs that can be used on a site. Poorly drained soils may require additional storage volume, surface area, and/or an underdrain system, which can significant raise costs compared to BMPs installed in well-drained soils.

- **Hydrologic factors** such as average annual rainfall, storm characteristics, catchment area runoff characteristics, and climate will affect BMP sizing and, therefore, costs to meet nutrient reduction objectives.
- **Seasonal construction considerations or weather delays** can influence BMP implementation costs due to changes in equipment usage, variations in material handling, or increased material costs. For example, dewatering volume, concrete curing time, and plant establishment are all affected by climate.
- **Material supply and demand and transportation costs** can have a tremendous impact on implementation. Locally available and manufactured materials can often keep BMP unit costs low and reduce procurement delays.
- **Availability of suitable plants** for the site and region (based on the local climate) and the level of planting needed for a particular BMP or nutrient reduction goal will influence cost. Additionally, planting influences the maintenance costs and could add additional costs such as irrigation.
- **Water quality regulatory requirements** and differences in acceptable limits for nutrient concentrations and/or runoff volumes influence the sophistication of the design, which can result in varying BMP capital and O&M costs.

6.5.2 Project Cost Factors

Project related costs can significantly affect the cost of a BMP and include the following:

- **Flexibility in site selection and site suitability** can impact costs throughout a region. Site specific parameters that influence costs include the ability to configure the site to allow efficient drainage design, the availability and accessibility of the work area, traffic control (in retrofit projects), site contamination, and existing infrastructure. In terms of nutrient reduction, areas with high amounts of nutrient-rich sources such as leaf litter, vegetation, and animal waste will require more effort and have greater costs to achieve the same concentration reduction as a similar site without those factors.
- **Land allocation and land use costs** are likely to create one of the largest differences in project costs. In some cases, DOTs could have a surplus of land in the ROW suitable for a BMP, while in other cases, the implementation of the BMP might require additional land purchases. In the latter scenario, the cost of land can be extremely variable by location depending on surrounding land use and local economy (Strassler et al., 1999).
- **Project scale and unit costs** will affect individual BMP costs. Larger projects with fewer, large scale BMPs can potentially be built at lower costs than smaller projects or projects with many distributed controls. Larger scale projects may have reduced per unit area management costs. Each BMP component may have fixed costs (for example, an inlet and outlet structure) regardless of size, and therefore similar elements for numerous BMPs may increase overall costs. Exceptions to this can occur if the use of more distributed controls helps avoid significant and costly conventional drainage infrastructure that would be integrated as part of the road project and/or for downstream improvements.
- **Type of project** – new road, retrofit, or lane addition – makes a significant difference in cost. Many BMP related costs can be added to a project at little additional cost in the case of a new roadway or lane addition. However, retrofit-specific costs can include project costs that would have likely been absorbed by a new construction project including mobilization, surveying, and traffic control. Additionally, retrofit projects are usually smaller, and unit prices are typically higher for smaller material quantities. Design costs for retrofits can be 150% or more of new construction costs because retrofits are designed as separate, individual projects with their own site visits, surveying, utility locates, and bidding process. Retrofits can also have unforeseen costs such as difficult site drainage or other difficulties that may not be encountered with a new construction project (URS, 2012).

6.5.3 Organizational O&M Cost Factors

DOT organizational O&M cost factors are those associated with O&M that may not be as explicitly valued, including traffic impacts associated with maintenance, agency training and equipment for O&M programs and activities, and uncertainty in planning for maintenance activities. The following guidelines for BMP prioritization would tend to result in lesser O&M impact to agencies:

- Prioritizing BMPs that require maintenance activities similar to those regularly conducted by DOT personnel
- Prioritizing BMPs that are currently in use and those that the agency has experience operating and maintaining
- Introducing promising new BMPs as pilot projects initially before using them on a broader scale to understand O&M requirements and cost-saving approaches

For BMPs for which the DOT agency does not have experience, it is important to develop a forecast of O&M activities including:

- Determining which activities are needed
- Estimating the necessary frequency of these activities
- Estimating the labor effort and equipment costs associated with these activities
- Estimating the other direct costs, such as materials and disposal

Estimating the programmatic costs associated with BMP maintenance

6.5.4 BMP Capital and O&M Cost Summary

Tables 6-1 through 6-3 summarize relative capital costs, O&M costs and frequency, and special nutrient considerations for source and runoff control BMPs.

Table 6-1. Relative source control BMP costs per lb of nutrients managed.

BMP	Capital Costs	O&M Cost per Visit & Frequency	O&M and Nutrient Control Considerations	Effective Life Span
Fertilizer Application Management	$-$$	$ - Variable frequency	• Depends on staff resources and frequency of new staff training for effectiveness	Dependent on O&M
Permanent Erosion and Sediment Control	$-$$	$ - Variable frequency	• Requires staff training for proper sediment removal and disposal techniques • Labor intensive in some locations	Dependent on O&M
Permeable Friction Course	$$	$-$$ - Low frequency	• Vacuum-assisted or regenerative air street sweeper needed to unclog pores	15-25 years
Pet Waste Control	$	$ - Variable frequency	• Depends on staff resources and frequency of new staff training • Proper placement of signage waste bags key to success	Dependent on O&M
Plant Material Management	$-$$	$ - Variable frequency	• Requires staff training for proper cutting and disposal techniques • Labor intensive in some locations	Dependent on O&M
Plant Selection and Installation Methods	$-$$	$ - Variable frequency	• Requires staff training for proper plant selection and soil care • Native plants provide nutrient uptake and require less maintenance	Dependent on O&M
Planting Medium Selection	$-$$	$ - Low frequency	• Requires testing of soil properties • Media selection can highly influence performance	Dependent on O&M
Street Sweeping	$	$-$$ - Variable frequency	• Vacuum-assisted and regenerative air sweepers more effective than mechanical sweepers • Poor sweep practices can move material into storm grates, causing higher nutrient discharges or affect conveyance based BMPs • Proactive sweeping is more cost-effective	Dependent on O&M
Winter Road Management	$-$$	$-$$ - Variable frequency	• Depends on staff resources and frequency of new staff training for effectiveness	Dependent on O&M

Legend:
$- under $5,000
$$- over $5,000

Source: WSDOE, 2005

Table 6-2. Relative gross solids removal BMP costs per lb of nutrients managed.

BMP	Capital Costs	O&M Cost per Visit & Frequency	O&M and Nutrient Control Considerations	Effective Life Span
Catch Basin Insert	$	$ - High frequency	• Poor maintenance or low maintenance frequency can cause outflow of nutrients due to clogging, bypassing flows and/or resuspending material • Clogging can also present traffic safety concerns	10-20 years
Catch Basin Sump	$-$$	$-$$- High frequency	• Poor maintenance or low maintenance frequency can cause outflow of nutrients due to clogging, bypassing flows and/or resuspending material	10-20 years
Nutrient Baffle	$-$$$	$-$$ - High frequency	• Poor maintenance or low maintenance frequency can cause outflow of nutrients due to clogging, bypassing flows and/or resuspending material	10-20 years
Oil/Water/Grit Separator	$$-$$$	$-$$- High Frequency	• Poor maintenance or low maintenance frequency can cause outflow of nutrients due to clogging, bypassing flows and/or resuspending material	10-20 years

Legend:
$- under $5,000
$$- $5,001- 10,000
$$$- over $10,000

Source: WSDOE, 2005

Table 6-3. Relative runoff control BMP costs per lb of nutrients managed.

BMP	Capital Costs (New Project/ Retrofit)	O&M Cost per Visit & Frequency	O&M and Nutrient Control Considerations	Effective Life Span
Bioretention	$$/$$-$$$ ($+ with underdrain)	$-$$ - Moderate frequency	• Pretreatment to remove coarse sediment and debris will reduce clogging and associated maintenance, as well as reduce the introduction of detrital nutrient sources • Limit compost/organic matter of media to prevent nutrient leaching • Adding a saturation zone can help aid denitrification • Performance dependent on effectiveness of pretreatment • Maintenance intervals may be shorter if plant roots and stems keep soils open for infiltration	5-12 years (restoration) 25 to 50 years (decommission)
Dry Detention Basin	$$/$$$	$-$$ - Low frequency	• Maintenance intervals may be shorter if vegetation is robust	5-12 years (restoration) 25 to 50 years (decommission)
Infiltration Facility	$$/$$-$$$	$-$$ - Low frequency	• Requires infrequent maintenance to scarify the surface and/or remove deposited sediment • Effective pretreatment will increase infiltration longevity	10-25 years (based on robust pretreatment)
Media Filter	$/$-$$	$-$$ - Low frequency	• Frequent inspection and maintenance to remove sediment from pretreatment forebay/chamber • Periodic maintenance possibly needed to replace media, or can become a source of nutrients	5-20 years
Media Filter Drain	$-$$/$$	$-$$ - Low to moderate frequency	• Requires infrequent maintenance to remove sediment, and maintain conveyance if tributary watershed is stabilized • Periodic maintenance possibly needed to replace media, or can become a source of nutrients	5-20 years (maintenance dependent)
Multi Chambered Treatment Train	$$/$$-$$$ (depends on components)	$$ - High frequency (depends on components)	• Frequent cleaning of pretreatment chamber • Infrequent replacement of media bed	10-20 years
Permeable Shoulders or Parking	$/$$$	$ - Moderate frequency	• Vacuum-assisted or regenerative air street sweeper needed to unclog pores	15-25 years

Table 6-3. Relative runoff control BMP costs per lb of nutrients managed. (Cont'd)

BMP	Capital Costs (New Project/ Retrofit)	O&M Cost per Visit & Frequency	O&M and Nutrient Control Considerations	Effective Life Span
Porous Pavement	$/$$$	$ - Moderate frequency	• Vacuum-assisted or regenerative air street sweeper needed to unclog pores	15-25 years
Subsurface Flow Wetland	$$/$$-$$$	$-$$ - Moderate to high frequency	• Pretreatment needed to reduce clogging potential • Vegetated systems may require year-round base flow • Add saturation zone to aid denitrification	5-12 years (restoration) 25 to 50 years (decommission)
Vegetated Filter Strip	$/$$	$ - Low frequency	• Nutrient performance will be based on vegetation types and underlying soil. • Requires periodic removal of undesirable vegetation	20-50 years
Wet Pond	$$-$$$/$$$	$-$$ - Low to moderate frequency	• Infrequent sediment removal in forebay • Infrequent vegetation harvesting to permanently remove nutrients • Multiple-cell design will provide more nutrient removal but more maintenance burden	5-12 years (restoration) 25 to 50 years (decommission)
Wetland Basin	$$-$$$/$$$	$-$$ - Low to moderate frequency	• Infrequent sediment removal in forebay • Infrequent vegetation harvesting to permanently remove nutrients • Initial vegetation establishment period requires highest level of maintenance • Multiple-cell design will provide more nutrient removal but more maintenance burden	15-25 years
Wetland Channel	$-$$/$$$	$-$$ - Low to moderate frequency	• Infrequent vegetation harvesting to permanently remove nutrients • Initial vegetation establishment period requires highest level of maintenance	5-20 years

Legend:
$- under $10,000
$$- $10,001- 20,000
$$$- over $20,000

Sources: WSDOT, 2014; Ballestero et al. 2007; LIDC, 2005.

6.6 Organizational Efforts

In addition to source control, gross solids removal and runoff management strategies, DOTs have employed internal and external coordination and education efforts to address nutrient issues. These efforts are both internal, focusing on DOT staff development and organizational support for nutrient management goals, and external, focusing on more far-reaching, multi-agency nutrient planning and management goals.

6.6.1 Internal Coordination and Education

DOT nutrient reduction efforts have profited from internal employee training for source control and runoff management strategies. Training, combined with tracking and reporting requirements and an organizational commitment to effective nutrient management can create internal expectations that proactively manage and address problems without the need for external regulation.

Training. Some DOTs including MDSHA, NCDOT and WSDOT provide targeted employee training for source control. Most DOT training programs are available for exchange or sharing among state transportation agencies upon request. FDOT has developed a Program for Nutrient Design as well as a Training Course for Nutrient Design (Renna, 2012).

A number of DOTs have training programs for fertilizer application, as discussed in Section 4.1.1. Oregon and Washington DOT's have a training program on Quality Biosolids Management, initially developed by Oregon State University. The program covers regulatory compliance, biosolids quality and testing, transportation to land application, nutrient management through calculation of agronomic rates and soil testing, site suitability assessment, and biosolids application (Sullivan, D., 1999).

Tracking and Reporting. Virginia and New York State DOTs are examples of state transportation agencies that track storm drain clean out. Tracking and reporting are also components of many NPDES permits and increasingly of cross-cutting environmental management systems.

Organizational Commitment. MDSHA staff report that the agency's organizational commitment has made their work a lot easier. Staff has been able to overcome the water quality challenges because of management support. To successfully implement needed changes, water quality managers need to be able to make recommendations and have organizational support (Pujara and Minami, 2013).

6.6.2 External Coordination and Education

External coordination is critical for DOTs, whether being aware of and participating in state modeling and planning efforts or identifying where DOTs could leverage watershed or municipal planning efforts to efficiently address nutrient reduction. As stated by MDSHA (Pujara and Minami, 2013):

> *There are also opportunity sites to do something, when we can't do something in the ROW; those are places MDSHA can leverage, often in partnership projects with others. In the TMDL business, it is so important to know what we own and what its use is, and then understanding what the future needs of the transportation system are.*

Other opportunities for external coordination include the DOT's requirements for connecting to the storm sewer system, cooperative public education campaigns with co-permittees or other state agencies, and collaborating to address restoration opportunities or needed erosion improvements.

DOT Storm Sewer Connections. Most DOTs require third parties to meet certain requirements in order to connect to the DOT storm sewer system. DOTs seek reasonable assurance that the project will not cause or increase flooding in roadways, and increasingly, DOTs seek assurance that the project will not increase stormwater nutrients.

In Florida, projects developing or improving property abutting DOT right-of-way must apply for a Drainage Connection Permit. Exceptions include single family homes and minor farming and agriculture improvement projects that 1) reduce impervious area, 2) increase onsite stormwater storage, and 3) maintain existing grades. FDOT District 4 (Ft. Lauderdale) requires land owners to have no direct connections to the FDOT storm sewer system, and control structures that discharge to FDOT must have permanent concrete weirs. The agency requires completion of an application form; paving, grading and drainage sheets for the entire site; control structure details; an existing survey; and a drainage report. The district indicates that water quantity is the focus of these efforts, though water quality is important (MarQuellus, B. et al., 2012).

Public and Private Partnerships. Public and private partnerships can help establish widespread management of nutrients. DOTs often collaborate with the public education component of local MS4 efforts and sometimes statewide campaigns, whether through stenciling storm drains, publishing brochures, or other public information resources. For example, FDOT participates in multi-agency street sweeping programs for litter and programs to control pet waste. The state has implemented a public education campaign targeting “personal pollution” that includes encouraging “Florida-friendly” yards and reducing nutrients used around the home (AASHTO, 2011b).

Collaborative planning efforts can help realize potential restoration sites and how best to address erosion prone areas on and off the right-of-way. As MDSHA identifies and addresses areas where stabilization is needed, the agency has observed that there are often opportunities to improve stormwater quality and address nutrients in runoff at nearby sites. In such cases, MDSHA often explores opportunities for cost-sharing. MDSHA is communicating with counties and local governments as it explores reforestation, outfall remediation, and restoration opportunities (Pujara and Minami, 2013).

A challenge that has arisen is that Maryland residents are now paying a new statewide stormwater treatment fee, and therefore are less willing to see MDSHA make any reductions in on-site efforts as a result of finding off-site restoration opportunities. Maryland communities feel that MDSHA should have the same responsibility and burden to treat stormwater onsite as other developments, which has slowed off-site restoration partnership efforts (Pujara and Minami, 2013). Thus, overall stormwater management effectiveness could be heightened if more agencies, including DOTs, looked beyond their project borders and had greater awareness of county-level plans to improve water quality while also carefully addressing public perception issues. In a survey conducted of DOTs on state TMDL development, DOTs indicated that the most significant success in their TMDL program was the relationship they developed with the state regulatory agency through early participation and collaboration. The benefits included a greater level of understanding on the part of the regulatory agency, more appropriate and achievable compliance goals, and increased education among other stakeholders on the actual impact of the DOT ROW (Abbasi and Koskelo, 2013).

6.7 Watershed-Based Approaches

Watershed-based approaches differ from project-based approaches in that water quality efforts are not restricted to the DOT project site. While project based approaches are typically related to direct stormwater metrics, such as nutrient loading or concentrations, watershed-based nutrient management approaches are more adaptive on mitigation for water quality impacts, and metrics may simply be economic, where payment is made to finance water quality mitigation outside of the project site. The goals of watershed-based mitigation are to provide additional choices for water quality management that may provide a greater overall benefit to the watershed. Project sites may have poor or contaminated soils, limited space, or may require impacts to sensitive areas such as wetlands, which make onsite placement of runoff control BMPs undesirable for water quality management. Additionally, a greater cost-benefit for public resources may be realized for nutrient management using watershed-based approaches that allow for collaborative involvement from both regulatory and non-regulatory agencies.

Some common watershed-based approaches, including those founded on pollutant loading, monetary exchange, and a combination thereof, are:

Restoration Mitigation. Restoration mitigation involves reestablishing aquatic functions and related physical, chemical, or biological characteristics within the watershed to provide a direct comparison of a reduction of pollutant loads. Widely available restoration opportunities include the physical stabilization of stream reaches, riparian buffer zones, and/ or restoration or creation of wetland areas.

Conservation Mitigation. Conservation mitigation involves permanent conservation of land within the watershed that has been identified to provide ecological benefits and a direct comparison of a reduction of pollutant loads. Common conservation opportunities include forest cover, open space, or riparian buffer to improve aquatic conditions or populations of threatened or endangered species.

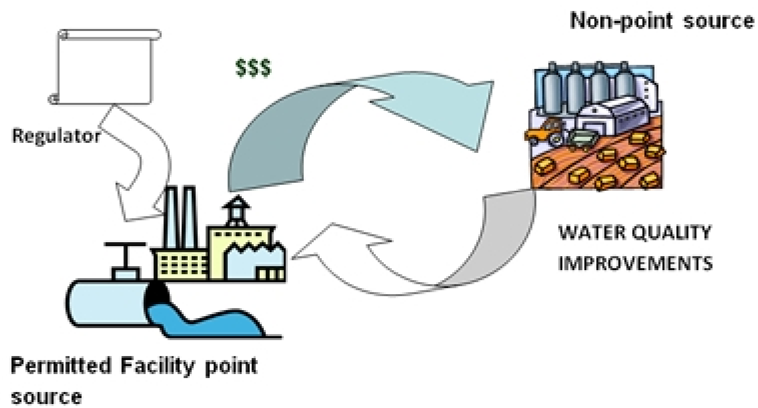
In-Lieu Fee Programs. In-lieu fee (ILF) programs allow permittees to buy compensatory mitigation credits, thereby transferring mitigation obligation from the transportation agency to the ILF program sponsor.

Stormwater Banking Mitigation. Stormwater banking provides off-site water quality treatment for a variety of land uses, including both highway and non-highway land uses. The stormwater bank determines the payments required to offset a quantifiable stormwater impact by investing in a water quality mitigation project within the same watershed. Types of banks include, but are not limited to, wetland banking, stream banking, and habitat banking.

Water Quality Trading and Ecosystem Service Markets. Trading programs allow permittees to meet regulatory obligations by purchasing environmentally equivalent (or superior) pollution reductions from another source at lower cost, thus achieving the same water quality improvement at lower overall cost. An ecosystem services marketplace establishes the ecological services of the watershed and provides opportunities to perform transactions to offset project impacts to the watershed through identification of environmental services or products that can be traded. Project impacts are defined in terms of how negatively it will impact the watershed's ability to provide its ecosystem services. The marketplace then estimates a monetary value for the ecosystem services impacts and establishes the costs for suitable remedial actions to offset those impacts.

Watershed-based approaches are become more streamlined and available as a mitigation strategy for nutrients. Current work, including NCHRP 25-37 A Watershed Approach to Mitigating Storm Water Impacts and FHWA Feasibility Study for the Development of a Framework for an Effective Stormwater Quality Credit/Banking/Trading System, is being completed that will provide comprehensive guidance for stormwater watershed approaches to meet NPDES compliance requirements and will include nutrient management as a component of the work. Project work for both projects is anticipated to be completed in 2014 and includes evaluation of existing crediting methodology and DOT guidance on use and implementation of watershed-based crediting programs.

Water quality trading approaches have U.S. EPA policy backing, specifically to encourage voluntary trading programs that facilitate implementation of TMDLs, reduce the costs of compliance with Clean Water Act (CWA) regulations, establish incentives for voluntary reductions and promote watershed-based initiatives (U.S. EPA, 2003). Because NPDES regulates only point source pollutant contributions, the focus of many water quality credit trading programs is to promote transactions between point (well-defined outflows) and nonpoint (diffuse runoff from mainly agricultural and urban areas) sources (Figure 6-9; Barisova and Roka, 2009).



Source: http://bearriverinfo.org/htm/water-quality-trading/water-quality-trading-conclusions
Figure 6-9. Schematic structure of a point source to nonpoint source transaction

Per U.S. EPA Water Quality Trading Policy (U.S. EPA, 2003), basic stormwater crediting programs are driven by an existing TMDL and existing regulations/ordinances that support trading of at least sediments and nutrients. Some of the key elements of water quality trading include:

- **Market structures** that determine the methods in which credits can be traded (exchanged)
- **Credit buyers and generators** between which credits are traded
- **Exchange types** that establish the entities between which trades can occur, such as between two permitted point source (PS) discharges or between a nonpoint source (NPS) and a PS discharge
- **Baseline conditions** that define how load reductions are measured for calculation of credits
- **Trading ratios** when trading cannot occur on a one-to-one basis because one credit generated is considered more or less impactful than another
- **Trading area** in which the pollutants can be traded, which defines the available credit suppliers and may place limitations to avoid hot spots of unacceptable localized impacts

A solid backbone for a watershed-based approach is a credit system that establishes protocol and metrics, such as equivalency mitigation ratios and criteria (appropriate "currency"), based on sound scientific principles. Several state and interstate programs exist, as can be found on the Environmental Trading Network website, which serves as a national clearinghouse for water quality trading projects (ETN, n.d.). In a crediting system, DOTs would act as stakeholders that buy and sell nutrient credits for load, concentration or volume reductions. The DOT might be part of a single market, or many, depending on the trading areas in their respective state. Most likely, the DOT will participate in a separate market for each water body. Participating in the market may provide economic savings by reducing the need to fund project-based technologies in order to meet NPDES permit requirement. However, joining such markets might require extra DOT resources including staffing and labor required to establish, maintain, and provide quality control for a water quality crediting program.

6.7.1 Existing Crediting Acceptance

There are many states that are currently assessing nutrient trading, but only a few have established programs. Examples include:

- Oregon – Oregon Department of Environmental Quality (OR DEQ) Water Quality Trading Internal Management Directive (OR DEQ, 2012)

- Virginia – Virginia Department of Environmental Quality (VA DEQ) Chesapeake Bay Nutrient Credit Exchange (VA DEQ, 2008)
- North Carolina – North Carolina Department of Environment and Natural Resources (NC DENR) Tar-Pamlico Nutrient Strategy (NC DENR, 2010)
- California – Lake Tahoe Water Quality Crediting & Trading Project (Buckley and Sokulsky, 2007)

These are a few programs that have demonstrated state acceptance of nutrient crediting as a mitigation opportunity, and continued monitoring of these programs will provide more insight into feasibility of establishing these programs for DOT agencies in meeting nutrient management goals.

6.7.2 Watershed Education

DOT nutrient management must consider individual, household, and public behaviors that generate pollution, as this can affect what is collected in the highway environment. Public education programs can be used as a means of source control to reduce behaviors that exacerbate the pollution in highway stormwater. Recent finding by the National Environmental Education & Training Foundation found that seventy eight percent of American's do not understand that stormwater runoff from roads, lawns, and agriculture is the most common source of water pollution (NEETF, 2005). DOTs should educate the public to raise awareness that will result in a change from behaviors that may negatively impact stormwater. Programs that DOTs can use include public outreach programs (EPA, 2006a), classroom education on stormwater (EPA, 2014a), outreach to commercial businesses (EPA, 2014b), and using targeted media promotion (EPA, 2006b). The effectiveness of these programs can be measured based on metrics similar to the following framework (adapted from SRDEM, 2014):

- How well is the community informed on how to become involved in the stormwater program?
- What partnerships exist between governmental and non-governmental entities?
- Does the public education program target the pollutant sources of greatest concern?
- Does the public education program target the correct audience?
- Is the outreach strategy effective at communicating with the target audience?

A successful campaign will provide a tailored message to a single target audience. Watersheds with multiple stormwater pollution issues should have multiple campaigns that address each issue separately. For example, proper disposal of pet waste and reducing public littering should have separate campaigns that target pet owners and litterers separately so each message is more effective.

7.0 Summary and Recommendations

Nutrients regulation trends indicate that federal regulations are establishing nutrient criteria and reduction framework programs for states and ecoregional areas. DOTs are currently stakeholders in nutrient TMDLs in at least eight states, and more states are expected to include DOT nutrient contributions in TMDL waste load allocations and implementation plans. Many regulatory and implementation issues have arisen as a result of DOT nutrient TMDLs, including an increase in design requirements and compliance demonstration methodologies. While it appears that most DOTs are seeing increased pressure on resources for nutrient management, there is also increased discussion on responsibility for nutrient TMDL requirements when it is shown there is a limited scientific nexus between the DOT discharge load and the receiving water impairment.

Nitrogen and phosphorus sources in the environment are varied in loading and applicability to different environments and, thus, nutrient source applicability has been defined in this report as the timeframe and location where management action(s) can be applied to control the form and transport of nutrients to stormwater. In this context, nutrient sources that are both controllable and located with the ROW should be considered DOT responsibility. Findings indicate that, in absence of nutrient contributions from surrounding land uses to the highway, nutrient concentrations in highway runoff are similar to, or even less than, that of urban runoff and are not significantly influenced by AADT. These findings may reflect the fact that higher AADT values typically correspond with more urban, piped drainage systems, which are less prone to influence by surrounding land uses in comparison with more rural, open ditch conveyance systems. DOTs can conduct a relative loading analysis using a contaminant loading model such as SELDM to assess DOT nutrient impacts to receiving waters to evaluate the need, if any, for nutrient management approaches.

Effective nutrient management depends greatly on understanding the complexities of the various nutrient removal processes for stormwater (i.e., infiltration, filtration, sedimentation, adsorption and precipitation, and biological uptake) and how these processes are affected by environmental factors (e.g., temperature, particulate and soluble form partitioning, pH, and vegetation and bacterial growth). Studies have shown that the effectiveness of phosphorus removal from stormwater depends greatly on partitioning and particle size with increased importance on targeted removal of bioavailable dissolved phosphorus via infiltration, adsorption, or plant uptake. Filtration or sedimentation for clays and silts is also critical as particulate phosphorus tends to be bound to finer particles. Nitrogen has many forms within stormwater and, similarly to phosphorus, each form has different treatment mechanisms. Nitrogenous solids removal from stormwater depends on partitioning and therefore filtration and settling as the primary removal mechanisms, whereas nitrate removal from stormwater relies on plant uptake and denitrification. Because denitrification requires anaerobic conditions, a saturation zone within BMPs for can provide improved nitrate removal. For both nitrogen and phosphorus, long-term sequestration of these nutrients in the environment via infiltration and plant uptake and harvest are key management approaches for DOTs to cost-effectively mitigate for on-going nutrient challenges.

Comprehensive nutrient management strategies for the highway environment include many components and considerations including limiting nutrients to runoff (source control BMPs), providing gross solids removal for particulate-bound nutrients (gross solids removal BMPs), and improving phosphorus and/or nitrogen treatment processes, such as adsorption, infiltration, plant uptake, and anaerobic denitrification (runoff control BMPs). There are limited performance data for source control and gross solids removal BMPs for nutrient management, but based on the latest available runoff control BMP data, it appears that

BMPs used to treat urban runoff can effectively treat most forms of nutrients found in highway runoff. BMP efforts for nutrient management should focus on the nutrient sources that are identified as controllable and located within the ROW, which include roadside fertilizer, sediment, pet waste, plant material, roadside compost, road sanding, deicing materials, and crumb rubber asphalt. Nutrient reduction efforts can be best realized with proper training for DOT staff and contractors for BMP design, installation and maintenance. For example, incorporation of nutrient leaching materials, such as planting media with a high P-index, can be counterproductive to management goals. BMP design and construction must also take into consideration site factors influential to nutrient removal processes such as soils, slope drains, karst aquifers, and compaction. Costs for source control and gross solids management BMPs tend to be cheaper compared with runoff control (treatment) BMPs. Thus, an approach to stormwater management where source control and gross solids management efforts are prioritized over treatment may amount to considerable cost savings in terms of capital expenditures and maintenance costs per the total nutrient load managed.

Some recommended cost-effective source control BMPs for nutrient control are pet waste control, and management of fertilizer application, winter road materials and plantings (materials, selection, installation, and growing medium). Other more costly source control BMPs are PFC and street sweeping. If maintained properly, catch basin inserts and sumps and nutrient baffles can be cost-effective gross solids removal BMPs. Though they are more expensive, oil/water/grit separators have also been shown to be effective gross solids removal BMPs while providing some reductions in nutrient concentrations.

With regard to runoff controls, BMPs that provide infiltration are the most effective strategy for nutrient control where space is available and soils are adequate. Influent and effluent concentration data analysis for runoff control BMPs show both removal and export for various nutrients forms though, generally, the most effective BMPs for all forms of nutrients are wet ponds and wetland basins. Sand filters and detention basins can be effective at reducing total phosphorus concentrations and vegetated filter strips and swales can be effective at reducing nitrate concentrations. However, media filters tend to export nitrate and vegetated systems tend to export phosphorus. Therefore, if infiltration or wet ponds are not feasible, a treatment train approach that utilizes filter strips or swales upstream of a media filter may be the most effective. In space constrained locations, the combination of gross solids removal BMPs followed by a media filter vault may be the only feasible option, but will require a higher level of maintenance to ensure long-term nutrient reductions. Enhanced nutrient removal within runoff control BMPs can be achieved via filter media such as sand or specialized treatment media or additives to traditional media such as iron filings, WTRs, and carbon-based materials (e.g., wood chips/sawdust, newspaper, biochar, activated carbon, etc.). Additionally, a saturation zone promotes denitrification, and a longer hydraulic residence time can increase settling for phosphorus and plant uptake for both nitrogen and phosphorus.

While project-based BMPs are still a mainstay of many regulatory programs, management approaches are trending toward more adaptable watershed-based mitigation. Some current watershed-based approaches gaining traction and often interrelated within the stormwater community include restoration and conservation mitigation, in-lieu fees, stormwater banking, water quality trading, and ecosystems services. Watershed-based approaches potentially involve many stakeholders, in addition to DOT agencies, and require significant planning and execution. However, there are successful systems currently underway that include sound protocols, metrics, and technology. Watershed-based management efforts by DOTs can include public education to increase awareness regarding nutrients, which, in turn, could make significant nutrient reductions in the highway environment and its receiving waters, requiring less overall DOT resources to be allocated toward nutrient effluent compliance measures.

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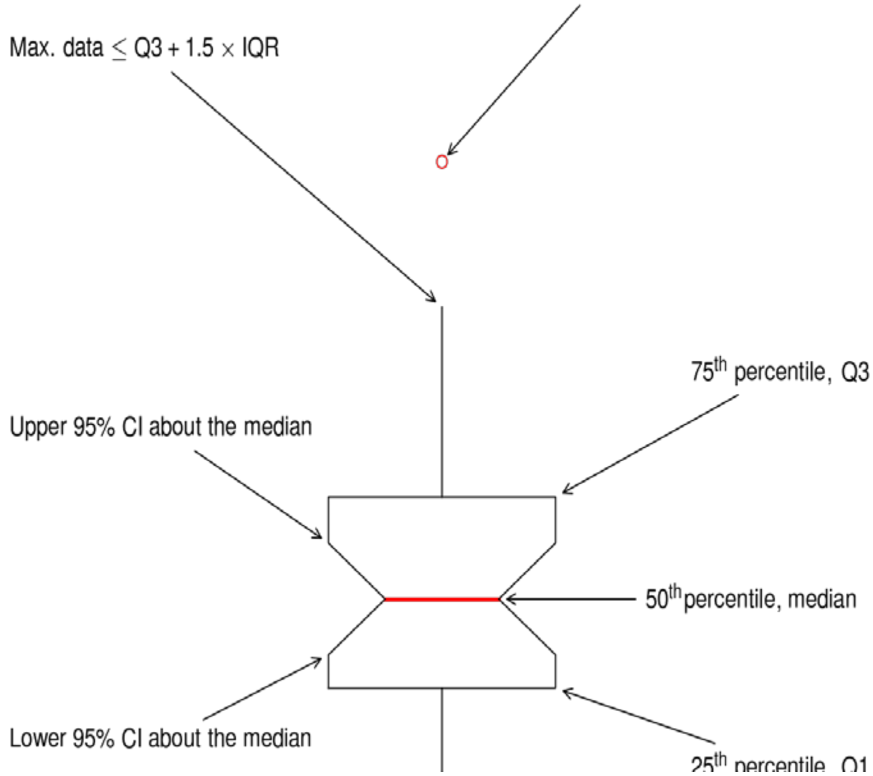
Appendix A

Detailed Nutrient Box and Whisker Plots

This appendix contains box and whisker boxplots comparing influent at effluent nutrient data at various BMP categories. The data come from the International Stormwater BMP Database (http://www.bmpdatabase.org). **Figure A-1** below explains the basic elements of box and whisker plots. Additionally, the following box and whisker plots use color to convey confidence in BMP efficacy. Influent-effluent data pairs whose effluent median 95% confidence intervals are entirely below the influent median 95% confidence intervals are filled with solid colors. However, when the median 95% confidence interval overlap or the effluent median concentration is greater than the influent median concentration, the boxplots are left hollow.



Note: in this case, IQR = Q3 – Q1.

Figure A-1. Legend explaining the basic elements of box and whisker plots.

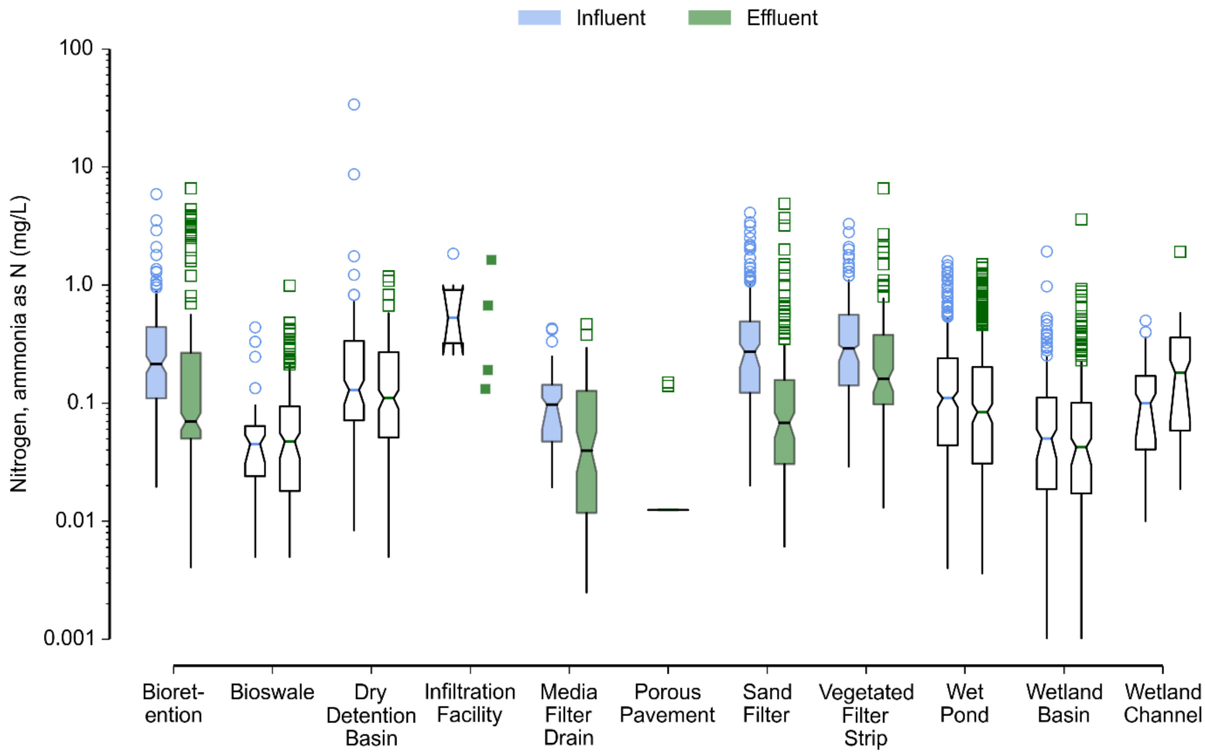


Figure A-2. Influent effluent box and whisker plots for Ammonia.

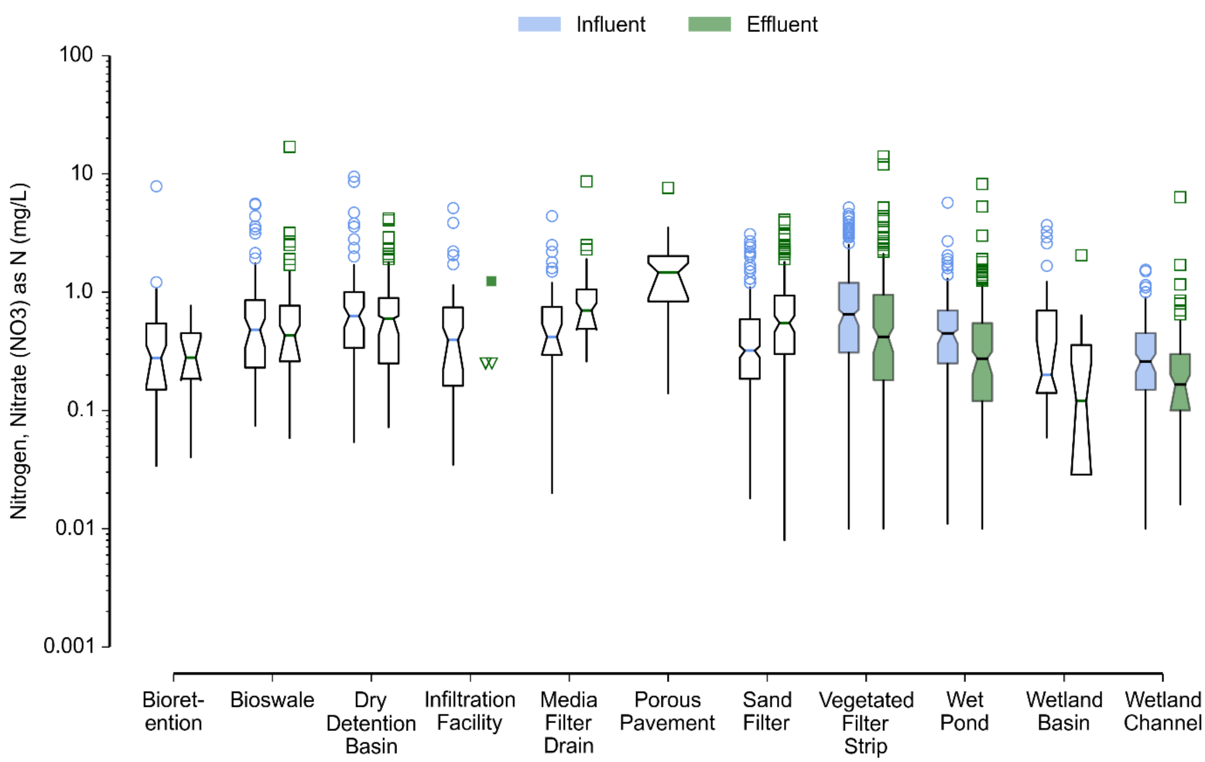


Figure A-3. Influent effluent box and whisker plots for Nitrate.

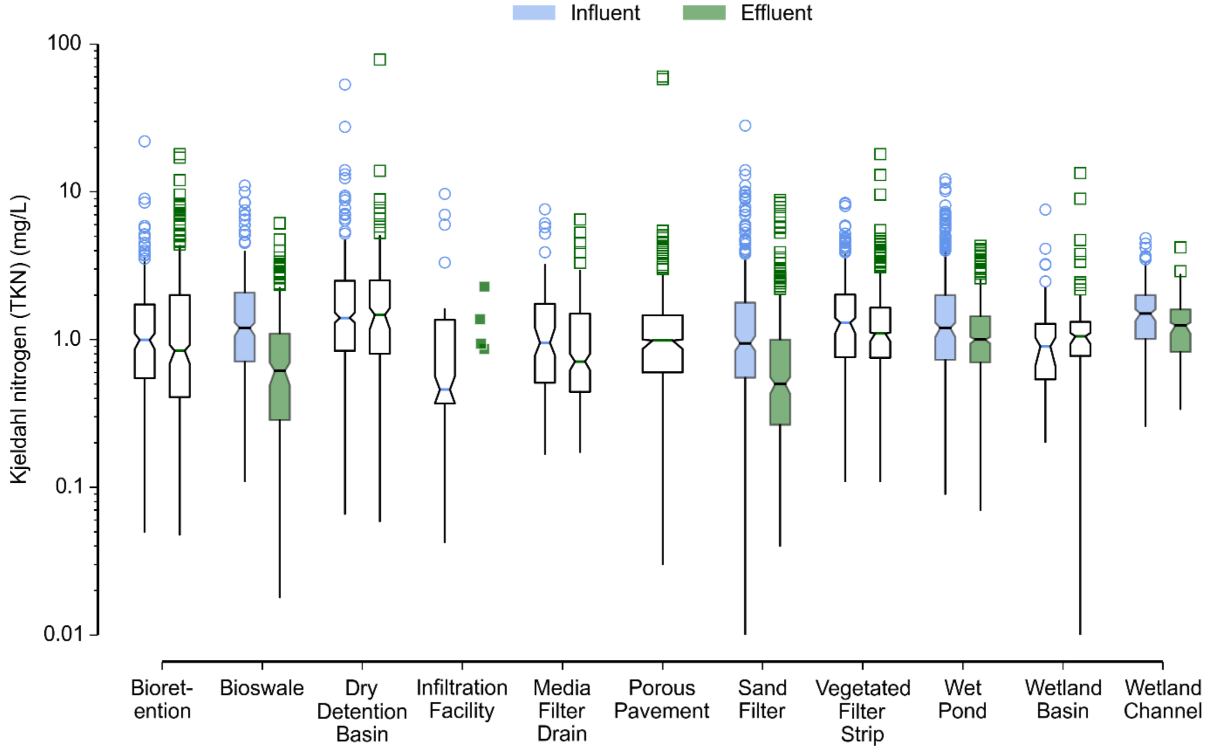


Figure A-4. Influent effluent box and whisker plots for Total Kjeldahl Nitrogen.

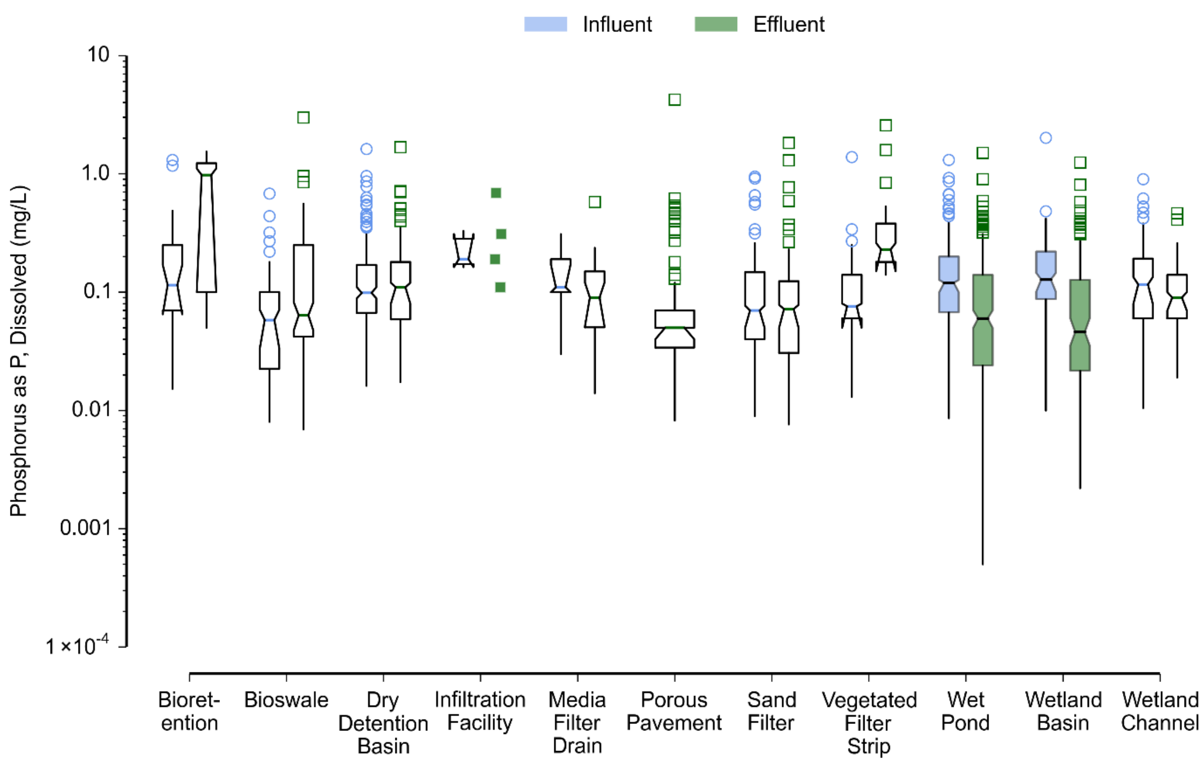


Figure A-5. Influent effluent box and whisker plots for Dissolved Phosphorus.

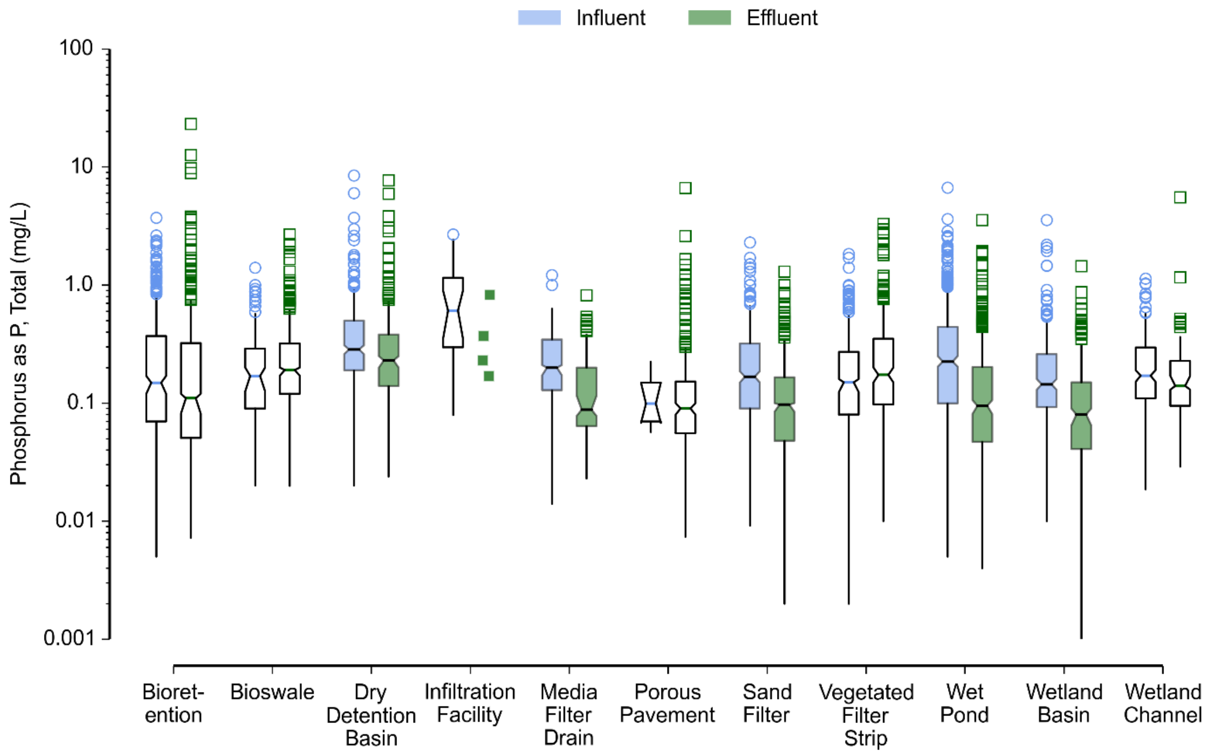


Figure A-6. Influent effluent box and whisker plots for Total Phosphorus.

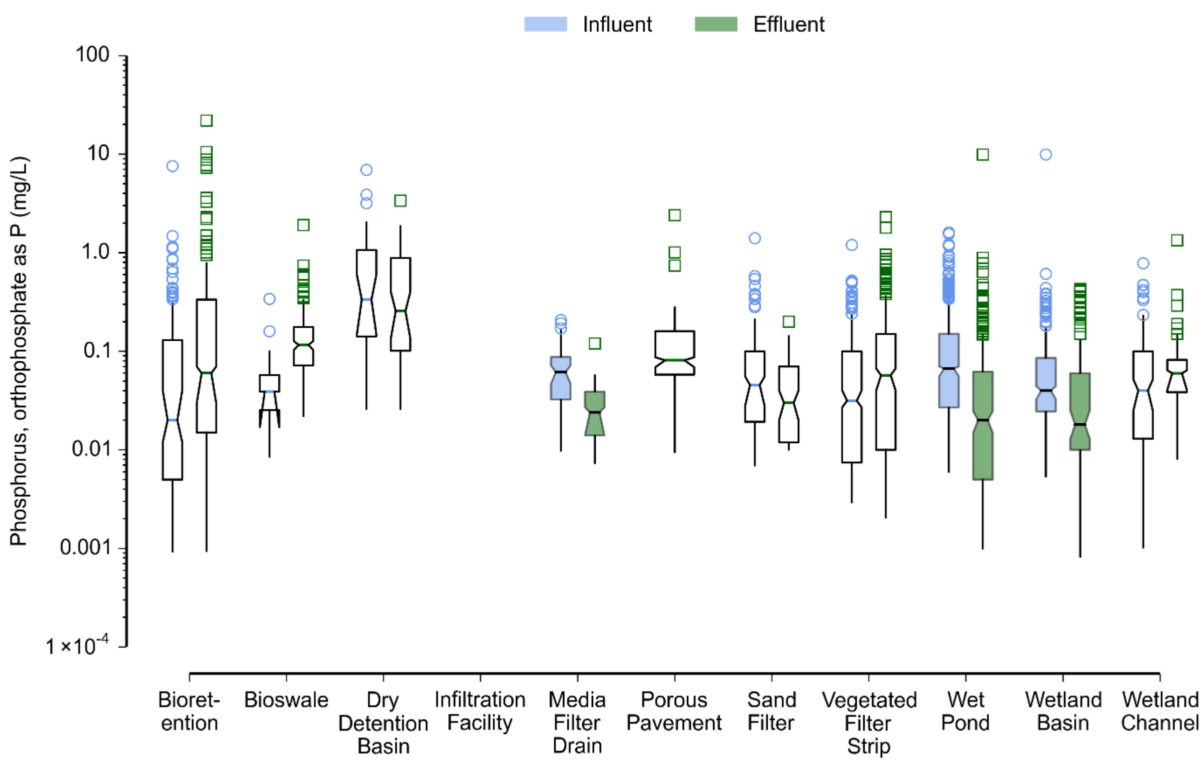


Figure A-7. Influent effluent box and whisker plots for Orthophosphate.

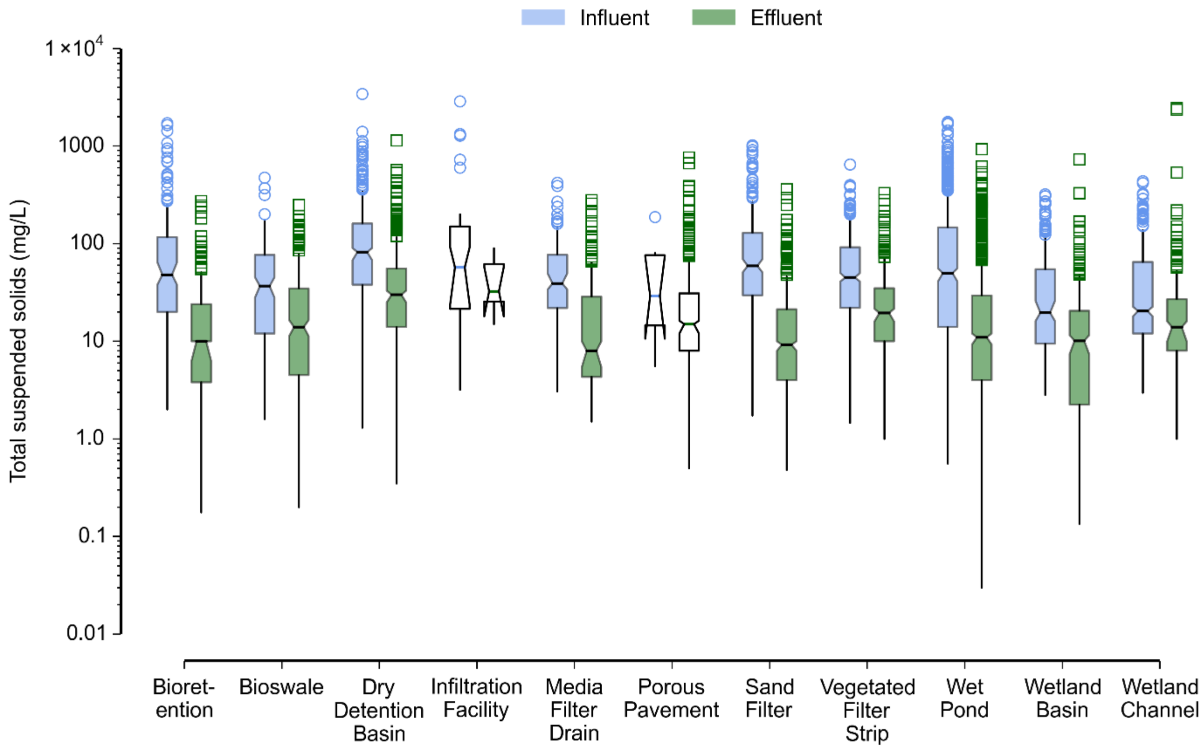


Figure A-8. Influent effluent box and whisker plots for Total Suspended Solids.

Appendix B

Statistical Table of Nutrient Data

Parameter	BMP Category	Influent			Effluent			Median CIs Are Independent	Mann-Whitney p-value < 0.05	Wilcoxon p-value < 0.05	Reduction
		N	Median	Median 95% Conf. Interval	N	Median	Median 95% Conf. Interval				
Ammonia (mg/L)	**Bioretention**	204	0.21	(0.18, 0.25)	146	0.07	(0.06, 0.08)	Yes	Yes	Yes	Yes
Ammonia (mg/L)	**Bioswale**	54	0.05	(0.03, 0.05)	226	0.05	(0.03, 0.06)	No	No	No	No
Ammonia (mg/L)	**Dry Detention Basin**	144	0.13	(0.1, 0.16)	134	0.11	(0.09, 0.13)	No	No	Yes	Yes
Ammonia (mg/L)	**Infiltration Facility**	6	0.53	(0.26, 0.99)	4	0.43	(0.13, 1.15)	No	Yes	Yes	Yes
Ammonia (mg/L)	**Media Filter Drain**	54	0.10	(0.06, 0.11)	64	0.04	(0.03, 0.06)	Yes	Yes	Yes	Yes
Ammonia (mg/L)	**Porous Pavement**	0	--	--	12	0.01	(0.01, 0.01)	No	Yes	Yes	No
Ammonia (mg/L)	**Sand Filter**	184	0.27	(0.2, 0.32)	186	0.07	(0.05, 0.08)	Yes	Yes	Yes	Yes
Ammonia (mg/L)	**Vegetated Filter Strip**	237	0.29	(0.23, 0.31)	164	0.16	(0.13, 0.2)	Yes	Yes	Yes	Yes
Ammonia (mg/L)	**Wet Pond**	432	0.11	(0.09, 0.13)	477	0.08	(0.07, 0.1)	No	Yes	Yes	Yes
Ammonia (mg/L)	**Wetland Basin**	199	0.05	(0.03, 0.06)	245	0.04	(0.03, 0.05)	No	No	No	Yes
Ammonia (mg/L)	**Wetland Channel**	66	0.10	(0.05, 0.12)	49	0.18	(0.07, 0.23)	No	Yes	Yes	No
Dissolved Phosphorus (mg/L)	**Bioretention**	22	0.11	(0.06, 0.17)	21	0.98	(0.1, 1.11)	No	No	Yes	No
Dissolved Phosphorus (mg/L)	**Bioswale**	71	0.06	(0.03, 0.07)	53	0.06	(0.05, 0.08)	No	No	Yes	No
Dissolved Phosphorus (mg/L)	**Dry Detention Basin**	156	0.10	(0.09, 0.11)	129	0.11	(0.08, 0.12)	No	No	No	No
Dissolved Phosphorus (mg/L)	**Infiltration Facility**	6	0.19	(0.16, 0.31)	4	0.25	(0.11, 0.5)	No	No	Yes	No
Dissolved Phosphorus (mg/L)	**Media Filter Drain**	19	0.11	(0.1, 0.17)	39	0.09	(0.05, 0.12)	No	No	No	Yes
Dissolved Phosphorus (mg/L)	**Porous Pavement**	0	--	--	125	0.05	(0.04, 0.05)	No	No	No	No
Dissolved Phosphorus (mg/L)	**Sand Filter**	84	0.07	(0.05, 0.08)	82	0.07	(0.05, 0.08)	No	No	Yes	No
Dissolved Phosphorus (mg/L)	**Vegetated Filter Strip**	21	0.08	(0.05, 0.08)	17	0.23	(0.15, 0.26)	Yes	Yes	No	No

Parameter	BMP Category	Influent N	Influent Median	Influent Median 95% Conf. Interval	Effluent N	Effluent Median	Effluent Median 95% Conf. Interval	Median CIs Are Independent	Mann-Whitney p-value < 0.05	Wilcoxon p-value < 0.05	Reduction
Dissolved Phosphorus (mg/L)	**Wet Pond**	339	0.12	(0.1, 0.13)	393	0.06	(0.05, 0.07)	Yes	Yes	Yes	Yes
Dissolved Phosphorus (mg/L)	**Wetland Basin**	54	0.13	(0.1, 0.14)	114	0.05	(0.04, 0.06)	Yes	Yes	No	Yes
Dissolved Phosphorus (mg/L)	**Wetland Channel**	121	0.12	(0.08, 0.13)	89	0.09	(0.07, 0.1)	No	No	Yes	Yes
Nitrate (NO3) (mg/L)	**Bioretention**	42	0.28	(0.16, 0.35)	19	0.28	(0.18, 0.41)	No	No	Yes	No
Nitrate (NO3) (mg/L)	**Bioswale**	95	0.48	(0.34, 0.6)	77	0.43	(0.27, 0.52)	No	No	Yes	Yes
Nitrate (NO3) (mg/L)	**Dry Detention Basin**	120	0.63	(0.5, 0.75)	113	0.60	(0.44, 0.63)	No	No	Yes	Yes
Nitrate (NO3) (mg/L)	**Infiltration Facility**	34	0.39	(0.22, 0.5)	4	0.13	(0.13, 1.24)	No	Yes	Yes	Yes
Nitrate (NO3) (mg/L)	**Media Filter Drain**	36	0.42	(0.3, 0.54)	35	0.70	(0.48, 0.81)	No	Yes	Yes	No
Nitrate (NO3) (mg/L)	**Porous Pavement**	0	--	--	32	1.46	(0.89, 1.76)	No	Yes	Yes	No
Nitrate (NO3) (mg/L)	**Sand Filter**	162	0.32	(0.28, 0.35)	174	0.55	(0.46, 0.63)	Yes	Yes	Yes	No
Nitrate (NO3) (mg/L)	**Vegetated Filter Strip**	240	0.65	(0.52, 0.71)	171	0.42	(0.31, 0.5)	Yes	Yes	Yes	Yes
Nitrate (NO3) (mg/L)	**Wet Pond**	197	0.45	(0.37, 0.48)	214	0.28	(0.2, 0.31)	Yes	Yes	Yes	Yes
Nitrate (NO3) (mg/L)	**Wetland Basin**	28	0.20	(0.14, 0.39)	14	0.12	(0.03, 0.25)	No	Yes	Yes	Yes
Nitrate (NO3) (mg/L)	**Wetland Channel**	112	0.26	(0.21, 0.3)	70	0.16	(0.1, 0.2)	Yes	Yes	No	Yes
Orthophosphate (mg/L)	**Bioretention**	214	0.02	(0.01, 0.04)	135	0.06	(0.03, 0.07)	No	Yes	Yes	No
Orthophosphate (mg/L)	**Bioswale**	26	0.04	(0.02, 0.04)	197	0.12	(0.1, 0.13)	Yes	Yes	Yes	No
Orthophosphate (mg/L)	**Dry Detention Basin**	34	0.33	(0.15, 0.59)	34	0.25	(0.14, 0.4)	No	No	No	Yes
Orthophosphate (mg/L)	**Infiltration Facility**	31	0.06	(0.02, 0.08)	0	--	--	No	No	Yes	No
Orthophosphate (mg/L)	**Media Filter Drain**	54	0.06	(0.05, 0.07)	42	0.02	(0.01, 0.03)	Yes	No	Yes	Yes

Parameter	BMP Category	Influent N	Influent Median	Influent Median 95% Conf. Interval	Effluent N	Effluent Median	Effluent Median 95% Conf. Interval	Median CIs Are Independent	Mann-Whitney p-value < 0.05	Wilcoxon p-value < 0.05	Reduction
Orthophosphate (mg/L)	**Porous Pavement**	0	--	--	89	0.08	(0.07, 0.09)	No	No	Yes	No
Orthophosphate (mg/L)	**Sand Filter**	100	0.05	(0.03, 0.06)	115	0.03	(0.02, 0.04)	No	No	Yes	Yes
Orthophosphate (mg/L)	**Vegetated Filter Strip**	288	0.03	(0.03, 0.04)	223	0.06	(0.04, 0.07)	No	Yes	Yes	No
Orthophosphate (mg/L)	**Wet Pond**	531	0.07	(0.06, 0.07)	493	0.02	(0.01, 0.02)	Yes	Yes	Yes	Yes
Orthophosphate (mg/L)	**Wetland Basin**	179	0.04	(0.03, 0.04)	147	0.02	(0.01, 0.03)	Yes	Yes	No	Yes
Orthophosphate (mg/L)	**Wetland Channel**	103	0.04	(0.03, 0.05)	63	0.06	(0.04, 0.06)	No	No	Yes	No
Total Kjeldahl Nitrogen (mg/L)	**Bioretention**	239	0.99	(0.86, 1.1)	179	0.84	(0.69, 0.92)	No	No	Yes	Yes
Total Kjeldahl Nitrogen (mg/L)	**Bioswale**	177	1.20	(1.06, 1.3)	325	0.61	(0.49, 0.69)	Yes	Yes	No	Yes
Total Kjeldahl Nitrogen (mg/L)	**Dry Detention Basin**	269	1.40	(1.3, 1.53)	246	1.47	(1.18, 1.64)	No	No	Yes	No
Total Kjeldahl Nitrogen (mg/L)	**Infiltration Facility**	25	0.46	(0.37, 0.56)	4	1.16	(0.86, 1.82)	Yes	Yes	Yes	No
Total Kjeldahl Nitrogen (mg/L)	**Media Filter Drain**	90	0.95	(0.78, 1.2)	97	0.71	(0.62, 0.8)	No	No	Yes	Yes
Total Kjeldahl Nitrogen (mg/L)	**Porous Pavement**	0	--	--	372	0.99	(0.86, 1)	No	No	Yes	No
Total Kjeldahl Nitrogen (mg/L)	**Sand Filter**	307	0.94	(0.84, 1.05)	312	0.50	(0.43, 0.56)	Yes	Yes	Yes	Yes
Total Kjeldahl Nitrogen (mg/L)	**Vegetated Filter Strip**	380	1.30	(1.1, 1.4)	272	1.10	(0.97, 1.11)	No	Yes	No	Yes
Total Kjeldahl Nitrogen (mg/L)	**Wet Pond**	501	1.20	(1.04, 1.3)	549	1.00	(0.94, 1.04)	Yes	Yes	Yes	Yes
Total Kjeldahl Nitrogen (mg/L)	**Wetland Basin**	85	0.90	(0.66, 1.03)	174	1.05	(0.93, 1.11)	No	Yes	No	No
Total Kjeldahl Nitrogen (mg/L)	**Wetland Channel**	150	1.50	(1.34, 1.6)	139	1.25	(1.1, 1.3)	Yes	Yes	Yes	Yes
Total Phosphorus (mg/L)	**Bioretention**	329	0.15	(0.12, 0.17)	232	0.11	(0.08, 0.12)	No	No	No	Yes
Total Phosphorus	**Bioswale**	217	0.17	(0.13, 0.2)	365	0.19	(0.17, 0.2)	No	Yes	Yes	No

Parameter	BMP Category	Influent N	Influent Median	Influent Median 95% Conf. Interval	Effluent N	Effluent Median	Effluent Median 95% Conf. Interval	Median CIs Are Independent	Mann-Whitney p-value < 0.05	Wilcoxon p-value < 0.05	Reduction
(mg/L)											
Total Phosphorus (mg/L)	**Dry Detention Basin**	333	0.28	(0.26, 0.31)	339	0.23	(0.2, 0.25)	Yes	Yes	Yes	Yes
Total Phosphorus (mg/L)	**Infiltration Facility**	36	0.61	(0.35, 0.9)	4	0.30	(0.17, 0.6)	No	Yes	Yes	Yes
Total Phosphorus (mg/L)	**Media Filter Drain**	97	0.20	(0.17, 0.21)	113	0.09	(0.08, 0.12)	Yes	Yes	Yes	Yes
Total Phosphorus (mg/L)	**Porous Pavement**	9	0.10	(0.07, 0.15)	356	0.09	(0.08, 0.1)	No	No	No	Yes
Total Phosphorus (mg/L)	**Sand Filter**	322	0.17	(0.15, 0.19)	323	0.10	(0.08, 0.1)	Yes	Yes	Yes	Yes
Total Phosphorus (mg/L)	**Vegetated Filter Strip**	388	0.15	(0.12, 0.16)	280	0.17	(0.15, 0.2)	No	Yes	Yes	No
Total Phosphorus (mg/L)	**Wet Pond**	845	0.23	(0.2, 0.25)	823	0.09	(0.08, 0.11)	Yes	Yes	Yes	Yes
Total Phosphorus (mg/L)	**Wetland Basin**	224	0.14	(0.13, 0.16)	259	0.08	(0.06, 0.09)	Yes	Yes	No	Yes
Total Phosphorus (mg/L)	**Wetland Channel**	195	0.17	(0.15, 0.19)	147	0.14	(0.13, 0.17)	No	Yes	No	Yes
Total Suspended Solids (mg/L)	**Bioretention**	254	48.13	(38, 64.25)	181	10.00	(6.34, 10)	Yes	Yes	Yes	Yes
Total Suspended Solids (mg/L)	**Bioswale**	221	36.77	(28, 45.26)	337	14.00	(11.3, 16.49)	Yes	Yes	Yes	Yes
Total Suspended Solids (mg/L)	**Dry Detention Basin**	357	82.00	(68, 90)	361	30.00	(25, 33)	Yes	Yes	Yes	Yes
Total Suspended Solids (mg/L)	**Infiltration Facility**	34	57.19	(23.87, 91.54)	10	32.50	(18, 57.5)	No	Yes	Yes	Yes
Total Suspended Solids (mg/L)	**Media Filter Drain**	96	39.13	(34, 49.47)	111	8.00	(5.45, 10)	Yes	Yes	Yes	Yes
Total Suspended Solids (mg/L)	**Porous Pavement**	11	29.21	(10.63, 74.37)	386	15.00	(12, 16.25)	No	Yes	No	Yes
Total Suspended Solids (mg/L)	**Sand Filter**	331	59.22	(51, 69.26)	332	9.24	(8, 10)	Yes	Yes	Yes	Yes
Total Suspended Solids (mg/L)	**Vegetated Filter Strip**	389	45.00	(41, 50)	286	19.50	(16, 21.5)	Yes	Yes	Yes	Yes

Parameter	BMP Category	Influent			Effluent			Median CIs Are Independ ent	Mann-Whitney p-value < 0.05	Wilcoxon p-value < 0.05	Reduction
		N	Median	Median 95% Conf. Interval	N	Median	Median 95% Conf. Interval				
Total Suspended Solids (mg/L)	**Wet Pond**	865	49.90	(41, 56)	883	11.00	(9.3, 12)	Yes	Yes	Yes	Yes