Phase I&II National Pollutant Discharge Elimination System
Permit No. 99-DP-3313 MD0068276
Permit Term October 2005 to October 2010

# ANNUAL REPORT UPDATE
# OCTOBER 21, 2014

Submitted to:

**Water Management Administration**
**Maryland Department of the Environment**
**1800 Washington Boulevard**
**Baltimore, MD 21230**

Submitted by:

**Maryland State Highway Administration**
**Office of Environmental Design**
**707 North Calvert Street, C-303**
**Baltimore, MD 21202**

Martin O'Malley, *Governor*
Anthony G. Brown, *Lt. Governor*

State Highway Administration
Maryland Department of Transportation

James T. Smith, Jr., *Secretary*
Melinda B. Peters, *Administrator*

Date: October 21, 2014

Re: Annual NPDES MS4 Phase I and II Report Update
Permit Term 10/2005 to 10/2010
Permit No. 99-DP-3313 MD0068276
Continuation

Mr. Raymond Bahr
Sediment, Stormwater, and Dam Safety Program
Water Management Administration
Maryland Department of the Environment
1800 Washington Boulevard, Suite 440
Baltimore, Maryland 21230

Dear Mr. Bahr,

The Maryland State Highway Administration (SHA) is pleased to submit this updated Annual Report for the National Pollution Discharge Elimination System (NPDES) Municipal Separate Storm Sewer System (MS4) permit as a continuation of coverage under the expired permit issued in October 2005. The updated report covers time period of October 2013 through September 2014. As with the previous Annual Report Update, this report includes updates for both Phase I and Phase II jurisdictions.

SHA remains committed to the environmental compliance and stewardship towards the preservation and restoration of the Chesapeake Bay and local waterways. We submitted a re-application for the NPDES Phase I MS4 permit on October 21, 2009 and anticipate the new permit to be issued within the next year. SHA will continue to comply with the current permit conditions until the new permit is received from MDE.

SHA has continued its progress this past year in fulfilling the requirements and purpose of this permit, and have been preparing to meet the anticipated conditions of the next permit. We continue to work closely with MDE to coordinate efforts with the Bay Total Maximum Daily Load (TMDL) and local TMDLs.

Included in this submission is one hard copy and an electronic version of the Annual Report Update along with accompanying digital geodatabase file information. The original geodatabase information was provided with the 2013 Annual Report Update on October 21, 2013, and the geodatabase information provided within only includes new data updates from this reporting period. All of the geodatabase information provided is prepared in compliance with the specifications outlined in the Draft NPDES MS4 Discharge Permit provided to SHA on June 26, 2012.

If you have any questions or need additional information regarding this delivery, please contact Ms. Karen Coffman at 410-545-8407 (or via email at kcoffman@sha.state.md.us) or myself at 410-545-8644 (or via email at rshreeve@sha.state.md.us). Thank you.

Sincerely,

Robert Shreeve, Deputy Director
Office of Environmental Design

Attachment

CC: Karuna Pujara
Dana Havlik
Sonal Sanghavi
Doug Simmons
Greg Welker

Phase I&II National Pollutant Discharge Elimination System
Permit No. 99-DP-3313 MD0068276
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# PART ONE

## STANDARD PERMIT CONDITIONS AND RESPONSES

Phase I National Pollutant Discharge Elimination System
Permit No. 99-DP-3313 MD0068276
Permit Term October 2005 to October 2010

# Annual Report Update
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1800 Washington Boulevard
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Office of Environmental Design
707 North Calvert Street, C-303
Baltimore, MD 21202

Prepared by:
McCormick Taylor, Inc.
509 South Exeter Street, Fourth Floor
Baltimore, Maryland 21202

# Executive Summary

Prepared by the Maryland State Highway Administration (SHA), this is the annual report required as part of the National Pollution Discharge Elimination System (NPDES) Phase I and II Municipal Separate Storm Sewer System (MS4) permit that was issued in October 2005 by the Maryland Department of the Environment (MDE) Water Management Administration (WMA). This report covers the time period of October 2013 to September 2014.

The following is a general overview and highlights significant achievements during the reporting period.

## Source Identification

The impervious accounting condition has been completed for the eleven Phase I and II counties and the three Phase II municipalities, and impervious restoration has been completed during this reporting period. Furthermore, GIS applications have become fully integrated and a regular schedule has been developed for data collection updates.

## Discharge Characterization

SHA continues to investigate and research topics to maximize water quality in our construction methods, permanent stormwater runoff controls, decisions in design, and maintenance techniques. SHA is conducting additional research activities related to meeting the anticipated waste load allocations for designated watersheds with a Total Maximum Daily Load (TMDL). Current research studies include: Management of Nitrogen in Stormwater Runoff Using a Modified Surface Sand Filters, Enhancements for N and P Removal from Stormwater Management Facilities for Multi-Modal Transportation Infrastructure in Maryland: Multi-Criteria Plant Selection for Vegetated Stormwater Control Measures, and Evaluation of Compost Effects on Stormwater Control Measure Performance.

## Management Program

SHA's program continues to effectively incorporate all permit components. We have successfully integrated the stormwater environmental site design (ESD) regulations into roadway design and construction projects. SHA continues to measure our performance in the areas of erosion and sediment control (ESC) during construction. SHA maintains our internal business goal of maximizing the number of functionally adequate stormwater facilities statewide.

The ESC Program developed and implemented the ESC Quality Assurance Toolkit (QA Toolkit). This tool allows field inspectors to enter inspection results directly into a field that is connected to the general ESC inspection database through the internet. This improves efficiency, accuracy of data entry and reporting.

## Watershed Assessment

SHA has incorporated watershed assessment efforts as described by the permit in the overall business process by continuing to evaluate highway drainage areas for stormwater management retrofit opportunities and coordinate with local jurisdictions on watershed restoration plans to maximize water quality benefits.

SHA exchanges the latest available geographic information system (GIS) highway data with permitted NPDES municipalities and provides the most recent spatial database of drainage assets and stormwater infrastructure to MDE. SHA completed the impervious surface accounting by the fourth annual report and continues systematically updating this dynamic layer. Looking towards the next MS4 permit, SHA is assessing areas that lack highway runoff control and treatment and implementing water quality improvement projects to maximize water quality benefits.

SHA also participates in a number of endeavors to expand and maximize watershed assessment initiatives and build partnerships with Federal, State, and local agencies. These include water quality banking, participating in the Environmental protection Agency's (EPA's) Green Highways Partnership, establishing a water resources registry, developing the framework to implement a watershed-based approach for managing stormwater, expanding green infrastructure, hosting a Recycled-Materials Task Force, and establishing milestone goals for TMDL impairment reduction.

## Watershed Restoration

SHA continues to construct stormwater management retrofits to increase pollutant control associated with highway runoff, although requirements for this permit condition to implement twenty-five significant stormwater management retrofit projects to improve water quality of highway runoff has been met. The watershed restoration projects mostly include functional enhancements and upgrades of outdated stormwater facilities that do not meet current design standards as well as construction of additional stormwater BMPs to treat currently untreated impervious surfaces. The watershed restoration projects include innovative approaches to conventional stormwater management methods and provide significant water quality benefits.

## Assessment of Controls

The Long Draught Branch stream restoration project was designated early in the permit term as the watershed restoration project for assessing pre and post construction controls. The monitoring plan for chemical, biological and physical data has been developed and pre-construction monitoring has been completed. The original project design was not permitted, and the project has been redesigned to address agency comments. The budget for construction funding is allocated for FY 2015 and 2016. We will continue the project with the post-construction monitoring when the project is completed.

In the interim, SHA performed monitoring of a failed infiltration basin at MD 175 in Howard County to assess pollutant removal efficiency of a technically deficient SWM BMP. In 2014, SHA initiated bioswale monitoring study to evaluate effectiveness of this widely used BMP and its pollutant removal efficiency.

## Program Funding

SHA's NPDES program remains fully funded, and has been a top priority. Also, despite the challenging economic situation, SHA and MDOT have begun funding Bay TMDL efforts and also supported procurement of NPDES engineering contracts.

## Total Maximum Daily Loads

The current SHA NPDES Phase I permit states that MDE has determined that owners of stormdrain systems that implement the requirements of the permit will be controlling stormwater pollution to the maximum extent practicable. SHA continues to address the water quality requirements of this permit. However, given the current mandate to restore the Chesapeake Bay by 2025 and the draft MS4 Phase I permit that requires that SHA meet assigned waste load allocations (WLAs) for the Bay and local watershed TMDLs, SHA continues to take many steps in order to position ourselves to meet these requirements in anticipation of the next permit term.

## Audit by the Environmental Protection Agency

The Environmental Protection Agency (EPA) conducted an audit in this past year to review SHA's compliance with the NPDES MS4 permit conditions. As a part of the auditing process, a field inspection was also conducted. SHA is awaiting the final report from EPA.

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*PART ONE*

# Standard Permit Conditions and Responses

## 1 Introduction

The Maryland State Highway Administration (SHA) is committed to continuing our National Pollutant Discharge Elimination System (NPDES) Program efforts, and is pleased to partner with the Maryland Department of the Environment (MDE), the Environmental Protection Agency (EPA) and other NPDES jurisdictions in order to achieve the program goals.

The original NPDES Phase I and II permit guided SHA through establishing our NPDES program. (The permit, MS-SH-99-011, was issued on January 8, 1999 and expired in 2004.) The current permit (99-DP-3313, MD0068276, issued October 21, 2005 and expired on October 21, 2010) focuses on improving water quality benefits, developing an impervious accounting database and developing a watershed-based outlook for stormwater management and NPDES program elements. SHA submitted a re-application for the NPDES Phase I Municipal Separate Storm Sewer System (MS4) permit on October 21 2009 and are anticipating a new permit being issued by May of 2015. SHA will continue to comply with the existing permit until the new permit is received.

This is the fourth update to the final annual report that was submitted October 2010 for the expired permit. This report covers the period from October 1, 2013 through September 30, 2014, and combines reporting for both Phase I and II jurisdictions. Part One lists permit conditions and explains SHA activities over the last year to comply with each one. Wherever possible, future activities and schedules for completion are provided. Part Two of this report discusses the SHA Stormwater Management (SWM) Facility Program in depth. Appendices are included at the end of the report that contains information on data and research and monitoring reports.

A CD is also included that contains portable document format (PDF) files of the entire report and delivery of database updates new from the previous submission with the last Annual Report Update in 2013. New tables for all the SHA NPDES MS4 Phase I and II data are included even records that were delivered in the past as the data requirements have changed (except where noted on the document included on the CD).

## A Administration of Permit

Administration coordinator for the NPDES Program is listed below and an organizational chart detailing personnel responsible for major program tasks is included on the following page as Figure 1-1.

Mr. Robert Shreeve
Deputy Director
Office of Environmental Design
(410) 545-8644
rshreeve@sha.state.md.us

The SHA coordinator for the MS4 permit is:

Ms. Karen Coffman
Office of Environmental Design
(410) 545-8407
kcoffman@sha.state.md.us

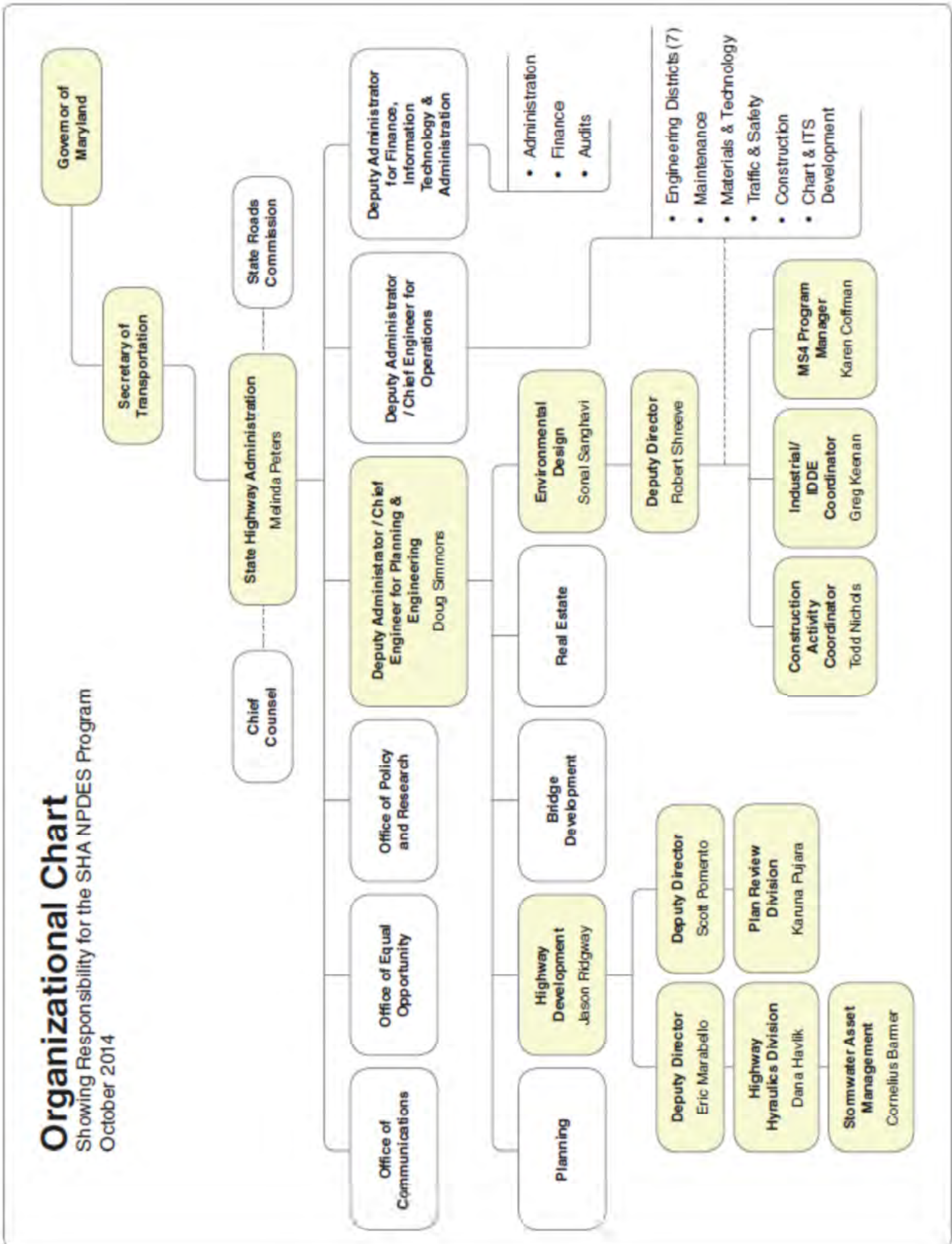


***Figure 1-1: 2014 Organizational Chart for SHA NPDES MS4 Permit Administration***

Within the past year, SHA was audited by the EPA to confirm compliance with the NPDES MS4 permit conditions. EPA reviewed:

- SHA's Business Plan
- NPDES Standard Operating Procedures
- Stormwater Management Program
- Erosion and Sediment Control Program
- Illicit Discharge Detection and Elimination Program
- Maintenance Shop Operating Procedures and Pollution Prevention Plan
- Trash and debris cleanup program
- Turfgrass Management Program
- Fertilization standards
- Pesticide utilization standards
- NPDES Database Management Program
- Impervious Accounting
- TMDL Program
- Quality Assurance Program

As a part of the Auditing process, a field inspection was also conducted to review Maintenance Shop conditions, typical roadside management conditions, and construction sites. See Figures 1-2 through 1-4 for field inspection photographs. SHA is awaiting the final report with auditing results from EPA.

***Figure 1-2: EPA Inspection of a Vacuum Truck used for Inlet Cleaning***

***Figure 1-3: EPA Inspection of an SHA Outfall***

***Figure 1-4: EPA Inspection of Erosion and Sediment Control Measures on a Construction Site***

## B Legal Authority

A description of the legal authority maintained by SHA was restated in the fourth annual report dated October 21, 2009 and remains unchanged.

# C Source Identification

According to the permit language, source identification deals with identifying sources of pollutants and linking those sources to specific water quality impacts on a highway district basis. Source identification is also tied to impervious surfaces and land uses.

For this permit term, MDE has defined the source identification effort as completing the description of the SHA storm drain and BMP system, submitting BMP data to MDE and creating an impervious surface account.

Maryland SHA has successfully completed the GIS development of SHA storm drain systems within the nine Phase I MS4 counties, two Phase II counties, and three Phase II municipalities. Maryland SHA has initiated identification of SHA storm drain systems outside of the permit areas. We are utilizing advances in technology and software improvements to more effectively and efficiently collect and maintain data sets. These process improvements will enhance communication between offices regarding the goals and needs for NPDES.

## C.1 Describe Storm Drain System

Requirements under this condition include:

a) *Complete Source identification requirements by October 21, 2009;*

b) *Address source identification data compatibility issues with each jurisdiction where data are collected. Data shall be organized and stored in formats compatible for use by all governmental entities involved;*

c) *Continually update its source identification data for new projects and from data gathered during routine inspection and repair of its municipal separate storm sewer system; and*

d) *Submit an example of source identification for each jurisdiction where source identification is being* compiled.

### C.1.a Complete Source Identification

SHA completed the identification and GIS development for our storm drain systems and stormwater management facilities in 2008, well before the October 21, 2009 deadline. Our focus has shifted to updating our source identification information for the nine MS4 counties, two Phase II counties, and three Phase II municipalities. We are also updating our current data structure to integrate new data standards provided in the latest version of Attachment A. Information on source identification updates and updates to the data structure is included under section C.1.c, Update Source ID Data.

### C.1.b Data Compatibility

SHA continues to provide data to the other NPDES jurisdictions and MDE as well as acquire data from them. The NPDES data generated by SHA is deployed using the Esri geodatabase data format in an ArcSDE enterprise environment and is either natively compatible with other jurisdictions, or can be exported to Esri shapefile format. The geodatabase and Data Dictionary can be reviewed in Appendix A.

MDE is currently in the process of updating their NPDES data requirements and SHA has coordinated with their consultant, Maryland Environmental Services (MES) by providing our TMDL data standards, NPDES Standard Procedures and geodatabase structure to them. SHA intends to continue involvement in this process with MDE.

#### Geospatial Database Development

SHA has developed a geospatial database for our source identification and inspection data. This database will be expanded to include other components of the program as they are brought together and as we update our standard procedures and inspection manuals. All of the SHA NPDES data including source identification, SWM facility inspections, outfall screening, outfall inspections, and impervious area acre amounts are currently housed in the database.

A SHA-wide web-based application, known as Enterprise GIS (eGIS), was developed to display content themes for decision making purposes. Content themes allow the user to overlay datasets without extensive knowledge of the Esri tool sets. NPDES data has been included as a content theme in eGIS. See Figure 1-5 below for an example.

Google Earth is an alternative method to present and communicate NPDES asset information to parties outside of the SHA network firewall. It provides a discrete and user-friendly framework for information to be communicated to SHA Districts and the consultant community through the distribution of KML and KMZ files that open directly in Google Earth. Refer to Figure 1-6 on the following page for a screenshot of information displayed in Google Earth.

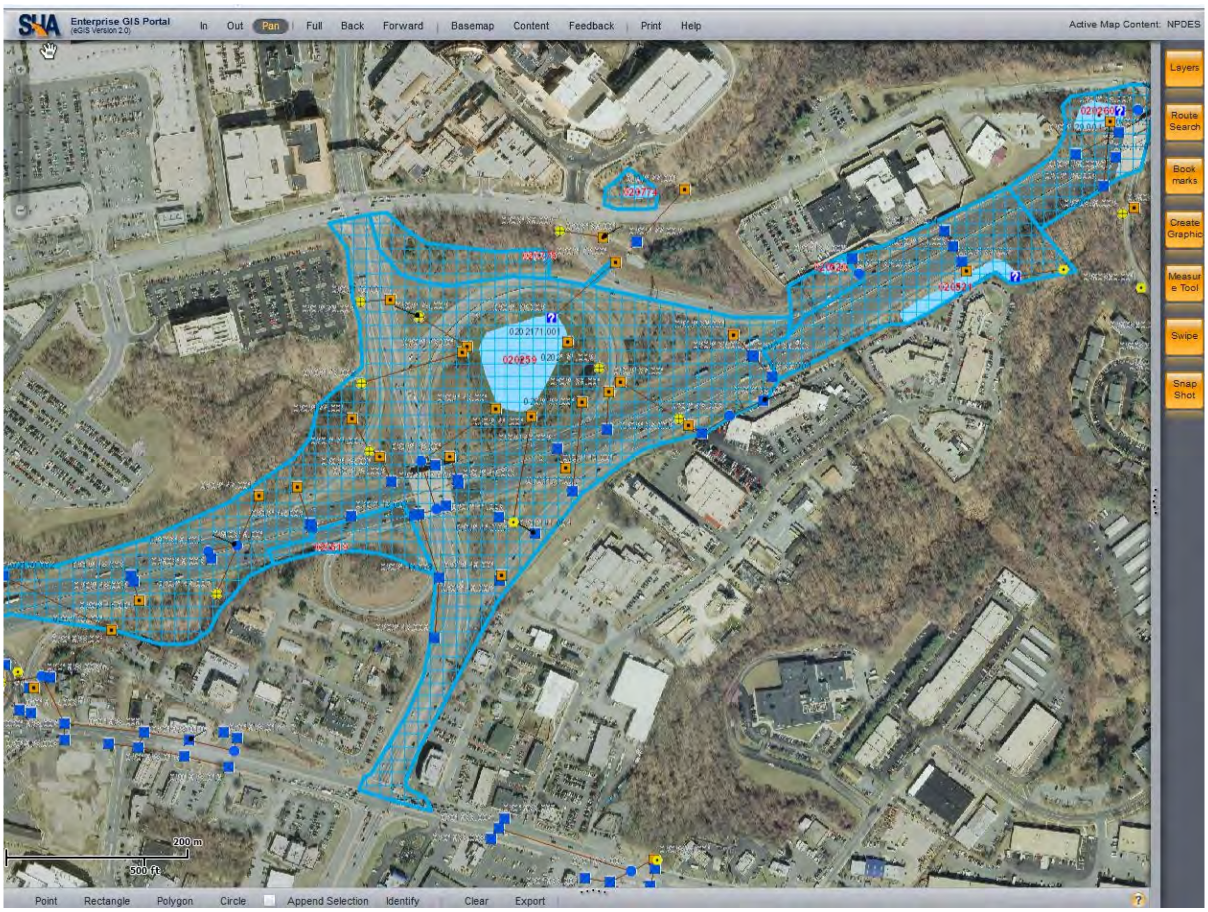


***Figure 1-5: eGIS Viewer Screenshot of SHA NPDES Dataset***

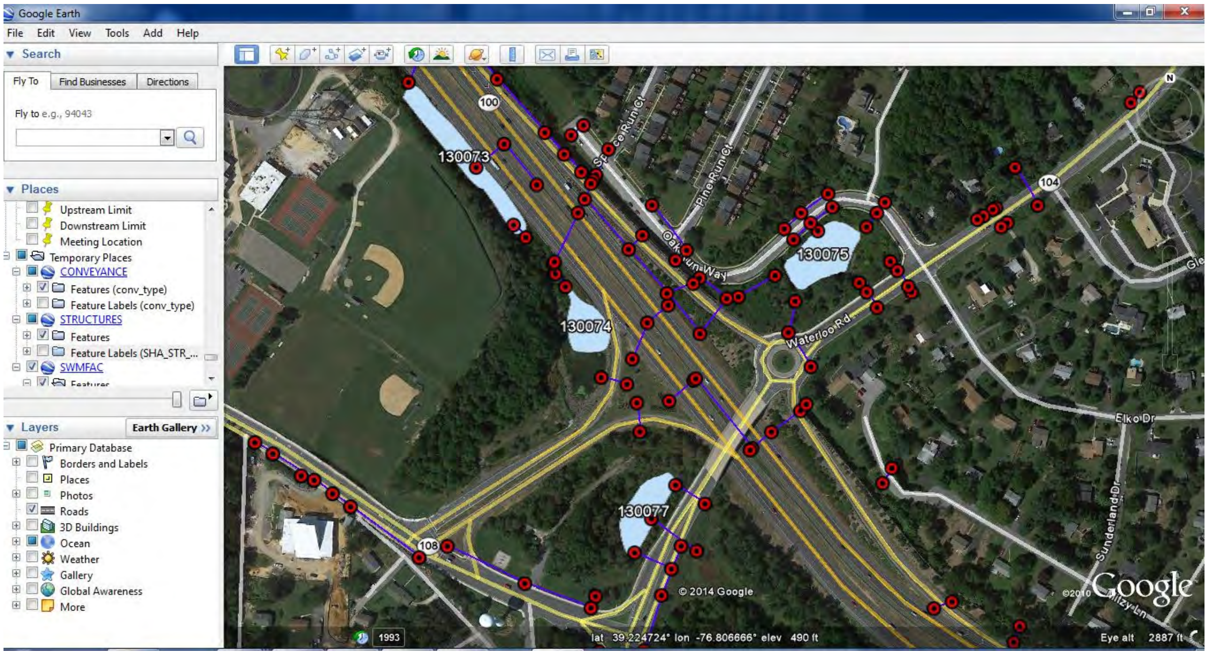


*Figure 1-6: Google Earth Screenshot of SHA NPDES Data Uploaded as KML*

**NPDES Software Development**

Descriptions of GIS software application development underway were included in the 2010 Annual Report. Application updates are performed using available resources and employing new technological advances. Table 1-1 represents the upgrade status.

**Data Management and Editing Tools Manual**

A recent addition to SHA standardized procedures for the NPDES program is the SHA *Data Management and Editing Tools Manual*. This manual outlines the data management workflow, discusses office and field editing applications that are used to assist in data collection and discusses the procedures and process for quality control of the stormwater database. SHA data managers and editors will utilize the procedures outlined in the manual to manage all the data and GIS needs for the SHA NPDES program.

*Table 1-1: Status GIS Applications*

| Phase of Development | % Complete |
|---|---|
| SWM Program Module | 100 |
| SWM Facility Numbering Module (eGIS) | 100 |
| eGIS Integration | 100 |
| eGIS IDDE Module | Planned |

### C.1.c Update Source Identification Data

Since the initial source identification has been completed for all the NPDES MS4 Phase I and II counties, the permit activity requirement for this condition now focuses on updating the source data.

Source identification updates are performed with the goal to meet the required three-year cycle and we have improved our processes in order to meet this update cycle timeframe. Future updates have been scheduled to meet this goal once the maintenance and remediation efforts have been completed for a particular county. Since the collection all NPDES MS4 Phase I and II areas was completed, the process for updating has been revised. Updates by county will be performed in four phases.

- SWM Features- This phase includes verification, inspection, and attributes updating of existing SHA stormwater facilities
- IDDE Update – This phase includes the verifications and inspection of all major and minor outfalls within SHA Right-of-Way to meet requirements of Illicit Discharge Detection and Elimination (IDDE).
- Data Quality - This additional step was recently added to the process due to the overall scale to the information. The phase includes quality control and assurance for the data set.
- New Feature Update- This phase includes the inputting, verification, and inspection all new SWM and drainage assets.

The schedule for initiation of these phases and future updates are as specified in Table 1-2. The latest data collected is as follows:

**Phase I**

Anne Arundel County – Updated identifications of the separate storm water system and outfall and BMP inspections were completed during this reporting period and are included in this report. Inspections within this county are underway and will be completed by December 2014.

Baltimore County – Updated identifications of the separate storm water system and outfall and BMP inspections were completed in 2012.

Carroll County – Updated identifications of the separate storm water system and outfall and BMP inspections were completed in 2012.

Charles County – Updated identifications of the separate storm water system and outfall and BMP inspections were completed in 2012.

Frederick County – Updated identifications of the separate storm water system and outfall and BMP inspections were completed and included in the 2011 Report. Updates to the information will begin in December of 2014.

Harford County – Updated identifications of the separate storm water system and outfall and BMP inspections were completed and included in the 2011 Report. Updates to the Information will be begin in October 2014.

Howard County – Updated identifications of the separate storm water system and outfall and BMP inspections were completed in 2012.

Montgomery County – Updated identifications of the separate storm water system and outfall and BMP inspections were included in the 2011 Report. Inspections within this county are underway and will be completed by October 2014.

Prince George's County – Updated identifications of the separate storm water system and outfall and BMP inspections were completed during this reporting period and are included in this report. Inspections within this county are underway and will be completed by October 2014.

**Phase II**

Cambridge, Cumberland and Salisbury Cities – This original inventory work was completed in 2014.

Cecil County – The GIS inventory of SHA storm drain, BMP and outfall information, and inspections in Cecil County was completed in 2008. Inspections within this county are underway and will be completed by October 2014.

Washington County –The GIS inventory of SHA storm drain, BMP and outfall data and inspections in Washington County was completed in 2012.

***Table 1-2: Source ID Schedule***

| Jurisdiction | SWM Feature | IDDE Update | Data Quality Update | New Feature Update |
|---|---|---|---|---|
| Anne Arundel County | March-14 | August-14 | November-14 | December-14 |
| Baltimore County | January-12 | February-12 | February-15 | May-15 |
| City of Cambridge | April-14 | Not Required | August-17 | December-16 |
| Carroll County | March-12 | March-12 | July-15 | July-15 |
| Cecil County | March-14 | October-14 | January-15 | May-15 |
| Charles County | March-12 | March-12 | July-15 | September-15 |
| City of Cumberland | September-14 | Not Required | September-17 | May-17 |
| Frederick County | December-14 | September-15 | May-18 | August-17 |
| Harford County | September-14 | September-14 | May-17 | May-17 |
| Howard County | January-12 | February-12 | March-15 | June-15 |
| Montgomery County | March-14 | March-14 | November-14 | December-14 |
| Prince George's County | March-14 | October-14 | November-14 | March-14 |
| City of Salisbury | April-14 | December-14 | August-17 | December-16 |
| Washington County | March-12 | April-12 | April-15 | June-15 |

## C.2 Submit BMP Data

Database tables are included on the attached CD as noted in the Introduction.

## C.3 Create Impervious Surface Account

This condition requires that SHA provide a detailed account of impervious surfaces owned by SHA and an account of those acres of impervious surface controlled by stormwater management, broken out by SHA engineering district. This account will be used to identify potential areas for implementing restoration activities.

We completed the impervious accounting requirement and the baseline accounting numbers were reflected in the 2010 report. Table 1-3 displays the baseline untreated impervious numbers for SHA by county and the progress of the restoration based on the requirement for twenty-five restoration projects (permit condition G.1). Figure 1-7 provides a graphic illustration of the progress.

*Table 1-3: SHA Impervious Restoration Accounting by County*

| County | Baseline Total Impervious | Baseline Untreated Impervious (AC) | Baseline Treated Impervious (AC) | Impervious Acres Restored by Permit Condition (AC) | Impervious Acres Restored by Permit Condition (%) | Adjusted Untreated Impervious (AC) | Total Impervious Treated (%) |
|---|---|---|---|---|---|---|---|
| Anne Arundel | 3979 | 3096 | 883 | 67 | 2.2% | 3029 | 23.9% |
| Baltimore | 4141 | 3790 | 350 | 279 | 7.4% | 3511 | 15.2% |
| Carroll | 1312 | 1198 | 114 | 0 | 0% | 1198 | 8.7% |
| Cecil | 1189 | 1174 | 15 | 0 | 0% | 1174 | 1.3% |
| Charles | 1324 | 1156 | 167 | 2 | 0.2% | 1154 | 12.8% |
| Frederick | 2397 | 2091 | 305 | 2 | 0.1% | 2089 | 12.8% |
| Harford | 1665 | 1487 | 178 | 21 | 1.4% | 1466 | 12.0% |
| Howard | 2144 | 1729 | 415 | 15 | 0.9% | 1724 | 20.1% |
| Montgomery | 3685 | 3058 | 628 | 8 | 0.3% | 3050 | 17.3% |
| Prince George's | 4535 | 4001 | 534 | 26 | 0.6% | 3975 | 12.3% |
| Washington | 2168 | 2073 | 95 | 0 | 0% | 2073 | 4.4% |
| **Totals** | **28,539** | **24,853** | **3,684** | **420** | **1.7%** | **24,443** | **14.4%** |

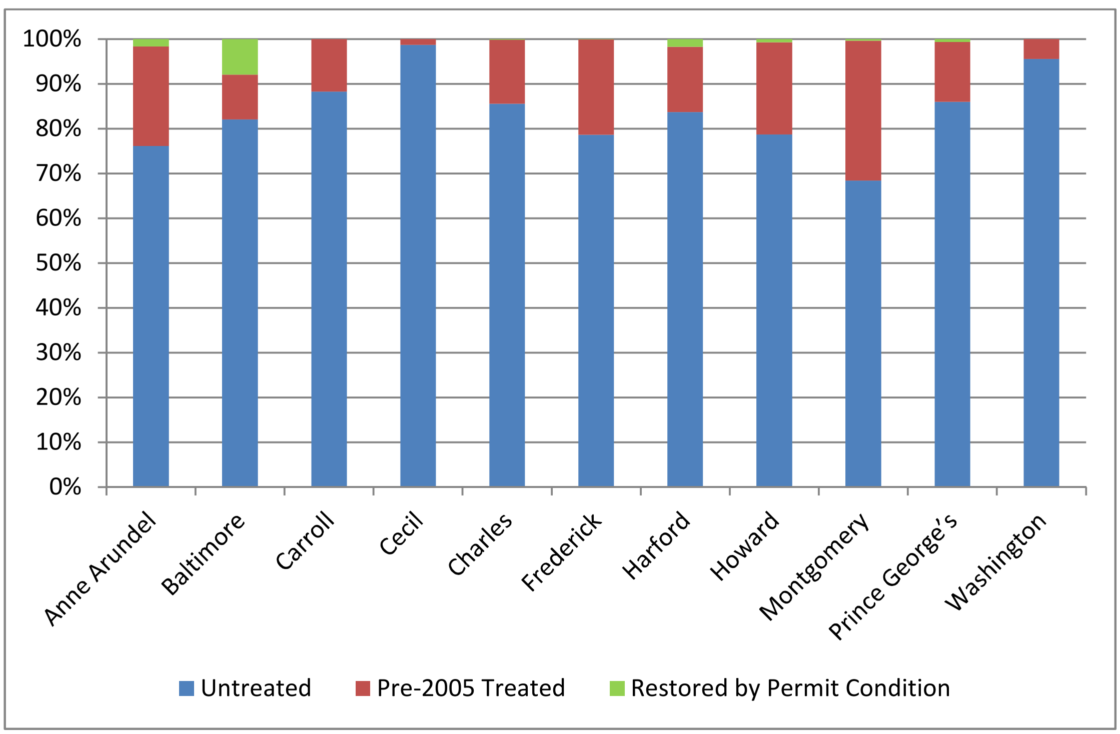


*Figure 1-7: SHA Impervious Restoration Progress by County*

**Impervious Layer Updates**

The impervious layer quantifying impervious surfaces owned and treated by SHA has been updated during the past reporting cycle. SHA has initiated development to update SHA impervious data in several counties during the reporting period, including Frederick and areas within Anne Arundel County. SHA performed an update to the associated drainage area delineations for stormwater BMPs in order to provide more accurate data of SHA and non-SHA impervious surfaces draining to each BMP. SHA is planning to enhance the impervious accounting by researching stormwater facilities and verifying the treatment provided for the impervious areas in order to develop new baselines for the next permit term.

Future updates to the remaining SHA Phase I MS4 impervious layers are planned, including Anne Arundel County, Howard County, Montgomery County and Prince Georges County.

Table 1-4 indicates the current status of impervious layer updates in each Phase I and Phase II MS4 county:
:

***Table 1-4: Impervious Layer Update Status***

| County | Impervious Layer Update Status |
|---|---|
| Anne Arundel County | In Progress |
| Baltimore County | Complete |
| Carroll County | Complete |
| Cecil County | Complete |
| Charles County | Complete |
| Frederick County | Complete |
| Harford County | Complete |
| Howard County | Planned |
| Montgomery County | Planned |
| Prince George's County | Planned |
| Washington County | Complete |

## D Discharge Characterization

SHA continues the efforts to identify best practices and to measure and quantify discharge characteristics through environmental research of stormwater runoff that flows from the highway network and associated facilities. Similar analyses are performed for discharges from SWM facility assets and other stormwater control measures (SCMs) implemented.

Auto-samplers are used as much as possible since it is often difficult to determine the exact timing of when precipitation events will occur and to allowing sufficient travel time to sampling locations, enhancing the value and usefulness of our monitoring efforts and help ensure more effective use of taxpayer funds. To ensure consistent, standardized reporting, collected samples are tested following strict adherence to the Standard Methods as specified by the American Public Health Association.

For several years, research has examined several areas, including:

- Grass swales
- Thermal impacts
- Pollutant removal efficiencies
- Urban runoff
- Wet infiltration
- Bioretention soil
- Sand filters
- Outfall Stabilization

The typical list of pollutants monitored in the pertinent discharge characterization studies includes:

- pH
- Temperature
- Total suspended solids (TSS)
- Nutrients
  - Total phosphorus (TP)
  - Total Kjeldahl nitrogen (TKN)
  - Oxidized nitrogen
- Heavy metals (total)
  - Copper (Cu)
  - Lead (Pb)
  - Zinc (Zn)
- Chlorides

In some instances, other monitored parameters include oil, grease, and other hydrocarbons; turbidity; and fecal coliforms.

The data from our research efforts and discharge characterization activities may be used towards new designs and evaluations of both existing and proposed SCMs. The information is also used to assess the effectiveness of current SWM asset function and service as the basis for long-term decision-making strategies.

Past research and discharge characterization activity data and result reports have been detailed during previous annual reporting periods, including the following.

*Annual Report: Pindell School Road Storm Sampling,* KCI, March 7, 2000.

*National Highway Runoff Study: Comparison to MSHA Sampling Results,* KCI, December 2001.

*Dulaney Valley Road I-695 Interchange Stream Monitoring at the Tributary to Hampton Branch,* KCI, Annual Reports dating 2000 to 2003.

Additional activities that have been previously reported in annual reports as noted by specific publication dates are as follows.

**First Annual Report (October 2006):**

*Low Impact Development Implementation Studies in Mt. Rainier, MD*, University of Maryland, December 2005.

*Grassed Swale Pollutant Removal Efficiency Studies (Part II – MDE/SHA Swale Comparison),* University of Maryland, October 2006.

*Mosquito Surveillance/Control Program for SWM Facilities in Baltimore, Howard, Montgomery and Prince Georges Counties (2003-2005)*, Millersville University, October 2006.

**Second Annual Report (October 2007):**

*Grassed Swale Pollutant Removal Efficiency Studies (Part III – Grass Check Dams)*, University of Maryland, August 2007.

*Literature Review: BMP Efficiencies for Highway and Urban Stormwater Runoff,* Progress Report, University of Maryland, September 2007.

*Underground SWM Thermal Mitigation Studies,* Progress Report, University of Maryland, August 2007.

*Prediction of Temperature at the Outlet of Stormwater Sand Filters*, Progress Report, University of Maryland, August 26, 2007.

**Third Annual Report (October 2008):**

*Grassed Swale Pollutant Removal Efficiency Studies: Field Evaluation of Hydrologic and Water Quality Benefits of Grass Swales with Check Dams for Managing Highway Runoff (Part III continuation)*, Progress Report, University of Maryland, October 2008.

*Thermal Impact of Underground Stormwater Management Storage Facilities on Highway Stormwater Runoff*, Progress Report, University of Maryland, October 2008.

**Fourth Annual Report (October 2009):**

*Field Evaluation of Water Quality Benefits of Grass Swale for Managing Highway Runoff (Part III – Grass Check Dams*), Progress Report, University of Maryland, July 2009.

*Nutrient Removal Optimization of Bioretention Soil Media, Progress Report*, University of Maryland, August 2009.

*Field Evaluation of Wet Infiltration Basin Transitional Performance*, Progress Report, University of Maryland, August 2009.

**Fifth Annual Report (January 2010) – Reports included in Appendices but not directly discussed in the report:**

*Field Evaluation of Water Quality Benefits of Grass Swale for Managing Highway Runoff*, Progress Report, University of Maryland, July 2009.

*Field Evaluation of Wet Infiltration Basin Transitional Performance*, Progress Report, University of Maryland, August 2009.

*Nutrient Removal Optimization of Bioretention Soil Media*, Final Report, University of Maryland, September 2010.

**Annual Report Update (October 2011):**

Although there were no reports or findings that were included, new studies on enhancing nitrogen and phosphorus removal in existing and proposed SWM facilities were initiated and work on the field evaluation of wet infiltration basin transitional performance continued.

**Annual Report Update (October 2012):**

*Field Evaluation of Wet Infiltration Basin Transitional Performance*, Progress Report, University of Maryland, July 2012.

*Management of Nitrogen in Stormwater Runoff Using a Modified Conventional Sand Filter*, University of Maryland, August 2012.

*Denitrification Optimization in Bioretention Using Woodchips as a Primary Organic Carbon Source*, First Year Progress Report, University of Maryland, July 2012.

**Annual Report Update (October 2013)**

*Final Report: Evaluation of Transitional Performance of an Infiltration Basin Managing Highway Runoff,* University of Maryland, 2012

*Final Report: Advanced Denitrification in Bioretention Systems Using Woodchips as an Organic Carbon Source*, University of Maryland, 2013

Progress reports on newly initiated research were also included in the annual report for the reporting period, specifically, these were the research projects entitled *Management of Nitrogen in Stormwater Runoff Using a Modified Conventional Sand Filter* and *Enhancements for N and P Removal from Stormwater Management Facilities for Multi-Modal Transportation Infrastructure in Maryland: Multi-Criteria Plant Selection for Vegetated Stormwater Control Measures*, both by the University of Maryland.

**Recently Completed Studies**

In May 2014, the University of Maryland submitted the final report for *Recommendations for the State Highway Administration on Stormwater Control Measures and Research Efforts for Multimodal Transportation Infrastructure in Maryland that Promote More Effective and Sustainable Stormwater Runoff Management*. The research effort, consisting of a literature review and synthesis, examined various types of SWM facilities and compared them with regards to pollutant removal efficiencies, types of pollutants removed, cost of installation, cost to maintain, and recommendations regarding future research. The study was summarized in the previous Annual Report, and the final report can be found in Appendix B.

Bioretention systems still lack the ability to effectively mitigate nitrogen concentrations from urban stormwater. In July of 2013, the University of Maryland completed the study. *Advanced Denitrification in Bioretention Systems using Woodchips as an Organic Carbon Source.* Column tests were conducted to evaluate the effect of nitrate concentration, stormwater retention time, limestone addition, and woodchip species, size, and mass percentage on the bioretention denitrification process. The study was summarized in the previous Annual Report, and the final report can be found in Appendix C.

**Ongoing Studies**

Continuing studies remain on schedule and current progress is as follows.

**Management of Nitrogen in Stormwater Runoff Using a Modified Conventional Sand Filter**

The surface sand filter is a common SWM facility type that was frequently used between 2003 and 2010. They continue to be a popular choice when conditions are appropriate for its use, such as the means of SWM for salt barn facilities; however, sand filters are not necessarily an optimal choice for reducing nutrient concentrations in stormwater runoff. Because of the number of sand filters in our asset inventory, and because we're interested in techniques to enhance existing facilities to increase nitrogen and phosphorus removal efficiencies, the University of Maryland has continued to examine ways in which nitrogen removal may be improved in sand filter facilities.

To reduce nitrogen loading, the proposed design divides the sand filter into three zones to promote ammonification, nitrification, and denitrification. Nitrification was observed to automatically occur during low nitrogen loadings and dry periods, without any modifications to sand filter design; however, to achieve adequate media contact time for key biological denitrification processes to occur, sorptive materials must be incorporated into the sand filter bed.

The first phase of the project focused on the selection of adsorbents to increase the uptake of ammonium. Clays, recycled materials, and sands were selected for study. The time necessary for sorption to reach equilibrium with these materials was found to be 24 hours; however, due to the low sorption capacity and instability in the structure of clay agglomerates, testing of Georgia attapulgite and brown montmorillonite were abandoned. Sorption tests continued with California aluminosilicate (CA), crushed brick (BR), red montmorillonite (MR), and clinoptilolite zeolite (ZT). The sorption capacity of ZT was found to be the greatest of all adsorbents, followed by MR.

The second phase focused on small scale column studies for the sorption of ammonium to provide more comprehensive determinations on adsorbent performance. Based on the results, the column studies were expanded for further study in the third phase to better examine nitrification and sorption simultaneously to quantify the rate of nitrification and determine the optimum media thickness.

In the third phase, it was found that zeolite added to sand results in greater nitrogen removal; however, the presence of road salts, often a result of winter deicing operations, significantly impairs and eliminates the enhanced nitrogen removal capacity of the zeolite. Even without the presence of road salts, the enhancement only appears to be viable for about 18 months.

The research has now entered its fourth phase. Additional considerations will be reviewed to determine if zeolite is a cost-effective means to improve nitrogen removal in sand filter facilities.

**Enhancements for N and P Removal from Stormwater Management Facilities for Multi-Modal Transportation Infrastructure in Maryland: Multi-Criteria Plant Selection for Vegetated Stormwater Control Measures**

The University of Maryland continues to examine vegetation selection used in bioretention and similarly-related vegetated SCMs (swales, bioswales, rain gardens, and planter boxes). While current criteria for plant selection are primarily based on survival, aesthetics and context, there may be facility performance benefits associated with specific plant species that may be quantified.

In the relationship between plants and soils, vegetation is known to help maintain soil porosity through root building and decay, promote nutrient extraction, and host beneficial microbial consortia in the rizosphere; however, we have found that during construction activities, successful vegetation establishment has also been a challenge, and we're concerned that this may also affect facility performance as well as aesthetic appeal and sustainability.

In phase one of the study, a full literature synthesis and review was completed and several plant species were identified that appear to better remove nitrogen and various forms thereof, phosphorus, hydrocarbons, and heavy metals. Vegetation appears to offer other benefits as well, such as providing habitats within SWM facilities along with shade, which may reduce thermal impacts to waterways; however, some vegetation may not meet expected aesthetic appeal. Specifically, it appears that *Eutrochium* (Joe Pye) species, *Iris versicolor*, *Juncus effusus*, and *Panicum virgatum* are very hardy and acceptable (see Figures 1-8 through 1-11.) *Juncus effusus* tends to appear messy and may not be suitable for high-visibility areas. *Panicum virgatum* may also get too tall and interfere with sight-distance. Species that appear to consistently fail to survive are *Ilex verticillata* (winterberry), *Ilex glabra 'shamrock'*, and *Onoclea sensibilis* (sensitive fern).

***Figure 1-8: Eupatorium dubium (Joe Pye Weed)***

***Figure1- 9: Panicum virgatum (Switchgrass)***

*Figure 1-10: Iris versicolor (Blue Flag Iris)*

*Figure 1-11: Juncus effusus (Soft Rush)*

The study has now entered its second phase. Examination of plant species will continue. The completion of a recommended plant list, and possibly a recommended plants-to-avoid list, is anticipated to be completed at the end of phase two.

### New Studies

New studies have also been initiated and are as follows.

### Evaluation of Compost Addition to Stormwater Control Measure Performance

To simultaneously achieve the goals of greater incorporation of recycled materials into our projects as well as facilitate meeting new requirements established by recent legislative mandates, we have initiated a research project with the University of Maryland to examine how compost may be used in SWM facilities.

Laboratory experiments to identify compost leachate composition and concentrations will be performed, as will experiments to determine how the infiltration rate through filter media may change with variable compost concentrations that replace portions of the shredded hardwood bark amounts. A final report detailing findings and future research and study needs will be generated. See Figure 1-12 below for a media comparison.


*Figure 1-12: SWM Filtration Media with Compost*

### US 40 Bioswale Monitoring Study

In 2014, SHA also initiated bioswale monitoring study at to evaluate effectiveness of this widely used BMP and its pollutant removal efficiency. The study site is located along US 40, west of I-81 in Washington County, at BMP 210197, 210198, and 210199. Monitoring equipment has been installed and the samplers are logging data. The research team has also completed the soil infiltration capacity measurements at all three sites. In the laboratory, the team has completed the digestion on the soil samples provided and measured the basic soil parameters. Testing for heavy metals in the samples is currently underway. Soil samples will be sieved and classified. A draft report is anticipated in December, 2014.

# E Management Program

A management program is required to limit the discharge of stormwater pollutants to the maximum extent practicable. The idea is to eliminate pollutants before they enter the waterways. This program includes provisions for environmental design, erosion and sediment control, stormwater management, industrial facility maintenance, illicit connection detection and elimination, and personnel and citizen education concerning stormwater and pollutant minimization.

## E.1 Environmental Design Practices

This permit condition requires that SHA take necessary steps to minimize adverse impacts to the environment through the roadway planning, design, and construction process. Engaging the public in these processes is also required.

The Maryland State Highway Administration has a strong environmental commitment that has only increased as the new Stormwater Management Act of 2007 was implemented in May 2010. Through this legislation, emphasis was placed on the use of environmental site design (ESD) techniques. We are actively working ESD measures into roadway projects.

SHA also continues to adhere to processes that ensure that environmental and cultural resources are evaluated in the planning, design, construction and maintenance of our roadway network. This includes providing opportunity for public involvement and incorporating context sensitive solutions. We also ensure that all environmental permitting requirements are met by providing training to our personnel (see E.6.b below) and creating and utilizing software to track permitting needs on projects as they move through the design, advertisement and construction processes.

**NEPA/MEPA Process**

SHA's National Environmental Policy Act/ Maryland Environmental Policy Act (NEPA/MEPA) design and planning process, includes developing and obtaining approval on environmental documentation for any project proposed utilizing state or federal funding. SHA also assists local jurisdictions through the environmental documentation process so they remain eligible to receive state/federal funds, such as Transportation Alternatives Program funds. An early step in the process is to identify the natural, community, and cultural resources that exist in the project study area and determine the level of environmental documentation and stakeholder involvement needed. The final environmental document may be a Categorical Exclusion (CE) for minor impacts, Finding of No Significant Impact (FONSI) for more substantial impacts or Environmental Impact Statement (EIS) for major impacts or when stakeholder controversy surrounds the project.

Increasingly, SHA is evaluating stormwater needs during the NEPA process to address Environmental Site Design requirements. This movement requires that stormwater concepts be developed during the planning process, and has affected the development process in several ways. Beginning the stormwater process earlier allows more realistic concepts to be presented during public meetings and allows more accurately assessments of right-of-way needs. The drawback to this approach, however, can be that assumptions made in terms of the stormwater requirements may not be the final approved requirements as plans change during the design process. This can have negative impacts on the permit approval process, public expectations, right-of-way acquisitions, and design schedules. SHA encourages the stormwater regulatory reviewers to participate in the planning process by attending interagency meetings, reviewing concept plans, and providing valid comments and concept approvals at the planning stage of design.

It should be noted, however, that the planning process for major projects and the project development timeline can be greater than cycles of regulatory changes for water quality. This further introduces complexity in decision making and public perception of accuracies of SHA projects and processes.

Effort is made to avoid or minimize environmental impacts. If impacts are unavoidable, however, mitigation is provided and monitored per regulatory requirements.

## E.2 Erosion and Sediment Control

Requirements under this condition include:

a) *Use of MDE's 2011 Standards and Specifications for Soil Erosion and Sediment Control, or any subsequent revisions, evaluate new products for erosion and sediment control, and assist MDE in developing new standards; and*

b) *Perform responsible personnel certification ('Green Card') classes to educate highway construction contractors regarding erosion and sediment control requirements and practices. Program activity shall be recorded on MDE's "green card" database and submitted as required in Part IV of this permit.*

### E.2.a MDE ESC Standards

SHA continues to comply with Maryland State and Federal laws and regulations for erosion and sediment control (ESC) as well as MDE requirements for permitting. We maintain compliance with the NPDES Stormwater Construction Activity permit for projects that disturb one acre or more of land.

We continue compliance with the Maryland Erosion & Sediment Control Guidelines for State and Federal Projects published in January 1990 and revised in January 2004. In December 2011, MDE published the 2011 Maryland Standards and Specifications for Soil Erosion and Sediment Control. Projects are designed and constructed in compliance with the new specifications. SHA updated their Erosion and Sediment control field guide to support the 2011 MDE specifications. The laminated book version is used as a field tool where users have the option of writing (dry erase) notes in the book.

SHA has implemented changes to construction inspection practices to maintain compliance with the NPDES Construction Activity Permit by drafting a new evaluation form to measure NPDES and Stormwater Management (SWM) requirements. We continue to submit applications for coverage under this general permit for all qualifying roadway projects.

**SHA ESC Quality Assurance Ratings**

SHA continues to use our improved Quality Assurance rating system for ESC on all roadway projects. This effort is designed to improve field implementation of ESC measures through a rating system (by issuing grades A – F) and by including incentive payments to the contractor for excellent ESC performance. Under this system, the contractor incurs liquidated damages for poor ESC performance.

SHA tracks quality assurance inspections and ratings for reporting to our business plan and StateStat. Increased numbers of inspections and better documentation have improved the overall performance of our ESC program. Incentive payments are made when the contractor receives an ESC rating score of 85% or greater over the course of each rating quarter (three months). A final incentive payment is also made for projects with an overall (average) rating of 85% or better.

On SHA design-build projects compensation for E&S response action related to severe weather is addressed by specification. This compensation is in addition to the incentive for excellent performance as stated above.

Liquidated damages are imposed on the contractor if the project receives a 'D' or 'F' rating. If two ratings of 'F' are received on a project, the ESC certification issued by SHA will be revoked from the contractor project superintendent and the ESC manager for a period of six months and successful completion of the certification training. This system of rewarding good performance and penalizing poor performance has shown to improve contractor responsibility for ESC practices. It has also improved water quality associated with earth disturbing and construction activities.

In FY 2014, a record number of inspections (4188) on a record number of projects (303) reviewed, yielded an overall compliance of

99.79. percent (See Figures 1-13 below and 1-14 on the following page).

In the past year, SHA prepared a revised standard form (OOC61) – Independent Quality Assurance Erosion and Sediment Control Field Investigation Report used for ESC and NPDES construction tracking in an effort to increase compliance with both State and Federal ESC regulations. This form is still draft and it is anticipated to be in use during the next reporting term.

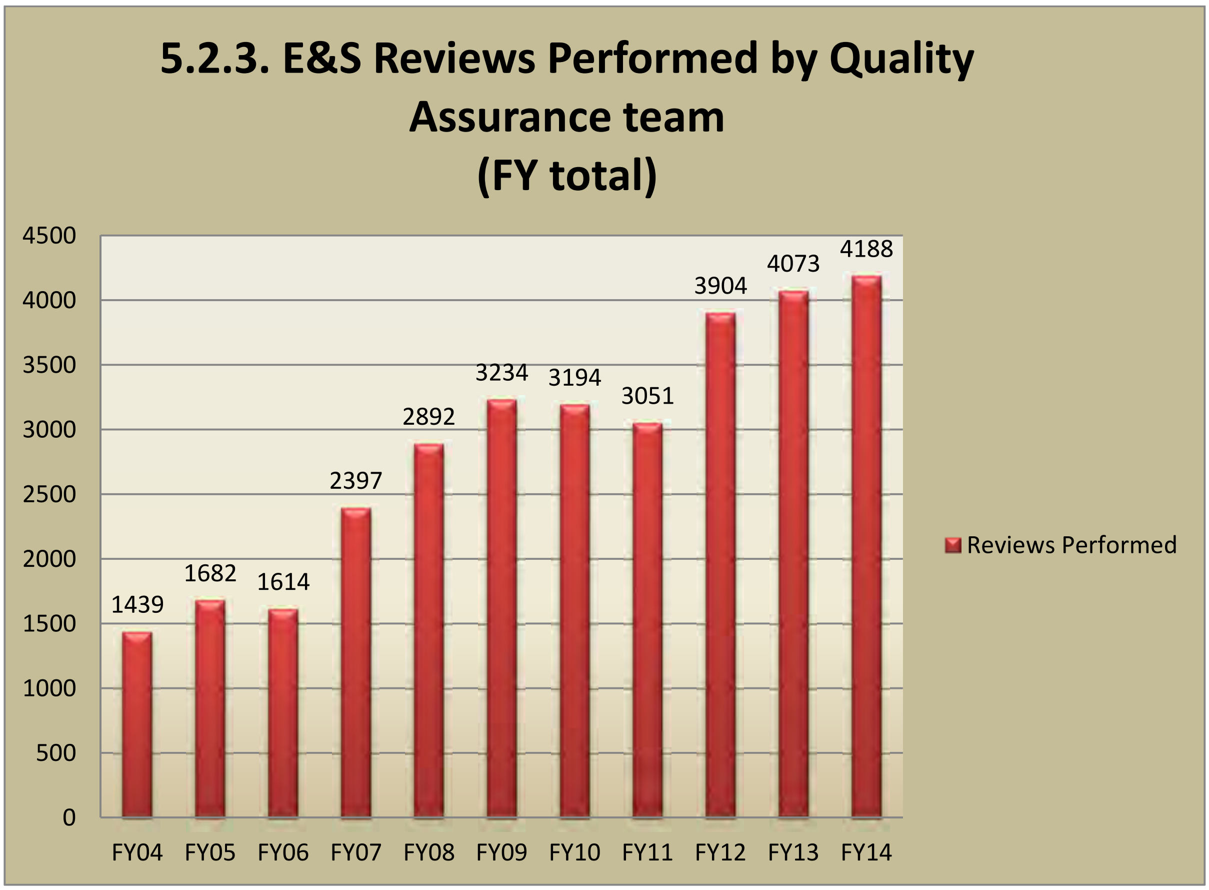


***Figure 1-13: Erosion and Sediment Control Reviews Performed for FY2014***

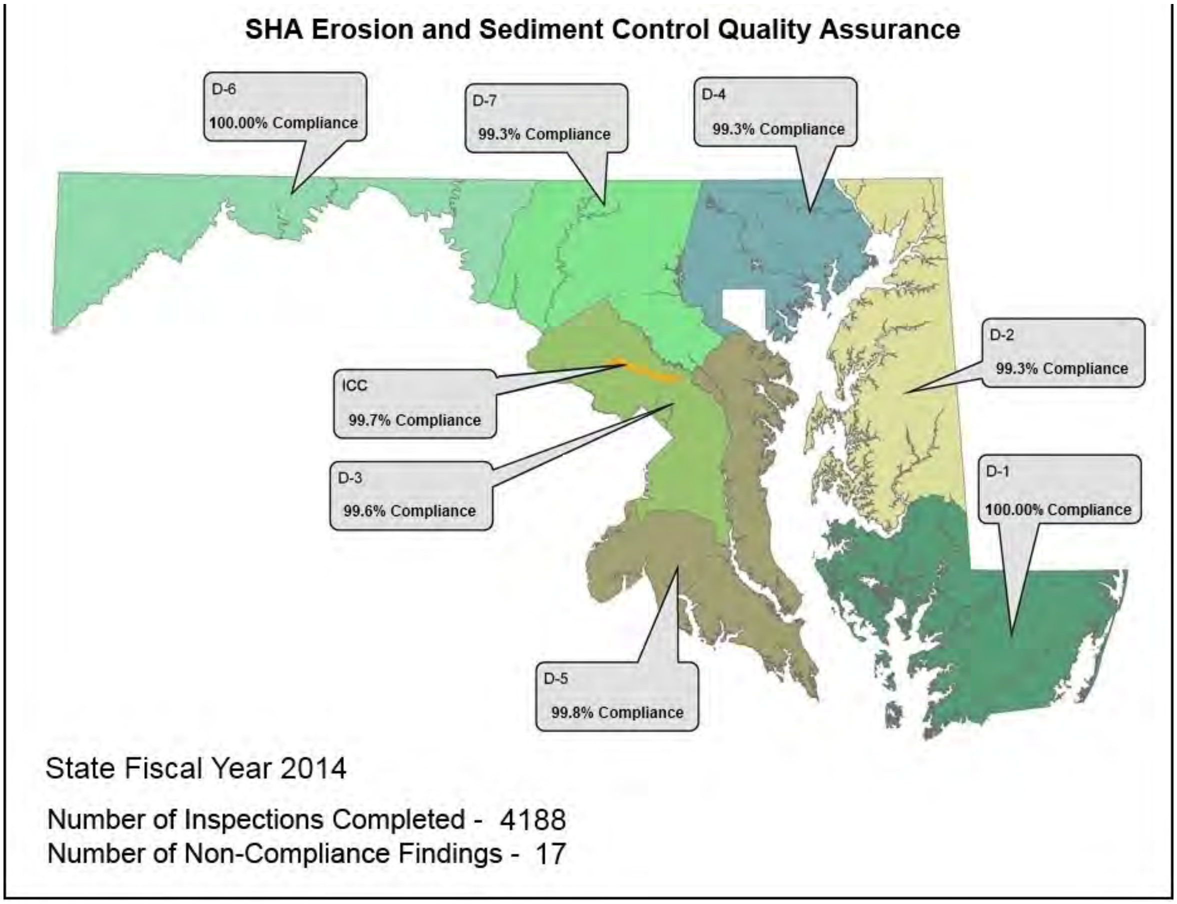


***Figure1-14: Erosion and Sediment Control Quality Assurance for FY2014***

### E.2.b Responsible Personnel Training for Erosion and Sediment Control (Green Card Certification)

SHA continues to provide a limited number of MDE's Responsible Personnel Training for Erosion and Sediment Control to SHA personnel, consultants, and contractors. MDE is revising a new training which will be available as an on line application.

**SHA Basic Erosion and Sediment Control Training (Yellow Card Certification)**

In addition to Green Card Training classes, SHA continues to present updated Erosion and Sediment Control training initiated in 2004. Classes include instruction and certification for the MDE Green Card. This Level I training is recommended for contractors and field personnel. It covers key requirements of the NPDES permit. Also covered are resources, and personnel for construction projects, ESC specifications/inspections, process for ESC modifications during construction, and stabilization. This certification expires three years from the date of issuance. In the past year, SHA updated and provided on-line training for Yellow Card (YC) and YC re-certification. Table 1-5 on the following page details the number of personnel certified for each of the training levels for the reporting period.

*Table 1-5: SHA ESC Training*

| Type of Training | No. Certified |
|---|---|
| Responsible Personnel (Green Card) | 318 |
| Level I (Yellow Card) | 365 |
| Level I (Yellow Card Recertification) | 342 |

## E.3 Stormwater Management

The continuance of an effective stormwater management program is the emphasis of this permit condition. Requirements under this condition include:

*a) Implement the stormwater management design principles, methods, and practices found in the 2000 Maryland Stormwater Design Manual, the 2009 update, and COMAR;*
*b) Implement a BMP inspection and maintenance program to inspect all stormwater management facilities at least once every three years and perform all routine maintenance (e.g., mowing, trash removal, tarring risers, etc.) within one year of the inspection; and*
*c) Document BMPs in need of significant maintenance work and prioritize these facilities for repair. The SHA shall provide in its annual reports detailed schedules for performing all significant BMP repair work.*

### E.3.a Implement SWM Design Manual and Regulations

SHA continues to comply with Maryland State and Federal laws and regulations for stormwater management (SWM) as well as MDE requirements for permitting. We also continue to implement the practices found in the *2000 Maryland Stormwater Design Manual* and the *Maryland Stormwater Management Guidelines for State and Federal Projects, April 15, 2010* for all projects. We have also implemented the requirements in the revised Chapter 5 of the 2000 Manual for environmental site design (ESD) and the Stormwater Management Act of 2007 for all new projects.

### E.3.b Implement BMP Inspection & Maintenance Program

Our continuing Stormwater Management (SWM) Facilities Program inspects, evaluates, maintains, remediates and enhances SHA BMP assets to maintain and improve water quality and protect sensitive water resources. Inspections are conducted on a cyclical basis as part of the NPDES source identification and update effort (see Section C, above). Maintenance and remediation efforts are accomplished after the inspection data has been evaluated and ranked according to SHA rating criteria.

Details of the SWM Facility Program are included as Part 2 of this document. Discussion of inspection results and maintenance, remediation, retrofit and enhancement efforts undertaken over the past year is included in that section.

### Stormwater As-Built Certification Process

SHA continues to improve the SWM facility as-built certification process in order to comply with the SWM approval and COMAR. This process assures verification of proper construction of the SWM facilities to meet the design intend. Throughout the construction process, the design engineer coordinates with the Office of Construction and the contractor to perform required inspections during construction and to document the information in the MDE approved as-built tabulations. The contactor's engineer certifies the SWM facility was constructed according to the approved design plans and within allowed tolerances as stated in the SHA issued Special Provision included in the contract documents. SHA has made the delivery of this certification a separate pay/bid item in the construction estimate.

The SHA project engineer coordinates with MDE on the review and approval of the as-built certified plan. The construction project cannot be closed and accepted for maintenance until the as-built plans have been accepted by MDE. Copies of the final approved as-built certifications are retained by SHA and integrated into the storm drain and BMP GIS/database. This information is then used as source identification updates are planned and assigned.

### E.3.c Document Significant BMP Maintenance

See Part 2 for SWM Facilities Program updates on major maintenance, remediation and BMP retrofits.

## E.4 Highway Maintenance

Requirements under this condition include:

a) *Clean inlets and sweep streets;*

b) *Reduce the use of pesticides, herbicides, and fertilizers through the use of integrated pest management (IPM);*

c) *Manage winter weather deicing operations through continual improvement of materials and effective decision making;*

d) *Ensure that all SHA facilities identified by the Clean Water Act (CWA) as being industrial activities have NPDES industrial general permit coverage; and*

e) *Develop a "Statewide Shop Improvement Plan" for SHA vehicle maintenance facilities to address pollution prevention and treatment requirements.*

### E.4.a Inlet Cleaning and Street Sweeping

Mechanical sweeping of the roadway is essential in the collection and disposal of loose material, debris and litter into approved landfills. This material, such as dirt and sand, collects along curbs and gutters, bridge parapets/curbs, inlets and outlet pipes. Sweeping prevents buildup along sections of roadway and allows for the free flow of water from the highway, to enter into the highway drainage system. See Figure 1-15 below for an example of SHA's street sweeping activity.

***Figure 1-15: Street Sweeping often takes place at night due to high traffic volumes in urbanized counties***

The SHA desired maintenance condition is 95% of the traveled roadway clear of loose material or debris. In addition, 95% of closed section roadways (curb and gutter) should have less than 1 inch depth of loose material, debris, or excessive vegetation that can capture debris, in the curb and gutter.

In addition to street sweeping, SHA owns and operates four vacuum pump trucks that routinely clean storm drain inlets along roadways. Sediment and trash make up the majority of the material that is removed. The vacuum trucks operate in central Maryland, spanning the following Counties: Anne Arundel, Baltimore, Calvert, Carroll, Charles, Frederick, Harford, Howard, Montgomery, Prince Georges and St. Mary's. This practice ensures safer roadways through maintaining proper drainage and improves water quality in Maryland streams by removing captured sediment and trash before they enter adjacent waterways.

See Figures 1-16 and 1-17 on the following page for examples of street vacuuming and inlet cleaning.

*Figure 1-16: SHA Shop Personnel Operating Vacuum Truck to Clean Roadside Debris*

*Figure 1-17: Inlet Before and After Vacuuming*

**Pollutant Reductions for Inlet Cleaning and Street Sweeping**

Sweeping and inlet cleaning are recognized as valid pollutant source reduction BMPs, however the means for crediting reductions is not well defined at this point. We are evaluating appropriate load reductions that can be claimed by SHA in meeting local and Bay TMDLs. This accounting will be added to reports for the next permit term.

The SHA Water Programs Division (WPD) is working with the SHA Office of Maintenance (OOM) to document current routes, to extend these activities to watershed-based, priority roadways and to characterize and quantify material and debris removed as a result of these activities. The result will be the development of procedures to optimize reporting of reductions associated with each of these activities and to better understand pollutant loads gathered from highways. It is hoped that this understanding will result in additional impervious surfaces treatment.

### E.4.b Reduction of Pesticides, Herbicides and Fertilizers

SHA has standards for maintaining the highway system and one of these standards is the *SHA Integrated Vegetation Management Manual for Maryland Highways, October 2003* (IVMM). This manual incorporates the major activities involved in the management of roadside vegetation including application of herbicides, mowing and the management of woody vegetation. In order to maximize the efficiency of funds and to protect the roadside environment, an integration of these activities is employed.

#### Herbicide Application

The majority of SHA's vegetation management is accomplished mechanically, through the use of mowers and brush axes. However, in areas where mechanical control is not practical or feasible, SHA manages vegetation through the use of targeted applications of herbicide.

SHA promotes the safe and responsible use of herbicide for this purpose. All SHA employees and contractors who apply herbicide on SHA rights-of-way must be registered with the Maryland Department of Agriculture (MDA) and operate under the supervision of a MDA-licensed pesticide applicator.

Environmental stewardship is a primary focus of SHA's business plan, and SHA encourages the use of selective herbicides and targeted application, rather than the broad application of non-selective herbicides. The use of herbicide is based on the plant species that is being targeted, so that the effects on other plants are minimized and soil residual activity is limited. Application rates are based on the minimum amount required to control the targeted plant species, so that the potential for runoff and non-point source contamination also is minimized.

Herbicide application equipment is routinely inspected and calibrated to ensure that applications are accurately applied in accordance to the IVMM, Maryland State law, and the herbicide label.

#### Nutrient Management Plans

The Maryland Lawn Fertilizer Law limits the total amount and restricts the timing of fertilizer applications associated with turfgrass establishment and maintenance. SHA uses slow-releasing nitrogen based fertilizers in conjunction with ground cover establishment operations. Topsoil is sampled and tested for major plant nutrients, pH, organic material, and soluble salts. The test results are used to develop a nutrient management plan (NMP) to ensure optimal nutrient levels and growing conditions and to avoid the application of excess fertilizer.

#### Mowing Reduction & Native Vegetation Establishment

A major initiative at the SHA is to reduce the extent of mowed areas within our right-of-way. The Administration's Turfgrass Management Policy has been revised to provide consistent guidance to decrease the size of mowed areas and the number of mowing cycles per year.

Several projects have been completed throughout the state to install and maintain reforestation and native meadow areas. Reforestation and native meadow areas require no to minimal mowing, preserve native vegetation, and enhance erosion control and nutrient uptake.

## E.4.c Winter Deicing Operations

SHA continues to test and evaluate new winter materials, equipment and strategies in an on-going effort to improve the level of service provided to motorists during winter storms while at the same time minimizing the impact of its operations on the environment.

One method employed to decrease the overall application of deicing materials is to increase application of deicing materials prior to and in the early stages of a winter storm (anti-icing). This prevents snow and ice from bonding to the surface of roads and bridges and ultimately leads to lower material usage at the conclusion of storm events, thus lessening the overall usage of deicers.

SHA is wrapping up its pilot program using GEOMELT 55, a de-sugared sugar beet molasses that may be blended with brine. This organic material, also known as beet juice, lowers the freezing point of the brine to -30 degrees. GEOMELT 55 also enables the brine to adhere to bridges and road surfaces better and longer, which extends the effectiveness of the deicer.

In addition, SHA is continuing its ‘sensible salting’ training of State and hired equipment operators in an on-going effort to decrease the use of deicing materials without jeopardizing the safety and mobility of motorists during and after winter storms.

Table 1-6 on the following page lists materials used by SHA in winter deicing operations.

**New Road Salt Management**

On May 20, 2010 the Governor approved Senate Bill 775, requiring SHA, in consultation with the Department of the Environment (MDE), to develop a best practices road salt management guidance document by October 2011. This document is necessary to reduce the adverse environmental impacts of road salt storage, application and disposal on Maryland’s water and land resources.

SHA posted the Statewide Salt Management Plan on its website in October 2011. The plan was subsequently updated on October 1, 2012. The plan provides guidance on snow and ice control operations with an emphasis on lessening the impact of salt on the environment. The plan covers all aspects of winter operations including:

- Safety and mobility of motorists during and after winter storms,
- Defining levels of service provided during winter storms,
- Establishing long-term goals to lessen the usage of salt, and reduce its impact on the environment,
- Salt and other winter materials,
- Material storage and handling,
- Winter storm fighting equipment,
- Training initiatives,
- Winter storm management from pre-storm preparations through post-storm operations,
- Post-storm material and equipment cleanup,
- Post-storm and post-season data analysis,
- Public education and outreach, and
- Testing and evaluation of new materials, equipment, and strategies for continual improvement.

SHA’s Office of Policy and Research (OPR) has recently issues a request for proposals to conduct a study “Balancing the Use of Salt with Safety and Mobility in Winter Maintenance Operations”. SHA plans to select a team and move forward with this research in time to apply recommendations for the 2015/2016 winter season.

*Table 1-6: SHA Deicing Materials*

| Material | Characteristics |
|---|---|
| Sodium Chloride (Rock and Solar Salt) | The principle winter material used by SHA. Effective down to 20° F and is relatively inexpensive. |
| Abrasives | These include sand and crushed stone and are used to increase traction for motorists during storms. Abrasives have no snow melting capability. |
| Calcium Chloride | A solid (flake) winter material used during extremely cold winter storms. SHA uses limited amounts of calcium chloride. |
| GEOMELT 55 | A de-sugared sugar beet molasses may be blended with the brine. Also known as "beet juice," this organic material lowers the freezing point of the brine to –30º F. The light brown material is environmentally safe and does not stain roadway surfaces |
| Salt Brine | Liquid sodium chloride or liquefied salt is a solution that can be used as an anti-icer on highways prior to the onset of storms, or as a deicer on highways during a storm. Used extensively by SHA. Freeze point of -6° F. |
| Magnesium Chloride (Mag) | A liquid winter material used by SHA for deicing operations in its northern and western counties. It has a freeze point of -26° F and has proven cost effective in colder regions. |

**Winter Operations Training**

<u>SHA Annual Snow College</u> – This training is offered every fall for new maintenance shop hires as well as 20% of veteran shop forces. The goal is to train all maintenance personnel over a five year period and repeat the process. This ensures that all maintenance personnel are exposed to current trends and technologies. The training presentations are included in the Statewide Salt Management Plan, Appendices II and III and topics covered include all aspects of winter operations with an emphasis on sensible salting. See Table 1-7 numbers trained this reporting period.

<u>Annual Maintenance Shop Winter Meetings</u> – Abbreviated salt management training is provided to all SHA maintenance forces annually at winter shop meetings. No data was available for 2012 on numbers trained.

<u>Hired Equipment Operator Training</u> – This training is provided to hired equipment contractors and operators every fall. The training presentations are included in the Statewide Salt Management Plan and topics covered include effective plowing, sensible salting and adhering to all pertinent SHA policies and procedures. No data was available for 2012 on numbers trained.

*Table 1-7: SHA Snow College Training*

| SHA District (Shops) | No. Participants |
|---|---|
| 1 (DO, WI, WO, SO) | 28 |
| 2 (CE, KE, QA, CO, TA) | 20 |
| 3 (MG, MF, PL, PM) | 35 |
| 4 (BG, BH, BO, HA) | 21 |
| 5 (AA, AG, CV, CA, CH, SM) | 15 |
| 6 (GA, AL, WA) | 34 |
| 7 (FR, CL, HO) | 71 |
| 1 (DO, WI, WO, SO) | 28 |

### E.4.d Industrial Permit Coverage

As discussed in the previous Annual Reports, SHA has implemented a Compliance Focused

Environmental Management System (CFEMS) to ensure multi-media compliance at all maintenance facilities statewide. The CFEMS covers procedures for management of environmental compliance issues, including those related to Industrial NPDES at maintenance facilities, such as spill response, material storage and vehicle washing. It includes the implementation of Standard Operating Procedures (SOPs), routine compliance inspections and environmental training covering a variety of media areas including stormwater management and spill prevention and response.

The CFEMS has been implemented in a phased approach, and as of June 2014 it covers 162 SHA facilities under a program of scheduled routine multimedia compliance assessments that include recommendations for stormwater improvements and pollution prevention. In addition, the CFEMS is now being directed toward maintenance operations as well as facility operations. As shown in Table 1-8, certain facilities are currently covered under the General Discharge Permit (12-SW). In June of 2014 SHA submitted the required Notices of Intent (NOIs) for coverage under MDE's new 12-SW general permit. SHA has implemented the new 12-SW requirements at permitted facilities statewide. Actions taken to meet 12-SW requirements include:

- Updated Storm Water Pollution Prevention Plans (SWPPP)
- Creation of standard operation procedure for Quarterly Visual Monitoring
- Updated compliance checklists for routine and quarterly inspections
- Trained shop personnel on new pollution prevention requirements
- Updated SWPPP maps
- Evaluated all permitted facilities for the presence of non-stormwater sources

The SHA Environmental Compliance Division (ECD) is continuing to perform routine inspections at all SHA facilities through its District Environmental Coordinators (DEC) to ensure stormwater pollution prevention BMPs are implemented and the new 12-SW permitting requirements are being met. The DECs and facility staff are responsible for ensuring compliance with all applicable permits, plans and regulations at facilities in their region.

***Table 1-8: Industrial NPDES Permit Status***

| District | Maintenance Facility | Permit Type |
|---|---|---|
| 1 | Berlin | General |
| | Cambridge | General |
| | Princess Anne | General |
| | Salisbury | General |
| | Snow Hill | General |
| 2 | Centreville | Individual – SW |
| | Chestertown | General |
| | Denton | General |
| | Easton | General |
| | Elkton | General |
| 3 | Fairland | General |
| | Gaithersburg | General |
| | Laurel | General |
| | Marlboro | General |
| 4 | Churchville | Individual – SW |
| | Golden Ring | General |
| | Hereford | General |
| | Owings Mills | General |
| 5 | Annapolis | General |
| | Glen Burnie | General |
| | La Plata | General |
| | Leonardtown | General |
| | Prince Frederick | General |
| 6 | Hagerstown | General |
| | Keyser's Ridge | Individual – GW |
| | La Vale | General |
| | Oakland | General |
| | Dayton | General |
| 7 | Frederick | General |

| Dist-rict | Maintenance Facility | Permit Type |
|---|---|---|
| 7 | Thurmont | General |
| | Westminster | General |
| | Hanover Auto Shop | General |
| Notes: SW = Surface Water, GW = Groundwater | | |

The SHA ECD also continues to encourage maintenance facilities to present funding requests for stormwater related improvements such as erosion stabilization, material storage improvements, and spill prevention / containment devices.

### E.4.e Statewide Shop Improvement Plans

As described above, SHA continues to maintain an effective Industrial Stormwater NPDES Program through ECD to ensure pollution prevention and permit requirements are being met at SHA maintenance facilities. Annually, and as change dictates, SHA updates its combined Storm Water Pollution Prevention Plans (SWPPP)/ Spill Prevention, Control, and Countermeasure (SPCC) Plans. As a continuing best management practice SHA has developed SWPPPs for facilities not required to have one (e.g. salt storage facilities). Throughout the reporting year, SHA continued to address potential stormwater pollution issues by implementing Best Management Practices (BMPs) and designing/constructing capital improvements. BMPs were identified during pollution prevention plan updates and routine inspections facilities. The status of BMP implementation for maintenance facilities is tracked by each District Environmental Coordinator during routine inspections. Potential capital improvements are prioritized based on risk to human health and the environment and funding availability. The following list details the major pollution prevention efforts and maintenance facility improvements since the last annual report.

**Completed Projects:**

- 12-SW permit review and update of all associated SWPPPs
- Standard Operating Procedure creation and updates to ensure compliance with 12-SW permit
- Petroleum storage tank system upgrades at various SHA maintenance facilities

**Ongoing Projects:**

- Statewide stockpile management assessment
- Statewide brine secondary containment assessment
- Wash bay master plan for facility upgrades - goal is to ensure indoor vehicle washing
- Salt barn repair plan
- Vacuum Truck Dewatering Station (VTDS) construction at La Plata shop and Mt. Airy Salt Storage Facility (See Figure 1-18)
- Initial assessment reports and preliminary design completed for erosion issues noted at various facilities statewide

- Statewide discharge sampling and reporting program for facilities with Individual Discharge Permits
- Routine compliance inspections at all SHA facilities (See Figures 1-19 through 1-21 on the following page)
- Annual multimedia compliance training provided to maintenance shop personnel

*Figure 1-18: Structure used for Inlet Cleaning Waste Dewatering*

*Figure 1-19: Stormwater Outfall Improvements at SHA Maintenance Shop*

*Figure 1-20: Installation of Silt Fencing around Soil Stockpile*


*Figure 1-21: Visual Monitoring Outfall Identification*

**Table 1-9: Capital Expenditures for Pollution Prevention BMPs**

| Fiscal Year | Expenditure |
|---|---|
| 2005 | $ 613,210 - actual |
| 2006 | $ 592,873 - actual |
| 2007 | $ 450,608 - actual |
| 2008 | $ 590,704 - actual |
| 2009 | $ 478,889 – actual |
| 2010 | $ 613,766 - actual |
| 2011 | $ 595,984 - actual |
| 2012 | $ 664,577 - actual |
| 2013 | $ 917,902 - actual |
| 2014 | $641,512 - actual |
| **2015** | $2,045,000 - projected |

Table 1-9 above shows the SHA capital expenditures towards industrial pollution prevention BMPs from the current and past six fiscal years. Projected expenditures for Fiscal Year 15 are also included.

## E.5 Illicit Discharge Detection and Elimination

Requirements under this condition include:

*a) Conduct visual inspections of stormwater outfalls as part of its source identification and BMP inspection protocols*

*b) Document each outfall's structural, environmental and functional attributes;*

*c) Investigate outfalls suspected of having illicit connections by using storm drain maps, chemical screening, dye testing, and other viable means;*

*d) Use appropriate enforcement procedures for eliminating illicit connections or refer violators to MDE for enforcement and permitting.*

*e) Coordinate with surrounding jurisdictions when illicit connections originate from beyond SHA's rights-of-way; and*

*f) Annually report illicit discharge detection and elimination activities as specified in Part IV of* *this permit. Annual reports shall include any requests and accompanying justifications for proposed modifications to the detection and elimination program.*

### E.5.a Visual Inspections and Remediation of Outfalls

The SHA Storm Drain and Outfall Inspection and Remediation Program (SOIRP) has seen an expansion from the original focus on the physical conditions and structural functionality of NPDES defined major outfalls which were documented using Chapter 4 of the *SHA NPDES Standard Procedures*, to performing comprehensive inspections of all SHA pipe outfalls. This expansion was initiated in an effort to locate and eliminate significant sources of pollution within the SHA highway drainage systems as well as address issues with degraded drainage infrastructure. In addition to assessing the current structural condition of the pipe and outfall structure, the inspections also identify eroded downstream channels that are contributing to the pollution of Maryland's waterways and the Bay, with the intent to restore these sites to reduce the pollutant loads.

The new outfall channel assessment criteria has been incorporated into the SOIRP through an new protocol and revisions to the SHA NPDES geodatabase structure. A new assessment protocol has been developed as Chapter 8, Rapid Assessment Guidelines for Outfall Channels and widely implemented throughout several highway corridors. It has become part of the SHA routine inventory and inspections conducted in compliance with permit source identification requirements, as noted above in Section C, Source Identification. This protocol describes the standard data collection and documentation required for performing outfall channel assessments and is used in conjunction with Chapter 4 by targeting unstable outfalls with poor ratings for further assessment for remediation. SHA is taking proactive approach to address failing infrastructure issues to prevent emergency repair situations. The record management system is currently under development and being integrated into SHA NPDES Geodatabase.

As a result of these investigations, several outfall stabilization projects have been initiated as listed in Table 1-10

***Table 1-10: Current Outfall Stabilization Projects***

| Project Number | Road | County | Location Description | No. of outfalls | Project Status |
|---|---|---|---|---|---|
| AA757 | MD 2 | AA | Between I-695 and US 50 | 5 | Under design |
| MO637 | US 29 | MO | At SWM Facility 150173 | 1 | Under construction |
| PG092 | MD 216 | PG | NB at Patuxent River Bridge | 1 | Under construction |
| HO408 | MD 100 | HO | Behind noisewall between MD 104 and Long Gate Parkway | 1 | Construction completed 2012 |
| BA712 | I-695 | BA | Minebank Run at Cromwell Bridge Road | 5 | Under Design |
| BA487 | I-83 | BA | Gunpowder Falls | 2 | Construction completed 2012 |
| BA487 | MD 147<br>I-695 | BA | Various locations ( Phase 2) | 4 | Construction Completed 2014 |
| AW730 | I-83 | BA | Near Cold Bottom Road | 4 | Under Design |
| PG554 | MD 4 | PG | At MP 2.6 | 1 | Construction completed 2012 |
| PG712 | I-495 | PG | 400 ft N of Ramp 2 MD 450 WB | 1 | Under Design |

| | | | | | |
|---|---|---|---|---|---|
| | | | to I 95 NB | | |
| CH374 | US 301 | CH | From MD 6 to Glen Albin Road | 2 | Emergency repair completed 2012 |
| BA144 | I-795 | BA | Near Red Run Buleward | 2 | Construction completed 2012 |
| HA365 | US 1 | HA | Conowingo Road Slope and Outfall Stabilization | 1 | Construction completed 2012 |
| AA169 | I-97 | AA | North of Benfield Blvd | 1 | Under Design |
| BA487 | Various | BA | 5 sites within BA County | 5 | Under Construction |
| PG070 | Various | PG | Various locations | 35 | Under design |
| M0160 | I-270 | MO | At Montrose Road | 1 | Under Design |
| AX158 | MD 202 | PG | Near Campus Way | 1 | Construction Completed 2012 |
| XY138 | MD185 | MO | At Rock Creek | 1 | Construction Completed 2013 |
| AT812 | I-495 | PG | At MD 450 near Metro Yard | 2 | Construction completed 2014 |
| AT812 | MD 210 | PG | Between MD 373 and Jenifer Drive | 1 | Construction completed 2014 |
| AW730 | MD 450 | AA | Near War Memorial | 1 | Under Design |
| AT688 | US 301 | AA, CH | Various locations | 9 | Under Design |
| CE403 | MD 272 | CE | N. of Rogues Harbor Road | 1 | Under Design |
| HA356 | AW | HA | Various locations | 11 | Under Design |

SHA continues to undertake projects related to outfall channel stabilization with drainage system improvements. The goal of these projects is to protect the receiving streams and improve the water quality within the watershed and restore failing drainage infrastructure to extend the drainage assets service life. Some of the projects are individually advertised or several sites are group under one advertised projects. Some less complex or more urgent sites are addressed with open ended construction contracts after the design plan is developed and permitted.

***Figure 1-22: I-495 Outfall Stabilization After Construction***

Examples of such projects are outfalls at MD210 and MD 495 and MD 450 at US 50 (See Figures 1-22 through 1-24.) This is one the innovative contracting mechanisms that allows SHA to efficiently deliver projects of an urgent nature. SHA typically manages three or four area wide contracts for drainage and stormwater asset remediation with annual expenditures of $3-$5 million.

***Figure 1-23: MD 210 Outfall Stabilization Before Construction***

***Figure 1-24: I-450 at US 50 Outfall Stabilization Before Construction***

### E.5.b Document each Outfall's Attributes

SOIRP outfall inspections are currently being conducted on outfalls in Charles, Calvert, and St. Mary's Counties. Inspections are conducted using the SHA SOIRP Program outfall inspection protocol, Chapter 4, of the *SHA NPDES Standard.* As discussed above, based on the inspection ratings developed from the Chapter 4 protocol, those with the poorest ratings are assessed for repair or remediation using the newly developed outfall assessment protocol, Chapter 8 of the SHA standard procedures. Details of each protocol and current work for the report period are discussed below.

**SOIRP Pipe and Outfall Inspections (Chapter 4)**

The first step in the expanded SOIRP process is to perform a visual evaluation of pipe and outfall conditions when pipes connect to headwalls or endwalls, and when pipes terminate at their own outfall locations, such as end sections, projecting pipes, or in some cases, connect directly to culverts. Pipes are rated on a scale of 0 to 5 to identify the overall condition of the pipe and outfall.

The inspection results are based on issues visually identified by the inspection crew. Often it is difficult to evaluate an entire pipe length, so the inspection is based only on what the inspection crew can visually identify. If the upstream end of the pipe is in worse condition than the downstream end, the inspection team assigns the worst rating (5). Photographs are taken for ratings of 3, 4, or 5, which are poor ratings, and as deemed necessary. These pipes and outfalls are then subjected to a second assessment (based on Chapter 8 discussed below) to determine the form and level of remediation necessary.

**Outfall Channel Rapid Assessment Guidelines (Chapter 8)**

The protocol for assessing outfalls is Chapter 8, Rapid Assessment Guidelines for Outfall Channels: Outfall Condition and Restoration Potential, and was included in the 2012 report as Appendix F. Use of this protocol is the second step in the SOIRP process and assesses each targeted outfall that was rated 3-5 in step one for remediation potential and urgency. The outfalls may be contributing to channel erosion, thus resulting in sediment transport to downstream receiving channels. SHA has two overall goals for these second level assessments. The first goal is for data collection and repair recommendations to augment our efforts in maintaining SHA infrastructure that will include GPS-locating of outfall channels downstream from SHA outfall structures, and completing standard inspection forms to be linked with the spatial outfall features. The GPS and form data are compiled into an outfall assessment geodatabase that is compatible for future migration into the SHA geodatabase inventory. This data will be used to prioritize the repair of SHA-owned infrastructure

### E.5.c Discharge Investigations

Over the past annual reporting period, October 2013 through September 2014, discharge screenings were completed in Montgomery County. As illicit discharges are found through the field screening process, SHA sends out a team to pull samples for more accurate laboratory analysis. If the discharge fails after laboratory analysis the inspection reports are delivered to local NPDES coordinators and MDE. To eliminate the discharge SHA follows the elimination process outlined in Figure 1-25 on the following page.

SHA has focused on follow up for existing illicit discharges that have been reported in previous annual reports, as well as illicit discharges that were discovered during this reporting period. Maryland Environmental Service (MES) is contracted to revisit both existing and recently reported illicit discharges to confirm an illicit discharge is still occurring and take a sample for laboratory analysis. Those discharges determined to be illicit will then follow the elimination process. During this reporting period, it was determined that out of the 208 outfalls screened, 95 had a discernible flow, 80 were sampled and three new identified illicit discharges will require additional follow-up to be eliminated. (See Table 1-11 summarizing past and present illicit discharges). In addition, MES also performs on-call inspections of potential illicit discharges that are reported by SHA field staff or the public. Two additional illicit discharges identified outside the regular inspection program require follow-up. SHA continues to remain committed to detecting and eliminating illicit discharges throughout our system.

***Table 1-11: Discharges Investigated from February 2001 to Date***

| County | Discharges Investigated | Illicit Discharges requiring follow-up[1] |
|---|---|---|
| Anne Arundel | 5 | 3 |
| Baltimore | 1 | 0 |
| Carroll | 22 | 3 |
| Cecil | 7 | 2 |
| Charles | 7 | 0 |
| Frederick | 16 | 4 |
| Howard | 19 | 3 |
| Montgomery | 83 | 6 |
| Harford | 1 | 1 |
| **Totals** | **160** | **22** |

*[1]SHA has updated its process of IDDE Notification Protocol and will deliver investigation reports to MDE and the appropriate jurisdiction after laboratory analysis confirms a discharge is illicit.*

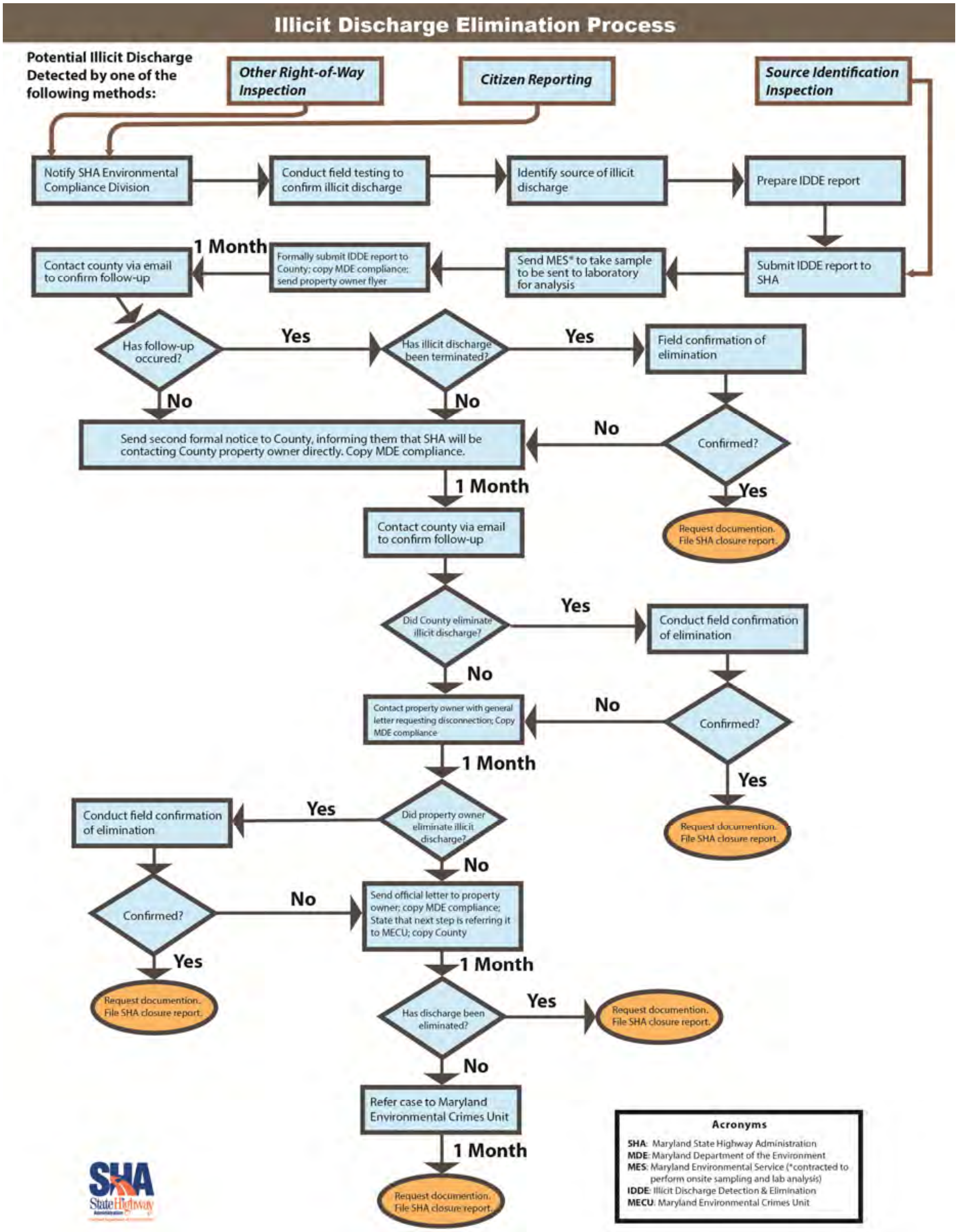


***Figure 1-25: SHA Illicit Discharge Elimination Process***

### E.5.d Use Appropriate Enforcement Procedures

Currently, SHA notifies MDE and the appropriate county NPDES coordinator, or their IDDE designee, when illicit discharges to SHA storm drain system are discovered. In order to achieve better elimination results and increase public awareness of the issue, SHA has implemented a process to notify property owners who are determined to be the origin of the illicit discharge(s). Educational materials on non-stormwater discharges and MS4 permits will be included with the initial notification. On February 20th, 2013 SHA met with representatives from the Office of the Attorney General's (OAG) Environmental Crime Unit (ECU) and representatives from MDE's Water Management Administration (WMA). The purpose of the meeting was to discuss SHA's IDDE program and enforcement protocol. It was noted that MDE/WMA has enforcement responsibility for illicit discharge compliance throughout the entire state of Maryland. SHA will work with local jurisdictions and MDE to eliminate illicit discharges. If attempts to eliminate the discharge fail after working with the local jurisdiction and MDE/WMA then MDE has the option of coordinating with OAG's ECU to resolve the illicit discharge. This process has been rolled out this reporting year

### E.5.f Annual Report Illicit Discharge Detection and Elimination Activities

Over the reporting period from October 2013 to September 2014, outfalls were screened in one Phase I county for illicit discharges: Montgomery. The geodatabase containing this data is included on the attached CD. During the reporting year, a total of nine discharges were closed out. Six discharges were determined to not have dry weather flow; two discharges were sent for laboratory analysis identifying parameters were within acceptable limits and one discharge was determined not to be illicit. Table 1-12 below shows information for the 13 remaining illicit discharges requiring follow-up. SHA's Environmental Compliance Division (ECD) manages SHA's IDDE program. ECD is continually reviewing the IDDE management program and process to determine areas that can be streamlined or updated. ECD will continue to coordinate with MDE, surrounding jurisdictions and property owners to eliminate illicit discharges.

***Table 1-12: Illicit Discharges Requiring Follow-up***

| Number | County | SHA-Structure # | Date | Potential Pollutant |
|---|---|---|---|---|
| 1 | Anne Arundel | 202689.001 | 08/16/2012 | Copper |
| 2 | Anne Arundel | 201478.001 | 08/17/2012 | Ammonia |
| 3 | Carroll | 600412.002 | 08/31/2012 | Sewage |
| 4 | Montgomery | 1501376.001 | 03/29/2011 | Detergents |
| 5 | Montgomery | 1500716.001 | 06/30/2004 | Chlorine |
| 6 | Montgomery | 1500848.001 | 06/29/2004 | Detergents |
| 7 | Howard | 1300455.001 | 10/23/2012 | Chlorine |
| 8 | Howard | 1301092.001 | 10/23/2012 | Ammonia & Copper |
| 9 | Howard | 1302186.001 | 11/21/2013 | Ammonia |

| Number | County | SHA-Structure # | Date | Potential Pollutant |
|---|---|---|---|---|
| 10 | Harford | 1202699.001 | 04/22/2014 | Detergents |
| 11 | Montgomery | 1540010.001 | 9/11/2014 | Ammonia |
| 12 | Montgomery | 1501352.001 | 9/19/2014 | Ammonia |
| 13 | Montgomery | 1541030.001 | 9/19/2014 | Chlorine |

## E.6 Environmental Stewardship

Requirements under this condition include:

a) *Environmental Stewardship by Motorists*

- i) *Provide stream, river, lake, and estuary name signs and environmental stewardship messages where appropriate and safe,*
- ii) *Create opportunities for volunteer roadside litter control and native tree plantings; and*
- iii) *Promote combined vehicle trips, ozone alerts, fueling after dark, mass transit and other pollution reduction actions for motorist participation.*

b) *Environmental Stewardship by Employees*

- i) *Provide classes regarding stormwater management and erosion and sediment control;*
- ii) *Participate in field trips that demonstrate links between highway runoff and stream, river, and Chesapeake Bay health;*
- iii) *Provide an environmental awareness training module for all areas of SHA;*
- iv) *Provide pollution prevention training for vehicle maintenance shop personnel;*
- v) *Ensure Integrated Pest Management instruction and certification by the Maryland Department of Agriculture for personnel responsible for roadside vegetation maintenance; and*
- vi) *Promote pollution prevention by SHA employees by encouraging combined vehicle trips, carpooling, mass transit, and compressed work weeks.*

### E.6.a Environmental Stewardship by Motorists

SHA continues many initiatives that encourage or target public involvement and participation in water quality programs. These initiatives cover the areas of litter control, watershed partnerships, community planting efforts and public education.

SHA public involvement and participation initiatives for the past year include:

**Annual Earth Day Celebration** –To commemorate this year's Annual Earth Day celebration, The SHA Earth Day Team sponsored a series of Learning Sessions and activities to promote environmental awareness and stewardship. The Learning Sessions were held at SHA Headquarters from April 29 through May 1, 2014. The topics included an herb garden tutorial and plant give away and tips on home composting (See Figure 1-26). Earth Day participants were also able to participate in a service project and lend a hand in giving SHA Headquarters and the Hanover Complex a landscaping make-over.

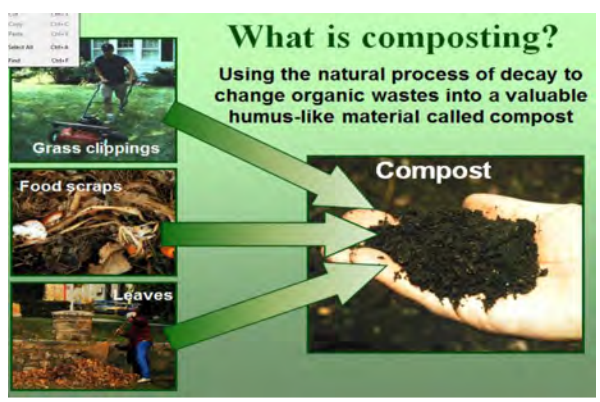


***Figure 1-26: Excerpt from Earth Day Composting Lessons***

## Adopt-a-Highway Program

This program encourages volunteer groups (family, business, school or civic organizations) to pick up litter along one to three mile stretches of non-interstate roadways four times a year for a two year period as a community service. Table 1-13 below identifies the participation for the AAH program over the current reporting period.

***Table 1-13: Adopt-a-Highway Program***

| Jurisdiction | Groups | # Bags | Miles Adopted |
|---|---|---|---|
| Anne Arundel | 6 | 171 | 7.25 |
| Baltimore | 54 | 828 | 61.25 |
| Carroll | 3 | 48 | 4.5 |
| Cecil | 20 | 274 | 24.5 |
| Charles | 0 | 0 | 0 |
| Frederick | 19 | 146 | 22 |
| Harford | 17 | 155 | 20.5 |
| Howard | 3 | 48 | 4.75 |
| Montgomery | 5 | 113 | 7.25 |
| Prince George's | 0 | 0 | 0 |
| Washington | 16 | 259 | 19.5 |
| Cumberland, Cambridge, Salisbury | 0 | 0 | 0 |
| Totals | 159 | 2123 | 185.75 |
| Data extracted from the Adopt-A-Highway database for the period 9/24/2013 to 9/10/2014 | | | |

## Sponsor-a-Highway Program

SHA also has a program that allows corporate sponsors to sponsor one-mile sections of Maryland roadways. Table 1-14 shows the miles currently being sponsored. The Sponsor enters into an agreement with a maintenance provider for litter and debris removal from the sponsored highway segment.

***Table 1-14: Sponsor-a-Highway Program***

| Jurisdiction | Available Miles | Miles Sponsored |
|---|---|---|
| Anne Arundel | 65.18 | 66.79 |
| Baltimore | 13.20 | 89.56 |
| Carroll | 0 | 0 |
| Cecil | 0 | 0 |
| Charles | 25.47 | 1.00 |
| Frederick | 12.00 | 11.68 |
| Harford | 5.81 | 3.61 |
| Howard | 24.24 | 25.74 |
| Montgomery | 4.71 | 45.98 |
| Prince George's | 51.02 | 56.28 |
| Washington | 14.73 | 2.23 |
| Cumberland, Cambridge, Salisbury | 0 | 0 |
| Totals | 224.61 | 304.87 |
| Data extracted from the Sponsor-A-Highway database for the period 9/24/2013 to 09/10/2014 | | |

## Partnership Planting Program

SHA develops partnerships with local governments, community organizations, and garden clubs for the purpose of beautifying highways and improving the environment. Community gateway plantings, reforestation plantings, streetscapes, and highway beautification plantings are examples of the types of projects that have been completed within the Partnership Planting Program. Table 1-15 on the following page lists the number of plants, counties, and numbers of volunteers for the last reporting period. See Figure 1-27 on the following page for a tree planting Partnership Planting project in Howard County.

*Table 1-15: Partnership Planting Program*

| NPDES County or Municipality | No. Plants | No. Volunteers |
|---|---|---|
| Anne Arundel | | |
| Baltimore | | |
| Cambridge | | |
| Carroll | 2000 Bulbs | 16 |
| Cecil | | |
| Charles | | |
| Cumberland | | |
| Frederick | 2000 Bulbs | 15 |
| Harford | | |
| Howard | 100 Trees, 6000 Bulbs | 31 |
| Montgomery | | |
| Prince George’s | | |
| Salisbury | | |
| Washington | | |
| Data extracted from the Partnership Planting Program database for the period 10/01/2013 to 09/30/2014 | | |

*Figure 1-27: Howard County Partnership Planting Project at MD 32*

## Maryland Quality Initiative (MdQI) 2012 Conference: ‘Quality Transportation – A Hybrid Approach’

The mission of MdQI is to provide the Maryland transportation industry a forum that fosters coordinated and continuous quality improvement in order to ensure safe, efficient, and environmentally sensitive transportation networks to meet the needs of all transportation stakeholders. This industry conference is held annually each winter and brings together public and private design and construction industry professionals in a forum of workshops, round table discussions, exhibits and networking. This year’s conference was held February 12 and 13 at the Baltimore Convention Center and approximately 300 engineers, consultants and contractors attended the conference, with lower than average attendance because of a winter storm. The participants included both public and private industry representatives. The website is www.mdqi.org.

Multiple topics were discussed including major projects, new technologies, procurement processes, and consensus building. Two sessions focused on NPDES related issues as described below:

*Emerging Changes in Environmental Business at SHA*: This session reviewed SHA’s new programs for delegated permit review authority and quality assurance. The purpose of these changes are to streamline and improve consistency and transparency for stormwater management and erosion and sediment control project review and permit approval.

*Going Green: What’s Next? The Chesapeake Bay TMDL*: This session gave an overview of SHA’s TMDL program including impervious treatment BMP types, reduction targets, progress, and next steps. See Figure 1-28 below for an excerpt from this presentation.


*Figure 1-28: Excerpt from What's Next: The Chesapeake Bay TMDL Presentation*

## E.6.b Environmental Stewardship by Employees

SHA continues to provide environmental awareness training to its personnel and is committed to continuing these efforts in the future. We have provided updated data for these efforts through the following training and awareness programs listed below:

**SHA Recycles Campaign**

In support of the SHA Business Plan, the Environmental Compliance and Stewardship Key Performance Area launched the SHA Recycles Campaign on April 22, 2008 to raise awareness and encourage change in consumer culture throughout the organization. The goal of this campaign is to reduce waste and litter by making conservation a priority, reusing what we previously discarded, and recycling as much as possible.

The SHA Recycles Campaign is working to build a consortium of stakeholders across the entire SHA organization towards this collective goal. The campaign encourages all employees to give feedback on what can be done to save energy and fuel, reduce or eliminate waste, improve current recycling efforts, or change business practices to conserve resources. It provides education and outreach through displays and presentations at SHA events such as the Annual Earth Day Celebration, and office-wide training and recognition days.

A State-wide Recycling Task Force has also been formed at SHA to examine key issues in recycling and identify ways to improve the SHA Statewide Recycling Program.

**Environmental Awareness Training (Chesapeake Bay Field Trips)**

This training is provided to all new employees and other employees seeking to improve their environmental awareness. This field trip demonstrates the link between highway runoff and its impacts on streams, rivers and on the health of the Chesapeake Bay. One trip was taken this reporting period on September 23, 2014 and 25 participants attended.

**Office of Highway Development (OHD) University**

Our Office of Highway Development continues its OHD-University training program for employees. Although primarily developed for engineers within OHD, others throughout the organization are invited to participate. The annual technical training sessions provide staff with the latest policy and design updates, including any changes to permitting requirements that affect policies and procedures. A myriad of key topics associated with the planning, design, construction, and maintenance phases of roadway network development are discussed, including SWM, ESC, permits, specific NPDES concerns, and TMDLs. During the current reporting period, the relevant trainings were not offered.

**Statewide Pesticide/Vegetation Management Training**

There are several types of internal training sessions for pesticide management that SHA provides annually. They include registration, re-certification, right-of-way pre-certification preparation, aquatic pre-certification preparation, and herbicide updates. The number of participants at each of these training sessions is listed below in Tables 1-16 and 1-17 on the following page. There was no Vegetation Management Conference (ENV200) or (ENV220), Pesticide Core and Right-of-Way Certification Preparation Class (ENV210), or Aquatic Pesticide Certification Preparation training held in 2014.

***Table 1-16: Pesticide Applicator Registration (ENV100)***

| SHA District | Number Trained |
|---|---|
| District 1 (DO,WI,WO,SO) | 6 |
| District 2 (TA,CO,QA,KE,CE) | 12 |
| District 3 (MO,PG) | 17 |
| District 4 (BA,HA) | 21 |
| District 5 (AA,CA,SM,CH) | 4 |
| District 7 (HO,CL,FR) | 14 |
| OFSD-Headquarters | 2 |
| OM-FMD | 1 |
| Other | 7 |
| Total | 84 |

***Table 1-17: Maryland Pesticide Safety Conference***

| SHA District | Number Trained |
|---|---|
| District 1 (DO,WI,WO,SO) | 8 |
| District 2 (TA,CO,QA,KE,CE) | 24 |
| District 3 (MO,PG) | 5 |
| District 4 (BA,HA) | 21 |
| District 5 (AA,CA,SM,CH) | 8 |
| District 6 (WA,AL,GA) | 6 |
| District 7 (HO,CL,FR) | 13 |
| Total | 85 |

**Maryland Department of Transportation (MDOT) Water Quality Policies and Water Quality Clearing House Web Page**

This is a continuing effort that provides information on department-wide water quality policies and other regulations applicable to transportation projects. This webpage is periodically updated with regulatory/policy changes and can be accessed at www.mdot.state.md.us and clicking on the 'Office of Environmental Programs' link on the left-hand panel. The tabs at the top of the page lead to information on state and environmental self-audit program; regulations for transportation facility operations such as storage tanks and spill prevention and response; environmental resources such as Smart, Green & Growing, MDE, MDNR and EPA; MDOT's environmental management system (EMS), environmental stewardship and sustainability efforts, and environmental planning initiatives.

**SHA Environment and Community Web Page**

SHA has developed an environmental awareness web page that is located on the SHA internet site (www.marylandroads.com). A recent addition to this webpage is a page called 'Cleaner, Greener Practices and Initiatives'. The webpage includes the following topics:

Innovation and Design

- Leadership in Energy and Environmental Design (LEED)
- Signal Systemization
- HOV
- Geographic Information System & Environmental Inventory Tool

Initiatives

- Wind Turbine
- Diesel and Biodiesel Fuels
- Recycling
- Litter Education

Maintenance

- Winter Operations
- Mowing Reduction
- Idling Policy
- Vehicle and Equipment Fleet
- Road Sweeping
- Ditch/Culvert Cleanings
- Litter Removal

SHA has also updated our website to include additional information about watershed restoration activities, which includes an overview of the purpose and BMP types that SHA is utilizing to address TMDLs and to treat impervious surfaces. An interactive map is also provided where community members can search for watershed restoration projects nearby. This can be found at:

www.roads.maryland.gov/index.aspx?pageid=333

**Employee Commuter Reduction Incentives**

SHA offers several incentives to reduce the number of drivers and/or number of commuter days/miles per week by Administration employees. Fewer commuter days and miles mean less vehicle pollutants entering the watershed.

Alternate work schedules include flexible work hours allowing employees to work compressed workweeks reducing the total number of commuting days and miles.

Teleworking allows employees to work from a remote location (presumably at or close to home) and also reduces the number of commuting days and miles per week. Each office has or is developing a teleworking policy.

Car-pooling has been encouraged at SHA for many years and reduces the number of commuters on the road. SHA car-pooling incentives include prioritizing parking space allocation to those in a designated car pool and Administration assistance in locating a carpool within the employee's residential area through parking database.

Bicycle commuting is also encouraged with SHA's support to promote bicycle safety laws, implementing new bike facilities throughout the state, and partnership in supporting National Bike to Work Day on May 17, 2014 (See Figure 1-29 below.)

Finally, employee ID badges allow state employees to acquire a free State Transit Employee Pass (STEP) that allows free access to MTA mass transit including the Baltimore area subway, light rail, and buses. This encourages the use of mass transit by SHA employees who live within the Baltimore area.

**SHA Vehicle and Equipment Idling Policy**

On September 22, 2009, the former SHA Administrator issued a policy regarding reduction in idling of engines for state equipment and vehicles. The purpose is to reduce fuel consumption by state forces, and if adhered to, will result in pollutant load reduction as well.


***Figure 1-29: SHA Administration Officials Partnered with MTA to promote Bike to Work Day on May 17, 2014***

# F Watershed Assessment

SHA has incorporated watershed assessment effort as described by the permit in the overall business process by contiguous evaluation of highway drainage areas for stormwater management retrofit opportunities and coordinating with local jurisdictions on their watershed restoration plans to maximize water quality benefits.

SHA exchanges the latest available geographic information system (GIS) highway data with permitted NPDES municipalities and provides the most recent spatial database of drainage assets and stormwater infrastructure to MDE. SHA completed the impervious surface accounting by the fourth annual report and continues to systematically update this data. SHA is assessing the areas that lack highway runoff control and treatment and implementing water quality improvement projects in cooperation with the Maryland's NPDES municipalities to maximize water quality benefits in areas of local concern.

### F.1 GIS Highway Data to NPDES Jurisdictions and MDE

SHA makes the GIS database of drainage and stormwater assets available to NPDES jurisdictions, and provides the most recent updates when the data is requested. SHA annually submits the latest version of the NPDES Geodatabase to MDE to incorporate into the statewide database for the Chesapeake Bay and local TMDL modeling. In addition, SHA provided the NPDES Geodatabase datasets to MDE for the required Historical BMP Cleanup deliverable on June 30, 2014.

## F.2 Complete Impervious Accounting by Fourth Annual Report

SHA completed the impervious accounting requirement for the all Phase I counties, by the fourth annual report, October 2009.

The issue of treatment credit accounting for impervious surfaces treated by entities other than the jurisdiction that has ownership of the surfaces is still not resolved between MDE and the MS4 jurisdictions. SHA has currently taken credit only for SHA-owned surfaces and not included in the accounting any non-SHA impervious surfaces to date. Although it is anticipated that this additional treatment credit will be applied to SHA in the future, thus increasing treatment currently provided.

The impervious accounting has been expanded to include Phase II counties, Washington and Cecil as well as the three jurisdictions (Cambridge, Cumberland and Salisbury) and the results are included in this report under Section C.3.

## F.3 Impervious Area Retrofits

SHA developed a protocol for site searches to identify most suitable location for stormwater management facilities that would directly treat the highway impervious surfaces runoff, preferably within existing SHA controlled right of way. We have also implemented alternative BMPs such as Tree Planting, Stream Restoration, and Pavement Removal as part of our Chesapeake Bay TMDL implementation plan discussed in Section J.

### F.4 Maximize Water Quality Improvements in Areas of Local Concern

SHA, as a transportation agency focusing on providing and maintaining a highway system that supports local and statewide economic development, also focuses on ensuring that highway projects meet all necessary SWM and water quality regulations. In addition, as part of the terms of the permit conditions, SHA adhered to the watershed restoration goals and priorities that have been established by local NPDES jurisdictions.

Past achievements to maximize water quality improvements within areas of local concern have been discussed in detail in annual reports of previous reporting periods. Past activities have included the following.

- Documenting watershed goals and priorities in partnership with the Maryland Department of Transportation (MDOT).
- Piloting a watershed-based SWM assessment on US 301 in partnership with Prince George's and Charles counties during the evaluation of transportation improvements within the corridor.
- Commencing work on a draft framework for implementing a watershed-based approach for SWM using a grant from the Environmental Protection Agency (EPA) and as part of the Green Highways Partnership (GHP) between SHA, the EPA, and the Federal Highway Administration (FHWA).
- Completion of watershed assessment and a retrofit study of the Indian Creek watershed in partnership with Prince George's County.
- Conducting watershed wide water quality site searches to a maintain positive balance in the SHA Water Quality bank
- Implementing an outfall inspection protocol and rating system, to systematically prioritize outfall channels stabilization projects in conjunction with stream restoration projects
- Preparing for TMDL milestones and allocation reduction strategies.

Updates for on-going or recently-reported endeavors are as follows.

**Water Quality Bank**

The Water Quality (WQ) Bank was established in 1992 as part of a Memorandum of Agreement (MOA) between SHA and MDE with the intent to facilitate construction of smaller roadway improvements where hardship in meeting the full water quality requirements can be demonstrated and allowing debiting an established bank to meet water quality requirements if credit exists in the 6-digit watershed account. Credit is achieved by over managing water quality on other projects. The bank tracks, on a project basis, the amount of impervious area required to be treated and how much is actually treated. For any project in which WQ treatment cannot be provided, in part or in full, a debit may be incurred. For projects that provide WQ treatment in excess of what is required, credits may be earned. Credits provide the means for debits to be possible. This flexibility not only allows SHA to deliver projects more efficiently, but also ensures that WQ management of SHA impervious areas is ultimately provided within each 6-digit watershed within the state. In addition, the tracking of watershed credits allows SHA the opportunity to consistently exceed the regulatory requirements and provide additional WQ treatment to regularly increase the percentage of the amount of impervious surfaces managed.

Credits and debits are tracked by acres of impervious surface and includes parking lots, roadways, sidewalks, and any other impervious surfaces within each 6-digit watershed.

A strict set of rules of how credits and debits may be applied are well-defined in the MOA:

- For impervious areas to be considered treated for WQ, stormwater runoff must be managed for the first inch of rainfall.
- If the existing impervious surface amount within limits of disturbance (LOD) of a project is greater than 40%, 50% of the existing impervious surfaces and 100% of new impervious surfaces must be managed for WQ.
- If the existing impervious surface amount is less than 40%, 100% of impervious areas must be managed for WQ, regardless of whether or not the impervious surface is existing or new.
- Based on the current SWM requirements, all potential opportunities to implement Environment Site Design (ESD) to the maximum extent practicable (MEP) must be exhausted and it must be demonstrated that structural and non-structural SWM facilities are not practicable to install before debits may be incurred from the

WQ Bank. A 20% surcharge is also incurred with each debit from the WQ Bank.

- When the amount of impervious surfaces managed for WQ exceed the requirements of a project, the excess may be applied as a credit to the WQ Bank.
- Credits to the WQ Bank are applied as follows: 100% for management of SHA-owned impervious surfaces and 80% for management of non-SHA-owned impervious surfaces.

As an additional effort to ensure enough credits are available in the WQ Bank should the need for debits arise, SHA initiates projects to specifically identify locations of unmanaged impervious surfaces in various locations throughout the 6-digit watersheds and implements retrofit projects to install SWM facilities to manage impervious surfaces for WQ. This allows SHA to provide more meaningful and effective management of WQ improvements within watershed areas in which WQ balances are low. This concept is parallels a working framework for watershed-based stormwater management by ensuring impervious surfaces are managed for WQ on a 6-digit watershed basis.

See Figure 1-30 below for a current snapshot of the Water Quality Bank.

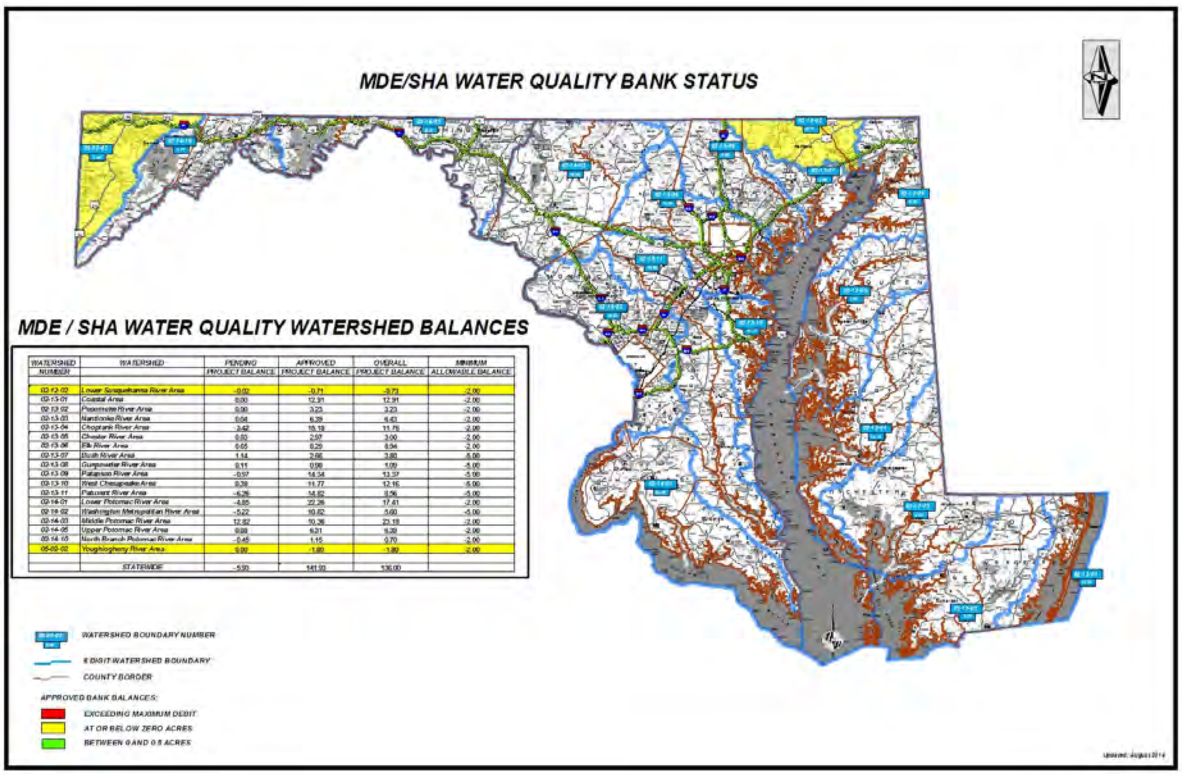


**_Figure 1-30: MDE/SHA Water Quality Bank Status (10/16/14)_**

One example project for the water quality bank is the SWM retrofit project for water quality improvement in Price Georges County at SW Loop of US301/MD214 interchange and NW Loop of US301/MD4 interchange. SHA is finalizing the design to provide treatment of currently untreated impervious surfaces in Patuxent River watershed. These are new SWM facilities designed to meet the current SWM water quality criteria. The project is scheduled to advertise for construction in spring 2015. Figure 1-31 shows the locations of the project sites. This is a water quality bank mitigation project.

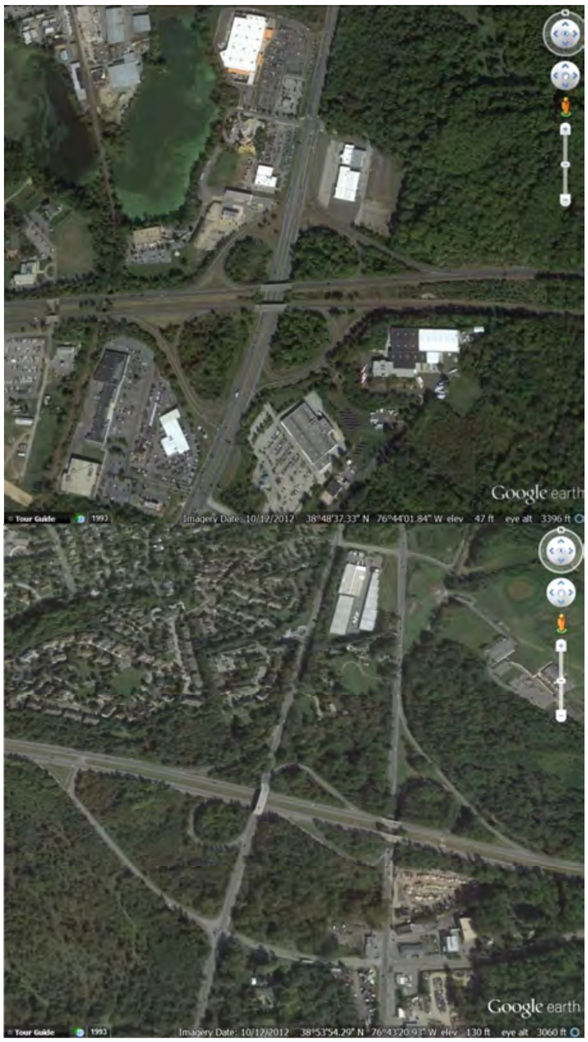


***Figure 1-31: US 301/MD 214 South/West Loop and US301/MD 4 North/West Loop – SWM Water Quality Retrofit Project Locations***

**Green Highways Partnership**

Green Highway Partnership has been established between EPA and the Federal Highway Administration (FHWA). The partnership creates a voluntary public/private network focusing on effective green transportation partnering, innovation, and collaboration between the environmental and transportation communities. SHA, as a leading partner in the Green Highway Partnership, has become involved in number of demonstration projects promoting innovative stormwater management practices, including low impact development strategies and water quality banking. In addition to the SHA transportation mission, SHA has incorporated this significant component in the business process in all aspects of project development including planning, design and permitting. See Appendix D for a summary Fact Sheet of the Green Highway Partnership.

**Watershed Resources Registry**

The Watershed Resource Registry (WRR) is a national pilot to integrate land-use planning, regulatory, and non-regulatory decision making using the watershed approach.

SHA, through the Green Highways Partnership, developed a GIS-based pilot Registry in close collaboration with all regulatory agencies including DNR, MDE, COE, USFWS, EPA, along with FHWA, Charles County, Prince Georges County, SHA and Maryland Environmental Services (MES).

WRR is a comprehensive web based mapping tool & replicable framework that with user friendly interface that:

- Integrates regulatory and non-regulatory programs
- Guides resource planners
- Conserves program resources
- Highlights for multiple environmental benefits
- Maximizes watershed benefits
- Is transparent and predictable

The WRR tool can be accessed at the following link, or see Figure 1-32 for a screenshot, or visit watershedresourcesregistry.com.

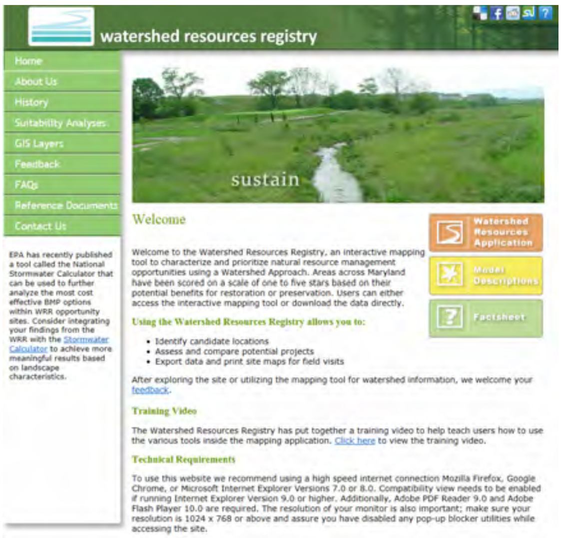


***Figure 1-31: Watershed Resources Registry Website Screenshot***

The objective of the Registry is to map natural resource areas that are a priority for preservation and to identify sites best-suited for ecosystem preservation and restoration. A major effort of the WRR process is a set of suitability analyses developed with sound science and the best professional judgment of regional experts, which will be used as a screening tool to target opportunity sites for the protection of high quality resources, restoration of impaired resources, and improvement of water resources. The analyses will specifically identify for:

- Upland Preservation, Upland Restoration
- Wetland Preservation, Wetland Restoration,
- Riparian Preservation, Riparian Restoration,
- Natural Stormwater Infrastructure Preservation
- Compromised Stormwater Infrastructure Restoration.

By having both regulatory and non-regulatory agencies base decisions from a WRR, integration and the use of the watershed approach will become implicit and "stovepipe" processes in decision making will become obsolete. The results will streamline the regulatory and non-regulatory processes and ensure maximum environmental results. The benefits of WWR in greater detail include the following:

- Helps agencies identify watershed restoration and protection opportunities to target improvements and evaluate results.
- Helps "connect the dots" between agencies, fostering shared vision and stronger relationships that produce better government and improved services to customers.
- Provides a wide variety of labor and cost efficiencies associated with streamlined processes, collaboration and shared resources.
- Helps provide a consistent evaluation framework that each state can establish based on stakeholder consensus (a data-driven "star" rating) through which watershed/geography/context sensitive decisions can be made.
- Helps agencies avoid or minimize negative environmental and natural resource impacts and informs decision-making.
- Fosters continuous improvement in the quality of data outputs through opportunities for collective intelligence and feedback (with appropriate controls).
- Significantly streamlines regulatory review processes and workflow for a variety of stakeholders, including state agency departments of natural resources, environmental protection, and planning, as well as federal organizations such as the Federal Highway Administration, US Army Corps of Engineers, Environmental Protection Agency, Natural Resources Conservation Service, and US Fish and Wildlife Service.
- Also significantly streamlines the evaluation of projects by users, including

conservation groups, permit applicants, and others, since it provides valuable information on existing resources and realities.
- Improves collaboration and coordination between agencies occurs because everyone is using the same data and tool. This promotes an upfront understanding of all of the issues by all of the stakeholders and reduces surprises along the way.
- Helps transportation planners identify potential impacts to resources early in the process.
- The transparency and collaboration central to WRR helps promote optimal watershed actions.
- Helps significantly streamline, integrate and enhance a variety of regulatory permitting processes and requirements
- Helps agencies identify and address data gaps, which improves data integrity and quality over time.
- The Registry's flexible data layers permit highly customizable outputs depending upon business user needs, providing a highly dynamic evaluation approach.
- Supplies a transferrable framework that can be used by states across the nation

In the past year, the members of the WRR Technical Committee have been working on the nationwide promotion of this new technology through AASTO Technology Implementation Group (TIG) and developed a marketing plan for potentially adopters of this technology. The targeted audience includes:

- Federal and State Transportation Agencies
- State Natural Resource & Environmental Quality Agencies
- State Regulatory Agencies
- Local Government Agencies and Authorities (cities/counties/toll road authorities)
- Private Sector Stakeholders (Architectural Engineering Firms, Mitigation Banks, Environmental Services Firms, Utility Companies, Developers, etc.)

In order to roll the WRR out nationally to private sector, local, state and federal governmental entities, the WRR Team is conducting the first national workshop on October 16 and 17, 2014 in Baltimore.

SHA has adopted WRR in spring 2012. The WRR application has been valuable for gathering environmental inventory information, assessing watershed needs, identifying potential mitigation sites. The future use of this tool is for suitable stormwater management site searches to meet regulatory requirements and for TMDL projects implementation.

**Framework to Implement a Watershed-Based Approach for Managing Stormwater**

The watershed approach framework for managing stormwater represents coordination and environmental management that focuses public and private sector efforts to address the highest priority problems within hydrologically-defined geographic

SHA has recognized the need for integrated environmental management through watershed – based approach for treatment of highways as well as off-site runoff to effectively reduce pollutant loads delivered to downstream reaches lakes, rivers, wetlands, estuaries, coastal waters, and ground water. The successful stormwater management can be achieved primarily by controlling point sources of pollution in many case outside of SHA controlled R/W, therefore close coordination and cooperation with all stakeholders in the watershed is unavoidable.

Therefore, SHA has developed the framework how to implement a watershed-based approach to SWM, recommendations how to cultivate partnerships, how to assess specific watershed needs, establish accountability, optimize budget spending, and promote sustainable systems within the transportation network and local communities

SHA has been a leading supporter of watershed based stormwater management and has defined this vision as of stormwater management concept that recognizes that highways coexist with other land uses in watersheds. SHA adopted this collaborative approach as it provides opportunity to plan and deliver the most effective protection and improvements to the watersheds. In support of this concept, SHA has taken significant step towards creating GIS database of more than 3300 stormwater facilities and associated drainage infrastructure that allows systematic evaluation of the effectiveness of stormwater controls on watershed scale.

A number of benefits derive from the watershed approach:

Close and frequent coordination with various local Programs and their watershed implementation plans results in better environmental benefits, positive social-economic impacts and more accurate financial planning. Information and data sharing, as well as joint review of watersheds assessment efforts for water protection, pollution control, fish and wildlife habitat protection and other aquatic resource protection programs, managers from all levels of government and regulatory agencies can better understand the cumulative impacts of land development, highway construction and other human impacts to determine the most critical problems within each watershed. Using this information to set priorities for action allows public and private managers from all levels to allocate appropriate financial and human resources to address the most critical needs. Part of the action is establishing environmental indicators to select appropriate activities to prioritize and address high priority issues as well as measure the success through implementation of appropriate and effective improvements rather than simply fulfilling programmatic requirements. SHA is committed to continue working within this framework as it has been in close coordination with local jurisdictions, all regulatory agencies, local watershed groups and public throughout all phases of project development process – including planning design and construction - to effectively address stormwater issues that result in significant and measurable environmental benefits.

The watershed based approach result in significant cost savings by leveraging and building upon the financial resources and the willingness of the stakeholders with interests in the watershed water quality improvements to take action. Through improved communication and coordination the watershed approach can reduce costly duplication of efforts and conflicting actions. Implementation of water quality banking, wetland mitigation and stream restoration as well as establishment of trading mechanism among various sectors not only results in significant environmental benefits, but also in streamlined permitting process, more efficient and timely delivery of projects, cost saving of public funds and reduction of potential adverse impacts.

Finally, SHA recognizes that the watershed approach strengthens teamwork between the public and private sectors at the federal, state and local levels to achieve the greatest environmental improvements with the resources available. The watershed approach builds a sense of community, reduce conflicts, increase commitment to the actions necessary to meet societal goals and, ultimately, improve the likelihood of sustaining long-term environmental improvements.

**Green Infrastructure Expansion**

SHA has been inventorying and examining existing green infrastructure within the right of way for past several years. Individual hubs as well as whole corridors have been assessed to evaluate the potential to expand these areas or increase corridor connections between hubs as part of improvements associated with transportation projects. In addition to providing improved habitat size and providing more corridors for migration or movement routes of wildlife, further benefits may include enhanced SWM via greater green space and runoff reduction techniques.

SHA recognizes that Green Infrastructure (GI) can mitigate stormwater concerns and address many components of MS4 programmatic goals. Green Infrastructure preservation and expansion is an nationwide effort, however, it cannot be standardized across the board; it must be designed for specific area and its constrains, since it is highly dependent on site specific factors such as soils, terrain and climate conditions to assure long term performance and sustainability. SHA is evaluating how Green Infrastructure should be incorporated into the site development design criteria and become an integral part of the stormwater management concept not only for visual appearance , but also to contribute to flooding reduction and water quality treatment.

Although there is a growing movement to incorporate green infrastructure expansion along with stormwater management within public right of way, not all GI techniques are appropriate, most suitable and cost effective for highway projects. Therefore, SHA is evaluating what specific strategies and techniques for GI should be implemented. The use of green infrastructure as a part of an overall ecosystem strategy seems to be right approach through comprehensive watershed basin planning and restoration to protect water resources and provide ecological uplift within impaired watersheds. Green infrastructure can contribute to increased resiliency and provide protection during frequent and most damaging storm events as well as significant flood and other extreme weather related events. SHA is targeting GI infrastructure techniques that would reduce highway runoff, provide water quality treatment and promote infiltration as well as capture and re-use of stormwater.

**Green Asset Management System**

SHA has begun establishing a database of environment assets on SHA right-of-way as part of the Green Asset Management System (GAMS). The assets to be built into this database include stormwater management BMPs, delineated wetlands, streams, forest stands, landscaped beds, restoration sites, and invasive species. GAMS is being integrated into eGIS. Currently, only invasive species are available for review in eGIS.

**Recycled Materials Task Force**

The Office of Materials and Technology created a task force to review, analyze, and implement greater use of recycled materials in transportation projects. Pertinent design offices actively participate in quarterly meetings. Design expertise includes materials, hydrology, environmental regulations, habitats and ecosystems, and highways. Members of regulatory agencies, industry manufacturers, and material suppliers also participate. As a result of these meetings, we have continued to increase opportunities to use recycled and reclaimed materials in transportation projects. As a result of these meetings, SHA has identified multiple recyclable materials that can be incorporated into highway projects. Most notably, SHA has increased the use of composted yard waste in ESC, roadside landscaping, stream restoration, and stormwater management facilities.

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recyclable materials that can be incorporated into highway projects. Most notably, SHA has increased the use composted yard waste in ESC, roadside landscaping, stream restoration, and stormwater management facilities.

**Local 8-Digit Impairments and TMDLs**

With the TMDL requirements anticipated for the next permit term, which is expected to focus on waste load reductions for urban stormwater runoff, we will be shifting our efforts to prioritize key segments of the Chesapeake Bay watershed along with local TMDL watersheds in which we are named as a contributor to the waste load allocation (WLA). Establishment of the 2-year milestones has begun and we have been making progress towards meeting set goals to achieving Bay TMDL requirements while demonstrating compliance with local TMDLs. We are programming and developing policies to coincide with the anticipated load reduction goals, which are further discussed in Section J. Additional endeavors in which we are currently involved are covered in Section G.

# G Watershed Restoration

SHA continues to construct stormwater management retrofits to increase pollutant control associate with highway runoff although requirements for this permit condition to implement twenty-five significant stormwater management retrofit projects to improve water quality of highway runoff has been met. In addition, SHA continues to partner with local jurisdictions on various watershed restoration initiatives and activities. The watershed restoration projects mostly include functional enhancements and upgrades of outdated stormwater facilities that are currently not meeting the latest design standards as well as construction of additional stormwater BMPs to treat currently untreated impervious surfaces. The watershed restoration projects include innovative approaches to conventional stormwater management methods such as stream restoration projects and drainage outfalls stabilization projects to restore degrading channels and prevent sediment and other pollutants transport to the downstream reaches and provide significant water quality benefits.

SHA continues to support local watershed activities by constructing and funding water quality projects such as stormwater retrofits and stream restoration projects within targeted watersheds. To comply with the permit conditions, SHA annually reports on watershed restoration activities progress, costs, schedules, implementation status and impervious acres proposed to be treated.

## G.1 Implement 25 Significant SWM Retrofit Projects

SHA has met the goal to complete the required twenty-five significant SWM Retrofit projects in the past annual reports. However, SHA continues the efforts to maximize treatment of untreated impervious surfaces in anticipation of the future permit requirements for a percentage treatment.

**Stormwater Facility Functional Upgrades, Enhancements, Retrofits and Restoration Projects**

These projects are not developed to meet stormwater management requirements of major highway projects , but they were specifically initiated to upgrade stormwater BMPs to meet current regulations and provide maximum water quality treatment, or to construct new SWM facilities for additional impervious surface treatment. SHA continues design and permitting activates for SWM retrofit project in I-695 and Cromwell Bridge Interchange to treat over 80 acres of impervious surface and offs site runoff from highly urbanized watershed (See Figure 1-33). This water quality improvement project is designed in conjunction of 4 outfalls stabilization that are tributaries to Minebank Run as well as the main channel restoration. The project is scheduled to advertise in summer 2015.

***Figure 1-33: MD 147 and I-695 SE Loop – SWM Water Quality Retrofit Project – a year after construction***

Several functional enhancement projects were initiated in Harford County to improve water quality of existing SWM facilities and provide maximum treatment of SHA highway runoff. The design concept has been developed and the project is proceeding to final stages of design. It will be advertised in fall 2015.

In addition to SWM retrofit and enhancement projects, stream restoration and drainage outfall channel stabilization projects were initiated address adverse impacts of urbanization to further reduce pollutant loads and improve water quality within targeted watershed. More detailed discussion of outfall stabilization projects is included in Section E.5.an of this report.

All restoration projects initiated or completed to meet the twenty-five project requirement are listed in Table 1-18 . A total of 124 water quality improvement projects were designed to treat an approximately 1089.79 acres of impervious surface (not including the Chester River Area projects, which are in Queen Anne's County).

SHA continue design and construction activities within medians of divided highways to address water quality of legacy pavement– the pre-1985 impervious surfaces. The detailed progress will be reported in the next reporting period after construction completion when as-built information is available to assure full functionality. Our current level of treatment by stormwater controls completed is 420 acres at 1.7% (See Table 1-3 in Section C). Design efforts are underway to increase restoration to 1089.79 acre at 4%.

***Table 1-18: Watershed Restoration Projects***

| Projects by Watershed | Retrofit Type | Status | Restored Impervious Acres |
|---|---|---|---|
| **Lower Susquehanna River – 02-12-02** | | | |
| BMP 120076 | SWM Retrofit | Complete | 2.82 |
| | | Total Treated: | **2.82** |
| **Bush River Area – 02-13-07** | | | |
| BMP 120069 | SWM Retrofit | Complete | 4.16 |
| BMP 120072 | SWM Retrofit | Complete | 4.68 |
| BMP 120073 | SWM Retrofit | Complete | 3.99 |
| BMP 120075 | SWM Retrofit | Complete | 1.77 |
| BMP 120081 | SWM Retrofit | Complete | 2.39 |
| BMP 120082 | SWM Retrofit | Complete | 1.00 |
| | | Total Treated: | **17.99** |
| **Gunpowder River – 02-13-08** | | | |
| I-83 Outfall Stabilization of Tribs. to Gunpowder Falls | Stream stabilization | Complete | 7.85 |
| Minebank Run Restoration, & WQ Improvements | Stream restoration, outfall stabilization, SWM retrofit*** | Design | 236.8 |
| BMP 030389 | SWM Retrofit | Complete | 2.43 |
| | | Total Treated: | **247.08** |
| **Patapsco River – 02-13-09** | | | |
| BMP 020120 | SWM Retrofit | Complete | 17.73 |
| BMP 020121 | SWM Retrofit | Complete | 0.96 |
| BMP 020122 | SWM Retrofit | Complete | 0.92 |
| BMP 020625 | SWM Retrofit | Design | 2.46 |
| BMP 030281 | SWM Retrofit | Complete | 8.35 |
| MD 139 Tributary to Towson Run Stabilization | Stream Stabilization | Complete | 260.30 |
| BMP 020111 | SWM Retrofit | Complete | 6.04 |
| BMP 020112 | SWM Retrofit | Complete | 0.56 |
| BMP 020098 | SWM Retrofit | Complete | 0.68 |
| BMP 020099 | SWM Retrofit | Complete | 0.75 |

| Projects by Watershed | Retrofit Type | Status | Restored Impervious Acres |
|---|---|---|---|
| BMP 020476 | SWM Retrofit | Complete | 3.79 |
| BMP 020477 | SWM Retrofit | Complete | Combined with 020476 |
| BMP 130197 | SWM Retrofit | Complete | 0.44 |
| BMP 130207 | SWM Retrofit | Complete | 1.57 |
| BMP 130221 | SWM Retrofit | Complete | 0.17 |
| BMP 130210 | SWM Retrofit | Complete | 0.24 |
| BMP 130217 | SWM Retrofit | Complete | 0.10 |
| I-695 Tributary to Steamers Run | Stream Stabilization | Under construction | 182.00 |
| | | Total Treated: | **487.06** |
| **West Chesapeake Bay – 02-13-10** | | | |
| BMP 020019 | SWM Retrofit | Complete | 1.22 |
| BMP 020022 | SWM Retrofit | Complete | 1.06 |
| BMP 020027 | SWM Retrofit | Complete | 1.59 |
| BMP 020029 | SWM Retrofit | Complete | 0.88 |
| BMP 020031 | SWM Retrofit | Complete | 2.29 |
| BMP 020088 | SWM Retrofit | Complete | 3.53 |
| BMP 020481 | SWM Retrofit | Complete | 2.09 |
| BMP 020522 | SWM Retrofit | Complete | 1.70 |
| BMP 020273 | SWM Retrofit | Complete | 1.18 |
| BMP 020491 | SWM Retrofit | Complete | 1.79 |
| BMP 020185 | SWM Retrofit | Complete | 0.48 |
| BMP 020198 | SWM Retrofit | Complete | 0.68 |
| BMP 020201 | SWM Retrofit | Complete | 1.01 |
| BMP 020205 | SWM Retrofit | Complete | 1.16 |
| BMP 020206 | SWM Retrofit | Complete | 0.49 |
| BMP 020210 | SWM Retrofit | Complete | 0.36 |
| BMP 020220 | SWM Retrofit | Complete | 0.72 |
| BMP 020258 | SWM Retrofit | Design | 3.27 |
| BMP 020260 | SWM Retrofit | Design | 1.41 |
| BMP 020268 | SWM Retrofit | Design | 7.08 |
| BMP 020393 | SWM Retrofit | Design | 4.35 |
| BMP 020394 | SWM Retrofit | Design | 3.27 |
| BMP 020014 | SWM Retrofit | Construction | 1.9 |
| BMP 020015 | SWM Retrofit | Construction | 0.73 |
| BMP 020016 | SWM Retrofit | Construction | 0.72 |
| BMP 020017 | SWM Retrofit | Construction | 0.16 |
| BMP 020018 | SWM Retrofit | Construction | 0.65 |
| | | Total Treated: | **45.5** |
| **Patuxent River – 02-13-11** | | | |
| BMP 160059 | SWM Retrofit | Complete | 3.2 |
| BMP 020488 | SWM Retrofit | Complete | 5.56 |
| BMP 160217 | SWM Retrofit | Complete | 0.64 |
| BMP 160219 | SWM Retrofit | Complete | 0.91 |
| BMP 160380 | SWM Retrofit | Complete | 3.42 |
| BMP 020301 | SWM Retrofit | Complete | 2.30 |
| BMP 020311 | SWM Retrofit | Complete | 0.28 |

| Projects by Watershed | Retrofit Type | Status | Restored Impervious Acres |
|---|---|---|---|
| BMP 020437 | SWM Retrofit | Complete | 4.13 |
| BMP 020299 | SWM Retrofit | Complete | 1.09 |
| BMP 130149 | SWM Retrofit | Complete | 0.48 |
| BMP 130150 | SWM Retrofit | Complete | 1.02 |
| BMP 130154 | SWM Retrofit | Complete | 0.47 |
| BMP 130159 | SWM Retrofit | Complete | 0.02 |
| BMP 130160 | SWM Retrofit | Complete | 0.52 |
| BMP 130162 | SWM Retrofit | Complete | 0.66 |
| BMP 130179 | SWM Retrofit | Complete | 2.10 |
| BMP 130180 | SWM Retrofit | Complete | 0.43 |
| BMP 130187 | SWM Retrofit | Complete | 0.13 |
| BMP 130188 | SWM Retrofit | Complete | 0.12 |
| BMP 130189 | SWM Retrofit | Complete | 0.03 |
| BMP 130190 | SWM Retrofit | Complete | 0.03 |
| BMP 130191 | SWM Retrofit | Complete | 0.05 |
| BMP 130192 | SWM Retrofit | Complete | 0.05 |
| BMP 130193 | SWM Retrofit | Complete | 0.10 |
| BMP 130194 | SWM Retrofit | Complete | 0.22 |
| BMP 130232 | SWM Retrofit | Complete | 0.03 |
| BMP 130242 | SWM Retrofit | Complete | 0.72 |
| BMP 130243 | SWM Retrofit | Complete | 3.49 |
| BMP 150228 | SWM Retrofit | Complete | 0.13 |
| BMP 150331 | SWM Retrofit | Complete | 0.23 |
| BMP 130047 | SWM Retrofit | Complete | 1.39 |
| | | Total Treated: | **24.77** |
| **Lower Potomac River – 02-14-01** | | | |
| BMP 160456 | SWM Retrofit | Complete | 1.70 |
| BMP 080014 | SWM Retrofit | Complete | 0.24 |
| BMP 080039 | SWM Retrofit | Complete | 0.10 |
| BMP 080040 | SWM Retrofit | Complete | 0.10 |
| BMP 080041 | SWM Retrofit | Complete | 0.12 |
| BMP 080042 | SWM Retrofit | Complete | 0.11 |
| BMP 080043 | SWM Retrofit | Complete | 0.28 |
| BMP 080044 | SWM Retrofit | Complete | 0.20 |
| BMP 080083 | SWM Retrofit | Complete | 0.06 |
| BMP 080095 | SWM Retrofit | Complete | 0.48 |
| | | Total Treated: | **3.39** |
| **Washington Metropolitan – 02-14-02** | | | |
| BMP 160607 | SWM Retrofit | Complete | 0.41 |
| BMP 160609 | SWM Retrofit | Complete | Combined with 160607 |
| BMP 160653 | SWM Retrofit | Complete | 15.80 |
| Long Draught Branch Restoration | Stream Stabilization | Design | 228 |
| BMP 150002 | SWM Retrofit | Complete | 0.31 |
| BMP 150003 | SWM Retrofit | Complete | 1.69 |
| BMP 150004 | SWM Retrofit | Complete | Combined with |

| Projects by Watershed | Retrofit Type | Status | Restored Impervious Acres |
|---|---|---|---|
| | | | 150003 |
| BMP 150005 | SWM Retrofit | Complete | Combined with 150003 |
| BMP 150172 | SWM Retrofit | Design | 1.25 |
| BMP 150173 | SWM Retrofit | Complete | 1.18 |
| BMP 150301 | SWM Retrofit | Complete | 0.28 |
| BMP 150362 | SWM Retrofit | Complete | 1.03 |
| BMP 150380 | SWM Retrofit | Complete | 1.05 |
| BMP 150550 | SWM Retrofit | Complete | 1.26 |
| BMP 150076 | SWM Retrofit | Complete | 1.25 |
| BMP 150059 | SWM Retrofit | Design** | 0 |
| BMP 150556 | SWM Retrofit | Design | 5.65 |
| | | Total Treated: | **259.16** |
| **Middle Potomac River – 02-14-03** | | | |
| Tributary to Tuscarora Creek Stabilization at US 340 and US 15 | Stream Stabilization | Complete | 1.94 |
| BMP 150270 | SWM Retrofit | Complete | 0.08 |
| | | Total Treated: | **2.02** |
| | | **TOTAL** | **1089.79** |

*Projects added since last report.
** Retrofit will be included in major highway projects

**Pavement Retrofit Projects**

SHA has been working with MDE to finalize Bay TMDL requirements for SHA in order to establish funding and resource needs for the future retrofit and implementation projects. SHA continues development and implementation of enhancement projects of existing SWM facilities as well as continues site search for water quality improvement projects. Funding has been allocated for design and construction of SWM retrofit projects to meet both the future waste load reductions and impervious treatment requirement. Future projects include conversion of older SWM facilities originally designed to manage water quantity into water quality sites. In addition, SHA is actively working on implementation of water quality treatment of legacy pavement through median bioswales designed within the open section roadways medians in Phase I and Phase II counties.

**Stream Project Assessments**

MD SHA has been designing stream restoration and stabilization projects as part of larger highway projects for fulfilling mitigation requirements, to ensure safe roadside areas for travelling public, and to ensure new bridge opening is in sync with the geomorphology and have long term stability. Other times these projects are implemented to provide stable conveyances from roadway outfalls or to minimize sediment transport beyond stream's natural rate such that these projects result in water quality improvements. These projects addressing mostly physical degradation issues of natural stream channels have been often perceived as additional impacts to aquatic resources even though some of the projects are remediating unintended past human impacts and the new impacts may be intended to result in some improvement to either physical, biological or both indexes. Additionally, actual environmental benefits are challenging to implement, prove, or quantify without monitoring data and scientific analysis. Therefore, SHA initiated assessment and monitoring study of completed and proposed stream restoration projects to make recommendations for design or construction changes as well as potential improvements to restoration strategies and methods. The data has been collected since 1998 at totally 14 sites for benthic, macro invertebrates, fishes and physical habitat. The stream assessments have been performed by Dr. R. P. Morgan and his students from the University of Maryland Frostburg, Center for Environmental Service.

The latest monitoring report is included in the Appendix E. In the past year, SHA and UMD have been collecting monitoring data at the following sites:

- Frederick County - US 15 Monocracy River/Tuscarora Creek:-Pre-construction
- Montgomery County - MD117 Long Draught Branch: Pre construction monitoring
- Harford County - Plumtree Run from east of Ring Factory Rd. to north of MD 24: Pre-construction monitoring
- Baltimore County - I-83 Pine Creek: Post restoration monitoring
- Anne Arundel County – Muddy Bridge Branch: Post restoration monitoring
- Prince Georges County – Little Paint Branch: Post restoration monitoring

**Restoration Project Database Delivery**

Data related to the retrofit projects was submitted with previous reports and can be made available upon request.

## G.2 Contribute to Local NPDES Watershed Restoration Activities

SHA actively participates in local water quality improvement projects and supports watershed interest groups and local jurisdictions in their watershed restoration activities. SHA has participated directly or indirectly in developing watershed plans as well as provided funding.

Additionally, SHA oversees the Federal Transportation Alternatives Program (TAP) and encourages the use of these funds by local jurisdictions and interest groups to fund water quality projects to mitigate the adverse impacts of roadway runoff. Under the new MAP-21 legislation enacted in 2012, TAP does not fund MDOT / SHA projects. The TAP funding is dedicated entirely to locally sponsored projects. However, the TAP funding can be used towards water quality initiatives when sponsored by a local jurisdiction. This year, Tap funded two water quality initiatives including:

- North Cypress Branch Stream Restoration – Anne Arundel County $585,000
- Westminster High School SWM Facility – Carroll County $180,944

The following is a summary of watershed activities undertaken by SHA during the report period:

**I-695 at Minebank Run Stream Restoration, Drainage and Water Quality Improvements – SHA**

This project was initiated to address multi outfall stabilization, stream restoration, SWM retrofits and reforestation. Minebank Run is within Gunpowder River watershed that is targeted by Baltimore County for restoration. The topographic survey has been completed; design work on this project has been initiated in 2011. Several pre-application and design concept scoping meetings with regulatory agencies have been conducted in past 3 years and the preliminary investigation (PI) design has been developed. The final design plans will be developed in 2015. The project is scheduled for construction in 2015-2016. This project will result in significant pollutant load reductions for the Gunpowder River watershed as well as improve local drainage infrastructure issues and adverse impacts of the upstream urbanization through upland SWM water quality retrofit within I-695 interchange, providing stable conveyance of the surface drainage, stabilizing 4 degraded outfall channels and restoration of the main channel to address the stream degradation This reach is located between two stream restoration projects lead by Baltimore County, therefore SHA has been coordinating with Baltimore County on the restoration efforts. See Figure 1-34.

***Figure 1-32: I-695 at Cromwell Bridge Minebank Run Retrofit Site***

**Westminster SWM Regional Pond – Carroll County**

This project has been developed by Carroll County and the construction is 35% completed. SHA's function was to provide a technical guidance through the procurement process and funding through Transportation Alternatives Program (TAP). The project is a SWM retrofit of a regional pond originally designed for flood control to treat currently untreated impervious surfaces within a 250 acre watershed. Totally 25 acres of SHA owned impervious surface will receive treatment when the project is completed. See Figure 1-35 for an area photograph.


***Figure 1-35: Westminster Regional Pond Retrofit Project Before Construction***

**Finksburg Industrial Park Regional SWM Facility – Carroll County**

This project is a retrofit of regional SWM facility proposed by Carroll County at MD 91 and MD 140 in Liberty Reservoir watershed. The project was initiated to improve water quality treatment capacity to meet local pollutant reduction goals. SHA functions as a project sponsor providing portion of the funding through Transportation Alternatives Program (TAP) funding. The proposed facility will treat 22 acres of impervious surfaces within 152 acres drainage area out of which 4 acres are SHA owned impervious surfaces at MD 91 and MD140. The project is past Final Review milestone, the design is 90% complete SHA continues to provide technical review and guidance through the project development, procurement and federal funding approval process. See Figure 1-36 for an area photograph.


***Figure 1-36: Finksburg Industrial Park Pond Retrofit Project before Construction***

**Laurel Lakes Task Force – Prince George's County**

The I-95/Contee Road project recently received design funding. Due to procurement and right-of-way challenges, SHA is pursing remediation of the outfall separate from the overall project. The project is being designed in accordance with the Stormwater Management Act of 2007, implementing ESD features.

**South River Federation – Anne Arundel County**

SHA and South River Federation have partnered to restore the headwaters of Broad Creek, a significant source of sediment to downstream waterways including the Chesapeake Bay. See Figure 1-37 for a view of existing conditions of a steeply cut bank along Broad Creek.

***Figure 1-37: Existing Conditions of Broad Creek***

South River Federation is providing funds for design through Department of Natural Resources Chesapeake & Atlantic Coastal Bays Trust Funds. SHA will fund and manage construction and have collaborated with South River Federation's consultant designers to provide geotechnical, permitting, right-of-way, and technical assistance. The project will reduce sediment and nutrient delivery by restoring stream and wetland functions through the promotion of stream and floodplain connectivity and increasing density of native vegetation. A failed dam will also be removed. Advertisement for construction is anticipated in January 2015. Sediment and nutrient reductions will be calculated and reported once design is finalized.

**Jabez Branch 3 Watershed Study – Anne Arundel County**

SHA is conducting a watershed assessment of Branch 3 of Jabez Creek to identify restoration opportunities. SHA is funding the study, which includes an existing conditions evaluation for the entire watershed, assessment of stream conditions to identify stability issues, prioritization of restoration areas, identify retrofit opportunities, and community outreach. The initial assessment is scheduled to be completed by November of 2014. Then, SHA will collaborate with Anne Arundel County and the Severn River Watershed Association to identify and prioritize potential restoration projects based on the assessment, and determine partnership opportunities for SHA and Anne Arundel County to collaborate on BMP implementation. See Figure 1-38 for a photo of existing conditions.

***Figure 1-38: Degraded Stream Banks along Jabez Creek***

## G.3 Report and Submit Annually

SHA had completed and submitted information on the twenty-five required watershed restoration projects and other activities to meet the permit requirement in the past reports. This included retrofit proposals, costs, schedules, implementation status and impervious acres receiving treatment though the project implementation. . Documentation in the form of construction plans, cost estimates and schedule for additional projects can be provided to MDE upon request. SHA continues planning, design, and construction activities to address various drainage, stormwater management, and water quality issues throughout the watersheds within 11 NPDES counties and watersheds statewide.

SHA also continues to reach out to the local agencies, watershed groups and jurisdictions to partner on variety of environmental mitigation and water quality improvement projects through TAP sponsorship program. SHA participates in local watershed steering committees and attends field meetings with watershed groups to discuss opportunities for stream restoration and stormwater retrofits to address stream degradation and reduce sediment transport in highly urbanized and sensitive watersheds. SHA continues evaluating opportunities to implement watershed restoration projects in cooperation with local jurisdictions as well as address citizens' concerns regarding drainage issues, flooding, erosion, sediment, highway runoff, stormwater management, TMDL, and other environmental issues.

# H Assessment of Controls

This permit condition requires SHA to assess the effectiveness of the NPDES stormwater program and progress towards improving water quality. SHA was required to develop and receive approval for a monitoring plan that should include chemical, biological, and physical monitoring according to parameters specified in the permit and to submit data annually.

## H.1 Restoration Site Approved by October 21, 2006

SHA developed a proposal and received approval for a watershed restoration project by October 21, 2006 for Long Draught Branch restoration. This project has been fully designed and prepared for advertisement, but it has undergone difficulties in obtaining the joint permit approval for construction and therefore has never been implemented. The monitoring plan for chemical, biological and physical data has been developed and pre-construction monitoring has been completed. The biological monitoring has been continued, while chemical and physical monitoring has been put on hold until the project design is restarted and funded again for construction. The new concept design has been developed in 2014 to address the concerns of multiple agencies and obtain the required permits (see Figure 1-39 below.). SHA will proceed with the joint permit application, so the project can be constructed in 2016-2017. Post construction monitoring data will be collected after the project completion for several consecutive years in accordance with the permit requirements and the previous delivered monitoring plan (See SHA First Annual Report, 2006, Appendix K). Meanwhile, biological monitoring continues, as mentioned in the Section G and Section D of this report. The detailed monitoring report is included in Appendix E.

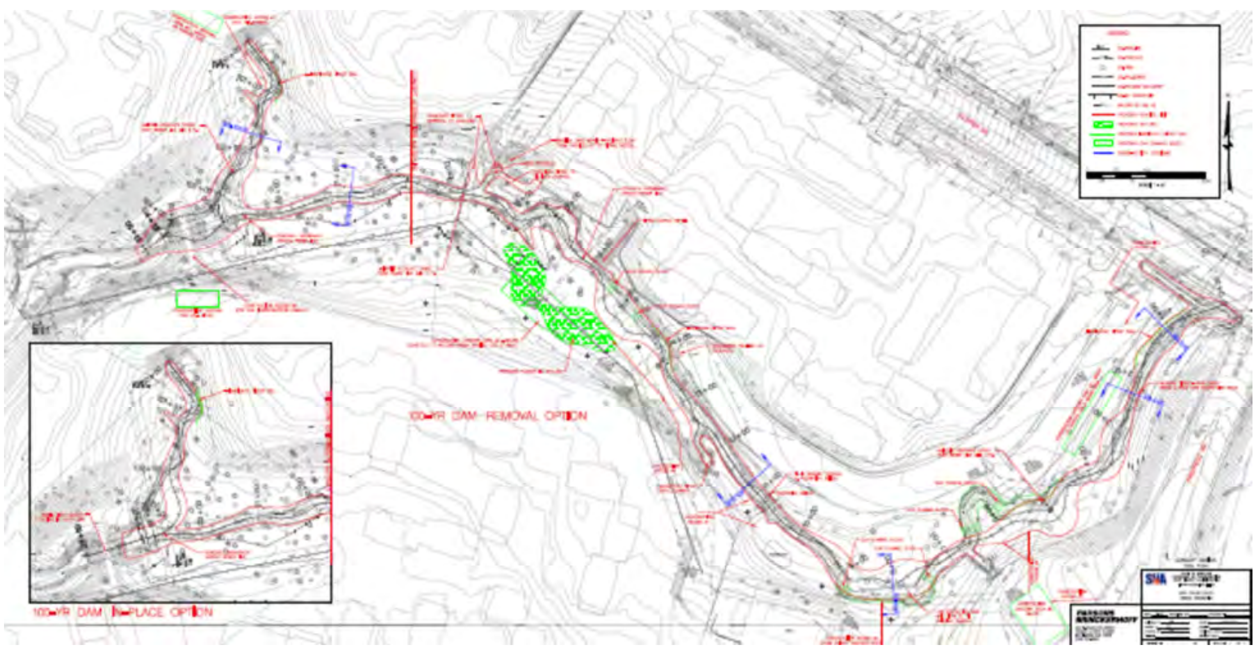


***Figure 1-39: Current Long Draught Branch Concept Design Plan***

## H.2 Monitoring Requirements

Based on the previous approval of the Long Draught Branch project by MDE-WMA, significant pre-construction monitoring (physical, chemical and biological) was performed. The final report for the pre-construction monitoring data was included in the SHA Third Annual Report, 2008, Appendix I. Since the project has been delayed, the post-construction monitoring data will not be available until after the construction is completed

In the interim, SHA performed monitoring of a failed infiltration basin at MD 175 in Howard

County to assess pollutant removal efficiency of a technically deficient SWM BMP. The study has been concluded and is summarized in the 2012 and the final report with monitoring results was included in Appendix A of the 2012 Annual Report.

As noted earlier in Section D, SHA initiated bioswale monitoring study at to evaluate effectiveness of this widely used BMP and its pollutant removal efficiency. The study site is located along US 40, west of I-81 in Washington County, at BMP 210197, 210198, and 210199. Monitoring equipment has been installed and the samplers are logging data. The research team has also completed the soil infiltration capacity measurements at all three sites. In the laboratory, the team has completed the digestion on the soil samples provided and measured the basic soil parameters. Testing for heavy metals in the samples is currently underway. Soil samples will be sieved and classified. A draft report is anticipated in December, 2014. See Figure 1-40 below for an image of the US 40 Bioswale.

***Figure 1-40: Bioswale in the Median of US 40***

## H.3 Annual Data Submittal

Monitoring data for Long Draught Branch pre-construction monitoring was included with previous reports. The 2014 biological monitoring data is included in the Appendix E of this report. The new monitoring data it will be delivered to MDE according to permit database format requirements, as it becomes available.

# I Program Funding

This condition requires that a fiscal analysis of capital, operation and maintenance expenditures necessary to comply with the conditions of this permit be submitted, and that adequate program funding be made available to ensure compliance.

This report represents end of fiscal responsibility for this permit term. SHA has been able to fund its obligations for the all past years with some adjustments. Fiscal analysis is therefore not needed until a new permit is issued. SHA has seen requirements presented for the Bay TMDL as part of WIP process and also has reviewed MS4 permits issued to others. In the near future, SHA will perform funding needs as the next SHA permit is finalized.

In 2006, SHA had procured open-end consultant contracts in the amount of $9 million in order to accomplish both the current Phase I and Phase II NPDES permits. We are currently in the process of procuring additional open-ended consultant contracts for NPDES services in the amount of $48 million for the next six years to continue our engineering efforts for the future. Additional contracts for environmental design services may also be utilized for NPDES related efforts, and SHA is in the process of procuring an additional $48 million in environmental design contracts within the next year.

SHA utilizes Capital Funds (Fund 74 – Drainage) for engineering and construction related activities associated with the NPDES MS4 Permit. Recently, SHA established an additional fund (Fund 82) category in 2012 for TMDL related engineering and construction activities. In addition to the funding commitment from these two funds, SHA seeks additional funding from a variety of sources such as the Chesapeake Bay Trust fund, State Planning and Research funds (SPR), and SHA Operations and Maintenance funds in completing NPDES requirements. SHA no longer uses TAP for state project funding because under the new MAP-21 legislation enacted in 2012, this funding is dedicated for locally sponsored projects only. However, SHA serves as a partner in administering these funds and encouraging their use for water quality initiatives.

Currently, SHA tracks only capital fund spending for the NPDES program as a whole and breaks out a few items such as NPDES Stormwater Facility Program and industrial activities. According to our current records, the total spent for the MS4 NPDES, the Stormwater Facility Program and the Industrial NPDES are listed in Table 1-19 below, and Fund 82 projections are shown in Table 1-20.

***Table 1-19: SHA Capital Expenditures for NPDES (State Fiscal Years)***

| Fiscal Year | Expenditure (Millions)* |
|---|---|
| 2005 | $ 3.40 |
| 2006 | $ 7.26 |
| 2007 | $ 5.74 |
| 2008 | $ 5.73 |
| 2009 | $ 6.42 |
| 2010 | $ 8.68 |
| 2011 | $ 11.62 |
| 2012 | $ 19.20 |
| 2013 | $ 28.54 |
| 2014 | $33.73 |

** Includes Fund 74, 82, Industrial, and SPR Funds. TAP Funds were included through 2012.*

***Table 1-20: Fund 82 Programmed Funding by Fiscal Year***

| Fiscal Year | 2014* | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|
| Dollars Allocated | $25.8 M | $60.2 M | $91.8 M | $106.8 M | $123.3 M | $108. M |
| GO Bond | -- | $45 M | $65 M | $85 M | $100 M | $100 M |
| TTF | $25.8 M | $15.2 M | $26.8 M | $21.8 M | $23.3M | $8.3 M |

***Actual Expenditures**

## J Total Maximum Daily Loads (TMDLs)

The current SHA NPDES Phase I permit states that MDE has determined that owners of stormdrain systems that implement the requirements of the permit will be controlling stormwater pollution to the maximum extent practicable. However, the current mandate is to restore the Chesapeake Bay by 2025, and the draft MS4 Phase I permit notes that jurisdictions will be required to meet assigned waste load allocations (WLAs) for the Bay and local watershed TMDLs. Therefore, SHA has taken many steps in order to position ourselves to meet these requirements. SHA is looking forward in developing funding and activities, but we are not prepared to report on all these activities in detail for this report period. A Watershed Restoration Plan will be prepared during the next permit term, and updates will be included in milestone progress reports and annual reports. Expenditures reflected in Table 1-20 on the previous page reflects this increased activity.

As of March 2013, SHA has consolidated our TMDL Program within the Office of Environmental Design. The purpose of this consolidation is to focus efforts and resources on complying with the requirements of SHA's NPDES MS4 Permit and the Bay TMDL. As part of the new program, there are several designated teams with a specific focus. These include:

- The County Coordination Team has been developed to focus on relationship building and information sharing. The purpose is to fully understand the intricacies of each county and establish partnerships so SHA can better plan and execute effective projects for nutrient and sediment reductions.

- The Data Modeling Team is focused on calculating SHA's baseline pollutant load and impervious surface treatment and developing pollutant reduction progress scenarios as treatment strategies are planned, programmed, and implemented.

- The Research Team has been tasked with conducting research to identify innovative best practice and strategies to improve water quality.

- Implementation Teams have also been established to identify sites and develop project designs for various BMP strategies. These include the Stream Stabilization Team, Stormwater Management Team, and Tree Planting Team.

- The Outreach Team is focused on preparing a public engagement campaign to educate people about SHA's TMDL program as well as anti-littering and environmental stewardship efforts.

Some of the additional activities SHA has undertaken to address WLAs and impervious restoration requirements anticipated for the next permit term include:

- As a result of Federal and State Transportation Trust Funds and House Bill 1515, the Transportation Infrastructure Investment Act of 2013, SHA has been allocated funding to comply with the WIP II. The appropriations are listed in Table 1-20 above. Based on the current funding available, SHA is in the process of identifying BMPs that are in-line with milestone goals.

- SHA has completed the 'outfall stabilization' protocol and is currently in the process of identifying treatment credit by conducting pilot studies on various roadways within NPDES counties. SHA has delivered the draft protocol to MDE and is currently awaiting a response.

- SHA has implemented a database to track BMPs, fulfill MDE's draft reporting geodatabase requirements, and satisfy other internal reporting requirements. The database was developed based on the results of a needs assessment to identify the necessary requirements. Since the initial database schema was implemented, SHA has employed additional functionality required for each major program component including: Planning; Project Design and Implementation; Monitoring; Reporting and Maintenance. The database continues to evolve to fulfill needs of the program as it progresses, and a series of application toolkits are under development to optimize the efficiency of the overall program management, tracking and reporting.

The SHA website has been updated to include more information on the TMDL program found at:

www.roads.maryland.gov/index.aspx?pageid=333.

This updated section includes an overview of the TMDL program, an interactive map of TMDL projects throughout the state, an overview of bay restoration strategies, frequently asked questions, documents and reports (including the MS4 Annual Report), and press release information. See Figure 1-41 below for a screen shot from the interactive map page.

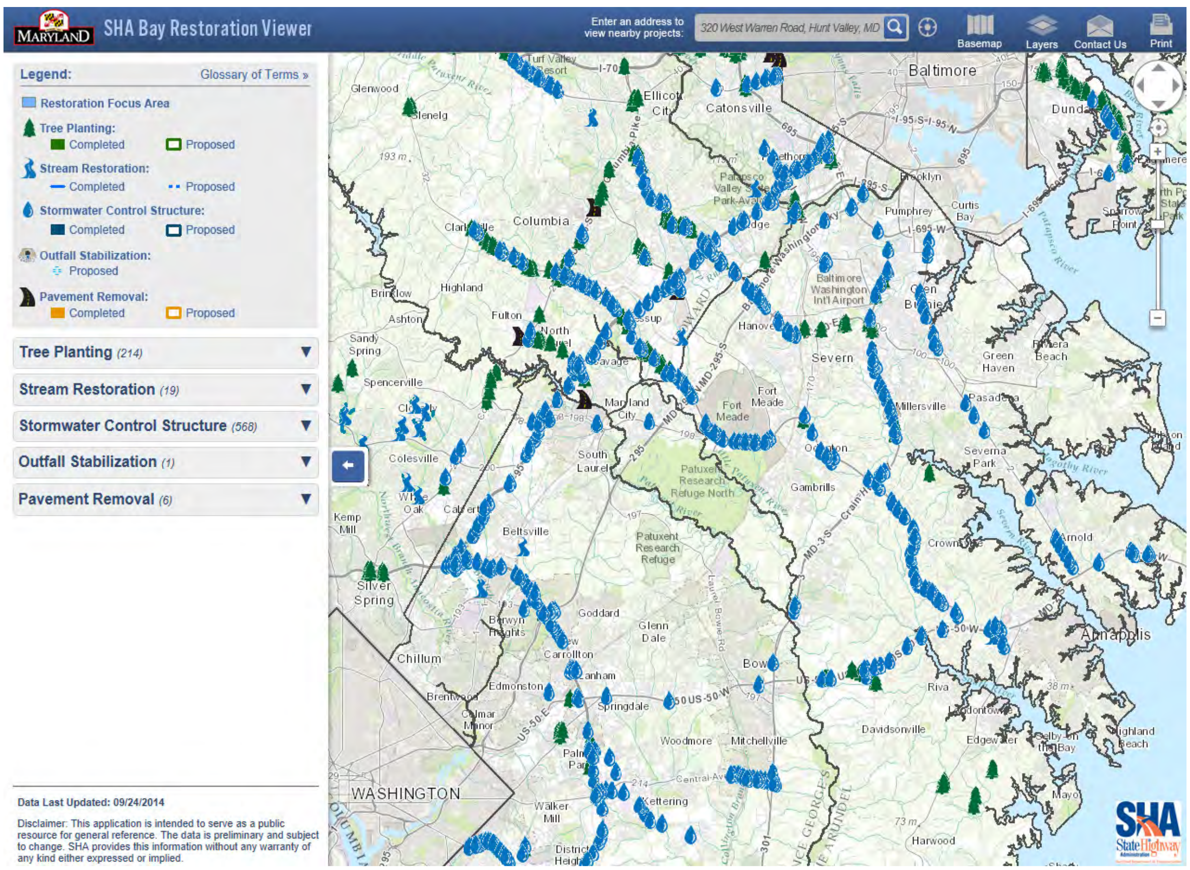


*Figure 1-41: Interactive TMDL Project Map*

Phase I&II National Pollutant Discharge Elimination System
Permit No. 99-DP-3313 MD0068276
Permit Term October 2005 to October 2010

# PART TWO

## STORMWATER FACILITIES PROGRAM

*PART TWO*

# ***Stormwater and Drainage Asset Program***

## Introduction

Maryland State Highway Administration (SHA) owns, operates, and maintains an extensive roadway network with a significant drainage and stormwater system. The Stormwater and Drainage Asset Management Program is established to operate and remediate permanent drainage and stormwater assets that convey and treat highway runoff. The program goal is to provide preventive and remedial solutions for the drainage and stormwater infrastructure within the right-of-way. As of 2014, SHA owns and maintains over 3,100 permanent stormwater management facilities, 180,000 hydraulic structures, and over 100,000 conveyances statewide. Since 1999, SHA has managed a comprehensive asset management program to locate, inspect, evaluate, and remediate these assets to sustain their functionality, improve water quality and stability, protect sensitive water resources, and provide an aesthetic and safe transportation system. SHA has developed comprehensive inspection and rating system to prioritize and plan remedial activities and preventive maintenance to extend the life expectancy of each asset.

Functionality criteria and business plan objectives have been established for the program. These criteria and objectives provide feedback and allow for results oriented actions and adoptable managing techniques. The program business objective is to have 90% of the assets functioning as originally intended.

The Program's primary goal, which is tied directly to the SHA Business Plan goal of providing a positive contribution to the water quality of the Chesapeake Bay, is to ensure that SHA's SWM facilities are fully functional and perform as intended. In addition, the Program has a secondary goal to strategically enhance overall SWM facility function of existing facilities to meet or exceed the latest SWM standards.

The Program represented in Figure 2-1 is divided into four major components. They are planning, design, construction, and operations.

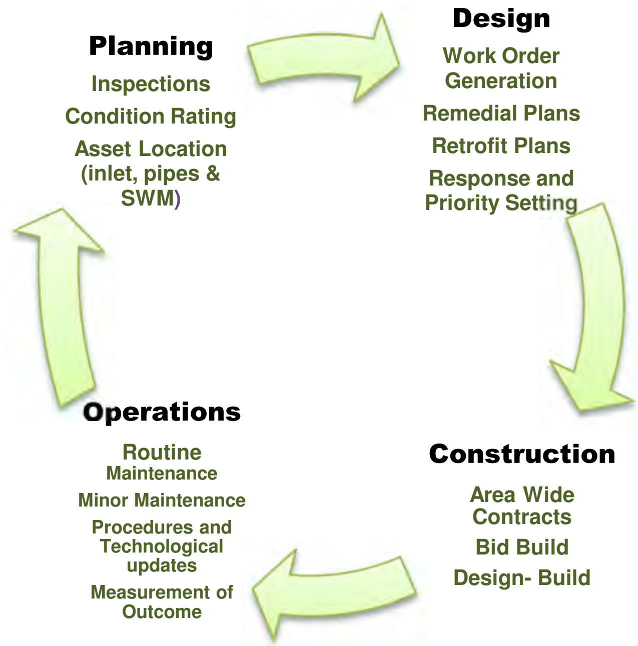


***Figure 2-1 - Stormwater Asset Management Program***

## A. Planning

The SHA Highway Hydraulics Division inspects hydraulics assets (pipes, channels, inlets, and manholes) and stormwater facilities for functionality. The overall goal is to have an up to date inventory, conduct inspections and perform rating assessments based on the SHA NPDES Standard Procedures Manual. This enables SHA to prioritize the repair, remediation, and retrofit of SHA-owned SWM facilities and infrastructure.

Assets receive a performance rating that is related to its asset type. For example, pipe and outfalls are rated based on the structural integrity.

The NPDES Municipal Separate Storm Sewer System (MS4) permit requires SHA to identify all storm drainage conveyance infrastructure that captures, treats, and conveys stormwater runoff from SHA properties in certain areas of the State. SHA is strategically expending its program to cover all areas of the State within its right-of-way. The properties associated with this drainage infrastructure include roadways, welcome centers, SHA shops, parking lots, and park and rides. Data includes identification and inspection of hydraulic structures, pipe conveyances, stormwater management facilities, and outfalls. In particular, inspections address:

- Visual, functional, and environmental enhancement, upgrade, and retrofit of SWM facilities, including upgrades related to safety.
- Site and SWM facility monitoring, research, and innovative technology tool development.

## B. Engineering

Assets with major deficiencies that entail more than minor maintenance require a detailed Remedial Assessment to determine specific causes of deficiencies and to develop a remedial action plan. Procedures have been developed that assist with decisions on maintenance, repair, and remediation of drainage and SWM assets. These assessment guidelines document the methodologies to be used in the field for assessing and determining remedial actions necessary for restoring stability and functionality. Also, the procedures provide information on field preparation, data management of collected information, as well as development of remedial assessment reports and work orders for maintenance crews.

The rating system is:

**I** **No Response Required -** The asset is functioning as designed. Re-schedule for the next multi-year inspection assessment period.

**II** **Minor Maintenance -** The asset is functioning as designed, but routine and preventative action should be performed to sustain effective performance.

**III** **Major Maintenance or Repair -** The asset is no longer functioning as originally designed and significant repair is necessary to restore original functionality. The facility is repaired to remain within the existing facility footprint.

**IV** **Retrofit Design -** The asset is no longer functioning as designed and cannot be restored to the original function as designed without a complete re-design and construction of a facility with a larger footprint.

**V** **Immediate Response -** The SWM facility has catastrophically failed and public safety hazards exist that require immediate corrective action.

**VI** **Abandonment -** The SWM facility is unsustainable and no longer provides sufficient benefit to warrant remedial design.

See Figure 2-2 for the Inspection and Engineering Process.

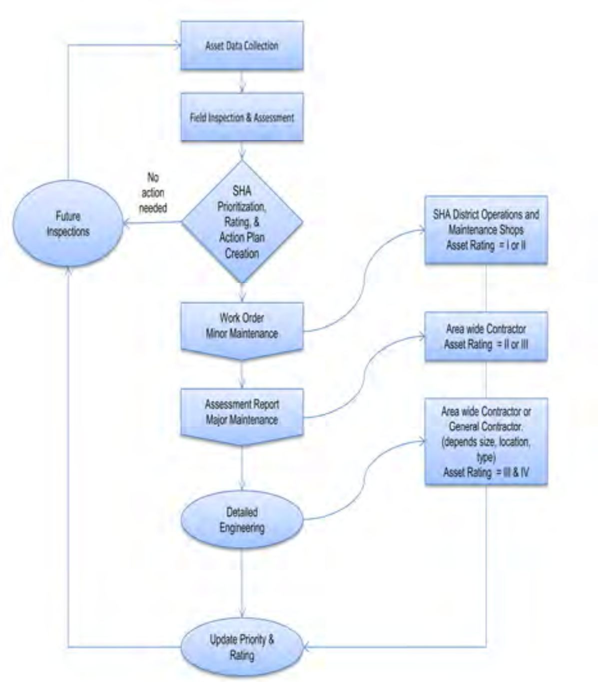


***Figure 2-2 - Inspection and Engineering Process***

## C. Construction

Construction activities are defined in work orders or plans are executed in asset management contracts. Routine upkeep or minor and preventive repairs are generally activities that address minor deficiencies and may include actions such as mowing, brush cutting, vegetative thinning, unwanted woody vegetation removal, invasive weed removal, and trash or debris removal.

SHA performs most of the work using open-end asset management construction contracts. Contracts are procured based on available funding, varying need for remediation, and other administrative factors. Additional coordination occurs with District maintenance departments to better address the routine maintenance needs of the growing inventory.

Activity schedules are based on local needs. In addition, geospatial data is used to assist in combining activities together such that activities can be performed on multiple facilities in proximity to one another, allowing greater efficiency of work completion at lower costs. Entire roadway corridors can often be completed within a few weeks. Often activities include total reconstruction to upgrade a facility in an attempt to enhance functions and increase treatment capacity

## D. Maintenance

Minor repair activities are performed by District Operational staff. To address significant deficiencies open-end construction contracts are deployed. The purpose of the repair activities is to restore the performance of the asset as well as prevent failure of specific functional elements. Actions may include dredging, sediment removal, and obstruction removal within pipes. Work also may include removal of sediment from facilities to maintain the required water volume. SWM facilities that require major or remedial repair are assigned an "III" rating.

## E. Inventory

SHA's SWM facility inventory database is frequently updated as new facilities are brought online. Updates occur statewide for SHA's entire highway and facility infrastructure in each Maryland county, including all Phase I and II MS4 locations as well as those locations not presently covered under the Phase I or II permits. Inventoried SWM facilities include those owned and maintained by SHA as well as those owned and maintained by other jurisdictions, municipalities, or entities because the SWM facilities receive and manage stormwater runoff from the SHA highway network. Table 2-1 summarizes the total number of SWM facilities that intercept and manage stormwater runoff from the SHA highway network and highway-related assets; the information is grouped by county.

The SHA SWM facility inventory includes all SWM facilities that intercept and manage runoff from SHA's highway network and roadway-related assets and includes SWM facilities not owned or maintained by SHA, but by other entities, including but not limited to counties, municipalities, other state agencies, and private entities.

Compared to the previous reporting period, several counties show an increase in the total number of SWM facilities managing runoff from SHA roadway networks and assets. Increases may occur for several reasons, including but not limited to, new developments adjacent to SHA roadways, improvements to the SHA roadway network, and construction of new SWM facilities in areas of the roadway network previously not serviced by adequate SWM facilities.

See Table 2-1 on the following page for a summary of the Stormwater Asset Management Program Statewide.

| Table 2-1 – Stormwater Asset Management Program in MS4 Counties | | | | | | |
|---|---|---|---|---|---|---|
| **County** | **No Action** | **Routine** | **Major Remedial** | **Retrofit Design** | **% Funct.** | **Total Invent.** |
| Anne Arundel | **187** | **283** | **98** | **23** | 79.5% | 591 |
| Baltimore | **108** | **92** | **64** | **3** | 74.9% | 267 |
| Carroll | **61** | **15** | **3** | **0** | 96.2% | 79 |
| Cecil | **6** | **9** | **0** | **0** | 100.0% | 15 |
| Charles | **93** | **3** | **0** | **0** | 100.0% | 96 |
| Frederick | **175** | **19** | **0** | **0** | 100.0% | 194 |
| Harford | **69** | **63** | **0** | **6** | 95.7% | 138 |
| Howard | **445** | **85** | **32** | **3** | 93.8% | 565 |
| Montgomery | **97** | **215** | **23** | **4** | 92.0% | 339 |
| Prince George's | **270** | **118** | **48** | **5** | 88.0% | 441 |
| Washington | **181** | **15** | **5** | **2** | 96.6% | 203 |
| **Totals** | **1692** | **917** | **273** | **46** | **92.4%** | **2928** |
| *SHA conducts Stormwater Asset Management Statewide, however, the information in this table represents MS4 Phase I and II jurisdictions only.* | | | | | | |

**Field Inspections**

Initial SWM facility field inspections and inventories have been completed for all counties, both MS4 and non-MS4 counties. The information is used to verify existing data in the SHA database as well as determine the SWM facilities functional rating and provide any necessary remedial action recommendations. The statewide inventory is continuously updated on a county-by-county basis.

## F. Repair and Remediation

This section summarizes the status of SHA repair and remediation activities in response to identified deficiencies of SWM facilities. Since SHA has a goal to ensure complete functionality and efficiency of all SHA owned and maintained SWM facilities, deficiencies are corrected in a timely manner. In addition, SHA seeks to enhance function beyond existing level of service as the need or opportunity arises to increase pollutant removal efficiency or to treat additional impervious surfaces.

Response actions are divided into four major categories of activities: no action, minor or routine upkeep and preventative maintenance, major repair, and retrofit or enhancement. Retrofit projects may include reconstruction of a facility to restore function, or to enhance the facility to deliver improved function, e.g. a non-functional infiltration trench may be retrofitted to a bioretention facility with an enhanced filter to increase pollutant removal efficiency. Figure 2-3 below shows the remediation ratings and the projected trend.

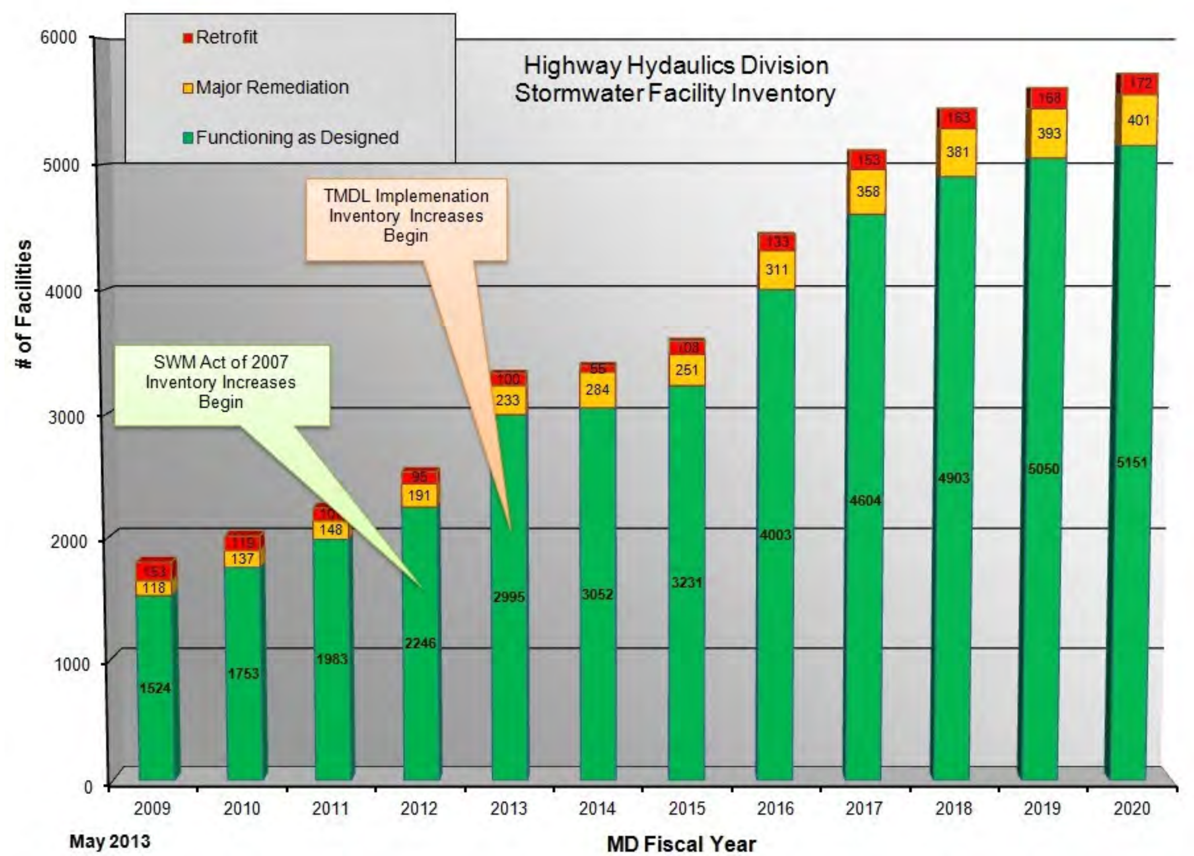


***Figure 2-3 – SHA Remediation Ratings and Historical Trend***

**Routine Upkeep**

Routine upkeep or minor and preventive repairs are generally activities that address minor deficiencies and may include actions such as mowing, brush cutting, vegetative thinning, unwanted woody vegetation removal, invasive weed removal, and trash or debris removal. These activities greatly help to maintain performance of a SWM facility and prevent or eliminate deteriorative conditions of key SWM facility elements. SWM facilities requiring routine upkeep are assigned "II" rating by SHA.

SHA is currently developing a statewide operational manual for stormwater and drainage assets.

**Major Repair**

Major repair activities are performed to address significant deficiencies of SWM facilities and are also performed through open-end construction contracts. The purpose of the repair activities is to restore the performance of a SWM facility as well as prevent failure of specific functional elements. Actions may include dredging, sediment removal, and obstruction removal within pipes. Work also may include removal of sediment from facilities to maintain the required water volume. SWM facilities that require major or remedial repair are assigned a "III" rating by SHA.

Figures 2-4 and 2-5 below show a SWM facility before and after construction.


***Figure 2-4 – SWM Facility 160883 Under Retrofit Construction***


BMP 160800 - OVERALL

***Figure 2-5 – SWM Facility 160800 After Construction***

**Retrofits - Design-Build and Asset Warranty**

SHA is presently developing design-build and asset warranty (DBAW) contracts to administer the asset remediation and improvement portion of the NPDES program to include all SHA drainage assets. The contract will use the design-build project framework already developed and implemented by SHA. The scope includes strategically planned activities to preserve functionality and sustain efficiency of SHA SWM facilities, remediate pipe assets that have exceeded the designed lifespan, and replace or enhance hydraulic structures. All of these activities require preliminary engineering. Contracts will cover entire districts but will consist of multiple specific sites. Each site will adhere to NEPA and federal authorization procedures.

Design engineers determine remedial actions that need to be completed for the targeted SWM facilities to return to the designed intention. This means that the facilities are currently not functioning as originally intended and engineering solutions are needed to return the facilities to their original state. These facilities require a SWM facility type change and retrofit and permit, involving detailed engineering and coordination. Pipe assets deemed to need major remediation must also be addressed. The design-build (DB) team will generate plans and construct the necessary improvements.

All work will require a warranty for function. The warranty will be assessed based on the criteria found in the SHA NPDES Standard Procedures Manual. The term of the warranty is 18 months after the completion of construction activities. SWM facilities must be inspected and receive an inspection rating of ‘A’. Conveyance systems will be required to receive an inspection rating of ‘1’. Drainage structures will be required to have no associated structure issues. Any items found to be deficient must be repaired by the DB team contractor at no additional cost to SHA for the duration of the warranty period.

**Immediate Response**

In the event of an emergency, SHA immediately performs work to ensure public safety. SHA responds to any outfall or SWM facility that requires immediate repair and remediation. Roadways are closed as necessary and detour routes are implemented as needed. Site assessment and investigation occurs at the subject location within hours by a multi-disciplinary team. On-call contractors are mobilized and plans for repairs are initiated within 24-hours.

## G. SWM Facility Retrofits, Visual and Functional Enhancement Projects

SHA continuously plans, designs and constructs functional enhancements and retrofits for SWM facilities. Projects are funded using state and federal funds. Site selection for enhancement projects is evaluated using several factors, including feasibility, permitting process complexity, and benefit analysis. SHA often seeks opportunities to improve the efficiencies of older SWM facilities that provide only minimum water quality treatment to achieve greater reduction of pollutant loads from highway runoff. SHA also seeks opportunities to manage greater amounts of untreated roadway areas to existing SWM facilities to increase the amount

As a part of SHA's greater improvement efforts and gaining increased benefit at smaller costs, projects to improve water quality involve treatment of additional impervious areas as well as provide replacement or upgrade to the existing drainage infrastructure. Projects also include rehabilitation of degraded outfalls, channel restoration, and slope stabilization. In addition to improvements of exiting SWM and drainage assets, SHA has begun SWM retrofits to provide water quality treatment of currently untreated pavement. All relevant information will be compiled and reported with the Bay TMDL milestone progress reports as well as in future NPDES Annual Reports.

## H. Data Management

SHA has performed an inventory of all SWM drainage infrastructure in each NPDES MS4 county and performs SWM facility inspections in all twenty-three counties. The statewide SWM facility inventory database was finalized in 2011. SHA has also proceeded with re-inspections. A new data collection effort has begun in non –MS4 counties. This effort involves continuous updates of GIS data for source identification and database records of inspection and remediation activities.

SHA has finalized the structure of the ESRI geodatabase and detailed schema that allows for the establishment and enforcement of topologic and/or network rules and unique data entry. Domain rules are updated as needed. The database format has resulted in improved data intelligence and integrity. SHA plans to integrate the geodatabase with other organizational initiatives such as eGIS and iMAP (discussed below) to improve communication between offices.

SHA uses two custom software programs to collect and store geospatial information: the Office Tool and the Field Tool. The Office Tool is used to input data as well as perform quality assurance (QA) reviews. The Field Tool is used with GPS coordinate units to collect and edit field data.

Along with the database format, the customized data viewer tool known as the NPDES Viewer, has been recently enhanced. The tool allows a user to view spatial information as well as digital images associated with each SWM facility, including as-built plans, photographs, inspection reports and other pertinent documents. NPDES Viewer is used to view data at various focus levels, such as highway corridors, SHA districts, counties, or watersheds.

A new component for SWM facility maintenance tracking, called the Remediation Tool, has been added to the NPDES Viewer. The application allows the tracking of routine upkeep and major repair activities, associated costs, retrofit project progress, and current functionality of SWM facilities. It also can output reports of data that can be shared with managers and administrators.

## I. Strategic Planning

The program in undergoing a strategic planning effort with the purpose of improving business processes to better serve our customers and efficiently use available resources. The planning effort will be completed in four phases

- Review of existing business processes and technical documents
- Review of new industry technologies and similar business processes for asset management
- Develop revised business processes and technical documents
- Implement business processes and new technology

## J. Summary

The NPDES MS4 permit requires SHA to identify all infrastructure that captures, treats, and conveys stormwater runoff from SHA facilities such as roadways, welcome centers, and park and rides, including hydraulic structures and stormwater management facilities. SHA owns and maintains approximately 3088 SWM facilities. Based on current estimates, SHA also owns and maintains over 130,000 hydraulic structures and 85,000 conveyances statewide. Since 1999, SHA has maintained and managed a comprehensive asset management program to locate, inspect, evaluate, and remediate stormwater facilities to sustain their functionality, improve water quality, and protect sensitive water resources. SHA has developed a comprehensive inspection and rating system to prioritize and plan remedial activities and preventive maintenance to extend the life expectancy of each asset.

The SHA Business Plan goals exceed the NPDES Phase I permit requirements by promoting a complete statewide inventory and maintaining high-efficiency SWM facility performance. A key goal is to maintain 90 percent of all SHA-owned SWM facilities at full functionality. Currently, 90.0% of the SHA-owned and maintained facilities within the inventory meet the functionality goal.

Key program components and structures exemplify a strategic approach to meet NPDES permit requirements, allowing for the enhancement of SWM facility performance efficiency and reducing the pollutant loads contained in highway runoff, significantly improving water quality in the sensitive Chesapeake Bay watershed and local waterways.

Phase I&II National Pollutant Discharge Elimination System
Permit No. 99-DP-3313 MD0068276
Permit Term October 2005 to October 2010

# APPENDIX A

## SHA DATABASE DICTIONARY

# Appendix A: SHA Database Dictionary

## A Introduction

The NPDES Annual Report database submittal includes an Esri file geodatabase and several Microsoft Excel files prepared in compliance with table specifications detailed in the *SHA's National Pollutant Discharge Elimination System (NPDES) Municipal Separate Storm Sewer System (MS4) Discharge Permit, Attachment A: Annual Report Databases,* which was provided to SHA on June 26, 2012.

This database dictionary for the submittal incorporates the existing specifications for the required attribute definitions within each table specification and includes additional fields and associated descriptions provided by SHA. Supplemental information for each layer is provided, as necessary, to detail the lineage of the datasets.

## B File Formats

The 2014 Annual Report databases for each table exhibit detailed in Attachment A of the permit are provided in Microsoft Excel and an ArcGIS 10.1 file geodatabase named *SHA_AttachmentA_Geodatabase.gdb*. This information was exported from the enterprise SDE geodatabase environment and processed into the required Attachment A table structures. A supplemental ArcGIS 10.1 file geodatabase of the full SHA stormwater facilities enterprise database has also been provided with this submittal.

## C Contents

Within the "Databases" folder on the CD deliverable, the following Microsoft Excel files are provided:

- Table A - Storm Drain Outfalls.xlsx
- Table B - Urban BMP SWM Facilities.xlsx
- Table C - Impervious Surfaces.xlsx
- Table C1 – Impervious Watershed Acreages.xlsx
- Table D - Water Quality Improvement Projects.xlsx
- Table E - Monitoring Site Locations.xlsx
- Table E1 - Monitoring Site Locations - Land Use.xlsx
- Table E2 - Monitoring Site Locations - SWM BMP.xlsx
- Table F - Chemical Monitoring Results.xlsx
- Table H – Biological Habitat Monitoring.xlsx
- Table I - IDDE.xlsx

The associated spatial databases are provided in support of the deliverable within two separate Esri file geodatabases:

- SHA_AttachmentA_Geodatabase.gdb - Includes all Attachment A spatial datasets.
- SHA_NPDES_2014geodatabase.gdb - Includes a full export of the SHA enterprise structural stormwater facility database.

Contents of the SHA_AttachmentA_Geodatabase.gdb are listed below and the contents and data structures are described in the following pages:

- TABLE_A_STORM_DRAIN_OUTFALLS *(feature class)*

- TABLE_B_URBAN_BMP_SWM_FACILITIES *(feature class)*
- TABLE_C_IMPERVIOUS_SURFACES *(feature class)*
- TABLE_C1_IMPERVIOUS_WATERSHED_ACREAGES *(table)*
- TABLE_D_WATERQUALITY_IMPV_PROJECTS *(feature class)*
- TABLE_E_MONITORINGSITES_LOCATIONS *(feature class)*
- TABLE_E1_MONITORINGSITES_LANDUSE *(table)*
- TABLE_E2_MONITORINGSITES_SWMBMP *(table)*
- TABLE_E3_MONITORINGSITES_DRAINAGEAREAS *(feature class)*
- TABLE_F_CHEMICAL_MONITORING_RESULTS *(table)*
- TABLE_H_BIOLOGICAL_HABITAT_MONITORING *(table)*
- TABLE_I_IDDE *(table)*

The contents of the SHA_NPDES_2014geodatabase.gdb are detailed below in Table A-1.

***Table A-1 SHA NPDES Geodatabase Contents***

| DATABASE SPATIAL LAYERS | TYPE | DESCRIPTION |
|---|---|---|
| SWMFAC | Feature Class | Polygon feature class that stores the spatial representation outline and tabular information pertaining to structural BMPs. Information includes location, BMP type, feature status, and other overlay attributes such as watershed. |
| BMP_CENTROID | Feature Class | Point feature class that stores the spatial representation of the SWMFAC polygon feature class records. |
| STRUCTURES | Feature Class | Point feature class that stores the spatial representation and tabular information pertaining to storm water structures (i.e., inlets, manholes, outfalls, control structures). Information includes structure type, feature status, major outfall (T/F), and other overlay attributes such as watershed. |
| CONVEYANCE | Feature Class | Line feature class that stores the spatial representation and tabular information pertaining to storm water conveyance (i.e., pipe and ditch). Information includes conveyance type, feature status, invert elevations, and other overlay attributes such as watershed. |
| DRAINAGE_STRUCTURE | Feature Class | Polygon feature class that stores the spatial representation and tabular information pertaining to structure features, mainly major outfalls. The drainage areas, in acres, is stored in the table. |
| DRAINAGE_SWMFACILITY | Feature Class | Polygon feature class that stores the spatial representation and tabular information pertaining to structural BMPs. The drainage areas, in acres, is stored in the table. |
| **DATABASE TABLES** | **TYPE** | **DESCRIPTION** |
| END_HEADWALL | Table | Contains the outfall and open upstream structures for a storm drain system, such as endsections, projection pipes, headwall, and endwalls. Information includes the type and material of the end structure. |
| INLET | Table | Contains the inlet features within the storm drain systems. Information includes the type and material of the inlet, the top of grate, and the length for COG and COS type inlets. |
| MANHOLE_CONN | Table | Contains the manhole and other connection features within the storm drain system. Information includes the material and top of manhole lid, when applicable. |
| PUMPSTN | Table | Contains the pump stations within the storm drain system. Information includes the station name, install date, number of pumps, and maximum capacity for the station. |

*Table A-1 SHA NPDES Geodatabase Contents*

| DATABASE SPATIAL LAYERS | TYPE | DESCRIPTION |
|---|---|---|
| SWMRISER | Table | Contains the storm water BMP control structure, such as box risers and pipe barrel risers. Information includes the material, if a trash rack exists, riser type, and the stage storage elevation. |
| WEIR | Table | Contains the weirs and emergency spillways related to storm water BMP storage controls. Information includes the material, if a trash rack exists, and the stage storage elevation. |
| STRUCTURE_ISSUE | Table | Contains issues related to the storm water structure features, and ranks the issue as non-emergency and hazard to public. Selected issues can be buried outfalls, broken grates, damaged slabs, or manhole missing. |
| FLDSC_SITE | Table | Contains the feature and site location information pertaining to an outfall structure, mainly major outfalls, which are being inspected for damage and screened for illicit discharge. Information included includes location and type of outfall. |
| INSPECTION | Table | Contains the inspection records for outfall structures that are inspected and screened for illicit discharge. Information includes date inspected, flow observed (Y/N), and scoring values for odor, deposits, vegetation condition, structure condition, and erosion. |
| FLOW_CHAR | Table | Contains the water sampling results for an illicit discharge chemical sampling of an outfall structure. Information includes a scoring value for the color and clarity of flow, floatable present, water and air temperature, and results for chemical parameters tested for, such as ammonia and chlorine. |
| FILE_ATTACH_STR | Table | Contains photographs and filenames related to the outfall structure inspection and screening recorded in the INSPECTION table. |
| BMP_INSPECTION | Table | Contains the inspection records for SWM BMPs that are inspected. Information includes inspection scores for structural, environmental, safety, and functionality parameters. These parameters include riser, embankment, vegetation, performance, safety, and ponding factors. |
| BMP_INSPECTION_ACTION | Table | Contains records related to maintenance actions observed during a BMP inspection. These actions include removal of sediment, fixing structural issues related to the BMP, and maintenance of vegetation and erosion issues. |
| CONCERNS | Table | Contains records related to invasive vegetation and/or contaminants, such as oil, observed during the BMP inspection. |
| FILE_ATTACH_SWM | Table | Contains photographs and filenames related to the BMP inspection recorded in the BMP_INSPECTION table. |
| DITCH | Table | Contains the ditch features within the storm drain conveyance. Information included includes ditch material and dimensions. |
| PIPES | Table | Contains the pipe features within the storm drain conveyance. Information includes the type, length, and dimension of the pipe. |
| PIPE_INSPECTION | Table | Contains the information about the location and overall rating of a pipe that is inspected. |
| P_INSP_REC | Table | Contains high level information pertaining to a pipe inspection, such as if the pipe discharges to water of the US, if the pipe is blocked, or if scour is occurring. |
| P_INSP_SUBRATING | Table | Contains detailed rating pertaining to a pipe inspection, such as severe rusting on base of pipe, invert deterioration, complete collapse of the pipe. |
| P_INSP_PHOTO | Table | Contains photographs and filenames related to the pipe inspection recorded in the PIPE_INSPECTION table. |
| CONTRACT | Table | Contains the list of contract plan sets related to storm drain features. Information includes the contract number, year, and the location and limits of the project. |
| FILE_SCAN | Table | Contains the list of contract plan sheets that relate to a storm water management facility. These sheets include title, profiles, details, grading, and/or landscaping plan sheets. |
| OWNER | Table | Contains a list of owners that maintain the storm drain features within SHA's NPDES database. Information includes contact information of the owner. |
| METADATA_INFO | Table | Contains information pertaining to how and when the storm drain features was added or edited in the SHA NPDES database. |

**Table A-1 SHA NPDES Geodatabase Contents**

| DATABASE SPATIAL LAYERS | TYPE | DESCRIPTION |
|---|---|---|
| REF_SWMFAC_BASELINE | Table | Contains information that associates each SWM Facility record to the 2009 baseline or 2011 current capacity indicator. |

## D Data Projection

These file geodatabase submittals have been re-projected from SHA's standard projection into the required projection for MDE, specifically NAD_1983_StatePlane_Maryland_FIPS_1900_Meters. The submittal geodatabases are developed in the following original spatial projection: NAD_1983_StatePlane_Maryland_FIPS_1900_Feet.

## E BMP / Structure System Numbering Convention

The BMP system numbering methodology applies a unique seven-digit identification number to each asset. The first two (2) digits indicate the county where the system is located. Table A-2 lists the county code numbers for Maryland. For county codes that begin with a zero (ex. Baltimore County 03), the leading zero is not dropped from any naming convention. The remaining five (5) digits represent the unique system number. For example, 130140 is system 140 located in Howard County (County Code 13).

**Table A-2 Maryland County Codes**

| Code | Abbreviation | County Name | Code | Abbreviation | County Name |
|---|---|---|---|---|---|
| 01 | AL | Allegany | 13 | HO | Howard |
| 02 | AA | Anne Arundel | 14 | KE | Kent |
| 03 | BA | Baltimore | 15 | MO | Montgomery |
| 04 | CA | Calvert | 16 | PG | Prince Georges |
| 05 | CO | Caroline | 17 | QA | Queen Anne's |
| 06 | CL | Carroll | 18 | SM | St. Mary's |
| 07 | CE | Cecil | 19 | SO | Somerset |
| 08 | CH | Charles | 20 | TA | Talbot |
| 09 | DO | Dorchester | 21 | WA | Washington |
| 10 | FR | Frederick | 22 | WI | Wicomico |
| 11 | GA | Garrett | 23 | WO | Worcester |
| 12 | HA | Harford | 24 | BC | Baltimore City |
| | | | 99 | SW | Statewide |

The individual drainage structures located within a system receive a unique three (3) digit identification number. For example, 1300140.007 is the seventh (.007) structure in the 140th drainage system in Howard County.

Numbering begins with the most downstream structure, usually the outfall, which is assigned the structure number of .001. Structures are then numbered as the system is traced upstream. For initial data collection or adding new systems, the most downstream structure in any system should be numbered .001. This is convention only, and structures may be numbered out of sequence in the existing geodatabase.

Each system that flows into a BMP is a separate system. The control structure and outfall for a stormwater BMP also starts a new system. Figures A-1 and A-2 show examples of system, structure, and BMP numbering.

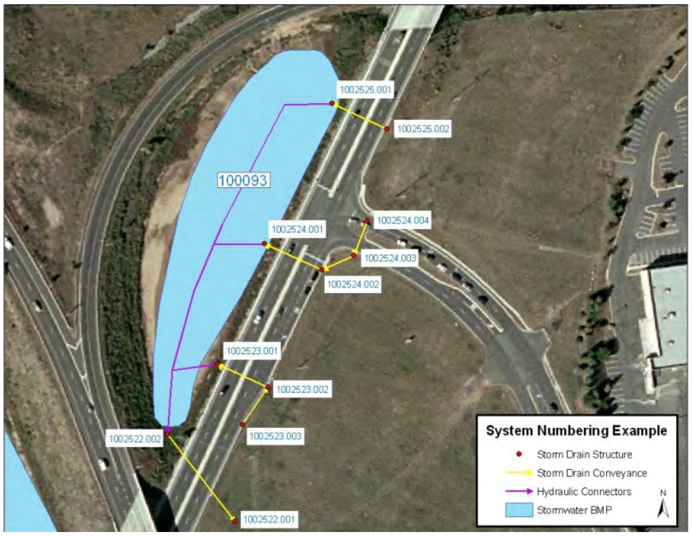


**Figure A-1 System No. Ex. 1**

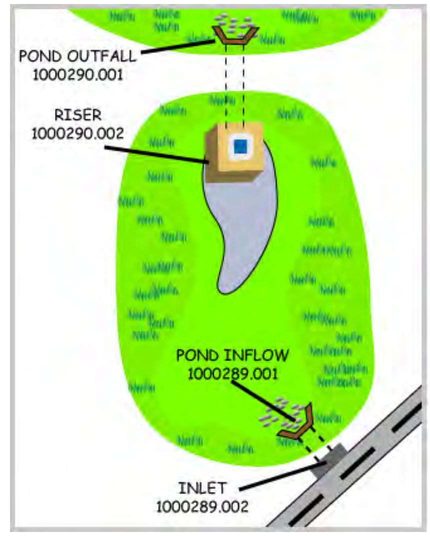


**Figure A-2 System No. Ex. 2**

The STRU_ID field definition in Attachment A tables requires a text field with a maximum length of 8 characters. MDE has requested that the STRU_ID number have the designation 'SHA' somewhere in the number. As defined above, SHA's unique STRU_ID values assigned are currently eight characters. SHA has added a field to the layers with Structure and BMP numbers called MDE_STRU_ID (text, 20) that has been processed to include the "SHA" prefix.

## F Attachment A - Table Specifications Attribute Definitions

The following tables provide the table specifications for the layers in the SHA_AttachmentA_Geodatabase.gdb. In the database specification table below, SHA provides a *Double* number field type in compliance with the required number field designations.

***TABLE_A_STORM_DRAIN_OUTFALLS:***

The data (See Table A-3) provided is a point feature class representing all existing major outfalls statewide within SHA drainage systems. The drainage area layer is provided as a reference feature class layer in the SHA_NPDES_2014geodatabase.gdb named "DRAINAGE_STRUCTURE". The outfalls can be joined to this layer using the STRUCTURE_ID common field. The list of outfall type codes are provided below in Table A-4.

***Table A-3. Storm Drain System Outfalls (Table A from Attachment A) - Attribute Structure***
***Feature Class Name: TABLE_A_STORM_DRAIN_OUTFALLS***

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| YEAR | DOUBLE | | Annual report year |
| OUTFALL_ID | TEXT | 11 | Unique outfall ID |
| MD_NORTH | DOUBLE | | Maryland grid coordinate (NAD 83 meters) Northing |
| MD_EAST | DOUBLE | | Maryland grid coordinate (NAD 83 meters) Easting |

### *Table A-3. Storm Drain System Outfalls (Table A from Attachment A) - Attribute Structure*
### *Feature Class Name: TABLE_A_STORM_DRAIN_OUTFALLS*

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| DIM_OUTFL | DOUBLE | | Outfall Dimensions in inches |
| WATERSHED_CODE | TEXT | 12 | Maryland 8 or 12-digit hydrologic unit code |
| TYPE_OUTFL | TEXT | 5 | Outfall Type (RCP, CMP, PVC, See Table A-4) |
| DRAIN_AREA | DOUBLE | | Drainage area to outfall (acres) [1] |
| LAND_USE | TEXT | 3 | Predominant land use[2] |
| *MDE_OUTFALL_ID | TEXT | 20 | Unique outfall ID with the prefix of "SHA" |

[1] GIS shapefile required
[2] Use attached Maryland Office of Planning land use codes
*Fields provided by SHA in addition to Attachment A

### *Table A-4 – Outfall Type Codes*

| Outfall Type Code | Description |
|---|---|
| PVC | Polyvinyl Chloride |
| RCP | Reinforced Concrete Pipe |
| HDPE | High Density Polyethylene |
| CONC | Concrete |
| SPP | Structural Plate Pipe |
| VC | Vitrified Clay |
| CMP | Corrugated Metal Pipe |
| CIP | Cast Iron Pipe |
| ACCMP | Asphalt Coated Corrugated Metal Pipe |
| BCCMP | Bituminous Coated Corrugated Metal Pipe |
| UNK | Unknown |
| OTHER | Other |
| ASRP | Aluminum Spiral Rib Pipe |
| TCP | Terracotta |

***TABLE_B_URBAN_BMP_SWM_FACILITIES*:** The data (see Table A-5) provided is a polygon feature class representing all existing SHA owned and maintained stormwater facilities statewide within SHA drainage systems. The drainage area layer is provided as a reference feature class layer in the SHA_NPDES_2014geodatabase.gdb named "DRAINAGE_SWMFACILITY". The stormwater facility BMPs can be joined to this layer using the FACILITY_ID common field. The impervious area information associated to the stormwater facilities is currently being updated to support the establishment of an accurate baseline. There are some facilities in the MS4 counties which do not have an impervious area acreage assigned due to limitations in the existing legacy data that is currently being processed with update improvements.

This layer includes the BASELINE_YEAR field which indicates if the facility is associated with the 2009 Baseline or the 2011 Current Capacity, or both due to a retrofit enhancement.

***Table A-5 Urban Stormwater BMPs (Table B from Attachment A) - Attribute Structure Feature Class Name: TABLE_B_URBAN_BMP_SWM_FACILITIES***

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| YEAR | DOUBLE | | Annual report year |
| STRU_ID | TEXT | 6 | Unique structure ID[5] |
| PERMIT_NO | TEXT | 15 | Unique permit number |
| STRU_NAME | TEXT | 254 | Structure name |
| ADDRESS | TEXT | 254 | Structure address |
| CITY | TEXT | 254 | Structure address |
| STATE | TEXT | 254 | Structure address |
| ZIP | TEXT | 254 | Structure address |
| MD_NORTH | DOUBLE | | Maryland grid coordinate (NAD 83 meters) Northing |
| MD_EAST | DOUBLE | | Maryland grid coordinate (NAD 83 meters) Easting |
| ADC_MAP | TEXT | 20 | ADC map book coordinate (optional if BMP has MD Northing\Easting) |
| WATERSHED_CODE | TEXT | 12 | Maryland 8 or 12-digit hydrologic unit code |
| STRU_TYPE | TEXT | 254 | Identify structure or BMP type[3] |
| LAND_USE | TEXT | 3 | Predominant land use[2] |
| CON_PURPOSE | TEXT | 254 | New development (NEWD), Redevelopment (REDE), or Restoration (REST) |
| DRAIN_AREA | DOUBLE | | Structure drainage area (acres)[1] |
| IMP_ACRES | DOUBLE | | Structure impervious drainage area (acres)[1] |
| TOT_DRAIN | TEXT | 254 | Total site area (acres) |
| WQ_VOLUME | TEXT | 254 | Volume of rainfall depth in inches managed by the practice |
| RCN | TEXT | 254 | Runoff curve number (weighted) |
| ON_OFF_SITE | TEXT | 254 | On or offsite structure |
| APPR_DATE | TEXT | 254 | Permit approval date |
| BUILT_DATE | DOUBLE | | Construction completion date |
| INSP_DATE | DATE/TIME | | Record most recent inspection date |
| GEN_COMNT | TEXT | 120 | General comments |

**Table A-5 Urban Stormwater BMPs (Table B from Attachment A) - Attribute Structure**
**Feature Class Name: TABLE_B_URBAN_BMP_SWM_FACILITIES**

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| LAST_CHANGE | TEXT | 254 | Date last change made to this record |
| *COUNTY | TEXT | 2 | Abbreviations for MD county. |
| *LOCATION | TEXT | 120 | Location descriptions |
| *BASELINE_YEAR | TEXT | 100 | 2009 baseline or 2011 current capacity indicator, for MS4 counties only. |
| *MDE_STRU_ID | TEXT | 20 | Unique structure ID with the prefix of "SHA" |
| [1] GIS shapefile required<br>[2] Use attached Maryland Office of Planning land use codes<br>[3] Use attached urban BMP type code<br>[5] Use attached unique structure identification codes<br>*Fields provided by SHA in addition to Attachment A | | | |

***TABLE_C_IMPERVIOUS_SURFACES*:**
The data provided (see Table A-6) is a polygon feature class representing all existing impervious area with SHA right-of-way. The layer identifies the impervious area that is treated by SHA facilities. Within the dataset provided, the data for all Phase I & II permitted counties have been updated and represent current impervious and treatment conditions. The drainage area layer is provided as a reference feature class layer in the SHA_NPDES_2014geodatabase.gdb named "DRAINAGE_SWMFACILITY". The stormwater facility BMPs can be joined to this layer using the FACILITY_ID common field. The restoration fields are null at this point in time and will be prepared after the planned completion of the impervious data development updates.

In addition, there is a table provided in the geodatabase with the following name, TABLE_C1_IMPERVIOUS_WATERSHED_ACREAGES (table), which includes the summary of impervious acreage by watershed.

**Table A-6. Impervious Surfaces (Table C from Attachment A) – Attribute Structure**
**Feature Class Name: TABLE_C_IMPERVIOUS_SURFACES**

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| YEAR | DOUBLE | | Annual report year |
| WATERSHED_CODE | TEXT | 12 | Maryland 8 or 12-digit hydrologic unit code |
| IMP_ACREAGE | DOUBLE | | Total impervious acreage in watershed[1] |
| IMP_CONTROLLED | DOUBLE | | Impervious acreage controlled to the maximum extent practicable[1] |
| IMP_BASELINE | DOUBLE | | Impervious acreage not controlled to the maximum extent practicable [1, 2] |
| RESTORATION_P | DOUBLE | | Impervious acreage proposed for watershed restoration[1] |
| RESTORATION_UC | DOUBLE | | Impervious acreage under construction for watershed restoration[1] |
| RESTORATION_C | DOUBLE | | Impervious acreage completed (since program inception) [1] |
| *SHA_OWNED | TEXT | 5 | Impervious ownership by SHA (Yes or No) |
| *STATUS | TEXT | 15 | Determines if the impervious area is within a treatment drainage area (Inside or Outside) |

**Table A-6. Impervious Surfaces (Table C from Attachment A) – Attribute Structure**
**Feature Class Name: TABLE_C_IMPERVIOUS_SURFACES**

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| *COUNTY | TEXT | 50 | County name |
| *SOURCE_DESC | TEXT | 200 | Identifies the imagery used to compile the impervious area (source year of aerial imagery) |
| *CAPTURE_METHOD | TEXT | 50 | Describes the capture method |
| *ACREAGE | DOUBLE | | Acreage of impervious surface |
| [1] GIS shapefile required<br>[2] Fixed baseline based on MDE Guidance and approval<br>*Fields provided by SHA in addition to Attachment A | | | |

**TABLE_D_WATERQUALITY_IMPV_PROJECTS:** The data (see Table A-7) provided is a polygon feature class representing the watershed restoration projects presented in the Table 1-19 - Watershed Restoration Projects. This layer references specifically the retrofit projects for stormwater facilities. There are six projects for stream restoration and stabilization that are not mapped yet, as these layers are under construction and the information has been provided in the Microsoft Excel file for those projects. The drainage area layer is provided as a reference feature class layer in the SHA_NPDES_2014geodatabase.gdb named "DRAINAGE_SWMFACILITY". The stormwater facility BMPs can be joined to this layer using the FACILITY_ID common field.

**Table A-7. Water Quality Improvement Project Locations (Table D from Attachment A) – Attribute Structure**
**Feature Class Name: TABLE_D_WATERQUALITY_IMPV_PROJECTS**

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| YEAR | DOUBLE | | Annual report year |
| STRU_ID | TEXT | 6 | Unique structure ID[5] |
| STRU_NAME | TEXT | 254 | Structure name |
| MD_NORTH | DOUBLE | | Maryland grid coordinate (NAD 83 meters) Northing |
| MD_EAST | DOUBLE | | Maryland grid coordinate (NAD 83 meters) Easting |
| WATERSHED_CODE | TEXT | 12 | Maryland 8 or 12-digit hydrologic unit code |
| STRU_TYPE | TEXT | 254 | Identify structure or BMP type[3] |
| LAND_USE | TEXT | 3 | Predominant land use[2] |
| DRAIN_AREA | DOUBLE | | Structure drainage area (acres)[1] |
| IMP_ACRES | DOUBLE | | Structure impervious drainage area (acres) [1] |
| WQ_VOLUME | TEXT | 254 | Volume of rainfall depth in inches managed by the practice |
| LINEAR_FT | DOUBLE | | Use this field for stream restoration or shoreline protection |
| POUNDS_TN | DOUBLE | | Use this field for street sweeping or inlet cleaning |
| POUNDS_TP | DOUBLE | | Use this field for street sweeping or inlet cleaning |

**Table A-7. Water Quality Improvement Project Locations (Table D from Attachment A) – Attribute Structure**
**Feature Class Name: TABLE_D_WATERQUALITY_IMPV_PROJECTS**

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| POUNDS_TSS | DOUBLE | | Use this field for street sweeping or inlet cleaning |
| APPR_DATE | TEXT | 254 | Permit approval date |
| BUILT_DATE | DOUBLE | | Construction completion date |
| INSP_DATE | DATE/TIME | | Record most recent inspection date |
| GEN_COMNT | TEXT | 120 | General comments<br>*Note: Provided in a field width of 255 characters to minimize data loss.* |
| LAST_CHANGE | TEXT | 254 | Date last change made to this record |
| *COUNTY | TEXT | 2 | Abbreviations for MD county. |
| *LOCATION | TEXT | 120 | Location descriptions |
| *BASELINE_YEAR | TEXT | 100 | 2009 baseline or 2011 current capacity indicator |
| *RESTORED_ACRES | DOUBLE | | Identifies the restored acreage for the project |
| *RETRO_COMPDATE | DOUBLE | | Identifies the year the retrofit was completed. |
| *STATUS | TEXT | 19 | Determines the status of the restoration project |
| *RESTORATION_TYPE | TEXT | 55 | Identifies the type of restoration project |
| *MDE_STRU_ID | TEXT | 20 | Unique structure ID with the prefix of “SHA” |

[1] GIS shapefile required
[2] Use attached Maryland Office of Planning land use codes
[3] Use attached urban BMP type code
[5] Use attached unique structure identification codes
*Fields provided by SHA in addition to Attachment A

***TABLE_E_MONITORINGSITES_LOCATIONS*:** The data (see Table A-8) provided is a point feature class representing the monitoring site locations associated with projects from 2013 through 2014.

**Table A-8. Monitoring Site Locations (Table E from Attachment A) – Attribute Structure**
**Feature Class Name: TABLE_E_MONITORINGSITES_LOCATIONS**

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| YEAR | NUMBER | | Annual report year |
| STATION | TEXT | 50 | Unique station and stream name |
| OUTFALL OR INSTREAM | TEXT | 10 | Outfall or instream station |
| WATERSHED_CODE | TEXT | 50 | Maryland 8 or 12-digit hydrologic unit code |
| MD_NORTH | DOUBLE | | Maryland grid coordinate (NAD 83 meters) Northing |

**_Table A-8. Monitoring Site Locations (Table E from Attachment A) – Attribute Structure_**
**_Feature Class Name: TABLE_E_MONITORINGSITES_LOCATIONS_**

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| MD_EAST | DOUBLE | | Maryland grid coordinate (NAD 83 meters) Easting |
| DRAIN_AREA | DOUBLE | | Drainage area in acres[1] |
| *STUDY_YEARS | TEXT | 50 | Range of years for the study |
| [1] GIS shapefile required<br>*Fields provided by SHA in addition to Attachment A | | | |

***TABLE_E1_MONITORINGSITES_LANDUSE*:** The data (see Table A-9) provided is a table of records representing the associated land use records for each specific monitoring site location during the period of 2013 through 2014. The STATION field can be used to associate the BMP records to the distinct monitoring site location.

**_Table A-9. Monitoring Site Locations – Multiple Land Use Values in Drainage Areas (Table E.1 from Attachment A) - Attribute Structure_**
**_Table Name: TABLE_E1_MONITORINGSITES_LANDUSE_**

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| YEAR | NUMBER | | Annual report year |
| STATION | TEXT | 50 | Unique station ID (associated with unique station ID in section E) |
| LAND_USE_RANK | DOUBLE | | Ranking of land use from predominant to least |
| LAND_USE | DOUBLE | | Identify land use[2] |
| DRAIN_AREA | DOUBLE | | Drainage area in acres[1] |
| [1] GIS shapefile required<br>[2] Use attached Maryland Office of Planning land use codes | | | |

***TABLE_E2_MONITORINGSITES_SWMBMP*:** The data (See Table A-10) provided is a table of records representing the associated stormwater BMPs for each specific monitoring site location during the period of 2013 through 2014. The STATION field can be used to associate the BMP records to the distinct monitoring site location.

**_Table A-10. Monitoring Site Locations – Multiple Stormwater BMPs in Drainage Areas (Table E.2 from Attachment A) - Attribute Structure_**
**_Table Name: TABLE_E2_MONITORINGSITES_SWMBMP_**

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| YEAR | NUMBER | | Annual report year |
| STATION | TEXT | 50 | Unique station ID |
| BMP_RANK | NUMBER | | Ranking of BMPs from predominant to last |
| STRU_TYPE | TEXT | 10 | Identify structure of BMP type[3] |

### *Table A-10. Monitoring Site Locations – Multiple Stormwater BMPs in Drainage Areas (Table E.2 from Attachment A) - Attribute Structure*
### *Table Name: TABLE_E2_MONITORINGSITES_SWMBMP*

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| BMP_DESCRIPTION | TEXT | 60 | Brief description of BMP |
| DRAIN_AREA | DOUBLE | | Drainage area in acres[1] |
| [1] GIS shapefile required<br>[3] Use attached urban BMP type code | | | |

***TABLE_E3_MONITORINGSITES_DRAINAGE***: The data (see Table A-11) provided is a feature class of records representing the associated drainage areas for the study area. There are currently no drainage area delineations generated for the monitoring sites.

### *Table A-11. Feature Class Name: TABLE_E3_MONITORINGSITES_DRAINAGE*

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| SHAPE_AREA | DOUBLE | | Determines the system generated area of the drainage extent in acres |

***TABLE_F_CHEMICAL_MONITORING_RESULTS***: There is no chemical monitoring data to report for the time frame of 2013 through 2014. The table (See Table A-12) would store records representing the chemical monitoring for events associated to the specific monitoring site locations. The STATION field can be used to associate the chemical monitoring records to the distinct monitoring site location.

### *Table A-12. Chemical Monitoring (Table F from Attachment A) - Attribute Structure*
### *Table Name: TABLE_F_CHEMICAL_MONITORING_RESULTS*

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| JURISDICTION | TEXT | 50 | Monitoring jurisdiction name |
| EVENT_DATE | DATE/TIME | | Date of storm event |
| EVENT_TIME | DATE/TIME | | Time monitoring begins |
| STATION | TEXT | 30 | Station name (associated w/ unique station ID in section E.) |
| OUTFALL_OR_INSTREAM | TEXT | 10 | Outfall or instream station |
| STORM_OR_BASEFLOW | TEXT | 10 | Storm or base flow sample |
| DEPTH | DOUBLE | | Depth of rain in inches |
| DURATION | DOUBLE | | Duration of event in hours and minutes |
| INTENSITY | DOUBLE | | Intensity = depth/duration |
| TOTAL_STORM_FLOW_VOLUME | DOUBLE | | Total storm flow volume in gallons |

***Table A-12. Chemical Monitoring (Table F from Attachment A) - Attribute Structure***
***Table Name: TABLE_F_CHEMICAL_MONITORING_RESULTS***

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| WATER_TEMP | DOUBLE | | Flow weighted average of water temperature (Fahrenheit) |
| pH | DOUBLE | | Flow weighted average of pH |
| BOD_dt | DOUBLE | | Biological Oxygen Demand detection limit used in analysis |
| BOD_EMC0 | DOUBLE | | EMC for Biological Oxygen Demand in mg/l using (0)* |
| BOD_EMC_dt | DOUBLE | | EMC for Biological Oxygen Demand in mg/l using (dt)** |
| TKN_dt | DOUBLE | | Total Kjeldahl Nitrogen detection limit used in analysis |
| TKN_EMC0 | DOUBLE | | EMC for Total Kjeldahl Nitrogen in mg/l using (0)* |
| TKN_EMC_dt | DOUBLE | | EMC for Total Kjeldahl Nitrogen in mg/l using (dt)** |
| NITRATE_NITRITE_dt | DOUBLE | | Record Nitrate + Nitrite detection limit used in analysis |
| NITRATE_NITRITE_EMC0 | DOUBLE | | Enter EMC for Nitrate + Nitrite in mg/l using (0)* |
| NITRATE_NITRITE_EMC_dt | DOUBLE | | Enter EMC for Nitrate + Nitrite in mg/l using (dt)** |
| TOTAL_PHOSPHORUS_dt | DOUBLE | | Record Total Phosphorus detection limit used in analysis |
| TOTAL_PHOSPHORUS_EMC0 | DOUBLE | | Enter EMC for Total Phosphorus in mg/l using (0)* |
| TOTAL_PHOSPHORUSEMC_dt | DOUBLE | | Enter EMC for Total Phosphorus in mg/l using (dt)** |
| TSS_dt | DOUBLE | | Total Suspended Solids detection limit used in analysis |
| TSS_EMC0 | DOUBLE | | EMC for Total Suspended Solids in mg/l using (0)* |
| TSS_EMC_dt | DOUBLE | | EMC for Total Suspended Solids in mg/l using (dt)** |
| COPPER_dt | DOUBLE | | Record Total Copper detection limit used in analysis |
| COPPER_EMC0 | DOUBLE | | Enter EMC for Total Copper in ug/l using (0)* |
| COPPER_EMC_dt | DOUBLE | | Enter EMC for Total Copper in ug/l using (dt)** |
| LEAD_dt | DOUBLE | | Record Total Lead detection limit used in analysis |
| LEAD_EMC0 | DOUBLE | | Enter EMC for Total Lead in ug/l using (0)* |
| LEAD_EMC_dt | DOUBLE | | Enter EMC for Total Lead in ug/l using (dt)** |
| ZINC_dt | DOUBLE | | Record Total Zinc detection limit used in analysis |
| ZINC_EMC0 | DOUBLE | | Enter EMC for Total Zinc in ug/l using (0)* |
| ZINC_EMC_dt | DOUBLE | | Enter EMC for Total Zinc in ug/l using (dt)** |
| HARDNESS_dt | DOUBLE | | Record detection limit used in analysis |
| HARDNESS_EMC0 | DOUBLE | | Enter EMC for Hardness in ug/l using (0)* |
| HARDNESS_EMC_dt | DOUBLE | | Enter EMC for Hardness in ug/l using (dt)** |
| TPH_dt | DOUBLE | | Record detection limit used in analysis |
| TPH_EMC0 | DOUBLE | | EMC for Total Petroleum Hydrocarbons in mg/l using (0)* |
| TPH_EMC_dt | DOUBLE | | EMC for Total Petroleum Hydrocarbon in mg/l using (dt)** |

***Table A-12. Chemical Monitoring (Table F from Attachment A) - Attribute Structure***
***Table Name: TABLE_F_CHEMICAL_MONITORING_RESULTS***

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| ENTEROCOCCI_dt | DOUBLE | | Record detection limit used in analysis |
| ENTEROCOCCI_EMC0 | DOUBLE | | EMC for enterococci in MPN/100 using (0)* |
| ENTEROCOCCI_EMC_dt | DOUBLE | | EMC for enterococci in MPN/100 using (dt)** |
| ECOLI_dt | DOUBLE | | Record E. Coli detection limit used in analysis |
| ECOLI_EMC0 | DOUBLE | | Enter EMC for E. Coli in MPN/100ml using (0)* |
| ECOLI_EMC_dt | DOUBLE | | Enter EMC for E. Coli in MPN/100ml using (dt)** |
| *LOCALCONCERN1_CHEM_TYPE | TEXT | 50 | Type of Chemical for Local Concern |
| LOCALCONCERN1_dt | DOUBLE | | Record detection limit used in analysis |
| LOCALCONCERN1_EMC0 | DOUBLE | | Enter EMC for in mg/l using (0)* |
| LOCALCONCERN1_EMC_dt | DOUBLE | | Enter EMC for in mg/l using (dt)** |
| *LOCALCONCERN2_CHEM_TYPE | TEXT | 50 | Type of Chemical for Local Concern |
| LOCALCONCERN2_dt | DOUBLE | | Record detection limit used in analysis |
| LOCALCONCERN2_EMC0 | DOUBLE | | Enter EMC for in mg/l using (0)* |
| LOCALCONCERN2_EMC_dt | DOUBLE | | Enter EMC for in mg/l using (dt)** |
| *LOCALCONCERN3_CHEM_TYPE | TEXT | 50 | Type of Chemical for Local Concern |
| LOCALCONCERN3_dt | DOUBLE | | Record detection limit used in analysis |
| LOCALCONCERN3_EMC0 | DOUBLE | | Enter EMC for in mg/l using (0)* |
| LOCALCONCERN3_EMC_dt | DOUBLE | | Enter EMC for in mg/l using (dt)** |
| *LOCALCONCERN4_CHEM_TYPE | TEXT | 50 | Type of Chemical for Local Concern |
| *LOCALCONCERN4_dt | DOUBLE | | Record detection limit used in analysis |
| *LOCALCONCERN4_EMC0 | DOUBLE | | Enter EMC for in mg/l using (0)* |
| *LOCALCONCERN4_EMC_dt | DOUBLE | | Enter EMC for in mg/l using (dt)** |
| *LOCALCONCERN5_CHEM_TYPE | TEXT | 50 | Type of Chemical for Local Concern |
| *LOCALCONCERN5_dt | DOUBLE | | Record detection limit used in analysis |
| *LOCALCONCERN5_EMC0 | DOUBLE | | Enter EMC for in mg/l using (0)* |
| LOCALCONCERN5_EMC_dt | DOUBLE | | Enter EMC for in mg/l using (dt)** |
| GEN_COMNT | TEXT | 255 | Monitoring comments/documentation |

*Fields provided by SHA in addition to Attachment A
**key:** **mg/l** = milligrams per liter **ug/l** = micrograms per liter **MPN** = most probable number per 100 milliliters

***Table A-13. Pollutant Load Reductions (Table G from Attachment A)***
***Table Name: N/A (no data available)***

This data is currently under construction and is not available at this time. The information will be provided with the next Annual Report submission.

***TABLE_H_BIOLOGICAL_HABITAT_MONITORING:***

The data (See Table A-14) provided is a table of records representing the associated biological and habitat monitoring projects performed during the period of 2013 through 2014.

***Table A-14. Biological and Habitat Monitoring (Table H from Attachment A)***
***Table Name: BIOLOGICAL_HABITAT_MONITORING***

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| YEAR | NUMBER | | Annual report year |
| STATION | TEXT | 50 | Unique station ID |
| WATERSHED_CODE | TEXT | 50 | Maryland 8 or 12-digit hydrologic unit code |
| MD_NORTH | DOUBLE | | Maryland grid coordinate (NAD 83 Meters) Northing |
| MD_EAST | DOUBLE | | Maryland grid coordinate (NAD 83 Meters) Easting |
| DRAIN_AREA | DOUBLE | | Drainage area in acres |
| BIBI | DOUBLE | | Benthic index of biological indicators |
| EMBEDDEDNESS | DOUBLE | | Rapid bioassessment protocol score for embeddedness |
| EPIFAUNAL | DOUBLE | | Rapid bioassessment protocol score for epifaunal |
| HABITAT | DOUBLE | | Rapid bioassessment protocol score for habitat |
| LAND_USE | NUMBER | | Predominant land use |
| STUDY_DATE | DATE/TIME | | Date the monitoring project occurred |

***TABLE_I_IDDE*:**

The IDDE results provided cover the period of September 2013 through September 2014 and represent screenings and samplings performed on major outfalls in Montgomery County. See Table A-15 for data descriptions. The drainage area layer is provided as a reference feature class layer in the SHA_NPDES_2014geodatabase.gdb named "DRAINAGE_STRUCTURE". The outfalls can be joined to this layer using the STRUCTURE_ID common field.

***Table A-15. Illicit Discharge Detection and Elimination (Table I from Attachment A) – Attribute Structure***
***Table Name: TABLE_I_IDDE***

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| YEAR | DOUBLE | | Annual report year |
| OUTFALL_ID | TEXT | 15 | Unique outfall ID used in Section A. database |
| SCREEN_DATE | DATE/TIME | | Field screening date |
| TEST_NUM | TEXT | 5 | Initial screening, follow-up test, 3rd, etc. |
| LAST_RAIN | DATE/TIME | | Date of last rain > 0.10" |
| SCRTIME | DATE/TIME | | Field screening time |
| OBSERV_FLOW | TEXT | 3 | Was flow observed? (yes/no) |

***Table A-15. Illicit Discharge Detection and Elimination (Table I from Attachment A) – Attribute Structure***
***Table Name: TABLE_I_IDDE***

| Column Name | Data Type | Length | Description |
|---|---|---|---|
| CFS_FLOW | DOUBLE | | Flow rate in cubic feet per second (CFS) |
| WATERTEMP | DOUBLE | | Water temperature (Fahrenheit) |
| AIRTEMP | DOUBLE | | Air temperature in (Fahrenheit) |
| CHEM_TEST | TEXT | 3 | Was chemical test performed? (yes/no) |
| pH | DOUBLE | | pH meter reading |
| PHENOL | DOUBLE | | Milligrams per Liter (mg/l) |
| CHLORINE | DOUBLE | | mg/l |
| DETERGENTS | DOUBLE | | mg/l |
| COPPER | DOUBLE | | mg/l |
| AMMONIA | DOUBLE | | Mg/l |
| ALGAEGROW | TEXT | 3 | Was algae growth observed? (yes/no) |
| ODOR | TEXT | 2 | Type of odor[4] |
| COLOR | TEXT | 2 | Discharge color[4] |
| CLARITY | TEXT | 2 | Discharge clarity [4] |
| FLOATABLES | TEXT | 2 | Floatables in discharge[4] |
| DEPOSITS | TEXT | 2 | Deposits in outfall area[4] |
| VEG_COND | TEXT | 2 | Vegetative condition in outfall area[4] |
| STRUCT_COND | TEXT | 2 | Structural condition of outfall[4] |
| EROSION | TEXT | 2 | Erosion in outfall area[4] |
| COMPLA_NUM | TEXT | 3 | Is screening complaint driven? (yes/no) |
| ILLICIT_Q | TEXT | 3 | Was illicit discharge found? (yes/no) |
| ILLICIT_ELIM | TEXT | 3 | Was illicit discharge eliminated? (yes/no) |
| *DRAINAGE_AREA | DOUBLE | | Structure Drainage Area[1] |
| *COUNTY | TEXT | 2 | Abbreviations for MD county. |

[1] GIS shapefile required
[4] Use Attached Pollution Prevention Activities Codes
* Fields provided by SHA in addition to Attachment A

Phase I&II National Pollutant Discharge Elimination System
Permit No. 99-DP-3313 MD0068276
Permit Term October 2005 to October 2010

# APPENDIX B

## RECOMMENDATIONS FOR EFFECTIVE AND SUSTAINABLE STORMWATER RUNOFF MANAGEMENT (MAY 2014)

# Recommendations for the State Highway Administration on Stormwater Control Measures and Research Efforts for Multimodal Transportation Infrastructure in Maryland that Promote More Effective and Sustainable Stormwater Runoff Management

**Project Duration:** May 2013 – May 2014

**Project Sponsor:**
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# Executive Summary

This document presents a comprehensive literature review on current stormwater control measures (SCMs) for use in urban and highway areas. SCMs reviewed are bioretention, grass swales, permeable pavements, sand filters, SWM (stormwater management) wetlands, infiltration basins, and porous friction courses (PFCs), as well as a non-structural practice: street sweeping. Each SCM was evaluated using the following criteria – (1) hydraulic performance, (2) water quality performance, and (3) economics, including construction, maintenance, and life cycle costs. Furthermore, synthesis of current design and feasibility for implementation prompted for the second project objective - a compilation of suggested areas for future research. The study approach is catered towards the needs of the Maryland State Highway Administration. Therefore, all project evaluations have specific emphasis on applicability to Maryland geography and climate as well as typical hydrology, pollutant constituents, and associated loadings from multi-modal transportation networks.

This review demonstrated two major themes in regard to hydraulic performance. First, regardless of type, a larger SCM will produce overall better hydraulic performance. Specifically, increasing the size of an SCM will result in more storage. In the best-case scenario, the SCM does not exhibit any discharge (smaller events), and greater storage space increases the probability of this scenario. The storage will not only provide temporary storage for the runoff, it is also likely that a higher retention time can lead to volume attenuation via infiltration and evapotranspiration.

The water quality performance of an SCM varies with the hydraulic loading, pollutant of interest and respective loading, and the SCM type. Table ES provides a summary of all SCMs reviewed and their respective water quality performance for a range of common pollutants. This review concludes that there is no “one size fits all model,” i.e., no one design of an SCM exists that can address all needs.

General performance trends are apparent that should be recognized. The selection and design of a particular SCM is governed by specific unit process operations, which act upon specific pollutant forms. Thus, for example, it is very important when evaluating water quality performance to distinguish between particulate and dissolved pollutants as these unit processes differ.

Typically, particulate-based pollutant removal can be predicted with a high degree of accuracy because sedimentation and filtration are very effective in many SCM designs. For this reason, all SCMs exhibit a high removal capability of TSS; for the most part, particulate phosphorus (PP) follows this same trend (Table ES).

Dissolved pollutants (e.g., forms of nitrogen, phosphorus, and heavy metals) are much more difficult to sequester and require design specialization to promote these processes. The unit processes that dictate the removal of dissolved constituents include nitrification/denitrification (i.e., removal of nitrogen) and chemical adsorption and ion exchange (i.e., removal of phosphorus, heavy metals, and hydrocarbons). Table ES reflects the difficulty of dissolved pollutant removal, as indicative of generally *low* removal for dissolved phosphorus and nitrate/nitrite.

Furthermore, one must denote the influent hydraulic conditions to better assess the water quality performance of an SCM. Hydraulic parameters such as volume attenuation, peak discharge, and retention time, in addition to being hydrologic metrics, have a direct effect on the pollutant removal processes.

**Table ES.** SCM Water Quality Summary Performance. Dash indicates inadequate data available.

| SCM | TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ / $NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Conventional* Bioretention | High | Medium | High | Medium | High | High | High | Low | Medium | Low |
| Grass swales | High | Low | High | Low | High | Medium | Medium | Low | Low | Low |
| Permeable Pavements | High | - | Medium | - | - | - | - | - | - | - |
| Surface Sand Filter | High | Low | High | Low | High | - | Medium | Medium | Medium | Low |
| SWM Wetland | High | - | High | - | - | - | - | Medium | Medium | Low |
| Infiltration Basin | High | - | High | - | - | - | - | - | - | - |
| PFCs | High | Medium | High | Low | - | Medium | Medium | Low | Low | Low |
| Street Sweeping | High | - | - | - | - | - | - | - | - | - |

***** Conventional Bioretention as specified in current SHA design requirements. As will be noted in this document, a number of enhancements are now available for bioretention which can increase pollutant removal performance.

Current research highlights the potential to incorporate design modifications to promote the unit processes that govern dissolved pollutant removal. For example, a conventional bioretention system as described in Davis et al. (2006) consists of a mulch/soil/plant-based SCM with the primary treatment medium consisting of a sandy soil, with a plastic perforated pipe subdrain. More current research suggests modifications to the conventional bioretention design, which include the installation of an upturned elbow drainage configuration and aluminum-based water treatment residual (Al-WTR) amended media. Respectively, these changes promote anaerobic conditions for denitrification for the removal of TN (particularly nitrate removal) and chemical sorption for the removal of dissolved P (phosphate ion). Media amendments are also translated to sand-media filters, where the addition of 5% iron by weight is responsible for significant phosphorus uptake improvements. To address dissolved pollutants (e.g., TN) in permeable pavements, the incorporation of extraneous sub-surface storage is a new design modification to promote denitrification under anaerobic conditions.

In regards to economics, little quantifiable data are available to make accurate conclusions. For this reason, extensive documentation regarding economic considerations is highly recommended for future research. Specifically, it is the location of the SCM that will affect the cost because of geography, land cost, native soil conditions, climate, and typical pollutant loadings. These factors must be documented and thus, accounted for, before a general formula to estimate cost (e.g., construction cost, annual maintenance cost, lifecycle cost) can be accurately synthesized for any SCM.

Future research highlights the importance of design modifications to each SCM to enhance pollutant removal, particularly dissolved pollutants. Overall, the goal of future SCM design is to allow for the successful removal of particulate-bound pollutants as well as dissolved pollutants. Furthermore, future studies should emphasize the applicability to Maryland climate and geography in regards to multi-modal transportation systems.

# Table of Contents

# Chapter 1: Introduction

## 1.1 Objective

The goal of this project is to provide a comprehensive literature review on current stormwater control measures (SCMs) applicable to Maryland highway systems. Based on this literature evaluation, a toolbox of recommended SCMs will be developed based on their ability to effectively manage highway runoff. A specific emphasis is placed on water quality improvement to address critical needs based on current Chesapeake Bay restoration regulations. However, impacts on water quantity will be addressed and discussed as appropriate and also in correlation to water quality performance when necessary. Furthermore, a roadmap for suggested research efforts for stormwater runoff management techniques that provide greater effectiveness and sustainability will be synthesized. This project focuses on its application to linear highways, specifically targeting pollutants (sediment, phosphorus, and nitrogen) addressed by the Maryland State Highway Administration (SHA) that are included Chesapeake Bay TMDL regulations. For this reason, only identified SCMs that can be applied to multi-modal linear transportation systems are included. Alternative stormwater management technologies such as green roofs will not be examined, as there is minimal feasible application in regards to highway systems. This study is intended to cover all literature of interest up to its publication date and will synthesize information as deemed appropriate in accordance to the project scope. Many of the research concepts reviewed are not currently part of the existing SHA SCM design. However, many of these concepts have been tested at the field scale and their discussion is appropriate for this extensive review. All findings, regardless of current SHA policy, should be considered for new design to improve water quality performance, as documented by the most up-to-date research findings.

## 1.2 Current State of Knowledge

Throughout the U.S. (and even worldwide), many municipalities, highway agencies, and other MS4 (Municipal Separate Storm Sewer Systems) permittees are facing challenges of increasing numbers and complexity of regulations and more stringent requirements for stormwater discharge. These challenges may be the result of Chesapeake Bay and/or local tributary TMDL requirements, specific numeric water quality limits, or general MS4 requirements. Consequently, many agencies and jurisdictions are investigating alternative SCMs and designs outside the scope of the Urban Stormwater Workgroup (USWG), the agency responsible for presenting a set of recommendations for the Chesapeake Bay Program's Water Quality Goal Implementation Team (WQGIT). Many of the same or similar challenges faced by SHA are also being faced, addressed, and documented by others. The science and engineering behind urban stormwater management and SCMs is changing rapidly with an emphasis on Low Impact Development (LID) and Environmental Site Design (ESD) technologies. More research is being conducted on runoff reduction and control, emphasizing the potential to reduce runoff volume and improve water quality through more cost effective designs. Therefore, a comprehensive literature review of SCMs would bring SHA up-to-date on the current state of knowledge.

Within the context of the review, it is important to recognize particular factors that may compromise data as they pertain to the objectives of SHA. These factors include but are not limited to climate, geography, and regulatory discrepancies based on the location of study. These factors will be identified and categorized appropriately.

## 1.3 Problem Definition

As part of its commitment to environmental protection, SHA continues to increase its knowledge base on the use of effective stormwater management technologies in multi-modal transportation projects. However, a lack of synthesized information regarding recognized SCMs and relative performance remains. Furthermore, gaps exist in published information pertaining to what technologies can specifically target pollutants to meet TMDL regulations and operate effectively under specific environmental conditions. Many SCM technologies are still immature and require more monitoring, research and development to more fully document the hydrologic and water quality benefits under various operational conditions. Design modifications and media enhancements are by-products of the continued research. Therefore, these modifications must be recognized and evaluated for potential implementation as well.

In order for SHA to effectively respond to challenges in managing stormwater runoff within the context of ever changing regulations based on Chesapeake Bay restoration, it must be continually informed on the latest information of SCM design and performance. A synthesis of quantitative performance and supporting information such as costs and maintenance, of specific SCMs, in association with other stormwater management issues will lead to better designs, more widespread, reliable implementation, and ultimately improved environmental quality.

## 1.4 Organizational Summary

This literature review is divided into five chapters. Chapter 1 presents introductory background information. Chapter 2 includes important SCM concepts, metrics and methods. This information is pertinent for understanding the literature review approach, specifically when evaluating the performance of specific SCMs and the subsequent analysis. The third chapter,

Chapter 3, includes the main section of the report – the SCM literature review. This chapter is further subdivided into individual SCMs – Bioretention, Swales/Bio-swales, Permeable Pavement, Sand Filters, Stormwater Wetlands, and other SCMs. Each SCM is reviewed extensively and organized as follows:

- Hydraulic property improvements
- Pollutant load reduction
- Potential for design modifications for improved performance (identified and if possible, evaluated from previous studies)
- Cost analysis
- Conclusions
- Future recommendations for design and improvement

All information is synthesized from a variety of sources, reflecting the most up-to-date research and applicability to highways, highway infrastructure, and multi-modal transportation networks in Maryland. Additionally, consideration is given to climatic conditions similar to Maryland.

Chapter 4 highlights SCM economics – construction costs, maintenance costs, maintenance time, and lifecycle of systems. It summarizes the information strictly pertaining to the topics presented in Chapter 3, but provides direct comparison between SCMs.

The final chapter, Chapter 5, provides a summary of all research pertaining to chapters 2, 3, and 4. It is split into three sections – (1) general hydraulic and water quality trends, (2) water quality summary specific to each SCM, and (3) future research and recommendations. Each SCM is subjected to the same water quality parameters and evaluated on a qualitative scale (low, medium, high) in regards to its demonstrated performance. Moreover, a consolidated table identifying the future research recommendations for each SCM is presented in this section (as referenced from Chapter 3 correlating to the specific SCM at hand). It offers suggestions for future research in areas with an emphasis on design, performance, and maintenance. All in all this culminating chapter summarizes all conclusions and provides the reader with a general comprehension of future research endeavors that are necessary to more effectively manage stormwater on linear transportation systems.

# Chapter 2: Background Information

This chapter discusses general metrics, pollutant speciation, unit processes, and economic documentation. The purpose of this chapter is to provide the reader with a general understanding of the types of hydraulic, water quality and cost analysis parameters that will be subsequently discussed throughout this report. Several examples of data and data presentation are given. Detailed analysis of these indicators will give the reader insight on how to interpret forthcoming figures, tables, and general discussion in Chapter 3 *Review of SCM Performance* and Chapter 4 *Maintenance and SCM Economics*, where the data are discussed in more detail.

## 2.1 Hydrology Metrics

### 2.1.1 Restorative Hydrologic Parameters

Davis (2008) proposed three metrics for describing the restoration of hydrologic conditions by bioretention facilities (Table 2-1). In turn, the three metrics, based on flow peak,timing, and runoff volume, characterize the hydrologic performance of a bioretention system by its ability to meet predetermined target values. The design is effective when the peak ratio ($R_{peak}$) and volume ratio ($\mathcal{F}_v$) are reduced, and the delay ratio ($R_{delay}$) is increased, all to designated target values. Thus, when provided, summaries of performance will be analyzed in accordance to these standards. While these metrics were proposed specifically for bioretention (Davis 2008), they are generically defined to measure hydraulic performance of any SCM.

Improvements to water quality and the corresponding processes that govern such change are a direct result of the hydraulic performance of the SCM. Moreover, the treatment processes that are responsible for water quality improvements in bioretention are not unique; rather, as to be discussed in later detail, these processes can be found across a wide-range of SCMs.

Unfortunately, these metrics are not universally accepted and employed in all SCM studies. When evaluating and quantifying hydrologic performance benefits across multiple sites, studies, and systems, it is helpful to have a set of predetermined standards to cross-reference. Moreover, an accurate representation of hydraulic metrics is an indication for water quality enhancement of the system. Therefore, it is recommended for future research that metrics are included as hydrologic performance is characterized by these three factors. Of the three discussed, volume reduction is the most important metric when evaluating hydraulic improvements. Volume reduction is important in itself, but also volume directly leads to reduction of pollutant mass loads. Mass loads are calculated as the product of runoff volume and pollutant concentration. Metrics based on peaks are increasingly being revised to more comprehensive overall evaluation of high flows and flows that exceed a target volume.

**Table 2-1**. Metrics proposed for use to describe the restoration of hydrologic condition by Davis (2008)

| Metrics | Calculation | Key | |
|---|---|---|---|
| *Effluent/influent volume ratio* $\mathcal{F}_{V24}$ | $\mathcal{F} = \frac{V_{out-24}}{V_{in}}$ | $V_{out-24} = outflow\ volume\ within\ 24\ hrs$ <br> $V_{in} = input\ volume\ into\ cell$ | Eq. 2-1 |
| *Peak rate ratio* $R_{peak}$ | $R_{peak} = \frac{q_{peak-out}}{q_{peak-in}}$ | $q_{peak-out} = effluent\ peak\ flow\ rate$ <br> $q_{peak-in} = influent\ peak\ flow\ rate$ | Eq. 2-2 |
| *Peak discharge time span ratio* $R_{delay}$ | $R_{delay} = \frac{t_{q-peak-out}}{t_{q-peak-in}}$ | $t_{q-peak-out}$ <br> $t_{q-peak-in}$ <br> *Time elapsed between the beginning of influent flow and the peak effluent and influent flows* | Eq. 2-3 |

### 2.1.2 Flow Duration Curves

Davis et al. (2012) proposed flow duration curves as a hydrologic performance metric tool. According to Davis et al. (2012), flow duration curves are used to summarize hydraulic response of a specific SCM by compiling flows measurements at small (e.g., 2-minute) intervals and synthesizing data into a single distribution curve.

In regards to design constraints, it is recommended to design a specific SCM based on its flow duration curve rather than its ability to reduce peak flow. This is because a flow duration curve provides an accurate representation of flow and volume reduction and encompasses the entire duration of flow. Furthermore, one can compare a flow duration curve of an SCM to a threshold erosive flow and determine the amount of time a threshold flow will be exceeded. In comparison, a sole focus on peak flow reduction does not address high flows and long durations that may result even if the peak is reduced. Flows may still exceed the threshold and is prolonged due to the peak flow reduction and subsequent shifting of high flows later in the event.

#### 2.1.2.1 Swale Flow Duration Curve

As an example, Figure 2-1 shows three swale flow duration curves (Davis et al. 2012).

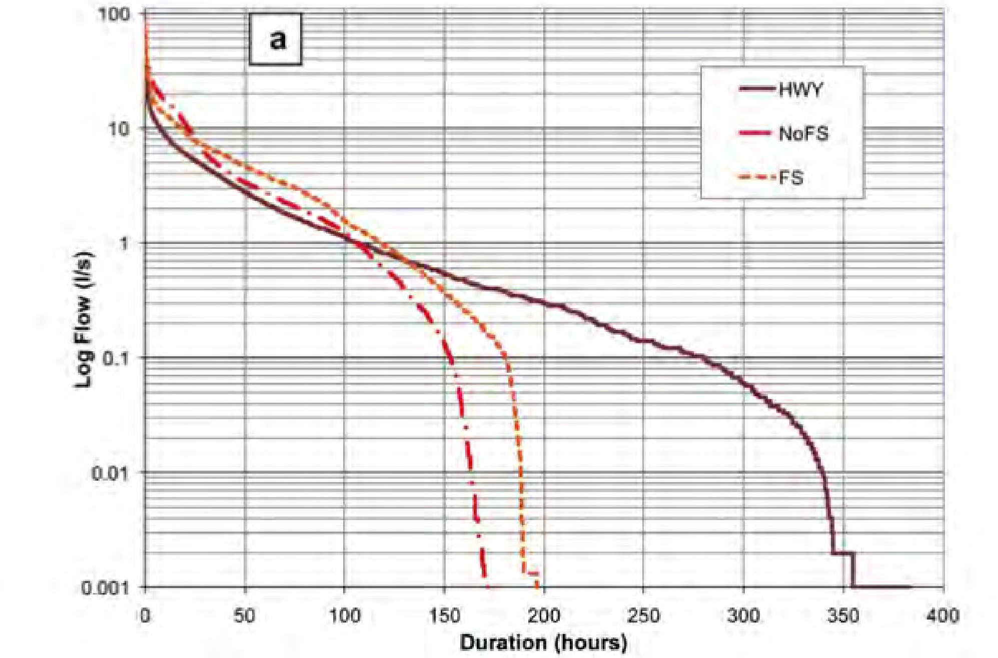


**Figure. 2-1**. Flow duration curve for swale and highway runoff showing the difference in runoff volume between 2 roadside swales (No-FS and FS) in comparison to highway runoff (HWY)
Source: Davis et al. (2012)

From Figure 2-1 it is clear that the incorporation of a swale as a roadside SCM is an effective means of reducing runoff for small and moderate-sized storms. In the case of large storms, the swales have no effect, and thus serve only as a means of conveyance for runoff. This is indicated by a sharp vertical drop for the No-FS and FS swale (no filter strip swale and filter strip swale, respectively as to be discussed in detail in Section 3.2 *Grass swales*). The similarity between the No-FS and FS flows indicates little difference in performance of the two swales. Not shown above, a horizontal line across the graph could represent a selected critical threshold flow. By following the intersection points of the horizontal line target with HWY, No-FS, and FS, one could interpolate the amount of time that the system will exceed the threshold and experience excessive erosion. By the shape of the flow duration curve, one can estimate the environmental response of a drainage area with the inclusion of a swale. Clearly, the environmental impact of the storm will be lessened, as the addition of a roadside swale will ensure a shorter period of erosion, if any. Of course, precise quantitative improvement would vary greatly with the location and design of the swale system and geographic factors (to be further discussed Section 3.2 *Grass swales*).

### 2.1.3 Probability Plots

As noted above, the SCM hydrologic parameter of most interest is the ability to reduce the total runoff volume. A probability plot is an excellent visualization of stormwater runoff hydrologic data, and more recently those of SCM performance (Davis 2008; Li et al. 2009). A probability plot is particularly useful for comparing one specific SCM across multiple designs. It will show common trends amongst designs and highlight differences in volume reduction, if any, as well.

A probability plot shows the relationship between the exceedance probability and a hydraulic parameter (e.g., discharge volume, peak flow, etc.). It is plotted on a logarithmic/probability scale, thus adjusting the data from a bell-shaped curve to a linear trend. A probability plot is created according to the following steps:

1. Record all hydraulic data (e.g., swale discharge volume from each event). Let $n$ be the number of recorded data points (e.g., number of storm events)
2. Rank measured values in descending order. Assign the variable $i$ to each storm, where the storm that produced the largest value is given a value of 1, and so on.
3. Use the modified Weibull Plotting Formula (Cunnane 1978) to determine each storm's exceedance probability ($p$)

$$p = \frac{i - 3/8}{n + 1/4}$$

4. Plot data on log-probability scale. The x-axis is *p* and y-axis is the hydraulic parameter data (e.g., discharge volume).

Davis et al. (2012) employed a probability plot to evaluate the volume attenuation of four swale designs (Figure 2-2). Figure 2-2 indicates that all four swale designs follow similar patterns of volume attenuation. Specifically, all swales completely capture the smallest 40% of storms, reduce total runoff volume for the next 40% of storms, and allow for no volume reduction for the 20% largest storms, as designated by the three treatment zones. The transition from volume attenuation (small and moderate sized storms) to flow conveyance (20% largest storms) is at approximately $1 \times 10^5$ L, where the slope of the plot dramatically changes (Figure 2-2). More details on the design characteristics of swales are discussed in Section 3.2 *Grass swales*.

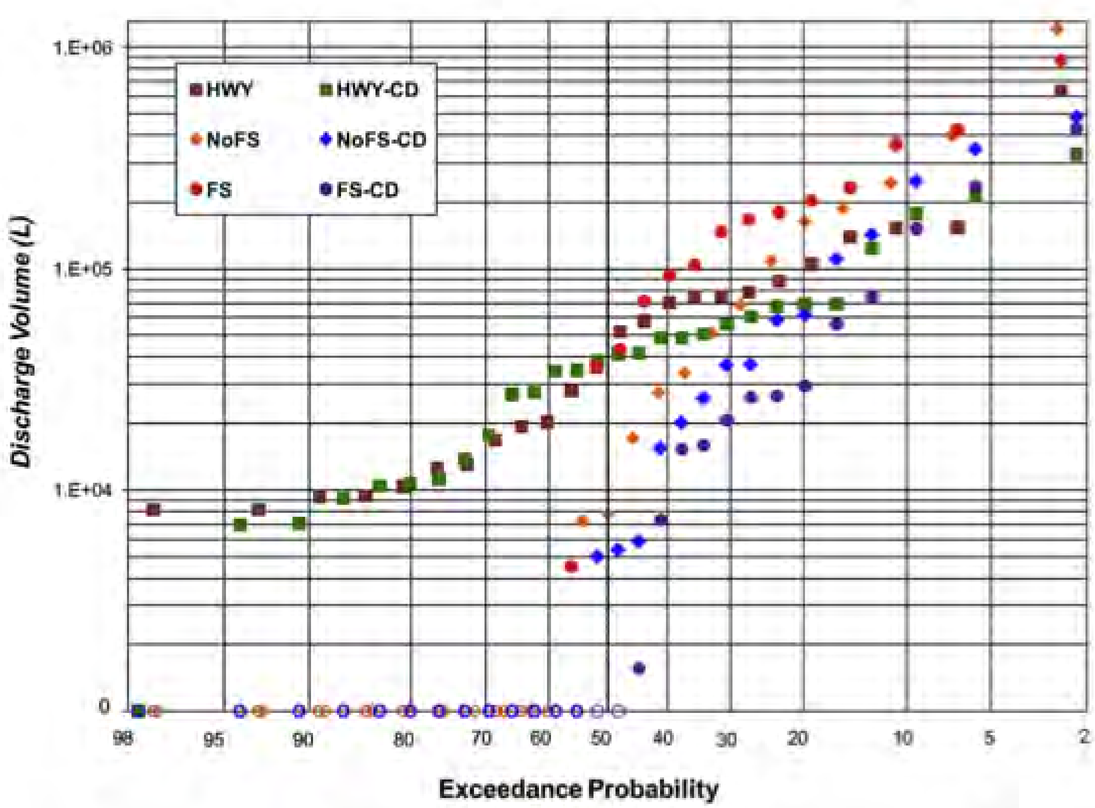


**Fig 2-2** – Normalized probability plot of volume attenuation of four swale designs in comparison to traditional highway (HWY) runoff
Source: (Davis et al. 2012)

## 2.2 SCM Performance Indicators

For the premise of this report, describing the water quality performance of SCMs as a pollutant percent removal will be avoided. This conforms with the International Stormwater Best Management Practice (BMP) Database whose website is utilized as the primary source for the following subsection (Wright Water Engineers and Geosyntec Consultants 2007). Table 2-2 summarizes key points from the BMP Database and clearly demonstrates why percent removal is misleading and thus not an accurate indicator of SCM performance.

**Table 2-2**. Rejection of percent removal as a performance indicator analysis as described in the *International Stormwater BMP Database*

| Reason Designation | Rationale |
|---|---|
| 1 | Percent reduction is a function of influent concentration. In most cases, a high influent concentration of a certain pollutant leads to a higher percent removal. The percent removal is not actually calculating how effective a system is performing, but rather reflecting how contaminated a certain volume of water is upstream of the SCM(s) |
| 2 | High percent removal may still contain concentrations of pollutants that exceed TMDL regulations. Without quantifiable concentrations, there is no way of knowing whether or not the SCM performs to meet these standards. |
| 3 | Calculations are inconsistent (e.g., event by event, mean of event percent removals, inflow median to outflow median, inflow load to outflow load, slope of regression of loads, slope of regression of concentrations). Since data are not (relatively) uniform, it is not possible to calculate a single percent removal from a particular data set. |
| 4 | Percent removal calculations are significantly affected by outliers (e.g., exceptionally high or low concentrations). In most cases, there is no statistical method to assess the uncertainty in the reported value. |
| 5 | It is possible a particular SCM case study does not have sufficient monitoring; the researcher rejects the null hypothesis and the reader cannot indicate if the SCM reduces anything. However, the percent removals are still published and are the only indicator of performance. |
| 6 | Small percent increases (or negative removal) have been published even when the influent and effluent concentrations are not statistically different from one another. |

When reviewing pollutant removal of a SCM, it is suggested to report the influent and effluent concentrations separately. Thus, percent removal is not recommended nor is it necessary when these two categories are properly documented. Effluent concentration has a much smaller uncertainty range whereas influent concentration will change under various hydraulic loadings and flow rates. With such high variations of influent concentration, percent removal will dramatically change. Fortunately, since the effluent concentration of a SCM can be measured with a high confidence level even under the various aforementioned conditions, it is the best representation of actual SCM performance. This is especially helpful when determining if a particular SCM meets water quality standards such as Chesapeake Bay TMDL regulations. Therefore, SCM performance shall be reported based on influent and effluent concentrations, and will be judged according to these parameters.

## 2.3 Water Quality Application to Linear Highway Networks

When addressing water quality, as with other project objectives, this review will concentrate its efforts on (1) applications to linear highway networks and (2) specific pollutants of identified interest. The major pollutants of interest are sediment (S), nitrogen (N), and phosphorus (P). When further discussion is required, the performance of an SCM may extend to other pollutants such as metals (i.e., zinc, copper, lead), and/or pathogens. These constituents have been identified due to their harmful environmental impact and/or regulatory status (e.g., current or proposed TMDL limits).

### 2.3.1 Nitrogen Concentration and Speciation

The forms of nitrogen in stormwater are ammonium ($NH_4$), nitrate ($NO_3$), nitrite ($NO_2$), dissolved organic N (DON), and particulate organic N (PON). Collectively these species form the total nitrogen (TN). The composition of these constituents in the water will change depending on land use and hydrologic conditions. It is important separate the TN removal into its respective constituents in any SCM system in order to thoroughly understand N behavior and fate. A recent study of a bioretention cell in College Park, MD recorded the EMC of TN and all forms of N. Table 2-3 summarizes the results of the study.

**Table 2-3**. EMCs of N Constituents from a Bioretention Cell in College Park, MD

| Constituent | Influent EMC (mg/L) | Effluent EMC (mg/L) |
|---|---|---|
| TN | 1.62 | 1.55 |
| $NH_3$ | 0.15 | <0.05 |
| $NO_3$ | 0.28 | 0.65 |
| $NO_2$ | 0.02 | <0.01 |
| DON | 0.25 | 0.63 |
| PON | 0.93 | 0.26 |

Source: Li and Davis (2014)

The input TN EMCs ranged from 0.75 to 3.3 mg/L (median = 1.5 mg/L), and output TN EMCs ranged from 0.71 to 2.4 mg/L (median = 1.4 mg/L) (Li and Davis 2014). The bioretention cell significantly reduced concentrations of PON, $NH_3$, and $NO_2$. However, the bioretention cell showed discharge of excess of $NO_3$ and DON.

Thus, the TN EMC values do not reflect what unit processes are performing well in the bioretention cell. Each form of nitrogen is affected differently, and only through individual examination, can one understand what unit processes are executed well and which are not.

While Li and Davis (2014) only focus on the speciation of N in a bioretention cell to better understand the unit processes responsible for each form of N removal, this should be employed in all studies. By separating TN into its individual constituents, one can understand what processes a particular SCM can execute well, and where improvements and modifications are necessary.

### 2.3.2 Phosphorus Concentration and Speciation

Phosphorus can exist in runoff in dissolved and particulate (solid) forms. In order to accurately depict the performance of an SCM to remove phosphorus these two phases of phosphorus should be analyzed separately. The processes responsible for the removal of dissolved and particulate phosphorus differ; particulate can be filtered and removed via sedimentation and filtration, while dissolved P typically requires enhanced media for high levels of adsorption. Therefore, the removal of total phosphorus (TP) is not an accurate representation of performance. Figure 2-3 shows the partitioning of P reflecting data collected at one highway segment in an urban setting of the Piedmont region of North Carolina percentage of each phase of P in regards to typical concentrations (Wu et al. 1998).

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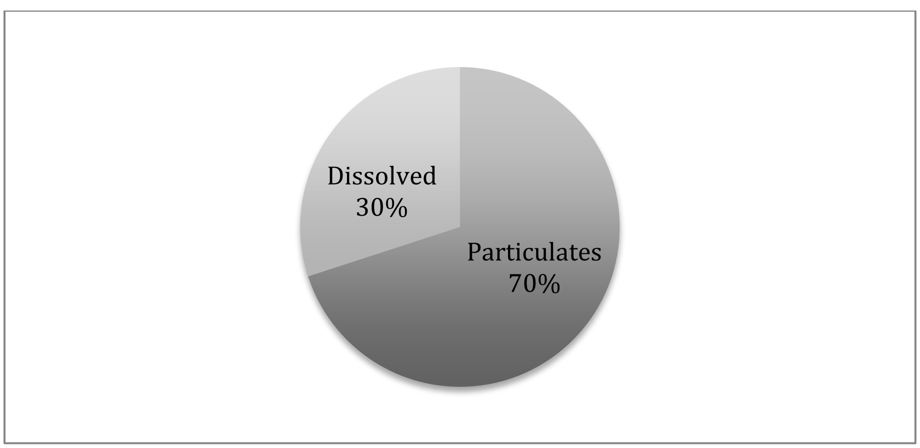


**Figure. 2-3**. Phases of P present in stormwater runoff.
Source: Wu et al. (1998)

## 2.4 Water Quality Metrics

A water quality probability plot shows the relationship between the exceedance probability and water quality performance (i.e., concentration of a particular pollutant). It is created similarly to that discussed for hydrology in Section 2.1.3 *Probability Plots*.

A probability plot emphasizes the treatment outcome and subsequent ecological impact of the discharge (Davis 2007). While Figure 2-4 displays the results for two bioretention cells, a probability plot can present water quality performance of any SCM. For this particular case, the selected pollutant was zinc; however, the inclusion of zinc within this section is only instructional, to provide demonstration of a probability plot and why it is an important tool for the evaluation of water quality improvements (if any); full discussion of zinc in bioretention will occur in Section 3.1. A probability plot should always be accompanied by a table displaying effluent EMCs (as opposed to percent reduction). Further analysis of a probability plot allows for comparison to target pollutant discharge concentrations to better comprehend performance in regards to specific goals of the designed SCM.

Li and Davis (2009) employed probability plots as visualization tools for the water quality performance of two bioretention cells, located in College Park (CP) and Silver Spring (SS). Figure 2-4 is a probability plot comparing the influent and subdrain discharge concentrations of zinc from both the CP and SS cells. The median output zinc levels (i.e., exceedance probability has a value of 50%) are 11 μg/L (CP) and 3 μg/L (SS). The target concentration is 120 μg/L, which is the Maryland fresh water acute and chronic limit for zinc, as indicated by the dashed line (Figure 2-4). The fresh water limits provide perspective for water quality for metals. Other water quality parameters are compared to other established limits.

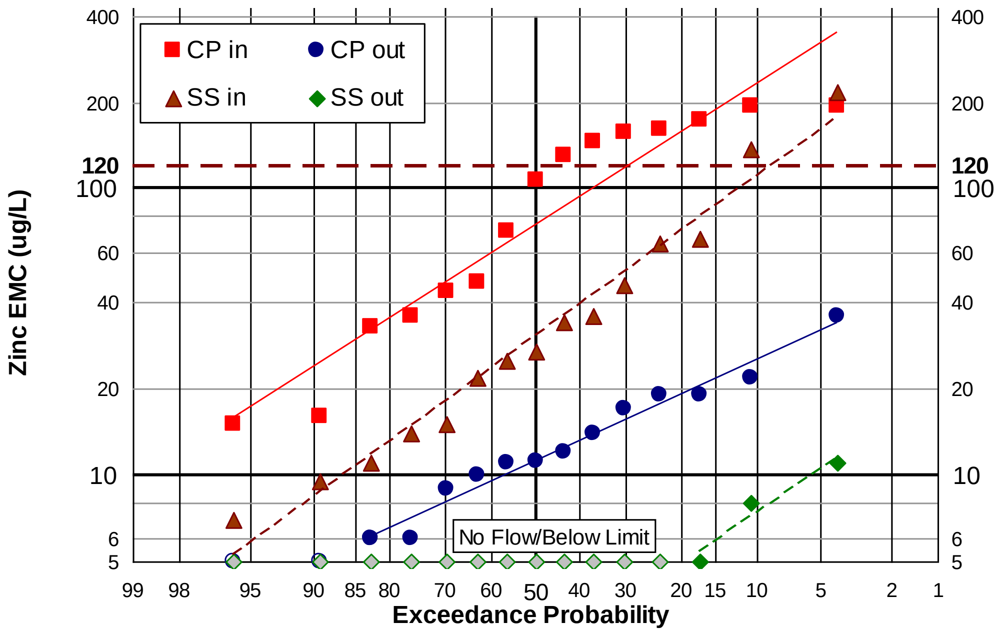


**Figure. 2-4.** Zinc concentration probability plot for Bioretention Cell CP and Cell SS data collection
Source: Li and Davis (2009)

## 2.5 Unit Processes for Water Quality Improvement

SCM selection is based on unit process performance, as one or more unit processes are responsible for the removal of a pollutant. The specific unit processes operative in the system will determine the capabilities and limitations of specific SCMs. Unit processes common for water quality improvement are summarized in Table 2-4. It is the ability and extent of a system to execute a unit process that will determine the removal of a pollutant, and thus overall water quality improvement. Therefore, the following subsection will discuss three major unit processes – (1) filtration and infiltration, (2) chemical adsorption, and (3) nitrification and denitrification.

**Table 2-4.** Common Unit Processes in SCMs for Runoff Management and Water Quality Improvement.

| Unit Process | Target Parameter or Pollutant(s) | Connection to SCM Technology |
|---|---|---|
| Infiltration | Runoff Volume Reduction | Bioretention, grassed swale, permeable pavement, infiltration basin |
| Evapotranspiration | Runoff Volume Reduction | Bioretention, grassed swales, SWM wetlands |
| Sedimentation | TSS | Grassed swales, sand filter, SWM wetland, infiltration basin |
| Filtration | TSS<br>Particulate phosphorus and metals | Bioretention, permeable pavement, PFCs, infiltration basin |
| Chemical Adsorption | Dissolved Phosphorus<br>Dissolved metals (e.g., Pb, Zn, Cu) | Bioretention, sand filter (with modified media) |
| Nitrification | Ammonium-Nitrogen | Bioretention, SWM wetlands |
| Denitrification | Nitrate-Nitrogen | Bioretention (with internal water storage), SWM wetlands |
| Biodegradation | Hydrocarbons | Bioretention |

### 2.5.1 Filtration and Infiltration

Filtration, coupled with infiltration, encompasses the two major unit processes that categorize Low Impact Development (LID) technologies. Categorically, filtration facilities contain a subdrain, which discharges into the storm drain system or receiving waters. Infiltration facilities do not have subdrain systems and collected stormwater is allowed to infiltrate into in-situ soils, reducing runoff volumes for only the more frequent small storms. Infiltration can provide for significant runoff volume reduction. SCMs with subdrains still provide for some volume reduction, depending on surrounding soil characteristics. From a water quality perspective, both SCM categories filter the runoff. This filtration removes particulate pollutants and pollutants affiliated with TSS, such as phosphorus and heavy metals. While many SCMs incorporate these processes in the design, permeable pavements and grass swales will be specifically discussed here to highlight these unit processes.

The design of permeable pavement promotes infiltration and includes filtration as its main mechanism for water quality improvement. During a storm event, a permeable pavement system allows water to infiltrate through its highly porous structure. Through infiltration, the permeable pavement will reduce the runoff peak flow and total runoff volume; the degree of reduction can be enhanced through sub-surface storage (as to be further discussed in Section 3.3 *Permeable Pavements*). As the water infiltrates and travels through the sub-surface layers, it will be subject to filtration as well. Permeable pavements have demonstrated high removal rates of particulate matter. However, these SCMs are also prone to clogging as the accumulation of particles trapped in the pores of the structure can result in very low infiltration rates. When this happens, the porous pavement acts more like a typical impervious pavement that does not allow for infiltration and filtration (Kuang and Fu 2013).

Swales also have the ability to reduce the mass loading of TSS for small-moderate sized storms through the processes of infiltration, filtration, and sedimentation within the grass layer. Davis et al. (2012) developed a boundary equation to delineate the threshold at which swales transition from fully storing and infiltrating runoff to generating measurable outflow. The hydraulic performance of the swale, in turn, directly affects the ability of the swales to improve water quality through the various unit processes. Generally, if the height of vegetation exceeds the flow depth of water, filtration is optimized and velocity is attenuated, promoting sedimentation and other processes. If the case is reversed, the filtration is reduced, the velocity is higher and the swale impact is greatly lessened.

### 2.5.2 Chemical Adsorption

The process of chemical adsorption refers to accumulation of dissolved substances on the surface of media components. Adsorption is the main mechanism by which dissolved phosphorus, hydrocarbons, and heavy metals are removed. Treatment efficiency is directly dependent on the media selection and often times, media enhancements to enable higher rates of chemical adsorption. Aluminum-based and iron-based media enhancements are of major interest because of their ability to attract the phosphate ion and thus promote high degrees of chemical sorption. Fine minerals and organic matter provide complexation sites for the binding of heavy metals. Metal adsorption increases with a high pH, and is most effective at a pH above of 6-7.

### 2.5.3 Leaching

Evidence to-date suggests that high levels of organic matter, especially compost, should be avoided in most SCMs as this organic matter can leach nutrients as it is weathered and mineralized. Thus, it is important to limit the amount of organic material in the media or applied as an additive to enhance plant growth. Unfortunately, no research to date addresses concerns of nutrient needs and initial plant establishment. Specifically, organic matter in the media can decompose and leach phosphorus (Clark and Pitt 2009). The addition of compost as an organic additive to bioretention media should be avoided because it will leach phosphorus (Hunt et al. 2012). In regards to effects of different types of compost in SCMs, no research has been completed to address this issue.

### 2.5.4 Hydrocarbon Biodegradation

Hydrocarbons such as polycyclic aromatic hydrocarbons (PAH) and other fuel-based hydrocarbons will biodegrade under some SCM conditions. Portioning of hydrocarbons is high in organic-rich media.

Typically, biodegradation of total petroleum hydrocarbons (TPH) occurs under aerobic conditions when pH (optimal range is 6-7), temperature, and nutrient levels do not limit microbial growth (Zhou and Crawford 1995; Mohn and Stewart 2000), as to further described in Section 3.1 *Bioretention*.. LeFevre et al. (2012) found that a short hydraulic residence time within the bioretention media and the level of organic matter may influence biodegradation.

### 2.5.5 Nitrification and Denitrification

Nitrogen is primarily removed from stormwater via the biological processes of nitrification-denitrification. Nitrifying bacteria convert ammonia to nitrate ($NO_3$) under aerobic conditions. However, to complete the removal process, nitrification must be coupled with denitrification. Under anaerobic conditions, nitrate is reduced to nitrogen gas ($N_2$), which is the end product and a benign form of nitrogen that can be released to the atmosphere. The process of nitrogen removal requires the creation of anaerobic conditions under which denitrification can occur with sufficient time to significantly remove the $NO_3$. Current novel bioretention designs include subsurface storage that becomes saturated to create anaerobic conditions. Often an upturned elbow subdrain configuration will promote such saturated conditions (Hunt et al. 2012).

## 2.6 Cost Metrics

Houle et al. (2013) developed quantified maintenance expenditures in the form of required personnel hours and economic costs expended for seven different SCMs, four of which directly correlate to the current research efforts (vegetated swale, bioretention, surface sand filter, and a porous asphalt pavement). The study, conducted by the University of New

Hampshire Stormwater Center (UNHSC) tested over 26 treatment strategies to-date (of publication), logging all inspection hours and maintenance activities over the course of six years (2004–2010). The systems were located at a field facility designed to distribute stormwater in parallel in order to normalize watershed characteristics, including pollutant loading, sizing, and rainfall. Specific results of each SCM will be presented subsequently in Chapters 3 and 4 as it pertains to the discussion at hand.

Maintenance tracking included initial observations using inspection checklists, written documentation in field books, photo-documentation of issues, and research staff assessments. Maintenance activities were evaluated by quantifying hours spent, assessing difficulty, and applying a standard cost structure. In a related study, Erickson et al. (2010) assigned each SCM activity a maintenance complexity. Each maintenance activity was thus converted to an associated cost depending on relative hourly expenses. This procedure can easily be adapted to local conditions, current economic climate, and regional cost variations; however scaled differences would likely produce similar unitless ratios (Houle et al. 2013).

- Minimal–$75/h–stormwater professional or consultant is seldom needed.
- Simple–$95/h–stormwater professional or consultant is occasionally needed.
- Moderate–$115/h–stormwater professional or consultant is needed approximately half the time.
- Complicated–$135/h–stormwater professional or consultant is always needed.

Maintenance activities can be further categorized by maintenance approach. Houle et al. (2013) adopts the following four approaches as first presented by Debo and Reese (2002):

- Reactive–complaint or emergency driven.
- Periodic and predictive–driven by inspections and standards embodied in an O&M plan; can be calendar-driven, known, or schedulable activities.
- Proactive–adaptive and applied increasingly more as familiarity with the system develops.

Both maintenance cost and approach categories can be correlated with SHA SCM remediation definitions. Below outlines the remediation definitions of SHA and the approximate associated cost, as presented in Houle et al. (2013), to formulate combined maintenance-economic parameters.

1. No Response Required
   The SWM facility is functioning as designed. Re-schedule for the next multi-year inspection assessment period. According to Houle et al. (2013), this would be categorized as minimal complexity and cost $75/h.

2. Minor Maintenance
   The SWM facility is functioning as designed, but routine and preventative action should be performed to sustain effective performance. Activities can typically be performed within an 8-hour workday by an average remediation crew. According to Houle et al. (2013), this would be categorized as simple complexity and cost $95/h.

3. Major Maintenance or Repair
   The SWM facility no longer functions as designed and significant repair is necessary to restore original functionality. The facility is repaired to remain within the existing facility footprint. Activities are more significant than minor remediation and likely require heavy equipment mobilization, construction materials and Maintenance of Traffic (MOT) plans. According to Houle et al. (2013), this would be categorized as moderate to complicated complexity and cost between $115-135/h.

4. Retrofit Design
   The SWM facility no longer functions as designed and cannot be restored to the original function as designed without a complete re-design and construction of a facility with a larger footprint, a different SWM facility type, or additional SWM facilities in the vicinity of the existing facility. According to Houle et al. (2013), this would be categorized as complicated complexity and cost $135/h.

5. Immediate Response
   The SWM facility has catastrophically failed and public safety hazards exist that require immediate corrective action. This particular remediation designation does not fit to one specific complexity according to Houle et al. (2013) economic predictions. However, this type of immediate and possible emergency response could be high cost and could exceed the upper limit of $135/h depending on the type of damage.

6. Abandonment
   The SWM facility is unsustainable and no longer provides sufficient benefit to warrant remedial design.

Generally speaking, an effective maintenance system takes time to develop and is specific to the SCM, overall design, system sizing, location, land use, and other watershed characteristics. Maintenance approaches are typically classified as adaptive. Likewise, Houle et al. (2013) found that maintenance activities are progressive, displaying an evolution from reactive to periodic and proactive.

## 2.7 Overall Design Consensus

The general consensus is that SCM selection is not a “one size fits all” model. There is not one set of criteria that can effectively select one SCM to meet specific goals regarding both hydraulic and water quality improvements, and addressing other concerns and constraints. Rather one must keep the context of the system at the forefront of all decision making. Thus, successful selection and subsequent design considerations must be chosen based on geographic factors, climatic conditions, and expected runoff volume. Essentially, it is these characteristics of the larger system at hand that will make each SCM design unique and subsequently, optimize performance for that designated area. It is only then that the watershed hydrology and water quality can significantly improve.

# Chapter 3: Review of SCM Performances

## 3.1 Bioretention

Bioretention is being increasingly adopted as a successful SCM to reduce adverse environmental affects and to address low impact development goals (Li and Davis 2009). It draws on the natural processes of infiltration, filtration, evapotranspiration, biological activity and groundwater recharge, unless otherwise specified (e.g., the facility is located in karst or hot spot areas), to improve both hydrologic and water quality conditions.

### 3.1.1 Background

3.1.1.1 General Terminology

First, it is important to define specific terminology to address any misconceptions and clarify all subsequent discussion of bioretention. Therefore, the terminology associated with bioretention is defined in Table 3-1. Figure 3-1 corresponds to Table 3-1, providing a cross-sectional view of the bioretention system with components labeled accordingly. Furthermore to follow SHA protocol, the terms rain garden and micro-bioretention will not be used as synonyms for a bioretention cell/system/facility. According to SHA, the difference between all three terms is the equations used to design the filter area and the maximum drainage area. A rain garden is defined as a smaller scale bioretention cell (with or without a subdrain) that is typically used for individual use and is not equipped to treat a high volume of urban stormwater; it has a maximum drainage area of 10,000 square feet and BSM depth of 12 inches. In contrast, a micro-bioretention area has a maximum drainage area of 20,000 square feet and BSM depth of 24-48 inches. While this terminology is not used by MDE, and thus SHA, a biofilter or bioinfiltration system is analogous to a bioretention system, except the design does not incorporate a subdrain. A bio-swale is a hybrid of a bioretention system and a grassed swale (as to be discussed in Section 3.2 *Grass Swales*). It has a linear configuration like a swale, but it includes vegetation and underlying media to promote infiltration and/or filtration (depending on the incorporation of a subdrain) to behave like a bioretention cell..

**Table 3-1**. Components and associated description of a bioretention cell with corresponding illustration in Figure 3-1

| Bioretention Component | Description |
|---|---|
| Bowl | The surface-ponding zone. Depth and volume must be designed. |
| Media | Known as bioretention soil mix (BSM). An engineered fill media with moderately high permeability. In general, design depth and media composition can vary, the design depth is defined as 4 feet and composition is pre-fined by SHA specification. Infiltration rate is pre-defined by MDE. |
| Root zone | Upper layer of the media available to the plant roots. Water stored in this region is available for both evapotranspiration and exfiltration. |
| Lower media zone | Lower media layer not readily available to roots. Water stored in this region is released through exfiltration. |
| Subdrain (optional) | Typically small-diameter (100–150 mm) plastic pipes. These drainage lines are located in the gravel layer below the fill media to collect water and convey it to the storm drain network or receiving stream. Subdrains are most often used when bioretention cells are located in slowly draining soils and are required when impermeable liners are used. While SHA does not implement this technique, the subdrain can be constructed with gate valves when soil conditions are marginally permeable. Subdrains should be below the root zone to prevent clogging. MDE requires that any facility with a subdrain must include an enhanced filter, which is stone storage area beneath the subdrain. |
| Internal water storage (IWS) (optional) | A subsurface portion of the media that provides additional storage volume in the bioretention cell. In permeable soils, water stored in this layer is principally released through exfiltration. The IWS layer is created by elevating the exit of the subdrain. |

Source: Hunt et al. (2012)

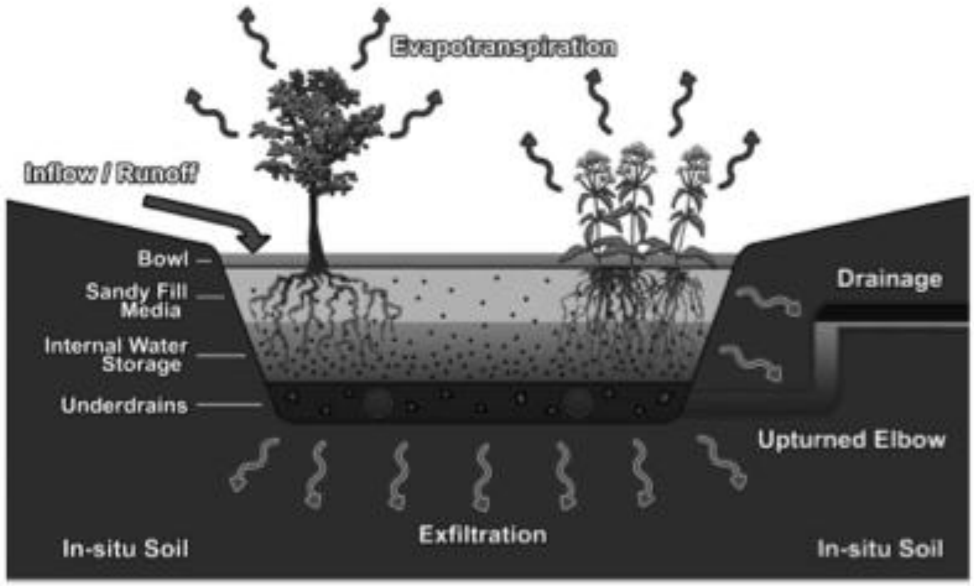


**Figure. 3-1.** Cross section of bioretention cell (image by Shawn Kennedy, NC State Univ.)
Source: Hunt et al. (2012).

In comparison to Figure 3-1, Figure 3-2 shows a typical design of a bioretention cell based on SHA requirements. This reflects a conventional bioretention cell as described in Davis (2006). As to be described in further detail later, some important differences (and similarities) between Figure 3-2 and current bioretention design components are listed below.

- Both current design and SHA include mulch at the top, vegetation, and sandy soil.
- It is possible to include an underdrain with an upturned elbow configuration to promote a saturated anoxic zone. This is a very inexpensive modification that can be high impact.
- It is possible to add media amendments to promote further phosphate adsorption.
- A sandy soil upper layer is highly recommended.
- Vegetation is very selective and high root density is encouraged for nutrient uptake and promotion of infiltration.

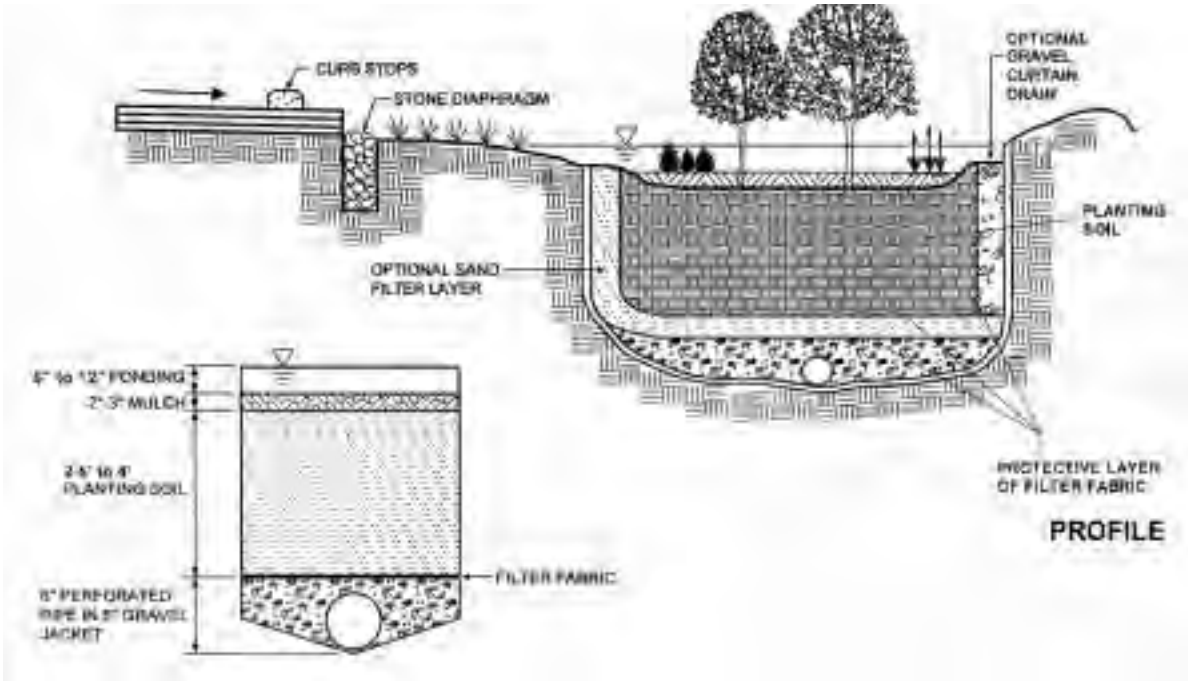


**Figure 3-2. Profile view of a bioretention system designed according to SHA protocols (Maryland Stormwater Design Manual 2009).**

### 3.1.1.2 Water Flow

Before one can understand how a bioretention cell works, one must understand the flow path of water through the system. Thus, the fundamental water balance analysis of the bioretention system is based on the two control volumes and media (e.g., native, engineered, amended) presented in Figure 3-3 (Davis et al. 2012). Runoff enters the bioretention cell and is directed into the bowl surface storage. Bowl storage will only occur if the runoff rate ($Q_{in}$) is greater than the rate of infiltration. Additional storage is available in the pore volume of the media. Through infiltration, the runoff enters the root zone and eventually the deeper layer. The antecedent moisture within the media controls the rate of infiltration and the pore space available; this is in turn a property of the media and characteristics of the previous rainfall (intensity, size, duration). After a long, intense period of rain, the media can reach a point of saturation, characterized as a state when all pore spaces are filled. The water can only exit the media through a subdrain, from evapotranspiration, or from percolation into the surrounding soils. All runoff that does exit via the subdrain (once infiltrated) will be held in storage or transmitted to native surrounding soil. Strictly looking at the design components of a bioretention cell, each will have a unique performance based on the surface bowl, media pore volume, moisture content (available storage) of the media, media/native soil interface, and drainage configuration (Davis et al. 2012).

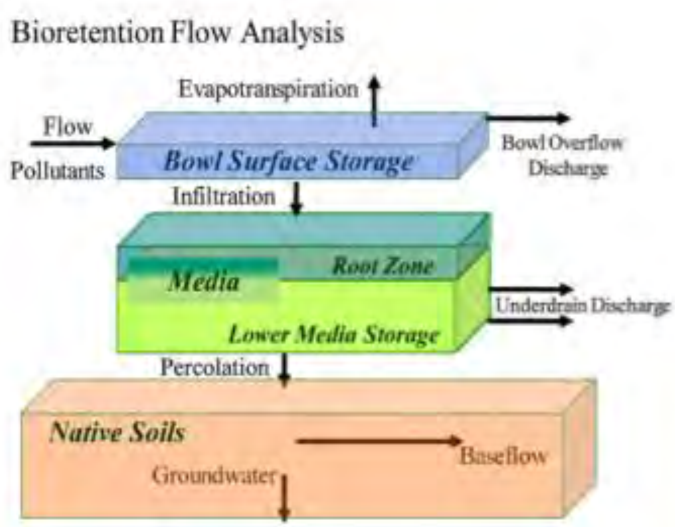


**Figure. 3-3.** Water balance in a bioretention system
Source: Davis et al. (2012)

### 3.1.2 General Design Components

The general design of a bioretention system is shown in Figure 3-1. This design configuration will be used as a traditional bioretention model. However, subsequent discussion explores the possibility of design modifications to further enhance pollutant removal to meet specific hydrologic and water quality goals.

3.1.2.1 Bioretention Abstraction Volume (BAV)

The bioretention abstraction volume (BAV) is the available storage space (or volumetric runoff capture) of the bioretention cell. It is calculated as the sum of the storage in the surface bowl and that within available media porosity in the root depth (Davis 2012).

$$Ave\ BAV = Bowl\ Vol. + RZMS \times (SAT - WP) + LMS \times (SAT - WP) \qquad \text{Eq. 3-1}$$

$$RZMS = root\ zone\ media\ storage\ volume$$

$$SAT = saturation\ point$$

$$WP = wilting\ point$$

$$LMS = lower\ media\ storage\ capacity$$

"To achieve a required BAV, the designer selects the bioretention surface area, the fill-media depth, and the plant-root depth. Other choices include the options to use a subdrain or create an IWS zone" (Hunt et al. 2012).

The goal of a BAV is to "convert" surface runoff to infiltration and evapotranspiration, the two main pathways that will improve hydraulic and water quality performance. Therefore, the larger the BAV relative to the contributing watershed, the more infiltration, ET, and lower effluent flow rate the bioretention cell will exhibit (Hunt et al. 2012). Jones and Hunt (2009) found that bioretention cells that had the proportionally largest surface areas (and media volumes) had the fewest occurrences of outflow. This was most likely a result of having more opportunities for intra and inter-event exfiltration and ET. Brown and Hunt (2011) demonstrated that the inclusion and increased size of an IWS layer limits the amount and occurrence of subdrain discharge.

Assuming a subdrain is present, the bioretention system does not discharge runoff until the media above is completely saturated; at this point, the subdrain discharge will occur quickly. The bowl storage, or a noticeable ponding effect, will only occur if runoff enters the system faster than the discharge rate of the subdrain and the percolation rate combined. Again, these consequences of saturation of the bioretention cell will occur less with increased available storage within the cell as demonstrated through several previous studies (Jones and Hunt 2009; Brown and Hunt 2011; Hunt et al. 2012).

### 3.1.3 Hydrologic Performance

As described in Section 2.2.1 *Restorative Hydrologic Parameters*, Davis (2008) proposed three metrics for describing the restoration of hydrologic conditions by bioretention facilities. With a specific emphasis on volume reduction ($\mathcal{F}_v$), the main focus of hydrologic improvement is the BAV. By increasing the available storage of a bioretention cell, one is simultaneously increasing the retention time of runoff in the system. Multiple ways exist to increase the BAV, however, the remainder of this discussion will focus on the design and performance of the BAV through (1) media properties and contact with runoff, (2) implementation of an internal water storage zone (IWS), and (3) vegetative root properties.

#### 3.1.3.1 Media Properties and Contact Time

Li et al. (2009) conducted a multiple-site field study and concluded that larger cells and those with deeper media depths will help reduce outflow volumes. A comparison of two Maryland bioretention sites, as cited in Li et al. (2009), reveal that both the College Park site (CP) and Silver Spring site (SS) delayed and reduced the runoff peak flows and diminished the runoff volume. However, the varied hydrologic performance can be explained through the respective media depths of the two; SS is 0.9 m deep and CP is 0.5-0.8 m. Furthermore, SS was also designed with a greater ponding depth (0.30 m) in comparison to CP (0.15 m). A greater ponding depth can contribute to the ability of the SS site to handle higher hydraulic loadings and overcome infiltration resistance from thicker media. The differences in ponding depth accounted for variations in storage depth – 0.06 cm and 0.31 cm over the drainage area, for the CP and SS sites, respectively. Finally, to evaluate the hydrologic benefits of the two bioretention cells, the metrics as noted in Davis (2008) were measured and summarized in Table 3-2.

**Table 3-2.** Differences in hydrologic performance for two bioretention cells using metrics proposed in Davis (2008)

| Site | $R_{peak}$ | $R_{delay}$ | $\mathcal{F}_{V24}$ |
|---|---|---|---|
| Target Values | $< 0.33$ | $\geq 6$ | $< 0.33$ |
| CP | 0.14 | 22 | 0.60 |
| SS | 0.02 | 200 | < 0.10 |

Adopted from: Li et al. (2009)

While both systems meet the target requirements, the SS site is more successful at exceeding the hydrologic criteria. It has a lower $R_{peak}$ and $\mathcal{F}_{V24}$ and a higher $R_{delay}$ in comparison to the CP site. These significant improvements can be traced back to the increased media-runoff contact time as a result of a larger BAV created by a larger bioretention size relative to the drainage area.

3.1.3.2 Internal Water Storage Zone (IWS)

It is possible to increase the hydrologic performance through the implementation of an internal water storage (IWS) zone (Table 3-1, Figure 3-1). Initially, an IWS layer was proposed to improve nitrogen removal (Kim et al. 2003). A raised subdrain outlet intentionally creates a submerged anaerobic zone, thus promoting denitrification. It was originally hypothesized that deeper IWS depths would correspond to larger storage and greater infiltration. For small storms, the IWS can drain the influent runoff entirely and promote groundwater recharge. The following subsection reflects the most current literature summarizing the hydrologic performance of bioretention cells that incorporate an IWS layer.

Li et al. (2009) compared two bioretention sites in Greensboro, N.C., designated as G1 and G2; the only difference in design was the incorporation of an IWS in G1 and the absence of one in G2. This accounted for a difference in storage capacity of the two cells, 0.46 cm and 0.35 cm over the drainage area, respectively. In 40 of the rainfall events at G1 there was no measurable outflow. The intensity and duration of storms varied greatly, and thus the ability of cell G1 to completely capture runoff responded accordingly. The varied response of the two bioretention cells for two consecutive rainfall events (separated by approximately 36 hours) highlights the better performing cell (G1). G1 was able to completely store and fill its available storage volume, whereas in the traditional G2 cell, as soon as water reached the bottom of the media, runoff existed through the subdrains. The lag time directly corresponds to the time the water needed to percolate through the media, and thus is reflective of the media properties (refer to Section 3.1.3.2.1. for further discussion). Nonetheless, the G1 cell was not completely drained before the next storm (1.5 days later); therefore, the total available storage was less than the designed volume (1.2 m deep). Li et al. (2009) further concluded that the addition of an IWS was only optimal for small storms, and for larger rainfalls it did not have a significant difference on performance. Thus, the inclusion of an IWS will increase hydraulic capacity of a bioretention cell. However, actual performance will vary based on surrounding soil characteristics.

#### 3.1.3.2.1 IWS and Media Properties

Brown and Hunt (2011) performed a field study to measure the hydrologic performance of bioretention cells with IWS zones in a region with sandy underlying soils (Rocky Mount, N.C). The two cells differed in vegetation and underlying soil texture. The first cell has shrubs and perennials (vegetation) and sand, known as the sand cell; the second has centipede turf and sandy clay loam (SCL). Monitoring of the bioretention cells occurred in two phases for 24 months. The first monitoring period spanned 16 months at an IWS depth of 0.6 m; the second monitoring period spanned 12 months at a reduced IWS depth of 0.3 m.

The results of this study agree with that of Li et al. (2009). Improved hydrologic performance is not simply dependent on the incorporation of an IWS layer. It is also dependent on underlying soil and surface infiltration rate. Therefore, it is important to compare performance considering all parameters rather than only the depth of the IWS.

The exfiltration rate of the two cells varied from 60-90 mm/h to 2.1-3.3 mm/h (2.9-3.5 in/hr.) for the sand cell and SCL cell, respectively. When the IWS was completely full, the sand cell had the ability drain within 3 hours; the SCL cell took approximately 7 and 5 days to fully drain during the first and second monitoring periods, respectively. Since there was a longer drainage time for the SCL cell, the probability of the cell producing outflow increased; this is especially true with greater sized rainfalls and shorter antecedent dry periods. SCL, in comparison to the sand, has a lower hydraulic conductivity, and thus a slower exfiltration rate. In turn, the SCL cell resulted in more ponding, and more events with overflow. Therefore, the runoff treated by the bioretention cell with sandier underlying soil (sand cell) and deeper IWS zone depth produced the most effective hydrology management results.

The fate of runoff in this optimal configuration can be identified as follows: 94% exfiltration, 4% evapotranspiration, 0% drainage, 2% overflow. It has the fastest infiltration rate and generated the least amount of overflow (Brown and Hunt 2011). Therefore, the texture of the surrounding soil is important, and not just the implementation and corresponding depth of the IWS.

#### 3.1.3.3 Vegetation

One can increase the average BAV through the careful selection of vegetation and corresponding root properties. Root depth is a function of plant type, available water, and soil type (Gregory 2006). According to Gregory (2006), more than 70% of the root mass is generally within the first 30-cm depth for plants. According to Eq. 3-1, the average BAV is dependent on the root zone media storage volume (RSAZ). Therefore, in order to maximize the BAV, it is necessary to select plants with deeper roots.

Coustumer et al. (2012) conducted a laboratory study in which the results indicated an added benefit of thick roots. This study concluded that thin-rooted plants had no significant impact on hydraulic conductivity. However, plants with thick roots increased hydraulic conductivity through the creation of macropores, thus increasing processes such an infiltration, percolation and exfiltration.

The creation of more pores allows for a greater storage volume of water, thus further promoting evapotranspiration (ET). The percentage of total inflow exiting a bioretention cell via ET is low – 10% and 4% in two studies (Li et al. 2009, Brown and Hunt 2011). However it is suggested that future researchers select vegetation with longer-reaching root masses in order to increase storage of water and promote higher rates of ET.

### 3.1.4 Water Quality Performance

Several aspects of water quality performances rely on the same processes as hydraulic improvements, i.e., infiltration, exfiltration, percolation, evapotranspiration (ET), and ground water recharge. Therefore, subsequent discussion will repeat aforementioned design characteristics that affect water quality performance via these processes.

Unfortunately, such overlapping can result in important trade-off between hydraulic conductivity and pollutant removal. Previous research further enforces this theory, as Bäckström (2002) proposed that pollutant removal is predicated on the hydraulic retention time $T_{hr}$; if hydraulic conductivity increases, then $T_{hr}$ decreases. This results in some discrepancy regarding the optimal design of a bioretention to meet target pollutant removal goals (as well as hydraulic improvements).

Currently in most SCM applications, many pollutants are targeted for removal, but rarely does every pollutant require treatment at a given location (Hunt et al. 2012). This subsection is organized by the targeted pollutant: (1) total suspended solids (TSS), (2) nitrogen (N), (3) phosphorus (P), (4) heavy metals and hydrocarbons, (5) pathogens, and (6) temperature.

#### 3.1.4.1 TSS

Generally speaking, bioretention cells are very successful at removing TSS and do not require special amendments to the design. The ability of a bioretention cell to remove TSS is largely dependent on sedimentation and filtration. This in turn, is a characteristic of the surface, underlying, and in-situ media. Larger, higher-density particles are effectively trapped by sedimentation. The media can also provide high removal rates of particulate matter through filtration. Smaller particles are captured by the media filtration through sedimentation, interception, and diffusion- transport mechanisms (Hunt et al. 2012). A majority of the total influent TSS concentration is treated and captured at the surface of the bioretention cell (Davis 2007; Li and Davis 2008; Hatt et al. 2009).

Bioretention performance described in DeBusk and Wynn (2011) shows that only 3 out of 28 recorded storms produced any outflow with measurable TSS. All 3 storms had a high inflow volume and peak flow. Despite such high influent hydraulic parameters, the filtration and sedimentation capabilities of the cell were not comprised. This study proved that a bioretention cell has the ability to effectively remove TSS under a variety of hydraulic conditions. These three storms reduced TSS EMCs from 44 to 33 mg/L, 224 to 9 mg/L, and 393 to 872 mg/L. The last data point reflects the highest outflow concentration and the only storm that produced outflow in the form of surface overflow. This negative reduction can further be explained by a recent application of new mulch on the surface and high inflow velocities (DeBusk and Wynn 2011).

The media selection will not have a significant impact on the performance of a bioretention and the ability to remove TSS. Furthermore, since a majority of TSS is captured at the surface, the system maybe prone to clogging. The findings of Coustumer et al. (2012) suggest that vegetation improves performance due to its ability to reduce the probability of clogging, which confirms the findings of Li et al. (2009). It is possible that the preferential flow paths created by the roots extend all the way to the surface and involve the stems, which, through expansion and movement, create apertures through which water can enter at the surface, thus alleviating potential clogging. Unfortunately, exact mechanisms by which vegetation affects hydraulic conductivity are unknown. It is important area of interest that should be incorporated in future studies.

3.1.4.2 Nitrogen

A recent study of a bioretention cell in College Park, MD recorded the EMC of TN and all forms of N (Li and Davis 2014). The input TN EMCs ranged from 0.75 to 3.3 mg/L (median = 1.5 mg/L), and output TN EMCs ranged from 0.71 to 2.4 mg/L (median = 1.4 mg/L). The bioretention cell significantly reduced concentrations of PON, $NH_3$, and $NO_2$. However, the bioretention cell showed discharge of excess $NO_3$ and DON.

PON is removed via filtration, as does TSS, so very successful performance of both is expected. The high $NH_3$ is removed via adsorption/ion exchange; this performance is consistent with previous field and laboratory studies. $NO_2$ is removed via oxidation, which occurs under aerobic conditions. The high $NO_3$ values suggest that $NO_2$, $NH_3$, and PON that were captured in the cell were later nitrified to $NO_3$ under the aerobic conditions. The leaching of DON is most likely due to a drained bioretention cell with sandy (encouraging an aerobic environment) and high organic matter. The extent of DON losses increases with increasing precipitation, higher total N inputs, and increasing sand content (Li and Davis 2014).

Li and Davis (2014) results indicate that dissolved nitrogen (i.e., DON and $NO_3$) are of primary concern. Typically organic nitrogen, ammonium ($NH_4$) and nitrate ($NO_3$) are contained in the runoff. Through aerobic conditions, bacteria are able to nitrify captured ammonium to nitrate. However, in order to reduce the nitrogen loading, nitrification must be coupled with denitrification. Davis et al. (2001) recognized the need for denitrification as early bioretention studies resulted in negative N removal. This was due to the accumulated organic nitrogen and nitrate in the water entering the facility; the oxic conditions promoted ammonification and nitrification. The effluent water frequently had a higher concentration of nitrogen in comparison to the influent. Denitrification is an anoxic process, where $NO_3^-$ is the electron acceptor and an organic material (within the engineered media) is the electron donor. The final product of denitrification is $N_2$, which is harmlessly released into the atmosphere, thus lowering the effluent nitrogen concentration.

3.1.4.2.1 Internal Water Storage Zone (IWS)

Figure 3-3 displays the coupling of nitrification-denitrification and offers a design alternative to the Davis et al. (2001) design proposal – an upturned elbow creating an internal water storage zone (IWS) as shown in Figure 3-4. The bottom layer of the media will be saturated and thus anaerobic; such conditions should promote denitrification and effectively reduce concentrations of $NO_3$.

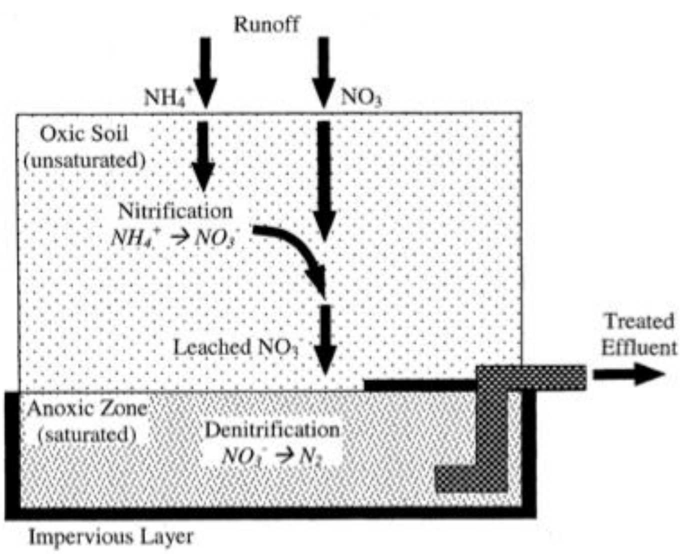


**Figure. 3-4**. Bioretention cell to promote denitrification by creating an IWS with an upturned elbow drainage configuration
Source: Kim et al. (2003)

Hunt et al. (2006) was one of many (i.e., Kim et al. 2003; Dietz and Claussen 2006) to compare an original bioretention site (subdrain governed by gravity with that of an IWS layer (upturned elbow of the subdrain). The upturned elbow forced the bottom 0.45 to 0.6 m (1.5 to 2 ft.) of the bioretention cell to remain saturated. However, the outflow concentrations of both sites indicated an increase of TKN, NOx, and TKN. The failings of this field study highlighted that the inclusion of an IWS layer is not just dependent on an upturned elbow. It is clear from Hunt et al. (2006) that the development of a saturated bottom layer, and thus N removal is dependent on other external factors such as (1) depth of bioretention cell, (2) soil constituents, and (3) presence of vegetation.

3.1.4.2.1.1 Depth

The nitrification-denitrification process is temperature-dependent and denitrification rates are particularly low in colder conditions. Overall, denitrification is controlled by the retention time of the media-water interface in the anoxic zone. As such, a deeper media layer and lower infiltration rate are needed. A minimum of 0.75 m (2.5 ft.) of media is required for nitrogen treatment with an IWS, but at least 0.9 m (3 ft.) is recommended (Hunt et al. 2012).

3.1.4.2.1.2 Media Properties

Media properties must focus on the prevention of leaching of nitrogen from the bioretention system. The two main forms of leached nitrogen noted in the study by Li and Davis (2014) were nitrate and dissolved organic nitrogen (DON). Research is required to identify an effective media to prevent the leaching of DON. The magnitude of DON export is the same as nitrate, accounting for 42% of the TN export from the bioretention system. Unfortunately, little is known about the chemical composition of DON, highlighting another difficulty in selecting an effective media.

For enhanced nitrogen removal, the designation of a denitrification zone is necessary. In order for denitrification to occur, there must be an available carbon source (an organic material). However, the media should not contain more than 5% of total weight or 10% of total volume organic matter; otherwise, leaching of organic material into the runoff will occur (Hunt et al. 2006; Clark and Pitt 2009). It is not necessarily to continually add a carbon source to the media because the levels of carbon naturally produced appear sufficient. These sources include plant roots, leaf litter, and breakdown of mulch (Hunt et al. 2012). Furthermore, while denitrification requires a carbon source, O'Neill and Davis (2012a,b) suggest refraining from compost as a media component or additive. This is because most compost will leach excessive phosphorus.

#### 3.1.4.2.1.3 Vegetation

Palmer et al. (2013) conducted a mesocosm lab study of four bioretention cells. The study emphasized the importance of denitrification when comparing bioretention sites with and without saturated zones. They found that compost and shredded cedar bark (C-sources) on the surface and a mineral aggregate drainage layer was sufficient for denitrification. Furthermore, this laboratory study stressed a focus on inclusion of a saturated zone rather than vegetation selection. The two treatment scenarios (both with a saturated zone, one with vegetation and one without) showed similar nitrogen removal. This study suggests that denitrification played an earlier and more significant role in nitrate removal, ultimately leaving the role of vegetation to be minimally pronounced. It is possible that this study does not capture the effects of vegetation because of the immaturity of the system.

Contradictory to the findings of Palmer et al. (2013), Lucas and Greenway (2008) suggest the presence of vegetation enhances TN and $NO_x$ removal, and large root mass vegetation is generally recommended. Furthermore, this study reported that at stormwater concentrations, TN discharged at an average concentration as low as 0.34 mg/L. Results of the mesocosms indicate that the relative nitrogen removal (TN and $NO_x$) is both a function of the presence of vegetation and media with a low hydraulic conductivity, i.e., the smaller pore spaces of the media increase

$T_{hr}$ and thus effect the success of nitrogen removal.

Brattieres et al. (2008) recommended specific plant species for bioretention use in Victoria, Australia. More recently, Lucas and Greenway (2011) suggested that any plant uptake is not prominent until after the development of the rhizosphere. This study observed more than 90% removal of nitrate after two years of plant establishment.

More recently, Li and Davis (2014) argued that the uptake of N via plant assimilation is only temporary. Typically higher concentrations of N are removed by the plants during the growing season; however, this N uptake has the potential to be re-released into the media during senescence or dormancy in the fall. This problem can be avoided with increased maintenance, i.e., the vegetation must be removed entirely from the facility to complete the N removal process.

3.1.4.2.1.4 IWS Design Amendment

While the IWS layer does improve TN and $NO_x$ removal, room still exists for improvement in design. Yang et al. (2013) proposes an alternative to a bioretention cell with an IWS layer created with upturned elbow-shaped subdrain (Figure 3-5). As noted previously, complete denitrification does not occur if the $T_{hr}$ is not sufficient. However, there is also a trade-off with decreasing the hydraulic conductivity of the media - a higher probability of overflow, assuming sufficient rain duration and intensity. Yang et al. (2013) suggest amending the design to support a biphasic bioretention site. Such a system requires (1) a sequence of anaerobic to aerobic conditions and (2) increased retention time.

The physical design of the biphasic bioretention facility contains a few primary differences from standard designs. First, runoff is first directed through the water saturated (anaerobic) zone and then the water unsaturated (aerobic) zone. The saturated zone is not made with an upturned elbow subdrain, but by placing an impervious liner to capture the first flush of runoff. In this layer, sediments are filtered and adsorption and/or biological treatment of pollutants occurs. At the bottom of this layer, U-shaped reverse drainage pipes only have perforated portions at the bottom. Overflow runoff is directed to the unsaturated zone through the drainage pipes. To promote a saturated zone beneath, an underdrainage configuration is employed to further increase the retention time. Finally, water exits through a final discharge pipe and discharged into a recharge zone. The recharge zone filled with pea gravel is designed to facilitate groundwater recharge (Yang et al. 2013).

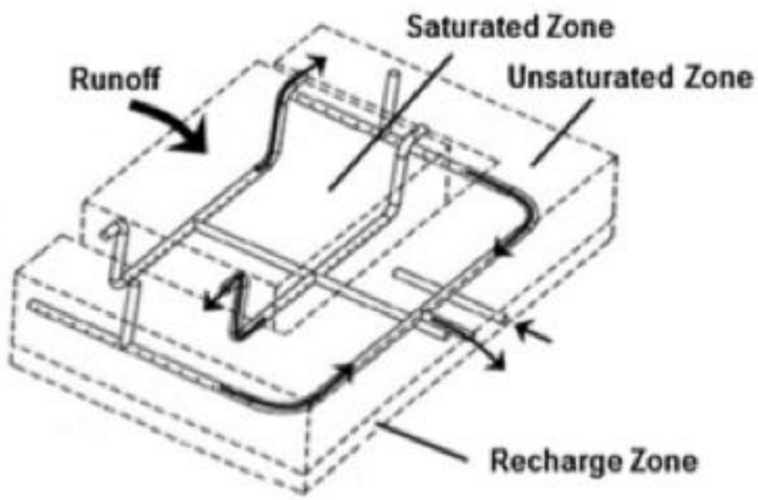


**Figure. 3-5.** Plan and cross-section view of biphasic bioretention cell used to promote coupled nitrification with denitrification
Source: Yang et al. (2013)

Currently, it is not recommended to adopt this new design as several concerns exist with this design. First and foremost, it is important to recognize the reversal of zones. Previous bioretention facilities had an unsaturated, leading to a saturated zone. The unsaturated, aerobic zones promoted ammonification and/or nitrification. While it is possible for ammonification to occur under anaerobic conditions, the rate is significantly decreased. Nitrogen enters a bioretention facility typically in the organic form and as $NO_3^-$. N must be oxidized to $NO_3^-$ before denitrification can occur.

The study attempts to counteract this supposed design challenge by refocusing attention on the increased retention time and hopefully further denitrification. Unfortunately, the only reliable data consist of the hydraulic performance under natural runoff conditions. In general, the hydraulic performance of the biphasic bioretention site was affected by initial water conditions in the saturated zone. A greater reduction in both peak flow and volume was observed when the saturated zone was less water saturated because of longer rainfall intervals and/or high ambient temperatures with high evapotranspiration rate. Under these conditions, water storage capacity in the saturated zone was increased (max. 1.58 $m^3$), and used to retain runoff during next event. While this performance coincides with general trends exhibited with bioretention cells with an IWS layer, no reliable data exist to complement the hydraulic improvements. Therefore, it is recommended that future studies record the hydraulic factors (peak flow and volume) as well as the water quality performance (influent and effluent concentration of pollutant of interest) to effectively evaluate the potential for future use (Hunt et al. 2012).

###### 3.1.4.2.2 Phosphorus

When addressing phosphorus (P) it is important to make the distinction between particulate and dissolved phosphorus. Particulate phosphorus follows the same removal mechanisms as TSS and the majority of the particulate matter is trapped at and/or near the bioretention media surface. The challenge of total phosphorus (TP) removal lies in the dissolved P concentration. Therefore, the remainder of discussion will elaborate on the mechanism of chemical sorption, the main method of dissolved phosphorus (DP) sequestration, and offer suggestions for improvement.

3.1.4.2.2.1 Media

The most important design factor when addressing DP is media selection to promote chemical sorption (Hunt et al. 2006; Hatt et al. 2009). The following subsections are divided into three areas of interest – (1) metrics to help predict P removal, (2) brief analysis of the organic material, including compost, in soil for P removal, and (3) media amendments suggestions (e.g., water treatment residual) to enhance chemical sorption.

3.1.4.2.2.1.1 Metrics

Two metrics can be incorporated to predict the removal of phosphorus based on soil/media properties. First, the P-index refers to the amount of innate phosphorus in the media, which must be limited for effective P removal. Next, the oxalate ratio (OR) predicts the P adsorptive capacity of bioretention media; it is recommended to be between 20-40 for high P-sorption capacity (O'Neill and Davis 2012a).

When the selected media innately has a high concentration of P, it can be detrimental to the system performance. The phosphorus index (P-index) of the fill media is an effective metric, calculated using the Mehlich-3 soil test methodology, to determine the level of phosphorus currently in the media (Hardy et al. 2003). Hunt et al. (2006) discovered that different P-index values for different field site media led to different P performance results in several NC studies. More specifically, the media P-index ranged from 86 to 100 in one site, which is considered high and 20 to 26, which is considered low-to-medium in another. When the P-index is lower, Hunt et al. (2006) surmised that the media promotes the adsorption of phosphorus, thus lowering the effluent TP concentration. A lower P-index allows for a greater amount of P to sorb onto the media without exhausting the adsorption capabilities (Clark and Pitt 2009). However, a lower P-index is not the only factor to enhance P-removal, as media enhancements can be recommended (to be discussed 3.1.4.2.2.4.3) to further extend the chemical sorption kinetics and capabilities.

O'Neill and Davis (2012a) recommend the addition of aluminum-based water treatment residual (WTR) to BSM. The two large-scale column studies confirmed the findings of previous studies (Kleinman et al. 2000; Elliot et al. 2002; Maguire and Sims 2002) that the oxalate ratio (OR) is a reliable and informative metric in predicting the P adsorption capacity of a medium for P sorption (Eq. 3-2).

$$OR = \frac{(Al_{ox}+Fe_{ox})}{P_{ox}} \qquad \text{Eq. 3-2}$$

with oxalate-extractable P ($P_{ox}$), Al ($Al_{ox}$), and Fe ($Fe_{ox}$) measured in mmol $kg^{-1}$. O'Neill and Davis (2012a) determined that an OR of at least 20 to 40 is necessary for enhanced-P bioretention media.

#### 3.1.4.2.2.1.2 Organic Material

It is important to limit the amount of organic material (OM) in the media or applied as an additive to enhance plant growth for effective P treatment. OM will decompose and leach phosphorus from the media (Clark and Pitt 2009); different forms of OM will leach at various degrees. Therefore, Clark and Pitt (2009) recommend against the use of OM to aid plant growth. As such, media low in P content has reliably produced good P sequestration (Hsieh and Davis 2005; Hsieh et al. 2007; Hunt et al. 2008; Hatt et al. 2009a; Passeport et al. 2009; Lucas and Greenway 2011).

Specifically, the addition of compost should always be avoided. Compost will leach P and thus, it is recommended to refrain from the addition of compost as an organic material (Hunt et al. 2012).

3.1.4.2.2.1.3 Enhanced Media

Amendments can be added to increase the media's adsorptive capacity for phosphorus. The ability of a bioretention facility to remove P is based on the media capacity to sequester P. Extensive literature in the agriculture sciences indicates that the capacity for P adsorption onto a soil depends on the content of amorphous aluminum and iron in the soil. O'Neill and Davis (2012a) explored the addition of drinking water treatment residuals (WTRs), a by-product of drinking water colloid removal, to bioretention media. O'Neill and Davis (2012b) designed two large-scale column studies to evaluate WTR addition. The control column (standard BSM) discharged a greater concentration of P than the influent concentration at the beginning; later on, the column showed some P removal. However, this removal was insignificant in comparison to the results of the amended media; in most cases the majority of P in the influent was removed. This is directly attributed to the added amorphous aluminum (hydr)oxide in WTR (O'Neill and Davis 2012a). Furthermore, the amended column demonstrated stable behavior when subjected to the standard flow and concentration conditions, while the P capacity of the control media was exhausted after two runs. The effluent dissolved P EMC was always < 10 $\mu g\ L^{-1}$. The control column exported P for all standard runs and control TP EMCs ranged from 156 to 322 $\mu g\ L^{-1}$. Control column effluent TP EMCs were 7 to 30 times greater than the amended media TP EMCs under standard conditions. The findings of these large-scale column studies recommend the addition of WTR to a point where the oxalate ratio is between 20 and 40 for enhanced P sequestration removal.

Lucas and Greenway (2011) studied bioretention mesocosms with BSM amendments - red mud, a by-product of bauxite processing; water treatment residuals (WTRs), a by-product of water treatment; and Krasnozem soil, a highly aggregated clay soil. This study concluded that the high sorption capacity of WTR presented the opportunity for this media amendment to effectively remove P in both stormwater and wastewater systems. Lucas and Greenway suggested WTR-30, which is 80% turf sand and 20% WTR, by mass; the WTR was obtained from the Redlands Shire water treatment plant on North Stradbroke Island near Brisbane, Australia. The mesocosms were subject to intermittent flows over 80 weeks that simulated 32 years of bioretention loading. In total, the Al-WTR retained up to 99% of applied $PO_4$-P. In comparison to the other proposed soil enhancements (Krasnozem and red mud), the WTR did not significantly decline in retention capabilities. The WTR-30 mixture did not exhibit saturation and/or leaching of phosphorus, unlike the other media additives; rather this treatment process retained the most P.

Recent results from a field research bioretention facility at the University of Maryland, College Park, conducted by Liu and Davis (2014) indicate that WTR application into the BSM provided many benefits. The additive does not negatively influence the infiltration mechanism of the bioretention system. Furthermore, pollutants that are removed via sedimentation and filtration, such as TSS and particulate phosphorus (PP) demonstrated a significant reduction in concentration.

Another application is the possibility of iron-enhanced bioretention; this application particularly applies to systems with a subdrain. Erickson et al. (2012) recommends that the iron-filings be added to the media directly above the subdrain. That way, any leaching of phosphates will be captured before the stormwater is discharged from the system. However, one concern with iron is that is must be kept under aerobic conditions. If an area with iron-amended media succumb to anaerobic conditions, it is likely that ferric iron will reduce. This process would dissolve the iron oxide coatings and release all the accumulated phosphorus up until that point.

In regards to DP, Liu and Davis (2014) speciated this category into soluble reaction phosphorus (SRP) and dissolved organic P (DOP). Regardless of influent loading, the effluent concentrations of SRP and DOP were consistently between 0.02 to 0.07 mg/L and 0.01 to 0.05 mg/L, respectively. The findings suggest that the addition of WTR can account for the adsorption removal of DP. This is further enforced through the portioning of TP by mass in the inflow and outflow concentrations. The inflow PP mass 76.6% of TP, yet outflow PP only represented 41.5% by mass. For this reason, the majority of TP reduction is accounted for by the reduction in PP (i.e., 83.3% of the TP mass reduction). The WTR-amended media reduced SRP and DOP mass by 60.3% and 59.3%, respectively. This suggests both SRP and DOP were removed by similar (sorption) mechanisms. Thus, Al-WTR decreased DP mass by approximately 60% (Liu and Davis 2014).

3.1.4.2.2.2 Flow Patterns

When two large-scale column studies were subject to an intermittent flow regime the column media adsorbed less P per unit media mass than the same media subjected to continuous flow. Under intermittent flow, the media has the opportunity to dry and allows for crystallization of hydrous oxides. Therefore, the flow conditions are an important variable that will effect the P removal of the media (O'Neill and Davis 2012a).

3.1.4.2.2.3 Internal Water Storage Zone (IWS)

Removal of nitrogen in a bioretention cell focuses on the design of an anaerobic zone to foster denitrification. However, the anaerobic conditions and increased residence time can result in the leaching of P.

If the media (typically enhanced media) contains Fe(III) in the IWS layer, it is possible that leaching will occur. Under saturated conditions, the reduction of Fe(III) minerals to dissolved Fe(II) will occur. Thus, any P adsorbed onto the iron media will be released. Therefore, if an IWS is utilized, it must be located below the P-sequestering portion of the media. As such, a 0.45–0.6 m (1.5–2 ft.) separation is recommended between the top of the IWS layer and the media surface (Hunt et al. 2012).

DP can precipitate (slow reaction) as calcium hydroxyapatite [$Ca_5(PO_4)_3(OH)$] in limestone aquifers (Strang and Wareham 2006). Consequently, the additional residence time provided by the saturated zone could allow this precipitation to occur. Barrett et al. (2013) indicated that three of four biofiltration lab-study column samples contained limestone. Consequently, the precipitation of DP appears to be the best explanation for the increase in DP removal in columns with saturated zones.

3.1.4.2.2.4 Vegetation

While vegetation plays a role in the sequestration of P, the majority of P is captured in the media. Assuming the vegetation is not fertilized, Lucas and Greenway (2008) showed that the presence of vegetation improved P removal. This agrees with findings of Barrett et al. (2013) as masonry sand, having no soil and no organic matter, provided very good removal and performed as well as the COA mix; the COA mix is a variation on the City of Austin's (TX) specification for biofiltration but lacking compost. Furthermore, vegetation plays a larger role in P removal as finer media is used. Barrett et al. (2013) showed this through a comparison between the COA and masonry sand, discovering that presence of plants provided more benefit for the lab study columns study with the COA medium (more fines) than for the columns with masonry sand (less fine). This is because certain media (e.g., sand) have a limited sorptive capacity, and it is quickly exhausted. Therefore, vegetation is necessary to remove P through plant uptake.

Typically in Barrett et al. (2013) experiments the biofiltration columns lacking vegetation tended to have the highest effluent P concentrations, and these concentrations increased over time. Vegetated columns had effluent concentrations at the end of the study that were almost as low as those observed initially, after nine months of observation.

3.1.4.3 Heavy Metals and Hydrocarbons

The removal of metals and hydrocarbons by bioretention has been successfully documented in multiple studies. This is directly attributed to the overlaying mulch layer and media. Hydrophobic organic compounds such as polycyclic aromatic hydrocarbons (PAH) and other fuel-based hydrocarbons will partition into organic matter at either the surface (mulch) or in the media (Hunt et al. 2012). Supplemental organic matter allows for a greater adsorption of hydrocarbons (Schwarzenbach et al. 2003). Metal adsorption is dependent on pH; at the usual low metal concentrations (10-100 µg/L) in urban stormwater runoff, the optimal pH range for the media is between 6 and 7. Both the organic and inorganic fractions of the media, particularly hydrous oxides (iron and aluminum oxides) provide complexation sites for the binding of metals.

LeFevre et al. (2012) collected 75 soil samples from 58 bioretention facilities and 4 upland sites around Minneapolis, Minnesota to evaluate the potential for petroleum hydrocarbon biodegradation in BSM. Typically, biodegradation of total petroleum hydrocarbons (TPH) occurs under aerobic conditions when pH, temperature, and nutrient levels do not limit microbial growth (Zhou and Crawford 1995; Mohn and Stewart 2000). It is possible that the short hydraulic residence time within the media and the level of organic matter may be insufficient to promote biodegradation. Again the addition of compost is discouraged because it will likely limit the bioavailability of TPH. Nonetheless the study shows that the soil samples encouraged TPH attenuation rather than accumulation. Finally, it is possible bioretention media may be more sustainable for treatment TPH-contaminated stormwater than retention ponds, which have been readily used in the past.

Hong et al. (2006) proved that the application of a thin layer of mulch is an effective means of reducing oil and grease (O&G) pollution from stormwater. Through a bench-scale infiltration study, the mulch layer trapped 80 to 95% of O&G (dissolved and particulate-associated naphthalene, dissolved toluene, and dissolved motor oil hydrocarbons) via sorption and filtration. PAHs were found to primarily be associated with particulates and were consequently captured in the top few centimeters of media in a field study (DeBlasi et al. 2009). Subsequently, 90% of all constituents biodegraded within 2-8 days. Likewise, Li and Davis (2008) found the most common metals in stormwater (Pb, Cu, Zn) are typically trapped within the top 20 cm (8 in.) of bioretention media.

Many studies have found high metals-removal abilities due to the strong affiliation between the media and metals; consequently, sequestration occurs at the surface of the bioretention facility (Davis et al. 2003; Hunt et al. 2008; Hatt et al. 2009b). With the accumulation of heavy metals, one mode of operation to regularly perform maintenance activities to preserve infiltration and thus extend the removal capacity for metals indefinitely (Hunt et al. 2012). It is suggested to remove a few centimeters of the surface material with each maintenance operation. It is possible that the metals could build up if left in the media over an extended period of time.

In regards to vegetation, little quantifiable data are available to prove that vegetation enhances the removal and capture of heavy metals and hydrocarbons in bioretention. LeFevre et al. (2012) proposed that greater vegetation and root density could provide for increased biodegradation performance. However, it is recommended to evaluate different types of vegetation and compare performance with that of non-vegetated facilities for more indicative results and final conclusions.

Sun and Davis (2007) found little accumulation of heavy metals (Cu, Pb, Zn, Cd) in grasses in a laboratory-scale bioretention study.

3.1.4.4 Pathogens

Due to financial constraints, pathogens in bioretention studies are measured via indicator species. The main sequestration mechanism is filtration because microbes can strongly sorb to organic media components and soils. Hathaway et al. 2009 and Passeport et al. (2009) both show high levels of indicator species capture, and thus indicate pathogen removal from runoff.

An important component to promote high rates of sequestration is the moderation of hydraulic conductivity. Laboratory studies suggest that low infiltration rates, thus lower hydraulic conductivity, result in higher rates of sequestration (Rusciano and Obropta 2007; Bright et al. 2010; Zhang et al. 2010). According to these studies, it is suggested that the infiltration rate be limited to 25-50 mm/h or 1-2 in/h. Furthermore, Hathaway et al. (2011) suggest a minimum of 0.6 m (2 ft.) for a fill-media depth, on the basis of field research in North Carolina.

If the design of a bioretention cell incorporates an IWS layer, water stored within this layer must not be near the surface; otherwise, the presence of water will promote the growth of bacteria. Unfortunately, little information is available quantifying the removal of bacteria/pathogens with the additional of an IWS layer. Referring to the design characteristics of Hathaway (2010), the IWS submerged zone should be deeper than 0.6 m (2 ft.) from the surface. In turn this will make the media depth of a bioretention cell a minimum of 0.6 m.

In regards to vegetation, there have not been any studies that specifically examine the influence of vegetation on bacteria/pathogen removal. Bacteria can die off in the media, which is dependent on particular environmental factors – UV radiation, desiccation, predation, temperature and nutrient availability. High-density vegetation can result in less UV light from reaching the media within the cell. Furthermore, vegetation can attract animals that will result in direct deposition of bacteria. All field studies to date (Hathaway et al. 2009, 2011; Hathaway 2010; Passeport et al. 2009) used vegetated systems. Therefore, it is recommended that future studies assess the impact of vegetation on the capture and sequestration of bacteria/pathogens.

3.1.4.5 Temperature

Jones and Hunt (2009) examined 4 field-study bioretention sites in western NC to evaluate the effect of bioretention designs on runoff temperature and to identify design modifications to better mitigate thermal pollution. When the bioretention site reduces runoff volume, the thermal impact to the receiving stream is consequently decreased as long as large increases in temperature do not result from the bioretention treatment. Jones and Hunt (2009) found that the largest volume reductions occurred when the media had the greatest hydraulic conductivity. It was concluded that when the hydraulic conductivity of the underlying soil is high enough to completely drain the bioretention cell between storm events, the thermal impact of overflow is likely minimal since the overflow would occur later in a storm when runoff temperatures have cooled (Jones and Hunt 2009). Therefore, bioretention cells with the proportionally largest surface areas (and media volumes) had the fewest occurrences of outflow. This can be explained through presumably greater rates of exfiltration and ET, and the BAV, as noted by Hunt et al. (2012).

### 3.1.5 Conclusions

When designing bioretention with hydrologic performance as the primary goal, the size of the system matters. Generally speaking, the bigger the system, the better hydrologic performance to be expected. Larger systems allow for increased water storage, increased hydraulic residence time, and thus lower outflow peak flows and volumes, via infiltration and ET.

Bioretention facilities do an excellent job of removing particulate matter via filtration and sedimentation. Great potential exists for the removal of dissolved pollutants as design amendments and media enhancements are further identified, researched, and documented for relative success to the entirety of the pre-identified goals of the system. The application of an IWS layer has the ability promote denitrification under anaerobic conditions with sufficient residence time. Furthermore, the chemical sorption of dissolved phosphorus has a greater affinity for enhanced media with Al-WTR (if it is placed only above the IWS layer, if present). With a greater understanding of the physical and chemical processes that govern the pollutant constituent removal, the ability of a bioretention cell to meet all predetermined hydrologic and water quality goals will be possible.

### 3.1.6 Future Research and Recommendations

While a broad range of research on bioretention cells exists, this only leads to more unanswered questions that can further develop this SCM to meet a larger variety of environmental goals. The following areas of research should be further explored to improve the current condition of bioretention cells as an identified SCM for managing runoff in Maryland.

- The role of vegetation in:
    - Nutrient removal
    - Pathogen removal
    - Water balance
- Effect of IWS on hydrology and water quality
- Design modifications for N removal
- Effect of geologic factors (e.g., sandy soils) on bioretention performance
- Effect of road salts on bioretention hydrologic and water quality performance
- Media properties – interdependence of the following prominent characteristics
    - High hydraulic conductivity
    - High filtering capability
    - High adsorption capacity
    - Minimal leaching of nutrients
    - Support vegetation
    - Inexpensive
- Underground storage integrated with bioretention
- Organic N processing
- Use of bioretention in treatment trains
- Selecting organic material for bioretention media
- Microbial communities for nutrient processing
- Long-term performance
- Role of surface mulch
- Fate and capture of hydrocarbons
- Effects of shape

## 3.2 Grassed Swales

Grassed swales are shallow grass-lined, typically flat-bottomed channels with vegetated bottoms and side slopes. It is an SCM originally designed simply for stormwater conveyance and is now commonly accepted as an effective means of urban stormwater control for multi-modal transportation systems. The following section focuses particularly on grass-lined dry swales as current research has been focuses almost exclusively on this type of swale (as opposed to bio-swales or wet swales). Very limited research is available on bio-swales, which, for the purposes of this document, are considered a sub-set of bioretention.

### 3.2.1 Background

A grassed swale is a channel that provides conveyance, water quality treatment and flow attenuation of stormwater runoff. It can receives flow only at its inlet point, or along the entire length via sheet flow. While a grassed swale is ideal for linear systems, and can thus manage flow adjacent to a highway, MDE's design requirements (that vary by county) often make swales impractical. Figure 3-6 is a diagram of a swale (with no bordering filter strip) located in Savage, MD. The primary stormwater control process of grassed swales is infiltration. Hydrologic and water quality enhancements can also be attributed to sedimentation (due to low velocity as a result of vegetation), filtration (by grass blades), and possibly biological processes. Furthermore, the designated length and available storage of the swale will greatly affect hydraulic and water quality improvements. Overall the performance of a grassed swale varies greatly with the storm intensity and duration; more specifically, the performance (or storm volume capture) decreases with these aforementioned factors.


**Figure. 3-6**. Roadside grassed swale in Savage, MD
Source: Davis et al. (2012)

Current SHA guidelines allow the use of a wet swale as presented in Figure 3-7. While this literature review does not focus on wet-swale performance and design, it is included because it is recommended for treatment of highway runoff and shares some design considerations with the dry swales reviewed in this Section.

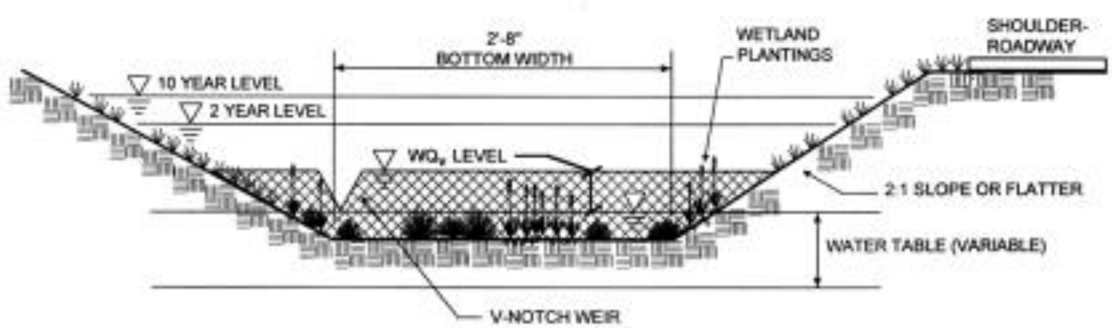


**Figure 3-7.** SHA profile view of wet swale (Stormwater Design Manual 2009).

### 3.2.2 General Design Guidelines

Barrett et al. (1988) performed a comprehensive field study in Austin, Texas to measure the efficiency of vegetative medians for removing constituents in highway runoff. Particularly, Barrett et al. (1998) compared the treatment of runoff from vegetative filter strips and a grassy swale, separately. Barrett et al. (1998) used the TSS concentrations as an indicator constituent for determining the removal pattern. Results of this study found that the optimal cross-sectional shape of a grassy swale is a "V". This results because the greatest removal occurs when the geometry of the median maximizes the length of the filter portion (or the sides).

Minimum swale design requirements and constraints are a function of the number of traffic lanes, climate, and types of vegetation (Barrett et al. 1998). Furthermore, it is necessary to avoid any erosion in the filter strip (if included in the grass swale system) at all costs. Barrett et al. (1998) noticed erosion at the top of the Walnut Creek median (in Austin, TX) that exposed bedrock and thus was deprived of vegetation. This exposed rock significantly reduced the effectiveness of treatment and contributed sediments to the runoff.

### 3.2.3 Hydrology Performance

#### 3.2.3.1 Water Path in Grassed Swales

The following reflects the path of water through a swale as adopted from Davis et al (2012). Each subsequent action is contingent on the preceding event reaching maximum capacity (up until discharge).

1. Infiltration
2. Surface flow
3. Storage
4. Discharge

3.2.3.2 Volume Attenuation

The volumetric performance of a grassed swale is dependent on the size, intensity, and duration of the rainfall event, based on the design used. Davis et al. (2012) examined two Maryland grass swales and found that they fully captured an average of 59% of storm events in a typical year; nearly half of the events have rainfall volume less than 0.254 cm and durations less than 2 h.

For small storms, a grassed swale can completely capture the event; this is noted by the absence of any measurable discharge. This represented about 40% of total annual storm events.

For moderate storms, a grassed swale will partially reduce the influent volume while still producing measurable outflow. This represented about 40% of total annual storm events.

For large storms, the ability of a swale to reduce volume is negligible. This occurs as swale flow is high and runoff conveyance is the dominant mechanism. This does not suggest any relation to the design of the swale where special considerations may be incorporated such as a filter strip and/or check dams. The largest storm category represented about 20% of total annual storm events.

3.2.3.3 Peak Flow

When addressing peak flow reduction it is necessary to have comparable conditions that promote volume reduction. Therefore, the swales ability to reduce peak flow follows a pattern analogous to the volume attenuation performance, as described above.

3.2.3.4 Flow Duration Curves

Flow duration curves represent an accurate metric to summarize hydraulic response of the swale, showing the entire storm duration of flow. This helps in understanding the level and intensity of erosion that can occur with a certain swale design during a particular storm.

### 3.2.4 Case Study: Savage, MD (Hydrology Review)

3.2.4.1 Overview

Davis et al. (2012) performed a comprehensive field test on MD Route 32, a four-lane limited access highway near Savage, Maryland to quantify the hydrologic response of four grassed swales. The design of the grassed swales incorporated two modifications to evaluate effects on hydrologic performance. The first design component was a filter strip (FS) in one swale and none in the second (No-FS); this was monitored from November 2004 to May 2006. The FS-swale includes a 15.2 m sloped (6%) grass filter strip pretreatment area between the roadway and swale channel. The No-FS swale was similarly constructed, but does not incorporate a filter strip area. The second monitoring period, installed 2 sets of vegetated check dams along the swale center (designated CD). The FS-swale has a total area of 0.312 ha and treats a roadway area of 0.224 ha on MD Route 32. Similarly, the No-FS swale has a total area of 0.431 ha and treats a roadway area of 0.225 ha just north of the FS-swale treatment area. In the second monitoring period, 2 sets of vegetated check dams were installed along the swale center (designated CD).

3.2.4.2 Volume Attenuation

The No-FS swale reduced the runoff volume by a mean of 34% compared to the concrete channel draining a 0.27 ha highway area (designated as HWY) in 10 events. In comparison to the No-FS swale, the FS swale had no statistically significant effect on reduction of runoff volume (compared with the same 10 events). With the incorporation of check dams, the volume (in moderate storms) reduced significantly. The No-FS-CD swale reduced the volume by a mean of

27%, and the FS-CD by 63%. The inclusion of a check dam improves the swales ability to reduce runoff volume, particularly for moderate storm events. Check dams provide greater water storage inside the swale channel, allowing increased infiltration and evapotranspiration (Davis et al. 2012).

### 3.2.4.3 Peak Flow

For moderate storms, both swales were able to capture the first flush of runoff through initial abstraction. Eventually the swale will generate runoff; the peak runoff is reduced with the smoothing of flow variation. This follows the trend of volume reduction for the swale. Likewise, the No-FS swale reduced the peak flow more effectively than the FS swale.

For large storms, both swales are able to capture the first flush and demonstrate some peak smoothing. However, without a significant volume reduction, there cannot be significant peak flow reduction.

### 3.2.4.4 Flow Duration Curves

In general, just the implementation of a swale on the roadside to a highway greatly reduces flows discharging from the highway, as indicated by the flow duration curves. Furthermore, the conclusions from these curves (as shown in Figure 3-8) coincide with those of the volume reduction.

Swales, regardless of design enhancements, do little when it comes to reducing the highest flows. However, smaller storms are greatly reduced and differences between swale designs can be noticed during these sized events. The No-FS swale can reduce the flow magnitude across nearly the entire flow duration better than the FS swale. This can be seen in Figure 3-8 by the respective difference in duration of flows for the two swales, as that for the

No-FS swale is clearly shorter. The No-FS and FS swales decreased the duration of measurable discharge by 52% and 45%, respectively.

While not shown in Figure 3-8, the FS-CD swale significantly decreased flows more than the No-FS-CD swale. The No-FS-CD and FS-CD swale decreased the duration of measurable discharge by 58% and 75%, respectively.

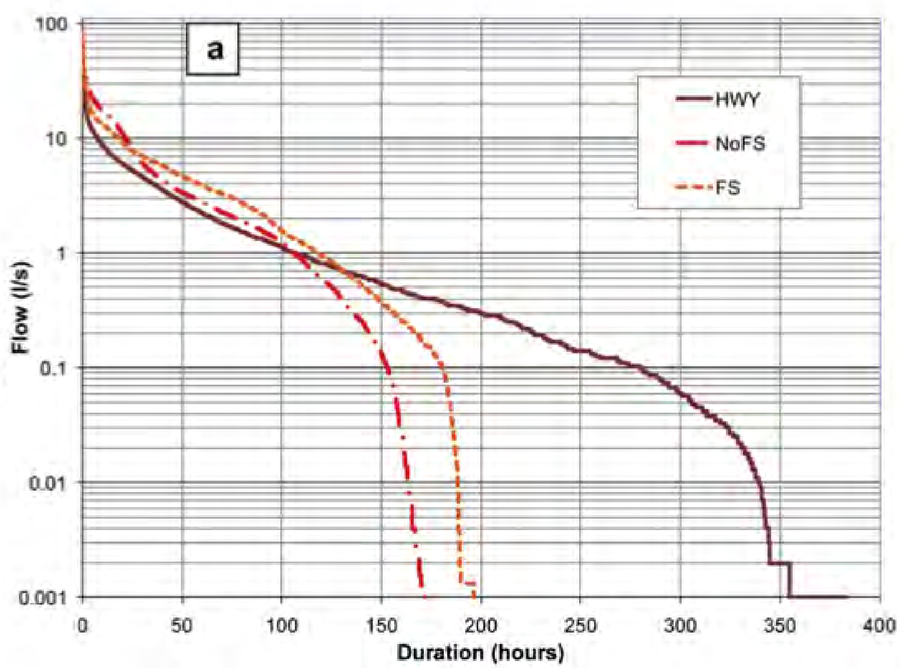


**Figure 3-8.** Flow duration curve for swale and highway runoff showing the differences in runoff volume between 2 roadside swales (No-FS and FS) in comparison to highway runoff (HWY)
Source: Davis et al. (2012)

### 3.2.5 Hydrology Design Conclusion

A swale hydrologic design must be based on the following criteria: (1) depth of water infiltration, and (2) depth in which no volume reduction occurs. By normalizing the runoff volume discharged by the swale, and subsequently, plotted against total input volume, one was able to determine an accurate capture depth. Davis et al. (2012) denotes volumetric storage capacity of the swale ranging from 18,000 L (lowest volume to show discharge) to 70,000 L (largest volume to show complete capture). This range corresponds to a capture depth of ranges 0.4-2.2 cm and a capacity depth of 2.3-3.3 cm. When quantifying design parameters, it is important to note ranges of values to denote the impact of infiltration that will occur concurrent with the input runoff loading (Davis et al. 2012).

### 3.2.6 Water Quality

#### 3.2.6.1 TSS

The main mechanisms to remove TSS are sedimentation and filtration. The ability of a swale to remove TSS is a function of time of concentration, flow path length, roughness, and influent particle size distribution (Stagge et al. 2012). TSS removal is most optimal on the longest flow path (along the length of the swale) and a shallower slope. The majority of TSS is removed during the first flush. Therefore, the ability of a swale to capture the initial runoff is key to high removal performance (Bertrand-Krajewski et al. 1998; Sansalone and Cristina 2004; Bach et al. 2010). The presence of a filter strip can potentially have a negative impact TSS removal with the formation of a “sediment lip,” resulting from a sediment accumulation at the pavement/median interface, as noted by Barrett et al. (1998). For the case of Barrett et al. (1998), the buildup was sufficient to diverge some sections of runoff to a curb and gutter system. In order to prevent this barrier, the elevation of the soil near the edge of pavement must be lower than the surface of pavement. Furthermore, the accumulated sediment should be removed via routine maintenance.

Deletic (2001) has developed a mathematical model of sediment transport in runoff over grass. This metric assesses sediment removal efficiency of grass filter strips and swales. It is a one-dimensional model simulating two processes: (1) generation of runoff and (2) sediment transport. Thus, with a known inflow particle size distribution this model is capable of predicting the particle size distribution of the outflow sediment. The model was developed for single rain events, but can be applied for a sequence of rain events assuming the initial soil wetness is constant.

Overall, the inclusion of a grass filter strip or check dam did not significantly improve TSS reduction (Stagge et al. 2012). Instead, the inclusion of each design modification posed potential problems that would be detrimental to the removal of TSS. In regards to the filter strip, it is possible that the filter strip would allow for resuspension or erosion during periods of high intensity storms that initially captured the pollutant during small-moderate events. The inclusion of check dams can actually increase the concentration of TSS as a result of significant total volume reduction.

3.2.6.2 Total Phosphorus (TP)

Swales without the inclusion of filter strips and/or check dams had little ability to decrease TP concentrations. Typically swales are most capable of treating storm events with influent TP concentrations greater than 0.7 mg/L, while less capable during storm events with low influent phosphorous concentrations (Stagge et al. 2012). The lesser P removal can be attributed to the particulate phase that is adsorbed to very fine particles that cannot be removed via sedimentation.

A filter strip significantly improved TP removal by an average of 0.2 mg/L. This relates to the ability of a filter trip to decrease peak and moderate TP concentrations. The addition of a check dam does not have a measurable effect on phosphorus removal.

3.2.6.3 Nitrogen

The main mechanisms for removal of N in grass swales are infiltration, plant uptake, and chemical/biological processes. Data suggest spikes in nitrogen export during summer months (Stagge et al. 2012). This is most likely caused by the organic nature of the swales; particularly this could reflect an increase in extraneous sources of nutrients such as mowing and leaf litter (Kruzic and Schroeder 1990). Dissolved nitrogen, especially nitrite and nitrate, which are highly soluble, are not well retained in swales. Pre-treatment filter strips and vegetated check dams improved nitrate removal, with the greatest improvement attributable to check dams (Stagge et al. 2012).

The incorporation of filter strips and especially vegetated check dams both significantly improve nitrate removal. Effluent concentrations of nitrate reveal leaching in the No-FS and FS swales, while decreased concentrations resulted from the No-FS-CD and FS-CD swales. This can be directly attributed to the increased hydraulic retention time, and thus the ability of the runoff to infiltrate the swale. Little effect on nitrite removal was determined from design alternatives. Effluent TKN measurements suggest these reductions coincide with those of nitrate. It is possible both nitrogen constituents stemmed from the similar sources. FS and CD do not affect the removal of TKN.

3.2.6.4 Chloride

Swales, regardless of design amendments, have negligible removal of chloride. Typically, swales increased the concentration of chloride by an order of magnitude, with the exception of de-icing events. The elevated chloride concentrations occur throughout the year, even with the primary application of NaCl as a de-icing agent in the winter. It is possible that a small number of large chloride pulses occur during the winter. This is further supported by Kaushal et al. (2005) who found elevated chloride concentrations in streams well after the application of road salts in the winter months.

Filter strips had a negative effect on the removal of chloride. The implementation of check dams had no effect on the treatment of chloride.

3.2.6.5 Heavy Metals

Swales are generally effective in the treatment of metals. They are most successful in the following order: zinc > copper > lead > cadmium. Zinc is the most heavily concentrated metal found in highway runoff, and also shows the greatest removal by the grass swale. It has a greater dissolved portion than particulate in comparison to other metals, but during smaller (less intense storms), infiltration will dominate the treatment process. This allows for greater removal of dissolved zinc, and thus overall greater treatment efficiency. Figure 3-9 is a pollutant duration curve for zinc which shows a significant decrease in exceedance over the fresh water toxicity limit with the implementation of a roadside swale (designated No-FS-CD and FS-CD), in comparison to highway runoff (designated HWY-CD). Exceedance of the target value is decreased from 81% to 88% to 9-27%.

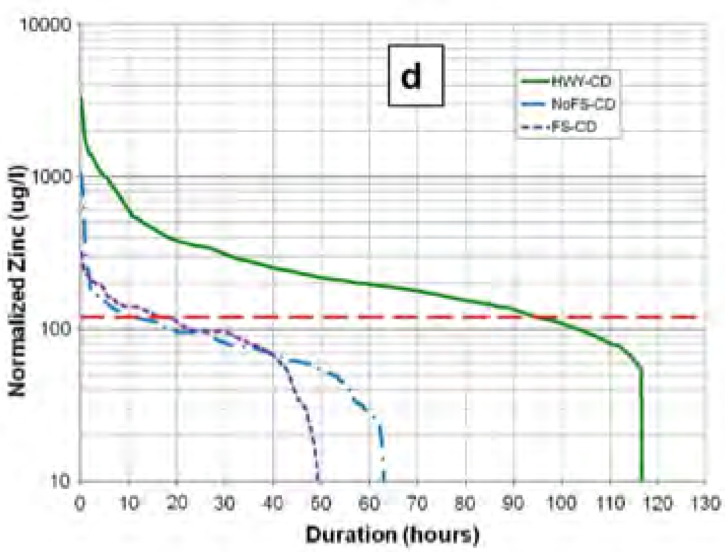


**Figure 3-9.** Pollutant duration curves for zinc for highway swale study as reported in Stagge et al. (2012). Line at 20 μg/L is Maryland Aquatic Toxicity Limit.

All swales, regardless of design amendments, significantly reduced the total EMCs for all mentioned metals. This can be further explained in Figure 3-9, where both swales had a check dam (CD) and one had a filter strip (FS) while the other did not (No-FS). Yet, there is little difference in performance of the swales, especially in comparison to the traditional highway runoff concentrations of zinc.

The inclusion of a filter strip only had a significant impact on the treatment of copper. Generally, swales exhibit a moderate capacity for treating copper. With the design modifications (inclusion of FS and/or CD), copper mass removal was statistically significant ranging from 42.3 to 81.1%.

### 3.2.7 Water Quality Conclusion

In regards to water quality, the inclusion of a filter strip did not help pollutant reduction except for the reduction of total phosphorus concentrations (~0.2 mg/L). The No-FS outperformed the FS strip when specifically analyzing TSS treatment, especially with the risk of large storms mobilizing stored TSS from small-moderate storms. Vegetated check dams did not impart any noticeable effect as well. The only constituent that demonstrated enhanced treatment was nitrogen.

Therefore, the inclusions of filter strips and/or check dams should be carefully evaluated with regards to pollutants of interest and at the risk of counteracting the performance of another constituent. Again, hydrologic properties and performance should not be ignored when deliberating the possibility of design modifications, and these characteristics will control the level of water treatment.

### 3.2.8 Maintenance and Cost

In comparison to other SCMs, swales are relatively inexpensive to maintain and require less man-hours. Houle et al. (2013) report that for the first year, annual maintenance costs $3000/ha and required around 35 hours; by the fourth year, the swale costs about $1700/ha to maintain and requires only 25 hours. When partitioning the maintenance cost into reactive, proactive, and periodic, it is clear that the majority (~$1800 of $2100) accounts for periodic which includes inspections and standards that are routine procedures. Subsequent maintenance cost corresponds to adaptive and applied treatments. This reflects the additional maintenance burden during the first months and year of vegetated establishment (Houle et al. 2013).

**Table 3-3**. Breakdown of swale expenses as documented at the University of New Hampshire Stormwater Center (UNHSC) by Houle et al. (2013)

| | |
|---|---|
| Original capital cost ($) | 29,700 |
| Inflated 2012 cost | 36,200 |
| Maintenance-capital cost comparison (yr) | 15.9 |
| Personnel (h/yr) | 23.5 |
| Personnel ($/yr) | 2030 |
| Materials ($/yr) | 247 |
| Subcontractor Cost ($/yr) | 0 |
| Annual O&M Cost ($/yr) | 2,280 |
| Annual maintenance/capital cost ($) | 6 |

Source: Houle et al. 2013

**Table 3-4.** Treatment cost of swales

| Parameter | Value |
|---|---|
| *Total suspended solids performance–annual load of 689 kg* | |
| Annual mass removed (kg) | 399 |
| Capital cost performance ($/kg) | 91 |
| Operational cost ($/kg/year) | 6 |

Source: Houle et al. 2013

The corresponding parameters for TP and dissolved nitrogen are not available from Houle et al. (2013). Values for N and P are incalculable because swale removal is constituted as negligible and calculation for pollutant treatment results in infinite cost.

### 3.2.9 Conclusions

The final design of a swale must incorporate hydrologic and water quality considerations for successful performance. Hydrologic design must depend on (1) depth of water infiltration, and (2) depth in which no volume reduction occurs. Davis et al. (2012) suggested that water quality could be improved through the inclusion of a check dam and/or filter strips. The following summarizes the case study's findings.

- The size of storm will dictate the amount (in unit volume) of the storm the grass-lined swale can capture.
    - Small storm = complete capture
    - Medium storm = some capture
    - Large storm = no capture
- In the case of grassed swales, the correlation between vegetation height and flow depth will affect volume attenuation. If the height of the vegetation exceeds the flow depth, filtration is optimized and velocity is attenuated. On the contrary, when the flow depth exceeds vegetation height, filtration is reduced and the velocity (and thus erosive potential) is higher.
- The filter strip only improved the removal of TP (~0.2 mg/L).
- Greater removal of TSS occurs without a filter strip, especially during large storms.
- Vegetated check dams improved only the removal of nitrogen.
- Check dams did not show significant improvements for any water quality constituent removal. Check dams can slow the water down and provide velocity attenuation.

### 3.2.10 Future Research and Recommendations

Future research should focus efforts on the removal of dissolved pollutants including phosphorus and nitrogen. Dissolved constituents require a longer retention time for infiltration and possible media enhancements to promote particular treatment processes below the surface.

Thus, analysis of phosphorus in should be subcategorized by the two phases – particulate and dissolved.

Through the work of Erickson et al. (2012), it is recommended that iron-sand filters be installed within ditch checks at frequent intervals in roadside swales. Ditch checks are common structures to control erosion by reducing the flow velocity within a swale. Adding iron-filings to the media will allow for the retention of dissolved phosphorus as well as the filtration of particulate pollutants.

Houle et al. (2013) attempted to quantify the cost of swales in regards to pollutant removal; however, this publication also revealed the flaws and shortcomings in current literature. It is recommended that future projects document all conditions, situations, and executive decisions in association with performance data. With clear documentation one may be able to develop a universal model that depicts an expected maintenance procedure(s) and cost regardless.

The following areas of research should be further explored to improve the current condition of grass swales as an identified SCM for managing runoff in Maryland.

- Effects of grass height and/or mowing frequency
- Evaluation of dissolved vis-a-vis particulate pollutants
- Adding in-line filters and/or adsorbents to swales
- Modification of swale soils to encourage infiltration
- Terracing swales to provide storage and infiltration
- Long-term swale performance
- Selecting vegetation for enhanced performance
- Matching swale capacity to water quality performance

## 3.3 Permeable Pavements

A permeable pavement system is a SCM characterized by its ability to provide a solid surface for vehicle and pedestrian traffic while treating stormwater via infiltration and subsurface storage to promote both hydraulic and water quality improvements. Typically permeable pavement systems are used to replace traditional parking lots, sidewalks, and roadways with less-dense traffic.

### 3.3.1 Background

A permeable (also called pervious, but incorrectly called porous) pavement is a paving material which allows water to infiltrate and be conveyed through its material matrix, open joints or voids (Drake et al. 2013). Permeable pavement systems are composed of a permeable paving surface material followed by layers of coarse aggregate materials. These sub-surface layers provide storage capacity during precipitation, as shown in Figure 3-10. (This figures shows a geotextile liner as an option, but is not included in SHA designs so as to promote infiltration. The optional subdrain can be considered as a design improvement that could be adopted by SHA. The subdrain could have an upturned elbow configuration composed of perforated pipes installed near or at the base of the bottom-most aggregate layer. The subdrain will collect the infiltrated runoff and carry it to a pre-existing stormwater system.

Generally, permeable pavements are designed to manage the rainfall that falls on them, preventing runoff formation. While they can handle some run-on from other areas, usually this is discouraged, as it is by SHA.

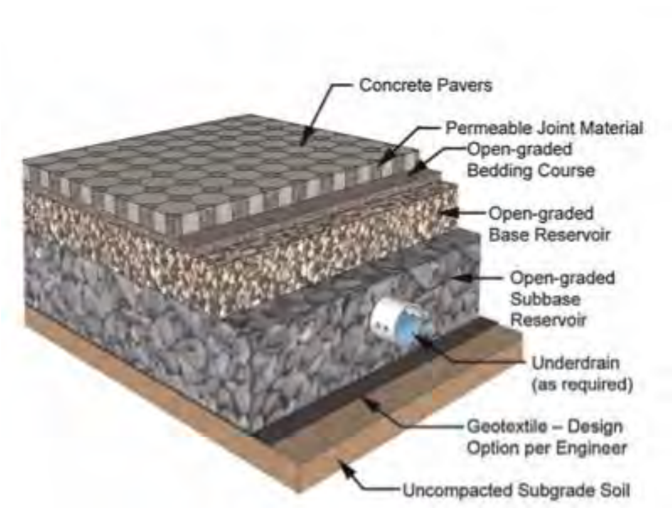


**Figure. 3-10**. Cross sectional area of a typical permeable pavement design with a subdrain incorporated
Source: Drake et al. (2013)

3.3.1.1 Classification

Multiple types of permeable pavement classifications exist, each of which has different functional, environmental, aesthetic and cost requirements (Drake et al. 2013). The most common permeable pavement systems are pervious concrete (PC) and pervious asphalt (PA, classified as porous asphalt by SHA), and permeable (or pervious) interlocking concrete pavers (PICP). PICPs are modular units separated by joints filled with open-graded aggregate (Drake et al. 2013). PC and PA are permeable surfaces of concrete and asphalt, respectively, where the binding agent coats the aggregate particles without filling the spaces between the particles (Kevern et al. 2010). In PC, the fine-grained aggregate is removed, leaving only coarse aggregate, water, and cement. The remaining aggregate is between 0.5 and 2.5 cm diameter and results in about 15-25% void space of the porous material (Tennis et al. 2004). PC and PA are particularly designed for vehicle traffic especially for parking lots, pedestrian, and low-density traffic roadways.

If a permeable pavement design is classified as monolithic (e.g., monolithic Permapave (PP), monolithic porous asphalt (PA)), this indicates that the structure consists of bound granular material such as concrete or asphalt, with the fines removed. On the other hand, a modular structure (e.g., modular Hydrapave) is constructed from individual pavers with a gap between each paver (Ferguson 2005).

Regardless of permeable pavement design, it is the base course layer that supports traffic loads and serves to retain a portion of the infiltrated rainfall. For example, a washed ASTM No. 5 stone base course layer can be installed at a varying depth between 22.5 and 25 cm. This base course layer was designed to support the expected parking lot traffic loading, estimated as 60-vehicle passes/day (Collins et al. 2008).

Rainfall intensity is the best predictor variable of any permeable pavement surface runoff generation and time to peak. Rainfall depth is the best predictor of permeable pavement total outflow volumes and peak flow reductions in comparison to traditional asphalt pavements (Collins et al. 2008).

The challenge of any pervious pavement design lies in its ability to treat dissolved pollutant loadings especially nitrogen and phosphorus. Collins et al. (2010) showed that the adjustment of flow patterns and contact time in the sub-surface layers may allow for the potential of further pollutant removal, particularly nitrogen if anaerobic conditions are present (as to be discussed in 3.3.3. *Multiple Pavement Design Evaluation*).

### 3.3.2 Previous Study Overview

The information below provides introductory material for the hydraulic and water quality performance-based assessment. With background knowledge on the context of the system, one can better understand the performance evaluation, as both studies are the premise of literature review in the forthcoming sections (3.3.3 and 3.3.4). Collins et al. (2008) specifically tests for variations among four different permeable pavement systems in comparison to traditional asphalt. Meanwhile, Kwiatkowski et al. (2007) and Horst et al. (2011) focus on a specific design (i.e., pervious concrete) and evaluate its performance in conjunction with an infiltration basin, or in a treatment train.

### 3.3.3 Multiple Pavement Design Evaluation

Collins et al. (2008) evaluated and compared the hydrologic differences between permeable pavements and standard asphalt, and hydrologic differences among various types of permeable pavements for a park lot sited in clayey soils in Eastern North Carolina. The hydraulic parameters included pavement surface runoff, total outflow volume, peak flow, and time to peak. Rainfall depths from sampled events ranged from 3.1 to 88.9 mm with mean and median rainfall depths of 22.1 and 14.0 mm, respectively. The lot was comprised of six 6 by 19 m pavement sections: two standard asphalt and four different permeable pavement sections (Figure 3-11). The four permeable pavement sections were as follows:

1. Pervious concrete (PC);
2. Permeable interlocking concrete pavers with 12.9% open surface area and openings filled with No. 78 stone (PICP1);
3. Concrete grid pavers with 28% surface open areas and opening filled with sand (CGP); and
4. Permeable interlocking concrete pavers with 8.5% surface open areas and openings filled with No. 78 stone (PICP2)

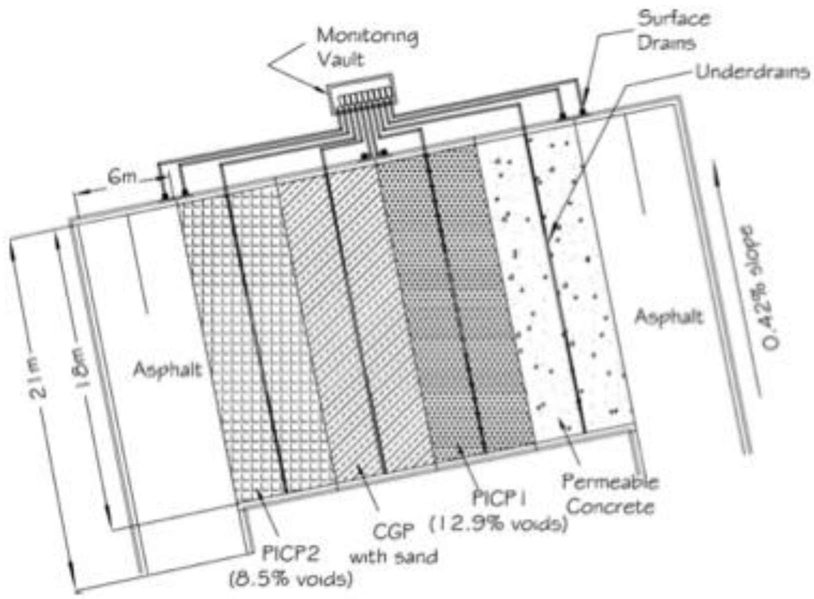


**Figure 3-11.** Top view of four different permeable pavement systems tested for hydraulic response differences in Collins et al. (2008).

This field site was also used to evaluate and compare nitrogen species effluent quality as documented in Collins et al. (2010).

Due to the low permeability of clayey soils, perforated corrugated plastic pipe (CPP) subdrains (d = 10 cm) were installed at the bottom of each system, thereby creating separate cells.

### 3.3.4 Treatment Train

Kwiatkowski et al. (2007) installed a pervious concrete system in combination with infiltration beds at Villanova University. The area was approximately 60% impervious consisting of a very light traffic road/walking path, several concrete walkways, two dormitories, and assorted grass areas. The pervious concrete was a medium to collect runoff and transmit to one of the three infiltration beds. The system consists of three linked infiltration beds lined with geotextile filter fabric, filled with coarse aggregate, and overlaid with pervious concrete, as shown in Figure 3-12. The natural soil beneath the infiltration SCM is silty sand. This area was monitored for two years and documented in Horst et al. 2011. Hydraulic and water quality improvements are explained in detail below.


**Figure. 3-12.** Photograph of Villanova University of permeable pavement infiltration bed system in courtyard documented in Horst et al. (2011).

### 3.3.5 Hydrologic Performance

Permeable pavements are able to substantially reduce flow volumes and peak flow rates through infiltration, exfiltration, and sub-surface storage. This is especially true in areas with sandy underlying soils (i.e., native soils with a high hydraulic conductivity) (Wardynski et al. 2013). However, to compensate for situ soils with poor permeability, a subdrain system can be configured, which may convey outflow runoff.

3.3.5.1 Total Volumes

In regards to volume reduction, the purpose of a permeable pavement is to reduce surface runoff. In order to avoid confusion, this section specifically discusses the total volume reduction, which occurred as subsurface drainage. Total outflow volume was influenced more by rainfall depth, rather than intensity.

Some general trends exhibited by all designs were documented in Collins et al. (2008). A negative correlation exists between antecedent dry period and outflow volumes. Furthermore, permeable pavements demonstrate a strong seasonal trend as greater outflows occur during the fall and winter months (Collins et al. 2008). If no subdrain is present, outflow should not occur and all captured runoff shall exfiltrate and thus contribute to ground water recharge.

More specifically, there were some differences among total volume capture of the four different systems. PICP1 system retained a greater volume of water, which can be attributed to increased subsurface storage volume below the pavement, and consequential increased exfiltration. The CGP cell also retained a significant volume of water, presumably due to the water retention within the pore spaces of the sand filling the pavement surface openings.

Collins et al. (2008) concluded that a permeable pavement system that successfully reduces surface runoff should have a configuration similar to Figure 3-13; this is a configuration of the PICP2. In this photograph, the area between the individual pavers was depressed, thus directing water into the voids. Also, water could not travel without passing over a channel, thus further promoting infiltration (Collins et al. 2008). The grid of surface channels and subsequent depressions allowed for further surface runoff reductions and is recommended in future design.

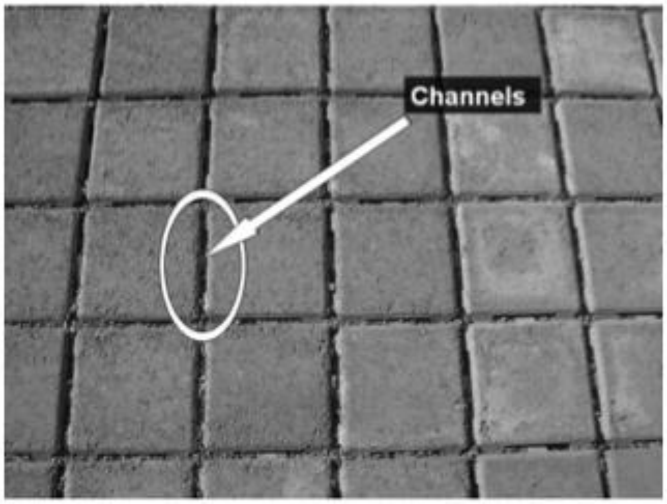


**Figure. 3-13**. Surface configuration of individual pavers with a channel grid cross section
Source: Collins et al. (2008)

3.3.5.2 Surface Runoff

All four permeable pavement sections (PC, PICP1, CGP, PICP2), as denoted in Collins et al. (2008) dramatically reduced surface runoff volumes. The surface runoff is dependent on the pavement surface infiltration rate and geometry. Accordingly, each design had a significantly different surface runoff response; expressed in order of highest runoff generation, pavements performed as follows: asphalt >> CGP ≈ PICP1 ≈ PICP2 ≈ PC, as shown in Table 3-5.

The infiltration rate is directly correlated to the physical properties of the fill media (i.e., pore spaces). With larger aggregate fill media, the individual pore space is much larger, and the permeable pavements are able to capture more surface runoff (Collins et al. 2008). In regards to the geometry of the system, it is possible that that surface configuration and shape of the pavement blocks have an impact on the surface and sub-surface flow of runoff.

**Table 3-5**. Percent Surface Runoff Reductions from Rainfall Depth

| | Asphalt | PC | PICP1 | CGP | PICP2 |
|---|---|---|---|---|---|
| **Mean percent reduction (%)** | 34.6 | 99.9 | 99.3 | 98.2 | 99.5 |

Adopted from: Collins et al. (2008)

3.3.5.2.1 Infiltration

The greatest mechanism for volume reduction is infiltration through the pavers. Collins et al. (2008) show that the surface infiltration rate affects the surface runoff reduction. Table 3-6 presents the average infiltration rates of the four different systems. Surface infiltration rate trends were as follows: PC >PICP1>PICP2>CGP (Collins et al. 2008). The higher infiltration rates of PC and PICP2 show a positive correlation to a higher surface runoff reduction; however, the factor geometry must also be taken into consideration before ranking the surface runoff reductions definitively.

**Table 3-6.** Surface Infiltration Rates (cm/h) of Four PP Systems

| | PC | PICP1 | CGP | PICP2 |
|---|---|---|---|---|
| June 2006 | 3,087 | 771 | 91 | 457 |
| September 2006 | 6,152 | 1027 | 89 | 171 |
| March 2007 | 4,466 | 1299 | 87 | 376 |
| July 2007 | 4,941 | 1536 | 101 | 267 |

Source: Collins et al. 2008

Kwiatkowski et al. (2007) evaluated the performance of infiltration in a pervious concrete system as part of a treatment train with three connecting infiltration basins. The study confirmed that pervious concrete performed up to standards with an infiltration rate of approximately 0.34 cm/s as previously noted in Tennis et al. (2004). The pervious concrete performed exceptionally well, with average inflow retention of more than 91%.

Furthermore, the pervious concrete captured and infiltrated runoff generated by storms of 5 cm (2 inches) or less. The rate of infiltration depends on the volume of water currently residing in the infiltration beds. When the infiltration bed is empty, the runoff begins to immediately infiltrate. During large storms it is possible for the bed to reach maximum capacity. In this scenario, the perforated pipes that are installed near the top of the lower infiltration bed capture overflow runoff. The pipes direct the runoff into the existing stormwater system to prevent runoff from flowing up and out of the pervious concrete.

However, infiltration does show seasonal effects; the infiltration rates during winter months will decrease as the viscosity of water increases in colder temperatures (Kwiatkowski et al. 2007; Horst et al. 2011). Over a two-year period, Emerson and Traver (2008) show that there has not been a statistically significant change in the infiltration capacity of any of three basins over time.

#### 3.3.5.2.2 Subdrain

The addition of a subdrain (regardless of configuration) is optional for the design of a permeable pavement system. However, when underlying in-situ soils exhibit poor infiltration rates, the implementation of a subdrain is recommended. With the application of a subdrain, one should expect a greater outflow than what would be expected in a sandy soil area, or an area where the in situ soil exhibits high permeability.

#### 3.3.5.2.3 Internal Water Storage Zone (IWS)

Wardynski et al. (2013) proved that the incorporation of an internal water storage zone (IWS) layer in a PICP design promotes even further total volume reduction. The entire 239-$m^2$ lot, in the mountainous area of Boone, NC, was divided into three cells, each of which differed by depths and drainage configurations. Cells B (deep internal water storage) and C (shallow internal water storage) had sumps (30 and 15 cm, respectively) created by their subdrains, forcing water to pond in the sub-base before outflow could occur. During the monitoring period, a total of 54 storm events greater than 2.5 mm occurred.

Results indicated that a greater storage area allowed for more volume reduction, as cell C had a total outflow of 4.3 cm, or a 99.5% reduction, while cell B experienced no outflow. Assuming 30% porosity for an empty aggregate storage layer, cell C can store up to 10 mm of water without producing any outflow for any single event. However, the effectiveness of an IWS layer directly depends on the hydraulic conductivity of the native soils, i.e., the rate of exfiltration. Such high exfiltration rates are attributed to the sandy loam underlying soils (Tyner et al. 2009).

3.3.5.3 Evaporation

Nemirovsky et al. (2013) conducted a laboratory study to identify the parameters that affect evaporation through pervious pavements and to quantify an evaporation rate typical of summer months in Philadelphia. Results indicate the evaporation is most prominent with favorable weather conditions when the permeable pavement system is saturated. The percentage of the total water budget accounted for in evaporation can range from negligible to moderate. To maximize the effect of evaporation, the porous area should be a large portion of the watershed, and the storm events should be small and infrequent (Nemirovsky et al. 2013).

Thus, evaporation can account for a considerable amount of volume reduction when the conditions are suitable. The laboratory study suggests that evaporation can play a larger role in total volume reduction when infiltration rate is poor or inhibited. While no system can remove

100% of its influent runoff via evaporation, it is possible that future permeable pavement system designs can promote this mechanism. However, extensive cost-analysis models must be constructed regarding multiple design criteria before any final recommendations can be made. Some preliminary suggestions found in Nemirovsky et al. (2013) will require further inquiry.

### 3.3.6 Water Quality Performance

3.3.6.1 TSS

TSS is removed from runoff via filtration that occurs in the matrix of voids within any permeable pavement system. It is possible that construction can contribute to an increase in TSS as the presence of fines could migrate to the bed during a storm (Kwiatkowski et al. 2007; Horst et al. 2011). Horst et al. (2011), who studied a pervious concrete system at Villanova University, found a high removal of suspended solids – inflow of 30.3 kg and outflow of 0.17 kg.

3.3.6.2 Nitrogen

Collins et al. (2010) recorded nitrogen removal from the four permeable pavement designs – PC, PICP1, CGP, and PICP2. Nitrogen speciation was as follows - nitrate-nitrite as nitrogen ($NO_{2,3}$-N), ammonium as nitrogen ($NH_4$-N), total nitrogen (TN), and organic nitrogen (ON).

The parking lot received light traffic over the course of the study, so many of the pollutant inputs to the lot were believed to be atmospherically deposited, resulting from rainfall or wind blown particles. Previous studies have determined that atmospheric deposition contributes to a large portion of the nitrogen found in stormwater (Wu et al. 1998; Line et al. 2002). Therefore, the performance of the four designs were evaluated by comparing subsurface drainage pollutant concentrations to those of atmospheric deposition and asphalt runoff.

The subsequent information is a direct summary from Collins et al. (2010). Table 3-7 shows a summary statistics of the four permeable pavement designs and the traditional asphalt surface.

**Table 3-7.** Summary EMCs demonstrating N-removal performance of traditional asphalt and four permeable pavements in North Carolina

| N Constituent | Atmospheric Deposition | Asphalt 1 | PC | PICP1 | CGP | PICP2 |
|---|---|---|---|---|---|---|
| Nitrate/Nitrite (mg/L) | 0.35 | 0.29 | 0.73 | 1.25 | 0.46 | 0.90 |
| Ammonium (mg/L) | 0.59 | 0.34 | 0.05 | 0.05 | 0.04 | 0.05 |
| Organic N (mg/L) | 0.37 | 0.61 | 0.50 | 0.43 | 0.44 | 0.43 |
| TN (mg/L) | 1.30 | 1.24 | 1.27 | 1.73 | 0.95 | 1.38 |
| pH (mg/L) | 6.7 | 7.2 | 9.2 | 8.1 | 7.9 | 7.9 |

Source: Collins et al. 2010

3.3.6.2.1 Nitrate-nitrite

The PICP1 cell produced a significantly higher $NO_{2,3}$-N outflow concentration than all other pavement sections and atmospheric deposition samples. The asphalt, atmospheric deposition, and CGP cell demonstrated significantly lower concentrations than all other pavement sections; no statistical differences were observed among these.

For all sampling sites, $NO_{2,3}$-N loads were positively correlated to rainfall depth. Asphalt and CGP cell $NO_{2,3}$-N loads were significantly lower.

3.3.6.2.2 Ammonium

No significant difference in $NH_4$-N concentration was found among permeable pavement types. All $NH_4$-N loading showed a positive correlation to rainfall depth. The $NH_4$-N atmospheric deposition load to asphalt surface load ratio was 2.7. However, for a higher traffic volume in central North Carolina, a ratio of 0.9 was found (Wu et al. 1998).

#### 3.3.6.2.3 Organic Nitrogen

ON concentrations were calculated by subtracting $NH_4$-N concentrations from TKN concentrations. No significant differences in ON concentrations were observed among pavements.

ON loads for all pavements were positively correlated to rainfall depth.

#### 3.3.6.2.4 Total Nitrogen

Overall, the CGP cell had the lowest mean and median TN concentrations, and PICP1 had the highest (Table 3-7). The PICP1 cell exhibited TN concentrations significantly greater than those of asphalt, atmospheric deposition and the CGP cell. TN concentrations in the asphalt, PC, PICP1, and PICP2 cells showed a positive correlation to atmospheric deposition. This suggests that these pavement sections simply convey all TN that is deposited atmospherically.

The aggregate base course and fill media allowed for the colonization of many microorganisms (Newman et al. 2002). The draining of the system with a subdrain created an aerobic environmental, thus promoting nitrification. This was evident by comparing the atmospheric deposition and asphalt concentrations of $NH_4$-N and $NO_3$-N to all four permeable pavements. Unfortunately, nitrification was not coupled with denitrification, and led an overall poor removal of TN.

CGP performed substantially better in regards to TN compared to the other permeable pavement systems because it was the only one that contained a sand area. In comparison to the other fill media (e.g., aggregate pebble and gravel), sand provides a greater surface area for microorganisms to colonize. With more biological activity and the possible assimilation of ammonium before nitrification began, CGP cell effluent TN concentration was much lower than the other pavers.

3.3.6.2.5 pH

Typical rainwater has a pH of about 5.0. Collins et al. (2008) concluded that all pavement systems (PC, PICP2, CGP, PICP2) were all effective in buffering acidic rainfall pH. All permeable pavements provided a greater buffering capacity than asphalt; the PC cell had the longest contact time with cementitious materials, therefore, it generated subsurface drainage with the highest pH.

Nitrification occurs most rapidly in neutral to alkaline environments. The optimal pH range for growth of the nitrifying bacteria is 7.6-8.8, which coincides with the subsurface drainage pH values ranging from 7.9-9.2. While pH allowed for the successful growth of bacteria, other environmental conditions did not allow for complete N removal via coupled nitrification and denitrification.

Horst et al. (2011) found that PC neutralizes the runoff to a final pH by about 8.0 in about 15 minutes of contact time. This is due to the runoff's contact with the pervious concrete and limestone aggregate, which are both basic (Kwiatkowski et al. 2007; Horst et al. 2011). Horst et al. (2011) show inflow runoff pH ranging between 4.17 and 8.42, and outflow pH ranging between 6.65 and 9.75.

3.3.6.3 Conductivity, Chloride, and TDS

Calcium chloride ($CaCl_2$) is used to melt snow and deice roads; it should be noted that NaCl is typically used to melt snow but still follows the same trends of conductivity. Horst et al. (2011) found a spike in conductivity for the soil collected under the infiltration bed during the winter months due to the dissolved ions ($Ca^{2+}$and $Cl^-$). During spring and summer months, the conductivity of the water collected is about the same of the runoff before treatment (Kwiatkowski et al. 2007; Horst et al. 2011). Horst et al. (2011) found inflow conductivity ranging from 2.96 to 89.2 μS/cm, and outflow conductivity ranging from 9.0 to 2860 μS/cm.

Total dissolved solids (TDS) follow the same trend as conductivity. The main TDS component was chloride ($Cl^-$), which had a negative removal during the winter months. This explains the poor removal of TDS.

#### 3.3.6.4 Thermal Impact

##### 3.3.6.4.1 Thermal Buffering

The sub-surface aggregate layers of a PICP design in the mountain region of North Carolina allowed for the successful buffering of stormwater temperature spikes (Wardynski et al. 2013). The system increasingly allows for the buffering of temperature with increasing sub-surface storage layers. For a PICP design with a deep IWS layer (30 cm deep) in comparison to a traditional subdrain configuration (with no IWS layer), the bottom of the cells were on average, 5.2 and 4.4°C cooler, respectively, than maximum temperatures just below the pavers.

In the Boone, NC studies, the maximum pavement surface temperature was 61°C; however, directly below the 7.6-cm-thick-pavers, the temperature was 26°C cooler (Diefenderfer et al. 2006). This demonstrates the ability of permeable pavements to insulate subsurface drainage layers from extreme temperature spikes. Minimum temperature of these permeable pavements at the bottom of cells never went below freezing; however, the minimum temperatures directly below the pavers were below 0°C. Therefore, profile depths of at least 47 cm appear to be sufficiently deep to prevent frost heave damage in the North Carolina mountains (Wardynski et al. 2013).

Daily maximum temperatures in NC also demonstrated a lag in comparison to the temperature at the top of the pavement (directly below the surface). The traditional subdrain system and shallow IWS layer had a lag of 7 h while the deep IWS layer had a lag of 10 h. The ability of permeable pavements to exhibit temperature lag is important to buffer thermally enriched runoff from afternoon storms, which contribute the highest runoff temperatures (Herb et al. 2008; Winston et al. 2011).

3.3.6.4.2 Internal Water Storage Zone (IWS)

Incorporating an IWS layer in the design of two PICP systems in the mountainous region of North Carolina provided effluent stormwater that did not exceed the critical trout threshold temperatures (Wardynski et al. 2013). Unfortunately, a permeable pavement system that had a traditional subdrain design did produce noticeable outflow that exceeded the avoidance threshold (for 10.5 hours) and the lethal 25°C threshold (0.7 h) during the 60-day stream temperature-monitoring period (Wardynski et al. 2013).

### 3.3.7 Maintenance

It is important to quantify regular maintenance activities because particulates that are captured and deposited on the surface will lower the infiltration rate of permeable pavements. These include but are not limited to sand, silt, and clay-sized particles (abraded pavement or tire debris) (Kuang and Fu 2013). This causes clogging of the porous material, and when infiltration rates drop to an extremely low level, the permeable pavement acts like a conventional pavement.

Vancura et al. (2012) found that clogging materials are most generally found within 12.7 mm (1/2 in.) from the pavement surface. The three methods of maintenance examined were a 200-mm (8-in.) vacuum hose, a vacuum street sweeper, and a regenerative air sweeper. The clogging material that remained after routine maintenance was not an issue because permeability was still restored. Furthermore, all machines were able to effectively remove all clogging materials within 3.18 mm (1/8 in.) of the surface (Vancurra et al. 2012).

The frequency of maintenance required to restore permeability is dependent on the rate at which clogging material is consolidated within the voids. This, in turn is related to the following (Vancura et al. 2012).

- Located of permeable pavement system in within its drainage area
- Quantity of particulate matter in runoff that the system treats
- Seasonal variation in organic material
- Disruption of landscaping of surrounding area

Kuang and Fu (2013) studied the effects of varying maintenance intervals of 6, 12, and 48 months (specimens A1, B1, and C1, respectively) to help guide the proper cleaning intervals for Cementitious porous pavement (CPP). Furthermore, this study measured the infiltration rate of specimens (A2, B2, and C3) to assess how much the cleaning methods used could recover infiltration rates in comparison to the initial level. The surface cleaning methods used include a high-pressure wash followed by vacuuming at one atmosphere (100 kPa) (Kuang and Fu 2013).

Infiltration rate and saturated hydraulic conductivity were measured. Specifically for CPP, previous studies have demonstrated that the unsaturated period lasts only approximately 30 min, and the performance under saturated condition is critical in real world situations (Aulenbach and Chan 1988; Andersen et al. 1999; Kuang et al., 2007a, b). Various levels of particulate material accumulated on the surface of the three sites (A1, B1, and C1). The A1 accumulated particle surface height was less than 0.5 mm, while B1 and C1 were approximately 0.8 to 2.0 mm. This can be attributed to the varying cleaning interval of 6, 12, and 48 months, respectively of each cell.

**Table 3.8** – Saturated infiltration rates and corresponding hydraulic conductivity for each system

| Specimen | A1 | B1 | C1 | A2 | B2 | C2 |
|---|---|---|---|---|---|---|
| Cleaned | No | No | No | Yes | Yes | Yes |
| $I_f$ (l/min $m^{-2}$) | 5.6 | 0.8 | 0.06 | 10.65 | 10.44 | 10.37 |
| $K_{sat}$ (cm/s) | 7.3 x $10^{-3}$ | 1.1 x $10^{-3}$ | $10^{-5}$ | 1.3 x $10^{-2}$ | 1.2 x $10^{-2}$ | 1.2 x $10^{-2}$ |

$I_f$, infiltration rate; $K_{sat}$, saturated hydraulic conductivity.

Source: Kuang and Fu (2013)

As shown in Table 3-8, the varying infiltration and $K_{sat}$ values indicate if and how much the system is clogged. For this scenario, the extent of clogging is represented by the thickness of the particle layer (Kuang and Fu 2013). B1 approached a point where it needed to be cleaned in order to improve the infiltration rate and hydraulic conductivity. For C1, which had gone 48 months without cleaning, the $K_{stat}$ value was too low to maintain any type of effective infiltration performance. However the results of A2, B2, and C2, confirm the effectiveness of the high-pressure wash followed by vacuuming to restore initial conditions. Even with the extreme case of C2, the 2.0 mm particle accumulation thickness on the surface was mostly removed by this maintenance technique (Kuang and Fu 2013).

Yong et al. (2013) conducted compressed time scale laboratory experiments over a span of 3 years testing three different types of permeable pavement designs – (1) monolithic porous asphalt (PA), (2) modular Hydrapave (HP), a product by Boral (national supplier of brick and clay pavers) clay and concrete, and (3) monolithic Permapave (PP). These laboratory experiments aimed to predict the physical clogging of the aforementioned design systems under varied flow conditions – (1) continuous inflow and (2) varied inflow with drying/setting sequences typical to the Brisbane Australia climate (Yong et al. 2013).

The results showed that the lifespan for the three designs varied greatly from PA, to HP to PP, from shortest to longest. PA accumulated a clogging layer on the surface and showed the earliest signs of clogging. HP showed similar trends of clogging but the physical clogging began just above the geotextile liner. This proved that the liner acted like a significant barrier, and clogged the fastest. PP showed no signs of clogging; this was expected because the sub-base was constructed of medium to large sized aggregates (5-20 mm) (Yong et al. 2013). However, while the PP system showed no signs of clogging, this laboratory experiment failed to test for water quality. Therefore, the implementation of only larger-sized aggregates cannot be recommended because the effluent pollutant constituents are not accounted for. It is probable that the while a maximum infiltration rate is produced, the rate of pollutant removal is low as it is a function of filtration, retention time, and finer aggregate material.

In regards to variable flow conditions, it was determined that the lifespans of all systems was nearly doubled when subjected to more natural conditions (i.e., varied inflow with wetting/dry seasons) (Yong et al. 2013). Therefore, it is recommended with future laboratory experiments that permeable pavements receive conditions more comparable to natural ones to better estimate the lifecycle of the system.

### 3.3.8 Conclusions

Previous studies have found that the permeability, evaporation rate, drainage rate, and retention properties of PICP are largely dependent on the percent of surface openings and the particle size distribution of the aggregate joint filling and bedding material (James and Shahin 1998; Anderson et al. 1999). Yet, it is possible to go beyond this classification for PICP design, as it is applicable for any permeable pavement design. Furthermore, as shown in Collins et al. (2008; 2010), there is a negligible difference among PC, PICP1, CGP, and PICP2. In regards to hydrologic performance, all reduced surface runoff between 98-99%. Specifically, the design of any system is to treat the rainfall that falls directly upon the surface, thus eliminating the possibility for additional runoff (assuming the entire impervious surface is not treated by PP).

The most up-to-date literature suggests that the removal of particulate matter from incoming water is very predictable. High removal rates are found assuming regular maintenance is performed to alleviate the potential for clogging. Additional storage space below the permeable pavements, as well as design and configuration of individual pavers influence the ability to a system to reduce the volume of influent runoff. The additional storage space can allow for a longer contact time between runoff and the subsurface area. This can promote unit processes that may be able to treat N, P, and other pollutants of interest under proper conditions (e.g., anaerobic vs. aerobic, soil composition).

### 3.3.9 Future Research Recommendations

While some information is known about permeable pavers with respect to hydrologic and particulate pollutant removal performance, impacts on dissolved pollutants is mostly unknown. Long-term issues related to paver maintenance and clogging require additional study as well.

- N removal in PP
- P removal in PP
- Run-on to permeable pavements and maximum capacity
- Permeable pavement treatment trains
- Underground storage combined with permeable pavements
- N and P in collected sediments
- Long-term performance
- Maintenance for PP

## 3.4 Sand Filters

Sand filter SCMs encompass a wide range of designs and configurations. A sand filter is a porous media filter that relies on the process of filtration to reduce pollutant concentration from stormwater. It generally does not impact runoff volume. Currently SHA is entirely installing surface sand filters. However, the research to-date focuses almost entirely on sub-surface sand filters. Nonetheless, the performance information for surface and sub-surface sand filters should be similar and comparable. For the duration of this section, all references of sand filters are specific to sub-surface sand filters unless otherwise noted.

### 3.4.1 Background

Sand filters have become increasingly popular over the past two decades, specifically in Austin, Texas and in the Mid-Atlantic region. The hydraulic capacity of a sand filter is a function of the hydraulic conductivity of the media and the accumulated solids on the filter surface (Urbonas 1999). Particles larger than the pore size of the media (typically within the first few centimeters) are the only constituents that will be filtered; the remaining pollutants will pass through the system (Erickson et al. 2007).

### 3.4.2 General Design Components

Generally speaking, sand filters are designed with (from the surface down) approximately 46 cm of ASTM C 33 sand, a layer of geotextile fabric, and a gravel sub-base that supports the system and quickly channels water toward a perforated pipe collection system. The geotextile fabric provides a barrier to prevent the sand from washing into the gravel sub-base. The perforated pipe collects the treated stormwater and delivers it to the stormwater conveyance system or directly to receiving waters (Claytor and Schueler 1996).

3.4.2.1 Austin Sand Filter Design

Barrett (2003) specifically employed an Austin-style (Texas) sand filter. An Austin sand filter has an open-air filter and a sedimentation basin separated by a concrete wall (Figure 3-14). The size of the sedimentation basin is designed to capture the entire water quality volume. The sedimentation basin is designed to discharge the captured runoff to the filter basin in 24 hours.

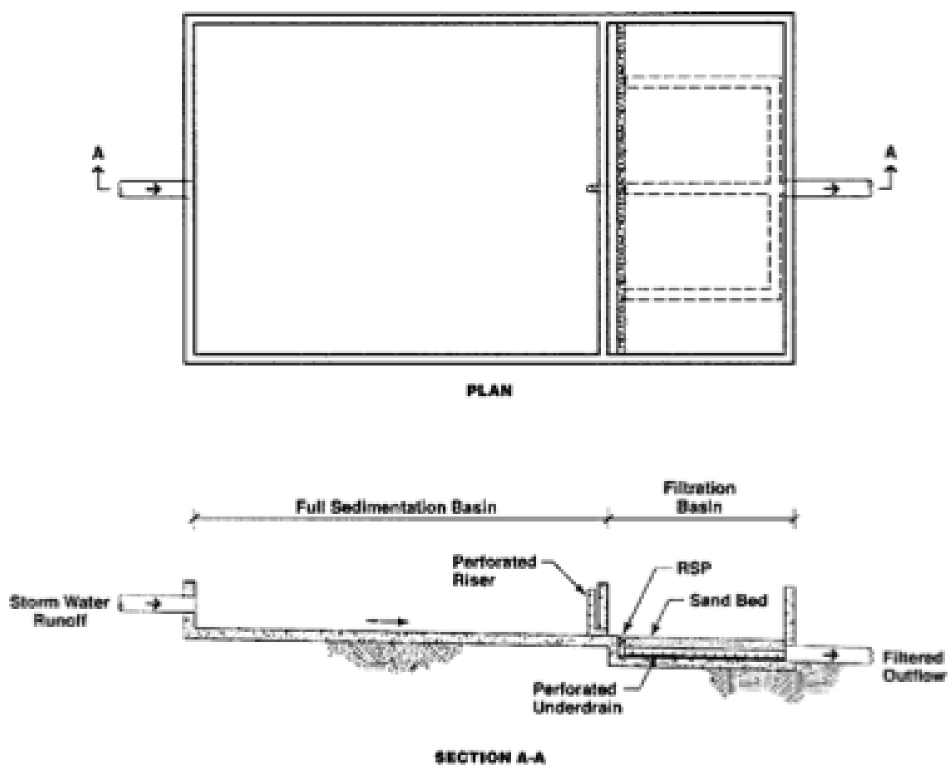


**Figure. 3-14.** Schematic drawing of an Austin-style sand filter at the 78/I-5 Park and Ride (PR) and La Costa (PR) sites both in San Diego, CA as referenced in Barrett (2003).

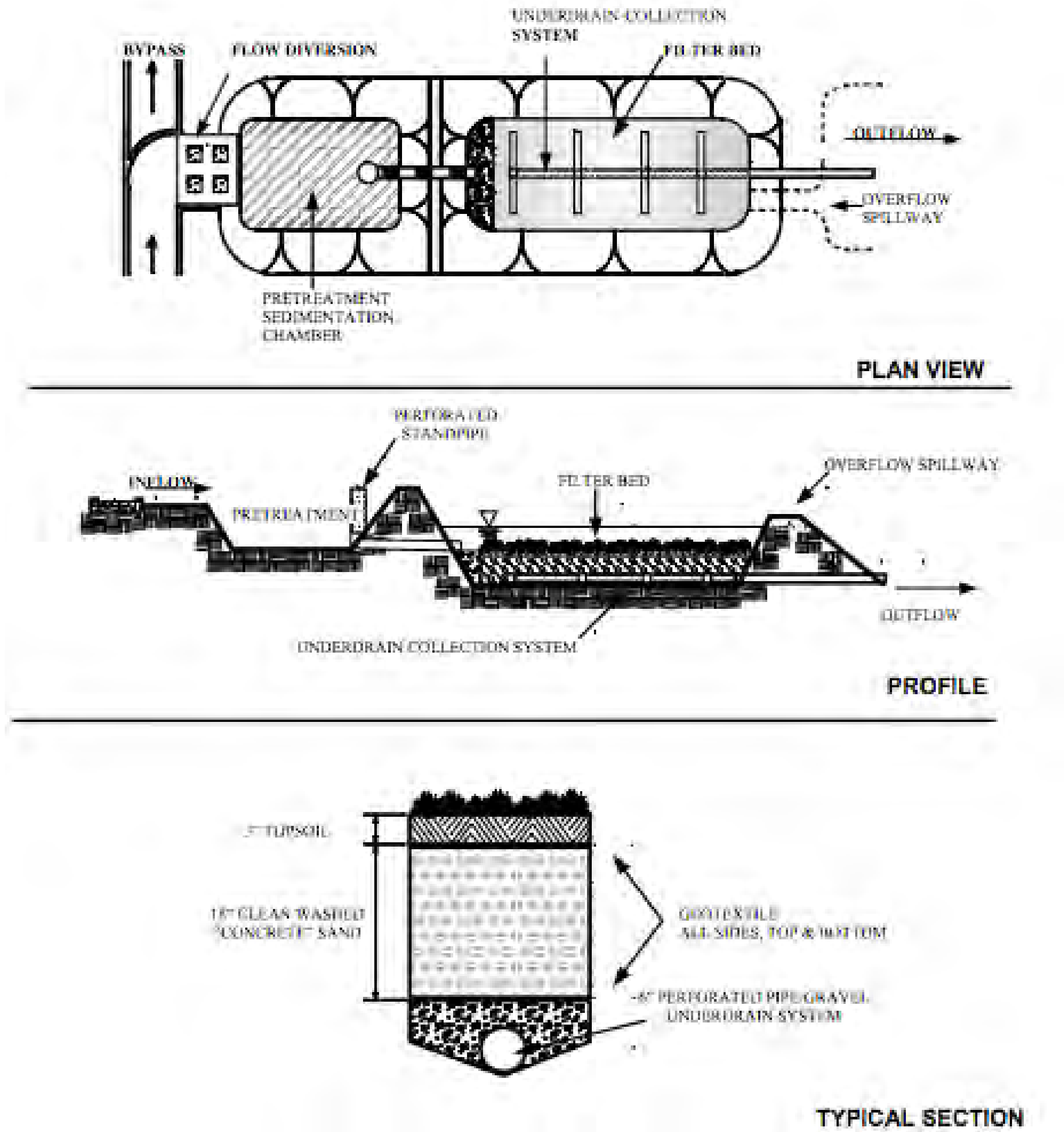


**Figure 3-15.** SHA design of a surface sand filter (Maryland Stormwater Design Manual 2009).

The SHA surface sand filter design (Figure 3-15) is comporable to that of the Austin-style sand filter (Figure 3-14). Both systems include a sedimentation basin for pretreatment, followed by the sand filter bed. The Austin sand filters are designed for a climate area that has a wet and dry season; the SHA design should reflect typical Maryland climate and rainfall.

### 3.4.3 Water Quality Performance

When characterizing the performance of a sand filter it is important to distinguish between particulate and dissolved pollutants. Typically, sand filters are highly successful when treating particulate matter. However, the processes that govern dissolved pollutant removal are not as prominent, and thus, sand filters generally display poor removal rates.

#### 3.4.3.1 Particulate Pollutant Removal

Barrett (2003) found that one could predict the effluent concentration of particulate pollutants regardless of the influent load through sand filters, as demonstrated by the small uncertainty in the estimate of the mean effluent concentrations.

##### 3.4.3.1.1 TSS

The TSS effluent concentration was found to be 7.8 mg/L with uncertainty at the 90% confidence level of 1.2 mg/L. The small uncertainty in the estimate of the EMC highlights a very consistent effluent quality for TSS in sand filters. The consistent effluent concentration suggests that there is little difference in the total mass of the smallest sized particles regardless of TSS influent concentration, as only the smallest size fraction can pass through the filter. This also implies that differences among influent concentrations are generally caused by larger sized fractions that will not pass through the filter. Barrett (2003) could not pinpoint the exact range of particle distribution sizes that is removed via the filter, and the fraction that remains suspended in the effluent stormwater, as future research is needed in this discipline of research.

3.4.3.1.2 Copper

Barrett (2003) revealed that the particulate copper behaved similarly to TSS regarding sand filter performance. Regardless of influent concentration, the effluent concentration was relatively constant at about 2 μg/L (Barrett 2003). This indicates that the majority of particulate copper is adsorbed to the larger sized TSS particles, both of which are trapped in the filter.

3.4.3.2 Dissolved Pollutant Removal

3.4.3.2.1 Nitrogen

Austin sand filters typically show a negative removal of nitrate, as the effluent concentration (1.10 mg/L) was significantly higher than the influent (0.63 mg/L) (Barrett 2003). Barrett's (2003) data report that some ammonium is converted to nitrate as indicated by the increase in nitrate. TKN concentration was reduced from 3.02 mg/L to 1.48 mg/L.

Total nitrogen (TN), the sum of nitrate and TKN, show slight removal (3.72 to 2.91 mg/L). However this is not representative of the negative removal of the nitrate. Therefore, TN is not an accurate representation of sand filter performance, and design amendments are necessary (as to be further discussed 3.4.4. *Design Modifications*).

3.4.3.2.2 Metals

When the influent concentration of dissolved metals is sufficiently high, the removal rate is substantial. As noted by Barrett (2003), this finding illuminates a broader behavior characterizing Austin sand filters – its affinity for metals and the adsorption on the sand grains or possible accumulation of sediment. This property of sand filters is further discussed in 3.4.4. *Design Modifications* typically regarding media amendments.

### 3.4.4 Design Modifications

While traditional practice of sand filters suggests high levels of particulate-bound pollutant removal, one cannot ignore the implications of dissolved pollutants. Enhancements to filter media can promote greater dissolved pollutant removal.

#### 3.4.4.1 Enhanced Phosphorus Removal

##### 3.4.4.1.1 Mechanism of Phosphorus Removal

Mechanisms for the removal of phosphorus include precipitation by calcium, aluminum, or iron, and surface adsorption to iron oxide or aluminum oxide; both chemical treatment methods are a function of pH. Phosphate retention by mineral soils has been summarized as follows (Reddy and D'Angelo 1994): "(1) in acid soils, phosphorus is fixed as aluminum and ferric phosphates, if the activities of these cations are high; (2) in alkaline soils, phosphorus fixation is governed by the activities of calcium and magnesium; and (3) phosphorus availability is greatest in soils with slightly acidic to neutral pH" as referenced in (Erickson et al. 2007). The median value for pH in stormwater is 7.4 ± 0.11 (Pitt et al. 2005). Therefore, the primary removal mechanism for phosphates with iron oxides is adsorption (Stumm and Morgan 1981). As iron oxidizes to form rust, phosphates bind to these iron oxides by surface adsorption (Erickson et al. 2012).

##### 3.4.4.1.2 Enhanced P Results

Erickson et al. (2007) conducted a series of column studies on four enhancements to C-33 sand filtration – (1) calcareous sand, (2) limestone, (3) chopped granular steel wool, and (4) steel wool fabric. Synthetic storm water runoff simulated under real storm conditions between ½ and 2 days dosed with variable dissolved phosphorus concentration (0.1 to 0.8 mg $PO_4$-P/L) was passed through the columns The columns consisted of approximately 10 cm of gravel subbase at the bottom, a PVC disk with holes for support of the media, a layer of filter fabric, and the filter media, as shown in Figure 3-15.

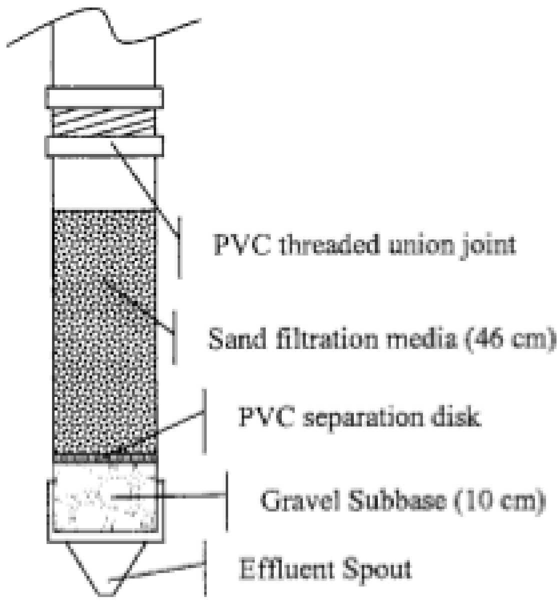


**Figure 3-15.** Column study set-up of enhanced sand media filtration, as conducted by Erickson et al. (2007).

Results indicate that steel-wool-amended media enhanced dissolved phosphorus removal from influent stormwater runoff. This media amendment increased the duration and capacity for dissolved phosphorus retention as compared to the original C-33 sand alone (Table 3-9). Furthermore, steel-wool-enhanced media did not significantly clog the filter as a consequence of enhanced pollutant retention.  Thus, it is potentially a cost effective alternative, as its predicted implementation will only raise construction costs by approximately 3-5% (Erickson et al. 2007). The disparities in filter fabric (woven generic, 150 µm, and 200 µm) contributed to the varied (~50-80%) percentage of phosphorus retained by mass. Different filter fabric properties accounted for varied residence time, and thus hydraulic conductivity. Therefore, as hydraulic conductivity increased, the percent of phosphorus retained decreased (Table 3-9).

**Table 3-9.** Summary of steel wool enhanced media performance of columns with different filter fabrics, as conducted by Erickson et al. (2007).

| Column | Enhancement[1] | Filter fabric | Hydraulic conductivity (cm/s) | Mean contact time with steel (s) | Mass P retained (mg) | % Retained by mass |
|---|---|---|---|---|---|---|
| D2 | 2% (36 g) | Woven generic | 0.0065 | 308 | 25.0 | 80.8% |
| E2 | 2% (36 g) | 150 μm | 0.0097 | 206 | 29.6 | 61.6% |
| F2 | 2% (36 g) | 200 μm | 0.0114 | 175 | 33.8 | 51.5% |

1. Steel wool enhancement – Data provided as % by mass added to C-33 sand media

More recently, Erickson et al. (2012) found a second alternative to enhanced C-33 sand filtration media – iron fillings. The results indicated that sand mixed with 5% iron filings capture an average of 88% phosphate for at least 200 m of treated runoff depth (Erickson et al. 2012). When iron filings was less than 5% by weight, the results showed little to no improvements in comparison to unenhanced media. The capture of phosphates was small and the filter did not demonstrate a change in hydraulic conductivity when the iron filings was < 5% by weight. According to Figure 3-16, the relationship between the depth of runoff treated and the cumulative phosphate retained is characteristic of both the performance and the capacity for a filter media to capture phosphates. The slope provides a clear indiciation of the capture performance. The steeper the slope, the more phosphate has been captured. A horizontal slope indicates no phosphate capture and a negative slope indicates phosphate leaching or release. Therefore, lines closer to the influent retain more phosphates than media with less iron filings. These lines, as referenced in Figure 3-16, that correspond to the most successful phosphorus retention are 5% iron (i.e., the solid blue, green, and yellow lines).

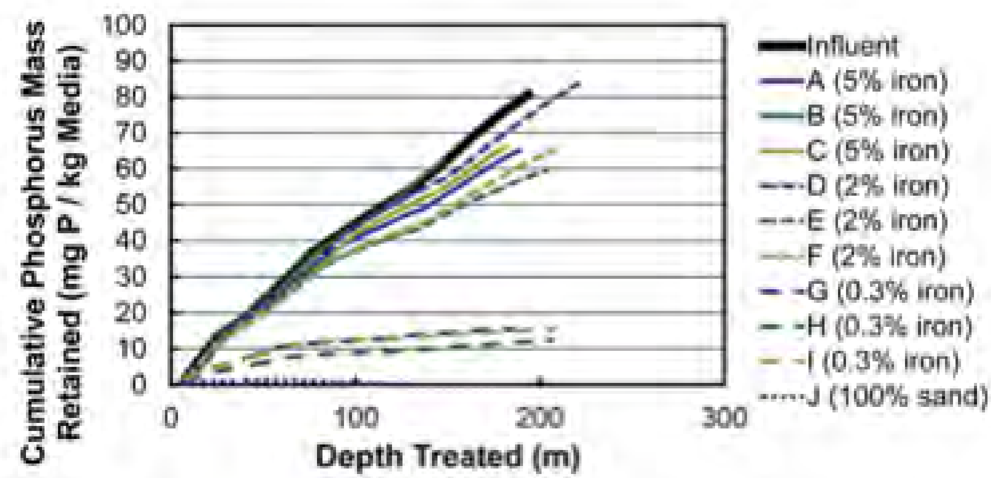


**Figure 3-16.** Cumulative phosphate mass retained (mg P/kg Sand and Iron Media) by 5%, 2%, 0.3% iron and 100% sand columns from Erikson et al. (2012).

3.4.4.2 Geotextile Filters

Geotextile filters are currently being reviewed as an alterative filtration SCM to remove particulate matter from urban stormwater runoff. Franks et al. (2013) proposed that a geotextile filtration media would be a better choice than sand because it is light and easily transportable. A laboratory column study determined that a geotextile with an opening size of 150 µm can remove TSS below a target concentration of 30 mg/L from a synthetic urban runoff via a filtration mechanism (Franks et al. 2013; Franks et al. 2014). The results also showed that the change in hydraulic conductivity of the filter system can be related to the concentration of captured TSS, which can also be used to predict the flow rate through the filter throughout its life-cycle.

The power model is as follows (Eq. 3-1).

$$y = 3 \times 10^{-5} \mathrm{X}^{-1.83};\ R^2 = 0.904 \qquad \text{Eq. 3-3}$$

where: x = solids captured (kg/m$^2$

y = hydraulic conductivity (m/s)

Unfortunately, this model has multiple limitations. For one, the sizes in the laboratory simulation represent published particle distributions that sand filters primarily treat; this range only accounts for a small portion of the possible particle sizes in highway runoff. The concentration of TSS can vary by season, location, and amount of traffic. However, the laboratory study computed an EMC from published concentrations and used this value (i.e., 200 mg/L) as the only influent concentration. Finally, it did not address the potential for biological growth on the filter. While nonwoven polypropylene geotextiles are inert to biological degradation, biological growth can occur in and on the material, especially when exposed to liquids with high organic content.

Franks et al. (2014) furthered this laboratory column study to investigate the efficacy of nonwoven geotextile filter systems to remove TSS from synthetic runoff. Results indicated that neither TSS concentration (100 or 200 mg/L) nor influent velocity (0.25 or 0.49 mm/s) significantly affected the capture of TSS. Particle-size distribution will affect the “cake”, or the accumulation of sediments on the surface. This will in turn affect the retention of particles and the hydraulic conductivity of the geotextile-filter cake system (Kutay and Aydilek 2004). Aydilek (2011) found that larger particles are more likely to block the filter.

Franks et al. (2014) also compared the performance and frequency of maintenance to a sand filter. The laboratory sand filters captured a greater total percentage of TSS (99.6-99.7%) than the geotextile filters (63.8%-94.5%). Yet, a sand filter generally clogs at a smaller mass of solid loads than the geotextile filters. The sand filters clogged at 3.45-4.08 kg/m$^2$, while the geotextiles clogged at 3.4-10.8 kg/m$^2$.

The clogging results indicated that a geotextile filter lasts more than 50% longer than a sand filter under urban stormwater conditions. After laboratory testing and the incorporation of various stormwater runoff parameters typical of Maryland, sand filters would require maintenance after only 147 days. On the other hand, a geotextile filter would only require maintenance after 231 days.

### 3.4.5 Maintenance and Cost

3.4.5.1 Construction Costs

As shown in Table 3-10, the initial construction cost of a sand filter when converted to constant 2012 dollars using consumer price index inflation rates (U.S. Department of Labor

(USDOL) 2012) is \$37,700 per hectare of impervious land cover (Houle et al. 2013). To compare with the construction cost as reported by Barrett (2003), it is suggested to refer to construction cost per WQV ($m^3$). Referring to Table 3-10, the Houle et al. (2013) cost is \$316/$m^3$ (assuming original cost); however, Table 3-11 shows cost per $m^3$ is between \$100-200 less (Barrett 2003). It is important to recognize the discrepancy, as this is a common theme when it comes to cost cross-referencing. For the purpose of this study, the inconsistency among cost can be attributed to location and time (year) of study.

**Table 3-10.** University of New Hampshire Stormwater Center (UNHSC) SCM Installation and Maintenance Cost Data, with Normalization per Hectare of Impervious Cover (IC) Treated, as documented by Houle et al. (2013)

| | |
|---|---|
| Original capital cost | 30,900 |
| Inflated 2012 capital cost | 37,700 |
| Water quality volume ($m^3$) | 97.7 |
| Cost/$m^3$ of WQV (Original cost) | 316.3 |
| Cost/$m^3$ of WQV (Inflated 2012 cost) | 385.9 |
| Maintenance-capital cost comparison (year)[1] | 5.2 |
| Hours of personnel/yr | 70.4 |
| Annual maintenance/capital cost (%) | 19 |

1. Number of years at which amortized maintenance costs equal capital construction costs.

Location can greatly affect the sand filter construction cost, as Table 3-11 shows varying base costs with respect to different locations. The base cost of all sites in Los Angeles is consistently higher in comparison to those in San Diego; this is because the condition of the media varied greatly between the two sites. In Los Angeles, all facility excavations were particularly deep, so extensive shoring was required during the construction phase. Also, pumps were required to return the treated runoff to the storm drainage systems. However, in San Diego, construction costs were significantly less because all devices were constructed to use gravity flow so the purchase, installation, and maintenance of pumps was not required. Also, the excavations were generally less deep, thus further reducing the total construction costs.

Barrett (2003) conducted a value engineering analysis on the La Costa sand filter to see if the installation of a settling basin would be more economically practical in the long-term. The analysis found that a basin of the same size and configuration would cost $161,000 in comparison to the $225,000 spent on the sand filter prototype. While this would reduce normalized cost from $200,000 to $150,000/ha, maintenance requirements would significantly increase. Therefore, Barrett (2003) concluded that the increased maintenance duties would outweigh the savings, making the installation of a settling basin not economically beneficial.

For the scope of this report, it is not suggested to formulate base costs and performance costs using information in Barrett (2003), based on date of publication.

**Table 3-11.** Construction costs of 5 retrofit sand filters by the California Department of Transportation (CALTRANS) as projects for maintenance yards and park-and-ride facilities in the Los Angeles and San Diego metropolitan areas as documented by Barrett (2003)

| Site | Location | Land Use | Base cost | WQV ($m^3$) | Cost/$m^3$ of WQV |
|---|---|---|---|---|---|
| Eastern regional | Los Angeles | Maintenance station | 246,986 | 115 | 2,980 |
| Foothill | Los Angeles | Maintenance station | 371,643 | 217 | 2,194 |
| Termination | Los Angeles | Park and ride | 353,850 | 222 | 2,088 |
| La Costa | San Diego | Park and ride | 165,444 | 286 | 788 |
| 78/I-5 | San Diego | Park and ride | 148,952 | 106 | 1,997 |

3.4.5.2 Maintenance Costs

Generally speaking, sand filters are considered a non-ideal SCM because of extensive maintenance requirements. Nevertheless, Barrett's (2003) three-year study on multiple Austin sand filters reveals that 49 hours per year are necessary for field activities (e.g., inspection, trash and debris removal, pump maintenance, dewatering, and media maintenance). Figure 3-17 shows that the most time-consuming maintenance activity is pump maintenance followed by inspection and media maintenance; most sand filters do not include a pump, thus significantly reducing the required maintenance hours. The high number of inspections and time spent for each inspection reflect a large majority during the wet season only. Again, while the maintenance times may seem high, it is also important to recognize the complications of the system at hand as access to sedimentation and filtration basins was severely compromised. Each of the basins was fitted with rung type ladders allowing maintenance personnel access. However, space was so limited that equipment access for major maintenance activities, such as sand replacement or cleaning of the sedimentation basin was infeasible (Barrett 2003).

Clogging of the sand filters occurred when the TSS load of the system was between 5 and 7.5 $kg/m^3$ of the filter area (Barrett 2003). Surprisingly, very little of the filter bed was utilized during the majority of storm events. There were even "parts of the filter bed that remained in their initial, prime condition" (Barrett 2003). The sedimentation basin would collect the stormwater in the lower areas and the entire filter bed would not be used because of the rapid infiltration rate. Therefore, a possibility exists to reduce the size of the filter bed; consequently this would increase maintenance frequency. The conclusion of this data study estimates that about 28 h/year of maintenance required activities due to the elimination of a level spreader, reduction of inspection frequency, and elimination of sites where a pump is needed. Clearly, this is a significant reduction from the initial predicted 49 h/year.

According to Houle et al. (2013) the annual maintenance cost as a percentage of the entire capital cost was the highest for sand filters in comparison to other SCMs (e.g., wet pond, dry pond, swale, bioretention system, subsurface gravel wetland, and a porous asphalt pavement). Furthermore, as indicated in Table 3-10, it will take about 5.2 years until the amortized maintenance cost equals the construction cost. However, it is important to recognize that maintenance and life cycle costs can also be measured from pollutant reduction. Particularly, if the pollutant of interest is TSS or another particulate-pollutant, then it is quite possible that a sand filter would be an optimal choice because of its affinity for particle pollutants via filtration and infiltration. Therefore, it is suggested that pollutant removal efficiency also be taken into consideration when measuring and comparing multiple SCMs for selection when cost is a primary concern.

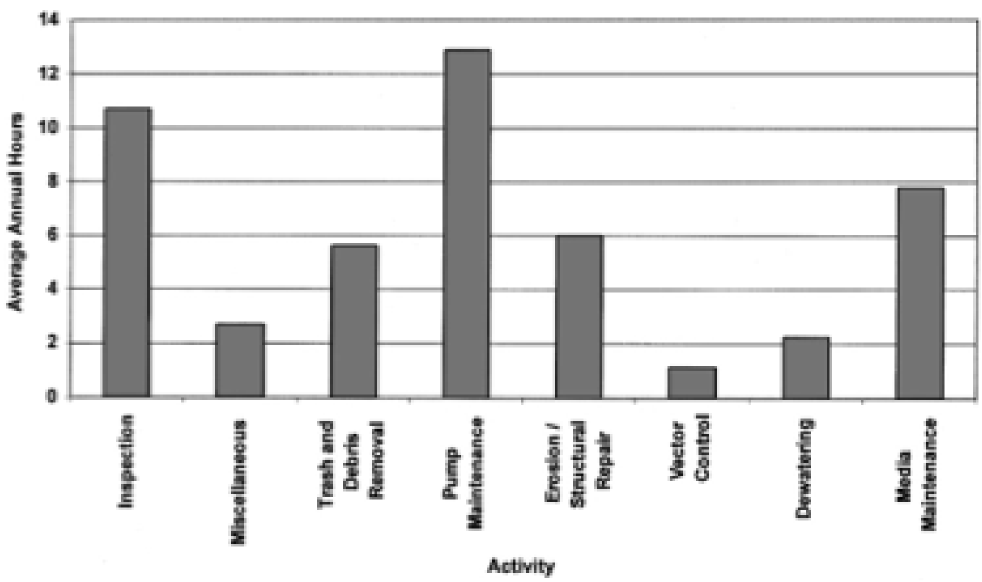


**Figure 3-17.** Field maintenance activities and respective average annual hours for sand filter sites as conducted by Barrett (2003).

### 3.4.6 Conclusions

Barrett's (2003) case study proved that the performance of pollutant removal by sand filters greatly depends on the phase of the pollutant – whether it is in the dissolved or particulate form. Examining the total effluent concentration of copper (dissolved plus particulate concentrations), performance from the sand filter could be misleading. It is recommended that the two phases be analyzed separately during evaluation for future research (Barrett 2003).

Furthermore, in order to better characterize SCM performance, it is suggested to report the effluent concentration rather than percent reduction. This will help determine if the discharged water meets the water quality standards and total maximum daily loads for the particular area (Barrett 2003). Finally, the report presented useful trends that all planners and/or engineers should consider when evaluating construction and maintenance with its respective costs.

- Construction cost will vary depending on site location
- Performance will vary depending on influent hydraulic and water quality properties
- The media properties will control the performance; ideally any media amendment(s) shall increase the removal of the pollutant(s) of interest

### 3.4.7 Future Research Recommendations

In order to improve dissolved phosphorus retention, it recommended for future studies to enhance C-33 sand media with 2% by weight steel wool fabric. Geotextile fabric can be implemented in multiple layers in order to increase retention time and thus improve water quality, specifically in regards to phosphorus removal.

While steel wool is promising, Erickson et al. (2012) suggested adding iron-filings to C-33 sand media, because it was cheaper than steel wool at the time of writing. This amended media has the possibility for implementation in other SCMs and is suggested for enhanced retention of dissolved phosphorus.

The following areas of research should be further explored to improve the current design and operation of sand filters as an identified SCM for managing runoff in Maryland.

- The possible use of shallow depth media for particulate matter removal
- Specialized media for dissolved pollutant removal in sand filters
- Use of denitrification chambers below sand filters for N removal
- Further media enhancements for P removal
- Media amendments targeted at dissolved N
- Geotextile filters as an alternative to sand filters
- Optimizing sand sizing in sand filters

## 3.5 Stormwater Management Wetlands

This subsection (*3.5 Stormwater Management Wetlands*) is a direct summary of the extensive recent review by Malaviya and Singh (2012). This study is the primary source regarding SWM wetlands and its applicability to multi-modal transportation systems. Regarding additional citations, these literature sources have been reviewed by Malaviya and Singh (2012) and cited when necessary within the context of this review. Malaviya and Singh (2012) examined the potential of SWM wetlands for stormwater treatment through a comprehensive literature review of the most current sources up to date of publication.

SWM wetlands (CWs) are engineered treatment systems that treat pollutants through biological, chemical, and physical processes, all of which are considered to be comparable to those occurring natural wetlands (Babatunde et al. 2008). The purpose of SWM wetlands is to "mimic natural wetland systems [which] offer a compromise between preservation of existing natural systems and exploitation of the unique biological and physiochemical processes of wetlands to remove low levels of contamination from large volumes of stormwater runoff" (Malaviya and Singh 2012). Figure 3-18 shows a generalized layout of an urban stormwater treatment wetland according to the California Stormwater Quality Association (2003). Figure 3-18 is directly comparable to shallow wetland with no noticeable differences.

The Maryland Department of the Environment (MDE) classifies stormwater wetlands into four major types– shallow wetland, extended detention shallow wetland, pond/wetland system, and pocket wetland (Maryland Stormwater Design Manual 2009). Shallow wetlands provide high water quality improvements in a shallow pool that has a large surface area. An extended detention shallow wetland provides water quality by a combination of shallow wetland and extended detention storage. A pond/wetland system differs from a shallow wetland for its deep permanent pool that is placed before the shallow wetland. In a pocket wetland, the high water table or groundwater interception helps maintain a shallow wetland pool.

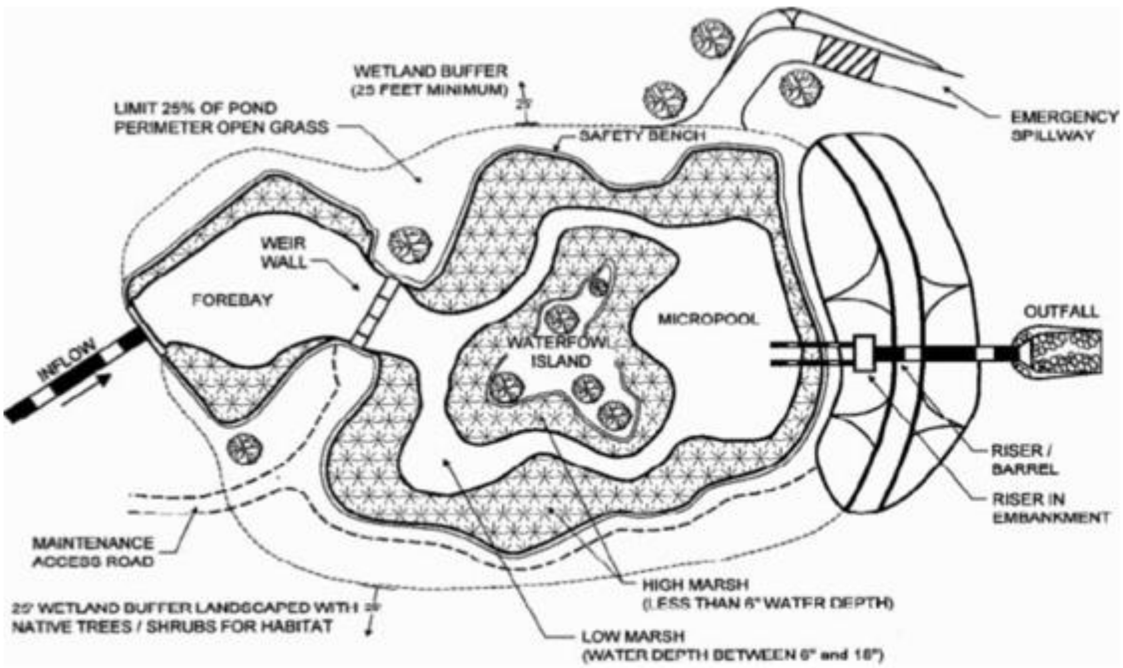


**Figure 3-18**. Common constructed wetland layout including forebay, low marsh, high marsh, and micropool from Maryland Stormwater Design Manual (2009).

### 3.5.1 Background

Natural wetlands are successful because they provide high levels of water treatment due to the ability of plants to uptake and/or degrade pollutants. However, new regulations in the U.S. protect natural wetlands from the accumulation of toxic chemicals, nutrients, and hydraulic loadings in wastewater (Kivaisi 2001); thus, natural wetlands are prohibited as a technology for stormwater management (Debusk et al. 1996).

There are two differences between natural and SWM wetlands. First, while the processes are intended to be analogous, processes in CWs are executed in a more controlled environment.

Secondly, the land required for a CW originates from a non-wetland ecosystem or a former terrestrial environment (Malaviya and Singh 2012).

### 3.5.2 Classification

Wetlands are classified based on macrophytes and the water flow regime of different rooted emergent systems (Brix 1994). The classification of macrophytes is broken down into three categories: (a) free-floating macrophyte-based systems, (b) submerged macrophyte-based systems, and (c) rooted emergent macrophyte-based systems. If CWs are categorized by water flow regime they include: (a) surface flow systems, (b) horizontal subsurface flow systems, (c) vertical subsurface flow systems, and (d) hybrid systems (Malaviya and Singh 2012).

Surface flow systems (SF) can easily be distinguished from subsurface flow systems (SSF). SF wetlands are densely vegetated and generally the depth does not exceed 40 cm. SSF wetlands include a bed or soil or gravel as substrate for the growth of the rooted emergent wetland plants. The direction of flow of the water, as controlled by gravity, determines whether the CW is classified as horizontal or vertical. The depth of a horizontal SSF is generally less than 0.6 m and the bottom is sloped to minimize flow above the surface. Meanwhile, in vertical SSF wetlands, water is added to the system via feeding and collection mechanisms. This is achieved by intermittent water application or by burying inlet pipes into the bed at a depth of 60-100 cm; the water is added directly into the bed, thus this CW is also called an infiltration wetland (Sundaravadivel and Vigneswaran 2001). A downside of subsurface flow systems is that they clog easily. Therefore, runoff with high concentrations of TSS and total solids are not recommended for these systems (Hammer 1994). Based on this information, FSS CWs are not a feasible SCM to implement to improve water quality from urban stormwater runoff.

The final CW is a hybrid system. Cui et al. (2009) recently constructed a hybrid CW by incorporating multiple types of CWs into a single system. This system was found particularly useful for removing nitrogen from the water (Cui et al. 2009).

### 3.5.3 General Design Guidelines

The design of a CW is to exploit physical, chemical, and biological processes of the system to enhance water quality (Imfeld et al. 2009). The ability of a CW to improve water quality is dependent on particular vegetation, sediments and soil, microbial biomass, and an aqueous phase containing the pollutants. The use of stormwater wetlands is limited by specific constructs, including soil types, depth to groundwater, contributing drainage area, and available land area (Malaviya and Singh 2012). Ideally, the CW is designed to treat organic matter, nitrogen, phosphorus, heavy metals, organic metals and pathogens (Haberl et al. 2003).

#### 3.5.3.1 Application to Linear Highway Networks

Pollutant characteristics from highway runoff (HRO) are functions of traffic characteristics (e.g., speed limit, traffic load), climate, long dry/wet periods, and rainfall intensity and durations (Crabtree et al. 2006). In the past, multiple studies have been completed where CWs were able to effectively manage HRO (e.g., Shutes et al. 1997; Shutes et al. 1999; Mitchell et al. 2002; Bulc and Slak 2003). Therefore, clear treatment goals for both water quantity and quality must be identified prior to defining appropriate design and operation parameters for any CW (Imfeld et al. 2009). All of the aforementioned studies included a first flush sedimentation tank, horizontal flow CW, wet pond, and a final vegetated retention area. While not included in all of these studies, a final settlement tank is recommended assuming sufficient land area. It should have a minimum water treatment capacity of 50 $m^3$ that extends across the width of the

CW. A final sedimentation basin will help to prevent fine sediments from entering the receiving water body (following the CW treatment facility) (Shutes et al. 1999).

CWs will not develop fully for 1-3 years post construction. Until the system is mature, it will not be capable of efficient treatment. The entire system must be installed and mature before it can manage HRO (Shutes et al. 1999).

#### 3.5.3.2 Forebay

MDE requires a forebay in the design of a CW. Influent HRO pollutant loadings consist of high levels of sediments. The forebay is commonly located before the micropool (Figure 3-18). The forebay traps the majority of sediment before the HRO enters the micropool.

#### 3.5.3.3 Soil

Ideally for soil type, it is recommended to install medium-fine textured soils for CWs (e.g., loams and silt loams). These soils are optimal for culturing vegetation, retaining surface water, promoting groundwater recharge, and capturing pollutants. For managing urban runoff, gravel is also a viable option for CWs. It provides the most suitable substrate for emergent plants growing in CWs, supporting adequate root growth and superior permeability (Shutes et al., 1999).

#### 3.5.3.4 Plant Selection

Vegetation highly varies the level of water quality treatment the CW can perform. It can be established by three methods: allowing natural vegetation to establish (not recommended), planting nursery vegetation, and seeding. While a higher diversity of plants can be established via the nursing method, it is important that this method only be executed during the growing season. Optimal plant selection is dependent on the following factors: type of wetland design (e.g., surface or subsurface, vertical flow or horizontal flow), the mode of operation (e.g., continuous, batch, or intermittent flow), and the loading rate and characteristics of influent waters (Cui et al. 2009).

Vegetation is important to the success of a CW because it helps reduce the velocity of the entering runoff. The reduced velocity is the primarily responsible for sediment and nutrient retention (Jones 1996). Therefore, it is suggested to consider vegetation whose stems persist even after the growing season. This provides year-round resistance to water flow. These plants include cattail (*Typha sp*.), iris (Iris *pseudacorus* or *I. versicolor),* rush (Juncus sp.), cordgrass (Spartina sp.), reedgrass (Calamagrostis sp.), sawgrass (Cladium *jamaicense),* and switchgrass (Panicum *virgatum)* (Malaviya and Singh 2012).

Two plants of particular interest are the common reed (Phragmites *australis)* and the reedmace (Typha *latifolia).* These two species have a large biomass both above (leaves) and below (underground rhizome system) the surface of the substrate. In the water, the plant tissues grow in all directions, creating an elaborate matrix, which is used to bind soil particles and provides a large surface area for the trapping/uptake of nutrients (Shutes 2001).

A treatment system dominated by submerged aquatic vegetation (SAV) is one of several advanced treatment technologies that was evaluated by the South Florida Water Management District and Florida Department of Environmental Protection (Knight et al. 2003). Many have observed that shallow aquatic systems dominated by SAV result in improved water quality in terms of clarity, TSS, pH, TP, and TN (Canfield and Hoyer 1992; O'Dell et al. 1995). This is because SAV systems have the ability to utilize nutrients from the water column and sediments. Since SAV typically occupy the majority of volume of the water column, it is able to remove nutrients without comprising the hydraulic flow in the column. As a community, the SAV can filter, detain, and cause sedimentation of suspended solids that contain organic P or adsorbed inorganic P (Malaviya and Singh 2012). Depite its seasonal nutrient removal performance, SAV does not provide significant frictional resistance to suspended sediments, thus it does not significantly reduce the velocity of runoff (Jones 1996).

3.5.3.5 Sizing

When designing CW for HRO, a few important parameters must be kept in mind. First, it should be large enough to retain the first flush of heavier (intensity and duration) storms. It should retain an average annual storm volume for a minimum of 3-5 hours; for an optimal design, this time should increase to 10-15 hours. For the CW design, the following criteria are recommended: a retention time of 24 hours, an aspect ratio (width:length) of 1:1 to 1:2, a slope of wetland bed of 1% maximum, a minimum substrate bed depth of 0.6 m, a substrate of 0.15 m of soil over 0.45 m pea gravel, and a substrate hydraulic conductivity of $10^{-3}$ m/s to $10^{-2}$ m/s (Shutes et al. 1999). Flow velocity should not exceed 0.3–0.5 m/s at the inlet zone to ensure effective sediment retention and removal. The inlet pipe must be carefully constructed so that optimal velocity is maintained across the width of the bed and the risk of clogging is minimized. Slotted inlet pipes are recommended where the slots are sufficiently large to prevent clogging by algae. Again, the velocity shall not exceed 0.7 m/s because high flow may damage the plants physically and deplete the effectiveness of the system (Shutes et al. 1999).

3.5.3.6 Location of CW

It is not necessary to implement a CW directly beside the road. However, if land area permits, centers of roundabouts and areas between the arms of slip roads can be optimal locations. (Shutes et al. 1999).

### 3.5.4 Performance

Unfortunately, Malaviya and Singh (2012) focus primarily on CW design rather than performance. Furthermore, the only quantitative information reported was in terms of percent removal; for the premise of this review, such a quantitative measurement is not indicative of actual performance. Thus, further discussion concerning qualitiative performance can only amount to generalizations.

The ability of a CW to successfully treat stormwater is a function of storm intensity, runoff volume, and wetland size (area and volume)(Barten 1987; Meiorin 1989; Carleton et al., 2001). The inflow rate of stormwater will affect retention time and thus, the degree of bottom scouring and resuspension of settled solids. The volume (size) of a CW will determine the fraction of capture from a storm.

CWs are successful in treating urban stormwater runoff as noted in multiple studies (Shutes et al. 1997; Shutes et al. 1999; Mitchell et al. 2002; Bulc and Slak 2003). Generally speaking, CWs are optimal for treating urban stormwater runoff because they can operate effectively under a wide range of hydraulic loads. Specifically, CWs are capable of water storage and peak-flow attenuation (DeLaney 1995), nutrient cycling and burial (Reddy et al. 1993), metal sequestration (Odum et al. 2000), sediment settling (Kadlec and Knight 1996) and breakdown of organic compounds (Knight et al. 1999). Barten (1987), Carleton et al. (2001), and Meiorin (1989), all suggest that CW performance is dependent upon hydraulic loading rate and detention time; consequently, the performance of CW is a function of storm intensity, runoff volume, and size (area and volume). The characterization of the contributing (non-homogeneous) watershed (i.e., deliniation to calculate a runoff coefficient) helped to estimate the long-term total hydrologic inputs and outputs (Carleton et al. 2001).

Carleton et al. (2001) further explains the CW performance as function of wetland strucutre and hydrology, climate, soils, vegetation, percent watershed imperviousness, etc. This studied modeled long-term pollutant removal using the same first-order steady flow design equations used for wastewater treatment wetlands, as a function of hydraulic loading rate and detention time. $NH_3$ and $NO_2$-$_3$ removals are a function of hydraulic loading rate, while TP removal is primarily influenced by mean detention time. During intermittent high inflow rates, TP settled solids may resuspend. This offsets the influence of a low mean hydraulic loading rate and decrease the overall removal of TP. Two major points from this study include a new methodology to calculate treatment area of the CW and prediction of long term performance. The rate constatns presented can be used together with a procedure (i.e., Wong and Geiger 1997) to calculate the area necessary to achieve a given degree of treatment by a CW. Furthermore, the long term performance can be predicted on the basis of the ratio of wetland surface area to contributing watershed area.

The removal of nutrients and solids in CWs relies on shallow water, high primary productivity, presence of aerobic and anaerobic sediments, and accumulation of natural litter (Mitsch and Gosselink 1993). Slow water flow allows for TSS to settle. Nitrogen is removed primarily by physical settlement, denitrification, and plant/microbial uptake (Bulc and Slak 2003).

#### 3.5.4.1 Performance Metrics

Lenhart and Hunt (2011) constructed and monitored a CW in the coastal plain of North Carolina to better evaluate the SCM under four different water quality metrics – (1) concentration reduction, (2) load reduction, (3) comparison to nearby ambient water quality monitoring stations, and (4) comparison to other wetlands studied in North Carolina. Measuring water quality based on concentration reductions should poor and even negative removal of the majority of pollutants. However, pollutant load measurements showed significant reduction due to intermittent storm infiltration and ET loss, to a point where discharge concentrations were similar to ambient river conditions for most pollutants. For this reason, it is important to consider the latter two metrics alongside pollutant load reductions. When comparing the performance of the River Bend CW to nearby monitoring stations, the mean TP inflow and outflow concentrations at the River Bend, N.C. wetland were greater than the 90% high concentrations at the ambient monitoring stations. Furthermore, the minimum TSS inflow and outflow concentrations at the River Bend wetland were approximately equal to the 90th percentile in-stream concentrations. Such high pollutant concentrations can be explained through comparison of other wetlands studied in NC. The River Bend wetland received lower concentrations compared to other studies for a majority of the pollutants. For example, TKN, $NH_4$ – N, and TN, influent concentrations were lower than the effluent concentrations from all other sites. It is possible that the wetland is not expected to significantly improve water quality when influent pollutant concentrations are so low.

Aerial atmospheric pollutant loadings from a CW study conducted in Manassas, Virginia, were comparable to results from other studies in the Washington, D.C. area. Comparison to other studies identified the watershed as a sink for high loadings of ammonium-N and net sources of organic N, P, and some metals to account for high influent loadings (Carleton et al. 2000).

Therefore, the water quality improvement of a CW should not solely rely on concentration reduction as an indication of performance. Results from each metric inevitably lead to different conclusions regarding pollutant reduction. Instead, water quality results should also be compared to nearby ambient water quality monitoring stations, and to other wetlands studied in the same region. Hydrologic improvements indicate that the CW reduced outflow peaks by an average of 80% and reduced runoff volume by an average of 54%. In almost every monitored event, a reduction in volumes occurred. Thus, according to Lenhart and Hunt (2011), CW should be considered a LID tool in a sandy soil area.

### 3.5.5 Maintenance and Cost

#### 3.5.5.1 Construction Cost

Little published data are available concerning construction costs for wetlands. However, it is possible to make certain assumptions when predicting cost of a CW. For instance, Brown and Schueler (1997) evaluated actual costs for 73 stormwater facilities in the mid-Atlantic region. Brown and Schueler (1997) assumed that CWs are 25% more expensive than stormwater ponds designed for an equivalent volume. Brown and Schueler (1997) developed Equation (3-2) to estimate the cost of a stormwater wetland:

$$C = 30.6^{0.705V} \quad \text{Eq. 3-4}$$

where: C = construction, design and permitting cost

V = volume needed to control 10-year storm ($ft^3$)

The total area of a CW is about 3-5% of the total land that drains to it. Compared to other SCMs this is particularly high. Moreover, in areas where land value is high, this will further increase the construction cost and potentially make this SCM impractical (Malaviya and Singh 2012). This conclusion follows the findings of Weiss et al. (2007) who conducted a comparative study between various HRO treatment options. The study concluded that wetlands are the most cost-effective systems in North America; however, this conclusion did not include land cost as a factor. Unfortunately, Weiss et al. (2007), as with most publications, did not provide a cost breakdown of the entire project.

Manios et al. (2009) also suggested that the excavation cost for the construction of wetlands should be a considerable construction cost variable. Typically, designers ignore this parameter but it comprises at least 20% of the construction cost. For this field-study, a storage tank was recommended as a control device to smooth the flow into the CW. The construction of a storage tank was at least 25% of the total construction cost. Another important conclusion of this study was the superiority of free water surface (FWS) systems. These systems are more suitable for the treatment of HRO both financially and construction-wise in comparison to SSF systems (Manios et al. 2009).

3.5.5.2 Maintenance

CWs require specific routine maintenance. The small forebay should be cleaned every year to prohibit excessive sediment buildup. Following the first three years of construction, biannual inspections are required during the growing and non-growing season. The main objective of these inspections is to monitor and regulate the sediment buildup. For optimal performance, the forebay should collect the majority of the sediments before the runoff enters the CW. This will ensure minimal accumulation of sediments in the wetlands; consequently, there will be minimal changes to water depth and changes in growing conditions, which can have a negative impact on the vegetation. Mosquito fish (*Gambusia sp.)* should be added to the CW to enhance natural mosquito and midge control. An annual vegetation harvest in summer appears to be optimum, because it is after the bird breeding season and mosquito fish can provide the needed control until vegetation reaches late summer density. Also, this allows time for re-growth for runoff treatment purposes before the wet season (California Stormwater Quality Association 2003).

### 3.5.6 Conclusions

Undoubtedly, CWs are effective for managing urban stormwater runoff. However, for the premise of SHA (along with other highway agencies), municipalities, and other MS4 permittees, the lack of quantifiable performance must be addressed. The purpose of implementing CWs is to improve water quality standards in accordance to Chesapeake Bay TMDL regulations; yet, without consistent, fully documented results, there is no guarantee that a CW will perform to standards. Therefore, further research must be conducted to evaluate CW performance based on influent and effluent concentrations under a variety of hydraulic loadings and design conditions.

Continuing the trend of minimal quantifiable data, the construction, maintenance and life cycle costs can be very misleading. While literature provides some indication of cost, it only displays certain tasks (e.g., excavation) as a percentage of total cost. Furthermore, while extensive maintenance procedures are outlined, there is a lack of time and associated costs. Therefore, in future studies, it is recommended to keep strict logging hours of maintenance procedures, expenditures, and additional costs employed for CW treating HRO.

### 3.5.7 Future Research Recommendations

The following areas of research should be further explored to improve the current condition of SWM wetlands as an identified SCM for managing runoff in Maryland.

- Water quality performance under a variety of hydraulic loadings
- Extensive field monitoring of Maryland constructed wetland
- Effects of forebay addition
- N processing
- P processing

- Performance in treatment train configuration
- Long term performance

## 3.6 Miscellaneous SCMs

The following section briefly discusses several additional SCMs – (1) infiltration basins, and (2) porous friction courses (PFCs). Finally, discussion concludes with an overview of street sweeping, an identified suitable non-structural practice compatible with urban areas.

### 3.6.1 Infiltration Basins

3.6.1.1 Introduction

Infiltration basins, as shown in Figure 3-19, and other SCMs that incorporate the process of infiltration are an integral faction of many LID technologies. Infiltration helps to restore the hydrology of a specified area to pre-developed conditions via significant volume reduction. Even though SHA does not currently construct infiltration basins, they have in the past. A scenario could exist where SHA would construct one to retrofit an existing infiltration trench or basin facility. An infiltration basin is constructed below the ground surface and can allow for ground water recharge as water infiltrates to the surrounding soils (assuming there is no subdrain in the design). Extended retention time and infiltration can improve the quality of runoff entering the groundwater or another external body of water.

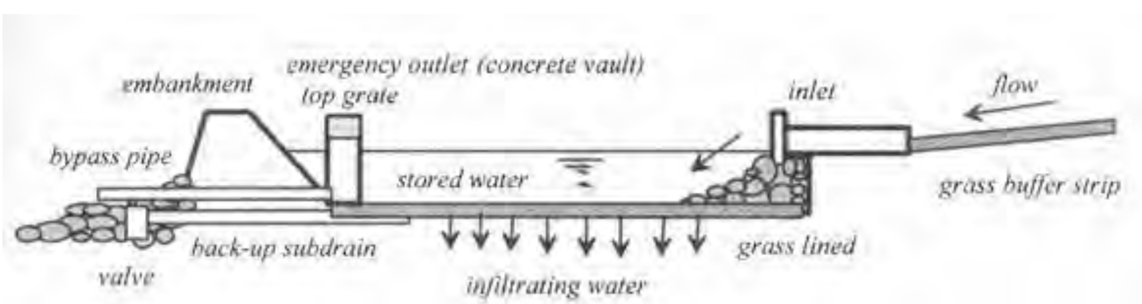


**Figure 3-19.** Side Profile of Infiltration Basin
Source: Qin et al. (2004)

In comparison to Figure 3-19, Figure 3-20 shows SHA's design of an infiltration basin. While SHA does take into account multiple storm year designs, this may not be sufficient according to current research recommendations because it does not take into account the continuous infiltration of the stored runoff into the underlying soil. It is possible the design could be oversized depending on the physical location the basin and the underlying soil characteristics.

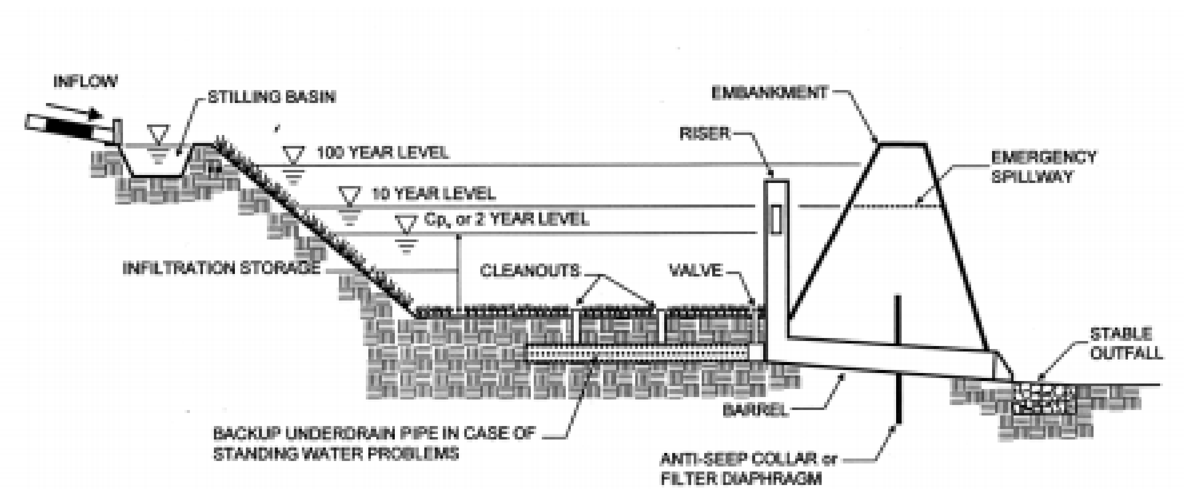


**Figure 3-20.** SHA design of an infiltration basin according to Maryland Stormwater Design Manual (2009).

### 3.6.1.2 General Design Guidelines

When discussing the design of an infiltration basin, it is not possible to refer to a standardized model because this does not exist. The two variables that greatly affect the performance of an infiltration basin are the surrounding soil properties (i.e., hydraulic conductivity) and the physical sizing/location of the basin. It is relatively simple to size an infiltration basin to physically hold to the predetermined water quality volume (WQV); however, this approach does not take into consideration the continuous infiltration of the stored runoff into the underlying soil. Without proper consideration of volume attenuation within the surrounding soils, the basin maybe oversized, which can lead to higher construction and subsequent maintenance costs.

#### 3.6.1.2.1 Hydraulic Conductivity

Braga et al. (2007) found that hydraulic conductivity is the dominant factor in regards to the infiltration rate. Braga et al. (2007) thoroughly evaluated the soil parameters that affect infiltration including, soil suction pressure head, volumetric soil moisture content and hydraulic conductivity before coming to this conclusion, which Emerson and Traver (2008) then adopted. Emerson and Traver (2008) extensively monitored two infiltration basins at Villanova University (PA). The findings from both infiltration basins concluded that the process of infiltration "follows a cyclic pattern with its highest values typically occurring in late summer and lowest in late winter" (Emerson and Traver 2008; Emerson et al. 2010). This follows a similar pattern of the changes in the hydraulic conductivity resulting from temperature-induced viscosity changes (Emerson and Traver 2008; Emerson et al. 2010). Other processes that affect the rate of infiltration are evaporation and biological processes.

#### 3.6.1.2.2 Siting and Sizing

An infiltration basin at Villanova University has the following dimensions: 1.8 m deep, 3.9 m long, and 3 m wide as documented in Emerson and Traver (2008) and Emerson et al. (2010); unfortunately the authors did not provide a schematic of the system that was documented. Despite seasonal variations of infiltration rates (i.e., the temperature dependency of the viscosity of water), the infiltration basin does not exhibit any evidence of a systematic decrease in performance. However, Emerson and Traver (2008) did find a significant decrease of infiltrated stormwater runoff after three years at the bottom of the basin, while infiltration through the sides remained active even after 3 years. The bottom infiltration was measured in incremental recession rates where rates began at 10 cm/h and after three years later approached 1 cm/h.

Both studies speculate that it is the ratio of the SCM's impervious drainage area to the SCM footprint that will result in the sooner-than-expected failures of the system (i.e., the bottom area infiltration failure). The basin's ratio is approximately 160:1; current PA design guidance for an infiltration trench recommends a 5:1 ratio (PADEP 2006). Thus, the higher ratio was purposely implemented to artificially accelerate longevity-related processes and exacerbate pollutant loadings. Furthermore, the 18 kg of suspended solids captured on the bottom led to an exponential clogging process. As the trench aged, the bottom of the trench likely became clogged to the point where additional suspended solids had little impact on the performance. This is the most likely explanation as to why the 2-3 year data showed only minimal change in regards to decreased infiltration rate. Furthermore, the clogging on the bottom had minimal to no impact on the performance of the sidewalls of the trench.

Specifically looking at the site location of the infiltration basin, the area had an excessively high areal loading rate, no pretreatment of influent runoff, and relatively deep storage bed (Emerson et al. 2010). Therefore, an infiltration basin must be "sited where the sediment load of the contributing area is minimized and pretreatment should be used to the maximum extent possible" (Emerson et al. 2010).

3.6.1.3 Failed Infiltration Basin

Natarajan (2012) studied a failed infiltration basin facility that was designed to treat highway runoff on I-95 in Maryland, U.S.A. Through continuous hydrologic and water quality sampling, the research study showed that the basin was naturally transforming into a wetland and/or wetpond-like practice. The transforming basin effectively reduced highway runoff via flow attenuation, and total volume and peak flow reductions. Sedimentation (TSS), adsorption (metals and phosphorus), and denitrification mainly controlled water quality improvements (i.e., pollutant EMCs and pollutant mass) for all parameters during both storm events and dry-weather periods.

The natural transformation of this basin leaves important hydrologic and water quality implications for future SCM implementation. Ultimately, this study can lead to more widespread and reliable implementation of SCMs.

3.6.1.4 Conclusions

The conclusions of Emerson and Traver (2008) can have important effects on future research, design, and continual monitoring. While Emerson and Traver (2008) only intensely monitored the basin for a relatively short period of time (in compared to expected lifecycle), the study highlighted the importance of long-term continuous monitoring. Such findings do not suggest any detrimental decrease in performance (i.e., clogging). It is possible that clogging processes are either (1) so small it can be insignificant on the effect of ponding or (2) counteracted by processes that improve the hydraulic properties of soil (Emerson and Traver 2008). Furthermore, when a system is subject to continuous long-term monitoring, temperature measurements must be an integral part of the data collection and analysis. As part of this continual monitoring plan, Machusick et al. (2011), who also worked on the same infiltration basin at Villanova University, emphasized the importance of groundwater monitoring to further hydraulic performance assessment and subsequent understanding. For this reason, Machusick et al. (2011) recommends, "groundwater monitoring be considered as a [SCM] site selection design tool and for site monitoring plans".

Since the infiltration rate is highly dependent on temperature, then the geographic and climactic conditions must be considered to ensure effective design. Consequently, the storage volume should be sized such that the SCM will sufficiently capture designed volumes of precipitation, even during periods of slower infiltration rates.

3.6.1.5 Future Research Recommendations

The following areas of research should be further explored to improve the current condition of infiltration basins as an identified SCM for managing runoff in Maryland.

- Effect and degree of clogging over lifecycle of infiltration basin
- Groundwater monitoring
    - Previous to SCM installation
    - Over the lifecycle
- Sizing of the basin as a function of temperature, and consequently geographic and climatic conditions
- Infiltration basin in treatment trains
- Pretreatment for infiltration basins
- Long-term continuous monitoring
- N and P removal

### 3.6.2 Porous Friction Courses (PFCs)

A porous friction course (PFC) is a "sacrificial layer of porous asphalt approximately 20 inches thick that is placed as an overlay on top of an existing conventional asphalt surface" (Barrett 2008). It has been used extensively in Texas, but also in North Carolina.

3.6.2.1 Introduction

Currently, the primary objective of PFCs is to minimize backsplash on highways. Further recognized benefits include reduced splash and spray, better visibility, better traction, reduced hydroplaning and less noise (Stotz and Krauth 1994; Berbee et al. 1999). Nonetheless, PFCs show relatively high potential to reduce the effluent concentration of pollutants within the porous structure (Barrett 2008). It differs from other SCMs because its success does not rely on infiltration or volumetric reduction of surface runoff from impervious surfaces (Eck et al. 2012).

Rather, a PFC's porous nature allows for the penetration of rainfall onto the original impervious road. As shown in Figure 3-21, water is transported "along the boundary between the pavement types until the runoff emerges at the edge of the pavement" (Barrett 2008).

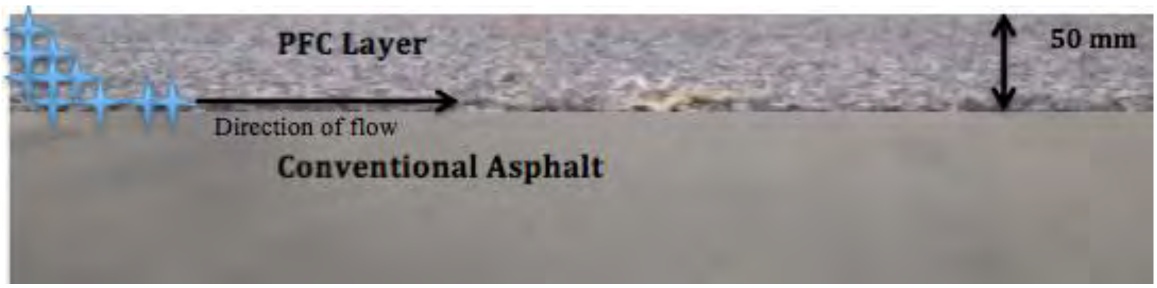


**Figure 3-21.** Incorporation of a PFC layer on asphalt and corresponding direction of flow
Adopted from: Klenzendorf et al. (2012)

### 3.6.2.2 Water Quality Performance

Many state transportation agencies, especially in Arizona, Georgia, Texas, California and Utah, are very interested in PFCs for their ability to remove or prevent pollutants from entering runoff. Generally, PFCs are exceptionally effective at removing particles and particulate bound pollutants, but exhibit poor (and often negative) removal of dissolved pollutants. In comparison to conventional asphalt, PFCs are highly capable of removing TSS from stormwater (Tables 3-13 and 3-14). However, the percent removals of dissolved pollutants such as $NO_{x,}$ phosphorus, and heavy metals (Cu and Pb) are significantly lower than TSS, and in some instances negative (i.e., leaching of a particular pollutant). Eck et al. (2011) monitored water quality at sites where paired data were collected from both PFCs and conventional pavement. The removal of nitrogen was negative (6-46%), that is nitrogen leached into the system, thus acting counterproductive (Eck et al. 2011). Following this trend, Barrett (2008) even found a doubling of dissolved phosphorus with a PFC overlay project on this section of Loop 360 in Austin, Texas.

The pollutants drain through the porous layer to the roadside rather than on directly on top of the pavement (Eck et al. 2011). Results from Eck et al. (2011) conclude that PFC water quality benefits last through the 10-year design life of the system. These results in both Texas and North Carolina were consistent with one another and previous studies in Texas (Barrett et al. (2006); Barrett and Shaw (2007); and Barrett (2008).

**Table 3-12**. Relative percent difference in runoff pollutant concentrations at sites where paired data were collected from both PFC and conventional pavement, as adopted from Klenzendorf et al. (2012)

| Monitoring Location | Data Source | TSS | $NO_3/NO_2$ | TKN | TP |
|---|---|---|---|---|---|
| A9, The Netherlands | 1 | -91% | N/A | N/A | N/A |
| Loop 360, TX (1) | 2 | -93% | 6% | -25% | -75% |
| Loop 360, TX (2) | 2 | -91% | 31% | -49% | -66% |
| A11, France | 3 | -81% | -69% | -43% | N/A |

TSS = total suspended solids; $NO_3/NO_2$ = nitrate/nitrite; TKN = total Kjeldahl nitrogen; Total P = total phosphorus; N/A = not available; TX = Texas. Note: Negative values indicate lower pollutant concentrations from PFC when compared to conventional pavement. Data sources: (1) Berbee et al., 1999; (2) Eck et al., 2011 (3) Pagotto et al., 2000.

**Table 3-13**. PFC performance from the initial monitoring site at Loop 360 in Austin, TX as adopted from Barrett (2008)

| Constituent | Conventional Asphalt | PFC | Reduction % |
|---|---|---|---|
| TSS (mg/L) | 118 | 8.8 | 93 |
| TKN (mg/L) | 1.13 | 1.09 | 3 |
| $NO_3$ / $NO_2$ (mg/L) | 0.43 | 0.41 | 6 |
| Total P (mg/L) | 0.13 | 0.08 | 36 |
| Dissolved P (mg/L) | 0.04 | 0.08 | −100 |
| Total copper (μg/L) | 27 | 13 | 52 |
| Dissolved copper (μg/L) | 5.9 | 9.8 | −66 |
| Total lead (μg/L) | 12.6 | 1.5 | 88 |
| Dissolved lead (μg/L) | <1.0 | <1.0 | N/A |

PFCs rely on filtration to remove pollutants, and thus dissolved pollutants will simply infiltrate the SCM without treatment. Eck et al. (2012) conducted a careful particle size analysis to better understand the role of particle processes on runoff water quality. It was concluded that in the < 3 μm range PFC is as effective, if not more, than filter strips, and comparable to a sand filter.

3.6.2.3 Maintenance and Cost

An important drawback of PFC deals with the uncertainty of its life cycle, and thus, the ambiguous quantification of cost and maintenance. A reoccurring theme in the literature is the uncertainty of the longevity of such heightened success with respect to particulate pollutants (Baladès et al. 1995; Pratt et al. 1995; Hunt and Collins 2008; USEPA 2009).

Consequently, many have determined that the relative age of the PFC influences the relative success of the SCM to reduce the total pollutant loading. Stotz and Krauth (1994), Berbee et al. (1999), Paggotto et al. (2000), and Barrett et al. (2006) all sampled runoff from relatively young PFCs (3 years old or less). Moores et al. (2013) tested multiple PFC sites of various ages in hopes to quantify its performance with respect to age. Collectively, the results confirmed findings in Berbee et al. (1999) and Barrett et al. (2006), that is, the quality of runoff may depreciate over the lifetime of the system. Moores et al. (2013) collected runoff samples at the Redvale state site over a 6-year lifespan, in Auckland, New Zealand, which contained significant concentrations of pollutants in the particulate form – suspended solids, copper, and zinc. Furthermore the data collected from this site strongly resembled those collected from impervious surfaces at Huapai and Westgate, two miles away; thus the system failed to perform as originally intended. The deterioration in runoff quality from Redvale PFC highlights the pertinent effects of clogging, which Lane (2008) has also reported. Since PFCs act as a filter, particles and particle-associated pollutants accumulate in the pores of the structure. With such accumulation, the effectiveness of the SCM reduces and the probability of the surface pavement responding to runoff resembling conventional pavement increases.

In order to combat the inevitable clogging and eventual failure, aggressive cleaning and maintenance methods are recommended. In Europe this includes vehicles designed to clean pavement and specifically retain the integrity of the PFC structure (Barrett et al. 2008). Others argue that maintenance beyond the periodic milling and resurfacing that occurs due to structural considerations is necessary (Eck et al. 2012).

3.6.2.4 Conclusions

While one cannot ignore the relative success of PFCs for particulate-based pollutants, the uncertainty related to life cycle, cost and system performance suggest that further research and testing in imperative (Barrett 2008; Moores et al. 2013). It is important to focus future research efforts on the effect of temperature on water quality performance.

3.6.2.5 Future Research Recommendations

To the authors' knowledge, PFCs have not been used in Maryland. The following areas of research should be further explored to improve the current condition of porous friction courses as an identified SCM for managing runoff in Maryland.

- Evaluate PFC performance in Maryland
- Removal of dissolved pollutants
- Possible change in the removal patterns and efficiency of particulate and dissolved pollutants over the lifecycle
- Impacts of freezing and colder temperatures

### 3.6.3 Street Sweeping

The following section discusses the current state-of-knowledge of street sweeping. The discussion is, primarily, a summary of the information presented by Kang et al. (2009) "Storm-Water Management Using Street Sweeping". This publication reflects the most current available peer-reviewed information concerning the non-structural SCM, street sweeping.

#### 3.6.3.1 Introduction

Street sweeping is typically used to pick up larger particulate matter – litter (any anthropogenic material) and natural origin debris (gravel and vegetation) to improve aesthetics (Kang et al. 2009). The efficiency will vary greatly based on sweeping frequency, sweeper operating speed, sweeping technologies, operator care, and initially deposited sediment load (Sutherland and Jelen 1997; USEPA 1999; Curtis 2002). Unfortunately of these previously published studies, little provide any insight of its ability to improve water quality directly following a storm. Furthermore, when assessing improvements to stormwater runoff quality, it is the ability of a street sweeper to pick up fine particulates that has the most significant impact.

#### 3.6.3.2 Classification

Currently, there are three distinct street sweeper technologies – mechanical broom sweeper, regenerative air sweeper, and vacuum assisted sweepers. Mechanical broom sweepers are the most well known due to lower capital and operational costs (Keating 2002). While it is can be operated at high speeds with low noise, providing more flexibility in sweeping schedules, mechanical street sweepers do not have a high efficiency removal of fine particles (Kang et al. 2009). A regenerative air sweeper first uses an air jet to raise particles on the street surface, and subsequently these particles are then captured via a vacuum up into a hopper. This type of sweeper can pick up most gross pollutants as well as fine particles with a higher efficiency compared to mechanical broom sweepers (Sutherland and Jelen 1997). A vacuum assisted sweeper uses a mechanical broom to place materials in the path of a vacuum intake that transports captured materials into a hopper (Kang et al. 2009). It is the most effective among the three types for removing fine particles. However, a vacuum assisted sweeper has a reduced efficiency in the removal of large materials and wet vegetation (Schilling 2005) as well as a low operating speed (Curtis 2002).

3.6.3.3 Performance Review

At the risk of oversimplifying the problem at hand, one may consider the following scenario – a greater frequency of sweeping will result in higher sweeping efficiency at the expense of higher associated cost. However, the exact efficiency of a street cleaner cannot be determined. Rather it is direct consequence of external factors such as the source area, land-use activities, operation skill, sweeping time, and antecedent dry period (Walker and Wong 1999). Therefore, the specified frequency and thus, removal efficiency of a street cleaner must be determined site-by-site.

This literature review particularly reevaluated 15 event mean concentration (EMC) datasets in order to formulate statistical power values to assess the probability of rejecting the hypothesis “that street sweeping does not cause reduction in EMCs” (Kang et al. 2009). Thus, the authors hoped such reevaluation of previously published datasets would show measurable reduction for TSS with high statistical power and no reduction for COD with low statistical power. Of the 15 datasets, only 4 had sufficient numbers of samples to produce high power values; of these, only 1 (Irish et al. 1995) detected a water quality improvement after sweeping for TSS in Austin, TX. The results of Irish et al. (1995) correlated with the proposed solution of

Kang et al. (2009): “That is, after street sweeping, measureable reduction was observed for TSS with high statistical power and no reduction was observed for COD with low statistical power” Kang et al. (2009).

### 3.6.3.4 Conclusions

Kang et al. (2009) recognized the shortcomings of previous studies to detect a difference in water quality from swept and unswept conditions. A limited number of observations, sweeping frequency, buildup rate, and rainfall characteristics are important factors that inhibit the ability to accurately characterize street sweeping performance. Thus, an accurate environmental impact of street sweeping is still not available in literature to date. Yet, Kang et al. (2009) is hopeful that new studies using modern sweeping technology and better statistical designs to detect probable differences will be possible.

### 3.6.3.5 Future Research Recommendations

The following areas of research should be further explored to improve the current condition of street sweeping as an identified non-structural SCM for managing runoff in Maryland.

- Matching street sweeping performance to water quality improvements
- Sweeping frequency evaluations
- N removal
- P removal

# Chapter 4: Maintenance and SCM Economics

Successful stormwater management must be mindful of proper maintenance and inspection procedures as to preserve the performance of a SCM or SCM system to a desired level. Maintenance can be categorized in a variety of ways as there is not an obligatory documentation practice. Regardless, maintenance involves a significant amount of resources (personnel, equipment, extraneous expenses, etc.), it is important to understand the maintenance procedure(s), frequency, and associated costs. Survey results from 28 Minnesota cities, 8 Wisconsin cities, and 2 Wisconsin counties revealed that the majority of SCM maintenance surrounded sediment buildup, litter and debris, or pipe clogging (Erickson et al. 2010). Furthermore, there is little documentation expressing the actual frequency and intensity of maintenance required (Erickson et al. 2010). Generally, the frequency of proper maintenance techniques to fix these conditions will depend on (1) site location and conditions, (2) original design, and (3) the implemented SCM. In the end, to effectively determine the most cost-effective maintenance procedure, one must develop a strategic monitoring plan, as described below.

## 4.1 Maintenance Inspection and Associated Cost

### 4.1.1 Overview

Welker et al. (2013) developed a three-tiered monitoring plan that can be applied to different SCMs based on specific data; for simplicity, the authors categorized the data as hydrologic, water quality, and ecological benefits, each with distinct monitoring equipment and procedures (Table 4-1). This “three-tiered monitoring plan can be used to determine the effectiveness of a SCM based on practicality and budget” (Welker et al. 2013). Moreover, the performance of a SCM is evaluated based on primary and secondary goals; collaboratively, a SCM shall encompass five stormwater management goals - (1) control the volume of runoff, (2) control runoff rates, (3) reduce pollutants, (4) promote evapotranspiration, and (5) establish habitat structure and function (Welker et al. 2013).

**Table 4-1.** Methods and Equipment for Hydrologic, Water Quality, and Ecological Monitoring as documented Welker et al. (2013)

| Type of monitoring | Data | Equipment | What it does | Special Considerations |
|---|---|---|---|---|
| **Hydrologic** | | | | |
| | Precipitation | Standard (e.g., graduated cylinder)<br>Electronic (e.g., tipping bucket) rain gauge | Measure site-specific rainfall | |
| | Infiltration rate | Staff gauges<br>Ultrasonic level detectors<br>Pressure transducers | Measure water surface elevation<br>Measure ponded depth | Water viscosity changes with temperature, so infiltration rate should be normalized to 20°C |
| | Runoff inflow/outflow | Visual inspection<br>Pressure transducer in conjunction with a weir | | Visual inspection can only show inflow; pressure transducer and weir can calculate both inflow and outflow volume |
| | Volumetric water content | Moisture meters<br>Reflectometers | Placed below soil to measure volumetric water content | Must be calibrated to site-specific soils |
| **Water Quality** | | | | |
| | Runoff samples | First-flush samplers<br>Autosamplers<br>Grab samples | Capture runoff in early stages of SCM (first-flush).<br>Capture ponded water samples (auto-samplers and grab samples by hand). | |
| | Subsurface samples | Lysimeters | Obtain subsurface water samples to determine changes in water quality as a function of depth | |
| **Ecological** | | | | |
| | Plant Diversity & Coverage | Planting diagram | Evaluated by inspection | |
| | Nutrient uptake | Not specified | Collecting vegetation samples<br>Separating the shoots from the stems<br>Weighing the mass of each sample<br>Assessing the amount of N and P in the two types of plant tissue per species | |
| | Insect & Animal Utilization | Biological assessments | Evaluate contribution of wet-pond and wetland SCMs to regional habitat and biological diversity | |
| | Soil conditions | Collection of soil samples | Analyzed for organic content, texture, particle size, and hydric state | |

### 4.1.2 Classification of Monitoring and Inspection

Welker et al. (2013) identifies three levels of potential monitoring of each SCM; the three levels are low, medium and high.

- Low level monitoring assures that the SCM is functioning as designed.
- The medium level monitoring focuses on how the SCM is working hydrologically.
- The high level monitoring includes detailed water-quality data collection and more-sophisticated ecological monitoring

### 4.1.3 Monitoring Frequency

How often the monitoring process takes place is divided into four categories – yearly, seasonal, event, and continuous.

- Monitoring is performed *yearly* ideally at the same time each year.
- Seasonal monitoring is performed in response to rain events once in each season. In the Northeast U.S., at least 0.6 cm of rain in an 8-h period are necessary for measureable quantities of runoff.
- Event monitoring is performed monthly. Like seasonal monitoring, there must be sufficient rain to provide measureable quantities of runoff.
- Continuous monitoring is performed for all rain events that produce measureable quantities of runoff.

### 4.1.4 Comparison of Different SCMs

The following tables (Table 4-2, 4-3, and 4-4) summarize the monitoring and inspection criteria for a low, medium, and high scale level for (1) infiltration SCMs, (2) bioinfiltration SCMs, and (3) wet pond and wetland SCMs. These are adopted from Welker et al. (2013), where further explanation of results can be explained.

**Table 4-2.** Qualitative Categorized Monitoring Criteria for Infiltration SCM as described in Welker et al. (2013).

| Monitoring Criteria | Low | Medium | High |
|---|---|---|---|
| **Hydrologic** | | | |
| Precipitation | | Seasonal: standard rain gauge | Continuous: electronic rain gauge |
| Infiltration Rate | | Seasonal: staff gauge | Continuous |
| Inflow and Outflow | Seasonal: visual inspection | Seasonal: visual inspection | Continuous |
| Volumetric water content | | | Continuous: sensors |
| **Water Quality** | | | |
| Surface water samples | | | Event: first flush and autosampler or grab |
| Subsurface water samples | | | Event: pore-water samplers |

**Table 4-3.** Qualitative Categorized Monitoring Criteria for Bioinfiltration SCM as described in Welker et al. (2013).

| Monitoring Criteria | Low | Medium | High |
|---|---|---|---|
| **Hydrologic** | | | |
| Precipitation | | Seasonal: standard rain gauge | Continuous: electronic rain gauge |
| Infiltration Rate | | Seasonal: staff gauge | Continuous |
| Inflow and Outflow | Seasonal: visual inspection | Seasonal: visual inspection | Continuous |
| Volumetric water content | | | Continuous: sensors |
| **Water Quality** | | | |
| Surface water samples | | | Event: first flush and autosampler or grab |
| Subsurface water samples | | | Event: pore-water samplers |
| **Ecological** | | | |
| Plant diversity and coverage | Seasonal: visual inspection | Seasonal: visual inspection | Seasonal: visual inspection |
| Nutrient uptake | Yearly: plant inventory | Yearly: plant inventory | Yearly: plant samples |

**Table 4-4.** Qualitative Categorized Monitoring Criteria for Wet-pond and Wetland SCM as described in Welker et al. (2013).

| Monitoring Criteria | Low | Medium | High |
|---|---|---|---|
| **Hydrologic** | | | |
| Precipitation | | Seasonal: standard rain gauge | Continuous: electronic rain gauge |
| Inflow and Outflow | Seasonal: visual inspection | Seasonal: visual inspection | Continuous |
| **Water Quality** | | | |
| Surface water samples | | | Event: first flush and autosampler or grab |
| **Ecological** | | | |
| Plant diversity and coverage | Seasonal: visual inspection | Seasonal: visual inspection | Seasonal: visual inspection |
| Nutrient uptake | Yearly: plant inventory | Yearly: plant inventory | Yearly: plant samples |
| Insect and animal utilization | | | Yearly: inspection |
| Soil conditions | | | Yearly: soil samples |

### 4.1.5 Cost Analysis

Table 4-5 summarizes the cost of monitoring and inspection separated according to low, medium, and high level (Welker et al. 2013). The authors emphasize that one must be mindful of the associated costs with each level of monitoring as data was collected in 2007-2008. Therefore, is quite possible certain maintenance procedures have become more efficient and/or effective, thus requiring less time. Furthermore, hourly rates may change with inflation and site-by-site location standards/requirements. Thus, this summary table should be used as a reasonable estimate and not as precise associated costs.

**Table 4-5.** Cost (U.S. Dollars) Analysis for Bioretention Monitoring

| Equipment | | Monitoring Personnel | | Laboratory | | |
|---|---|---|---|---|---|---|
| Item | **Cost ($)** | **Hours** | **Cost ($)** | **No. of tests (TSS, TDS, nutrients, metals, chloride)** | **Cost ($)** | **Total ($)** |
| **Low Level** | | | | | | |
| | | 8 | 240 | | | 240 |
| **Medium Level** | | | | | | |
| Rain gauge (graduated cylinder) | 35 | 34 | 1020 | | | 1065 |
| Staff gauge | 10 | | | | | |
| Total | 45 | | | | | |
| **High Level** | | | | | | |
| Rain gauge (tipping bucket) | 400 | 65 | 1920 | 335 | 4020 | 10,565 |
| Ultrasonic level detector | 700 | | | | | |
| V-notch weir | 200 | | | | | |
| Pressure transducer | 200 | | | | | |
| Data logger | 1200 | | | | | |
| Automated sampler | 1300 | | | | | |
| First-flush samplers | 250 | | | | | |
| Lysimeters | 375 | | | | | |
| Total | 4625 | | | | | |

## 4.2 Maintenance Procedures and Associated Costs

Houle et al. (2013) developed quantified maintenance expenditures by analyzing personnel hours and economic costs at the University of New Hampshire Stormwater Center (UNHSC). The data presented was collected over the course of a 6-year study (2004-2010). Specifically, this source exemplifies proper documentation of maintenance and associated expenses. Maintenance tracking consisted of initial observations using inspection checklists, written documentation in field books, photo documentation of issues, and research staff assessments. Maintenance activity documentation included SCM name, activity description, labor hours to complete task, materials, and name of staff members involved. Annual maintenance strategies were evaluated by quantifying hours spent, assessing difficulty of activities, and applying a standard cost structure. The SCMs that coincide with the interests of highway SCM infrastructure are (1) vegetated swale, (2) sand filter, (3) bioretention systems, and

(4) porous asphalt pavement (Table 4-6).

Overall, this case study revealed that an effective maintenance program takes time to properly develop and execute. Furthermore, it is dependent on the following factors:

- Specific to the individual SCM
- Overall design
- System sizing
- Location
- Land use
- Watershed characteristics

Houle et al. (2013) adopt a maintenance approach first introduced by Debo and Reese (2002).

- Reactive – compliant or emergency driven
- Periodic and predictive – driven by inspections and standards in O&M plan; these are typically known/scheduled activities
- Proactive – adaptive and applied increasingly more as familiarity with system develops

The case study found that the majority of maintenance activities are progressive: maintenance tasks often start out as reactive (the most expensive category of maintenance) but subsequently evolve into periodic and proactive approaches (Houle et al. 2013). Over the 6-year study, the vegetated swale, bioretention, and porous asphalt systems reached a steady state after a few years of operation (Houle et al. 2013).

Most importantly, this case study introduced the importance of uniform and diligent documentation in regards to maintenance expenditures (i.e., labor hours and equipment cost). The lack of conclusive data in many tables (Table 4-2, 4-3, 4-4, 4-5) reiterate the trend of little to no documentation regarding maintenance, life cycle, and associated costs during research field studies. Ideally, this study should emphasize future research to include cost and maintenance metrics as introduced previously.

This case study, however, fell short when calculating the marginal costs for maintenance activities associated with TSS, TP, and TN. These costs were converted to annualized costs per system per watershed area treated (Table 4-6). Annual maintenance expenses as a percentage of capital costs ranged from 4% to 19% for the SCMs of interest. When nitrogen and phosphorus were considered, the costs per mass removed represented a range from reasonable to cost-prohibitive. For this reason, data regarding specific water quality improvements should not be considered reliable and appropriate for current SCM practice. Capital costs for SCMs are presented in terms of dollars per hectare of impervious cover (IC) treated (real and constant dollars), and maintenance expenditures are presented as an annualized percentage of capital costs, a measure routinely used for projected SCM cost estimates (Houle et al. 2013).

**Table 4-6.** UNHSC SCM Installation and Maintenance Cost Data, with Normalization per Hectare of IC Treated as documented in Houle et al. (2013).

| Parameter | Vegetated Swale | Sand Filter | Bioretention | Porous Asphalt |
|---|---|---|---|---|
| Original capital cost ($) | 29700 | 30900 | 53300 | 53900 |
| Maintenance-capital cost comparison (yr) | 15.9 | 5.2 | 12.8 | 24.6 |
| Personnel (h/yr) | 23.5 | 70.4 | 51.1 | 14.8 |
| Personnel ($/yr) | 2030 | 6940 | 4670 | 939 |
| Materials ($/yr) | 247 | 272 | 272 | 0 |
| Subcontractor costs ($/yr) | 0 | 0 | 0 | 1730 |
| Annual O&M costs ($/yr) | 2280 | 7210 | 4940 | 2670 |
| Annual maintenance /capital cost (%) | 6 | 19 | 8 | 4 |

## 4.3 Shortcomings in Maintenance

Weiss et al. (2007) aimed to develop both a cost comparison tool (based on total construction cost not including land acquisition) and an effectiveness comparison tool (based on mass of total suspended solids and total phosphorus removed) for six identified SCMs. Moreover, the endeavor sought to create a feasibility tool that can be used to compare the cost and impact on water quality of the available SCMs. The SCMs researched in Weiss et al. (2007) that coincide with the interest of this literature review are SWM wetlands, bioretention systems, and sand filters. While this publication does not serve as an accurate source to establish a defining relationship between cost and water quality, it does highlight the shortcomings in past publications.

The Weiss et al. (2007) study highlights the uncertainty in the data for all SCMs, which is a direct result of varied design parameters, regulation requirements, soil conditions, site specifics etc. (Weiss et al. 2007). Such undocumented variables made data highly scattered and it was difficult to reach a definitive conclusion. While land acquisition is an important variable when defining the total cost of a SCM, it was disregarded due to the extreme range of land costs and variability from site to site. This study concludes that SWM wetlands are the least expensive SCM, assuming that suitable land is available for wetland development. However, SWM wetlands typically require large areas to allow for adequate runoff storage volumes and long flow paths. Thus the areas where land is expensive, the cost effectiveness of SWM wetlands may drastically change.

In regards to operation and maintenance (O&M) for all SCMs under investigation, no data were found that documented actual O&M costs. Weiss et al. (2007) employed a summary table from USEPA (1999), where O&M costs were expressed as a percentage of total construction costs. Undoubtedly, since the date of publication (circa 1999), design and exercised technology has made significant improvements; thus such information cannot be deemed applicable to the current condition of SCMs and stormwater management.

Therefore, Weiss et al. (2007) cannot provide a valuable cost comparison tool of total SCM costs or an effective cost comparison tool for water quality; it does exhibit great understanding of the flaws in documented and literature. Before a general and accurate tool can be developed and utilized by planners and engineers, there must be more available information regarding the following:

- Land acquisition costs
- Regular O&M procedures and corresponding costs
- Any degradation in performance which must be compensated with increased O&M procedure(s)
- Construction costs with corresponding design specifications

# Chapter 5: Summary and Future Research Recommendations

## 5.1 Overview

In general, certain shortcomings exist throughout the comprehensive review and diagnosis of all SCMs (e.g., bioretention, grass swales, permeable pavements, sand filters, SWM wetlands, etc.). The two major trends are (1) failure of SCM design to treat all water quality and quantity concerns, and (2) lack of meticulous economic documentation regarding costs, life cycle analysis, and maintenance.

The selection and design of a particular SCM is governed by consideration of specific unit processes for water quantity and quality impacts. Typically the processes that govern particulate-pollutant removal can be predicted with a high degree of confidence. These mechanisms, filtration and sedimentation, successfully remove such pollutants in most if not all recorded storms. However, dissolved pollutants are much more difficult to sequester and require design specialization to promote these processes. Dissolved pollutants (e.g., nitrogen, phosphorus, heavy metals) can pass through the SCM without any removal if the design does not incorporate conditions that specifically target the removal of the dissolved pollutant of interest.

For example, in order to remove nitrogen, water-saturated, anoxic conditions must be present; therefore, the design must include sub-surface storage that allows for such conditions and adequate retention time for the microbial process to transpire. Furthermore, the removal of dissolved phosphorus relies on chemical adsorption to the media. The inorganic phosphate group, $PO_4$(-III), will bind to Al(III)- and Fe(III)-based minerals present in the media. Thus, the media is responsible for binding the phosphorus and the effluent runoff will have a significant reduction of phosphorus.

However, the processes of nitrification-denitrification (i.e., nitrogen removal) and chemical sorption (i.e., phosphorus removal) have certain limitations and the SCM design must account for this. Denitrification relies on anoxic conditions to reduce nitrogen from $NO_3^-$ to $N_2$ (g). However, if a more favorable oxidizing agent (e.g., $O_2$ or Fe(III)) is present, this compound will be the electron acceptor instead of $NO_3^-$.

Nonetheless, care must be taken when implementing internal water storage. Anoxic conditions that are necessary for nitrate removal may prove detrimental to P capture. Under anoxic conditions, Fe(III) minerals can become reduced, and consequently, release all captured phosphorus as well. Here is where the main challenge in SCM lies – the incorporation of designs to account for all natural limitations of chemical, biological, and microbial processes that govern the removal of pollutants.

While the processes that improve water quality and quantity guide the entire decision making process, currently, there is no "one size fits all" model. Rather it is recommended to use general design recommendations with certain amendments and/or enhancements as deemed appropriate for more comprehensive (yet complex) pollutant removal processes.

Important to understanding the treatment processes in specific SCMs is having appropriate detailed information about the runoff water quality parameters. Most pollutants of interest are present in runoff in the form of different species. Examples include phosphorus (particulate P, organic P, inorganic P), nitrogen (particulate N, organic N, ammonium-N, nitrate-N), and metals (particulate, dissolved complexed metals). Speciation information is important to properly evaluate mechanisms of treatment, where specific mechanisms may act on one form of a pollutant but not another.

Additionally, dynamic information on pollutant concentrations and species in runoff is important. Species and concentrations are dynamic and can be different for different storm events and can change during an event. Quantitative information on the first flush characteristics of a runoff event may lead to more compact and efficient designs, allowing for smaller footprints.

In regards to economics, little information is provided within the majority of publications. Therefore, it is difficult to quantify current and even future construction costs and associated life cycle costs. In order to minimize cost it is necessary to have definitive maintenance procedures and the associated predicted frequency that will provide the most cost-effective result both monetarily and functionality. Furthermore, the economics of an SCM system will be directly attributed to the location due to land costs, available space, average constituent concentrations, soil properties, rainfall patterns, and seasonal temperature. These factors should be well documented because of the variable geography and climate of Maryland. With specific site information readily available, definitive economics metrics can be developed with a high degree of accuracy.

The following subsection (5.2 *SCM Performance Summary*) shows the current performance success levels of common SCMs as reflected in the most current literature. Subsequently, subsection 5.3 (*Future Research Recommendations*) provides a comprehensive list of current research needs categorized by SCM. All incorporate possible design enhancements that require more research before a final assessment can be made.

## 5.2 SCM Performance Summary

The performance summary is categorized by SCM. Only certain parameters are used to designate performance qualitatively based on available research and applicability to highway transportation systems in Maryland. The removal of constituents is summarized on a low, medium, and high rating. These categories are based on measured data, supported by unit operation considerations. These designations also follow those used in the *Pollutant Load Reductions for the Total Maximum Daily Loads for Highways* (NCHRP). Therefore, data presented in the NCHRP report will be adopted into a table format that coincides with the SCM in each discussion as available. If inadequate information is available, this is designated with a dash (-). The water quality constituents are as follows:

- Total suspended solids (TSS)
- Total P
- Dissolved phosphorus (DP)
- Particulate phosphorus (TP)
- Total N
- Total Kjeldahl nitrogen (TKN)
- Nitrate/Nitrite ($NO_3^-$/$NO_2^-$)
- Total zinc
- Total copper
- Dissolved copper (DC)
- Total lead
- Chloride
- Hydrocarbons

### 5.2.1 Bioretention

#### 5.2.1.1 Conventional Bioretention Design

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ /$NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | Medium | High | Medium | High | High | High | Low | Medium | Low |

#### 5.2.1.2 Incorporation of IWS Storage Zone

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ /$NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | Medium | High | Medium | High | High | High | Medium | Medium | Medium |

#### 5.2.1.3 Media Enhancements – Addition of WTR

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ /$NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | High | High | Medium | High | High | High | Low | Medium | Low |

#### 5.2.1.4 Enhanced N and P Removal

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ /$NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | High | High | Medium | High | High | High | Medium | Medium | Medium |

#### 5.2.1.5 NCHRP Bioretention

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ /$NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | High | - | - | - | - | - | - | - | - |

### 5.2.2 Grass swales[1]

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ /$NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | Low | High | Low | High | Medium | Medium | Low | Low | Low |

1. Low removal of chloride ($Cl^-$)

5.2.2.1 NCHRP Grass swales

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ /$NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| Low-Medium | Low | | | High | - | - | - | - | - |

### 5.2.3 Permeable Pavements[1]

The summary of permeable pavement performance reflects the three mentioned design alternatives – (1) permeable interlocking concrete pavers (PICP), (2) pervious concrete (PC), and (3) permeable asphalt (PA), as the performance does not significantly change for any parameter (hydraulic or water quality).

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ /$NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | - | Medium | - | - | - | - | - | - | - |

1. Low removal of chloride ($Cl^-$)

### 5.2.4 Sand Filters

5.2.4.1 Traditional C-33 Sand (i.e., No Media Enhancements)

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ / $NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | Low | High | Low | High | High | Medium | Medium | Medium | Low |

5.2.4.2 Media Enhancements – 5% Iron Fillings by Weight in C-33 Sand

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ / $NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | High | High | High | High | - | Medium | Medium | Medium | Low |

5.2.4.3 NCHRP Austin Sand Filters

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ / $NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | Medium | High | - | Medium-High | Medium | High | Medium | - | - |

### 5.2.5 Stormwater Management Wetlands

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ / $NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | - | High | - | - | - | - | Medium | Medium | Low |

5.2.5.1 NCHRP SWM wetlands

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ / $NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | Medium-High | - | - | Medium | Medium | High | Low-Medium | - | - |

### 5.2.6 Infiltration Basin

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ / $NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | - | High | - | - | - | - | - | - | - |

5.2.6.1 NCHRP Infiltration Basin

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ / $NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | High | - | - | High | - | - | - | - | - |

### 5.2.7 Porous Friction Courses (PFCs)[1]

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ / $NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | Medium | High | Low | - | Medium | Medium | Low | Low | Low |

1. Low removal of dissolved copper

5.2.7.1 NCHRP Porous Friction Courses (PFCs)

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ / $NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | - | - | - | High | Medium | High | - | - | - |

### 5.2.8 Street Sweeping

| TSS | TP | PP | DP | Total Zinc | Total Copper | Total Lead | TN | TKN | $NO_3^-$ /$NO_2^-$ |
|---|---|---|---|---|---|---|---|---|---|
| High | - | - | - | - | - | - | - | - | - |

5.2.8.1 NCHRP Performance Modeling of Street Sweeping

| TSS | Nutrients<br>Nitrogen & Phosphorus | Metals<br>Lead, Copper, Zinc |
|---|---|---|
| 45 to 70% reduction in annual loads | 35 to 60% reduction in phosphorus annual loads | 25 to 60% reduction in annual loads |

### 5.2.9 NCHRP Discussion

For the most part, the results from the NCHRP agree relatively well with the conclusions drawn here. In some instances, the qualitative performances from the NCHRP do not directly correlate to the findings of this study. Generally speaking, these discrepancies arise from the date of publication (e.g., 2003-2006) of the source and/or the collection and analysis of pollutants. However, conclusions from both suggest the need for future research needs to improve water quality performance, as outlined in the *Section 5.3 SCM Future Recommendations*.

## 5.3 SCM Future Research Recommendations

Based on this summary of research, the following provides a listing of research needs for the various highway SCMs. Some recommendations are specific, other are more general.

### 5.3.1 General SCM Performance

- Uniform metrics for both hydraulic and water quality measurements
- Economic considerations
- Minimizing maintenance
- Detailed information for highway runoff water quality, to include chemical concentrations at the species level and changes in pollutant concentrations with time over rainfall events (pollutograph).

### 5.3.2 Bioretention

- The role of vegetation in:
    - Nutrient removal
    - Pathogen removal
    - Water balance
- Effect of IWS on hydrology and water quality
- Design modifications for N removal
- Effect of geologic factors (e.g., sandy soils) on bioretention performance
- Effect of road salts on bioretention hydrologic and water quality performance.
    - Include analysis of salt composition since different types of salts may be used individually or in combination.
- Media properties – interdependence of the following prominent characteristics
    - High hydraulic conductivity
    - High filtering capability
    - High adsorption capacity
    - Minimal leaching of nutrients
    - Support vegetation
    - Inexpensive
- Underground storage integrated with bioretention
- Organic N processing
- Use of bioretention in treatment trains
- Selecting organic material for bioretention media
- Microbial communities for nutrient processing
- Long-term performance
- Role of surface mulch

- Fate and capture of hydrocarbons
- Effects of shape

**5.3.3 Grass swales**

- Effects of grass/vegetation characteristics on swale performance
  - Grass/vegetation species
  - Grass/vegetation height
  - Mowing frequency
- Evaluation of dissolved vs. particulate pollutants
- Adding in-line filters and/or adsorbents to swales
- Modification of swale soils to encourage infiltration
- Terracing swales on slopes to provide storage and infiltration
- Refining check dam design to improve swale performance
- Long-term swale performance
- Selecting vegetation for enhanced performance
- Determining impacts of swale design conditions on water quality/treatment performance

**5.3.4 Permeable Pavements**

- N removal
- P removal
- Run-on to permeable pavements
- Permeable pavement treatment trains
- Underground storage combined with permeable pavements
- N and P in collected sediments
- Long-term performance

**5.3.5 Sand Filters**

- The possible use of shallow depth media for particulate matter removal
- Specialized media for dissolved pollutant removal in sand filters
- Use of denitrification chambers below sand filters for N removal
- Further media enhancements for P removal
- Media amendments targeted at dissolved N
- Use of geotextile filters as an alternative to sand filters
- Optimizing sand sizing in sand filters

| |
|---|
| **5.3.6 Stormwater Management Wetlands** |
| • Water quality performance under a variety of hydraulic loadings<br>• Extensive field monitoring of Maryland constructed wetland<br>• Effects of forebay addition and sizing<br>• N processing<br>• P processing<br>• Effects of temperature on wetlands performance<br>• Performance in treatment train configuration<br>• Long term performance<br>    o 1 year after construction<br>    o 3 years after construction<br>    o 5 years after construction<br>    o >10 years after construction |
| **5.3.7 Infiltration Basins** |
| • Effect and degree of clogging over lifecycle of infiltration basin<br>• Groundwater monitoring<br>    o Previous to SCM installation<br>    o Over the lifecycle<br>• Sizing of the basin as a function of temperature, and consequently geographic and climatic conditions<br>• Infiltration basin in treatment trains<br>• Pretreatment for infiltration basins<br>• Long-term continuous monitoring |
| **5.3.8 Porous Friction Courses (PFCs)** |
| • Research on PDCs in Maryland (only have been used in TX and NC)<br>• Removal of dissolved pollutants<br>• Possible change in the removal patterns and efficiency of particulate and dissolved pollutants over the lifecycle |
| **5.3.9 Street Sweeping** |
| • N removal<br>• P removal<br>• Matching street sweeping performance in water quality improvements |

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Phase I&II National Pollutant Discharge Elimination System
Permit No. 99-DP-3313 MD0068276
Permit Term October 2005 to October 2010

# APPENDIX C

## ADVANCED DENITRIFICATION IN BIORETENTION SYSTEMS USING WOODCHIPS AS AN ORGANIC CARBON SOURCE (JUNE 2013)

# Advanced Denitrification in Bioretention Systems using Woodchips as an Organic Carbon Source

| | |
|---|---|
| **Project Duration:** | August 2011 – June 2013 |
| **Project Sponsor:** | Christie Minami, P.E.<br>Highway Hydraulics Division<br>Maryland State Highway Administration<br>707 North Calvert Street C-201<br>Baltimore, MD 21202 |
| **Project Coordinators:** | Allen P. Davis, PhD, P.E<br>Professor<br>Ian J. Peterson<br>Graduate Research Assistant<br>Department of Civil and Environmental Engineering<br>University of Maryland<br>College Park, MD 20742 |

## July 22, 2013

# Abstract

Bioretention systems still lack the ability to effectively mitigate nitrogen concentrations from urban stormwater. Column tests were conducted to evaluate the effect of nitrate concentration, stormwater retention time, limestone addition, and woodchip species, size, and mass percentage on the bioretention denitrification process. Denitrification of artificial stormwater appeared to follow pseudo-first-order kinetics. A 0.8 day average retention time showed the highest nitrate removal percentage of 82.4 $\pm$ 0.4%. Longer retention times correspond to greater removal efficiency. Willow Oak and Red Maple woodchips resulted in the highest total nitrogen removal efficiencies at 61.9 $\pm$ 0.8% and 61.8%, respectively. Smaller woodchips and higher woodchip mass percentage corresponded to greater nitrate removal efficiencies, but also higher organic nitrogen leaching. Media containing 4.5% 5 mm Willow Oak woodchips by mass represented optimum conditions with a pseudo-first-order denitrification rate of 4.1 $\pm$ 4.6 $day^{-1}$ with nitrate concentrations of 1.5 to 4.5 mg/L N.

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# 1. Introduction

## 1.1. Background

Increases in pollutant and stormwater loads from urban areas have caused a push for mitigation. As urban areas develop, natural ecosystems, previously conducive to infiltration of stormwater, have become impervious (Davis et al. 2012, Morgan et al. 2013, Son et al. 2013). Roads, parking lots and buildings act as non-point sources of pollution (Davis et al. 2012, Morgan et al. 2013). As impervious surface area increases, runoff volumes become larger, which cause stream bank erosion and habitat loss (Davis et al. 2012). Increases in mobilized pollutants cause eutrophication of surface water bodies and other water quality concerns (Ergas et al. 2010, Morgan et al. 2013, Son et al. 2013). These adverse effects amount to losses in waterfront property, recreational areas, drinking water supply, and wildlife habitat (Ergas et al. 2010, Davis et al. 2012). As a way of mitigating the impact of urban development, stormwater control measures (SCM) are employed to increase water quality and decrease the amount of runoff discharged to water bodies (Brown and Hunt 2011, Davis et al. 2012, Hunt et al. 2012). Runoff from impervious surfaces is collected and managed in SCMs such as bioretention cells, rain gardens and vegetated swales (Brown and Hunt 2011, Davis et al. 2012, Hunt et al. 2012). Here water is allowed to infiltrate into the ground, naturally filtering out pollutants and returning urban areas closer to pre-development hydrologic conditions (Brown and Hunt 2011, Davis et al. 2012, Hunt et al. 2012). Although effective, these technologies are still somewhat immature and more research is needed to optimize their efforts.

Treatment for nitrogen using SCM's is one area that needs improvement. Nitrogen is one of the limiting nutrients associated with the eutrophication of lakes and rivers

(Ergas et al. 2010). Eutrophication is the change in the volume and diversity of biomass in an aquatic ecosystem (Ergas et al. 2010). Increases in nutrients that are usually scarce cause rapid growth of some species, resulting in the death of others (Ergas et al. 2010). Therefore, a spike in nitrogen can rapidly accelerate eutrophication when left unchecked. Bioretention is a very effective means of mitigating the effects of urban development and has shown some promise in the area of nitrogen treatment (Kim et al. 2003, Brown and Hunt 2011, Davis et al. 2012, Hunt et al. 2012). The goal of this research is to design a layered bioretention system that optimizes the efficiency of nitrogen removal from stormwater runoff. This will be achieved by determining the optimum conditions for denitrification.

**1.1.1.** Bioretention Systems

Bioretention cells are typically shallow (2-4 ft deep) areas of very porous media (Li and Davis 2009). The media is usually topped by a mulch layer to retain moisture and prevent unwanted vegetated species (Li and Davis 2009, Davis et al. 2012, Hunt et al. 2012). Selected vegetation is planted in the bioretention cell to promote evapotranspiration and uptake of pollutants (Li and Davis 2009, Davis et al. 2012, Hunt et al. 2012). Stormwater from the target watershed is directed into the bioretention cell where it quickly infiltrates. Pollutants are removed from the water as it passes through the media by means of filtration, adsorption, biological processes, and/or plant uptake (Li and Davis 2009, Davis et al. 2012, Hunt et al. 2012). Clean water can then recharge groundwater by infiltrating further or be taken up by plants (Li and Davis 2009, Davis et al. 2012, Hunt et al. 2012). What remains is usually collected by an underdrain that discharges into surface waters (Li and Davis 2009, Davis et al. 2012, Hunt et al. 2012). In effect, this technology greatly reduces hydraulic and pollutant loads from urban stormwater.

Treatment of nitrogen using bioretention has been studied in a few different research endeavors (Kim et al. 2003; Hsieh et al. 2007; Ergas et al. 2010). Different designs have been able to remove anywhere from 70 to 90 percent of the total nitrogen in runoff when in highly controlled laboratory settings (Kim et al. 2003; Hsieh et al. 2007; Ergas et al. 2010).

**1.1.2.** Nitrogen in Stormwater

Typical urban stormwater event mean concentrations are approximately 1 to 3 mg/L total nitrogen depending on the land use (Collins et al. 2010). Typically one third of the total nitrogen will be in the form of organic nitrogen, one third will be ammonium, and one third will be oxidized nitrogen (Collins et al. 2010). The data collected by Collins et al. (2010) show that storms vary greatly in intensity and stormwater runoff also varies in nitrogen concentration. First flush is considered the first portion of a given storm (usually 1.3 to 1.9 mm of rainfall) on a watershed (Flint and Davis 2007). It is widely accepted that the runoff from the first flush contains the highest contaminant concentrations and could be as high as 90% of the total contaminant mass (Bach et al. 2010). Flint and Davis (2007) found that 85% of the total nitrogen mass is carried by the first 1.3 mm of runoff in storms that exceed 1.3 mm of rainfall.

A bioretention facility designed to incorporate nitrogen into its treatment processes must do so by following the nitrogen cycle (Ergas et al. 2010). Figure 1 shows a simplified version of how the nitrogen cycle occurs naturally and the corresponding valance states of each form of nitrogen. The goal in nitrogen treatment is to ultimately

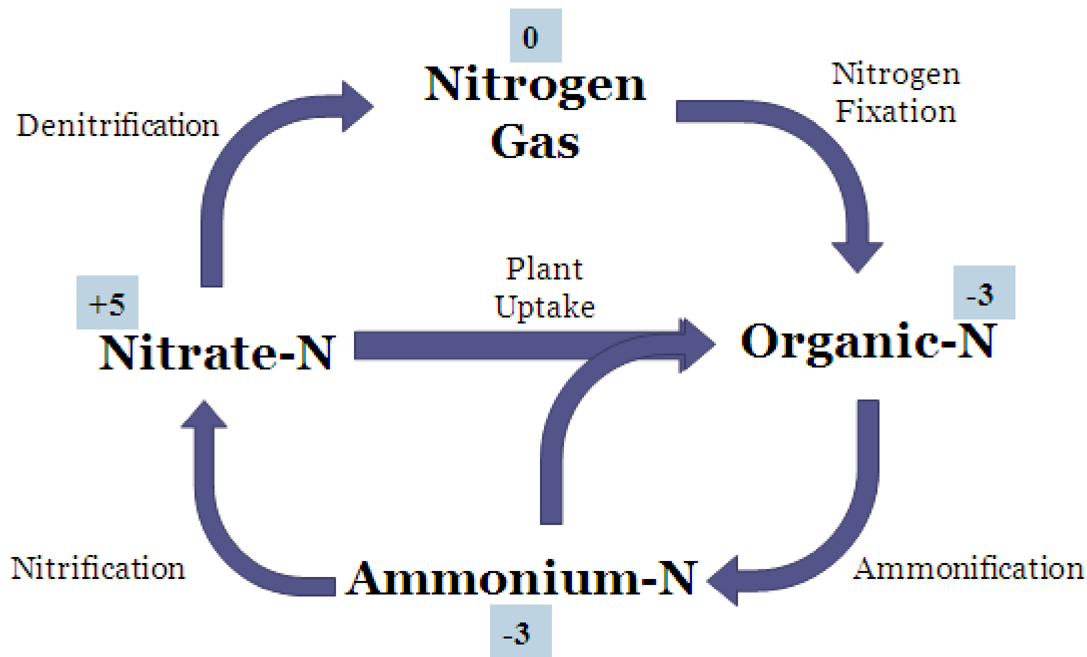


**Figure 1: Simplified version of the nitrogen cycle. The highlighted numbers indicate the oxidation state of each form of nitrogen.**

convert all forms to nitrogen gas which is released into the atmosphere. Organic nitrogen, from decaying organic matter, is converted to ammonium (ammonification). Ammonium is then oxidized to nitrite and then further oxidized to nitrate (nitrification). Nitrate can be returned to organic material because it is readily plant available (plant uptake). Uptake by plants is a significant pathway for nitrate loss (Bratieres et al. 2008). Nitrate can also be reduced by bacteria to nitrogen gas which is released into the atmosphere (denitrification).

These steps naturally occur very slowly if at all but are made more rapid by bacterial processes (Collins et al. 2010). Organic nitrogen is broken down over time and ammonium can then undergo nitrification. Nitrification requires the availability of oxygen. Typically, oxygen in air is used by bacteria to oxidize the ammonium. According to Hsieh et al. (2007), during storm events organic and ammonium nitrogen are the adsorbed to media in a bioretention system and the nitrification process occurs in the time between storm events. In Maryland, on average there are six days between storm events (Hsieh et al. 2007).

Biologically, nitrate reduction can follow assimilatory or dissimilatory pathways (Blowes et al. 1994). Nitrate can be reduced to ammonia and assimilated by the bacterial cell or used as a terminal electron acceptor in respiration (Blowes at al. 1994). In stormwater treatment both processes take place to effectively remove nitrogen from aquatic/terrestrial systems. Denitrification reduces the valance state of nitrogen from +5 to 0 (Stumm and Morgan 1996). There are four steps in the denitrification pathway (Lee et al. 2000). Each step is carried out by a different enzyme produced by denitrifying microbes (Lee et al. 2000). The different steps are listed in equation 1.

$$NO_3{}^- \rightarrow NO_2{}^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \qquad (1)$$

Denitrifying bacteria have their highest rate of nitrate reduction near pH 8 (Glass and Silverstein 1998). Ultimately, respiration will convert nitrate into nitrogen gas which is released into the atmosphere.

**1.1.3.** Denitrification

Denitrifying bacteria require anoxic conditions (the absence of molecular oxygen in the presence of nitrate) in order to reduce nitrate (Kim et al. 2003). This is because most denitrifying bacteria are facultative and will use oxygen as a terminal electron acceptor because it is more efficient (Blowes et al. 1994). After oxygen is depleted the bacteria will then begin to convert nitrate into nitrogen gas while using the attached oxygen as a terminal electron acceptor (Blowes et al. 1994).

Proper conditions for denitrification can be achieved by saturating the media in the lower layer of a bioretention cell (Kim et al. 2003, Ergas et al. 2010). This makes oxygen from the atmosphere inaccessible (Kim et al. 2003, Ergas et al. 2010). Therefore, the amount of time that stormwater runoff is retained in the bioretention system greatly effects the microbial processes that reduce nitrates to nitrogen gas (Leverenz et al. 2010; Robertson 2010). Several methods are used to saturate this layer. Some of these methods are using a media with low porosity (Hsieh et al. 2007; Ergas et al. 2010), using an upturned underdrain (Hunt et al. 2006, Chen et al. 2013, Zinger et al. 2013), or by controlling outflow (Lucas and Greenway 2011a). By slowing down flow through the system by using low porosity media or controlled outflow, the media becomes saturated. An upturned underdrain is implemented by placing the outlet of the underdrain higher than the collection piping. The upturned underdrain causes saturation by requiring hydraulic head in order to cause outflow.

Denitrifying bacteria also require a source of organic carbon (Kim et al. 2003). Several studies have been conducted to determine the best carbon source for denitrification in bioretention. Sawdust, woodchips, alfalfa, and newspaper are some of the sources studied (Kim et al. 2003; Leverenz et al. 2010; Robertson 2010). Woodchips appear to provide consistent, reliable and lasting results (Robertson 2010). Kim et al. 2003 determined that it was possible to achieve a steady state nitrate removal percentage with woodchips, alfalfa and newspaper near 100%. Sawdust was a bit lower but still showed above 90% removal in a steady state simulation (Kim et al. 2003). Kim et al. 2003 determined that, while woodchips provide adequate and high removal percentages, newspaper provided the most consistent removal results based on fluctuations in hydraulics and nitrate concentrations.

Denitrification typically has a zero-order reaction rate in most SCMs (Leverenz et al. 2010). However, a first-order reaction rate can be used to model denitrification at low temperatures with low nitrate concentrations (Leverenz et al. 2010, Robertson 2010). Low concentrations were defined as concentrations less than 10 mg/L of nitrate as N (Leverenz et al. 2010).

Leverenz et al. (2010) determined that an anoxic environment of woodchips should exhibit a first-order denitrification rate constant between 1.41 and 1.30 $days^{-1}$. However, Robertson (2010) found that zero-order kinetics represented a better fit to collected data. In that study a zero order denitrification rate was observed at 15.4 to 23.0 mg N $L^{-1}$ $day^{-1}$ (Robertson 2010). After aging woodchips for 7 years the rate was found to be about half of the initial rate (Robertson 2010). Because nitrogen levels in stormwater are typically below the 10 mg/L level identified by Leverenz et al. (2010), first-order kinetics may be used. Following a first-order model for denitrification, it is estimated that concentrations of nitrate will be below 0.2 mg/L N if water is retained for more than 1 to 1.5 days. This calculation uses the rate constants reported by Leverenz et al. (2010) and assumes that stormwater contains initial nitrate concentrations of 1 to 3 mg/L N and nitrate is the limiting nutrient.

#### **1.1.4.** Woodchips

Robertson (2010) determined that woodchips had very good longevity for denitrification in agricultural runoff, approaching 10 years as an effective carbon source. One drawback of using woodchips is they initially cause a spike in organic carbon effluent concentrations which diminishes over time (Robertson 2010). Typically, a system that induces denitrification uses a homogeneous media. For example, Robertson (2010) used a media consisting of only woodchips. While this has proven effective in a steady state system, the effluent concentrations of organic carbon are much higher than is necessary to sustain the microbial population (Leverenz et al. 2010, Roberson 2010). Therefore, media should be redesigned to limit the release of organic material in a system that operates more closely to field situations.

No available literature has defined the effect of woodchip size on the denitrification process. The size of the woodchips inversely relates to the total woodchip surface area which could contribute to the availability of carbon. Larger woodchips have less surface area from which to leach organic carbon. Therefore, larger woodchips leach less organic carbon than smaller woodchips of the same mass. A standard woodchip size distribution from a disc chipper, developed by Hartmann et al. (2006), is presented in Figure 2. Different distributions of woodchip sizes would affect the woodchips surface area and adjust the availability of organic carbon.

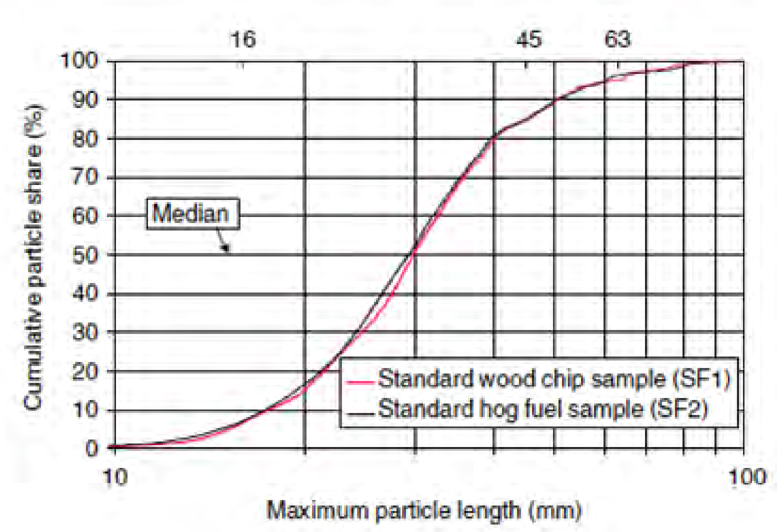


**Figure 2: Standard woodchip particle size distribution from a disc chipper (Hartmann et al. 2006)**

Literature has yet to define the effect of woodchip species on the denitrification process. Different types of wood have different carbon contents and vary in hardness. The carbon content of hardwoods ranges from 46.27 to 49.97 percent (Lamlom and Savidge 2003). Softwoods have slightly higher carbon contents ranging from 48.55 to 55.16 percent (Lamlom and Savidge 2003). These woods are not always easily attainable. Some of the most commonly harvested woods in Maryland are cherry, oak and maple for hardwoods and pine for softwoods (MCAE 2004; USFWS 2001).

## 1.2. Research Objectives

The goal of this research is to optimize the denitrification efficiency in a modified bioretention system design. In order to evaluate and optimize this design several objectives have been identified.

1. Develop a laboratory scale version of a denitrification layer, and provide media that create the conditions necessary for the growth and development of denitrifying bacteria.

In order to address this objective, columns are designed to provide conditions similar to those in the denitrification section of a bioretention system. The denitrification process is evaluated in column tests with media containing woodchips. These tests are compared to column tests where denitrification is inhibited. The contrast between these column tests provides evidence of the presence or absence of denitrifying microorganisms.

2. Model the denitrification process in the system using zero or first-order kinetics in order to determine which better describes the data. Use this model to determine how long stormwater should be retained in the media.

Zero and first-order models are developed using the column and assumptions…

and applied to the denitrification data. These models are compared for goodness of fit and then used to evaluate the factors affecting the denitrification process in the system.

The amount of time that stormwater runoff is retained in the bioretention system greatly effects the microbial processes that reduce nitrates to nitrogen gas (Leverenz et al. 2010; Robertson 2010). The amount of time stormwater runoff is retained in the denitrification media is varied in a series of column tests. These provide insight into the effect of retention time on the efficiency of bioretention systems.

3. Evaluate different media compositions and their effect on microbial denitrification.

Adjusting the media composition of the denitrification layer in a series of column tests provides insight into how different media affects the denitrification process. The woodchip species, woodchip mass percentage, woodchip size, and limestone content in the media are varied in these column tests. The resulting data are compared to evaluate the effect of different media characteristics on the denitrification process

4. Provide design recommendations for a full scale bioretention system using the information gathered.

All of the factors evaluated with respect to denitrification in a bioretention system, when quantified, are optimized in order to further improve nitrogen removal using a variety of SCMs. Using the results of the column studies, optimum design conditions are used to form practical recommendations for nitrogen treatment bioretention systems.

# 2. Methodology

## 2.1. Laboratory Design

In order to simulate a field situation in a newly designed bioretention layer, synthetic stormwater is passed through a column similar to the one depicted in Figure 3. The column will be used to address the goals identified previously for denitrification of first flush runoff using bioretention systems. The column was designed around typical bioretention parameters. Because excavation below 120 cm (4 feet) usually requires some kind of stabilization, bioretention cells are kept shallower than the 120 cm depth (Brown and Hunt 2011). The column constructed is 80 cm (~2.6 feet) high with media to the height of 70 cm (2.3 feet). This will provide enough height for a denitrification layer. The column is wrapped in foil, as shown in Figure 4, in order to prevent

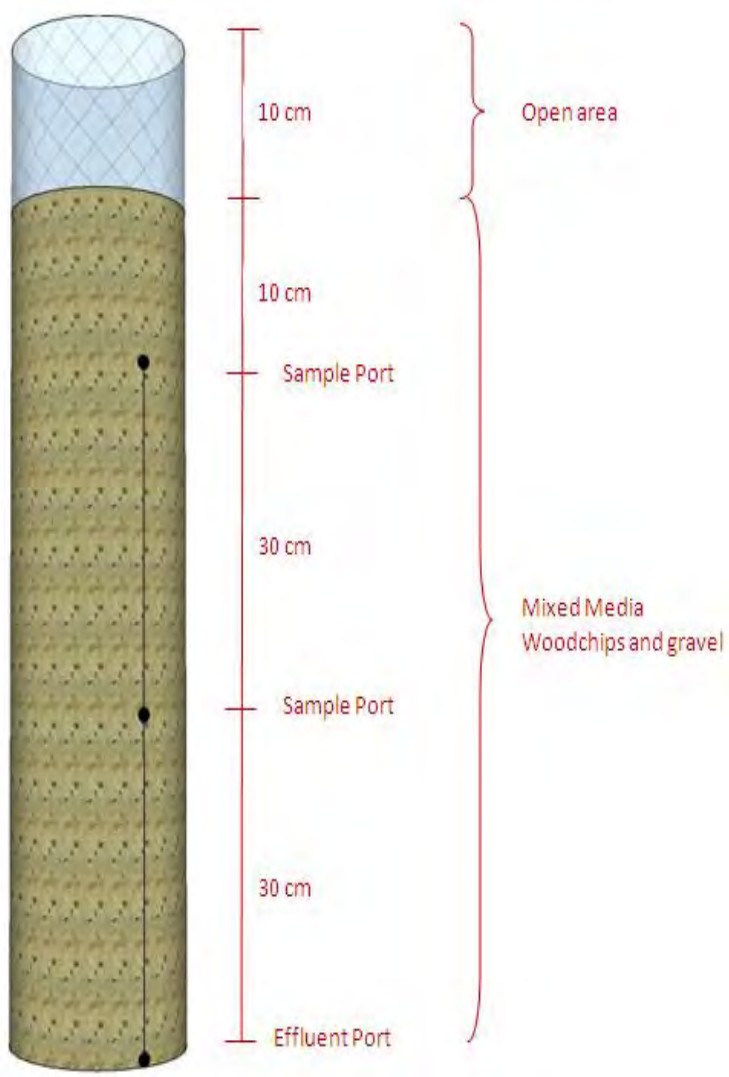


**Figure 3: Model bioretention system column design for testing the effect of identified factors affecting the denitrification process.**

light from entering the media. In a field situation light will not penetrate the surface, so it is necessary to mimic that environment.

The column design includes three sampling ports. The bottom port is a valve that is adjusted to the appropriate effluent rate for each experiment. Before the test begins the effluent rate is set. This is done by filling an empty column to the point where media would be fully saturated and setting the flow rate to previously determined rates. An Orion redox/ORP electrode is placed in the middle sampling port in order to monitor the oxidation/reduction potential in the solution during the test (Figure 4).

**Figure 4: Constructed model bioretention system columns wrapped in aluminum foil to prevent light from entering.**

Synthetic stormwater is used to represent typical first flush runoff pollutant concentrations of nitrate. Assuming that all the nitrogen carried by the stormwater is converted to nitrate before entering the denitrification layer, nitrate is the only source of nitrogen added to the synthetic stormwater in varying concentrations. The nitrate is added in the form of $NaNO_3$.

Phosphate, as $NaPO_4$, is added at urban runoff levels (0.1 mg/L) to encourage bacterial growth. Sodium chloride (NaCl) is added at 0.01 M in order to fix the ionic strength.

Synthetic stormwater is pumped into the top of the column using a peristaltic pump at 22.2 mL/min and an approach velocity of 0.32 m/min until the media is completely saturated. Pumping stops when the system is completely saturated because in a field setting, at saturation, it is expected that any excess water would overflow or bypass the denitrification layer.

Each test is conducted three times with 7 days in between loading events. This is done to mimic field conditions (Hsieh et al. 2007). The three replicates are conducted on the same media in succession. All three tests are conducted in the same manner according to the constraints identified herein.

All of the effluent is collected in order to conduct a water balance and determine the change in water quality parameters. Samples were collected in different time increments during the expected drainage period. Sample volumes are based on the volume needed to conduct different analytical methods. For each sample the pH, concentrations of nitrate, nitrite, Total Kjeldahl Nitrogen, phosphorus, and total organic carbon were determined. Sample temperature was also monitored using a mercury thermometer to ensure that the experiment remained at room temperature. The oxidation/reduction potential was monitored inside the column throughout the sampling event.

## 2.2. Experimental Sets

The media used in the columns consist of a mixture of woodchips and pea gravel. Pea gravel is used in order to optimize the structural capacity of the media as well as provide large porosity and thus large storage capacity. Each test will have different variations of this media mixture.

Wood samples were collected from recently cut trees on University of Maryland campus grounds. Bark from the samples was removed using a hammer and chisel. Samples were then chipped by a Vermeer BC1000 XL 20" drum chipper. In order to reduce the likelihood of contamination, the chipper was allowed to run for 5 minutes in between each species that was chipped. Chips samples were thoroughly rinsed with tap water and air dried for approximately two days. When dry, the samples were sieved through 25.5 mm, 19 mm, 13 mm, 9.5 mm, and No. 4 (5 mm) sieves. This was done on an automatic shaker for 15 minutes. The sorted chips were collected and sealed for storage in large waterproof non-transparent plastic bags.

**Table 1: The factors investigated in the column studies are described. The collected data will be used to provide design recommendations for the optimization of nitrate removal in bioretention systems.**

| Factor | Description |
|---|---|
| **Inhibition** | Adding Sodium Azide to the stormwater to inhibit microbial denitrification |
| **Nitrogen Concentration** | Adjusting the concentration of nitrate that enters the system |
| **Retention Time** | Varying the amount of time stormwater runoff is retained in bioretention |
| **Woodchips Species** | Different wood species used as a carbon source for denitrifying bacteria |
| **Woodchip Size** | Availability of carbon variation through differing chip sizes |
| **Woodchip Mass** | Varied carbon availability through woodchip content in bioretention media |
| **pH** | Media amended with limestone to raise the pH |

In order to determine the most effective media for the nitrate treatment process, tests were conducted with variations in the media. The different variations are referred to in Table 1. For regional considerations the most available woods in Maryland were evaluated for their effects on the denitrification process. Four different hard woods and one soft wood were chosen for their availability in the region. These woods can be found in Table 2 with their Latin names and corresponding carbon contents.

The amount of woodchips in the media was varied at 1%, 2.5%, and 4.5% by mass. The remaining media was pea gravel. The size of the woodchips was also evaluated for its effect on the denitrification process. Three different size distribution tests were conducted. The size rages were No. 4 (5 mm) to 9.5 mm, 9.5 mm to 13 mm, and 13 mm to 19 mm.

**Table 2: Five wood species, available regionally, that were used to determine the effect of varying woodchip species on the denitrification process in a bioretention cell. Carbon contents for each wood species are identified as it may affect the culturability of denitrifying bacteria (USFWS 2001; Lamlom and Savidge 2003; MCAE 2004).**

| Wood Type | Species (Scientific Name) | Carbon Content (%) |
|---|---|---|
| **Wild Cherry** | Prunus serotina | 49.53 ± 0.18 |
| **Willow Oak** | Quercus phellos | 49.57 ± 0.22 |
| **Red Maple** | Acer negundo | 49.34 ± 0.53 |
| **Virginia Pine** | Pinus strobus | 49.74 ± 0.16 |
| **American Beech** | Fagus grandifolia | 46.60 ± 0.39 |

The samples were soaked for a period of two days prior to being packed in the columns. Chips were completely submerged in the same solution as was used for artificial stormwater, which was described previously. This soaking has several purposes. Because it will take time to build a bacteria colony in the column it is advantageous to start growth prior to running the column. Soaking the woodchips will also allow the chips to become fully saturated; dry chips will absorb water. In order to conduct an accurate water balance it is necessary to have as little influent water absorbed as possible.

Immediately after the soaking period the artificial stormwater was drained and the chips were mixed with washed pea gravel. Pea gravel was purchased in 50 lb bags from The Home Depot. The bags contained ASTM #8 pea gravel (0.3 mm to 9.5 mm). Peas gravel was thoroughly rinsed with tap water and then heated in the furnace for 4 hours at 600 °C. The mixed media was then packed into the column. The media was compacted using a compaction rod at six inch increments. Each layer received 20 blows from the compaction rod. Media was packed in layers until it reached a height of 70 cm. This provided a freeboard of 10 cm in the column.

In each set of experiments the outlet size is adjusted to drain stormwater at different rates. The effluent rate varies over time with the height of the water in the column. These varying flow rates are identified by the centroid retention time (CRT) for the runoff in the column. Centroids were calculated using a volume weighted average. The summation of the collected volumes multiplied by the respective times they were collected was divided by the total volume collected. Each set of experiments were averaged together to obtain the centroid.

$$CRT = \frac{\sum V_i * t_i}{V_{Total}} \quad (2)$$

Equation 1 shows the general form of the equation used to calculate the centroids; where *V* indicates volume, *i* indicates the sample number, and *t* indicates time. Table 3 provides the centroid times, initial flow rates, and sample collection times for the different tests.

**Table 3: End times (min) at which samples were collected for the different centroid retention times. Samples were collected continuously (example: sample 1 for the 0.4 day centroid was collected from 0 to 150 min at which time sample 2 began to be collected). The initial effluent rate set before the test for each centroid is also shown.**

| Centroid | 0.4 Days | 0.6 Days | 0.8 Days | 1.0 Days | 1.3 Days |
|---|---|---|---|---|---|
| Effluent Rate | 2.1 (mL/min) | 1.7 (mL/min) | 1.4 (mL/min) | 1.2 (mL/min) | 1.0 (mL/min) |
| **Sample #** | | | | | |
| **1** | 150 min. | 180 min. | 225 min. | 270 min. | 300 min. |
| **2** | 195 min. | 420 min. | 1200 min. | 1200 min. | 1710 min. |
| **3** | 660 min. | 1200 min. | 1860 min. | 1860 min. | 2640 min. |
| **4** | 1050 min. | 1680 min. | 2640 min. | 2700 min. | 4080 min. |
| **5** | 1110 min. | 2730 min. | 3450 min. | 4080 min. | 4620 min. |
| **6** | 2100 min. | | | | |

A series of tests were conducted at the 0.8-day centroid in order to assess the ability of the design to promote denitrification. First, a column was packed with media containing 4.5% Willow Oak woodchips and 95.5% pea gravel by mass. The woodchips used were those passing the 9.5 mm sieve and retained on the No. 4 (5 mm) sieve. The concentration of nitrate in the artificial stormwater was 3 mg/L N in addition to the phosphate and sodium chloride. Nitrate reduction was monitored in the effluent to show that denitrification was taking place. These experimental conditions were used as a standard for comparison with all the tests conducted. Unless otherwise noted, the identified constraints were used in all of the tests discussed hereafter.

In order to prove that denitrification was the means by which nitrate concentrations were being reduced, a set of tests were run that inhibited microbial denitrification. Bremmer and Yeomans (1986) showed that denitrification in soil inoculated with denitrifying bacteria was most retarded when using potassium azide as an inhibitor. Azide is toxic and inhibits denitrification by killing the microorganisms that carry out that process (Fiuza et al. 2002). Therefore, in the inhibited experiments of this research, woodchips were soaked for 48 hours in artificial stormwater that also containing 1000 mg/L sodium azide ($NaN_3$) (Hong et al. 2006). In addition, artificial stormwater run through the system also contained 50 mg/L $NaN_3$ (Hong et al. 2006). The effects of the inhibited experiments were used for comparison with non-inhibited experiments. For comparison, a test was also run on media consisting solely of pea gravel.

To evaluate effects of N concentrations, different concentrations of nitrate in the artificial stormwater were evaluated to include 1.5 and 4.5 mg/L N. Five different centroids were used to determine the effect of time on the denitrification process. The initial flow rate for the 0.4, 0.6, 0.8, 1.0, and 1.3 day centroid times are 2.1, 1.7, 1.4, 1.2 and 1.0 mL/min respectively (Table 2).

Lastly the media was amended with limestone in order to raise the pH of the system. Media was amended with 5% and 10% limestone by volume. The size of the limestone used was passing the 13 mm sieve and retained on the 6.5 mm sieve.

### 2.3. Analysis

All collected samples were tested for nitrate using Standard Method 4110-$NO_3^-$ Ion Chromatographic method (APHA, 1992). Nitrite was tested using Standard Method 4500-$NO_2^-$ C - Ion Chromatographic method (APHA, 1992). A Dionex ICS-1100 Ion Chromatography instrument was used for these measurements with an IonPac AS22 column. Eluent contained 4.5mM $Na_2CO_3$ and 1.5 mM $NaHCO_3$. Nitrite measurements were checked using Standard Method 4500-$NO_2^-$ B - Colorimetric method (APHA, 1992). TKN was measured using Standard Method 4500-$N_{org}$ B Macro-Kjeldahl method (APHA, 1992). The addition of nitrate, nitrite, and TKN resulted in the total nitrogen concentration. Total organic carbon was measured using Standard Method 505 Organic Carbon (Total) (APHA, 1992). Total phosphorus was measured using Standard Method

4500-P phosphorus (APHA, 1992). All chemicals and manufacturers are listed in Table 4.

**Table 4: List of chemicals used in analytical methods with manufacturer and location of production.**

| Chemical Name | Formula | Manufacturer | Location of Production |
|---|---|---|---|
| **Ammonium Molybdate** | $(NH_4)_6Mo_7O_{24}\bullet 4H_2O$ | Fisher Scientific | Fair Lawn, NJ 07410 |
| **Ascorbic Acid** | $C_6H_8O_6$ | J.T. Baker | Phillipsburg, NJ 08865 |
| **Boric Acid** | $H_3BO_3$ | Fisher Scientific | Fair Lawn, NJ 07410 |
| **Cupric Sulfate** | $CuSO_4$ | Fisher Scientific | Fair Lawn, NJ 07410 |
| **Ethyl Alcohol** | $C_2H_6O$ | Pharco Products Inc. | Brookfield, CT 06804 |
| **Hydrochloric Acid** | $HCl$ | Fisher Scientific | Fair Lawn, NJ 07410 |
| **Methylene Blue** | $C_{16}H_{18}N_3SCl$ | Acros Organics | Geel, Belgium |
| **Methyl Red** | $C_{15}H_{15}N_3O_2$ | Acros Organics | Geel, Belgium |
| **N-(1-Naphthyl)-Ethylene-Diamine Dihydrochloride** | $C_{12}H_{16}Cl_2N_2$ | Acros Organics | Geel, Belgium |
| **Nitric Acid** | $HNO_3$ | Fisher Scientific | Fair Lawn, NJ 07410 |
| **Phenolphthalein** | $C_{20}H_{14}O_4$ | Fisher Scientific | Fair Lawn, NJ 07410 |
| **Phosphate Standard** | $NaPO_4$ | Ricca Chemical | Arlington, TX 76012 |
| **Potassium Antimonyl Tartrate** | $K(SbO)C_4H_4O_6\bullet 0.5H_2O$ | Fisher Scientific | Fair Lawn, NJ 07410 |
| **Potassium Persulfate** | $K_2S_2O_8$ | Fisher Scientific | Fair Lawn, NJ 07410 |
| **Potassium Sulfate** | $K_2SO_4$ | Acros Organics | Geel, Belgium |
| **Sodium Azide** | $NaN_3$ | Fisher Scientific | Fair Lawn, NJ 07410 |
| **Sodium Bicarbonate** | $NaHCO_3$ | Fisher Scientific | Fair Lawn, NJ 07410 |
| **Sodium Carbonate** | $Na_2CO_3$ | Fisher Scientific | Fair Lawn, NJ 07410 |
| **Sodium Hydroxide** | $NaOH$ | Fisher Scientific | Fair Lawn, NJ 07410 |
| **Sodium Hydroxide-Thiosulfate** | $NaOH\bullet Na_2S_2O_3$ | Ricca Chemical | Arlington, TX 76012 |
| **Sodium Nitrate** | $NaNO_3$ | J.T. Baker | Phillipsburg, NJ 08865 |
| **Sodium Nitrite** | $NaNO_2$ | EM Science | Gibbstown, NJ 08027 |
| **Sulfuric Acid** | $H_2SO_4$ | Fisher Scientific | Fair Lawn, NJ 07410 |
| **Sulfuric Acid (Titrant)** | $H_2SO_4$ | HACH Company | Loveland, CO 80539 |

Using the data collected from these tests, combined with measurements of pH and oxidation reduction potential, a mass balance was constructed to show the inflow and outflow characteristics. Concentrations measured below the lowest standard are reported as half of the lowest standard (Table 5). Best practices were followed in regards to quality assurance and quality control. Regular standard checks were conducted every 10 samples. If the standard check was not within 10% of the expected value the system was recalibrated. All instruments are listed in Table 5 and undergo regular and continued maintenance according to instrument operation manuals. All glass and plastic-ware was hand washed and soaked in 0.5 N acids (HCl or $HNO_3$).

**Table 5: List of analytical methods from Standard Methods and the corresponding instruments and detection limits.**

| Method | Instrument | Measured | Detection Limit (mg/L) |
|---|---|---|---|
| **4110-$NO_3^-$ Ion Chromatographic** | Dionex ICS-1100 | $NO_3^-$ N | 0.2 |
| **4500-$NO_2^-$ C - Ion Chromatographic** | Dionex ICS-1100 | $NO_2^-$ N | 0.2 |
| **4500-$NO_2^-$ B - Colorimetric** | Shimadzu UV160U | $NO_2^-$ N | 0.02 |
| **4500-$N_{org}$ B Macro-Kjeldahl** | NA | TKN | 0.2 |
| **505 Organic Carbon (Total)** | Shimadzu TOC-5000 | Total Organic Carbon | 0.5 |
| **4500-P phosphorus** | Shimadzu UV160U | Total P | 0.01 |

# 3. Results and Discussion

## 3.1. Establishing Denitrification

The design of the column was able to provide the conditions required to induce the denitrification process. Synthetic runoff showed a decrease in the concentration of nitrate over time when passed through media containing woodchips. Figure 5 shows the nitrate-N concentrations in the effluent of a column packed with only pea gravel in comparison with the three runs for a column with 4.5% WO woodchips by mass. While the nitrate concentrations in the column with WO woodchips decreases from 3 mg/L-N until it reaches and remains below the detection limit of 0.2 mg/L-N, the concentration of nitrate in the pea gravel column remain near 3 ($\pm$ 0.11) mg/L-N. The pea gravel column provided little to no nitrate removal. This is in agreement with the fact that denitrifying

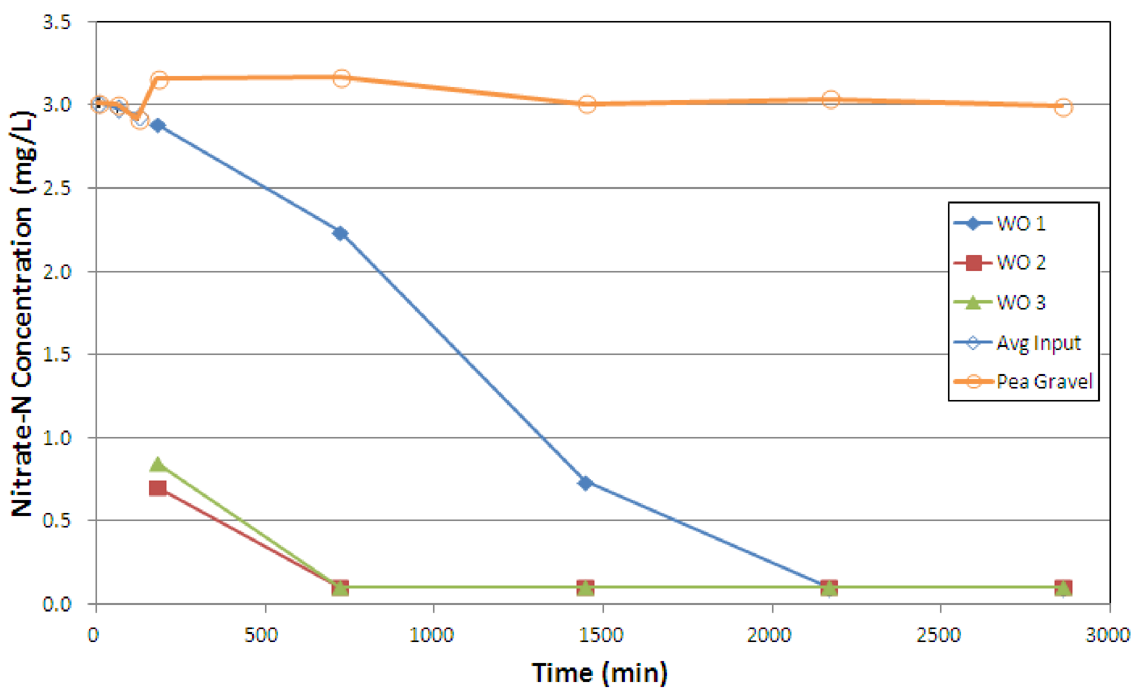


**Figure 5: Nitrate-N concentrations of collected samples from a column packed with Willow Oak woodchips and samples collected from a column containing only pea gravel. These tests were conducted with a centroid retention time of 0.8 days. Three different events are displayed for the WO column and one event for the pea gravel column. All columns were loaded at 1.2 L/hr for 2.25 hrs with artificial stormwater.**

bacteria require anaerobic conditions and the presence of organic carbon (Blowes et al. 1994; Kim et al. 2003). With no organic carbon, denitrifying bacteria lack the ability to function and reproduce (Blowes et al. 1994; Kim et al. 2003).

Run 1 appears to have a delay in the nitrate reduction. This shoulder indicates that microbial populations have not been fully established nor produced the enzymes necessary to carry out denitrification. Runs 2 and 3, however, do not have a shoulder, indicating that microbial populations have been established. Runs 2 and 3 are also very similar which suggests that further tests would have similar results.

For all three runs the pH of WO column samples ranged from 5.90 to 6.72 with an average of 6.29. The values of pH from the blank column were slightly higher, between 6.60 and 7.07 with an average of 6.85. This suggests that the presence of organic material

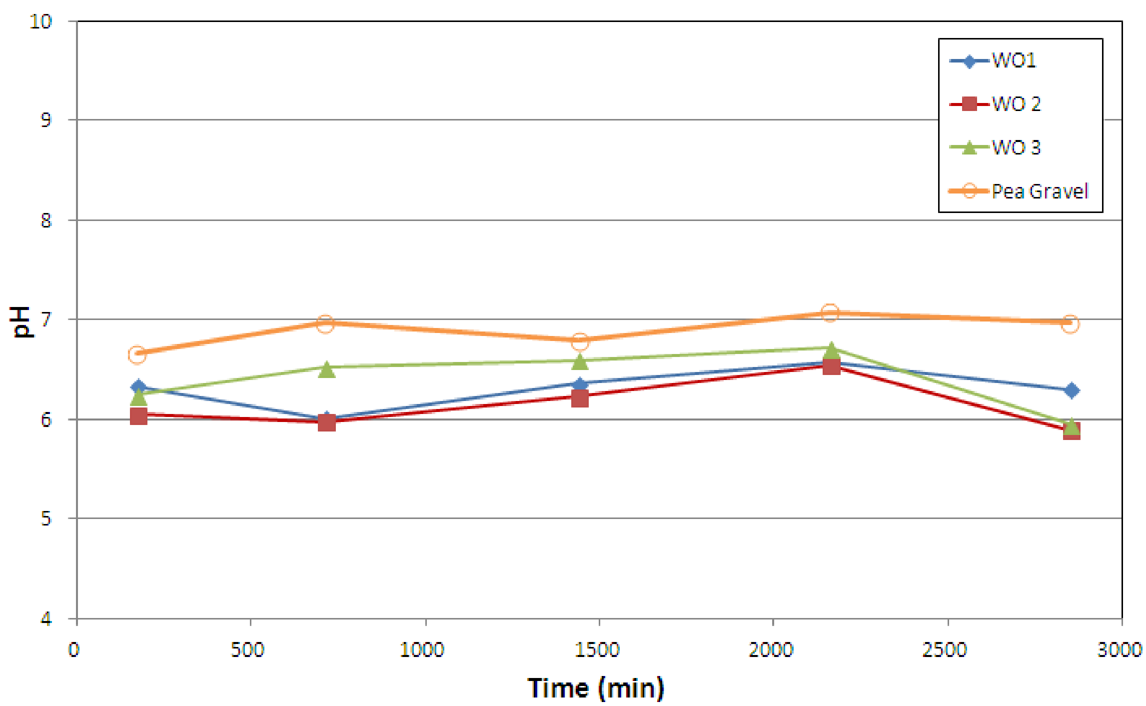


**Figure 6: The pH of collected samples from a column packed with Willow Oak woodchips and a pea gravel column. This test was conducted with a centroid retention time of 0.8 days (1150 minutes). Three different events are displayed for the WO column and one event for the pea gravel column. All columns were loaded at 1.2 L/hr for 2.25 hrs with artificial stormwater.**

slightly decreases the pH of the column. Figure 6 shows a comparison between the pH of the pea gravel column and the three WO column runs over time.

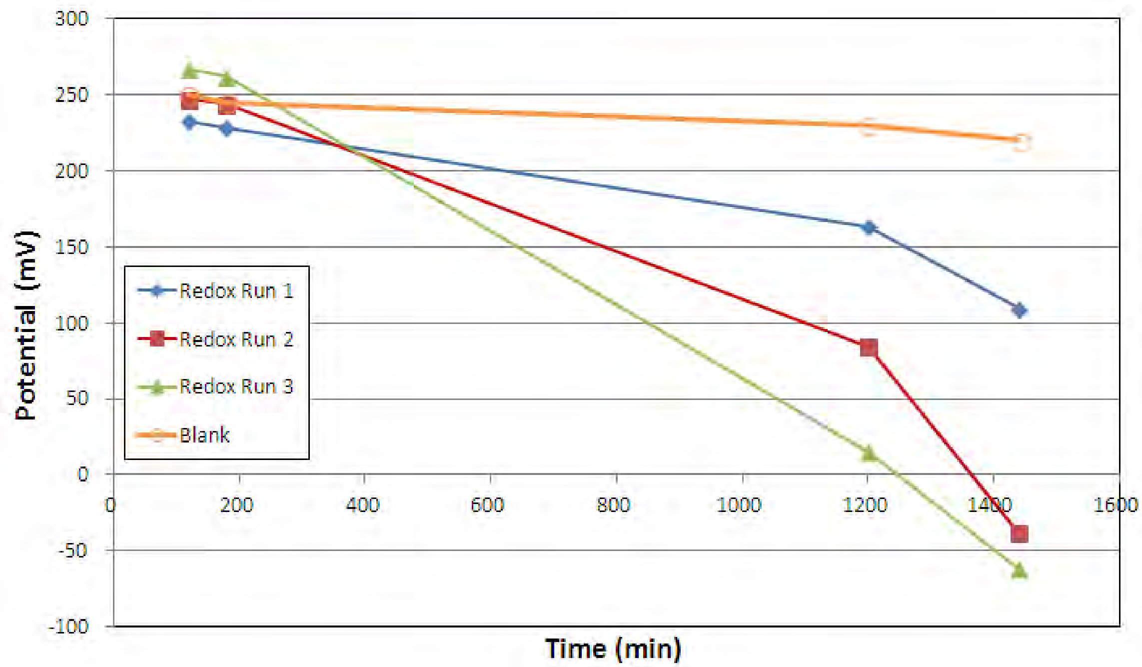


**Figure 7: Oxidation Reduction Potential of collected samples from a column packed with Willow Oak woodchips and a pea gravel column. This test was conducted with a centroid retention time of 0.8 days. Three different events are displayed for the WO column and one for the pea gravel column. Columns were loaded at 1.2 L/hr for 2.25 hrs with artificial stormwater.**

The location of the oxidation/reduction probe allowed for readings for the first half of each test. The first run for a column containing woodchips shows an initially oxidizing environment with a potential near 250 mV (Figure 7). The potential slowly deceases over time suggesting that the environment is becoming more and more reducing (Figure 7). The reducing environment is conducive to denitrification (Blowes et al. 1994). Similar results are seen in the following runs, also shown in Figure 7. Again the potential starts near 250 mV and decreases over time, and, in these second two runs, reach below zero indicating a fully reducing environment. Denitrification takes place when the potential of an aquatic environment is between 200 and -200 mV (Stumm and Morgan 1996). The trend in the oxidation/reduction potential of column suggests that the media provides a good environment for denitrification. The potential in the column decreases below 200 mV, where denitrification is expected to be favorable, at around 400 minutes. The slope in the data indicates that oxygen is becoming much less available over time. In contrast, the oxidation reduction potential of the pea gravel column again starts near 250 mV but never reached below 200 mV (Figure 7). This suggests that the environment never becomes anaerobic when no organic carbon is present, and is not conductive to denitrification.

For comparison with the measured values, the equilibrium oxidation/reduction potential for the reduction of nitrate to nitrite was predicted using the Nernst equation (Eq. 3). The chemical formula for the half reaction of nitrate reduction to nitrite is shown in Equation 4.

$$E = E^0 - \frac{RT}{nF} \ln (Q) \qquad (3)$$

$$NO_3^{-1} + 2H^+ + 2e^- = NO_2^{-1} + H_2O \qquad (4)$$

$$Q = \frac{[NO_2^-]}{[NO_3^-][H^+]^2} \qquad (5)$$

*E* is the potential of the system, $E^0$ is the standard half reaction potential (+420 V for the reduction of nitrate to nitrite) (Stumm and Morgan 1996), *R* is the universal gas constant (8.314 J $K^{-1}$ $mol^{-1}$), *T* is the absolute temperature (298 K at room temperature), *n* is the number of electrons transferred (2 for the reduction of nitrate to nitrite), *F* is the Faraday constant ($9.649 * 10^4$ C $mol^{-1}$, and Q is the reaction quotient (Eq. 5). Table 6 shows the predicted potential in the column and the difference between those predicted values and the measured values.

**Table 6: Predicted oxidation/reduction potential and corresponding measured potential for a column packed with Willow Oak woodchips. These tests were conducted with a centroid retention time of 0.8 days. Three different events are displayed for the WO column. All columns were loaded at 1.2 L/hr for 2.25 hrs with artificial stormwater.**

| | Time(min) | pH | $NO_2^-$ (mg/L) | $NO_3^-$ (mg/L) | Oxidation Reduction Potential (mV) Measured | Oxidation Reduction Potential (mV) Predicted |
|---|---|---|---|---|---|---|
| Run 1 | 712.5 | 6.01 | 0.24 | 2.25 | 228.6 | 113.9 |
| | 1440 | 6.36 | 0.92 | 0.74 | 163.0 | 89.2 |
| | 2160 | 6.58 | 0.18 | 0.10 | 109.4 | 37.1 |
| | | | | | | |
| Run 2 | 712.5 | 5.98 | 0.01 | 0.10 | 244.1 | 112.8 |
| | 1440 | 6.23 | 0.01 | 0.10 | 84.6 | 92.0 |
| | 2160 | 6.55 | 0.01 | 0.10 | -38.4 | 77.2 |
| | | | | | | |
| Run 3 | 712.5 | 6.53 | 0.01 | 0.82 | 261.9 | 103.4 |
| | 1440 | 6.60 | 0.01 | 0.31 | 15.3 | 59.4 |
| | 2160 | 6.72 | 0.01 | 0.10 | -62.0 | 55.3 |

One reason that these predictions vary from the measured values is that the system is dynamic. This means that the nitrogen species are constantly changing and the potential changes accordingly. All of the species of nitrogen cannot be measured so some reactions are unaccounted for in the calculation of the potential. The electrode used to measure the potential in the column represents the environment as a whole. Nitrate reduction to nitrite is not the only process taking place that affects the system potential. However, those are the only measured concentrations that can be applied to the Nernst equation.

Early calculated values tend to underpredict the potential while later values tend to overpredict. This may be representative of a dynamic system. As nitrate is reduced to nitrite the concentration of nitrate decreases while nitrite increases. This would result in a decreasing potential, which is evident in both the measured and calculated values. When nitrite begins to be reduced to nitric oxide the concentration of nitrite also begins to decrease. As a result, the potential of the system decreases much more quickly than the calculated values indicate. Therefore calculated values overpredict the potential.

The media containing woodchips resulted in leaching of phosphorus and organic carbon. Figure 8 shows the inflow and outflow concentrations of phosphorus over time for all three runs. Figure 8 is an example of effluent total phosphorus concentrations which closely reflects the total phosphorus concentration in all the experiments conducted. The empty markers show the inflow concentrations of 0.1 mg/L phosphorus and the solid markers show collected sample concentrations. The first sample of the first run showed a spike in phosphorus concentration. After the first sample the effluent had only slightly increased concentrations of phosphorus, near or below 0.15 mg/L phosphorus. This is consistent with all of the experiments being discussed unless otherwise mentioned.

Figure 9 shows the inflow and outflow concentrations of organic carbon over time for all three runs. Total organic carbon concentrations for WO 1 were at or near 50 mg/L

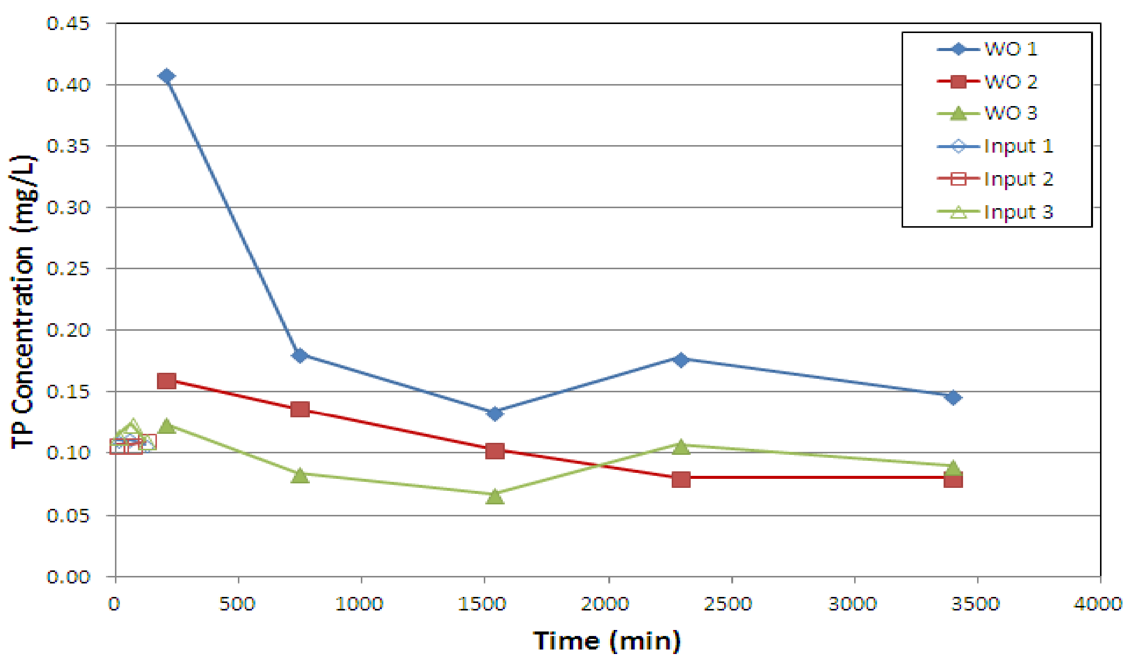


**Figure 8: The concentration of total phosphorus in collected samples from a column packed with Willow Oak woodchips. This test was conducted with a centroid retention time of 1.0 days. Three different events are displayed. Columns were loaded at 1.2 L/hr for 2.25 hrs with artificial stormwater.**

throughout the collection period. The subsequent runs showed lower concentrations with the exception of the first sample of WO 2 (Figure 9). In a study using woodchips as an organic carbon source for denitrification in septic systems, Robertson (2010) also found an initial spike in organic carbon concentrations in the effluent. In a steady state continuous flow system the organic carbon concentration decreased and began to stabilize over time (Robertson 2010). The consistency of the second two runs of this study suggests that steady state is reached after the first run is completed. The trend also suggests that, had testing continued, subsequent runs would have similar results. These observations are in close agreement with Robertson (2010). Robertson (2010) also attributed these concentrations of leached nutrients to the organic material in the media.

Nitrogen was also leached from the media, and measured as TKN. The TKN for WO 1 remained above 1 mg/L for all of the samples tested. The subsequent runs showed much lower concentrations near 0.5 mg/L. The TKN trend is similar to that of the total

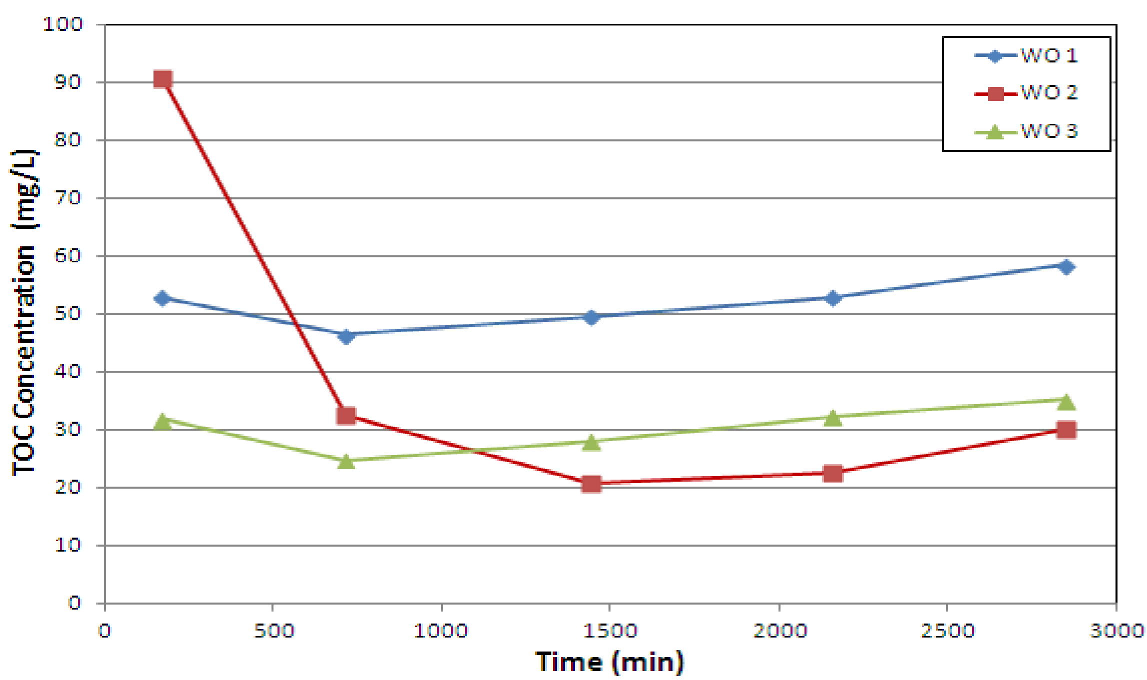


**Figure 9: Total organic carbon concentrations of collected samples from a column packed with Willow Oak woodchips. This test was conducted with a centroid retention time of 0.8 days. Three different loading events are displayed. Columns were loaded at 1.2 L/hr for 2.25 hrs with artificial stormwater.**

organic carbon, suggesting that the two concentrations are linked or respond similarly to the changing environment. The pea gravel test was in agreement with these observations where no nitrogen, phosphorus, or organic carbon was leached. The source of those nutrients is therefore assumed to be the wood chips. Most of the research done on nitrate removal efficiency in bioretention systems does not account for other forms of nitrogen and therefore there are no specific examples to compare these data to. However, Robertson (2010) makes note of the link between organic material and leached nutrients, specifically organic carbon. That research suggests that adjustments in the amount of organic material would have significant effects on the leaching of these nutrients (Robertson 2010). Concentrations of each nitrogen species and the total nitrogen concentrations over time for run 3 of the WO column can be seen in Figure 10. The total nitrogen was calculated by adding the concentrations of TKN, nitrate, and nitrite.

The first run of the 0.8-day centroid retention time shows a nitrite concentration that starts below the detection limit (0.01 mg/ L-N) and increases over time until it peaks around 1.0 mg/L-N (Figure 10). This concentration is reached around halfway through the experimental duration, about 1500 minutes. Afterward the concentration decreased until it was below the detection limit (0.01 mg/L-N) in the final sample. This reflects, very clearly, the sequential microbial processes that reduce nitrate to nitrite and then to other forms of nitrogen and ultimately to nitrogen gas. As nitrate is converted to nitrate, nitrate concentrations decrease while nitrite concentrations increase (Blowes et al. 1994). As nitrite concentrations build, microbes begin to produce enzymes to convert that nitrite to nitric oxide, which is also depicted in Figure 10 by the decrease in nitrite concentrations after 1500 minutes (Blowes et al. 1994).

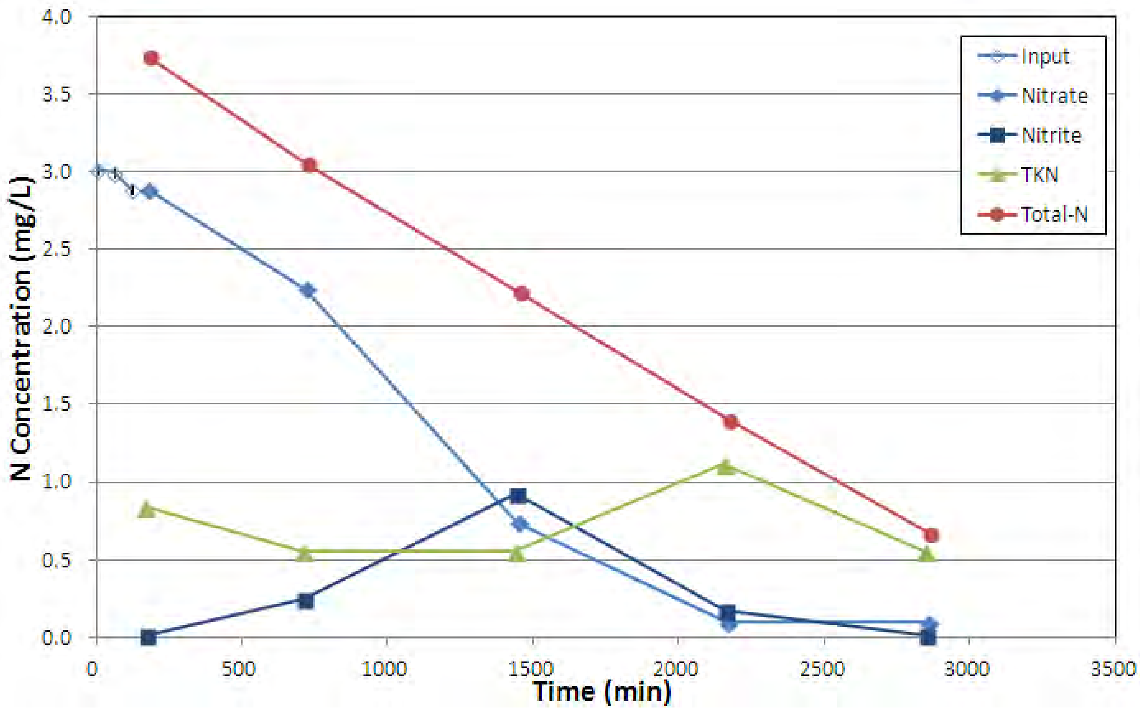


**Figure 10: Nitrogen concentrations of collected samples from a column packed with Willow Oak woodchips. This test was conducted with a centroid retention time of 0.8 days. Run 3 of the different events are displayed. Columns were loaded at 1.2 L/hr for 2.25 hrs with artificial stormwater.**

Data for the column with media containing WO woodchips was reproduced in a separate set of three runs. The average total nitrogen removal efficiencies for the two sets were 60.3% and 62.4%, which is the average difference between the total nitrogen mass in the influent and the effluent for the three runs. The average nitrate removal efficiencies for the two sets of data were 81.6% and 82.7%, which is similarly the average of the three runs' difference between the total nitrate-N mass in the influent and the total nitrate-N mass in the effluent. Figure 11 shows the second set of data. The similarity between these data and those presented in Figure 5 is clear. While run 1 of each set has a much slower reduction in the concentration of nitrate, runs 2 and 3 of each set have decreased to near 0.5 mg/L N by the first collected sample. Nitrate concentrations remain near or below the detection limit for the remaining samples collected. This suggests that the data presented herein are reliable and reproducible.

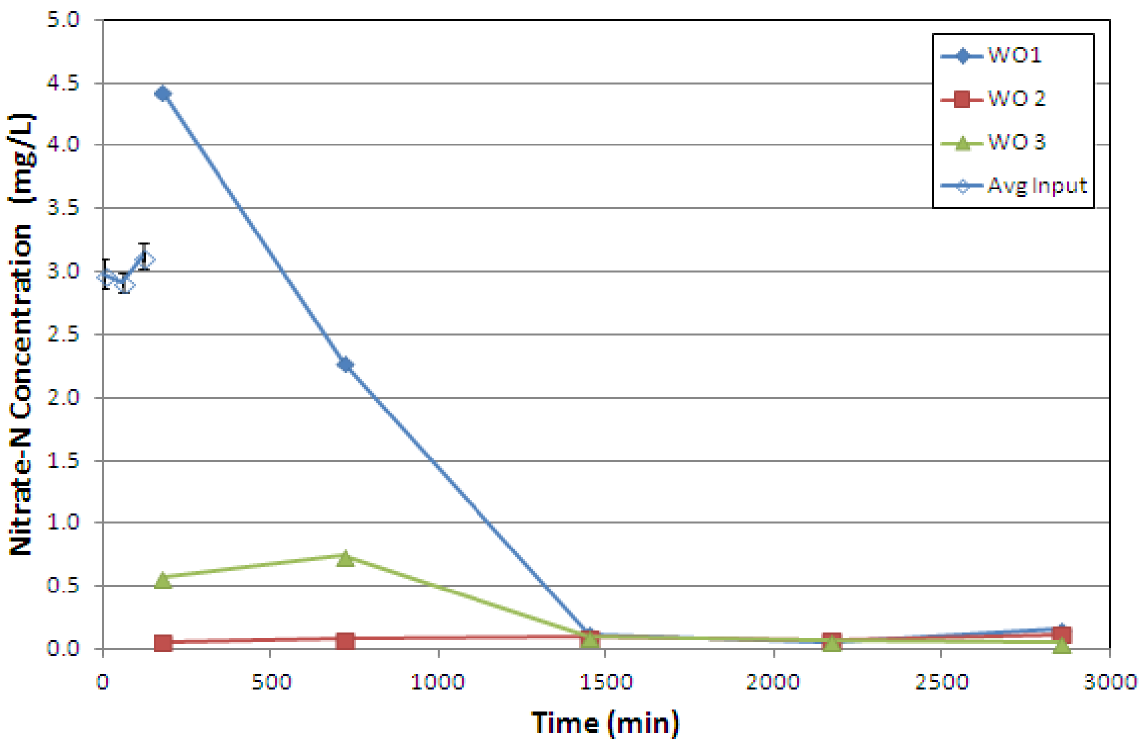


**Figure 11: Nitrate-N concentrations of collected samples from a column packed with Willow Oak woodchips. These tests were conducted with a centroid retention time of 0.8 days. Three different events are displayed for the WO column. Columns were loaded at 1.2 L/hr for 2.25 hrs with artificial stormwater.**

Similar to the pea gravel test, the tests inhibited with azide showed effluent concentrations of nitrate at or near the inflow concentration of 3 mg/L-N (Figure 12). Bremmer and Yeomans (1986) showed that azide has the greatest ability to retard microbial denitrification. These data are in agreement and show that higher concentrations of azide can fully inhibit denitrification. The pH of the inhibited samples ranged from 5.86 to 6.56 with an average of 6.27. The oxidation/reduction potential in the column showed a consistent oxidizing environment. Similar to the pea gravel column, the potential in the inhibited column never reached below 200 mV. However, the inhibited column leached much higher concentrations of phosphorus, organic carbon and TKN. These concentrations varied between runs and samples. The average concentrations of total phosphorus, total organic carbon, and TKN were 0.51, 106, and 2.50 mg/L, respectively.

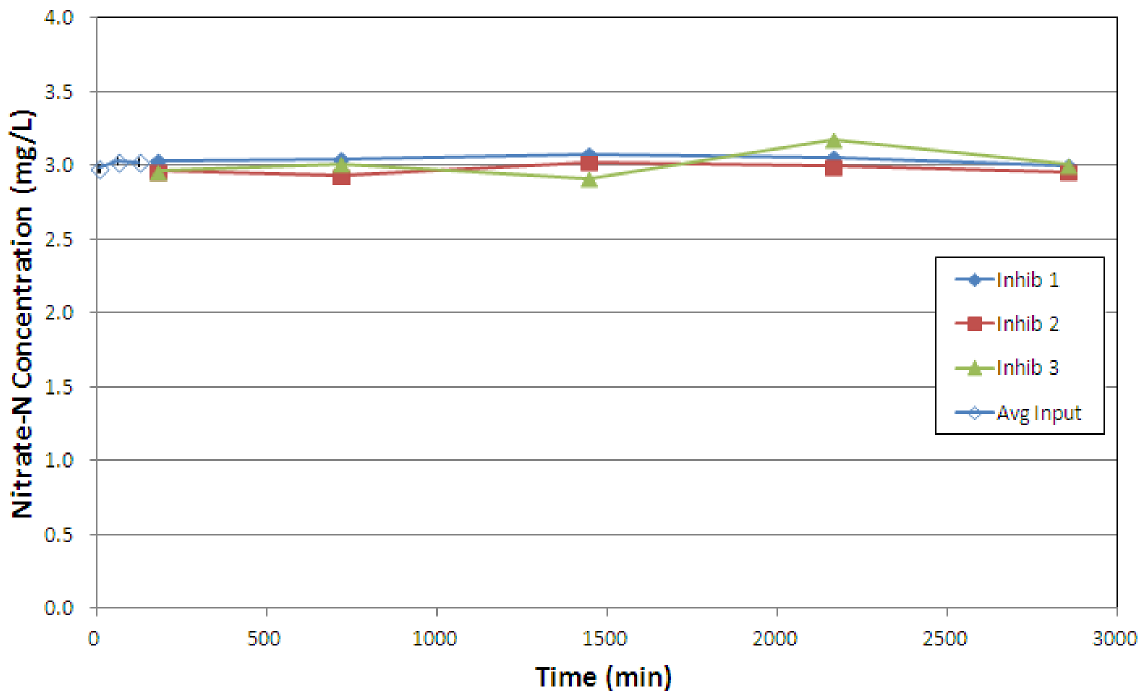


**Figure 12: Nitrate-N concentrations of collected samples from a column packed with Willow Oak woodchips. These tests were conducted with a centroid retention time of 0.8 days. Three different events are displayed for the WO column. Column was loaded at 1.2 L/hr for 2.25 hrs with artificial stormwater containing 50 mg/L Sodium Azide for inhibition of microbial denitrification.**

Because no reduction of nitrate is found when microbial denitrification is inhibited, these data suggest that the reduction of nitrate in the WO column was due to populations of denitrifying microbes. No other research has been identified that uses a similar method for identifying the effect of denitrifying microbes in a bioretention system. However, Chen et al. (2013) conducted quantitative PCR on media similarly designed for denitrification in bioretention systems. In the analysis, Chen et al. (2013) identified strains of denitrifying bacteria. While Chen et al. (2013) did not use woodchips as the sole source of organic carbon, the columns in that study created conditions similar to those used in this study. That study had a saturated zone containing organic material that became anaerobic due to saturation (Chen et al. 2013). The similarities in environmental conditions and the contrasting nitrate concentrations from inhibitory and non-inhibitory columns strongly agree with the evidence presented in Chen et al. (2013).

The lack of nitrate reduction in the inhibited column also suggests that the scaled bioretention design provides the conditions necessary for improved nitrate removal from stormwater runoff. Kim et al. (2003), Hsieh et al. (2007), Bratieres et al. (2008), Ergas et al. (2010), Leverenz et al. (2010), Robertson (2010), Zinger et al. (2013), and Chen et al. (2013) all identify that the conditions needed for denitrification to take place in a stormwater management application are an anaerobic media, typically created by being fully saturated, containing a source of organic carbon. This research also found those conditions to be necessary and conducive to the growth of denitrifying microbes.

### **3.2.** Effect of Nitrate Concentration

Varying the inflow concentrations of nitrate from 1.5 to 4.5 mg/L-N did not have an effect on the pH of the samples collected. The average pH for the 1.5, 3.0, and 4.5 mg/L N inflow columns were 6.30, 6.29, and 6.42, respectively. Collectively the samples ranged in pH from 5.75 to 7.32. The oxidation/reduction potential of the columns, however, varied greatly. While the potential in the 3.0 mg/L inflow column behaved as expected and decreased over time, the other two columns were less predictable. The 1.5 mg/L column started with a potential near 200 mV in all three runs but did not show any discernible trend thereafter (Figure 13). The 4.5 mg/L inflow column showed a decrease in potential over time in run 1 but increases in potential in runs 2 and 3 (Figure 14). This suggests that, for an unknown reason, the columns did not consistently create conditions conducive to denitrification when varying the concentration of nitrate in the artificial stormwater.

While there were slight variations between the three different column studies, consistent nutrient concentrations were leached. Average concentrations of total phosphorus from the 1.5, 3.0, and 4.5 mg/L inflow columns were 0.11, 0.37, and 0.16 mg/L P, respectively. Average concentrations of total organic carbon were 28, 41, and 22 mg/L C, respectively, and TKN were 1.10, 0.78, and 0.90 mg/L N, respectively.

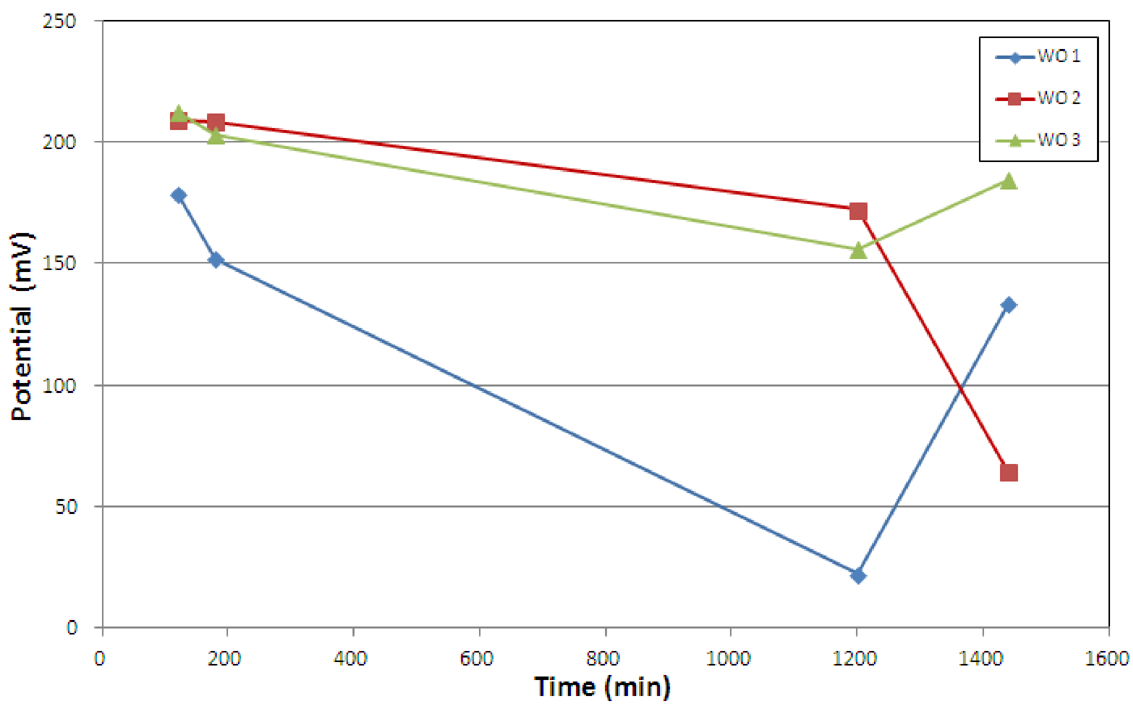


**Figure 13: Oxidation Reduction Potential of collected samples from a column packed with Willow Oak woodchips. This test was conducted with a centroid retention time of 0.8 days. Three different events are displayed for the WO column. Columns were loaded at 1.2 L/hr for 2.25 hrs with artificial stormwater containing 1.5 mg/L N.**

The removal of nitrogen by the column had no discernible pattern. Total nitrogen mass removal efficiencies for the 1.5, 3.0, and 4.5 mg/L N inflow columns were 13.7%, 60.3%, and 24.4%, respectively. Nitrate mass removal efficiencies for the 1.5, 3.0, and 4.5 mg/L N inflow columns were 67.9%, 81.6%, and 42.8%, respectively.

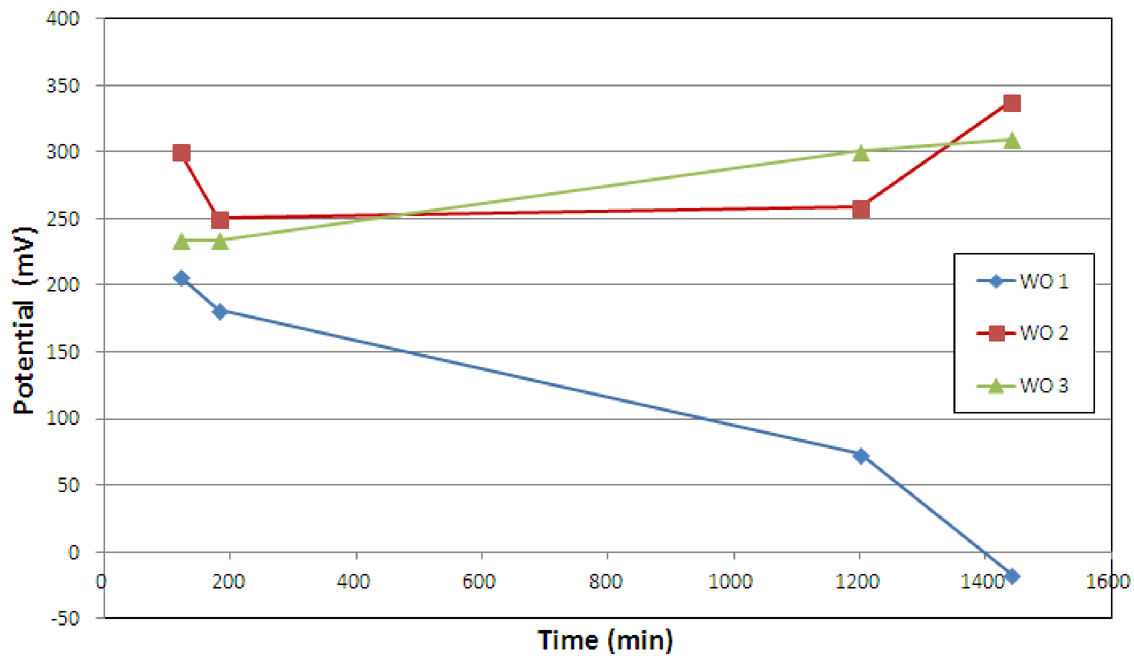


**Figure 14: Oxidation Reduction Potential of collected samples from a column packed with Willow Oak woodchips. This test was conducted with a centroid retention time of 0.8 days. Three different events are displayed for the WO column. Columns were loaded at 1.2 L/hr for 2.25 hrs with artificial stormwater containing 4.5 mg/L N.**

In order to better quantify and characterize the effect of varying inflow concentrations of nitrate on the denitrification process, two models were developed. Robertson (2010) and Leverenz et al. (2010) both evaluated modeling denitrification using either zero or first order models. Robertson (2010) used a septic system design with woodchips as an organic carbon source to accommodate treatment of agricultural runoff and found that a zero-order model most accurately depicted the data. Leverenz et al. (2010) conducted a lab scale evaluation of wetland treatment with woodchips as a carbon source and found that first-order kinetics most accurately modeled denitrification. While there are similarities, neither of these experiments accurately reflects the conditions in a bioretention system. Robertson (2010) is more closely related but has a more controlled environment than in a bioretention system and received stream runoff that contained much higher concentrations of nitrate (3.1 to 48.8 mg/L-N) than are typically seen in urban settings. Leverenz et al. (2010) had a horizontal continuous flow system modeled to represent a wetland and not a bioretention system. Both Robertson (2010) and Leverenz et al. (2010) have an abundance of organic material ensuring that carbon is not limiting.

Taking previous evaluations into consideration, pseudo-zero and first-order models were developed to represent the denitrification process in the present bioretention column. The rate constant for these models is a function of woodchip species, woodchip size, woodchip availability, pH, and temperature. The pseudo-zero and first-order model equations are shown in Eq. 7 and Eq. 8, respectively. These equations are derived from Eq. 6, which is a simple nitrate-N mass balance for the column. The full derivation of these models can be found in the appendix. Both models assume a completely mixed system because as water passes through the media it is mixed. There is no direct pathway through the column and the media is homogeneous. Therefore, it can be assumed that all stormwater retained in the column is in the same environment and undergoing the same processes. Outflow from the system is assumed to begin when the column is completely full. Therefore, inflow is not represented in Eq. 6. Very little effluent drains from the column during the filling period which is only a fraction of the total drainage time and the elimination of inflow from the equation greatly simplifies the derivation.

$$\frac{dM}{dt} = -Q * C - r * V \quad (6)$$

$$C = C_0 + k_0 * t \quad (7)$$

$$C = C_0 * e^{k_1 * t} \quad (8)$$

For the pseudo-zero-order model rate, r, is equal to $k_0$, and for the pseudo-first-order model r is equal to $k_1$ times C. Q is the effluent rate, $C$ is the concentration of nitrate-N of the sample at time $t$, and $C_0$ is the inflow concentration of nitrate-N. $k_0$ and $k_1$ are the rate constants for the psedo-zero and first-order models, respectively. These models were fitted to the collected data using least squares with a fixed intercept at the inflow concentration. Rate constants were used as fitting parameters. The pseudo-zero-order

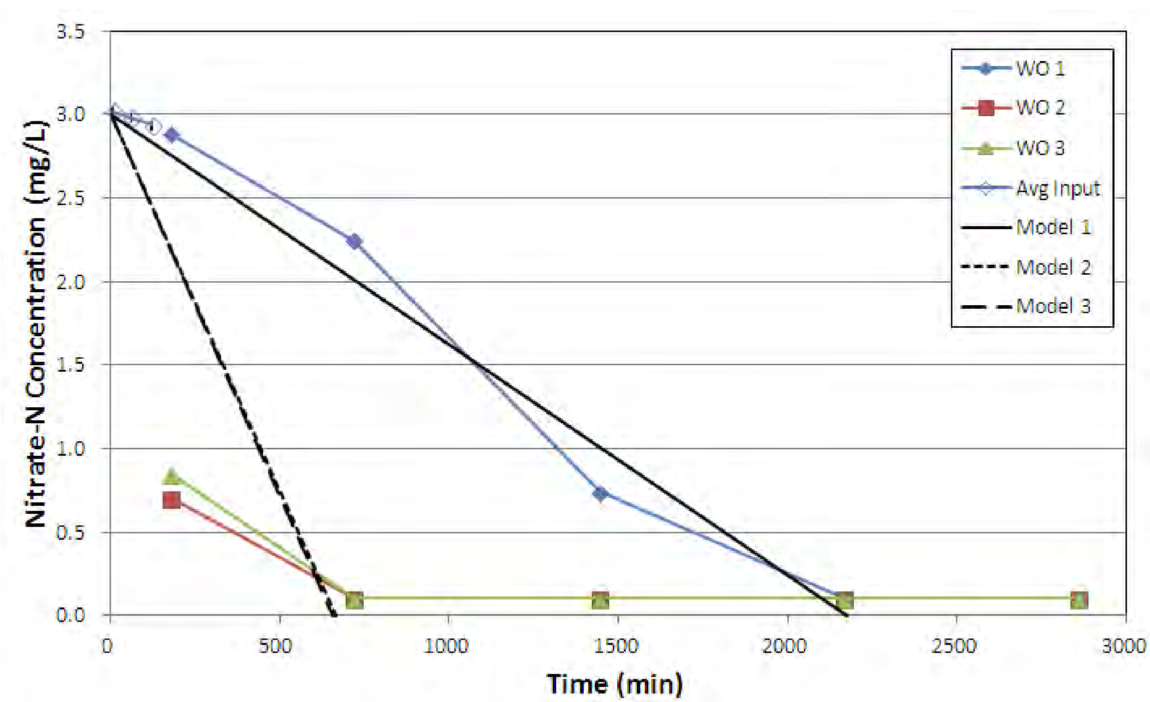


**Figure 15: Fit of a pseudo-zero-order model to the Nitrate-N concentrations of collected samples from a column packed with Willow Oak woodchips. These tests were conducted with a centroid retention time of 0.8 days. Three different events are displayed for the WO column.**

model was fitted only to the points in the experimental phase where nitrate concentrations were decreasing. After the concentration of nitrate fell below the detection limit no more points were used (Figure 15). In Figure 15, model 1 and 2 overlap. All of the effluent data collected were used in fitting pseudo-first-order models to the data (Figure 16). The resulting rate constants were compiled in order to better compare each of the factors being discussed. pseudo-zero and first-order rate constants can be found in Table 7 for the average of all three runs, the average of runs 2 and 3, and run 3 alone for each set of data collected. Table 7 also shows the average total nitrogen and nitrate removal efficiencies for all of the factors being evaluated.

For the majority of the testing conducted the nitrate removal curve for Run 1 was very different from the subsequent two runs. The difference between run 1 and the

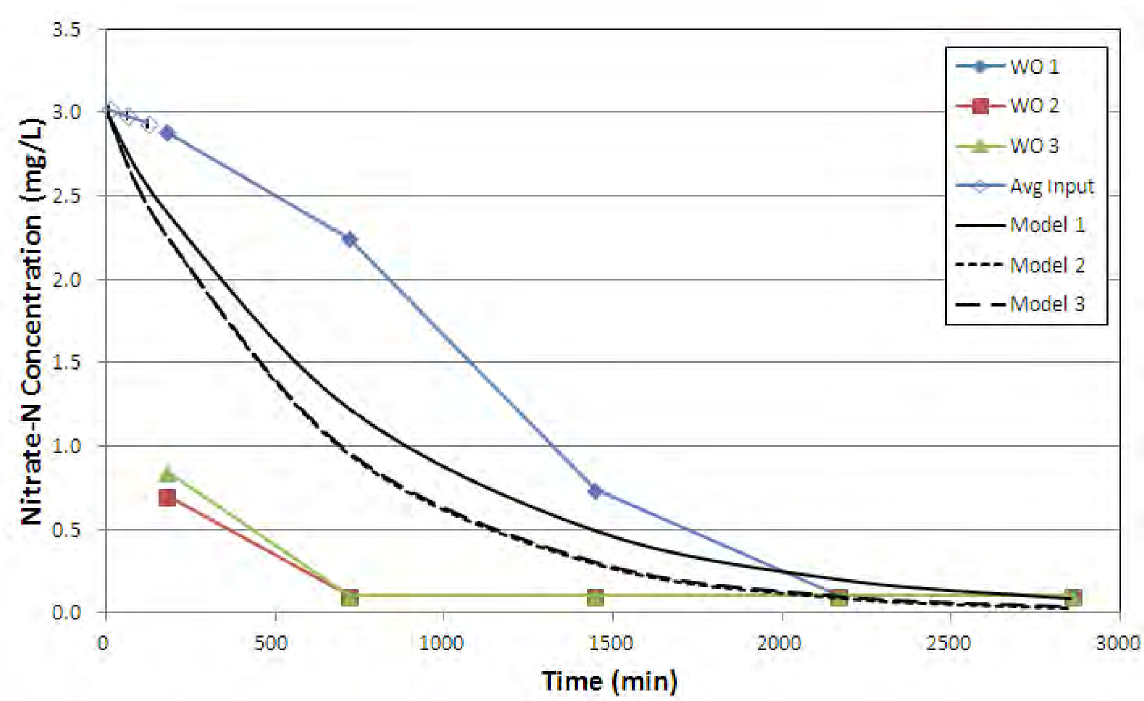


**Figure 16: Fit of a pseudo-first-order model to the Nitrate-N concentrations of collected samples from a column packed with Willow Oak woodchips. These tests were conducted with a centroid retention time of 0.8 days. Three different events are displayed for the WO column.**

subsequent runs suggests that an average of the rate constants for all three runs does not accurately represent an established system. The average of the last two runs was more appropriate for most sets of data. The similarity of the last two runs suggests that subsequent runs would behave similarly. The second two runs did not have a shoulder, which was evident in run 1 (Figure 16). Therefore, it is expected that subsequent runs would not have a shoulder and an acclimation model would not accurately represent an established system. Some of the data sets continued to change from run 2 to run 3 suggesting that in some cases more than one run was necessary for the system to reach a steady state. Because run 3 represents the most established media, the discussion of rate constants will be based on the third run for each set of data. All of these data can be found in Table 7.

Altering the concentration of nitrate in the inflow did not have the expected effect. According to the models, the rate constants should not be affected by a change in the initial concentration of nitrate. However, 1.5, 3.0, and 4.5 mg/L N inflow columns had pseudo-zero-order rate constants of 1.30, 6.57, and 3.11 mg/L/day respectively for run 3. The pseudo-zero-order rate constants were not constant as the models predicted and neither was there a discernible trend in the change of the rate constants. The pseudo-first-order rate constants had less variability with inflow concentration of nitrate. The 1.5, 3.0, and 4.5 mg/L N inflow columns had pseudo-first-order rate constants of 1.39, 11.41, and 1.53 $day^{-1}$ respectively for run 3.

One explanation of the non-conformity of the rate constants with the model predictions is different models may more accurately predict the data at different influent

**Table 7:Rate constants and removal efficiencies for bioretention column denitrification. The three-run average, run 2 and 3 average, and run 3 pseudo-zero and first-order rate constants are listed for each column test. The corresponding combined three run total nitrogen and nitrate removal percentage is also shown for each column test.**

| | | Pseudo-Rate Constants | | | | | | | | Removal Efficiency | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Zero Order | | | | First Order | | | | | |
| | | Total Avg (mg/L•day) | Run 2&3 Avg | Run 3 (mg/L•day) | Average $R^2$ | Total Avg ($day^{-1}$) | Run 2&3 Avg ($day^{-1}$) | Run 3 ($day^{-1}$) | Average $R^2$ | Total Nitrogen (%) | Nitrate (%) |
| | Blank | ND | ND | 0.01 | 0.00 | ND | ND | 0.00 | 0.00 | -1.01 | -1.01 |
| | Inhibbited | 0.01 | 0.01 | 0.03 | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | -80.58 | 0.37 |
| Nitrate - N | 1.5 mg/L | 1.85 | 1.40 | 1.30 | 0.91 | 2.20 | 1.76 | 1.39 | 0.93 | 13.7 | 67.9 |
| | 3.0 mg/L | 5.02 | 6.53 | 6.57 | 0.64 | 10.39 | 14.98 | 11.41 | 0.92 | 61.9 | 82.4 |
| | 4.5 mg/L | 3.12 | 2.16 | 3.11 | 0.62 | 1.87 | 0.91 | 1.53 | 0.74 | 24.4 | 42.8 |
| Retention Time | 0.4 Days | 4.51 | 4.13 | 4.20 | 0.87 | 3.07 | 2.89 | 3.04 | 0.93 | 6.5 | 51.0 |
| | 0.6 Days | 2.99 | 2.07 | 1.94 | 0.61 | 1.94 | 1.70 | 1.46 | 0.74 | 30.1 | 49.5 |
| | 0.8 Days | 5.02 | 6.53 | 6.57 | 0.64 | 10.39 | 14.98 | 11.41 | 0.92 | 61.9 | 82.4 |
| | 1.0 Days | 2.34 | 2.28 | 1.86 | 0.64 | 1.52 | 1.63 | 1.45 | 0.78 | 41.8 | 59.6 |
| | 1.3 Days | 1.58 | 1.30 | 1.34 | 0.89 | 1.21 | 0.85 | 0.94 | 0.95 | 50.1 | 65.9 |
| Woodchip Species | Wild Cherry | 2.83 | 3.23 | 3.24 | 0.83 | 2.34 | 2.92 | 3.02 | 0.93 | 37.5 | 71.4 |
| | Willow Oak | 9.94 | 13.68 | 3.46 | 0.60 | 13.15 | 19.13 | 12.73 | 0.88 | 61.3 | 82.1 |
| | WO Repeat | 5.02 | 6.53 | 6.57 | 0.69 | 7.62 | 10.83 | 10.09 | 0.97 | 62.4 | 82.7 |
| | Red Maple | 2.83 | 3.10 | 3.17 | 0.80 | 2.17 | 2.67 | 3.31 | 0.91 | 61.8 | 73.6 |
| | Virginia Pine | 2.78 | 3.39 | 3.20 | 0.60 | 9.77 | 14.20 | 4.21 | 0.90 | 47.4 | 78.4 |
| | American Beech | 4.22 | 3.31 | 3.31 | 0.75 | 4.18 | 4.08 | 4.00 | 0.96 | 34.4 | 87.2 |
| Chip Size | 5 mm | 5.02 | 6.53 | 6.57 | 0.64 | 10.39 | 14.98 | 11.41 | 0.92 | 61.9 | 82.4 |
| | 9 mm | 2.41 | 2.47 | 2.09 | 0.87 | 1.65 | 1.52 | 1.43 | 0.92 | 51.4 | 60.9 |
| | 13 mm | 2.55 | 2.56 | 2.09 | 0.90 | 1.67 | 1.81 | 1.40 | 0.93 | 46.2 | 63.2 |
| Chip Mass | 1.0% | 1.43 | 1.66 | 1.71 | 0.42 | 1.10 | 1.47 | 1.56 | 0.58 | 42.2 | 48.9 |
| | 2.5% | 3.74 | 4.61 | 5.98 | 0.69 | 4.00 | 5.41 | 7.22 | 0.93 | 57.8 | 68.7 |
| | 4.5% | 5.02 | 6.53 | 6.57 | 0.64 | 10.39 | 14.98 | 11.41 | 0.92 | 61.9 | 82.4 |
| Limestone | 0.0% | 5.02 | 6.53 | 6.57 | 0.64 | 10.39 | 14.98 | 11.41 | 0.92 | 61.9 | 82.4 |
| | 5.0% | 2.83 | 3.25 | 3.37 | 0.73 | 2.99 | 3.95 | 5.94 | 0.89 | 61.0 | 66.1 |
| | 10.0% | 2.90 | 3.13 | 3.44 | 0.70 | 3.85 | 5.18 | 8.86 | 0.92 | 61.9 | 68.2 |

concentrations of nitrate. Robertson (2010) found that a zero-order model better fit the data. In that study influent nitrate concentrations were as high as 48.8 mg/L N (Robertson et al. 2010). Leverenz et al. (2010) suggested that denitrification may follow first order kinetics when the influent nitrate concentrations are low (less than 10 mg/L-N). The bioretention experiments fall below that suggested threshold, which suggests that first-order kinetics may be a better model. However, the average pseudo-zero-order model $R^2$ values for the 1.5, 3.0, and 4.5 mg/L N inflow columns were only 0.91, 0.64, and 0.62, respectively. The average pseudo-first-order model $R^2$ values for the 1.5, 3.0, and 4.5 mg/L N inflow columns were 0.93, 0.92, and 0.74, respectively. These goodness-of-fit statistics give a clear indication that the pseudo-first-order model better describes the data. The pseudo-zero-order model is fitted to fewer points. All of the points are used when fitting the pseudo-first-order model to the data. Even with fewer points fitted to the pseudo-zero-order model, the $R^2$ values pseudo-first-order kinetics better model the data.

Leverenz et al. (2010) found that after two years the first-order denitrification rate constant in a woodchip media was between 1.30 and 1.41 $days^{-1}$. Robertson (2010) reported first-order rate constants for fresh pine and fresh hardwood woodchip media to start at 2.3 $day^{-1}$ and 2.4 $day^{-1}$, respectively. Further testing showed decreasing rate constants over time (Robertson 2010). The 3.0 mg/L N column had a pseudo-first-order rate constant of $11.4 \pm 1.9$ $day^{-1}$, for run 3. The rate constant for this column is higher than those reported in literature. However, this value has reproducibility and is, therefore, used in comparison with all of the tests conducted.

## 3.3. Effect of Retention Time

When varying the retention time of the columns, the pH of the samples remained relatively consistent and ranged from 5.90 to 7.50. The average pH of the 0.4 (575), 0.6 (860), 0.8 (1150), 1.0 (1450), and 1.3 days (1875 minutes) centroid retention time columns was 6.67, 6.47, 6.29, 6.53, and 6.69, respectively. The oxidation/reduction potential in the columns all started between 200 and 350 mV. However, the potential in shorter retention time columns did not reach the low levels that longer retention time columns did. The lowest potential measured for the 0.4 day centroid retention time column was 70.8 mV at 255 minutes while the lowest potential measured for the 1.3 day centroid retention time column was -454.5 mV at 2640 minutes. It is evident from these data that the longer the water is retained in the media the more reducing the environment becomes.

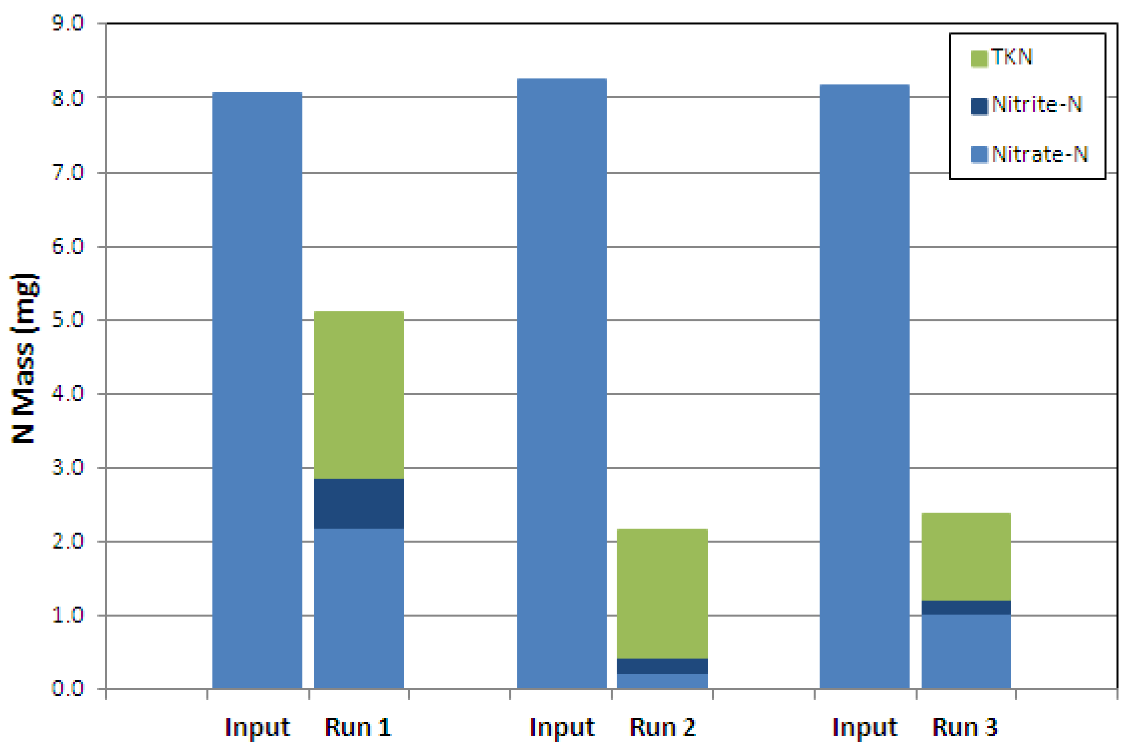


**Figure 17: Total nitrogen mass in the effluent (Run #) is compared to its respective input mass from the artificial stormwater for a column packed with Willow Oak woodchips. This test was conducted with a centroid retention time of 0.8 days. Three different events are displayed. Columns were loaded at 1.2 L/hr for 2.25 hrs with artificial stormwater.**

Nutrient concentrations were relatively unaffected by changing retention times as well. The average total phosphorus concentrations in samples from the 0.4, 0.6, 0.8, 1.0, and 1.3 days centroid retention time columns were 0.20, 0.14, 0.22, 0.14, and 0.13 mg/L P, respectively. The 0.4, 0.6, 0.8, 1.0, and 1.3 days centroid retention time columns produced average TKN concentrations of 1.16, 0.69, 0.78, 0.65, and 0.73 mg/L N, respectively, and average total organic carbon concentrations of 50.8, 28.7, 40.5, 29.6, and 21.8 mg/L C, respectively.

The total nitrogen mass in and out of the columns for the 0.8-day centroid retention time is presented in Figure 17. Each of the three successive runs is shown. It is evident that the TKN mass varies only slightly between runs. However, nitrate mass in the second and third runs are less than the first run suggesting that after the first run the microbial communities are established and can effectively reduce the nitrate concentrations.

In Figure 18 the amount of nitrogen mass in the effluent of the different centroid retention times are compared to the influent nitrogen mass. The three different runs for each retention time are combined in their respective columns. The far left column is the average total input nitrogen mass for the different centroid retention times. Research suggests that microbial denitrification requires time on the order of days to effectively reduce nitrate concentrations (Leverenz et al. 2010; Robertson 2010; Chen et al. 2013). Chen et al. (2013) suggests that prolonged periods of saturation are necessary to create anoxic environments that promote microbial denitrification. The use of a permanently saturated zone by means of an upturned underdrain is used in that lab scale study (Chen et al. 2013). The general trend in these data confirms that longer retention times have the effect of greater removal of total nitrogen mass and nitrate mass (Figure 18). The more

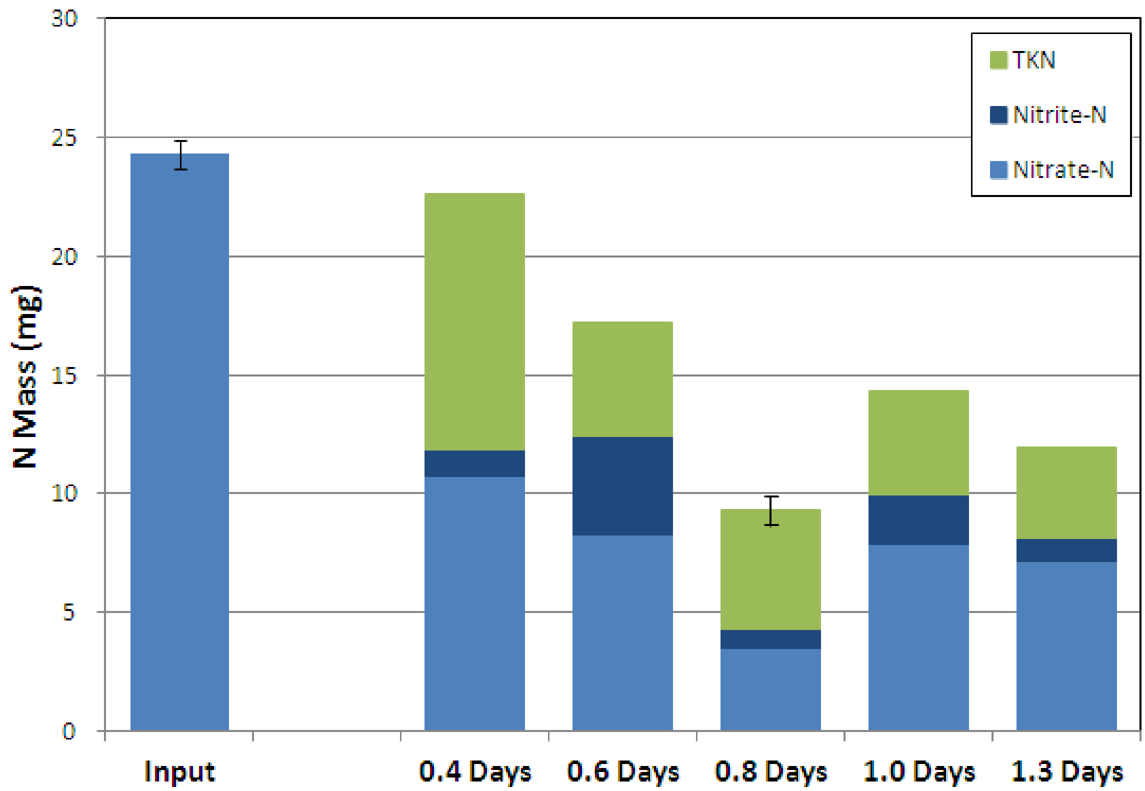


**Figure 18: Nitrogen mass compared for different stormwater centroid retention times using Willow Oak woodchips. The columns are labeled by the centroid retention times used and are compared to the average input nitrogen mass. Each column represents the combined mass of the three successive runs conducted for each centroid retention time. The input mass is the average of the five combined masses.**

time the stormwater remains in the saturated media, the greater amount of nitrogen removal is expected.

The pseudo-first-order model predicts that nitrate concentration decreases with time, but that time should not vary the rate constant. Therefore, it is expected that these rate constants are independent of the amount of time the water is in the column. The rate constants for the 0.4, 0.6, 0.8, 1.0, and 1.3 day centroid columns are 3.0, 1.4, 11.4, 1.4, and 0.9 day$^{-1}$, respectively for run 3 (Table 7). The trend in these numbers suggests that denitrification occurs more quickly with shorter retention times. This disagrees with the mass analysis, the model, and other research (Robertson 2010, Leverenz et al. 2010, Chen et al. 2013).

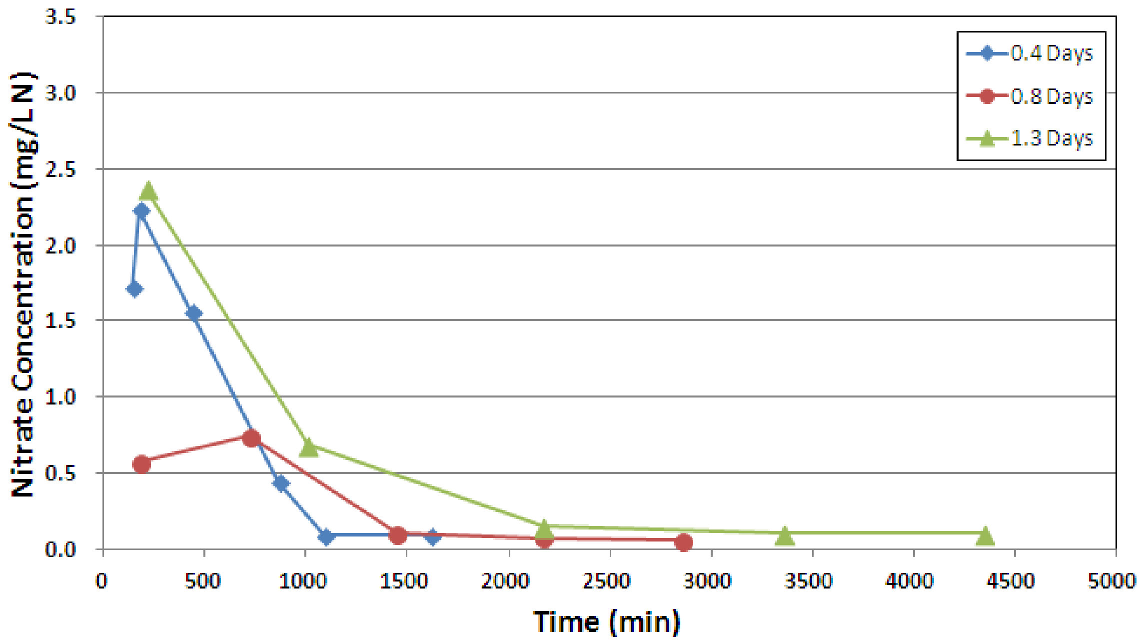


**Figure 19: Nitrate-N concentrations of collected samples from run 3 for columns packed with Willow Oak woodchips. The tests were conducted with centroid retention times of 0.4, 0.8, and 1.3 days. The comparison among the three denitrification curves shows that the point at which the concentration reaches below the detection limit is stretched by greater amounts of time between samples.**

One explanation of the trend in the data is that the time of sample collection skews the data. With shorter retention times, the points are grouped more closely together providing for a better fit to the data. With the longer retention times, the points are spaced farther apart. Later samples begin to fall below the detection limit and remain constant thus stretching the pseudo-first-order model to those later points that do not map the decreasing nitrate concentrations. Figure 19 compares the run 3 nitrate concentrations for the 0.4, 0.8, and 1.3 day centroid retention time. Notice that while the rate constant for the 0.4 day centroid is greater than all the other centroids, the trend in the curve of each data set is similar. The greater amount of time between detections for the longer retention times makes it more difficult to determine the precise time when nitrate concentrations reach the detection limit. This effectively stretches the denitrification process and results in decreased rate constants. Therefore, it is difficult to make an accurate comparison of the effect of retention time based on these rate constants.

## 3.4. Effect of Varying Media

### 3.4.1. Woodchip Species

When varying the woodchip species in the media, the pH of the samples again remained relatively consistent and ranged from 5.38 to 7.55. The oxidation/reduction potential in the columns all started between 200 and 400 mV. After 1200 min the potential decreased to between -100 and 200 mV for all columns. Nutrient concentrations varied slightly with changing chip type. The Wild Cherry (WC), Willow Oak (WO), Red Maple (RM), Virginia Pine (VP), and American Beech (AB) columns produced average TKN concentrations of 1.55, 0.78, 0.54, 0.99, and 2.14 mg/L N, respectively, and average total organic carbon concentrations of 152.9, 40.5, 42.4, 99.7, and 44.5 mg/L C, respectively. It appears that WC and VP leached greater amounts of TKN and organic carbon, suggesting that they degrade more quickly than the others woodchip species. The first run of AB leached a large amount of TKN which brought its average concentration up. While the second two runs did not leach as much TKN, significant amounts were still leached, averaging 1.40 mg/L N in the second two runs. The high amounts of TKN in the AB samples suggest that the carbon to nitrogen ratio is lower than the other woodchip species. According to Lamlom and Savidge (2003) AB has the lowest carbon content of the woodchip species being tested (Table 2). This agrees with the results of this study and the amount of TKN leached from the AB column

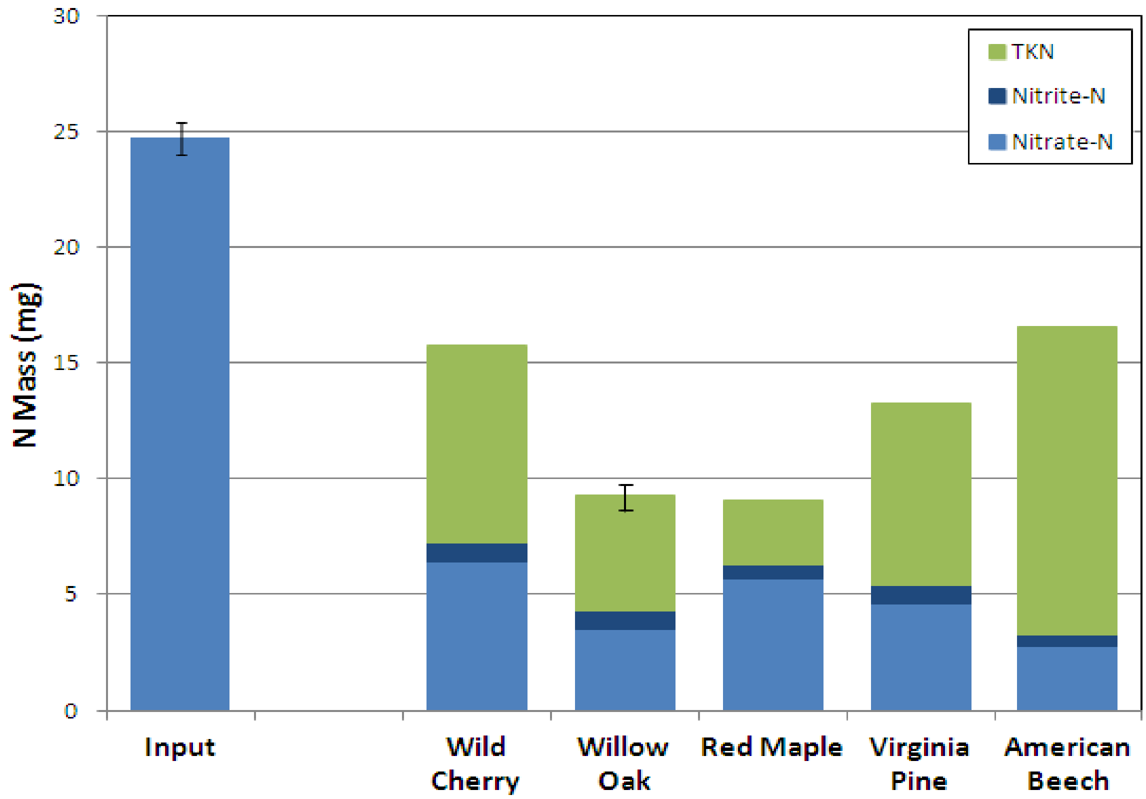


**Figure 20: Total nitrogen mass compared for different woodchip species used in the media. The columns are labeled by the wood species used and are compared to the average input nitrogen mass. Each column represents the combined mass of the three successive runs conducted for each species. The input mass is the average of the five combined masses.**

suggests that AB also degrades more quickly than the remaining two chip types, WO and RM.

Figure 20 shows the amount of nitrogen mass in the effluent of the columns with different woodchip species compared to the influent nitrogen mass. While AB is the most effective at nitrate removal, it leaches the largest amount of TKN, and it has the highest combined total nitrogen mass in its effluent. Willow Oak is the most effective at reducing the total nitrogen concentration in the effluent by not only substantially reducing nitrate concentrations but also leaching less TKN than the other wood types. RM shows the greatest overall reduction in nitrogen mass because very little TKN leached out of the system. No significant variation can be seen between the effluent nitrite mass for each of the wood species.

The pseudo-first-order rate constants for the WC, WO, RM, VP, and AB columns were 3.0, 11.4, 3.3, 4.2, and 4.0 $day^{-1}$, respectively, for run 3 (Table 7). The similarity in rate constants suggests that the denitrification process is unaffected by woodchip species with the exception of WO which had a much higher rate constant than the other woodchip species. However, the nutrient data reveal that different woodchips leach varying amounts of organic carbon and TKN. WO and RM provide the necessary environment for microbial denitrification while leaching the least organic carbon and TKN. Therefore, of the five woodchips species tested, WO and RM woodchips provide the optimum treatment media for bioretention denitrification.

**3.4.2.** Woodchip Size

The pH of the collected samples was unaffected by differing woodchip sizes in the media. In each case the pH of the samples collected remained relatively consistent, between 5.55 and 6.97 throughout the tests. The oxidation/reduction potential in the columns all started between 200 and 300 mV, and followed the same trend as was indicated previously, decreasing over time making the environment more reducing. Slight decreases of nutrient levels were noted in the effluent with increasing size of the woodchips in the media. The 5 mm (No. 4 to 9.5 mm), 9.5 mm (9.5 mm to 13 mm), and 13 mm (13 mm to 19 mm) woodchip columns produced average total phosphorus concentrations of 0.22, 0.10, and 0.12 mg/L P, respectively, average TKN concentrations of 0.79, 0.35, and 0.54 mg/L N, respectively, and average total organic carbon concentrations of 40.5, 38.3, and 34.4 mg/L C, respectively.

This decrease in nutrients relative to woodchip size suggests that nutrient leaching is dependent on the surface area of the woodchip. The larger woodchips have smaller total surface area per mass and therefore less contact area with the retained water. The decreased surface area due to woodchip size causes less nutrient leaching. As a result, denitrifying microorganisms appear to be slightly limited by the availability of organic carbon. This is reflected by the nitrate mass reduction depicted in Figure 21. While less TKN leached from the larger woodchip columns, the decrease in nitrate reduction caused the total nitrogen mass to increase with increasing woodchip size (Figure 21).

This pattern was also reflected in the rate constants for the varying woodchip sizes. The rate constants for the 5 mm, 9.5 mm, and 13 mm woodchip columns were 11.4, 1.4,

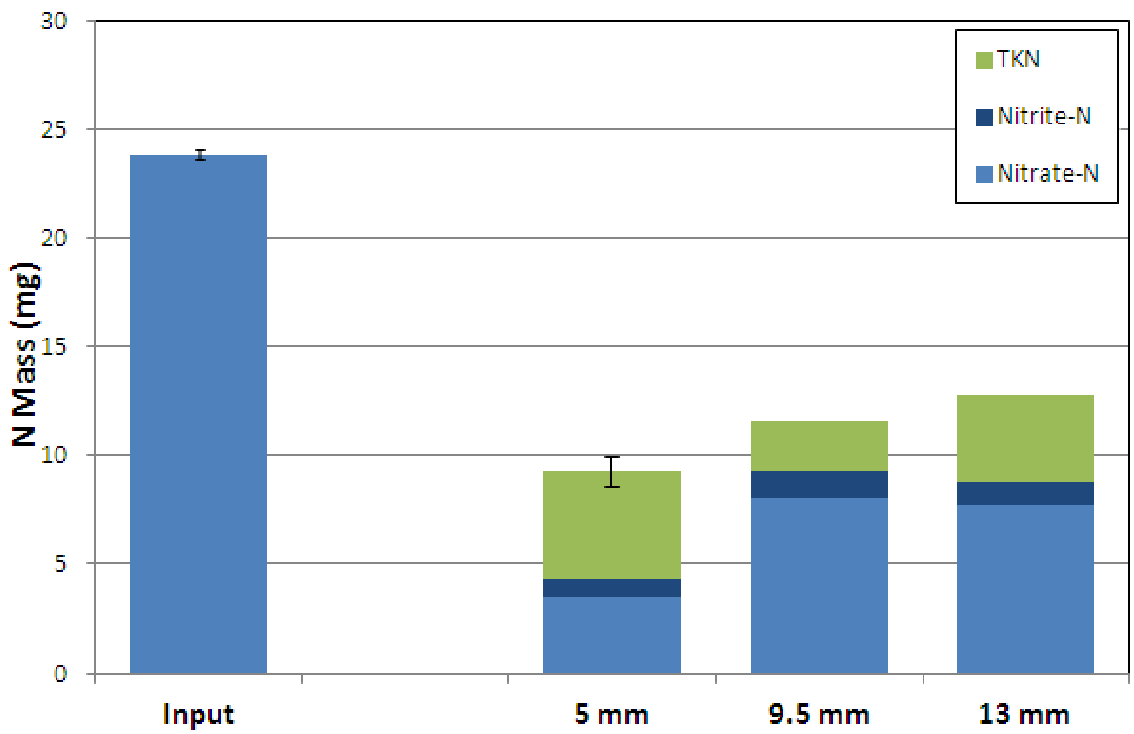


**Figure 21: Total nitrogen mass compared for different woodchip sizes of the same species used in the media. The columns are labeled by the chip sizes (mm) used and are compared to the average input nitrogen mass. Each column represents the combined mass of the three successive runs conducted for each size woodchip. The input mass is the average of the three combined masses.**

and 1.4 $day^{-1}$, respectively, for run 3 (Table 7). Again, the smaller woodchips provided for more availability of organic carbon and thus faster denitrification rates. However, while it is notable that the 5 mm woodchip column had a higher rate constant, there was little to no change in the rate constant from the 9.5 to 13 mm columns. Therefore, the 5 mm woodchips provide the best media option but it is difficult to make a distinction between the 9.5 and 13 mm woodchip media.

**3.4.3.** Woodchip Mass Percentage

Sample pH was unaffected by changing the percentage of woodchip mass in the media as well. In each case the pH of the samples collected remained relatively consistent, between 6.08 and 7.40 throughout the tests. The oxidation/reduction potential in the columns all started between 200 and 300 mV, but the potential decreased less in columns with less organic material. The minimum potentials reached in the 1%, 2.5%, and 4.5% woodchip columns were 236.6, 120.0, and -62.0 mV, respectively. This begins to suggest that as organic material becomes more limited, fewer microorganisms are present to consume dissolved oxygen. This leads to environments that move from oxidizing to reducing much more slowly than those with more available organic material and are therefore not optimum.

Nutrient availability emphasizes the effect of decreasing woodchip mass percentage in the media. The columns with less woodchip mass have less available phosphorus, TKN and organic carbon. The 1%, 2.5%, and 4.5% woodchip columns had average total organic carbon concentrations of 12.7, 27.8, and 40.5 mg/L C, respectively. Total phosphorus and TKN followed the same trend. This emphasizes that the media with less organic material does not provide the optimum environment for denitrification.

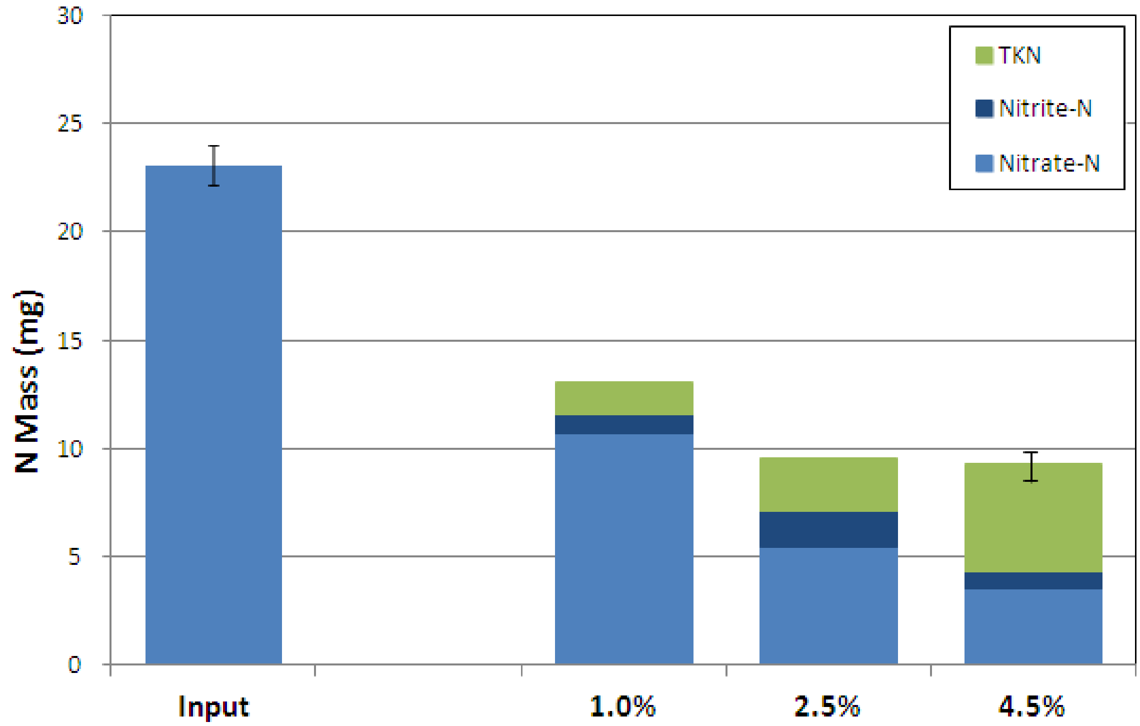


**Figure 22: Total nitrogen mass compared for media containing different amounts of woodchips of the same species. The columns are labeled by the percent of woodchips in the media by mass and are compared to the average input nitrogen mass. Each column represents the combined mass of the three successive runs conducted for each percent mass. The input mass is the average of the three combined masses.**

Further emphasizing this point, Figure 22 compares the combined total nitrogen mass in the effluent of all three runs of each column. Figure 22 shows that increased woodchip mass corresponds to greater decreases in nitrate and total nitrogen mass in the effluent. The slight increases of TKN in the effluent as a result of more woodchip mass are negated by decreases of nitrate. Denitrification rate constants also agree with the effect of changing woodchip mass in the media. The pseudo-first-order rate constants for the 1%, 2.5%, and 4.5% woodchip columns were 1.5, 7.2, and 11.4 day$^{-1}$, respectively, for run 3. The columns with media containing more woodchip mass were able to promote faster denitrification. This trend may also suggest that even larger woodchip mass percentages would provide more nitrate removal. However, this assumption is negated by

Robertson (2010). The rate constants found in that study were 2.3 and 2.4 $day^{-1}$, which are less than those reported in this study (Robertson 2010). Robertson (2010) used a media containing solely woodchips and found very large amounts of organic carbon were leached from the system when nitrate concentrations were rate limiting. While that study does not report the TKN leached, it can be assumed that the high organic carbon corresponds to large amounts of TKN being leached as well. From a total nitrogen perspective, the leached TKN may completely negate the nitrogen being removed through denitrification. The excess organic carbon from Robertson (2010) and similarity in rate constants suggest that further increasing woodchip mass percentages in the media would not significantly increase the nitrate removal efficiency of the media. Instead, nitrate removal would remain constant with increasing woodchip mass percentages while TKN leaching would continue to increase. Therefore, considering the ratios evaluated in this study, 4.5% woodchips by mass in the media provides the optimum environment for denitrification.

**3.4.4.** Limestone Amendment

The limestone added to the media helped buffer the media and raise the pH of the environment. While the pH of the samples collected increased with the addition of limestone to the media, the pH of the samples did not reach the desired pH of 8.0. The average pH of the collected samples from columns with media containing 0%, 5%, and 10% limestone by mass was 6.29, 7.31, and 7.20 respectively. Note that the difference in pH between the 5% and 10% limestone columns is negligible. This suggests that the addition of more limestone would not further raise the pH. The oxidation/reduction decreased over time to become more reducing. Nutrient availability changed with the

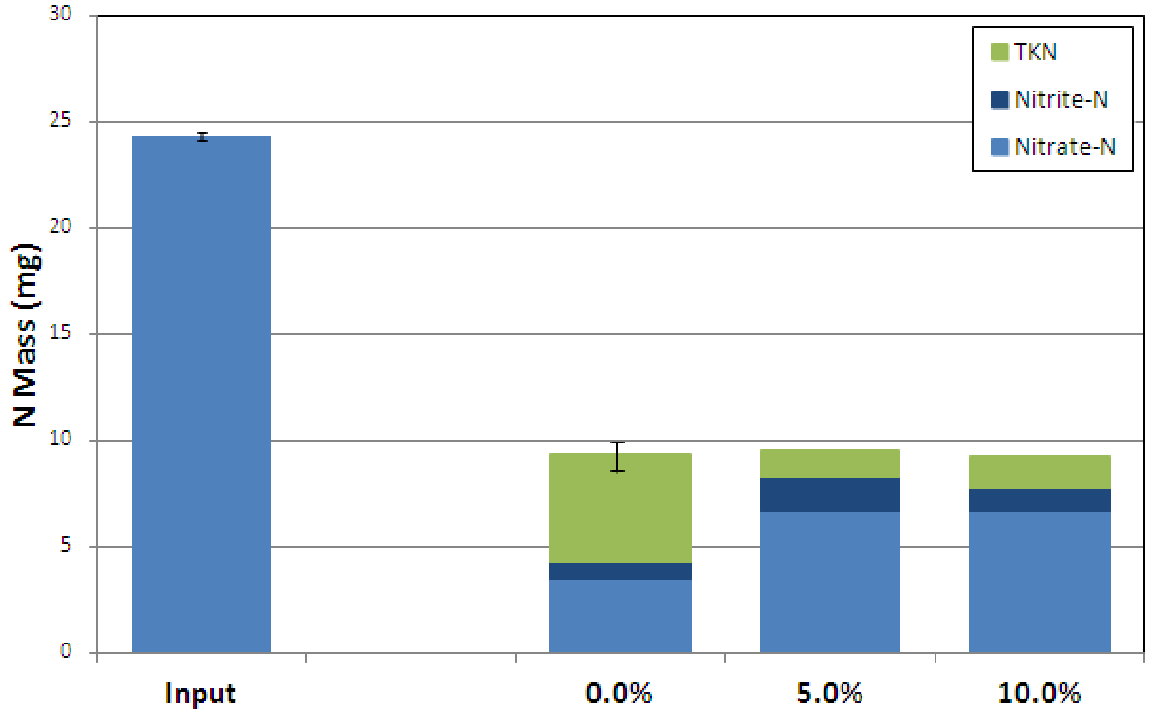


**Figure 23: Total nitrogen mass compared for media containing different amounts of limestone. The columns are labeled by the percent of limestone in the media by mass and are compared to the average input nitrogen mass. Each column represents the combined mass of the three successive runs conducted for each percent mass. The input mass is the average of the three combined masses.**

percentage of limestone in the media. The increasing limestone percentage corresponded to decreasing nutrient concentrations.

The addition of limestone to the media did not have the desired effect on denitrification. Glass and Silverstein (1998) state the optimum pH for denitrification is near 8.0. The addition of the limestone brought the pH up one full unit from 6.3 to 7.3, but the nitrate removal efficiency decreased. Figure 23 shows the comparison of the combined three runs of total nitrogen mass leaving the columns. The removal of total nitrogen was not greatly affected by increasing limestone content in the media. However, the removal of nitrate decreased with the addition of limestone. The rate constants for the

0%, 5%, and 10% limestone columns were 11.4, 5.9, and 8.9 $day^{-1}$, respectively. The rate of denitrification seems to be negatively affected by the addition of limestone.

The limestone added to the media may have caused localized pH increase. While the pH of the effluent only increased to 7.3, the pH near the limestone particles may have been much higher. The high pH near the limestone particles may have killed some bacteria which resulted in less nitrate reduction than expected even thought pH increased. Therefore, these data suggest that limestone may be effective at increasing the pH but should be applied differently to the media in order to prevent localized microbial die-off. A different media additive may be able to adequately buffer the environment to a pH of 8.0, without the localized die-off of microbial populations, which may improve the denitrification process.

## 3.5. Design Factors

The laboratory scale bioretention design successfully removed up to 87.2% of nitrate and 62.4% of total nitrogen in the synthetic stormwater through the denitrification process. The pseudo-first-order rate constants corresponding to the 3rd run for all columns where inflow nitrate concentration and retention time were varied were averaged, along with the WO column replicates (Table 7). In total, 8 runs were averaged together. According to the pseudo-first-order model, the rate constants from these columns should not be affected by these system variations. The average rate constant for these data was $4.1 \pm 4.6$ $day^{-1}$.

A design has been developed that would target concentrations of nitrogen in stormwater and treat runoff nitrogen following the nitrogen cycle. The design is a controlled and sustainable system that also requires little to no maintenance. The design deviates from typical bioretention designs by taking into account a first flush treatment. If a first flush consideration is applied to runoff collected by a bioretention facility, then it can be assumed that treating the first 1.3 mm of runoff could remove up to 84% of the total nitrogen it is carrying (Flint and Davis 2007). Treating the first flush more strictly while allowing whatever remains to be treated normally would effectively optimize the design.

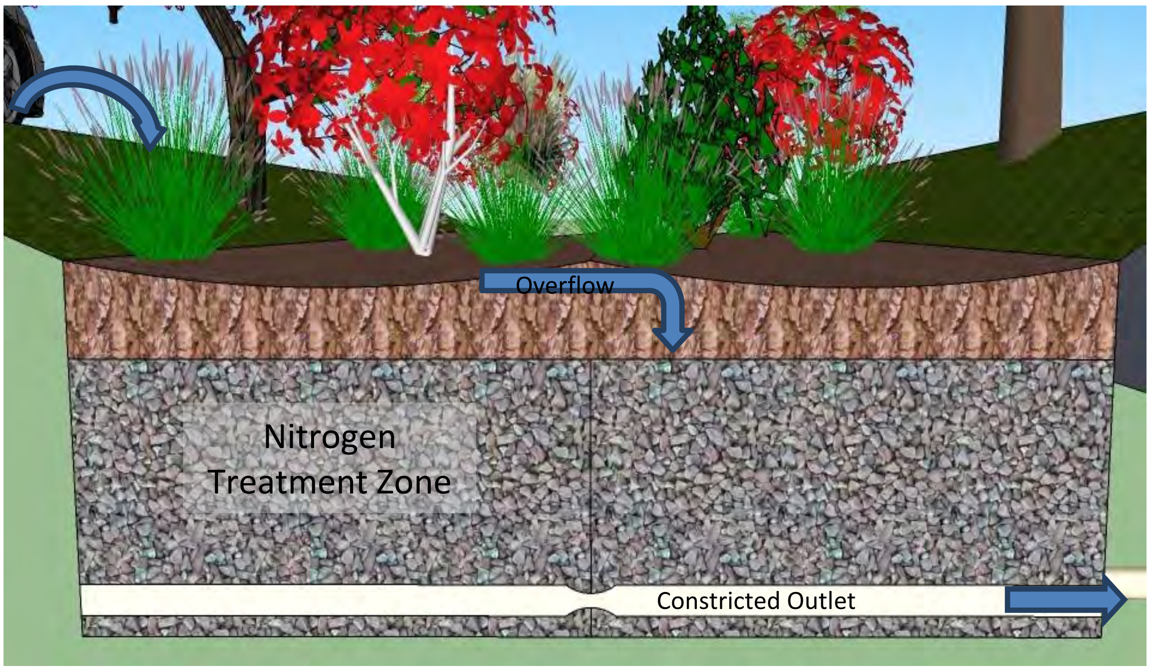


**Figure 24: Design alteration to a standard bioretention cell. The cell is split into a treatment train. The first section (Nitrogen Treatment Zone) will remove nitrogen and other pollutants from the first flush of a storm while the second portion filters any overflow that exceeds the storage capacity of the first section.**

Typical bioretention is considered one homogenous unit. Water runs in and is infiltrated over the entire surface area. Denitrification, being a time sensitive process, can be optimized by increasing the retention time of runoff. By increasing the retention time, however, the volume of water that can be treated by the bioretention is decreased. One way to achieve large retention times while maintaining the ability to treat large storms is to split the bioretention into two parts or a treatment train. With a split bioretention the first flush of a storm can be treated in a portion of the bioretention cell that is designed to have a large retention time. If a storm is large enough to surpass the available storage volume, overflow would spill into the second portion of the bioretention facility. This portion would filter water quickly and thus allow the entire storm to be treated. Figure 24 shows a design that would facilitate the desired treatment method.

The storm size that can be captured in the denitrification layer of a bioretention treatment train system would vary with the size of the bioretention system. Table 8 shows the largest storm that could be captured by the denitrification layer of the bioretention treatment train. The values assume that all rainfall becomes runoff and the entire watershed is 100% impervious (Table 8). Bioretention system surface area ratios are similar to those defined in Davis et al. (2013), where the bioretention systems ranged from 3% to 7% of the surface area of the corresponding watershed. Table 8 assumes the denitrification layer is 40 cm deep which is a little more than half of the depth of a 70 cm deep bioretention system (Zinger et al. 2013). This media depth increases the retention capacity of the denitrification layer for maximum treatment. Typically denitrification layers in bioretention systems are near 18 cm in depth (Kim et al. 2003, Ergas et al. 2010, Chen et al. 2013). The assumed porosity of the media is 0.5.

**Table 8: The maximum storm size that can be captured by the denitrification layer of a bioretention treatment train with varying bioretention sizes and nitrogen treatment layer sizes. This assumes that all rainfall becomes runoff, the entire watershed is impervious, and a denitrification layer media depth of 40 cm.**

| Percent of Watershed that is bioretention | Percent of bioretention area for nitrogen treatment | Max storm size nitrogen treatment can handle (cm) |
|---|---|---|
| **3** | 40 | 0.24 |
| **3** | 50 | 0.3 |
| **3** | 60 | 0.36 |
| **5** | 40 | 0.4 |
| **5** | 50 | 0.5 |
| **5** | 60 | 0.6 |
| **7** | 40 | 0.56 |
| **7** | 50 | 0.7 |
| **7** | 60 | 0.84 |
| **10** | 40 | 0.8 |
| **10** | 50 | 1 |
| **10** | 60 | 1.2 |

Bioretention designs for treating nitrogen may be constructed in layers to follow the nitrogen cycle (Hsieh et al. 2007; Collins et al. 2010; Ergas et al. 2010). The path that nitrogen will follow through a bioretention system is presented in Figure 25. Organic nitrogen and ammonium are absorbed into the top media layer and later oxidized (Collins et al. 2010). Because oxygen is more available between storm events, nitrification will take place in this top layer when it is not raining (Hsieh et al. 2007). The average amount of time between storm events should be enough to effectively oxidize the organic and ammonium nitrogen to nitrate or nitrite (Hsieh et al. 2007). In a storm, the nitrate and nitrite from the top layer are subsequently carried with the stormwater into the denitrification layer. Because denitrification requires anoxic conditions, the media in the denitrification layer will be fully saturated during a storm event and allowed to drain

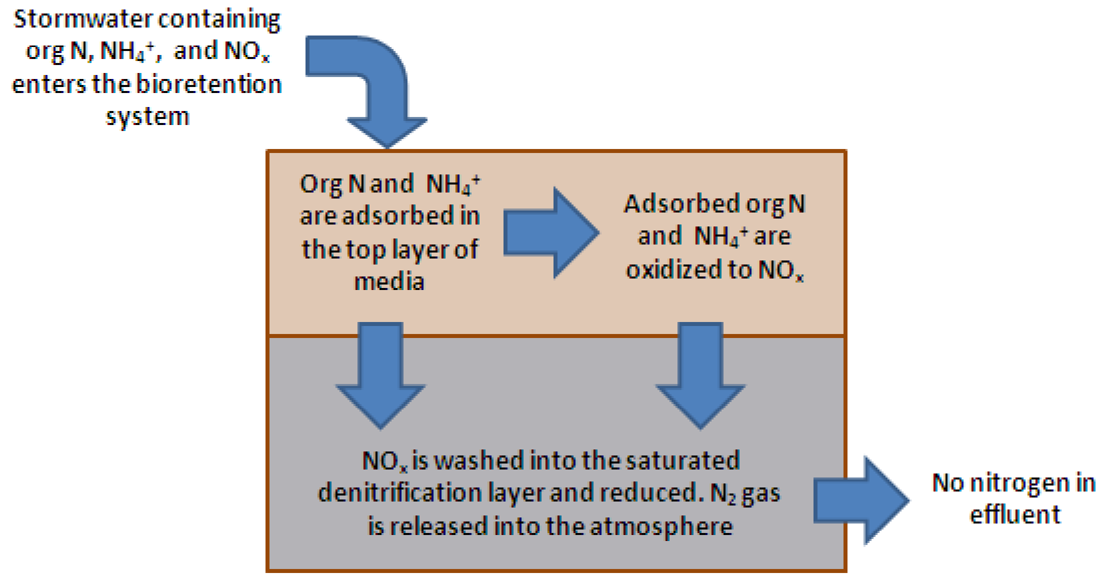


**Figure 25: A flow chart of the processes that nitrogen in stormwater runoff undergoes in the bioretention treatment train system.**

slowly. Saturation can be accomplished by decreasing the size of the outlet, incorporating an upturned underdrain, or a combination of the two. This will allow the media to treat oxidized nitrogen in a large amount of water for a longer duration.

The optimum denitrification layer media contains 4.5% Willow Oak or Red Maple woodchips that range from 5 mm to 9.5 mm in size and no limestone is added. Assuming the nitrogen in stormwater entering the denitrification layer (40 cm deep) of a bioretention treatment train system has been fully converted to nitrate at concentrations of 3 mg/L N (Collins et al. 2010) and stormwater is retained for an average of 1.0 day, which is the amount of time that microorganisms took to reduce nitrate concentrations to below detection in the research columns, following pseudo-first-order kinetics and using the average rate constant stated previously, the stormwater captured by the denitrification layer would have an average effluent nitrate concentration of 0.05 mg/L N. The result is

62% reduction in the total nitrogen mass in the stormwater. Assuming that 90% of the nitrogen mass is contained in the first flush which is treated in the denitrification layer, 56% of the total nitrogen is removed from the stormwater. These numbers do not account for water loss due to infiltration or plant uptake which would increase the nitrogen mass reduction.

This study did not use plants for possible additional removal of nitrogen. Planting *C. appressa* or *M. ericifolia* in the media has been shown to result in 70% nitrogen removal (Bratieres et al. 2008). While that study was conducted in Australia, vegetation provides a key role in the removal of nitrogen from stormwater in bioretention applications (Bratieres et al. 2008, Lucas and Greenway 2008, Davis et al. 2012, Hunt et al. 2012). Zinger et al. (2013) found that introducing a saturated zone to a media that was not optimized for denitrification improved total nitrogen removal efficiencies. However, vegetation must be harvested after the growing season; otherwise decaying biomass would contribute to the inflow nitrogen concentrations (Davis et al. 2012). This increases maintenance costs. A treatment train with an optimized denitrification process, combined with nitrogen removal by vegetation would provide an environment with optimum nitrogen removal from stormwater runoff.

# 4. Conclusion

## 4.1. General Conclusions

Treatment of nitrogen in urban stormwater using bioretention is a technology in its infancy. Modifying typical bioretention designs into a treatment train could improve nitrogen removal efficiencies. This could be done by ensuring that first flush runoff is treated in a denitrification zone while excess runoff is treated traditionally. By creating a system that fully saturates a media containing woodchips as an organic carbon source, available oxygen is depleted and anoxic conditions are created. These conditions, favorable to microbial denitrification, were successfully tested in a laboratory setting. A system where microbial denitrification was inhibited by azide was contrasted with one that was not inhibited. This contrast gave evidence to support the ability of the media to sustain a population of denitrifying microorganisms. This evidence suggests that the treatment train bioretention system would provide the conditions necessary for denitrification and effective removal of nitrate from runoff.

The concentration of nitrate in the influent ranged from 1.5 to 4.5 mg/L N which is considered low in denitrification applications not treating stormwater runoff. Denitrification in systems with low concentrations of nitrate tends to follow first-order kinetics. While the data are not conclusive, it appears that pseudo-first-order kinetics provide the best model for denitrification in this system. A fully established system with optimum media conditions had a denitrification rate constant of $4.1 \pm 4.6$ $day^{-1}$.

Retaining stormwater in the denitrification zone for greater amounts of time appears to cause greater reduction of nitrogen concentrations in stormwater runoff. Concentrations of nitrate in stormwater decreased to below 0.2 mg/L in about 1.0 days

(1440 min). Retaining stormwater for this amount of time should remove nitrate from the runoff.

Of the five wood species tested, Willow Oak and Red Maple were found to most substantially reduce the amount of nitrogen in the stormwater. Media with Willow Oak and Red Maple woodchips reduced concentrations of total nitrogen in the runoff by up 60% and 62%, respectively. It is unknown why these two species are able to provide a more suitable environment for denitrification.

Increases in woodchip size decreased the surface area of the woodchips, thereby decreasing the amount of organic carbon available to the denitrifying bacteria. Smaller woodchips corresponded to higher nutrient availability which resulted in greater nitrate reduction. At 4.5% woodchips by mass, media containing 5 mm woodchips removed 82% of nitrate from stormwater runoff while 13 mm woodchips removed 63%. However, in order to preserve the longevity of the system a combination of woodchip sizes may be more effective.

Similarly the percent mass of woodchips in the media directly related to the availability of nutrients and greater reduction of nitrate concentrations. It is expected that greater percentages of woodchips in the media would increase effluent nutrient concentrations resulting in reduced efficiency. Further analysis is needed to determine the percentage of woodchips needed to optimize the media.

While the pH of the system did increase as a result of limestone additions to the media, it did not increase to the desired pH of 8.0. The pH for 5% and 10% limestone columns was 7.3 and 7.2, respectively. The addition of limestone to the media did not raise the efficiency of the system as a result of increased pH. Total nitrogen removal for media containing 0%, 5% and 10% limestone by mass was 82%, 66%, and 68%, respectively. Another media additive may result in higher pH and greater nitrogen removal.

The optimum environment for microbial denitrification from this study is a saturated media with 4.5% woodchips by mass. The woodchips should be Oak or Maple. The woodchips should vary in size greater than 5 mm in order to provide longevity and prevent clogging the system. Assuming all the nitrogen in runoff containing 3 mg/L N was converted to nitrate and the total volume of a storm was retained in the denitrification layer, this media could effectively reduce nitrate concentrations in urban stormwater runoff by more than 90% and total nitrogen by more than 60%. When incorporated into the treatment train design, first flush runoff would be treated at these efficiencies. This would provide an effective buffer for mitigating the problematic effects of urban runoff on natural water bodies.

## 4.2. Practical Recommendations

Implementation of a treatment train bioretention system would improve water quality through greater nitrogen reduction in stormwater runoff. The first section of the treatment train would filter water while improving nitrogen mass reduction through denitrification of the first flush runoff. The denitrification layer should be optimized by providing the media described. Overflow from large storms would filter through the second section of the treatment train. With this stepped system, runoff from both large and small storms is treated and the first flush runoff from these storms is targeted for nitrogen removal.

This design can be implemented using different methods for creating a saturated denitrification layer. While this paper discusses the effect of controlled outlets, upturned underdrains are also a viable option for maintaining saturated media. Reducing the outlet size of the underdrain may also cause saturation of the denitrification layer. However, saturation of other layers when using a reduced outlet size could result in heavy metals leaching. In order to prevent this issue a bypass would be needed above the denitrification layer to allow stormwater to overflow into the second section of the treatment train.

## 4.3. Future Research

These design recommendations need to be evaluated in a field scale application. Stormwater inflow and effluent from each section of the treatment train should be monitored for concentrations of nitrogen species. Total, organic, ammonium, nitrate, and nitrite nitrogen should be monitored. Water level in the denitrification layer of the bioretention system should be monitored to ensure that the media is being completely saturated. Stormwater retained in the denitrification layer may infiltrate further and recharge groundwater which would greatly reduce effluent nitrogen mass. Samples should be taken from within the media to ensure that denitrification is taking place before stormwater infiltrates into the groundwater. The rate of denitrification should be monitored over a period of 10 years to ensure the media provides the necessary nutrients for denitrification for a desirable lifespan.

Further evaluation of woodchip species is needed to determine the cause of increased microbial denitrification when certain woodchips are present. Understanding the conditions which cause greater microbial activity could provide further design recommendations. The effect of woodchips surface area should also be further analyzed for its effect on the availability of organic carbon and the denitrification process. Media additives should be evaluated for their effect on the pH of the system and the denitrification process. Limestone should also be included in this study in different configurations in order to further assess its ability to buffer the system without killing the microbial population.

The denitrification layer may have a more optimum layout. For instance, rather than having a homogeneous media in the denitrification layer, all of the woodchips can be placed in a layer at the bottom and have a porous saturated media above. This may cause the system to operate more like a plug flow system. Denitrification would take place when stormwater reaches the woodchip layer. Implementing a shallow adsorbent media layer below the woodchips may adsorb leached organic material and further reduce the total nitrogen in the effluent. These design adjustments should be evaluated for improved effluent water quality.

# Appendix I-A

| | | | | |
|---|---|---|---|---|
| Woodchip Species: | Willow Oak | Avg. Retention Time: | | 0.8 Days |
| Woodchip Size: | 5mm | Start date: | Run 1: | 5/22/12 |
| Woodchip Mass: | 4.5% | | Run 2: | 5/29/12 |
| Limestone Content: | 0.0% | | Run 3: | 6/5/12 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 2.982 | 2.86 | 3.10 |
| 60 | 2.982 | 2.95 | 2.82 |
| 120 | 3.011 | 3.16 | 3.20 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.12 | 0.14 | 0.10 |
| 60 | 0.12 | 0.12 | 0.10 |
| 120 | 0.11 | 0.14 | 0.10 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 4.43 | 0.10 | 0.57 |
| 712.5 | 2.28 | 0.10 | 0.74 |
| 1440 | 0.10 | 0.10 | 0.10 |
| 2160 | 0.10 | 0.10 | 0.10 |
| 2850 | 0.10 | 0.10 | 0.10 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.08 | 0.06 | 0.05 |
| 712.5 | 0.63 | 0.06 | 0.05 |
| 1440 | 1.08 | 0.05 | 0.05 |
| 2160 | 0.06 | 0.05 | 0.05 |
| 2850 | 0.06 | 0.05 | 0.05 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 1.68 | 0.70 | 0.32 |
| 712.5 | 1.68 | 0.98 | 0.43 |
| 1440 | 1.12 | 0.00 | 0.58 |
| 2160 | 1.68 | 0.00 | 0.56 |
| 2850 | 1.40 | 0.00 | 0.70 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.44 | 0.25 | 0.22 |
| 712.5 | 0.33 | 0.20 | 0.16 |
| 1440 | 0.33 | 0.17 | 0.10 |
| 2160 | - | - | 0.14 |
| 2850 | - | - | 0.11 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 253.0 | 400.7 | 383.0 |
| 180 | 264.6 | 392.7 | 386.1 |
| 1200 | 159.9 | 133.4 | -115.7 |
| 1440 | 82.0 | - | -426.3 |
| 1650 | -51.4 | - | - |
| 2640 | -482 | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 52.82 | 90.82 | 31.72 |
| 712.5 | 46.29 | 32.45 | 24.73 |
| 1440 | 49.52 | 20.66 | 27.94 |
| 2160 | 52.89 | 22.38 | 32.20 |
| 2850 | 58.52 | 29.94 | 35.18 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.19 | 0.28 | 0.25 |
| 712.5 | 0.56 | 1.58 | 1.10 |
| 1440 | 0.26 | 0.50 | 0.46 |
| 2160 | 0.22 | 0.24 | 0.25 |
| 2850 | 0.23 | 0.12 | 0.28 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 7.05 | 6.35 | 6.99 |
| 712.5 | 7.30 | 6.54 | 6.70 |
| 1440 | 7.13 | 6.75 | 6.87 |
| 2160 | 7.27 | 6.83 | 6.71 |
| 2850 | 7.34 | 7.55 | 6.87 |

Temperature ($^{o}C$)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 24 | 26 | 24 |
| 712.5 | 22 | 23 | 23 |
| 1440 | 23 | 24 | 22 |
| 2160 | 23 | 23 | 22 |
| 2850 | 24 | 22 | 22 |

# Appendix I-B

| | | | | |
|---|---|---|---|---|
| Woodchip Species: | Willow Oak | Avg. Retention Time: | | 0.8 Days |
| Woodchip Size: | 5mm | Start date: | Run 1: | 3/14/13 |
| Woodchip Mass: | 4.5% | | Run 2: | 3/20/26 |
| Limestone Content: | 0.0% | | Run 3: | 3/26/13 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 3.011 | 3.02 | 3.02 |
| 60 | 2.994 | 2.96 | 3.00 |
| 120 | 2.889 | 2.94 | 2.98 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.12 | 0.10 | 0.11 |
| 60 | 0.12 | 0.08 | 0.11 |
| 120 | 0.10 | 0.10 | 0.10 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 2.89 | 0.70 | 0.85 |
| 712.5 | 2.25 | 0.10 | 0.10 |
| 1440 | 0.74 | 0.10 | 0.10 |
| 2160 | 0.10 | 0.10 | 0.10 |
| 2850 | 0.10 | 0.10 | 0.10 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.01 | 0.01 | 0.01 |
| 712.5 | 0.24 | 0.01 | 0.01 |
| 1440 | 0.92 | 0.01 | 0.01 |
| 2160 | 0.18 | 0.01 | 0.01 |
| 2850 | 0.01 | 0.01 | 0.01 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.84 | 0.56 | 1.12 |
| 712.5 | 0.56 | 0.84 | 0.56 |
| 1440 | 0.56 | 0.56 | 1.12 |
| 2160 | 1.12 | 0.28 | 1.96 |
| 2850 | 0.56 | 0.56 | 0.56 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.44 | 0.36 | 0.12 |
| 712.5 | 0.10 | 0.14 | 0.34 |
| 1440 | 0.15 | 0.14 | 0.08 |
| 2160 | 0.13 | 0.13 | 0.06 |
| 2850 | 0.12 | 0.08 | 0.11 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 232.7 | 247.0 | 267.1 |
| 180 | 228.6 | 244.1 | 261.9 |
| 1200 | 163.0 | 84.6 | 15.3 |
| 1440 | 109.4 | -38.4 | -62.0 |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 46.73 | 81.66 | 53.68 |
| 712.5 | 44.65 | 76.58 | 44.61 |
| 1440 | 50.87 | 68.84 | 47.10 |
| 2160 | 69.05 | 73.51 | 51.97 |
| 2850 | 83.33 | 82.60 | 62.37 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.27 | 0.27 | 0.26 |
| 712.5 | 0.77 | 1.03 | 1.00 |
| 1440 | 0.28 | 0.29 | 0.25 |
| 2160 | 0.33 | 0.43 | 0.39 |
| 2850 | 0.26 | 0.27 | 0.28 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 6.34 | 6.05 | 6.25 |
| 712.5 | 6.01 | 5.98 | 6.53 |
| 1440 | 6.36 | 6.23 | 6.60 |
| 2160 | 6.58 | 6.55 | 6.72 |
| 2850 | 6.30 | 5.90 | 5.96 |

Temperature ($^{o}$C)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 26 | 22 | 22 |
| 712.5 | 26 | 22 | 23 |
| 1440 | 22 | 21 | 23 |
| 2160 | 21 | 21 | 23 |
| 2850 | 21 | 21 | 24 |

# Appendix I-C

| | | | |
|---|---|---|---|
| Woodchip Species: | Willow Oak | Avg. Retention Time: | 0.8 Days |
| Woodchip Size: | 5mm | Start date: | Run 1: 3/14/13 |
| Woodchip Mass: | 4.5% | | Run 2: 3/20/13 |
| Limestone Content: | 0.0% | | Run 3: 3/26/13 |
| | | Inhibbited | |

Inflow Data - Contained 50 mg/L $NaN_3$

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 3.045 | 2.99 | 2.91 |
| 60 | 3.014 | 3.00 | 3.09 |
| 120 | 3.072 | 2.99 | 3.01 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.11 | 0.13 | 0.10 |
| 60 | 0.10 | 0.12 | 0.10 |
| 120 | 0.10 | 0.13 | 0.11 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 3.03 | 2.97 | 2.96 |
| 712.5 | 3.04 | 2.93 | 3.01 |
| 1440 | 3.07 | 3.02 | 2.91 |
| 2160 | 3.05 | 3.00 | 3.17 |
| 2850 | 3.00 | 2.96 | 3.01 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.01 | 0.01 | 0.01 |
| 712.5 | 0.01 | 0.01 | 0.01 |
| 1440 | 0.01 | 0.01 | 0.01 |
| 2160 | 0.01 | 0.01 | 0.01 |
| 2850 | 0.01 | 0.01 | 0.01 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 1.96 | 3.92 | 2.52 |
| 712.5 | 2.24 | 2.52 | 1.96 |
| 1440 | 2.24 | 2.24 | 1.68 |
| 2160 | 3.92 | 2.52 | 2.24 |
| 2850 | 3.08 | 2.52 | 1.96 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.90 | 0.66 | 0.82 |
| 712.5 | 0.76 | 0.94 | 0.88 |
| 1440 | 0.83 | 0.82 | 0.87 |
| 2160 | 0.72 | 0.84 | 0.57 |
| 2850 | 0.76 | 0.89 | 0.71 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 243.1 | 232.8 | 222.2 |
| 180 | 240.2 | 221.7 | 225.5 |
| 1200 | 207.4 | 217.4 | 215.8 |
| 1440 | 205.4 | 210.6 | 221.6 |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 76.7 | 202.1 | 108.4 |
| 712.5 | 94.8 | 128.1 | 67.0 |
| 1440 | 111.2 | 98.0 | 54.7 |
| 2160 | 154.9 | 106.8 | 58.8 |
| 2850 | 158.9 | 102.3 | 63.6 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.26 | 0.28 | 0.26 |
| 712.5 | 0.79 | 1.00 | 0.97 |
| 1440 | 0.25 | 0.27 | 0.25 |
| 2160 | 0.39 | 0.35 | 0.37 |
| 2850 | 0.27 | 0.27 | 0.28 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 5.86 | 6.04 | 6.19 |
| 712.5 | 6.04 | 6.20 | 6.34 |
| 1440 | 6.39 | 6.38 | 6.46 |
| 2160 | 6.18 | 6.40 | 6.56 |
| 2850 | 6.34 | 6.39 | 6.33 |

Temperature ($^{o}C$)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 26 | 22 | 22 |
| 712.5 | 26 | 22 | 23 |
| 1440 | 22 | 21 | 23 |
| 2160 | 21 | 21 | 23 |
| 2850 | 21 | 21 | 24 |

# Appendix I-D

| | | | | |
|---|---|---|---|---|
| Woodchip Species: | None | Avg. Retention Time: | | 0.8 Days |
| Woodchip Size: | N/A | Start date: | Run 1: | 3/30/13 |
| Woodchip Mass: | N/A | | Run 2: | N/A |
| Limestone Content: | 0.0% | | Run 3: | N/A |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 3.02 | | |
| 60 | 3.00 | | |
| 120 | 2.98 | | |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.10 | | |
| 60 | 0.10 | | |
| 120 | 0.10 | | |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 3.16 | | |
| 712.5 | 3.17 | | |
| 1440 | 3.00 | | |
| 2160 | 3.04 | | |
| 2850 | 2.99 | | |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.01 | | |
| 712.5 | 0.01 | | |
| 1440 | 0.01 | | |
| 2160 | 0.01 | | |
| 2850 | 0.01 | | |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.00 | | |
| 712.5 | 0.00 | | |
| 1440 | 0.00 | | |
| 2160 | 0.00 | | |
| 2850 | 0.00 | | |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.11 | | |
| 712.5 | 0.11 | | |
| 1440 | 0.10 | | |
| 2160 | 0.10 | | |
| 2850 | 0.11 | | |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 250.7 | | |
| 180 | 230.6 | | |
| 1200 | 218.5 | | |
| 1440 | 200.7 | | |
| 1650 | 200.3 | | |
| 2640 | - | | |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | ND | | |
| 712.5 | ND | | |
| 1440 | ND | | |
| 2160 | ND | | |
| 2850 | ND | | |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.26 | | |
| 712.5 | 1.00 | | |
| 1440 | 0.25 | | |
| 2160 | 0.39 | | |
| 2850 | 0.28 | | |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 6.66 | | |
| 712.5 | 6.98 | | |
| 1440 | 6.79 | | |
| 2160 | 7.08 | | |
| 2850 | 6.97 | | |

Temperature ($^{o}$C)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 26 | | |
| 712.5 | 26 | | |
| 1440 | 26 | | |
| 2160 | 26 | | |
| 2850 | 26 | | |

# Appendix I-E

| | | | |
|---|---|---|---|
| Woodchip Species: | Willow Oak | Avg. Retention Time: | 0.8 Days |
| Woodchip Size: | 5mm | Start date: | Run 1: 11/12/12 |
| Woodchip Mass: | 4.5% | | Run 2: 11/26/12 |
| Limestone Content: | 0.0% | | Run 3: 12/3/12 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 1.476 | 1.48 | 1.48 |
| 60 | 1.491 | 1.49 | 1.49 |
| 120 | 1.527 | 1.53 | 1.53 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | - | 0.11 | 0.09 |
| 60 | - | 0.08 | 0.09 |
| 120 | - | 0.10 | 0.10 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 1.27 | 1.04 | 1.02 |
| 712.5 | 0.10 | 0.56 | 1.03 |
| 1440 | 0.10 | 0.10 | 0.15 |
| 2160 | 0.10 | 0.23 | 0.24 |
| 2850 | 0.10 | 0.10 | 0.10 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.21 | 0.01 | 0.01 |
| 712.5 | 0.93 | 0.01 | 0.01 |
| 1440 | 0.25 | 0.01 | 0.01 |
| 2160 | 0.10 | 0.01 | 0.01 |
| 2850 | 0.01 | 0.01 | 0.01 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 5.32 | 0.28 | 0.56 |
| 712.5 | 1.12 | 0.60 | 0.56 |
| 1440 | 1.96 | 1.68 | 0.28 |
| 2160 | 1.40 | 0.28 | 0.56 |
| 2850 | 1.12 | 0.28 | 0.56 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | - | 0.19 | 0.09 |
| 712.5 | - | 0.13 | 0.06 |
| 1440 | - | 0.14 | 0.06 |
| 2160 | - | 0.16 | 0.05 |
| 2850 | - | 0.11 | 0.06 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 178.6 | 209.4 | 212.7 |
| 180 | 151.9 | 208.6 | 203.1 |
| 1200 | 22.0 | 172.5 | 156.1 |
| 1440 | 133.2 | 64.5 | 184.8 |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 35.59 | 34.73 | 21.59 |
| 712.5 | 30.22 | 29.65 | 18.22 |
| 1440 | 31.54 | 28.57 | 17.54 |
| 2160 | 29.71 | 30.42 | 21.69 |
| 2850 | 28.62 | 31.25 | 25.42 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.23 | 0.27 | 0.28 |
| 712.5 | 0.61 | 1.12 | 1.15 |
| 1440 | 0.38 | 0.44 | 0.27 |
| 2160 | 0.28 | 0.26 | 0.39 |
| 2850 | 0.26 | 0.27 | 0.27 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 6.12 | 6.65 | 6.48 |
| 712.5 | 6.28 | 6.49 | 6.42 |
| 1440 | 5.83 | 6.34 | 6.63 |
| 2160 | 5.87 | 5.90 | 6.84 |
| 2850 | 6.51 | 6.21 | 5.95 |

Temperature ($^{o}$C)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 23 | 21 | 22 |
| 712.5 | 20 | 19 | 20 |
| 1440 | 19 | 18 | 22 |
| 2160 | 19 | 19 | 21 |
| 2850 | 15 | 21 | 21 |

# Appendix I-F

| | | | | |
|---|---|---|---|---|
| Woodchip Species: | Willow Oak | Avg. Retention Time: | | 0.8 Days |
| Woodchip Size: | 5mm | Start date: | Run 1: | 11/12/12 |
| Woodchip Mass: | 4.5% | | Run 2: | 11/26/12 |
| Limestone Content: | 0.0% | | Run 3: | 12/3/12 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 4.073 | 4.07 | 4.07 |
| 60 | 4.311 | 4.31 | 4.31 |
| 120 | 4.411 | 4.41 | 4.41 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | - | 0.12 | 0.14 |
| 60 | - | 0.11 | 0.10 |
| 120 | - | 0.12 | 0.12 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 2.50 | 4.07 | 4.34 |
| 712.5 | 1.01 | 7.46 | 1.41 |
| 1440 | 0.10 | 4.31 | 1.73 |
| 2160 | 0.10 | 2.58 | 0.10 |
| 2850 | 0.10 | 0.81 | 0.10 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.05 | 0.01 | 0.01 |
| 712.5 | 1.37 | 0.03 | 0.04 |
| 1440 | 1.43 | 0.70 | 0.43 |
| 2160 | 0.26 | 0.55 | 0.01 |
| 2850 | 0.01 | 0.27 | 0.01 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 2.52 | 0.56 | 1.12 |
| 712.5 | 2.24 | 0.56 | 0.84 |
| 1440 | 2.24 | 0.00 | 0.56 |
| 2160 | 1.12 | 0.28 | 0.28 |
| 2850 | 0.56 | 0.00 | 0.56 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | - | 0.20 | 0.09 |
| 712.5 | - | 0.11 | 0.10 |
| 1440 | - | 0.09 | 0.25 |
| 2160 | - | 0.10 | 0.50 |
| 2850 | - | 0.12 | 0.06 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 207.1 | 301.4 | 233.9 |
| 180 | 181.8 | 250.1 | 233.8 |
| 1200 | 73.2 | 258.8 | 300.6 |
| 1440 | -16.5 | 338.4 | 310.1 |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 33.15 | 31.06 | 20.66 |
| 712.5 | 18.61 | 23.09 | 14.56 |
| 1440 | 25.13 | 19.78 | 14.10 |
| 2160 | 24.75 | 21.81 | 16.53 |
| 2850 | 22.52 | 22.35 | 18.22 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.24 | 0.27 | 0.27 |
| 712.5 | 0.78 | 1.15 | 1.15 |
| 1440 | 0.40 | 0.39 | 0.28 |
| 2160 | 0.28 | 0.29 | 0.32 |
| 2850 | 0.27 | 0.26 | 0.25 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 6.01 | 6.72 | 6.78 |
| 712.5 | 6.34 | 6.50 | 6.51 |
| 1440 | 6.10 | 6.15 | 6.87 |
| 2160 | 6.09 | 5.75 | 7.32 |
| 2850 | 6.61 | 6.12 | 6.41 |

Temperature ($^{o}C$)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 23 | 21 | 22 |
| 712.5 | 20 | 19 | 20 |
| 1440 | 19 | 19 | 22 |
| 2160 | 19 | 19 | 21 |
| 2850 | 15 | 21 | 21 |

# Appendix I-G

| | | | | |
|---|---|---|---|---|
| Woodchip Species: | Willow Oak | Avg. Retention Time: | | 0.4 Days |
| Woodchip Size: | 5mm | Start date: | Run 1: | 4/10/12 |
| Woodchip Mass: | 4.5% | | Run 2: | 4/17/12 |
| Limestone Content: | 0.0% | | Run 3: | 4/24/12 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 2.379 | 3.29 | 2.91 |
| 60 | 2.526 | 3.16 | 2.99 |
| 120 | 2.764 | 3.18 | 3.11 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.11 | 0.11 | 0.12 |
| 60 | 0.10 | 0.11 | 0.11 |
| 120 | 0.10 | 0.10 | 0.11 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 140 | 2.21 | 2.42 | 1.72 |
| 177.5 | 2.13 | 2.05 | 2.23 |
| 432.5 | 1.19 | 1.36 | 1.56 |
| 860 | 0.07 | 0.75 | 0.44 |
| 1085 | 0.06 | 0.06 | 0.09 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 140 | 0.08 | 0.05 | 0.06 |
| 177.5 | 0.10 | 0.05 | 0.05 |
| 432.5 | 0.57 | 0.05 | 0.06 |
| 860 | 0.32 | 0.12 | 0.11 |
| 1085 | 0.06 | 0.05 | 0.05 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 140 | 0.84 | 0.84 | 1.68 |
| 177.5 | 1.16 | 0.80 | 1.64 |
| 432.5 | 3.36 | 0.56 | 1.40 |
| 860 | 3.36 | 0.38 | 0.68 |
| 1085 | 3.36 | 0.28 | 0.29 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 140 | 0.30 | 0.25 | 0.31 |
| 177.5 | - | - | - |
| 432.5 | 0.10 | 0.20 | 0.14 |
| 860 | - | - | - |
| 1085 | - | 0.17 | 0.16 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 194.5 | 115.0 | 296.0 |
| 180 | 191.2 | 120.0 | 291.0 |
| 1200 | 173.0 | 70.8 | 290.5 |
| 1440 | - | - | - |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 140 | 106.9 | 63.37 | 29.12 |
| 177.5 | 87.21 | 53.49 | 23.07 |
| 432.5 | 66.16 | 48.37 | 21.06 |
| 860 | 69.27 | 42.88 | 24.88 |
| 1085 | 73.54 | 44.84 | 26.86 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 140 | 0.25 | 0.19 | 0.28 |
| 177.5 | 0.15 | 0.27 | 0.18 |
| 432.5 | 1.54 | 1.53 | 1.43 |
| 860 | 0.14 | 0.26 | 0.24 |
| 1085 | 0.10 | 0.22 | 0.30 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 140 | 6.10 | 6.80 | 6.51 |
| 177.5 | 5.95 | 6.43 | 6.55 |
| 432.5 | 6.54 | 6.19 | 6.75 |
| 860 | 7.01 | 6.65 | 6.71 |
| 1085 | 7.42 | 6.92 | 7.13 |

Temperature ($^{o}$C)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 140 | 22 | 25 | 24 |
| 177.5 | 23 | 23 | 24 |
| 432.5 | 21 | 22 | 23 |
| 860 | 21 | 22 | 22 |
| 1085 | 22 | 21 | 21 |

## Appendix I-H

| | | | |
|---|---|---|---|
| Woodchip Species: | Willow Oak | Avg. Retention Time: | 0.6 Days |
| Woodchip Size: | 5mm | Start date: Run 1: | 5/22/12 |
| Woodchip Mass: | 4.5% | Run 2: | 5/29/12 |
| Limestone Content: | 0.0% | Run 3: | 6/5/12 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 3.101 | 3.05 | 3.07 |
| 60 | 3.259 | 3.05 | 3.08 |
| 120 | 3.339 | 3.10 | 3.09 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.11 | 0.11 | 0.11 |
| 60 | 0.11 | 0.11 | 0.12 |
| 120 | 0.11 | 0.11 | 0.11 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 150 | 3.05 | 1.68 | 1.00 |
| 300 | 2.16 | 2.29 | 2.06 |
| 810 | 0.10 | 0.97 | 1.85 |
| 1440 | 0.10 | 0.68 | 0.78 |
| 2205 | 0.10 | 0.10 | 0.39 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 150 | 0.10 | 0.10 | 0.10 |
| 300 | 0.76 | 0.10 | 0.10 |
| 810 | 2.20 | 0.10 | 0.10 |
| 1440 | 1.61 | 0.55 | 0.10 |
| 2205 | 1.45 | 0.10 | 0.10 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 150 | 1.68 | 1.12 | 0.28 |
| 300 | 1.12 | 1.12 | 0.28 |
| 810 | 0.84 | 0.56 | 0.28 |
| 1440 | 0.84 | 0.56 | 0.00 |
| 2205 | 0.84 | 0.56 | 0.28 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 150 | 0.47 | 0.18 | 0.12 |
| 300 | 0.14 | 0.11 | 0.08 |
| 810 | 0.14 | 0.09 | 0.08 |
| 1440 | 0.11 | 0.08 | 0.08 |
| 2205 | 0.14 | 0.09 | 0.10 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 265.4 | 335.2 | 266.2 |
| 180 | 254.3 | 328.1 | 262.0 |
| 1200 | -43.6 | 280.7 | 213.5 |
| 1440 | -72.7 | 295.7 | 219.8 |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 150 | 59.85 | 33.28 | 32.34 |
| 300 | 34.86 | 24.79 | 21.45 |
| 810 | 36.53 | 20.60 | 17.19 |
| 1440 | 34.95 | 20.66 | 18.04 |
| 2205 | 35.17 | 22.19 | 19.09 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 150 | 0.27 | 0.24 | 0.26 |
| 300 | 0.54 | 0.54 | 0.55 |
| 810 | 1.13 | 1.03 | 0.87 |
| 1440 | 0.26 | 0.33 | 0.24 |
| 2205 | 0.29 | 0.27 | 0.27 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 150 | 5.92 | 6.51 | 6.55 |
| 300 | 5.96 | 6.31 | 6.71 |
| 810 | 6.25 | 6.74 | 6.80 |
| 1440 | 6.08 | 6.88 | 6.92 |
| 2205 | 6.39 | 6.57 | 6.45 |

Temperature ($^{o}C$)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 150 | 21 | 23 | 22 |
| 300 | 21 | 21 | 21 |
| 810 | 22 | 21 | 21 |
| 1440 | 21 | 22 | 21 |
| 2205 | 21 | 23 | 21 |

# Appendix I-I

Woodchip Species: Willow Oak
Woodchip Size: 5mm
Woodchip Mass: 4.5%
Limestone Content: 0.0%

Avg. Retention Time: 1.0 Days
Start date: Run 1: 5/22/12
Run 2: 5/29/12
Run 3: 6/5/12

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 3.101 | 3.05 | 3.07 |
| 60 | 3.259 | 3.05 | 3.08 |
| 120 | 3.339 | 3.10 | 3.09 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.11 | 0.11 | 0.11 |
| 60 | 0.11 | 0.11 | 0.12 |
| 120 | 0.11 | 0.11 | 0.11 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 195 | 3.38 | 1.48 | 1.19 |
| 735 | 2.10 | 1.89 | 1.73 |
| 1530 | 0.10 | 0.12 | 0.73 |
| 2280 | 0.10 | 0.10 | 0.46 |
| 3390 | 0.10 | 0.10 | 0.39 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 195 | 0.10 | 0.10 | 0.10 |
| 735 | 1.04 | 0.10 | 0.10 |
| 1530 | 1.90 | 0.33 | 0.10 |
| 2280 | 0.53 | 0.10 | 0.10 |
| 3390 | 0.10 | 0.10 | 0.10 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 195 | 1.40 | 0.84 | 0.56 |
| 735 | 1.12 | 0.84 | 0.28 |
| 1530 | 1.40 | 0.84 | 0.00 |
| 2280 | 0.00 | 0.56 | 0.28 |
| 3390 | 0.84 | 0.56 | 0.28 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 195 | 0.41 | 0.16 | 0.12 |
| 735 | 0.18 | 0.14 | 0.08 |
| 1530 | 0.13 | 0.10 | 0.07 |
| 2280 | 0.18 | 0.08 | 0.11 |
| 3390 | 0.15 | 0.08 | 0.09 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 225.5 | 283.3 | 318.1 |
| 180 | 220.4 | 285.0 | 319.6 |
| 1200 | -54.7 | 233.5 | 365.7 |
| 1440 | -21.9 | 250.5 | 367.4 |
| 1650 | -11.2 | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 195 | 53.26 | 30.67 | 30.23 |
| 735 | 33.54 | 26.57 | 18.09 |
| 1530 | 31.40 | 24.39 | 17.08 |
| 2280 | 41.53 | 24.68 | 20.78 |
| 3390 | 38.64 | 24.70 | 28.72 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 195 | 0.28 | 0.23 | 0.29 |
| 735 | 0.88 | 0.88 | 1.15 |
| 1530 | 0.39 | 0.42 | 0.40 |
| 2280 | 0.28 | 0.30 | 0.27 |
| 3390 | 0.28 | 0.27 | 0.24 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 195 | 6.02 | 6.79 | 6.63 |
| 735 | 6.12 | 6.47 | 6.47 |
| 1530 | 6.16 | 6.74 | 6.98 |
| 2280 | 5.95 | 6.77 | 6.30 |
| 3390 | 6.62 | 7.09 | 6.80 |

Temperature ($^{o}$C)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 195 | 21 | 23 | 22 |
| 735 | 21 | 21 | 21 |
| 1530 | 21 | 21 | 21 |
| 2280 | 21 | 22 | 21 |
| 3390 | 20 | 23 | 22 |

# Appendix I-J

| | | | | |
|---|---|---|---|---|
| Woodchip Species: | Willow Oak | Avg. Retention Time: | | 1.3 Days |
| Woodchip Size: | 5mm | Start date: | Run 1: | 8/14/12 |
| Woodchip Mass: | 4.5% | | Run 2: | 8/21/12 |
| Limestone Content: | 0.0% | | Run 3: | 8/27/12 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 2.962 | 3.09 | 3.02 |
| 60 | 3.078 | 3.21 | 3.09 |
| 120 | 3.105 | 3.28 | 3.12 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.12 | 0.12 | 0.10 |
| 60 | 0.12 | 0.10 | 0.11 |
| 120 | 0.14 | 0.10 | 0.07 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 207.5 | 2.37 | 2.28 | 2.17 |
| 1000 | 0.69 | 2.48 | 1.92 |
| 2170 | 0.15 | 0.97 | 0.72 |
| 3355 | 0.10 | 0.10 | 0.10 |
| 4345 | 0.10 | 0.10 | 0.10 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 207.5 | 0.11 | 0.07 | 0.07 |
| 1000 | 0.82 | 0.09 | 0.07 |
| 2170 | 0.11 | 0.19 | 0.07 |
| 3355 | 0.07 | 0.07 | 0.07 |
| 4345 | 0.07 | 0.07 | 0.07 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 207.5 | 4.48 | 0.84 | 0.28 |
| 1000 | 0.56 | 0.56 | 0.56 |
| 2170 | 0.84 | 0.56 | 0.28 |
| 3355 | 0.28 | 0.56 | 0.28 |
| 4345 | 0.28 | 0.28 | 0.28 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 207.5 | - | 0.14 | 0.11 |
| 1000 | 0.22 | 0.12 | 0.07 |
| 2170 | 0.16 | 0.05 | 0.16 |
| 3355 | 0.16 | 0.10 | 0.07 |
| 4345 | 0.20 | 0.11 | 0.09 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 283.8 | 318.1 | 274.1 |
| 180 | 276.4 | 322.5 | 291.2 |
| 1200 | 124.8 | 229.9 | 154.8 |
| 1440 | 98.5 | 171.6 | 108.2 |
| 1650 | -71.6 | 134.1 | 86.2 |
| 2640 | -455 | 19.2 | -408 |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 207.5 | 36.82 | 18.53 | 14.48 |
| 1000 | 27.45 | 17.26 | 12.34 |
| 2170 | 26.78 | - | 13.12 |
| 3355 | 28.33 | 19.78 | 15.40 |
| 4345 | 32.66 | 24.04 | 18.25 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 207.5 | 0.22 | 0.28 | 0.25 |
| 1000 | 0.51 | 0.83 | 1.10 |
| 2170 | 0.26 | 0.41 | 0.46 |
| 3355 | 0.28 | 0.28 | 0.25 |
| 4345 | 0.28 | 0.28 | 0.28 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 207.5 | 6.14 | 6.79 | 6.99 |
| 1000 | 6.48 | 7.50 | 6.70 |
| 2170 | 6.45 | 6.38 | 6.87 |
| 3355 | 6.27 | 6.12 | 6.71 |
| 4345 | 6.79 | 7.36 | 6.87 |

Temperature ($^oC$)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 207.5 | 23 | 22 | 24 |
| 1000 | 23 | 22 | 23 |
| 2170 | 22 | 21 | 22 |
| 3355 | 22 | 21 | 22 |
| 4345 | 22 | 21 | 22 |

# Appendix I-K

| | | | |
|---|---|---|---|
| Woodchip Species: | Wild Cherry | Avg. Retention Time: | 0.8 Days |
| Woodchip Size: | 5mm | Start date: | Run 1: 7/3/12 |
| Woodchip Mass: | 4.5% | | Run 2: 7/10/12 |
| Limestone Content: | 0.0% | | Run 3: 7/17/12 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 3.17 | 3.35 | 3.05 |
| 60 | 3.145 | 3.41 | 3.13 |
| 120 | 3.182 | 3.42 | 3.11 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.14 | 0.10 | 0.11 |
| 60 | 0.15 | 0.12 | 0.12 |
| 120 | 0.14 | 0.11 | 0.13 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 2.98 | 1.68 | 1.74 |
| 712.5 | 2.54 | 1.06 | 0.92 |
| 1440 | 0.51 | 0.06 | 0.09 |
| 2160 | 0.06 | 0.06 | 0.13 |
| 2850 | 0.06 | 0.07 | 0.11 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.06 | 0.06 | 0.05 |
| 712.5 | 0.09 | 0.05 | 0.05 |
| 1440 | 0.76 | 0.05 | 0.05 |
| 2160 | 0.23 | 0.05 | 0.05 |
| 2850 | 0.05 | 0.05 | 0.05 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 1.40 | 1.12 | 0.84 |
| 712.5 | 0.84 | 1.12 | 1.12 |
| 1440 | 1.12 | 0.84 | 0.56 |
| 2160 | 1.68 | 1.96 | 1.40 |
| 2850 | 0.84 | 4.76 | 3.64 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.30 | 0.27 | 0.19 |
| 712.5 | 0.24 | 0.19 | 0.18 |
| 1440 | 0.29 | 0.19 | 0.19 |
| 2160 | 0.23 | 0.21 | 0.19 |
| 2850 | - | 0.22 | 0.17 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 204.7 | 310.9 | 331.8 |
| 180 | 290.7 | 304.6 | 318.0 |
| 1200 | 396.8 | 115.9 | 408.1 |
| 1440 | - | - | - |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 173.7 | 177.9 | 122.9 |
| 712.5 | 172.8 | 131.5 | 89.5 |
| 1440 | 194.3 | 151.3 | 113.8 |
| 2160 | - | 164.5 | 126.0 |
| 2850 | 219.2 | 178.3 | 124.5 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.25 | 0.25 | 0.27 |
| 712.5 | 0.99 | 0.90 | 1.02 |
| 1440 | 0.49 | 0.37 | 0.27 |
| 2160 | 0.29 | 0.26 | 0.26 |
| 2850 | 0.22 | 0.27 | 0.25 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 6.54 | 5.76 | 5.38 |
| 712.5 | 6.20 | 6.41 | 5.92 |
| 1440 | 5.77 | 6.53 | 5.91 |
| 2160 | 6.00 | 6.38 | 5.48 |
| 2850 | 5.99 | 6.11 | 6.06 |

Temperature ($^{o}C$)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 24 | 25 | 24 |
| 712.5 | 23 | 22 | 23 |
| 1440 | 22 | 22 | 22 |
| 2160 | 22 | 22 | 23 |
| 2850 | 22 | 22 | 23 |

# Appendix I-L

| | | | |
|---|---|---|---|
| Woodchip Species: | Red Maple | Avg. Retention Time: | 0.8 Days |
| Woodchip Size: | 5mm | Start date: | Run 1: 8/14/12 |
| Woodchip Mass: | 4.5% | | Run 2: 8/21/12 |
| Limestone Content: | 0.0% | | Run 3: 8/28/12 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 2.962 | 3.09 | 3.02 |
| 60 | 3.078 | 3.21 | 3.09 |
| 120 | 3.105 | 3.28 | 3.12 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.12 | 0.12 | 0.10 |
| 60 | 0.12 | 0.10 | 0.12 |
| 120 | 0.14 | 0.10 | 0.08 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 3.04 | 2.05 | 1.49 |
| 712.5 | 2.71 | 1.45 | 1.00 |
| 1440 | 0.29 | 0.10 | 0.10 |
| 2160 | 0.10 | 0.10 | 0.10 |
| 2850 | 0.10 | 0.10 | 0.10 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.07 | 0.07 | 0.07 |
| 712.5 | 0.13 | 0.10 | 0.08 |
| 1440 | 0.43 | 0.07 | 0.07 |
| 2160 | 0.08 | 0.07 | 0.07 |
| 2850 | 0.07 | 0.07 | 0.07 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 1.68 | 0.28 | 0.28 |
| 712.5 | 1.12 | 0.56 | 0.00 |
| 1440 | 1.40 | 0.56 | 0.00 |
| 2160 | 0.56 | 0.28 | 0.00 |
| 2850 | 0.84 | 0.56 | 0.00 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.44 | 0.16 | 0.14 |
| 712.5 | 0.35 | 0.13 | 0.09 |
| 1440 | 0.28 | 0.14 | 0.11 |
| 2160 | 0.28 | 0.17 | - |
| 2850 | 0.27 | 0.19 | 0.10 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 265.0 | 258.1 | 253.4 |
| 180 | 247.2 | 275.1 | 275.1 |
| 1200 | 104.6 | 163.9 | 391.2 |
| 1440 | 90.8 | -95.7 | 399.0 |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 44.76 | 31.95 | 31.23 |
| 712.5 | 43.78 | 45.95 | 25.81 |
| 1440 | 49.89 | 43.80 | 32.37 |
| 2160 | 53.21 | 50.66 | 35.33 |
| 2850 | 55.82 | 56.25 | 35.67 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.24 | 0.24 | 0.29 |
| 712.5 | 0.56 | 0.77 | 1.12 |
| 1440 | 0.29 | 0.31 | 0.34 |
| 2160 | 0.29 | 0.28 | 0.22 |
| 2850 | 0.28 | 0.26 | 0.23 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 7.28 | 6.76 | 7.01 |
| 712.5 | 6.29 | 6.08 | 5.95 |
| 1440 | 6.16 | 7.00 | 7.43 |
| 2160 | 6.10 | 6.31 | 6.41 |
| 2850 | 6.38 | 6.21 | 6.17 |

Temperature ($^{o}$C)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 24 | 22 | 13 |
| 712.5 | 23 | 21 | 22 |
| 1440 | 23 | 22 | 22 |
| 2160 | 22 | 21 | 22 |
| 2850 | 22 | 21 | 21 |

# Appendix I-M

| | | | | |
|---|---|---|---|---|
| Woodchip Species: | Virginia Pine | Avg. Retention Time: | 0.8 Days | |
| Woodchip Size: | 5mm | Start date: | Run 1: | 5/22/12 |
| Woodchip Mass: | 4.5% | | Run 2: | 5/29/12 |
| Limestone Content: | 0.0% | | Run 3: | 6/5/12 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 2.982 | 2.86 | 3.10 |
| 60 | 2.982 | 2.95 | 2.82 |
| 120 | 3.011 | 3.16 | 3.20 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.12 | 0.14 | 0.10 |
| 60 | 0.12 | 0.12 | 0.10 |
| 120 | 0.11 | 0.14 | 0.10 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 2.91 | 0.10 | 1.17 |
| 712.5 | 2.79 | 0.39 | 1.08 |
| 1440 | 1.34 | 0.11 | 0.12 |
| 2160 | 0.22 | 0.08 | 0.06 |
| 2850 | 0.08 | 0.07 | 0.09 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.08 | 0.06 | 0.06 |
| 712.5 | 0.36 | 0.06 | 0.06 |
| 1440 | 0.78 | 0.05 | 0.06 |
| 2160 | 0.71 | 0.06 | 0.06 |
| 2850 | 0.05 | 0.10 | 0.06 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 1.68 | 0.00 | 0.73 |
| 712.5 | 1.68 | 1.40 | 0.98 |
| 1440 | 0.56 | 3.36 | 1.82 |
| 2160 | 1.18 | 0.00 | 0.70 |
| 2850 | 0.84 | 0.00 | 0.00 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.34 | 0.19 | - |
| 712.5 | 0.24 | 0.33 | 0.08 |
| 1440 | 0.25 | 0.11 | 0.12 |
| 2160 | - | - | 0.13 |
| 2850 | - | - | 0.13 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 252.2 | 435.4 | 426.2 |
| 180 | 245.5 | 418.2 | 416.3 |
| 1200 | 173.2 | 50.4 | -48.3 |
| 1440 | - | - | - |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 108.8 | 161.6 | 87.4 |
| 712.5 | 109.2 | 107.4 | 71.7 |
| 1440 | 112.2 | 70.0 | 77.4 |
| 2160 | 112.4 | 82.4 | 82.8 |
| 2850 | 125.5 | 94.9 | 91.2 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.17 | 0.26 | 0.22 |
| 712.5 | 0.56 | 1.56 | 1.00 |
| 1440 | 0.24 | 0.56 | 0.36 |
| 2160 | 0.18 | 0.29 | 0.26 |
| 2850 | 0.26 | 0.21 | 0.26 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 7.04 | 6.28 | 6.66 |
| 712.5 | 6.54 | 6.57 | 6.84 |
| 1440 | 6.75 | 6.46 | 6.73 |
| 2160 | 6.86 | 6.59 | 6.62 |
| 2850 | 6.79 | 6.87 | 6.81 |

Temperature ($^{o}$C)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 24 | 26 | 24 |
| 712.5 | 22 | 23 | 23 |
| 1440 | 23 | 24 | 22 |
| 2160 | 23 | 23 | 22 |
| 2850 | 24 | 22 | 22 |

# Appendix I-N

| | | | |
|---|---|---|---|
| Woodchip Species: | American Beech | Avg. Retention Time: | 0.8 Days |
| Woodchip Size: | 5mm | Start date: | Run 1: 7/3/12 |
| Woodchip Mass: | 4.5% | | Run 2: 7/10/12 |
| Limestone Content: | 0.0% | | Run 3: 7/17/12 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 3.17 | 3.35 | 3.05 |
| 60 | 3.145 | 3.41 | 3.13 |
| 120 | 3.182 | 3.42 | 3.11 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.14 | 0.10 | 0.11 |
| 60 | 0.15 | 0.12 | 0.12 |
| 120 | 0.14 | 0.11 | 0.13 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 1.91 | 1.48 | 1.44 |
| 712.5 | 0.06 | 0.71 | 0.82 |
| 1440 | 0.06 | 0.09 | 0.13 |
| 2160 | 0.07 | 0.08 | 0.11 |
| 2850 | 0.06 | 0.06 | 0.10 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.66 | 0.06 | 0.06 |
| 712.5 | 0.05 | 0.05 | 0.06 |
| 1440 | 0.05 | 0.05 | 0.06 |
| 2160 | 0.05 | 0.05 | 0.06 |
| 2850 | 0.05 | 0.05 | 0.06 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 6.07 | 2.24 | 1.68 |
| 712.5 | 3.36 | 1.40 | 1.40 |
| 1440 | 3.08 | 1.12 | 1.40 |
| 2160 | 3.08 | 0.56 | 1.40 |
| 2850 | 2.49 | 1.68 | 1.12 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.53 | 0.33 | 0.19 |
| 712.5 | 0.48 | 0.30 | 0.12 |
| 1440 | - | 0.29 | 0.12 |
| 2160 | 0.49 | 0.31 | 0.12 |
| 2850 | - | 0.29 | 0.15 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 275.1 | 364.7 | 411.8 |
| 180 | 271.2 | 343.8 | 402.2 |
| 1200 | 267.2 | -337 | -168 |
| 1440 | - | - | - |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 60.81 | 43.52 | 23.75 |
| 712.5 | 72.28 | 27.56 | 17.60 |
| 1440 | - | 32.26 | 23.47 |
| 2160 | 76.18 | 44.58 | 29.54 |
| 2850 | 93.91 | 45.82 | 31.33 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.26 | 0.25 | 0.29 |
| 712.5 | 1.25 | 0.86 | 0.68 |
| 1440 | 0.32 | 0.27 | 0.39 |
| 2160 | 0.28 | 0.27 | 0.27 |
| 2850 | 0.18 | 0.23 | 0.27 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 6.83 | 6.55 | 6.57 |
| 712.5 | 6.99 | 7.02 | 6.75 |
| 1440 | 6.38 | 7.19 | 6.90 |
| 2160 | 6.64 | 6.58 | 6.43 |
| 2850 | 6.21 | 7.13 | 7.20 |

Temperature ($^{o}$C)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 24 | 25 | 24 |
| 712.5 | 23 | 22 | 23 |
| 1440 | 22 | 22 | 22 |
| 2160 | 22 | 22 | 23 |
| 2850 | 22 | 22 | 23 |

# Appendix I-O

| | | | | |
|---|---|---|---|---|
| Woodchip Species: | Willow Oak | Avg. Retention Time: | | 0.8 Days |
| Woodchip Size: | 9mm | Start date: | Run 1: | 5/22/12 |
| Woodchip Mass: | 4.5% | | Run 2: | 5/29/12 |
| Limestone Content: | 0.0% | | Run 3: | 6/5/12 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 2.977 | 2.98 | 2.89 |
| 60 | 3.007 | 3.01 | 2.94 |
| 120 | 3.095 | 3.10 | 2.94 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | - | 0.09 | 0.09 |
| 60 | - | 0.10 | 0.08 |
| 120 | - | 0.09 | 0.10 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 2.18 | 2.96 | 1.87 |
| 712.5 | 1.27 | 1.59 | 2.03 |
| 1440 | 0.32 | 0.10 | 0.64 |
| 2160 | 0.10 | 0.10 | 0.10 |
| 2850 | 0.59 | 0.22 | 0.10 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.10 | 0.10 | 0.10 |
| 712.5 | 0.49 | 0.28 | 0.10 |
| 1440 | 0.25 | 0.10 | 0.10 |
| 2160 | 0.10 | 0.10 | 0.10 |
| 2850 | 0.10 | 0.10 | 0.10 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.28 | 0.28 | 0.84 |
| 712.5 | 0.28 | 0.28 | 0.28 |
| 1440 | 0.00 | 0.56 | 0.56 |
| 2160 | 0.00 | 0.56 | 0.56 |
| 2850 | 0.00 | 0.28 | 0.56 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | - | 0.13 | 0.12 |
| 712.5 | - | 0.12 | 0.08 |
| 1440 | - | 0.10 | 0.06 |
| 2160 | - | 0.10 | 0.09 |
| 2850 | - | 0.09 | 0.09 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 247.5 | 234.3 | 251.8 |
| 180 | 202.6 | 226.5 | 249.3 |
| 1200 | 180.8 | 221.4 | 243.5 |
| 1440 | 94.6 | 223.7 | - |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 82.64 | 40.20 | 25.18 |
| 712.5 | 50.63 | 31.66 | 20.47 |
| 1440 | 49.02 | 29.96 | 19.88 |
| 2160 | 63.73 | 29.04 | 20.95 |
| 2850 | 55.01 | 32.52 | 24.18 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.27 | 0.27 | 0.28 |
| 712.5 | 0.94 | 1.19 | 1.17 |
| 1440 | 0.40 | 0.39 | 0.40 |
| 2160 | 0.27 | 0.28 | 0.28 |
| 2850 | 0.28 | 0.27 | 0.19 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 6.02 | 6.62 | 6.52 |
| 712.5 | 6.07 | 6.41 | 6.32 |
| 1440 | 6.24 | 6.94 | 6.36 |
| 2160 | 5.55 | 6.77 | 6.21 |
| 2850 | 6.74 | 6.97 | 6.46 |

Temperature (°C)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 19 | 21 | 20 |
| 712.5 | 18 | 18 | 18 |
| 1440 | 18 | 17 | 19 |
| 2160 | 18 | 17 | 19 |
| 2850 | 18 | 18 | 20 |

# Appendix I-P

| | | | | |
|---|---|---|---|---|
| Woodchip Species: | Willow Oak | Avg. Retention Time: | | 0.8 Days |
| Woodchip Size: | 13mm | Start date: | Run 1: | 5/22/12 |
| Woodchip Mass: | 4.5% | | Run 2: | 5/29/12 |
| Limestone Content: | 0.0% | | Run 3: | 6/5/12 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 2.977 | 2.98 | 2.89 |
| 60 | 3.007 | 3.01 | 2.94 |
| 120 | 3.095 | 3.10 | 2.94 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | - | 0.09 | 0.09 |
| 60 | - | 0.10 | 0.08 |
| 120 | - | 0.09 | 0.10 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 2.78 | 1.74 | 2.08 |
| 712.5 | 1.85 | 1.44 | 2.05 |
| 1440 | 0.39 | 0.10 | 0.61 |
| 2160 | 0.30 | 0.10 | 0.10 |
| 2850 | 0.10 | 0.10 | 0.10 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.10 | 0.10 | 0.10 |
| 712.5 | 0.27 | 0.10 | 0.10 |
| 1440 | 0.29 | 0.10 | 0.10 |
| 2160 | 0.10 | 0.10 | 0.10 |
| 2850 | 0.10 | 0.10 | 0.10 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.84 | 0.84 | 0.84 |
| 712.5 | 0.56 | 0.84 | 0.84 |
| 1440 | 0.28 | 0.28 | 0.56 |
| 2160 | 0.28 | 0.28 | 0.56 |
| 2850 | 0.28 | 0.00 | 0.84 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | - | 0.17 | 0.13 |
| 712.5 | - | 0.14 | 0.22 |
| 1440 | - | 0.10 | 0.04 |
| 2160 | - | 0.10 | 0.09 |
| 2850 | - | 0.11 | 0.08 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 271.1 | 316.1 | 362.9 |
| 180 | 259.0 | 320.2 | 360.1 |
| 1200 | 239.2 | 315.6 | 382.8 |
| 1440 | 111.3 | 331.9 | - |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 54.16 | 34.33 | 24.38 |
| 712.5 | 33.31 | 30.73 | 20.12 |
| 1440 | 47.77 | 32.53 | 18.86 |
| 2160 | 55.49 | 32.79 | 21.83 |
| 2850 | 51.69 | 35.04 | 22.76 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.26 | 0.27 | 0.27 |
| 712.5 | 0.70 | 1.12 | 1.14 |
| 1440 | 0.41 | 0.38 | 0.48 |
| 2160 | 0.26 | 0.28 | 0.26 |
| 2850 | 0.29 | 0.28 | 0.25 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 6.26 | 6.57 | 6.46 |
| 712.5 | 6.51 | 6.37 | 6.24 |
| 1440 | 6.37 | 6.85 | 6.38 |
| 2160 | 5.77 | 6.73 | 6.44 |
| 2850 | 6.67 | 6.75 | 6.27 |

Temperature ($^{o}C$)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 19 | 21 | 20 |
| 712.5 | 18 | 18 | 18 |
| 1440 | 18 | 17 | 19 |
| 2160 | 18 | 17 | 19 |
| 2850 | 18 | 18 | 20 |

# Appendix I-Q

| | | | |
|---|---|---|---|
| Woodchip Species: | Willow Oak | Avg. Retention Time: | 0.8 Days |
| Woodchip Size: | 5mm | Start date: Run 1: | 1/14/13 |
| Woodchip Mass: | 1.0% | Run 2: | 1/21/13 |
| Limestone Content: | 0.0% | Run 3: | 1/28/13 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 2.836 | 2.84 | 2.84 |
| 60 | 3.021 | 3.02 | 3.02 |
| 120 | 2.839 | 2.84 | 2.84 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.14 | 0.13 | 0.13 |
| 60 | 0.11 | 0.10 | 0.10 |
| 120 | 0.09 | 0.08 | 0.08 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 2.76 | 1.46 | 1.56 |
| 712.5 | 4.25 | 1.39 | 1.38 |
| 1440 | 3.95 | 1.23 | 1.22 |
| 2160 | 0.84 | 0.43 | 0.19 |
| 2850 | 0.30 | 0.28 | 0.10 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.04 | 0.04 | 0.01 |
| 712.5 | 0.05 | 0.03 | 0.01 |
| 1440 | 0.48 | 0.10 | 0.03 |
| 2160 | 0.60 | 0.15 | 0.02 |
| 2850 | 0.69 | 0.05 | 0.01 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 1.12 | 0.14 | 0.28 |
| 712.5 | 0.28 | 0.00 | 0.14 |
| 1440 | 0.84 | 0.00 | 0.00 |
| 2160 | 0.56 | 0.14 | 0.00 |
| 2850 | 0.56 | 0.00 | 0.14 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.12 | 0.07 | 0.01 |
| 712.5 | 0.05 | 0.01 | 0.01 |
| 1440 | 0.01 | 0.01 | 0.01 |
| 2160 | 0.01 | 0.01 | 0.01 |
| 2850 | 0.01 | 0.01 | 0.01 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 307.8 | 345.0 | 245.3 |
| 180 | 296.6 | 340.9 | 352.0 |
| 1200 | 238.0 | 304.0 | 329.7 |
| 1440 | 236.6 | 279.5 | 322.3 |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 14.17 | 12.75 | 11.12 |
| 712.5 | 14.23 | 10.40 | 6.94 |
| 1440 | 15.29 | 12.55 | 10.00 |
| 2160 | 16.72 | 14.51 | 11.46 |
| 2850 | 16.93 | 10.19 | 13.34 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.26 | 0.25 | 0.27 |
| 712.5 | 0.93 | 1.01 | 1.01 |
| 1440 | 0.28 | 0.27 | 0.26 |
| 2160 | 0.43 | 0.28 | 0.28 |
| 2850 | 0.29 | 0.28 | 0.26 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 6.95 | 7.20 | 6.21 |
| 712.5 | 6.95 | 7.05 | 6.26 |
| 1440 | 7.14 | 7.02 | 6.44 |
| 2160 | 7.40 | 7.08 | 6.60 |
| 2850 | 6.81 | 7.07 | 6.37 |

Temperature ($^{o}C$)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 21 | 20 | 21 |
| 712.5 | 21 | 19 | 20 |
| 1440 | 21 | 19 | 22 |
| 2160 | 20 | 20 | 21 |
| 2850 | 20 | 20 | 22 |

# Appendix I-R

| | | | |
|---|---|---|---|
| Woodchip Species: | Willow Oak | Avg. Retention Time: | 0.8 Days |
| Woodchip Size: | 5mm | Start date: | Run 1: 1/14/13 |
| Woodchip Mass: | 2.5% | | Run 2: 1/21/13 |
| Limestone Content: | 0.0% | | Run 3: 1/28/13 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 2.836 | 2.84 | 2.84 |
| 60 | 3.021 | 3.02 | 3.02 |
| 120 | 2.839 | 2.84 | 2.84 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.14 | 0.13 | 0.13 |
| 60 | 0.11 | 0.10 | 0.10 |
| 120 | 0.09 | 0.08 | 0.08 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 2.41 | 1.42 | 1.18 |
| 712.5 | 2.65 | 0.97 | 0.29 |
| 1440 | 0.51 | 0.10 | 0.10 |
| 2160 | 0.10 | 0.10 | 0.10 |
| 2850 | 0.10 | 0.29 | 0.10 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.05 | 0.01 | 0.01 |
| 712.5 | 0.55 | 0.08 | 0.01 |
| 1440 | 2.58 | 0.01 | 0.01 |
| 2160 | 0.68 | 0.01 | 0.01 |
| 2850 | 0.01 | 0.01 | 0.01 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 1.40 | 0.28 | 0.84 |
| 712.5 | 0.00 | 0.28 | 0.00 |
| 1440 | 0.28 | 0.00 | 0.00 |
| 2160 | 0.84 | 0.28 | 0.00 |
| 2850 | 0.56 | 0.28 | 2.80 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.13 | 0.09 | 0.08 |
| 712.5 | 0.06 | 0.01 | 0.01 |
| 1440 | 0.01 | 0.01 | 0.01 |
| 2160 | 0.01 | 0.01 | 0.01 |
| 2850 | 0.06 | 0.01 | 0.01 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 235.3 | 239.3 | 242.6 |
| 180 | 225.6 | 237.5 | 247.1 |
| 1200 | 151.2 | 194.5 | 140.1 |
| 1440 | 147.0 | 208.5 | 120.0 |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 23.49 | 33.24 | 24.03 |
| 712.5 | 27.22 | 24.15 | 17.18 |
| 1440 | 29.23 | 29.31 | 24.28 |
| 2160 | 31.84 | 32.74 | 28.18 |
| 2850 | 39.45 | 20.84 | 31.70 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.26 | 0.27 | 0.26 |
| 712.5 | 0.93 | 1.00 | 0.99 |
| 1440 | 0.26 | 0.27 | 0.26 |
| 2160 | 0.46 | 0.39 | 0.36 |
| 2850 | 0.27 | 0.28 | 0.26 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 6.50 | 6.69 | 6.25 |
| 712.5 | 6.35 | 6.59 | 6.18 |
| 1440 | 6.64 | 7.00 | 6.38 |
| 2160 | 6.92 | 6.98 | 6.37 |
| 2850 | 6.31 | 7.11 | 6.08 |

Temperature ($^{o}$C)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 21 | 20 | 21 |
| 712.5 | 21 | 19 | 20 |
| 1440 | 21 | 19 | 22 |
| 2160 | 20 | 20 | 21 |
| 2850 | 20 | 20 | 22 |

# Appendix I-S

| | | | |
|---|---|---|---|
| Woodchip Species: | Willow Oak | Avg. Retention Time: | 0.8 Days |
| Woodchip Size: | 5mm | Start date: | Run 1: 11/12/12 |
| Woodchip Mass: | 4.5% | | Run 2: 11/26/12 |
| Limestone Content: | 5.0% | | Run 3: 12/3/12 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 2.934 | 2.95 | 2.86 |
| 60 | 2.963 | 3.07 | 2.94 |
| 120 | 3.157 | 3.09 | 2.93 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.11 | 0.11 | 0.13 |
| 60 | 0.11 | 0.11 | 0.13 |
| 120 | 0.11 | 0.11 | 0.13 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 3.46 | 2.86 | 1.20 |
| 712.5 | 2.62 | 0.92 | 0.71 |
| 1440 | 0.46 | 0.10 | 0.10 |
| 2160 | 0.10 | 0.41 | 0.29 |
| 2850 | 0.38 | 0.48 | 0.10 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.01 | 0.03 | 0.01 |
| 712.5 | 0.29 | 0.08 | 0.03 |
| 1440 | 2.16 | 0.01 | 0.01 |
| 2160 | 1.62 | 0.01 | 0.01 |
| 2850 | 0.01 | 0.01 | 0.01 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.42 | 0.42 | 0.70 |
| 712.5 | 0.14 | 0.14 | 0.14 |
| 1440 | 0.14 | 0.14 | 0.14 |
| 2160 | 0.14 | 0.14 | 0.14 |
| 2850 | 0.14 | 0.14 | 0.14 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.21 | 0.13 | 0.15 |
| 712.5 | 0.15 | 0.13 | 0.11 |
| 1440 | 0.10 | 0.14 | 0.11 |
| 2160 | 0.12 | 0.14 | 0.10 |
| 2850 | 0.11 | 0.16 | 0.12 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 287.1 | 291.6 | 327.0 |
| 180 | 265.6 | 303.5 | 326.5 |
| 1200 | 139.8 | -9.7 | 12.7 |
| 1440 | 109.7 | -87.1 | -50.1 |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 51.54 | 29.65 | 53.21 |
| 712.5 | 47.73 | 41.30 | 38.35 |
| 1440 | 58.08 | 54.35 | 44.50 |
| 2160 | 59.42 | 63.09 | 51.08 |
| 2850 | 85.21 | 73.35 | 50.76 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.26 | 0.30 | 0.30 |
| 712.5 | 0.81 | 1.03 | 1.06 |
| 1440 | 0.27 | 0.29 | 0.26 |
| 2160 | 0.37 | 0.53 | 0.36 |
| 2850 | 0.27 | 0.28 | 0.28 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 6.99 | 7.18 | 7.13 |
| 712.5 | 7.36 | 7.39 | 7.26 |
| 1440 | 7.00 | 7.40 | 7.50 |
| 2160 | 7.59 | 7.46 | 7.79 |
| 2850 | 7.09 | 7.31 | 7.24 |

Temperature ($^{o}C$)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 20 | 18 | 20 |
| 712.5 | 20 | 19 | 19 |
| 1440 | 20 | 19 | 19 |
| 2160 | 19 | 19 | 20 |
| 2850 | 19 | 19 | 20 |

# Appendix I-T

| | | | | |
|---|---|---|---|---|
| Woodchip Species: | Willow Oak | Avg. Retention Time: | | 0.8 Days |
| Woodchip Size: | 5mm | Start date: | Run 1: | 11/12/12 |
| Woodchip Mass: | 4.5% | | Run 2: | 11/26/12 |
| Limestone Content: | 10.0% | | Run 3: | 12/3/12 |

Inflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 2.934 | 2.95 | 2.86 |
| 60 | 2.963 | 3.07 | 2.94 |
| 120 | 3.157 | 3.09 | 2.93 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 5 | 0.11 | 0.11 | 0.13 |
| 60 | 0.11 | 0.11 | 0.13 |
| 120 | 0.11 | 0.11 | 0.13 |

Outflow Data

Nitrate (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 3.15 | 2.51 | 0.93 |
| 712.5 | 2.17 | 1.79 | 0.59 |
| 1440 | 0.30 | 0.10 | 0.10 |
| 2160 | 0.53 | 0.41 | 0.10 |
| 2850 | 0.10 | 0.38 | 0.10 |

Nitrite (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.01 | 0.01 | 0.01 |
| 712.5 | 0.54 | 0.09 | 0.03 |
| 1440 | 1.91 | 0.01 | 0.01 |
| 2160 | 0.01 | 0.01 | 0.01 |
| 2850 | 0.01 | 0.01 | 0.01 |

TKN (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.14 | 0.14 | 0.70 |
| 712.5 | 0.14 | 0.42 | 0.28 |
| 1440 | 0.14 | 0.14 | 0.28 |
| 2160 | 0.14 | 0.14 | 0.14 |
| 2850 | 0.14 | 0.14 | 0.14 |

Total Phosphorus (ppm)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.18 | 0.17 | 0.13 |
| 712.5 | 0.12 | 0.15 | 0.10 |
| 1440 | 0.11 | 0.16 | 0.11 |
| 2160 | 0.13 | 0.16 | 0.12 |
| 2850 | 0.15 | 0.16 | 0.13 |

Redox Potential (mV)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 120 | 205.3 | 208.5 | 219.7 |
| 180 | 193.9 | 194.1 | 225.0 |
| 1200 | 160.4 | 141.7 | 160.3 |
| 1440 | 147.0 | 110.3 | 94.1 |
| 1650 | - | - | - |
| 2640 | - | - | - |

Organic Carbon (PPM)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 56.85 | 39.24 | 63.65 |
| 712.5 | 58.28 | 45.09 | 44.44 |
| 1440 | 67.65 | 63.31 | 48.17 |
| 2160 | 87.62 | 70.46 | 52.39 |
| 2850 | 112.2 | 76.91 | 45.85 |

Volume (liters)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 0.26 | 0.27 | 0.29 |
| 712.5 | 0.78 | 1.04 | 1.04 |
| 1440 | 0.27 | 0.28 | 0.28 |
| 2160 | 0.36 | 0.50 | 0.36 |
| 2850 | 0.26 | 0.28 | 0.28 |

pH

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 7.00 | 7.15 | 6.99 |
| 712.5 | 7.12 | 7.35 | 7.18 |
| 1440 | 7.01 | 7.48 | 7.47 |
| 2160 | 6.81 | 7.40 | 7.79 |
| 2850 | 6.72 | 7.34 | 7.20 |

Temperature ($^{o}C$)

| Time (min) | Run 1 | Run 2 | Run 3 |
|---|---|---|---|
| 172.5 | 20 | 18 | 20 |
| 712.5 | 20 | 19 | 19 |
| 1440 | 20 | 19 | 19 |
| 2160 | 19 | 19 | 20 |
| 2850 | 19 | 19 | 20 |

# Appendix II-A

First order Model Derivation

Assume completely mixed
Assume no outflow at t=0
Column full at t=0

$$\frac{dM}{dt} = \cancel{Q_{in} * C_{in}} - Q_{out} * C_{out} - r * V \tag{1}$$

No inflow
Assume first order decay

$$-r = K_1 * C_{out} \tag{2}$$

$$\frac{dM}{dt} = -Q_{out} * C_{out} + K_1 * C_{out} * V \tag{3}$$

$$\frac{dM}{dt} = V\frac{dC}{dt} + C\frac{dV}{dt} \tag{4}$$

Substitute $-Q_{out}$ for dV/dt

$$\frac{dM}{dt} = V\frac{dC}{dt} - C * Q_{out} \tag{5}$$

Set equation 5 and equation 3 equal

$$\cancel{-Q_{out} * C_{out}} + K_1 * C_{out} * \cancel{V} = \cancel{V}\frac{dC}{dt} \cancel{- C * Q_{out}} \tag{6}$$

Effluent and volumes cancel out and we are left with

$$\frac{dC}{dt} = K_1 * C_{out} \tag{7}$$

Integrate

$$\int_{C_0}^{C} \frac{dC}{C_{out}} = \int_{0}^{t} K_1 * dt \tag{8}$$

$$\ln(C) - \ln(C_0) = K_1 * t \tag{9}$$

Final model

$$\boldsymbol{C = C_0 * e^{K_1 * t}} \tag{9}$$

# Appendix II-B

Zero order Model Derivation

Assume completely mixed
Assume no outflow at t=0
Column full at t=0

$$\frac{dM}{dt} = \cancel{Q_{in} * C_{in}} - Q_{out} * C_{out} - r * V \tag{1}$$

No inflow
Assume zero order decay

$$-r = K_0 \tag{2}$$

$$\frac{dM}{dt} = -Q_{out} * C_{out} + K_0 * V \tag{3}$$

$$\frac{dM}{dt} = V\frac{dC}{dt} + C\frac{dV}{dt} \tag{4}$$

Substitute $-Q_{out}$ for dV/dt

$$\frac{dM}{dt} = V\frac{dC}{dt} - C * Q_{out} \tag{5}$$

Set equation 5 and equation 3 equal

$$\cancel{-Q_{out} * C_{out}} + K_0 * \cancel{V} = \cancel{V}\frac{dC}{dt} \cancel{- C * Q_{out}} \tag{6}$$

Effluent and volumes cancel out and we are left with

$$\frac{dC}{dt} = K_0 \tag{7}$$

Integrate

$$\int_{C_0}^{C} dC = \int_{0}^{t} K_0 * dt \tag{8}$$

$$C - C_0 = K_0 * t \tag{9}$$

Final model

$$\boldsymbol{C = C_0 + K_0 * t} \tag{10}$$

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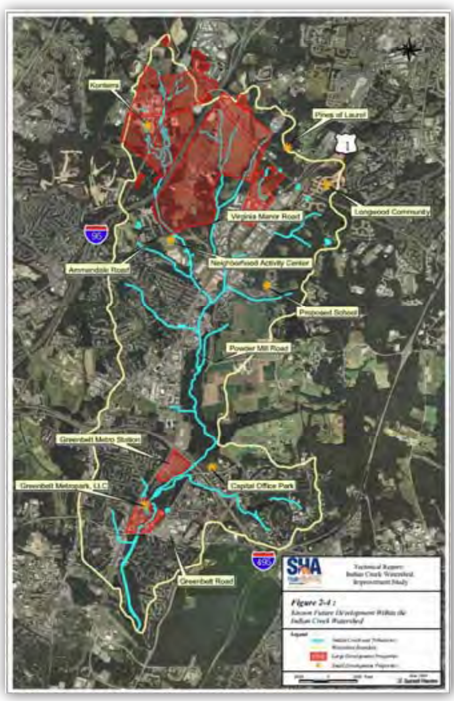
# APPENDIX D

## GREEN HIGHWAY PARTNERSHIP FACTSHEET

## WHAT ARE GREEN HIGHWAYS?

Under the GHP, green highways are not defined by a list of requirements. Green highways are defined by an effort to go "beyond compliance" and leave the project area "better than before" through community partnering, environmental stewardship, and transportation network improvements in safety and functionality. What this means differs from project to project, and location to location. Therefore, the Green Highways Partnership discusses characteristics of a green highway that will integrate transportation functionality and ecological sustainability.




Indian Creek Watershed Improvement Study sponsored by Maryland State Highway Administration.

## INTRODUCTION

Transportation systems in the United States provide valuable opportunities for mobility, commerce and recreation. Various transportation activities such as roadway construction and maintenance, vehicle travel, and vehicle maintenance, can result in water quality and quantity impacts including flooding and erosion, increased concentrations of heavy metals, salts, oil and grease, nutrients and suspended solids. (EPA, 1996, Granato, 2003)

Transportation planning is undergoing significant changes due in part to a growing awareness in the scientific and government communities of the need for more integrated ecosystem approaches and transportation regulation that requires more ecologically sensitive transportation planning and design. (Venner, September 2005)

Applying stormwater management techniques to address water quality and water quantity concerns is now common practice in highway projects. Best Management Practices (BMP) are typically designed to meet regulatory requirements, and are focused on treating and managing runoff within the rights-of-way (ROW) of highways. Whereas, the GHP approach focuses on activities beyond the right-of-way and within the watershed for better-than-before results.

**The Green Highways Watershed Approach** to stormwater management, recognizes that highways coexist with other land uses within watersheds, and a collaborative approach provides an opportunity for highway agencies to plan and deliver the most cost-effective protection, even improvement, to watersheds. To aid in watershed recovery, address watershed impairments, and to be prepared to address future potential water quality standard requirements, designers must begin thinking outside of the right-of-way. The following principals outline the framework for the GHP Watershed Approach to Stormwater Management for Transportation Projects.

### GHP WATERSHED APPROACH PRINCIPLES:

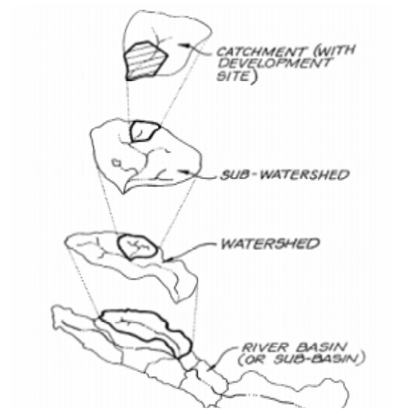
1. Views regulatory compliance as a minimum requirement for acceptance.
2. Requires a stormwater management plan considering watershed-wide needs, that is based on collaborative watershed improvement goals and plans, and developed in collaboration with local governments and resource agencies.
3. Focuses on achieving good environmental results for the watershed in a cost-effective manner, not just meeting regulatory requirements by using traditional, end-of-pipe approaches.
4. Integrates stormwater plans into project development and project features.
5. Uses collaborative partnerships to leverage and deliver a combination of watershed improvements to cohesively and consciously produce tangible results.
6. A coordinated mitigation/enhancement strategy is important – coordination with other projects in the watershed is necessary.

## KEYS TO ACHIEVING THE GHP WATERSHED APPROACH

1. DOT should form partnerships with others, such as local governments, resource agencies and private groups in areas of planned major projects to combine resources to improve watersheds.
2. Develop a watershed improvement plan that reflects a consensus between resource agencies and local governments and which includes other data/efforts such as watershed management and green infrastructure plans, tributary strategies, watershed restoration action strategies, 303(d) lists, TMDLs, and Biological Stream Surveys.
3. Watershed improvement plans should include a menu of environmental enhancement projects with cost estimates, environmental benefits, restoration goals, constraints/feasibility, and relative priority.
4. Coordinating local government and private funding for mitigation and watershed improvement purposes are key to achieving cumulative and coordinated watershed benefits.
5. Use a combination of conventional (structural and non-structural) and new BMPs to fit the watershed needs, sustainability goals, and the context of their surroundings.
6. Coordination with other projects–DOT or other–is important to get a coordinated mitigation/enhancement strategy.

## WHAT IS A WATERSHED?

A land area that drains to a common body of water such as a lake, river, bay, or ocean. Watersheds supply drinking water, provide recreation and respite, and sustain life. A watershed is a natural asset that should be managed accordingly.




The Watershed Management Units (Clemens, et al., 1996, Center for Watershed Protection, Article 28, Basic Concepts in Watershed Planning

| Watershed Management Unit | Typical Area (square miles) |
|---|---|
| Catchment | 0.05 to 0.50 |
| Subwatershed | 1 to 10 |
| Watershed | 10 to 100 |
| Subbasin | 100 to 1,000 |
| Basin | 1,000 to 10,000 |

## A WATERSHED APPROACH:

Is hydrologically defined
- Geographically focused
- Includes all stressors (air, land and water)

Involves all stakeholders
- Includes public (federal, state, local) and private sector
- Is community based
- Includes a coordinating framework

Strategically addresses priority water resource goals (water quality, habitat)
- Integrates multiple programs (regulatory and voluntary)
- Based on sound science
- Aided by strategic watershed plans
- Uses adaptive management

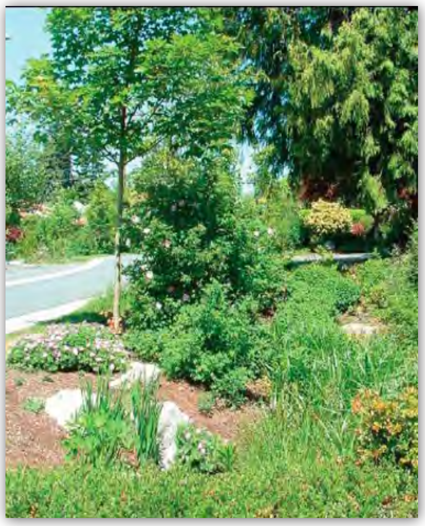
## Green Highway Watershed-Based Stormwater Management Benefits

The GHP process advocates an ecosystem, watershed-based approach for all phases of project development including planning, design, construction, and maintenance. Some key features and benefits are highlighted below:

| GHP Process | Process Highlights | Benefits |
|---|---|---|
| Planning | Integration of Watershed Management, Wildlife Management, and green infrastructure plans Land Use, into the transportation planning process. | Saves time and money and increases public support<br>Support a collaborative vision<br>Provides for predictability and conservation on larger scales |
| Project Development & NEPA Review<br><br>Design and Construction<br><br>LID/ESD for Linear Facilities and Watersheds | • Stormwater management plans should be integral part of project development and NEPA studies.<br>• Watershed needs should be the focus of stormwater management plans, not just on-site regulatory compliance.<br>• Project's minimum responsibilities should be established based on regulatory compliance and a plan should consist of a combination of on-site and watershed-wide stormwater management opportunities, including banking and trading.<br>• Both in-kind and out of kind BMPs should be in the plan, to obtain the best environmental result in a cost-effective manner.<br>• Combine use of natural LID facilities with non-structural and structural BMPs to enhance infiltration and evapotranspiration and reduce runoff and pollutant loads to water resources throughout the watershed.<br><br>Examples include but are not limited to:<br>• Bioretention<br>• Porous pavement<br>• Soil amendments,<br>• Forrest buffers<br>• Infiltration trenches<br>• Stream and wetlands restoration | Protects Watershed<br><br>Combinations of on-site and off-site structural and non-structural & low impact development best management practices will enable restoration of pre-existing hydrologic patterns and reduce pollutant loadings<br><br>Low Impact Development practices (LID) out perform conventional Best Management Practices (BMP's) for reductions of runoff and treatment of pollutants<br><br>Promotes real time innovation<br><br>Improves quality of decisions<br><br>Opportunity to minimize disruption of natural resources and hydrology<br><br>Allow for more efficient and effective use of resources |
| Monitoring and Maintenance<br><br>Pollution Prevention | • Maximize the use of native species in highway and roadway planting to reduce the need for irrigation and maintenance.<br>• Incorporate integrated pest management control to minimize need and use of fertilizers and pesticides.<br>• Monitor select pilot project and assess effectiveness | Reduces Resource Use<br><br>Improves overall performance<br><br>Extends performance and value |

Abbreviations: LID- Low Impact Development; BMP- Best Management Practice; NEPA - National Environmental Protection Act

## RELATIONSHIP BETWEEN THE GHP WATERSHED APPROACH AND GREEN INFRASTRUCTURE (GI)



The EPA's Office of Water defines green infrastructure as essentially encouraging infiltration, evapotranspiration or reuse of stormwater, with significant utilization of soils and vegetation rather than traditional hardscape collection, conveyance and storage structures. GI consists of an interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions, sustains clean air and water, and provides a wide array of benefits to people and nature. It Incorporates principles of: landscape ecology, conservation biology, restoration ecology, and watershed management.

Common green infrastructure approaches include green roofs, trees and tree boxes, rain gardens, vegetated swales, pocket wetlands, infiltration planters, vegetated median strips, reforestation, and protection and enhancement of riparian buffers and floodplains.

The GHP approach utilizes GI in the design and implementation of stormwater BMP's along with watershed restoration and protection, including ecosystem management.

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For more detail visit
www.greenhighways.org
www.dot.gov/perfacc2006/environstew.htm

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Permit Term October 2005 to October 2010

# APPENDIX E

## ASSESSMENT OF STREAM RESTORATION PROJECTS IN MARYLAND (JULY 2014)

# Assessment of Stream Restoration Projects in Maryland

# *2013-2014 Report*

**Prepared for:**

**Maryland Department of Transportation**
**State Highway Administration**
**Highway Hydraulics Division**
**707 North Calvert Street**
**Baltimore, MD 21202**

**Prepared by:**


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**July 2014**

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## Introduction

The Maryland Department of Transportation, State Highway Administration (SHA) receives state and federal funding for assessment of stream restoration projects in Maryland. SHA requires scientific support (primarily biological) to assess and/or to monitor a selected set of stream restoration projects already completed, or projected to be done in the future, by the administration. Information collected from these studies, undertaken by the Appalachian Laboratory of the University of Maryland Center for Environmental Science, provides a framework and historical database of recommendations for future SHA stream restoration projects, and for assessment and potential revitalization of existing SHA restoration projects throughout Maryland.

## Rationale

Stream restoration is of critical importance to the State of Maryland, as well as to the entire Chesapeake Bay watershed. The overall quality of life, now and in the future, is highly dependent on aquatic ecosystem integrity for both the quantity and quality of freshwater (Simon 1999). The integrity of surface water resources is dependent on chemical variables, flow regimes, biotic factors, energy sources, and habitat structure (Karr et al. 1986). Over the last quarter century, numerous surveys of fish and benthic communities assessed freshwater ecosystem health (Simon 1999). Significant advances in this arena led to the development of integrative ecological indices, such as Indices of Biotic Integrity (IBIs), which relate fish communities to both biotic and abiotic ecosystem components (Karr 1981, Karr et al. 1986). Coupled with chemical-physical water quality attributes, habitat quality (and often quantity) is important to consider when examining fish and benthic communities, especially for any and all derived IBIs (Yoder and Smith 1999).

Stream restoration strongly focuses on revitalization of the physical habitat. However, indices of habitat quality to assess post-restoration processes have lagged behind both fish and benthic IBI development. In part, this is because of the difficulty in developing accurate, precise and complete methodologies to assess quantitatively and qualitatively habitat characteristics (Platts 1976, Platts et al. 1983). The impetus for including stream habitat as an important measure came initially from western restoration activities (reviewed in Platts et al. 1983). For example, Binns (1979) developed a Habitat Quality Index for trout streams, soon to be followed by both Habitat Evaluation Procedures models (HEP) and Habitat Suitability Index models (HSI) for use with the U. S. Fish and Wildlife Service in-stream flow models. Important improvements in more generalized habitat models came with the development of EPA's Rapid Bioassessment Protocols (Plafkin et al. 1989) and the Ohio EPA's Qualitative Habitat Evaluation (Rankin 1989).

Wallace (1990) points out that there are a number of factors to consider in looking at stream recovery, especially in light of recent restoration attempts for lotic systems. Recolonization of a disturbed or restored area is a function of many factors, often depending on stream size. Implicit in restoration is that long-term stream physical stability eventually recovers. However, benthic macroinvertebrates respond to many disturbances, and restoration processes directed towards only the physical habitat may not take into account other critical stressors present in the watershed. The importance of nearby biotic refugia, as a source for recolonization is also critical (Wallace 1990), especially upstream refugia and, to a degree, the presence of either downstream or nearby lateral watershed refugia.

Hall et al. (1999, 2002) initially developed a Physical Habitat Index for Maryland using data collected from the first round of the Maryland Biological Stream Survey (MBSS), soon followed by the development of a revised Physical Habitat Index for Maryland (Paul et al. 2002). Coupled with the development of fish IBIs (Roth et al. 1998) and benthic IBIs (Stribling et al. 1998) from the MBSS data set, powerful analytical tools are now available to assess stream integrity in Maryland, and to examine restoration efficiency. These biotic indices were robust, and allowed inferences on stream integrity and stability, either regionally, statewide, or at site-specific levels. In addition, these indices were even more refined with additional MBSS rounds completed, especially with the development of coldwater fish IBIs and a finer level of benthic IBIs (Southerland et al. 2005, 2007).

Functional rehabilitation of degraded streams is critical, since streams may provide multiple environmental benefits, as well as critical ecological services (Morris and Moses 1999, National Research Council 1992). Functional rehabilitation is the major key to stream restoration since a return to pre-colonization stream status is impossible, especially in Maryland, where complex patterns of land use evolved since pre-colonial days. However, analytical evaluation of stream restoration or enhancement projects is often lacking. Monitoring these projects often serves as an important "first step" in evaluating effectiveness, and is essential to adaptive resource management (Bash and Ryan 2002). Downs and Kondolf (2002) and Morgan (2005) noted that post-project appraisals, or evaluations of restoration effectiveness, are critical to assess both short-term and long-term performance attainment of stream restoration projects. Often, this critical step is lacking in most restoration projects (Downs and Kondolf 2002). SHA project analyses completed from 1998 to 2010 for SHA were discussed in Morgan et al. (2010). In this report, eight recommendations for the assessment improvement of SHA stream restoration projects were described.

## Project Objective

The overall project objective is to assess and monitor completed and proposed SHA stream restoration projects and to make recommendations for future restoration projects, as well as for the improvement and revitalization of current restoration projects. In addition, a monitoring schedule for examining all completed stream restoration projects in the long-term (5, 10, and 25 years) was developed based on results for each SHA stream restoration site, and is in constant refinement with new sites added, and old sites revisited.

# Materials and Methods

### Site Locations

Site details for each SHA restoration location are described in the results and discussion section, with benthic macroinvertebrate data summaries found in Appendix A. Control sites are often very difficult to find in highly developed urban watersheds or in headwater streams. We always attempted to find control sites upstream of pre-restoration or post-restoration sites; however, many of these restoration sites were in the extreme upper part of a watershed and did not reflect the restoration area, or there were changes in control sites during the study. To compensate for this problem, we employed data from all rounds of the MBSS for comparison to the restoration site. Normally, one would try to collect samples where the condition is present and where it is absent, with all other factors being the same (Green 1979). This approach determines an effect at a site relative to a control. However, there is so much anthropogenic activity in the landscape of the coastal plain and Piedmont, as well as other physiographic provinces of Maryland, that watersheds are strongly altered through time and space. It may be necessary at some sites to move downstream into the lower part of a watershed and then determine current conditions to assess the upstream site. However, this is not the desired approach.

### Benthic Macroinvertebrates

Assessment of benthic macroinvertebrates at each sampling site followed benthic macroinvertebrate protocols for MBSS sampling (Kazyak 1996, Stranko et al. 2010). At each pre-construction or post-construction project, two samples (~ 10-20 sweeps each with D-nets depending on stream size) were taken within the project boundary after site surveys (lower and middle sections, if possible). One sample was always collected near the lower (downstream boundary) of the project. The middle sample was collected approximately one-third to one-half of the distance from the upper upstream boundary of the project (benthic sampling was modified dependent on site characteristics). Two additional samples, serving as replicate controls, were collected upstream of the stream restoration project, assuming that the upstream area served as a suitable control area. If no suitable upstream control was present, one or two site samples were taken downstream. For any pre-construction sites, two benthic samples were taken within the proposed project boundaries, along with two controls from an upstream area (or downstream area) if possible. We identified a number of MBSS reference streams to provide baselines for benthic invertebrate quality for the project.

### Benthic Field Sampling Protocols

A series of D-net samples (a total of ~ 1-2 $m^2$) were taken at each sampling location (Kazyak 1996), with an emphasis on selecting riffle/run habitat. Benthic macroinvertebrate sampling was conducted in order to qualitatively describe the community composition and relative abundance in favorable habitats. All survey methods for benthic macroinvertebrates followed MBSS protocols (Kazyak 1996), with benthic samples, as often as possible, collected from stream riffle areas because this is typically the most productive habitat in stream ecosystems. When riffle habitat was not present, other habitats sampled in the following order of preference were: gravel/broken peat and/or clay lumps in run areas; snags/logs that create partial dams or are in run habitat; undercut banks and associated root mats in moving water; submerged aquatic vegetation and associated bottom substrate in moving water; and detritus/sand areas in moving water. In the field, samples were transferred to polyethylene bottles and preserved in denatured ethanol. These benthic samples were collected during the MBSS spring index period and during the MBSS fall index period (Kazyak 1996), weather conditions permitting.

### Benthic Laboratory Protocols

In the laboratory, samples were washed, picked, and organisms stored in 70% isopropyl alcohol. The first 300 organisms (to the nearest grid) were picked for identification to the lowest taxon possible (Plafkin et al. 1989), with the first 100 organisms separated for calculation of the MBSS BIBI. Only the 100 organism sample was used for calculations since the MBSS BIBI development was based on this sample number. If the sample contained less than 300 organisms, the sample was picked completely.

### Benthic Macroinvertebrate Statistical Protocols

A revised Maryland benthic index of biotic integrity (BIBI) was employed for this project (Southerland et al. 2005, 2007). The new BIBI was broken into Coastal Plain, Eastern Piedmont and Combined Highlands (Table 1). For any of the three MBSS strata, BIBI scores were determined by adding the threshold score for each metric, and then dividing by the number of metrics for each stratum. The BIBI collected at each station was compared to the control area as well as to MBSS reference stations in the vicinity of the SHA project. An IBI score range of 4.0 - 5.0 is rated as good, 3.0 - 3.9 is fair, 2.0 - 2.9 is poor, and 1.0 - 1.9 is very poor (Table 2).

### Physical Habitat Assessment

Stream physical habitat data is an essential component of any biological assessment program. Habitat data is normally used to assess trends in water quality and to investigate the influence of land use practices that may affect stream water quality. Habitat assessments, based on an earlier MBSS protocol (Kazyak 1996), were performed at all SHA sites in order to determine biological integrity and fishability. Although there are now revised physical habitat metrics for the MBSS (Paul et al. 2002), the Maryland physical habitat index (MPHI), developed by Hall et al. (1999, 2002) based on MBSS fish IBI data sets, was calculated and compared to control areas and to MBSS reference data in the vicinity of the SHA project. This approach was used to maintain consistency in the physical habitat index measurement over time, especially for those SHA sites being revisited since the earliest sites were initiated in Fall 1998 (Morgan et al. 2010).

A number of variables were assessed qualitatively at each site. These include the following: instream habitat, epifaunal substrate, velocity/depth diversity, pool/glide/eddy quality, riffle quality, channel alteration, bank stability, embeddedness, channel flow status, and shading (scores assigned for each metric). Observations of the surrounding area were used to evaluate aesthetic value (based on amounts of human refuse) and remoteness (based on ease of access and presence of human activity). The presence, or absence, of other stream habitat features (i.e., morphological characteristics, stream channelization, woody debris, and land uses visible from each site) was also recorded for each site. In the field, physical habitat assessments were integrated across controls and across the stream restoration area.

Physical habitat metrics with the best discriminatory power for SHA coastal plain sites were: instream habitat, velocity/depth diversity, pool/glide/eddy quality, embeddedness, maximum depth and aesthetic rating. The final index calculations for the coastal plain weighed all metrics equally except embeddedness, maximum depth, and aesthetics that were weighted ½. The final equation used for the coastal plain habitat index (CPPHI) was:

$$\text{CPPHI}= (\text{instream habitat} + \text{velocity/depth diversity} + \text{pool quality} \\ – \text{embeddedness}/10+ \text{maximum depth}/10+ \text{aesthetics}/2)/ 6.$$

Physical habitat metrics with the best discriminatory power for SHA non-coastal plain sites (primarily Piedmont) were: instream habitat, velocity/depth diversity, riffle/run quality, embeddedness, number of rootwads and aesthetic rating. All metrics were weighted equally except embeddedness (weighted ½) and aesthetics (weighted $^{1}/_{3}$). The final equation used for the non-coastal plain habitat index (NCPHI) was:

$$\text{NCPHI}= [\text{instream habitat} + \text{velocity/depth diversity} + \text{riffle/run quality} – \\ \text{embeddedness}/10 + 3(\text{number of rootwads}) + \text{aesthetics}/3]/ 6.$$

Each metric was calculated by site, and a statistically based algorithm was used to convert the physical habitat score to centiles (Hall et al. 1999, 2002). Physical habitat categories were defined as: good being > 72 (> 50$^{th}$ centile), fair 42-72 (30$^{th}$ to 50$^{th}$ centile), poor 12-42 (10$^{th}$ to 30$^{th}$ centile) and very poor < 12 (10$^{th}$ centile).

In addition, digital images were periodically taken for each site to document selected stream habitat features, and then forwarded to SHA. Selected site images from the field are embedded within the report, along with site maps generated through Google$^{TM}$earth.

| Table 1. MBSS BIBIs for Maryland by stratum and with metric scoring thresholds. | | | |
|---|---|---|---|
| **Stratum and Metric** | **Thresholds** | | |
| | **1** | **3** | **5** |
| **Coastal Plain (7)** | | | |
| Number of taxa | < 14 | 14-21 | ≥ 22 |
| Number of EPT taxa | < 2 | 2-4 | ≥ 5 |
| Number of Ephemeroptera taxa | < 1 | 1-1 | ≥ 2 |
| Percent intolerant to urban | < 10 | 10-27 | ≥ 28 |
| Percent Ephemeroptera | < 0.8 | 0.8-10.9 | ≥ 11 |
| Number of scraper taxa | < 1 | 1-1 | ≥ 2 |
| Percent climbers | < 0.9 | 0.9-7.9 | ≥ 8 |
| **Eastern Piedmont (6)** | | | |
| Number of taxa | < 15 | 15-24 | ≥ 25 |
| Number of EPT taxa | < 5 | 5-10 | ≥ 11 |
| Number of Ephemeroptera taxa | < 2 | 2-3 | ≥ 4 |
| Percent intolerant to urban | < 12 | 12-50 | ≥ 51 |
| Percent Chironomidae | > 63 | 4.7-63 | ≤ 4.6 |
| Percent clingers | < 31 | 31-73 | ≥ 74 |
| **Combined Highlands (8)** | | | |
| Number of taxa | < 15 | 15-23 | ≥ 24 |
| Number of EPT taxa | < 8 | 8-13 | ≥ 14 |
| Number of Ephemeroptera taxa | < 3 | 3-4 | ≥ 5 |
| Percent intolerant to urban | < 38 | 38-79 | ≥ 80 |
| Percent Tanytarsini | < 0.1 | 0.1-3.9 | ≥ 4 |
| Percent scrapers | < 3 | 3-12 | ≥ 13 |
| Percent swimmers | < 3 | 3-17 | ≥ 18 |
| Percent Diptera | > 50 | 27-49 | ≤ 26 |

| Table 2. Narrative descriptions of stream biological integrity associated with each of the BIBI (or FIBI) scores. | | |
|---|---|---|
| Good | BIBI score 4.0 - 5.0 | Comparable to reference streams considered to be minimally impacted. Fall within the upper 50% of reference site conditions. |
| Fair | BIBI score 3.0 - 3.9 | Comparable to reference conditions, but some aspects of biological integrity may not resemble the qualities of these minimally impacted streams. Fall within the lower portion of the range of reference sites. |
| Poor | BIBI score 2.0 - 2.9 | Significant deviation from reference conditions, with many aspects of biological integrity not resembling the qualities of these minimally impacted streams, indicating some degradation. |
| Very Poor | BIBI score 1.0 - 1.9 | Strong deviation from reference conditions, with most aspects of biological integrity not resembling the qualities of these minimally impacted streams, indicating severe degradation. |

## Results and Discussion

Each current SHA restoration project evaluated in 2013-2014 will be reviewed, discussed and synthesized into the context of regional Maryland values, as derived from the Maryland Biological Stream Survey (all rounds). Basic information collected at each site for FY14 is included in each site summary. In the past, summary lists of benthic invertebrates collected at each restoration site (all controls plus middle restoration and lower restoration samples) were included within each site discussion. These benthic taxa lists are now placed in Appendix A to reduce excessive tables within each section. Any cell within the benthic summary tables marked with an asterisk indicates fewer than 100 organisms were present in the sample for that site (for the 300 + samples, metric calculations were not done if less than 100 organisms were present in the sample).

**Little Paint Branch (LPB)**

**Site Description:** Little Paint Branch (LPB) is a third-order tributary to Paint Branch, located within the Potomac-Washington Metro Basin extending from Piscataway Creek in Prince George's County to the Little Monocacy River in Montgomery County. This SHA western Coastal Plain site was a pre-restoration site in 1998-99, and then designed a restoration effort in the 1999-2000, 2000-2001, 2001-2002, and 2002-2003 work. The control and SHA restoration sections were revisited in September 2013 and April 2014 (an eleven-year span between sample collections).

Overall, the streamside habitat of Little Paint Branch is very stable since a great deal of control in the lateral and upstream watershed is exerted through the Maryland-National Capital Park and Planning Commission, with numerous park facilities present. However, there is a major sewage line and a paved recreational trail paralleling the stream (eastside) throughout the control and restoration areas, as well as a road and parking lots on the west side of Little Paint Branch. There are a few small surface seeps present, especially during the spring period.

Of interest is the upstream control area. Between the present and 2003, there appears to have been some additional stream restoration efforts, obliterating the previous control site. Consequently, we selected two upstream control areas similar to those that were present in 1999.

**Site Coordinates:**

| Site coordinates for Little Paint Branch (Figure LPB 1). | | | |
|---|---|---|---|
| Station | Latitude (N) | Longitude (W) | Comments: |
| Middle | 39.036203 | -76.930532 | Middle restoration site. |
| Lower | 39.034963 | -76.930013 | Lower restoration site. |
| Alpha Control | 39.038520 | -76.930911 | Upstream control one |
| Beta Control | 39.039363 | -76.930859 | Upstream control two |

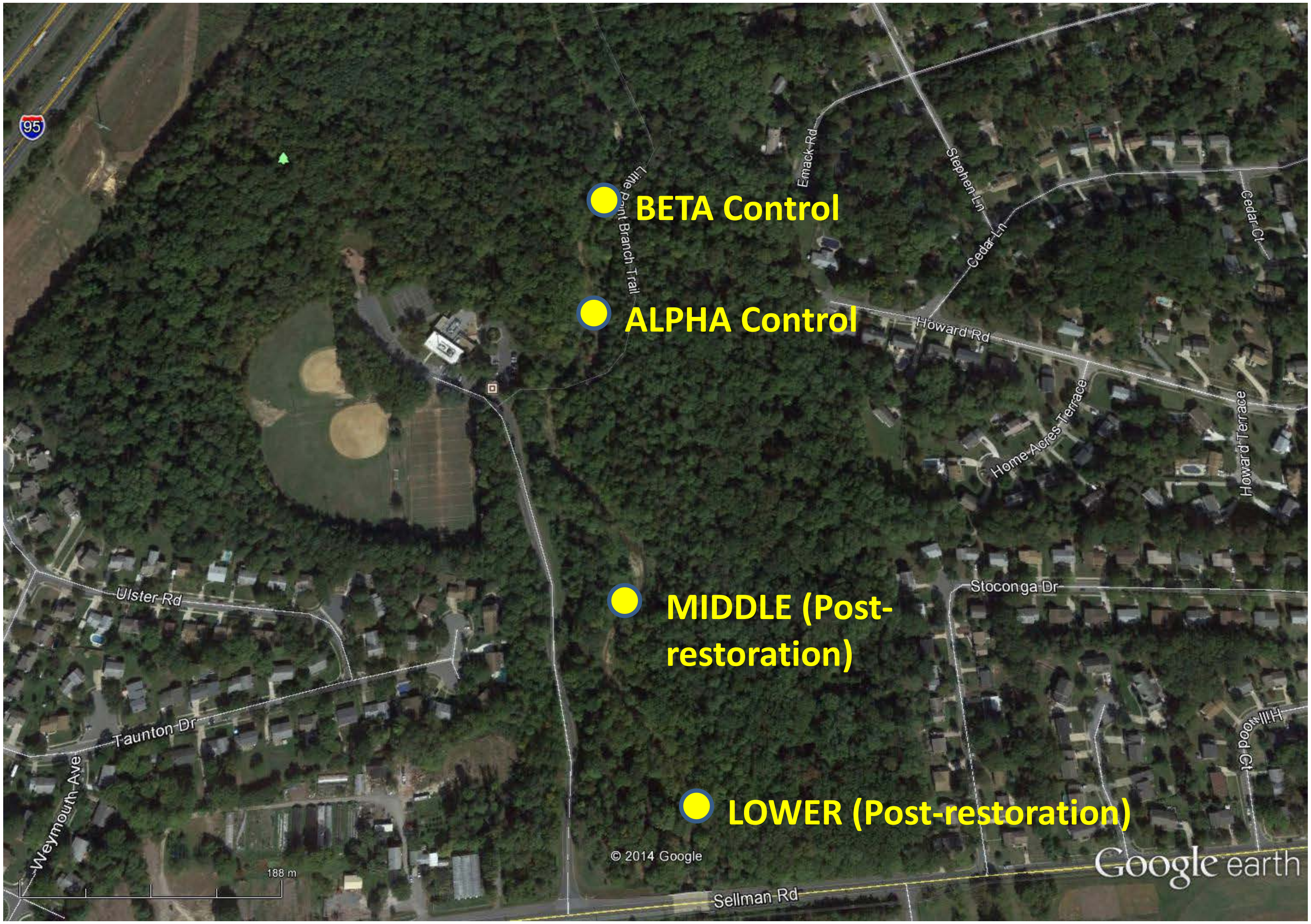


Figure LPB 1. Site locations for sampling of Little Paint Branch (Montgomery County).

**Fall 2013 Benthic Community (LPB) -** For those stations with a 100 + macroinvertebrate count, taxa richness was moderate at all stations while the number of EPT taxa was high at all sites (Table LPB 1). The number of ephemeropteran taxa was low at the Beta Control station and moderate at the remaining sites. The percent of macroinvertebrates intolerant of urban conditions was extremely low at all sites, while percent ephemeroptera in the sample was moderate at all sites. The number of scraper macroinvertebrates was moderate at the Middle Restoration site and high at the remaining sites. The percent of macroinvertebrate climbers was low at both restoration sites and moderate at the control stations.

Hydropsychidae larvae dominated the EPT collections at all sites, with baetid nymphs the dominant ephemeropteran collected. The ephemeropteran, *Baetis* sp., and the gastropod, *Ferrissa* sp., were the dominant macroinvertebrate climbers collected. The IBI ranged from 2.7 at the Middle Restoration site to 3.3 at the Alpha Control site.

For stations with a 300 + macroinvertebrate count, taxa richness and total EPT taxa were high at all the sites (Table LPB 2). The number of ephemeroptera taxa was moderate at all sites. The percent of macroinvertebrates intolerant of urban conditions was low at all sites while the percent of macroinvertebrate clingers was moderate at all sites. The number of scraper taxa was high at all sites while percent empheroptera and percent climbers was moderate at all the sites. Hydropsychidae larvae dominated the EPT collections. Baetid nymphs were the only ephemeropteran collected. The gastropod, *Feressia* sp., and the chironomid, *Micropsectra* sp., were the dominant climbers collected.

**Table LPB 1. Data summary of benthic macroinvertebrates collected in D-frame samples on 30 September 2013 at stations in Little Paint Branch.**

| Coastal Plain Metrics | Riffle Community (100 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Taxa Richness | 20 | 20 | 19 | 20 |
| Total EPT Taxa | 5 | 8 | 6 | 5 |
| Ephemeropteran taxa | 1 | 0 | 1 | 1 |
| % Intolerant Urban | 0% | 0.7% | 0% | 0% |
| % Ephemeroptera | 3.0 | 2.1% | 3.8% | 2.5% |
| No. Scraper Taxa | 2 | 5 | 2 | 1 |
| % Climbers | 1.6% | 3.5% | 0 | 0.8% |
| IBI | 3.3 | 3.0 | 3.0 | 2.7 |

**Table LPB 2. Data summary of benthic macroinvertebrates collected in D-frame samples on 30 September 2013 at four stations in Little Paint Branch.**

| Coastal Plain Metrics | Riffle Community (300 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Taxa Richness | 22 | 29 | 22 | 25 |
| Total EPT Taxa | 5 | 8 | 6 | 6 |
| Ephemeroptera taxa | 1 | 1 | 1 | 1 |
| % Intolerant Urban | 0% | 0.3% | 0% | 0% |
| % Ephemeroptera | 3.0% | 2.3% | 4.2% | 2.0% |
| No. Scraper Taxa | 3 | 7 | 4 | 4 |
| % Climbers | 2.7% | 2.6% | 0.9% | 1.2% |

**Spring 2014 Benthic Community (LPB) -** For all stations with a 100 + macroinvertebrate count, taxa richness, total EPT taxa, percent climbers, and number of scraper taxa were moderate to high at the Alpha Control and the two restoration sites (Table LPB 3). However, they were low at the Beta Control site. Ephemeroptera taxa, percent ephemeroptera and percent intolerant macroinvertebrates were low at all the stations. Hydropsychidae larvae dominated the EPT collections at all sites. Although few in number, two genera of chironomid larvae were the dominant climber taxa found in the samples. The IBI ranged from 1.0 at the Beta Control station to 2.7 at the Middle Restoration site.

For stations with a 300+ macroinvertebrate count, taxa richness and total EPT taxa, and number of scraper taxa were moderate to high at all the sites (Table LPB 4). The percent of climbers was low at the Beta Control site and moderate at the remaining sites. The number of ephemeroptera taxa, percent ephemeroptera and percent intolerant macroinvertebrates were low at all the stations. Hydropsychidae larvae dominated the EPT collections. The chironomid larvae, *Micropsectra* sp. and *Polypedilum* sp. were the dominant climbers collected. Abundance was low at the at all the sites. Although the samples were entirely picked, less than 300 macroinvertebrates were found.

Although taxa richness (11-29 taxa found in the 100 + and 300 + samples) is moderate in Little Paint Branch, there is a lack of EPT taxa and Ephemeroptera taxa, as well as very few intolerant urban species. In part, this is a function of the Coastal Plain benthic assemblage where EPT taxa are not found in great abundance. Also, recruitment from upstream, and potentially downstream, refugia may be slow. Below Sellman Road, Little Paint Branch in tightly constricted with little riparian buffer present. It may be an important to sample Little Paint Branch downstream of Sellman Road and further upstream into the headwaters of the Little Paint Branch watershed to assess the status of benthic populations.

**Table LPB 3. Data summary of benthic macroinvertebrates collected in D-frame samples on 4 April 2014 at stations in Little Paint Branch.**

| Coastal Plain Metrics | Riffle Community (100 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Taxa Richness | 15 | 11 | 17 | 16 |
| Total EPT Taxa | 3 | 1 | 4 | 5 |
| Ephemeroptera taxa | 0 | 0 | 0 | 0 |
| % Intolerant Urban | 0.0% | 0.0% | 1.1% | 1.0% |
| % Ephemeroptera | 0.0% | 0.0% | 0 | 0 |
| No. Scraper Taxa | 2 | 0 | 3 | 5 |
| % Climbers | 2.8% | 0.0% | 3.2% | 1.0% |
| IBI | 2.4 | 1.0 | 2.4 | 2.7 |

**Table LPB 4. Data summary of benthic macroinvertebrates collected in D-frame samples on 4 April 2014 at stations in Little Paint Branch.**

| Coastal Plain Metrics | Riffle Community (300 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Taxa Richness | 18* | 15* | 18* | 19* |
| Total EPT Taxa | 3* | 2* | 4* | 5* |
| Ephemeroptera taxa | 0* | 0* | 0* | 0* |
| % Intolerant Urban | 0.0%* | 0.0%* | 0.8%* | 0.7%* |
| % Ephemeroptera | 0.0%* | 0.0%* | 0.0%* | 0.0%* |
| No. Scraper Taxa | 2* | 1* | 3* | 5* |
| % Climbers | 2.4%* | 0.5%* | 1.6%* | 1.4%* |

**LPB Physical Habitat –** The entire stream restoration area from Sellman Road to the footbridge is stable and represents an excellent example of a good restoration project (Figure LPB 2). The only area where there appeared to be a problem was downstream of the footbridge crossing Little Paint Branch. Based on construction plans, the west bank has changed over time. Cross vanes, J-vanes, and instream boulders appear to be stable throughout the restoration area (Figure LPB-2a, 2b, and 2c). We observed that some exposed root wads are decaying over time, a factor that perhaps should be considered in future design planning (Figure LPB-2d).

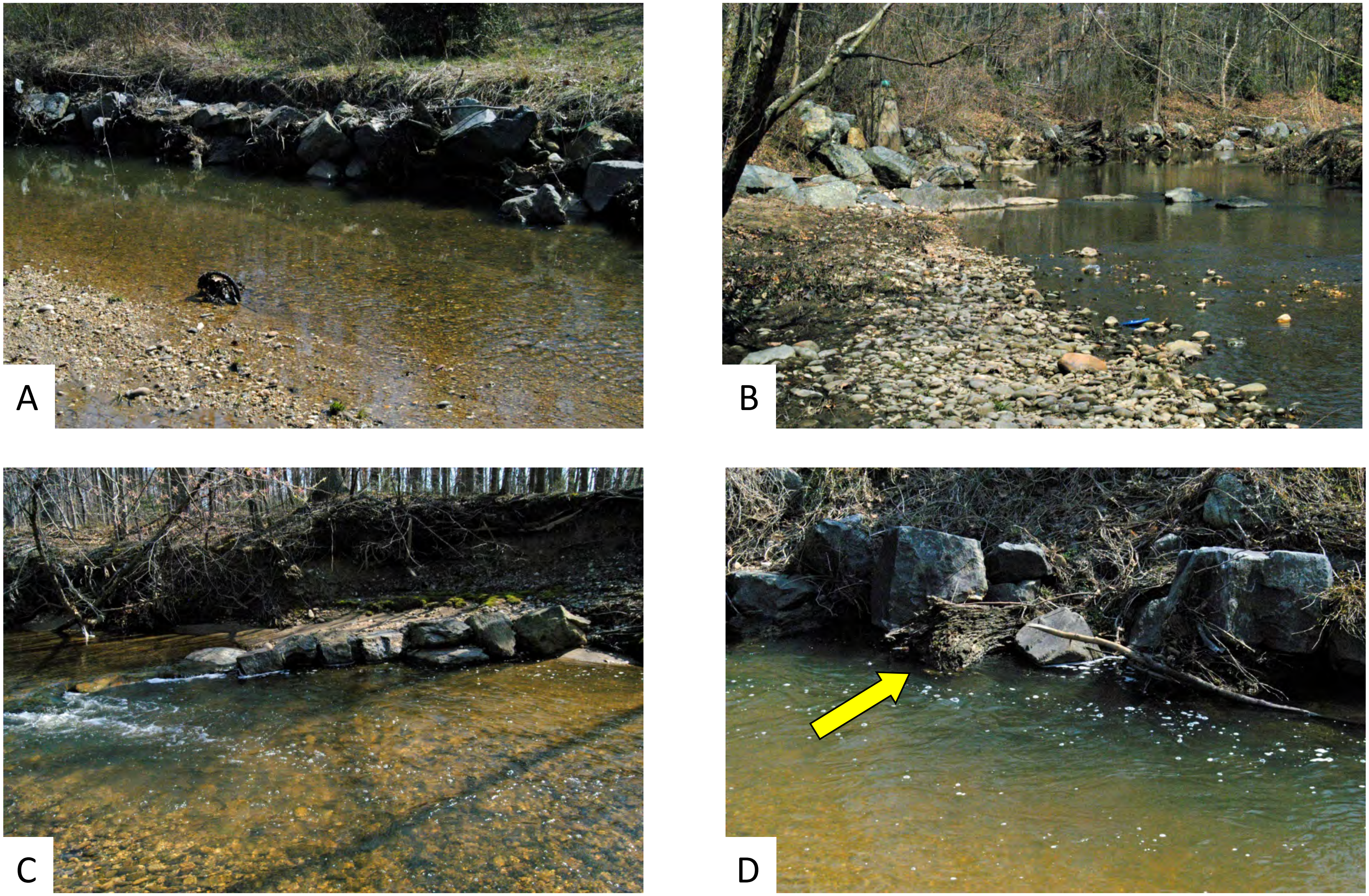


Figure LPB 2. Stream restoration structures in Little Paint Branch. A) stream bank stabilization and root wads along east side of LPB; B) upstream view of LPB near Middle Restoration site; C) cross vane – note depth of water and substrate; and D) close up of root wad showing some decomposition over time.

**Table LPB 5. Summary of average IBI values for benthic macroinvertebrates (BIBI) and physical habitat (MPHI) for Little Paint Branch, using 1999 – 2003 data and current 2013-2014 data (shaded).**

| Station | Fall BIBI | Spring BIBI | MPHI |
|---|---|---|---|
| Control Site (99-03) | 3.1 | 2.2 | 85.7 |
| Control Site (13-14) | 3.1 | 1.7 | 77.6 |
| Lower Restoration Site (99-03) | 3.0 | 2.1 | |
| Lower Restoration Site (13-14) | 3.3 | 2.4 | |
| Middle Restoration Site (99-03) | 3.3 | 2.2 | |
| Middle Restoration Site (13-14) | 3.0 | 2.7 | |
| Restoration Site MPHI (99-03) | | | 83.5 |
| Restoration Site MPHI (13-14) | | | 85.3 |

**Past versus Present –** Based on the work done from 1999 to 2003 and the current effort from 2013 to 2014, Little Paint Branch is stable (Table LPB 5). All fall BIBI values for both control sites and the two restoration sites vary little, indicating a strong stability in the benthic community. It is interesting to note that the spring BIBI values are significantly lower than the fall BIBI values, illustrating the importance of sampling during at least two of the recommended time periods for benthic organisms. The lower spring BIBI value may be function of winter conditions, with perhaps salt inputs from I-95 and an altered hydrograph from upstream impervious surface. The MPHI values are also in close agreement, again indicting stability in the physical habitat over time (Table LPB 5).

**<u>Recommendations:</u> Little Paint Branch serves as a 'poster child' for stream restoration activities in Maryland, especially in the western Coastal Plain. This site is well restored, since it appears that Little Paint Branch restoration site is reaching equilibrium, with additional stream restoration efforts upstream of the SHA project area. We recommend a ten-year monitoring for Little Paint Branch site in the future, extending the next survey to 2023-2024 (FY2024). There may be a need to assess physical habitat in five years to determine rootwad stability and upstream habitat.**

**Long Draught Branch (LDB)**

**Site Description:** Long Draught Branch is a small first order stream located in a very highly urbanized area of Montgomery Country that includes residential development, large and small office complexes, shopping centers and very large amounts of impervious surface due to parking lots, extensive road systems and numerous buildings (Figure LDB 1). A segment of Long Draught Run flows through a park area with a swimming pool and playground. Many of the parking areas adjacent to apartment units have direct flow pathways into the stream through rip-rapped drainage swales.

Throughout its stream course until it enters Clopper Lake, there are numerous storm drains discharging into the stream as well as drainage from parking lots and roads. There is also a major sewage line paralleling the stream throughout the proposed restoration area with a few surface seeps present.

**Site Coordinates:**

| Site coordinates for Long Draught Branch (Figure LDB 1). | | | |
|---|---|---|---|
| Station | Latitude (N) | Longitude (W) | Comments: |
| Middle | 39.142313 | -77.225865 | Projected middle restoration site. |
| Lower | 39.144377 | -77.228521 | Projected lower restoration site. |
| Alpha Control | 39.143820 | -77.222785 | Upstream control One |
| Beta Control | 39.143660 | -77.222066 | Upstream control Two |


Figure LDB 1. Site locations for sampling of Long Draught Branch (Montgomery County).

**Fall 2013 Benthic Community (LDB) -** For subsamples with a 100 + macroinvertebrate count, taxa richness was low at the Beta Control and moderate at remaining sites (Table LDB 1). Total EPT taxa, number of ephemeroptera taxa, and percent macroinvertebrates intolerant of urban conditions were low at all stations. The percent of chironomids was moderate at all stations. The percent of macroinvertebrate clingers was moderate at both control sites and low at both restoration sites. *Cheumatopsyche* sp. larvae dominated the EPT collection. When found, baetid nymphs dominated the ephemeropteran taxa. Hydropsychidae larvae were the dominant macroinvertebrate clinger collected. The IBI was 2.0 at the Alpha Control station and 1.7 for the remaining sites.

Although a heavily urbanized area, the number of taxa present in the stream was surprising (14-20 in the 100 + organism count). However, there were a high percentage of the organisms present as chironomids at all stations, with a high percent of clingers present. EPT taxa were low, reflecting poor water quality in Long Draught Branch, and variability in the flow regime due to impervious surface.

**Table LDB 1. Data summary of benthic macroinvertebrates collected in D-frame samples on 16 September 2013 at four stations in Long Draught Branch.**

| | Riffle Community (100 + subsample) | | | |
|---|---|---|---|---|
| **Metric** | **Alpha Control** | **Beta Control** | **Lower Restoration** | **Middle Restoration** |
| Taxa Richness | 15 | 14 | 20 | 17 |
| Total EPT Taxa | 1 | 1 | 2 | 2 |
| Ephemeroptera taxa | 0 | 0 | 1 | 1 |
| % Intolerant Urban | 0% | 0% | 1.1% | 0% |
| % Chironomidae | 30.1% | 20.4% | 34.7% | 42.8% |
| % Clingers | 51.5% | 37.2% | 21.1% | 26.4% |
| IBI | 2.0 | 1.7 | 1.7 | 1.7 |

For subsamples with a 300 + count, taxa richness was moderate at the control stations and high at the restoration stations (Table LDB 2). Total EPT taxa, number of ephemeroptera taxa, and percent of macroinvertebrates intolerant of urban conditions were low at all stations. The percent of chironomids was moderate at all stations. The percent of macroinvertebrate clingers was low at the Beta Control and Lower Restoration stations and moderate at Alpha Control and Middle Restoration sites. *Cheumatopsyche* sp. dominated the EPT taxa and was the dominant macroinvertebrate clinger collected. Baetid nymphs, when found, were the dominant ephemeropteran collected.

**Table LDB2. Data summary of benthic macroinvertebrates collected in D-frame samples on 16 September 2013 at stations in Long Draught Branch.**

| Metric | Riffle Community (300 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Taxa Richness | 20 | 15 | 25 | 25 |
| Total EPT Taxa | 1 | 1 | 4 | 2 |
| Ephemeroptera taxa | 0 | 0 | 2 | 1 |
| % Intolerant Urban | 0% | 0% | 3.3% | 0.3% |
| % Chironomidae | 27.5% | 20.4% | 35.4% | 43.2% |
| % Clingers | 52.1% | 30.0% | 17.2% | 37.7% |

**Spring 2014 Benthic Community (LDB) -** For subsamples with a 100 + macroinvertebrate count, EPT taxa, number of ephemeroptera taxa, percent intolerant macroinvertebrates, and percent clingers were low (Table LDB 3). Taxa richness and percent chironomids were low at the control stations and moderate at the restorations stations. *Cheumatopsyche* sp. dominated the EPT taxa and was the dominant macroinvertebrate clinger collected. The IBI value ranged from 1.0 at the control sites to 1.7 at the restoration sites (very poor). Abundance was low at the Middle Restoration site, resulting in less than 100 macroinvertebrates found.

**Table LDB 3. Data summary of benthic macroinvertebrates collected in D-frame samples on 4 April 2014 at stations in Long Draught Branch.**

| Metric | Riffle Community (100 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Taxa Richness | 8 | 10 | 17 | 17* |
| Total EPT Taxa | 0 | 1 | 1 | 1* |
| Ephemeroptera taxa | 0 | 0 | 0 | 0* |
| % Intolerant Urban | 0.0% | 0.0% | 0.0% | 0.0%* |
| % Chironomidae | 74.0% | 72.9% | 30.2% | 38.8%* |
| % Clingers | 0.0% | 4.2% | 2.4% | 28.4%* |
| IBI | 1.0 | 1.0 | 1.7 | 1.7 |

For subsamples with a 300 + count, all metrics at the control sites were low (Table LDB 4). When found, *Cheumatopsyche* sp. was the dominant EPT taxa and the dominant macroinvertebrate clinger as well. Abundance was low at the Alpha, Lower and Middle Restoration sites. Although the entire sample was picked, less than 300 macroinvertebrates were found.

**Table LDB 4. Data summary of benthic macroinvertebrates collected in D-frame samples on 4 April 2014 at stations in Long Draught Branch.**

| Metric | Riffle Community (300 + subsample) | | | |
|---|---|---|---|---|
| | **Alpha Control** | **Beta Control** | **Lower Restoration** | **Middle Restoration** |
| Taxa Richness | 11* | 14 | --- | --- |
| Total EPT Taxa | 0* | 1 | --- | --- |
| Ephemeroptera taxa | 0* | 0 | --- | --- |
| % Intolerant Urban | 0.0%* | 0.0% | --- | --- |
| % Chironomidae | 76.2%* | 76.3% | --- | --- |
| % Clingers | 0.0%* | 3.63% | --- | --- |
| IBI | 1.0 | 1.0 | --- | --- |

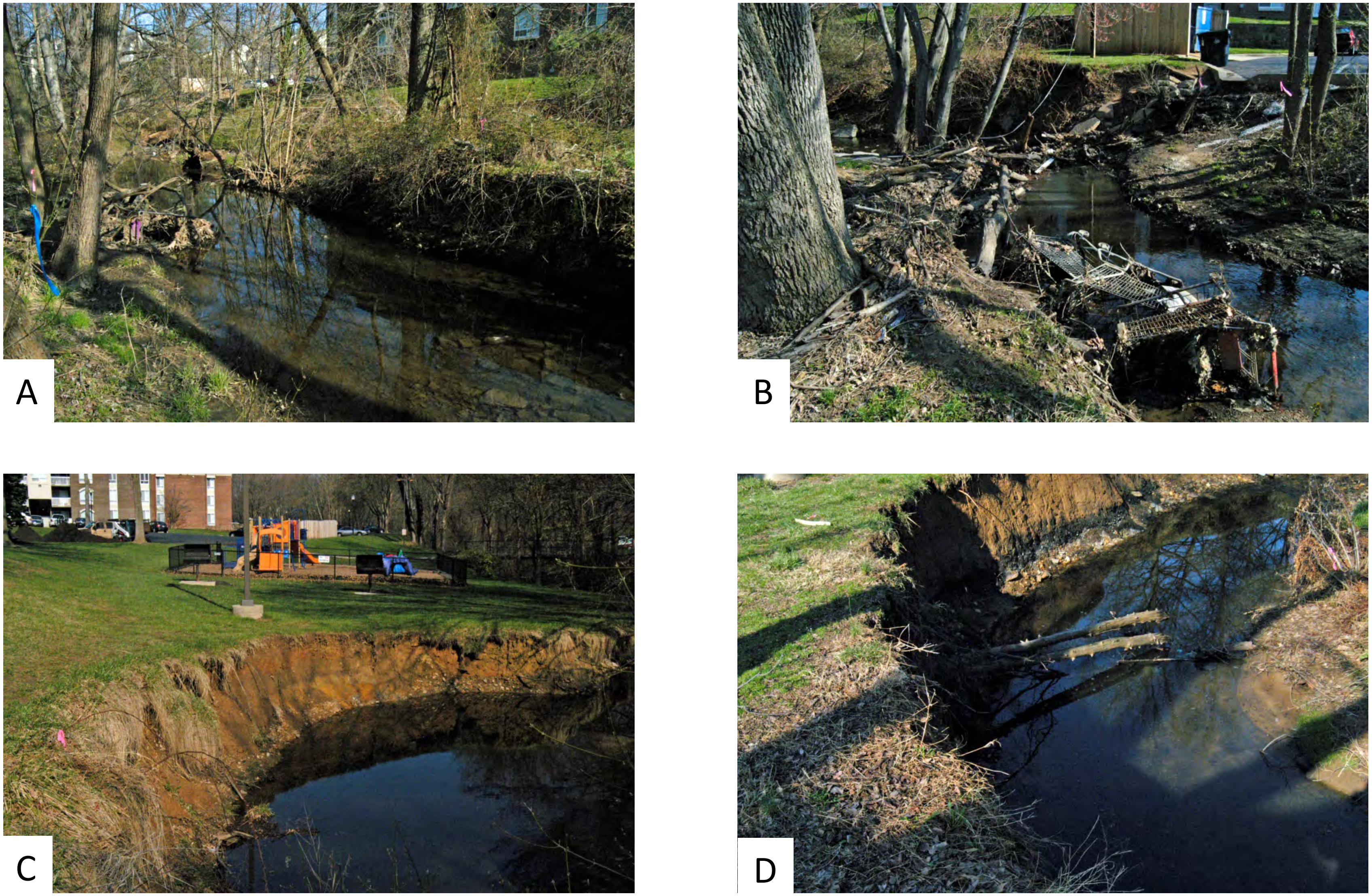


Figure LDB 2. Physical habitat of Long Draught Branch – A) typical bank structure along stream side; B) a world's record for the number of shopping carts in a 10-m stream segment; C) bank area near swimming pool and playground – this is a prominent feature along the grassy area of the site; and D) sediment deposition (~ 80-90 cm) over old streamside riparian vegetation.

**Physical Habitat:** Physical habitat in the control area was good, although there was a limited buffer width along the stream. Shading was good for most of the control area. However, there were three problems that we observed during all benthic sampling in the upper control region. First, there was a dam upstream of the control area that formed a small pond clogged with cattails (dam coordinates: 39°08’33.74”N; 77°13’10.95”W). During the summer, this shallow pond would create high temperature spikes downstream during storm events and may even create excessive stream temperatures during the summer without storm events. In addition, there were several outfalls from pavement discharging into the stream that would generate significant temperature spikes during summer rain events. Second, Long Draught Branch flowed underground through large culverts for a significant distance (an estimate of ~ 0.18 km). Third, the stream originated very close to I-270 and West Diamond Avenue from spring seeps in this area. Consequently, the upstream characteristics of Long Draught Branch affected both the control and the potential stream restoration area.

The stream area to be restored on Long Draught Branch was truly an urban mess (Figure LDB 2). There were numerous, large (~1 m high) undercut banks and large amounts of large urban debris, including shopping carts, bicycles, mattresses and springs. There was some shading along the stream, but the stream buffer was broken in most areas, with a fairly large expanse of grass in the park area. We also observed some whitish-brown effluent draining from a culvert into the stream, as well as some surface drainage problems from a stream sewer system very close to Long Draught Branch. The MPHI was 55.4 for the control area and 47.2 for the restoration area. Basically, the restoration area was a classic example of the effects of urbanization on physical habitat structure.

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**Assessment Recommendation: Long Draught Branch is a contentious pre-restoration site. Prior to the construction of any proposed stream stabilization projects, it should be resampled at least one more time, and then 2-4 years after the completion of construction.**

**Muddy Bridge Branch (MBB)**

**Site Description:** Muddy Bridge Branch is a small first order stream flowing into Sawmill Creek (Maryland western Coastal Plain). This stream is a post-restoration site adjacent to the Baltimore Washington International airport near Aviation Boulevard (Figure MBB 1) and I-97, and was last surveyed in 2002 (Morgan et al. 2010). The site is unique in that it is essentially hemmed in by large commercial buildings on both sides, with large parking areas. The control site is to the west of Aviation Boulevard, with the stream in this area being in close proximity to the BWI airport infrastructure. Consequently, the stream receives runoff from numerous parking areas and roadways frequently.

In the early studies, we noted that the stream banks in the restored area were in fair to good condition, although approximately 25 m of forested buffer was removed during the restoration process. In 2002, rootwads and woody debris were absent in the restoration site – these stream elements were found in the control reach. However, the vegetation along the restoration site regenerated substantially from 1998 to 2002 and should be providing the stream with adequate protection from erosion in the future (with an exception noted in the report). Because of the parent geology in the area, an orange flocculent material (presumably from glauconitic sandstones) is often present in the stream.

We did not conduct any surveys between Cromwell Bridge Road and I-97 in the earlier work, nor did we examine this stream section in the 2013-2014 work. Any future work should take into account this section and establish another sampling area close to I-97, and perhaps downstream of I-97 since there was some restoration activity in this area based on the project design.

**Site Coordinates:**

Site coordinates for Muddy Bridge Branch (Figure MBB 1).

| Station | Latitude (N) | Longitude (W) | Comments: |
|---|---|---|---|
| Middle | 39.175685 | -76.644208 | Middle restoration site. |
| Lower | 39.174986 | -76.641769 | Lower restoration site. |
| Alpha Control | 39.177064 | -76.649902 | Upstream control one |
| Beta Control | 39.177909 | -76.651161 | Upstream control two |

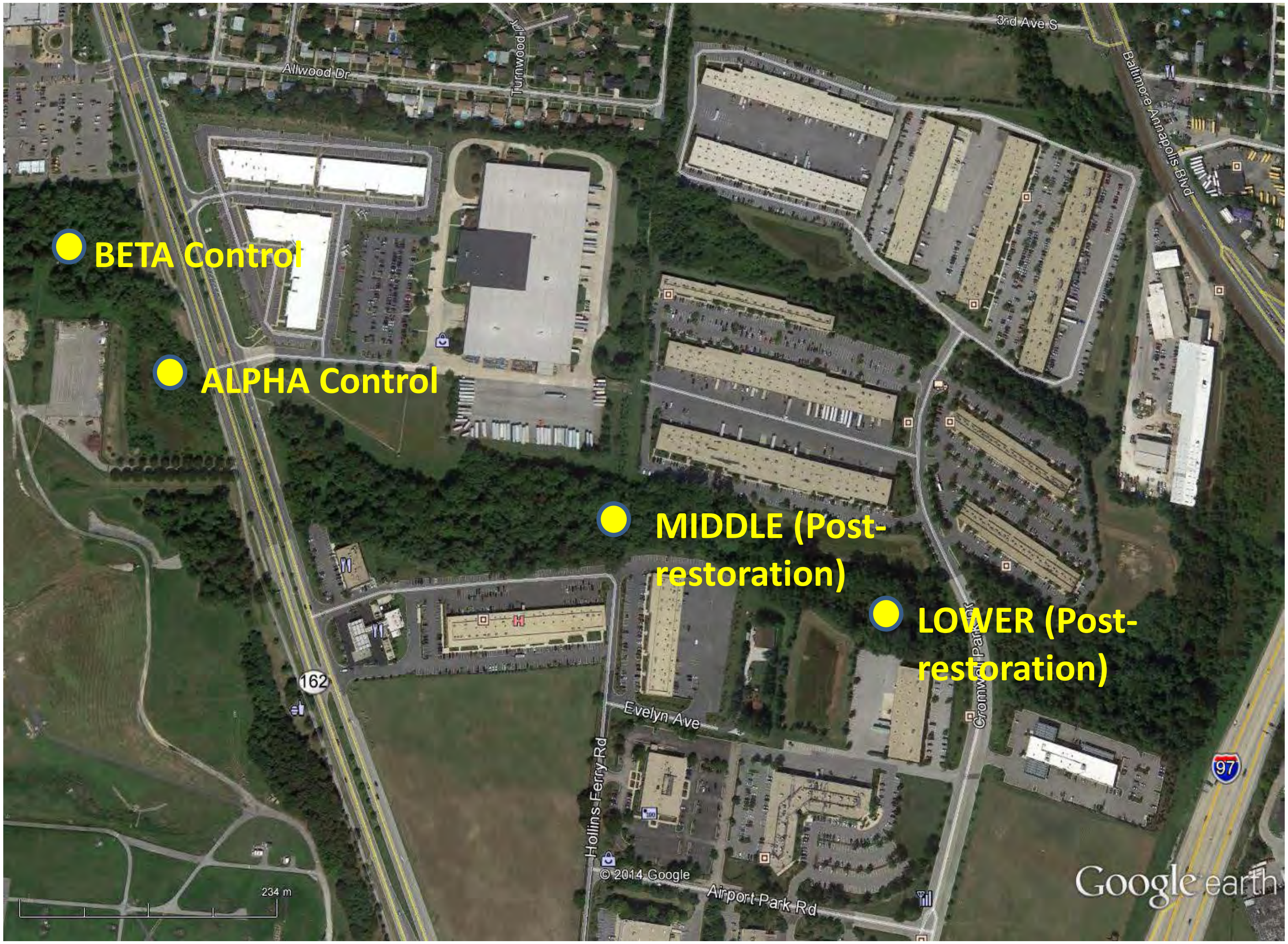


Figure MBB 1. Site locations for sampling of Muddy Bridge Branch (Anne Arundel County).

**Fall 2013 Benthic Community (MBB) –** At Muddy Bridge Branch, both the Alpha and Beta Control stations were not collected due to low flows upstream of the restoration area in September. For the lower and middle restoration subsamples with a 100 + macroinvertebrate count, taxa richness, and percent of macroinvertebrates intolerant of urban conditions were low (Table MBB 1). Total EPT taxa, number of ephemeroptera taxa, percent of ephemeropteran, and number of scraper taxa were moderate. The percent of macroinvertebrate climbers was high. *Cheumatopsyche* larvae dominated the EPT collection. Baetid nymphs dominated the ephemeroptera taxa, although the number of taxa were low (not unexpected in the western Coastal Plain). The chironomid larva, *Polypedilum* sp. was the dominant macroinvertebrate climber. The IBI was 2.7 (poor) for both restoration sites.

**Table MBB 1. Data summary of benthic macroinvertebrates collected in D-frame samples on 30 September 2013 at stations in Muddy Bridge Branch.**

| Metric | Riffle Community (100 + subsample) | |
|---|---|---|
| | Lower Restoration | Middle Restoration |
| Taxa Richness | 11 | 13 |
| Total EPT Taxa | 2 | 3 |
| Ephemeroptera taxa | 1 | 1 |
| % Intolerant Urban | 1.0% | 0.9% |
| % Ephemeroptera | 2.0% | 2.6% |
| No. Scraper Taxa | 1 | 1 |
| % Climbers | 21.4% | 22.6% |
| IBI | 2.7 | 2.7 |

For subsamples with a 300 + count, taxa richness, total EPT taxa, number of ephemeroptera taxa, and percent ephemeroptera were moderate at all stations (Table MBB 2). The number of macroinvertebrates intolerant of urban conditions was low at all sites. The number of scraper taxa and percent of macroinvertebrate climbers were high at both stations. *Cheumatopsyche* sp. dominated the EPT taxa. Baetid nymphs were the dominant ephemeropteran collected.

**Table MBB 2. Data summary of benthic macroinvertebrates collected in D-frame samples on 30 September 2013 at stations in Muddy Bridge Branch.**

| | Riffle Community (300 + subsample) | |
|---|---|---|
| **Coastal Plain Metrics** | **Lower Restoration** | **Middle Restoration** |
| Taxa Richness | 15 | 20 |
| Total EPT Taxa | 3 | 4 |
| Ephemeroptera taxa | 1 | 1 |
| % Intolerant Urban | 0.7% | 0.4% |
| % Ephemeroptera | 3.7% | 2.1% |
| No. Scraper Taxa | 2 | 2 |
| % Climbers | 32.8% | 18.6% |

**Spring 2014 Benthic Community (MBB) -** The Beta Control station was not collected due to low flows. The overall abundance of benthic organisms was very low at all stations. Although entire samples were picked, less than 100 macroinvertebrates were found. The percent of climbers was moderate at the control site and high at the restoration sites. All other metrics were low. No EPT macroinvertebrates were found. The only climber collected was the chironomid *Polypedilum* sp. The IBI was 1.3 for the control station and 1.6 for the two restoration sites.

**Table MBB 3. Data summary of benthic macroinvertebrates collected in D-frame samples on 4 April 2014 at stations in Muddy Bridge Branch.**

| | Riffle Community (100 + subsample) | | |
|---|---|---|---|
| **Coastal Plain Metrics** | **Alpha Control** | **Lower Restoration** | **Middle Restoration** |
| Taxa Richness | 8* | 4* | 8* |
| Total EPT Taxa | 0* | 0* | 0* |
| Ephemeroptera taxa | 0* | 0* | 0* |
| % Intolerant Urban | 0.0%* | 0.0%* | 0.0%* |
| % Ephemeroptera | 0.0%* | 0.0%* | 0.0%* |
| No. Scraper Taxa | 0* | 0* | 0* |
| % Climbers | 2.2%* | 14.3%* | 19.0%* |
| IBI | 1.3 | 1.6 | 1.6 |

**Table MBB 4. Summary of average IBI values for benthic macroinvertebrates (BIBI) and physical habitat (MPHI) for Muddy Bridge Branch, using 1999 – 2002 data and current 2013-2014 data (shaded). (NS = not sampled due to low flows).**

| Station | Fall BIBI | Spring BIBI | MPHI |
|---|---|---|---|
| Control Site (98-02) | 2.1 | 1.6 | 69.4 |
| Control Site (13-14) | NS | 1.3 | 44.4 |
| Lower Restoration Site (98-02) | 2.8 | 1.9 | |
| Lower Restoration Site (13-14) | 2.7 | 1.6 | |
| Middle Restoration Site (98-02) | 2.7 | 1.9 | |
| Middle Restoration Site (13-14) | 2.7 | 1.6 | |
| Restoration Site MPHI (98-02) | | | 73.7 |
| Restoration Site MPHI (13-14) | | | 86.0 |

Although still in the poor range for the BIBI, the restoration sites are on the high end of the poor BIBI range for the Fall samples (Table MBB 4). However, the Spring BIBI for all sites was low (1.3 – 1.9) - the very poor range for the BIBI. This pattern is becoming typical of many restoration sites where the Fall BIBI is always higher than the Spring BIBI (this pattern has also been observed in other non-SHA benthic studies conducted by the AL in central and western Maryland). The reasons for this dichotomy are unclear. However, many of the SHA restoration sites have a high percent impervious surface in their watersheds that may strongly influence the benthic community during winter and springtime flows. It appears that there is a rebound in the benthic community over the summer that is reflected in the higher Fall BIBI scores.

**Physical Habitat:** Physical habitat throughout the restored area was very stable, with an increase in the MPHI at the restoration site, with the control lower than in the previous studies (Table MBB 4). Throughout much of the restoration area, there was strong stability in the structures placed in the stream (Figure MBB 2). We verified these structural components using the design plans from SHA. There was a high degree of shading (> 50%) present throughout the restoration area, although there were some gaps in the streamside canopy. A number of exotic plants were present in both the control and restoration areas.

The most critical problem in Muddy Bridge Branch was irresponsible recreation. Some local idiot(s) created an ORV/ATV trail into the restoration area through a gap near Cromwell Bridge Road (Figure MBB 3a-d). There is now an extensive series of trails throughout the lower restoration section, with at least two crude bridges constructed to cross the stream. The idiots cut down streamside trees (Figure MBB 3d) to build the bridges. In addition, there was some human refuse present in this area – what a mess.

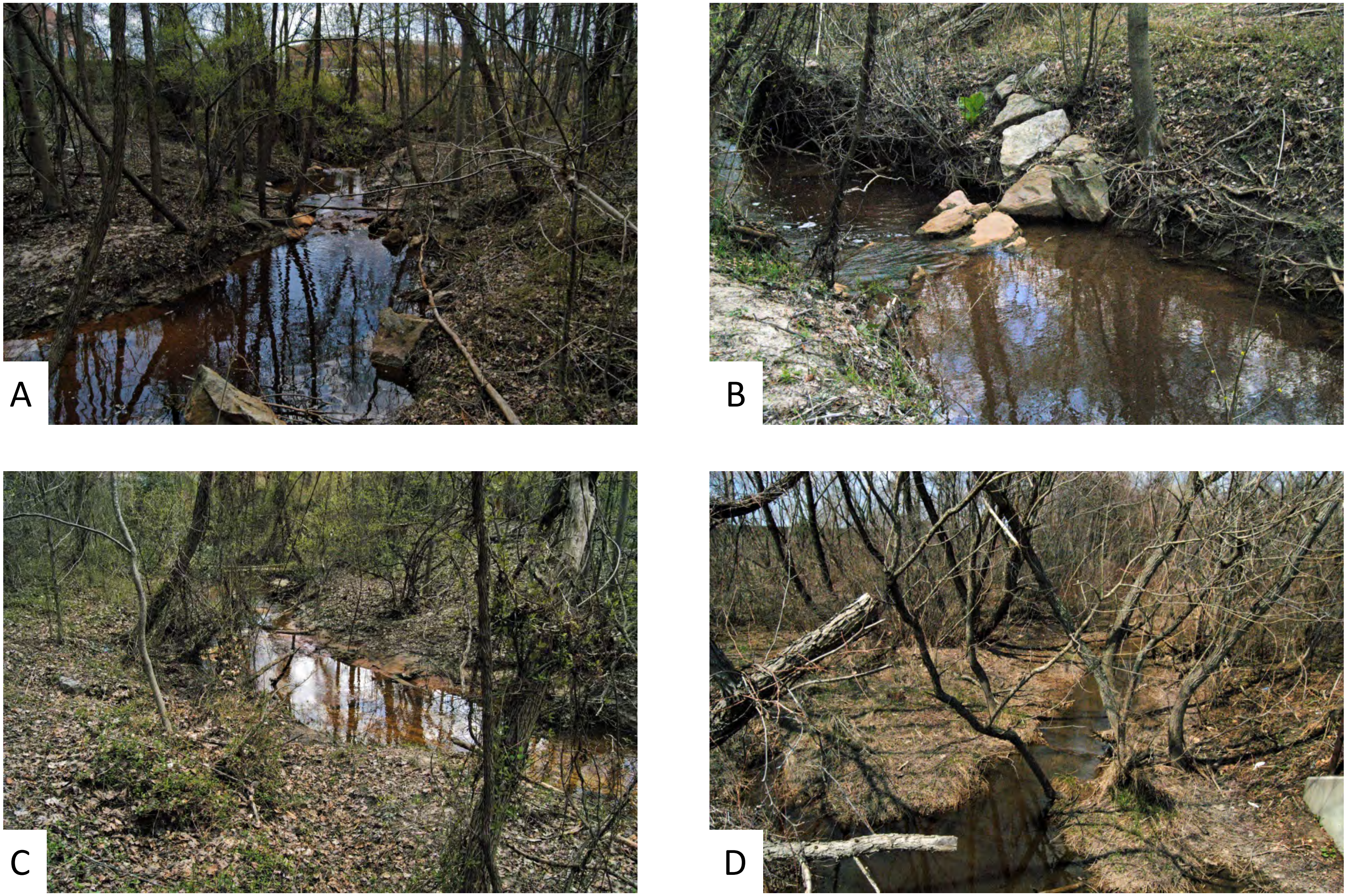


Figure MBB 2. Physical habitat of Muddy Bridge Branch – A) typical restored bank structure along stream side; B) stable vane structure; C) riparian vegetation along Muddy Bridge Branch; and D) control area above Route 162.

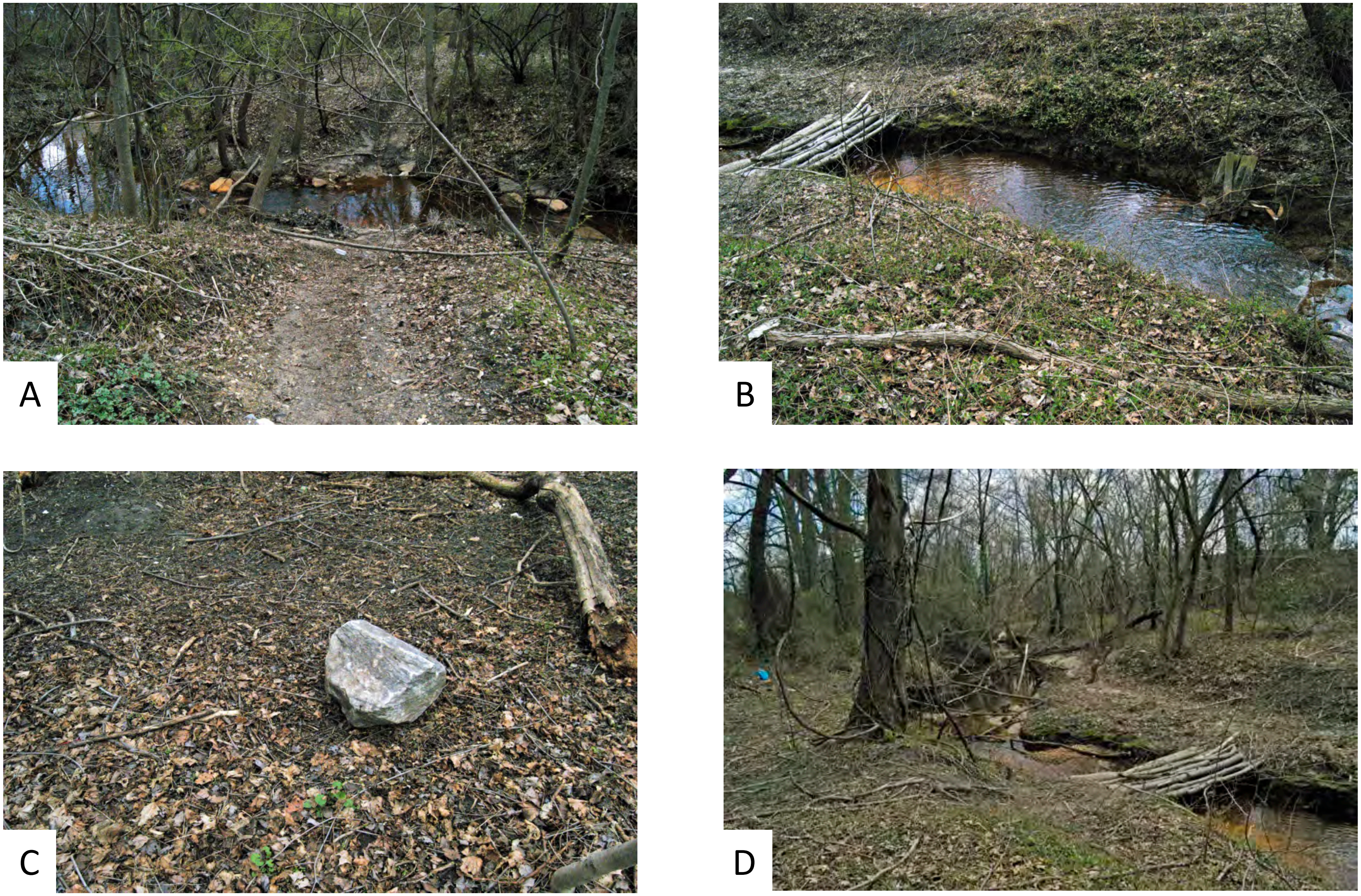


Figure MBB 3. Damaged physical habitat of Muddy Bridge Branch – A) ORV trail across stream; B) crude bridge using trees cut from riparian zone; C) boulder moved out of stream; and D) bridge area showing tree cutting and trampling of vegetation in riparian area.

**Recommendations:** **Based on the MPHI and BIBI scores, we consider this site to be restored, although there are now major threats to the stream from irresponsible recreational usage and general urbanization impacts. We recommend that this site be reevaluated on a ten-year cycle. It may be important to monitor land-use changes in this watershed since the site is located in an area of heavy development, although it appears that all available hectares are now developed. Future changes in landscape structure could continue to alter stream structure in Muddy Bridge Branch.**

**Piney Creek (PIC)**

**Site Description:** Piney Creek is a second order stream and is a tributary to the Gunpowder River, which flows into Loch Raven Reservoir and then into Chesapeake Bay (Figure PIC 1). Piney Creek is located within the eastern Piedmont province, and is adjacent to I-83, north of Baltimore. This site was listed previously as an outstanding example of a SHA stream restoration project (Morgan et al. 2010).

In the March 2012 sampling, it was difficult to locate the restoration area since typical stream restoration structures were not observed. Consequently, we started a stream reconnaissance downstream until it was obvious that the stream habitat was fairly natural, even though the stream ran very close to I-83. While working back upstream, we observed fabric material and bank slumping next to I-83 and the scattered remnants of most in-stream restoration structures. Essentially, the entire stream restoration area was destroyed by extremely high flows resulting from very heavy rain from Tropical Storm Lee, tracking along the eastern United States from September 1 – 11, 2011.

For the 2013-2014 work effort, Piney Creek was resampled on 23 September 2013 and 24 March 2014. Physical habitat was reassessed and numerous images were taken throughout the site (Figure PIC 1).

**Site Coordinates:**

| Site coordinates for Piney Creek (Figure PIC 1). | | | |
|---|---|---|---|
| Station | Latitude (N) | Longitude (W) | Comments: |
| Middle | 39.560444 | -76.664394 | Middle restoration site. |
| Lower | 39.558727 | -76.664268 | Lower restoration site. |
| Alpha Control | 39.561537 | -76.664668 | Upstream control one. |
| Beta Control | 39.562161 | -76.664848 | Upstream control two. |


Figure PIC 1.  Site locations for sampling of Piney Creek (Baltimore County).

**Fall 2013 Benthic Community (PIC):** For stations with a 100 + macroinvertebrate count, taxa richness was high at the Beta Control and moderate at the remaining sites (Table PIC 1). The number of EPT taxa was moderate at all sites, with the percent of macroinvertebrates intolerant of urban conditions low at all sites. The percent chironomids in the sample were moderate at all stations. The percent of clingers was highest at the Middle Restoration site and moderate at the three remaining sites. Hydropsychidae larvae and baetid nymphs dominated the EPT collections at all sites. Ephemeropteran taxa were surprisingly low, and may be a reflection of Tropical Storm Lee effects. Hydropsychid larvae were also the dominant macroinvertebrate clinger. The IBI ranged from 2.3 at the Lower Restoration site to 3.0 at the Middle Restoration site.

**Table PIC 1. Data summary of benthic macroinvertebrates collected in D-frame samples on 23 September 2013 at stations in Piney Creek.**

| | Riffle Community (100 + subsample) | | | |
|---|---|---|---|---|
| **Metric** | **Alpha Control** | **Beta Control** | **Lower Restoration** | **Middle Restoration** |
| Taxa Richness | 20 | 26 | 22 | 20 |
| Total EPT Taxa | 8 | 6 | 7 | 10 |
| Ephemeroptera taxa | 2 | 1 | 1 | 3 |
| % Intolerant Urban | 7.7% | 4.3% | 8.8% | 6.7% |
| % Chironomidae | 34.6% | 38.3% | 36.0% | 23.8% |
| % Clingers | 66.3% | 63.8% | 59.6% | 77.1% |
| IBI | 2.7 | 2.7 | 2.3 | 3.0 |

For stations with a 300 + macroinvertebrate count, taxa richness was high at all the sites (Table PIC 2). The number of EPT taxa was high at the control sites and moderate at the restoration sites. The number of ephemeroptera taxa was moderate at the Middle Restoration site and high at the remaining sites. The percent of macroinvertebrates intolerant of urban conditions was low at all sites. The percent of macroinvertebrate clingers was moderate at all sites. Hydropsychidae larvae and baetid nymphs dominated the EPT collections at all sites. Hydropsychid larvae were also the dominant macroinvertebrate clinger.

**Table PIC 2. Data summary of benthic macroinvertebrates collected in D-frame samples on 23 September 2013 at stations in Piney Creek.**

| | Riffle Community (300 + subsample) | | | |
|---|---|---|---|---|
| **Metric** | **Alpha Control** | **Beta Control** | **Lower Restoration** | **Middle Restoration** |
| Taxa Richness | 27 | 33 | 33 | 27 |
| Total EPT Taxa | 13 | 11 | 10 | 9 |
| Ephemeroptera taxa | 4 | 4 | 4 | 3 |
| % Intolerant Urban | 7.8% | 3.9% | 6.6% | 6.8% |
| % Chironomidae | 33.3% | 38.5% | 35.6% | 26.0% |
| % Clingers | 67.6% | 61.8% | 64.1% | 73.6% |

**Spring 2014 Benthic Community (PIC):** For stations with a 100 + macroinvertebrate count, taxa richness, number of EPT taxa, percent of intolerant macroinvertebrates, percent chironomids, and percent clingers were moderate at all the sites (Table PIC 3). The number of ephemeroptera taxa was low at the Alpha Control and Middle Restoration sites and moderate at the remaining sites. *Ephemerella* sp. nymphs dominated the EPT collections at all sites. Ephemerellid nymphs were also the dominant macroinvertebrate clinger. The IBI ranged from 2.7 at the Alpha Control and Middle Restoration sites to 3.0 at the remaining sites.

**Table PIC 3. Data summary of benthic macroinvertebrates collected in D-frame samples on 24 March 2014 at stations in Piney Creek.**

| Metric | Riffle Community (100 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Taxa Richness | 19 | 23 | 24 | 17 |
| Total EPT Taxa | 6 | 9 | 9 | 6 |
| Ephemeroptera taxa | 1 | 2 | 2 | 1 |
| % Intolerant Urban | 29.7% | 34.3% | 21.6% | 25.5% |
| % Chironomidae | 42.6% | 29.3% | 31.5% | 42.7% |
| % Clingers | 63.4% | 70.7% | 68.5% | 62.7% |
| IBI | 2.7 | 3.0 | 3.0 | 2.7 |

For stations with a 300 + macroinvertebrate count, taxa richness was high at all stations (Table PIC 4). The number of EPT taxa was high at the Beta Control and Lower Restoration sites and moderate at the remaining sites. The number of ephemeroptera taxa, and percent of intolerant macroinvertebrates, percent of chironomids in the collection, and percent of clingers were moderate at all the stations. Hydropsychidae larvae and ephemerellid nymphs dominated the EPT collections while ephemerellid nymphs were the dominant macroinvertebrate clinger.

**Table PIC 4. Data summary of benthic macroinvertebrates collected in D-frame samples on March 2014 at stations in Piney Creek.**

| Metric | Riffle Community (300+ subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Taxa Richness | 29 | 34 | 37 | 28 |
| Total EPT Taxa | 10 | 14 | 12 | 10 |
| Ephemeroptera taxa | 3 | 2 | 3 | 2 |
| % Intolerant Urban | 31.9% | 38.4% | 28.6% | 25.0% |
| % Chironomidae | 39.7% | 36.0% | 31.4% | 43.2% |
| % Clingers | 64.4% | 65.2% | 71.7% | 61.0% |

**Table PIC 5. Summary of average IBI values for benthic macroinvertebrates (BIBI) and physical habitat (MPHI) for Piney Creek, using 1999–2002 data and current 2013-2014 data (shaded). Piney Creek data collected in 2012 work was not included. Because of the size of the restoration area, only one site was done in the earlier work.**

| Station | Fall BIBI | Spring BIBI | MPHI |
|---|---|---|---|
| Control Site (02-03) | 3.9 | 4.1 | 73.0 |
| Control Site (13-14) | 2.7 | 2.9 | 73.0 |
| Middle Restoration Site (02-03) | 4.2 | 4.0 | |
| Middle Restoration Site (13-14) | 2.7 | 2.9 | |
| Restoration Site MPHI (02-03) | | | 74.1 |
| Restoration Site MPHI (13-14) | | | 50.4 |

Both the control site and the restoration site declined in BIBI values as compared to previous Piney Creek studies (Table PIC 5). Current BIBI values are now in the upper range of the poor category. In addition, the MPHI value for the restoration site declined significantly from the earlier set of studies, presumably a result of excessive rainfall affecting the restoration area.

**Physical Habitat:** At one time, this restoration site was listed as a great example of SHA stream restoration efforts (Morgan et al. 2010). However, Tropical Storm Lee essentially destroyed the entire restoration reach, with stream damage throughout the entire watershed. There was significant movement of stream bed material and bank slumping in the restored area, including downcutting of the stream bed (Figure PIC 2c). Of concern is the bank alteration next to I-83, where severe slumping (Figure PIC 2b) may present problems in the future for the highway. There is the potential for construction of an imbricated wall, as was done at the Piney Run site, throughout this stream segment. The stream channel now runs close to I-83 and another major rain event (tropical storm or hurricane) close to the magnitude of Tropical Storm Lee could potentially cause road collapse and consequent closure.

In addition, there was damage to most rock structures placed in the stream channel as seen in Figure PIC 2c, with the stream not in close contact to these structures anymore. We also observed the presence of a large culvert that funnels water from the west side of I-83 through to Piney Creek. During large storm events, this culvert would alter the normal stream hydrograph.

**Assessment Recommendation**: Site should be reassessed 3-5 years after any habitat remediation work on Piney Creek is completed by SHA.

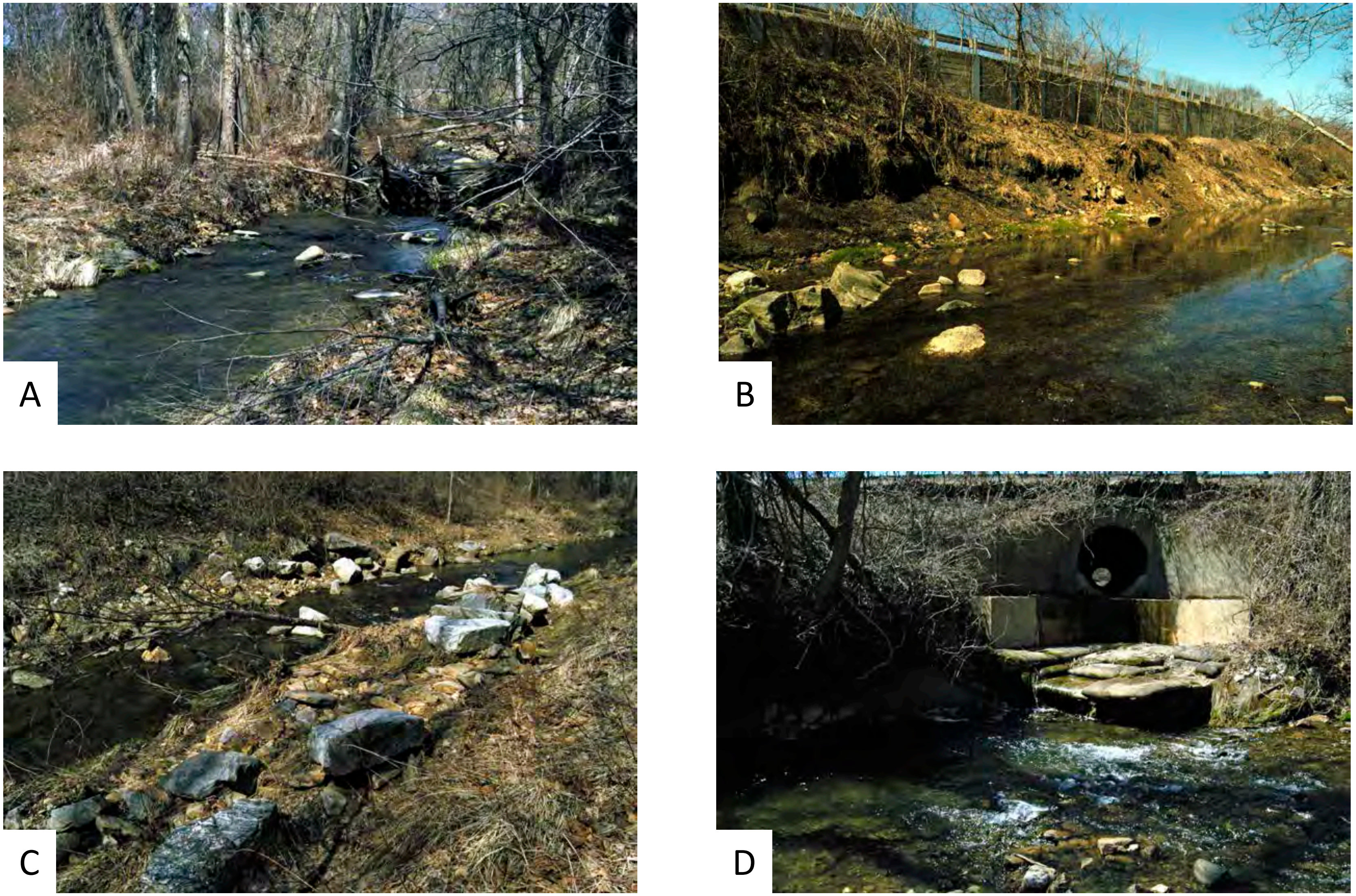


Figure PIC 2. Physical habitat of Piney Creek – A) upstream control area; B) slumping area adjacent to I-83 on the west bank of Piney Creek; C) destroyed J-vane – note downcutting of stream bed; and D) large road drainage culvert upstream of control area on Piney Creek.

**Plumtree Run (PTR)**

**Site Description:** Plumtree Run (pre-construction in the FY12-13 work and now very early post-construction in Spring 2014) is a first-order stream located in Harford County near Bel Air, MD (Figure PTR 1). It parallels Route 24 from it headwaters to West Ring Factory Road and then crosses under Route 24. The stream area restoration to be completed in 2014 is between West Ring Factory Road and Route 24. At the lower end of the restoration area, Plumtree Run crosses back under Route 24 and then eventually flows into the Atkisson Reservoir (the headwaters of Winters Run draining into the Bush River).

Plumtree Run presented a past problem in benthic analyses since it is located on the Fall Line in Maryland, with the Piedmont to the west and the western Coastal Plain to the east of the site. After consultation with MBSS personnel and examining the MBSS data base, we assigned Plumtree Run to the eastern Piedmont for current and future reports. In addition, we completed partial sampling of Plumtree Run on 24 March 2014, but did not sample the lower restoration area. In this stream segment, there was active construction and restoration work occurring while we were sampling the controls and the middle restoration site. Consequently, we returned on 21 April 2014 and sampled the lower restoration area as well as taking a second set of control samples.

The upper headwaters of Plumtree Run are heavily affected by urbanization, with numerous, large residential and commercial developments on either side of the stream, along with a large hospital complex, road infrastructure, and shopping centers. There is an overabundance of parking for the hospital, MD DMV and the shopping centers, as well as high road density in the Atkisson Run watershed (~ 4.0 km/km$^2$).

**Site Coordinates:**

| Site coordinates for Plumtree Run (Figure 3). | | | |
|---|---|---|---|
| Station | Latitude (N) | Longitude (W) | Comments: |
| Middle | 39.509828 | -76.339641 | Middle site. |
| Lower | 39.507872 | -76.338807 | Lower site. |
| Alpha Control | 39.511721 | -76.342286 | Upstream control one. |
| Beta Control | 39.512320 | -76.342612 | Upstream control two. |
| Gamma Control | 39.506910 | -76.339581 | Downstream control one. |
| Delta Control | 39.506712 | -76.339755 | Downstream control two. |


Figure PTR 1. Site locations for sampling on Plumtree Run (Harford County).

**Fall 2013 Benthic Community:** Restoration sites were not collected in September due to low flows. For the control samples with a 100 + macroinvertebrate count, taxa richness, total EPT taxa, and number of ephemeroptera taxa were generally moderate while percent macroinvertebrates intolerant of urban conditions was low (Table PTR 1). The percent of chironomids was moderate at the Control sites. The percent of clingers and climbers was moderate. *Baetis* sp., *Cheumatopsyche* sp. and *Chimerra* sp. larvae dominated the EPT collection and clinger category. For Piedmont metrics, the IBI ranged from 2.0 to 2.7 at the control sites (poor range).

**Table PTR 1. Data summary of benthic macroinvertebrates collected in D-frame samples on 23 September 2013 at control stations in Plumtree Run.**

| **Piedmont Metrics** | **Riffle Community (100+ subsample)** | | | |
|---|---|---|---|---|
| | **Alpha Control** | **Beta Control** | **Gamma Control** | **Delta Control** |
| Taxa Richness | 17 | 16 | 16 | 20 |
| Total EPT Taxa | 4 | 4 | 5 | 4 |
| Ephemeroptera taxa | 1 | 1 | 1 | 1 |
| % Intolerant Urban | 0.9% | 4.3% | 4.4% | 2.0% |
| % Chironomidae | 52.8% | 16.1% | 50.0% | 40.0% |
| % Clingers | 38.0% | 75.3% | 43.3% | 61.0% |
| IBI | 2.0 | 2.7 | 2.3 | 2.0 |

For subsamples with a 300 + count, taxa richness was high (Table PTR 2). Numbers of ephemeroptera taxa, macroinvertebrates intolerant of urban conditions were moderate. The number of scraper taxa was high, with the percent of clingers and climbers moderate. The % Chironomidae was high at three of the control stations. Ephemeroptera taxa was low in both the 100 + and 300 + samples.

**Table PTR 2. Data summary of benthic macroinvertebrates collected in D-frame samples on 23 September 2013 at control stations in Plumtree Run.**

| **Piedmont Metrics** | **Riffle Community (300 + subsample)** | | | |
|---|---|---|---|---|
| | **Alpha Control** | **Beta Control** | **Gamma Control** | **Delta Control** |
| Taxa Richness | 26 | 25 | 25 | 31 |
| Total EPT Taxa | 5 | 5 | 6 | 7 |
| Ephemeroptera taxa | 1 | 1 | 1 | 1 |
| % Intolerant Urban | 0.6% | 4.6% | 4.1% | 2.0% |
| % Chironomidae | 48.2% | 22.8% | 45.1% | 40.7% |
| % Clingers | 54.3% | 74.9% | 68.6% | 66.8% |

**Spring 2014 Benthic Community:** For subsamples with a 100 + macroinvertebrate count and Piedmont metrics, taxa richness, total EPT taxa, number of ephemeroptera taxa and percent macroinvertebrates intolerant of urban conditions were low (Table PTR 3). The percent of chironomids was moderate at the Sigma and Upper Control and Lower Restoration sites and high at the remaining stations. The percent of clingers was moderate at the Alpha Control, high at Sigma Control, and low at the remaining stations. The IBI for Piedmont metrics ranged from 1.0 at Beta and Delta Controls and Middle Restoration to 2.3 at Sigma Control.

**Table PTR 3. Data summary of benthic macroinvertebrates (100 +) collected in D-frame samples on 24 March (Alpha Control, Beta Control, Delta Control and Middle Restoration) and 21 April 2014 (Sigma Control – downstream, Upper Control – equal to Alpha and Beta Controls, and Lower Restoration) stations in Plumtree Run.**

| | Riffle Community (100 + subsample) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Piedmont Metrics** | **Alpha Control** | **Beta Control** | **Delta Control** | **Sigma Control** | **Upper Control** | **Lower Restoration** | **Middle Restoration** |
| Taxa Richness | 11 | 10 | 11 | 17 | 14 | 18 | 13 |
| Total EPT Taxa | 4 | 2 | 1 | 4 | 3 | 3 | 2 |
| Ephemeroptera taxa | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| % Intolerant Urban | 0.0% | 0.0% | 0.9% | 0.0% | 0.0% | 0.8% | 0.0% |
| % Chironomidae | 67.6% | 74.5% | 90.4% | 34.5% | 43.8% | 49.6% | 90.4% |
| % Clingers | 32.4% | 24.5% | 4.4% | 76.1% | 27.6% | 20.7% | 4.3% |
| IBI | 1.3 | 1.0 | 1.0 | 2.3 | 1.3 | 1.7 | 1.0 |

Abundance was low at the Lower Restoration site, so no 300 + count was available for that station (Table PTR 4). For subsamples with a 300+ count and Piedmont metrics, taxa richness was high at the Beta Control, low at the Middle Restoration, and moderate at the remaining sites. The number of EPT taxa collected was moderate at Beta and Sigma Control sites and low at the remaining stations. Numbers of ephemeroptera taxa and percent intolerant macroinvertebrates were low at all stations. The percent of Chironomids was moderate at Alpha, Sigma, and Upper Control sites and high at the remaining stations. The percent of clingers was moderate at Beta and Upper Control and Middle Restoration and high at the remaining sites.

**Table PTR 4. Data summary of benthic macroinvertebrates collected in D-frame samples on 24 March (Alpha Control, Beta Control, Delta Control and Middle Restoration) and 21 April 2014 (Sigma Control – downstream, Upper Control – equal to Alpha and Beta Controls, and Lower Restoration) stations in Plumtree Run.**

| | Riffle Community (300 + subsample) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Piedmont Metrics** | **Alpha Control** | **Beta Control** | **Delta Control** | **Sigma Control** | **Upper Control** | **Lower Restoration** | **Middle Restoration** |
| Taxa Richness | 18 | 25 | 20. | 24 | 22 | -- | 14 |
| Total EPT Taxa | 4 | 5 | 2 | 5 | 3 | -- | 2 |
| Ephemeroptera taxa | 0 | 0 | 0 | 0 | 0 | -- | 0 |
| % Intolerant Urban | 0.6% | 1.7% | 0.9% | 1.7% | 2.7% | -- | 0.0% |
| % Chironomidae | 68.7% | 74.2% | 87.7% | 32.1% | 40.1% | -- | 90.2% |
| % Clingers | 85.6% | 67.9% | 80.4% | 76.7% | 55.2% | -- | 44.3% |
| IBI | 2.3 | 2.3 | 2.0 | 2.7 | 2.0 | -- | 1.3 |

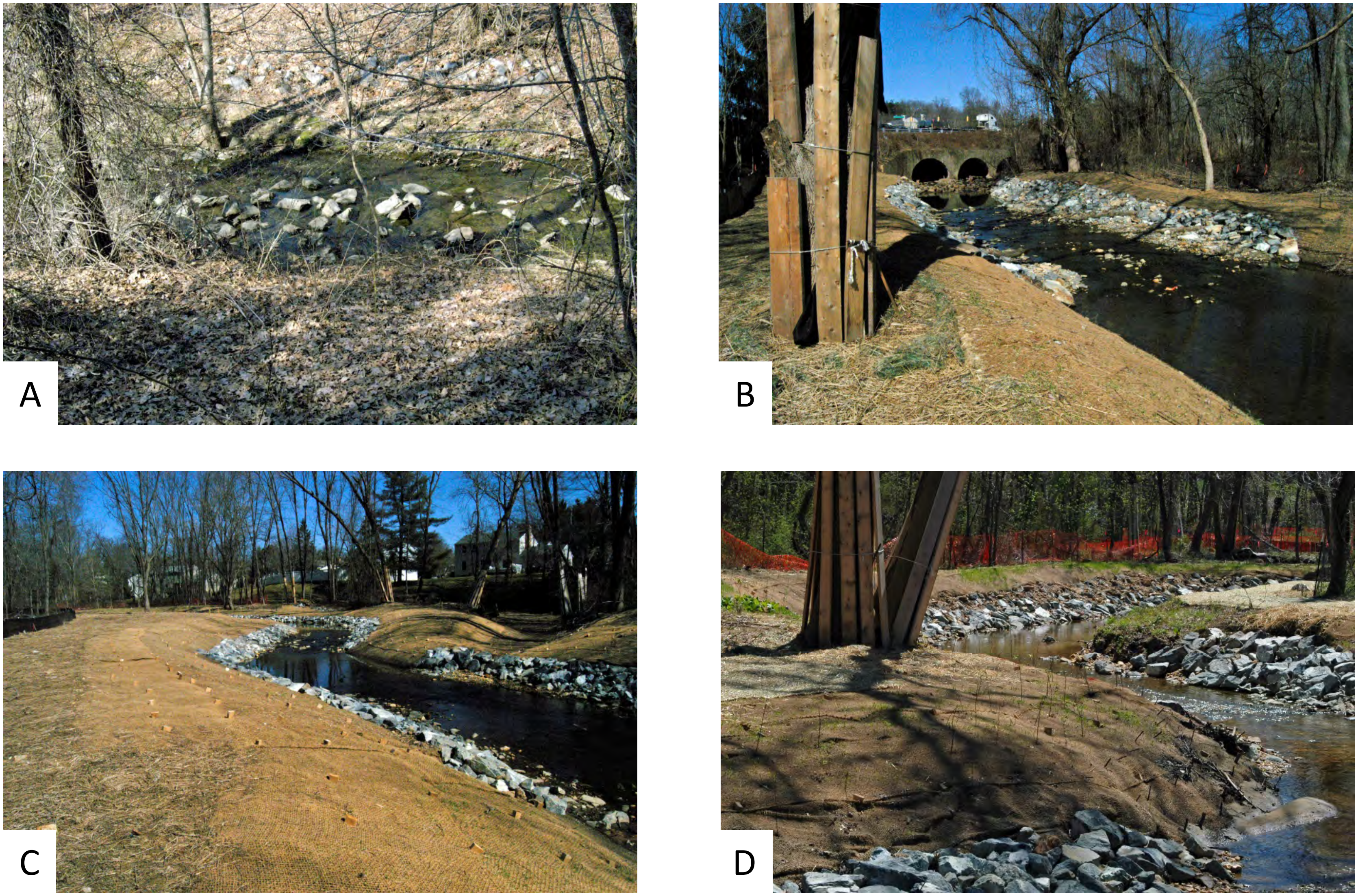


Figure PTR 2. Physical habitat of Plumtree Run – A) upstream control area (alpha and beta); B) upstream restoration area of Plumtree Run just below upstream control area; C) middle restoration area; and D) lower restoration area (note trunk protection around large tress in b and d).

**Physical Habitat**: For Plumtree Run, the upstream control area (Figure PTR 1) is bounded by heavy development for a distance of ~ 1.2 km upstream to its approximate spring source. For most of the stream length, the stream is well shaded with relatively good stability along the banks, with a variety of plant species present (native and introduced). This stream corridor varies greatly in width as a function of housing developments and commercial properties. The eastern bank of Plumtree Run is in close proximity to Route 24 in the lower section, and is effectively forced into a channel with some gradient. There appeared to be some stream stabilization work in the past when Route 24 was constructed. In the control area, the stream bottom is a mixture of boulders, cobble, gravel, and some fine sediment. We will do a complete habitat assessment in 2014-2015 now that the construction phase is complete for Plumtree Run.

The restoration area, ~ 0.64 km in length, is downstream of the junction of Route 24 and West Ring Factory Road, and ends where Plumtree Run crosses under Route 24 again (see PTR 2 for images of the upper control area and restoration work). In this area, Plumtree Run has more of a flood plain than in the control area. Substrate throughout this control area was quite variable, ranging from large cobble to fine silt and clay. Also, there were a number of root wads present along the banks with deep pools present that provided fish habitat (fish were observed throughout the restoration area). Shading was good throughout the restoration reach, but bank stability was poor reflecting the flashy nature of the stream. There was an abundance of multiflora rose as well as other native and non-native plant species.

**Assessment Recommendation:** Now that the construction phase is completed for the Plumtree Run restoration, sampling should be done for the next two years, followed by either a five or ten year cycle.

**Tuscarora Creek - Monocacy River Project**

**Project Description**: Currently, SHA plans to improve the interchange of Monocacy Boulevard and Route 15 in the near future. As part of the project design, SHA was planning to install a level spreader system to collect runoff in order to mitigate any potential runoff effects from the road system in the area. However, SHA recently decided in 2013 not to install a level spreader system. After this decision was made, there were no more water quality collections done in 2014. The current work assesses nutrient levels in Big Tuscarora Creek and Little Tuscarora Creek, with implications discussed as to the importance of determining baseline nutrient data.

**Site Description:** Station descriptions are listed within the site coordinate table, with all stations currently being in the pre-construction phase, especially the two stations close to the interchange. Basic water quality parameters include total nitrogen, total phosphorus, conductivity and total suspended solids (this suite of water quality parameters may be expanded in the future if needed at other sites). In addition, stable isotope analyses of carbon, nitrogen and oxygen were concurrently analyzed for these six stations.

**Site Coordinates:**

| Site coordinates for six Tuscarora Creek (TCM) stations in Frederick County (Figure TUSKY 1). Big Tuscarora enters the Monocacy River above Route 26, and the Little Tuscarora joins the Big Tuscarora just northwest of Willowbrook Road. | | | |
|---|---|---|---|
| TCM Station | Latitude | Longitude | Comments: |
| TUSKY 001 | 39°27’47.74”N | 77°23’37.43”W | Big TCM at railroad bridge crossing. |
| TUSKY 002 | 39°27’51.02”N | 77°24’37.43”W | Big TCM below bridge on US Route 15 near Monocacy Boulevard. |
| TUSKY 003 | 39°28’36.05”N | 77°25’15.48”W | Big TCM at bridge on Bloomfield Road. |
| TUSKY 004 | 39°28’10.56”N | 77°25’00.98”W | Little TCM below bridge on Opossumtown Pike. |
| TUSKY 005 | 39°29’27.15”N | 77°25’39.48”W | Big TCM below bridge on Sundays Lane. |
| TUSKY 006 | 39°27’55.33”N | 77°26’56.76”W | Little TCM below bridge on Yellow Springs Road. |


Figure Tusky 1. Site locations for sampling of Big Tuscarora Creek (1, 2, 3 and 5) and Little Tuscarora Creek (4 and 6) in Frederick County, MD.

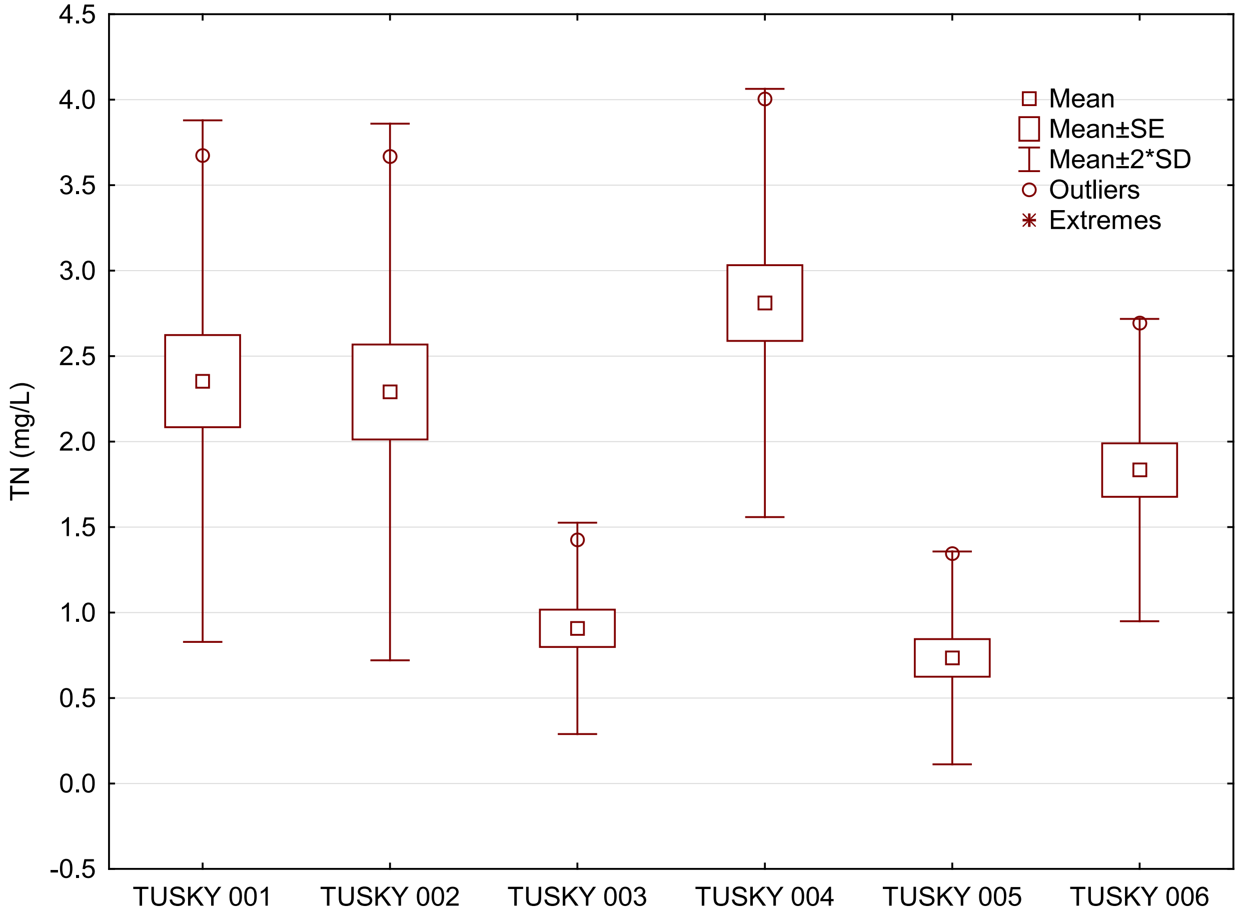


Figure Tusky 2. Box plots of TN (mg/L) for the six Tuscarora Creek stations.

**TN** – For the six Tuscarora Creek stations (Figure Tusky 2), four sample sites exceeded both the 25th (1.6 mg/L) and the 75th (1.8 mg/L) TN percentile estimates for the Northern Piedmont ecoregion of Maryland (Morgan et al. 2013). The driver for TN at both TUSKY 001 and 002 is the Little Tuscarora Creek (TUSKY 004 and 006) where mean TN was 2.8 and 1.8 mg/L respectively (Table TUSKY-1). In the Tuscarora watershed, there are significant agricultural practices although this area is rapidly being urbanized due to its proximity to Route 15 and the western edge of Frederick, especially the Little Tuscarora Creek watershed. The two upstream Big Tuscarora stations (TUSKY 003 – 0.91 mg/L and 005 – 0.73 mg/L) did not exceed the 25th (1.6 mg/L) TN percentile, although the values were slightly higher than the estimated Y-intercept TN value of 0.51 mg/L (Morgan et al. 2013). The highest TN value observed was 4.0 mg/L at TUSKY 004 and the lowest 0.47 mg/L at TUSKY 005.

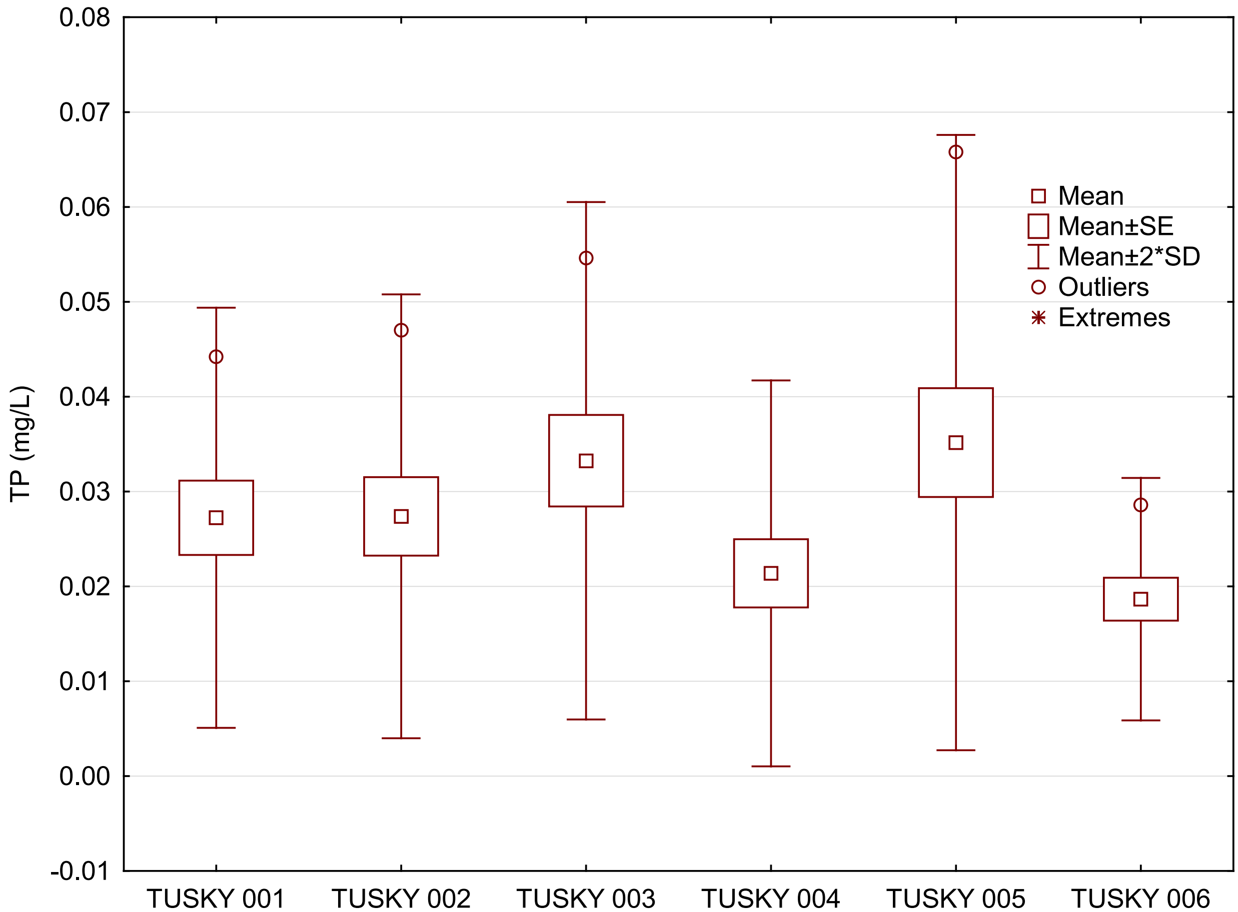

Figure Tusky 3. Box plots of TP (mg/L) for the six Tuscarora Creek stations.

**TP** – For the six Tuscarora Creek stations (Figure Tusky 3), all stations exceeded both the 25th (0.010 mg/L) and the 75th (0.015 mg/L) TP percentile estimates for the Northern Piedmont ecoregion of Maryland (Morgan et al. 2013). The two stations on Little Tuscarora were the lowest with mean values of 0.021 mg/L (004) and 0.019 mg/L (006), with the other four stations ranging from 0.021 – 0.035 mg/L mean TP (Table TUSKY-1). The highest TP value observed was 0.066 mg/L at TUSKY 005 and the lowest 0.0080 mg/L at TUSKY 004. These elevated TP levels also reflect agricultural practices within the Tuscarora watershed.

**Table TUSKY – 1. Summary statistics for TN, TP, TSS and conductivity for the six Tuscarora Creek stations (Figure 4) sampled from 2012 through 2013 during baseflow conditions for six sampling dates.**

| Parameter/Station | Mean | SD | Minimum | Maximum |
|---|---|---|---|---|
| **TN (mg/L)** | | | | |
| TUSKY 001 | 2.4 | 0.76 | 1.5 | 3.7 |
| TUSKY 002 | 2.3 | 0.78 | 1.3 | 3.7 |
| TUSKY 003 | 0.91 | 0.31 | 0.60 | 1.4 |
| TUSKY 004 | 2.9 | 0.63 | 1.9 | 4.0 |
| TUSKY 005 | 0.73 | 0.31 | 0.47 | 1.4 |
| TUSKY 006 | 1.8 | 0.44 | 1.3 | 2.7 |
| **TP (mg/L)** | | | | |
| TUSKY 001 | 0.027 | 0.011 | 0.012 | 0.044 |
| TUSKY 002 | 0.027 | 0.011 | 0.012 | 0.047 |
| TUSKY 003 | 0.033 | 0.014 | 0.016 | 0.057 |
| TUSKY 004 | 0.021 | 0.010 | 0.0080 | 0.036 |
| TUSKY 005 | 0.035 | 0.016 | 0.015 | 0.066 |
| TUSKY 006 | 0.019 | 0.0064 | 0.011 | 0.029 |
| **TSS (mg/L)** | | | | |
| TUSKY 001 | 6.0 | 4.2 | 2.0 | 13.8 |
| TUSKY 002 | 5.6 | 4.1 | 1.2 | 13.0 |
| TUSKY 003 | 4.1 | 3.8 | 0.40 | 10.8 |
| TUSKY 004 | 4.5 | 3.9 | 1.4 | 13.2 |
| TUSKY 005 | 3.3 | 2.4 | 1.0 | 7.4 |
| TUSKY 006 | 9.6 | 9.0 | 0.80 | 28.2 |
| **CONDUCTIVITY (µS/cm)** | | | | |
| TUSKY 001 | 293 | 106 | 154 | 510 |
| TUSKY 002 | 278 | 102 | 147 | 486 |
| TUSKY 003 | 162 | 59.9 | 86.3 | 276 |
| TUSKY 004 | 292 | 63 | 215 | 407 |
| TUSKY 005 | 155 | 62 | 80.3 | 279 |
| TUSKY 006 | 175 | 31 | 138 | 230 |

**TSS** – The six Tuscarora sites ranged from 3.3 to 9.6 mg/L average TSS, with a low TSS of 0.40 at TUSKY 003 and a high of 28.2 mg/L at TUSKY 006 during baseflow measurements (Table TUSKY 1). There appears to be variation in the measurement of TSS at each site as evidenced by the large SD values observed.

The criteria for total suspended solids (TSS) and turbidity criteria are unclear, with only a few states having set criteria for a number of reasons. Three states - Utah, North Dakota, and South Dakota - have similar criteria for their cold water streams; 35 mg/L, 30 mg/L, and 30 mg/L as a 30 day average or 58 mg/L daily maximum, respectively. Both Utah and South Dakota have higher thresholds for warm water streams; 90 mg/L and 150 mg/L as a 30 day average or 263 mg/L daily maximum, respectively. TSS is a good indicator of poor water quality, identifying water quality deterioration leading to aesthetic issues, higher water treatment costs, biotic decline and an overall degrading of aquatic environments.

**Conductivity** – For the six Tuscarora stations mean conductivity ranged from 155 µS/cm at TUSKY 005 to 293 µS/cm at TUSKY 001 (Table TUSKY-1). The lowest value was 80 µS/cm at TUSKY 005, with the highest (510 µS/cm) at TUSKY 001. Average stream specific conductivity at the six sites exceeded the $25^{th}$ percentile (145 µS/cm) for the Northern Piedmont (Morgan et al. 2012). This elevated specific conductivity reflects the urban stream syndrome (Walsh et al. 2005) where there is frequently high stream conductivity due to inputs from road salts and numerous other sources.

**Stable Isotopes –** One of the key questions in global nitrate dynamics is the origin of nitrate in the water column (Chang et al. 2002, Kendall et al. 2007), an important factor to consider in the TMDL nutrient process. To determine nitrate origin in the Tuscarora Creek watershed, we collected stable isotope samples concurrently with general water quality sampling at the six stations, followed by determination of $\delta^{15}N$(‰) and $\delta^{18}O$(‰) in nitrate ($NO_3$) by the CASIF (http://casif.al.umces.edu/) at the Appalachian Laboratory.

For $\delta^{15}N$, values ranged from ~ -5.3 to +8.9 (Figure Tusky-4), with $\delta^{18}O$ ranging from -8 to +10. For oxygen, the typical $\delta^{18}O$ range was observed that correlates with the soil nitrification of ammonia and organic matter (Chang et al. 2002, Kendall et al. 2007), presumably from the ammonia in both fertilizer and precipitation. The $\delta^{15}N$ range also agrees with the presence of ammonia in fertilizer and precipitation although the higher $\delta^{15}N$ values suggest denitrification processes in soil ammonia. Because of high TN in the watershed, we suspect that the major nitrogen driver is agricultural practices, with the potential for significant nitrate pools in groundwater.

There was a significant linear relationship ($\rho = 0.0006$) of $\delta^{15}N$(‰) to $\delta^{18}O$(‰), although explanatory power was weak with a $r^2 = 0.23$ (Figure Tusky-4), but the overall pattern was similar to the $\delta^{15}N$(‰) to $\delta^{18}O$(‰) relationship observed in agricultural Mississippi River sites by Chang et al. (2002).

Using a bag plot (Sun and Genton 2011), we determined that there were 17 distinct outliers (35%) for $\delta^{15}$N(‰) and $\delta^{18}$O(‰) values (Figure Tusky-5). These outliers are the marked points outside of the light and dark blue areas of the graph (the dark blue area represents an envelope of the 50% central region around the median for $\delta^{15}$N and $\delta^{18}$O, and the light blue area the maximum non-outlier envelope, or 1.5 times the central region empirical rule), with the shape of the bag approximating the linear regression model (Figure Tusky-4). Eleven of the 17 data points were either June or July samples, while six points were other months. This may indicate some variation in soil nitrogen processes during the summer and perhaps into the fall. The $\delta^{15}$N and $\delta^{18}$O data suggests that atmospheric nitrate, nitrate fertilizer, and manure and septic waste inputs are minimal and the stream nitrogen patterns relate more to ammonia in fertilizer and precipitation (Kendall et al. 2007).

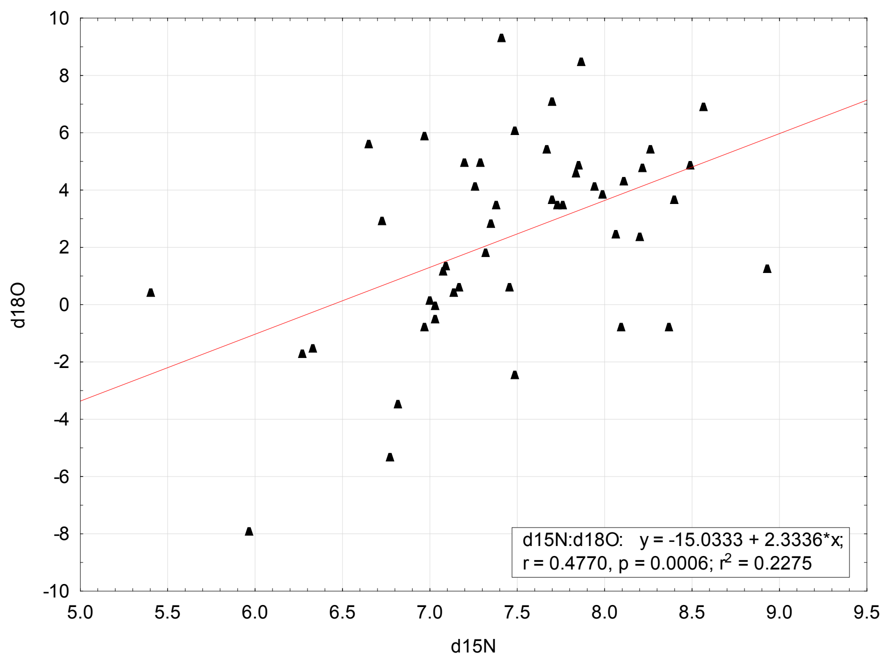


Figure Tusky 4. Linear relationship of $\delta^{15}$N(‰) to $\delta^{18}$O(‰) in nitrate for the six Tuscarora stations sampled from 2012 to 2013.

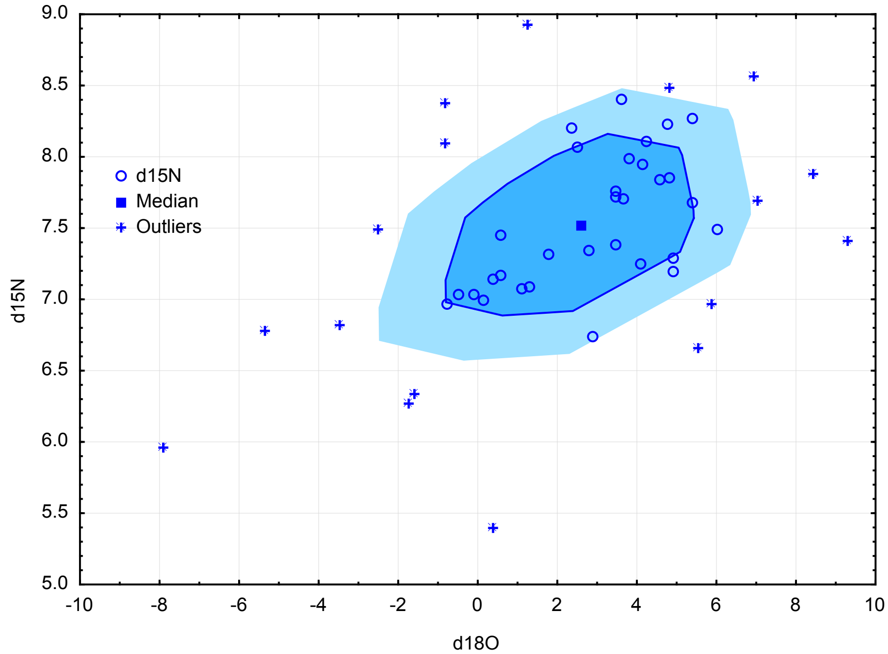


Figure Tusky 5. Bag plot of the relationship of $\delta^{15}N$(‰) to $\delta^{18}O$(‰) in nitrate for the six Tuscarora stations sampled from 2012 to 2013.

**Assessment Recommendation:** SHA plans to improve the interchange of Monocacy Boulevard and Route 15 in the very near future. As part of the initial project design, SHA was planning to install a level spreader system as part of their overall TMDL efforts. However, the level spreader system will not be constructed at this interchange.

We did gather some important data from the Tuscarora Creek watershed work. Assuming that level spreader systems, or other comparable stormwater treatments systems, were to be installed at other projects, it is important to determine the water quality of not only the stormwater treatment facility but also the receiving water (perhaps coupled with spatial-temporal baseflow sampling in the watershed). For example, there were elevated levels of nutrients present at both Tusky 001 and 002 (close to the Monocacy Boulevard and Route 15 interchange), and that stormwater discharges would probably be low in comparison to the baseflow levels seen for nutrients in the lower reach of the watershed. Conceivably, overall water quality from stormwater treatment would be masked by the water quality of the receiving water for many SHA projects in Maryland.

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## APPENDIX A.

Basic benthic invertebrate summary sheets for all SHA restoration sites sampled in 2013-2014 throughout the Maryland Piedmont and Coastal Plain.

## Little Paint Branch – September 2013

**Table LPB 1. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 m²) at sites in Little Paint Branch on 30 September 2013. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | Little Paint Branch Sampling Sites (100 + subsample) | | | |
|---|---|---|---|---|
| **Taxa** | **Alpha Control** | **Beta control** | **Lower Restoration** | **Middle Restoration** |
| Turbellaria | 7 | | 3 | |
| Nemotoda | 1 | | 1 | |
| Nemerta | 3 | 3 | 1 | 4 |
| **Annelida** | | | | |
| Oligochaeta | | | | |
| Lumbriculidae | 5 | | 4 | 6 |
| **Gastropoda** | | | | |
| Ancylidae | | | | |
| *Ferrissia* sp. | | 2 | | |
| Planorbidae | | 1 | | |
| **Pelycepoda** | | | | |
| Sphaeriidae | 1 | | | |
| **Crustaceae** | | | | |
| Amphipoda | | | | |
| Crangonyctidae | | | 1 | |
| *Crangonyx* sp. | | 1 | | |
| **Insecta** | | | | |
| Colelmbola | | | | |
| Ephemeroptera | | | | |
| Baetidae | 2 | 3 | 5 | 3 |
| *Acentrella* sp. | | | | |
| *Baetis* sp. | 2 | | | |
| Odonata | | | | |
| Coenagrionidae | | | | |
| *Argia* sp. | | 1 | | |
| *Enallagma* sp. | | | | |
| Gomphidae | | | | 1 |
| Trichoptera | | | | |
| Glossosomatidae | | | | |
| *Glossosoma* sp. | | 1 | | |
| Hydropsychidae | 20 | 32 | 22 | 20 |
| *Cheumatopsyche* sp. | 25 | 27 | 9 | 18 |
| *Hydropsyche* sp. | 19 | 4 | 9 | 3 |
| *Symphytpsyche* sp. | 18 | 14 | 21 | 16 |
| Hydroptilidae | | | | |
| *Hydroptila* sp. | | 2 | | |
| *Leucotrichia* sp. | | 2 | 16 | |
| Philopotomatidae | 1 | | 3 | |
| *Chimerra* sp. | 5 | 2 | 22 | 3 |

**Table LPB 1 (continued).**

| Taxa | Little Paint Branch Sampling Sites (100 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta control | Lower Restoration | Middle Restoration |
| Coleoptera | | | | |
| Elmidae | | | 1 | 1 |
| *Macronychus* sp. | | | 1 | |
| *Stenelmis* sp. | 1 | | | 1 |
| Psephenidae | | | | |
| *Psephenus* sp. | 1 | | | |
| Diptera | | | | |
| Chironomidae | 4 | 5 | 7 | 22 |
| Tanypodinae | 2 | 1 | | 3 |
| Orthocladinae | | | 1 | 4 |
| *Corynoneura* sp. | | | 1 | 2 |
| *Eukieferella* sp. | | 1 | | |
| *Orthocaldius* sp. | 6 | 11 | 3 | 5 |
| *Thienemanilla* sp. | 3 | 2 | 1 | 1 |
| *Zalutschia* sp. | | | | |
| Chironomini | 1 | 4 | | |
| Pseudochironomini | 1 | | 1 | |
| *Pseudochironomus* sp. | 3 | 16 | 2 | 1 |
| *Polypedilum* sp. | | | | 1 |
| Tanytarsini | 1 | 2 | 1 | |
| *Micropsectra* sp. | | 1 | | |
| *Rheotanytarsus* sp. | | 2 | | 1 |
| Empididae | | | | |
| *Hemerodromia* sp. | 1 | 3 | | 1 |
| Simulidae | 1 | | 1 | 1 |
| Tipulidae | | | | |
| *Antocha* sp. | 1 | | 3 | 3 |
| *Tipula* sp. | | | | 1 |

**Table LPB 2. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 $m^2$) at sites in Little Paint Branch on 30 September 2013. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | **Little Paint Branch Sampling Sites (300 + subsample)** | | | |
|---|---|---|---|---|
| **Taxa** | **Alpha Control** | **Beta Control** | **Lower Restoration** | **Middle Restoration** |
| Turbellaria | 22 | 5 | 10 | 7 |
| Nemotoda | | | 1 | |
| Nemerta | 7 | 15 | 4 | 7 |
| **Annelida** | | | | |
| Oligochaeta | | | | |
| Lumbriculidae | 9 | 1 | 9 | 13 |
| **Gastropoda** | | | | |
| Ancylidae | | | | |
| *Ferrissia* sp. | 3 | 5 | 1 | 2 |
| Lymnaeidae | | | | |
| Physidae | | 1 | | |
| Planorbidae | | 1 | | |
| **Pelycepoda** | | | | |
| Sphaeriidae | 1 | | | |
| **Crustaceae** | | | | |
| Amphipoda | | | | |
| Crangonyctidae | | | 4 | 1 |
| *Crangonyx* sp. | | 1 | | |
| *Synurella* sp. | | 6 | | 1 |
| **Insecta** | | | | |
| Ephemeroptera | | | | |
| Baetidae | 7 | 9 | 14 | 7 |
| *Baetis* sp. | 3 | | | |
| Odonata | | | | |
| Coenagrionidae | | | | |
| *Argia* sp. | | 2 | | |
| *Enallagma* sp. | 1 | | | |
| Gomphidae | | | | 1 |
| Trichoptera | | | | |
| Glossosomatidae | | | | |
| *Glossosoma* sp. | | 1 | | |
| Hydropsychidae | 71 | 97 | 49 | 64 |
| *Cheumatopsyche* sp. | 47 | 68 | 25 | 55 |
| *Hydropsyche* sp. | 46 | 8 | 27 | 13 |
| *Symphytpsyche* sp. | 40 | 39 | 49 | 60 |
| Hydroptilidae | | | | 2 |
| *Hydroptila* sp. | | 2 | | |
| *Leucotrichia* sp. | | 5 | 35 | 2 |
| Philopotomatidae | 1 | | 4 | 1 |
| *Chimerra* sp. | 11 | 7 | 43 | 11 |

**Table LPB 2 (continued).**

| Taxa | Little Paint Branch Sampling Sites (300 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Coleoptera | | | | |
| Elmidae | 3 | 2 | 3 | 3 |
| *Macronychus* sp. | | | 1 | |
| *Stenelmis* sp. | 1 | 1 | | 5 |
| Psephenidae | | | | |
| *Psephenus* sp. | 1 | | | |
| Diptera | | | | |
| Chironomidae | 14 | 21 | 18 | 43 |
| Tanypodinae | 8 | 3 | 1 | 3 |
| Orthocladinae | 4 | 3 | 1 | 4 |
| *Corynoneura* sp. | | | 1 | 3 |
| *Eukieferella* sp. | | 5 | 2 | |
| *Orthocaldius* sp. | 9 | 24 | 4 | 8 |
| *Thienemanilla* sp. | 4 | 2 | 2 | 3 |
| Chironomini | 1 | 8 | 2 | 1 |
| *Apedilum* sp. | | | | 1 |
| *Polypedilum* sp. | | | 1 | 1 |
| Pseudochironomini | 1 | | 3 | |
| *Pseudochironomus* sp. | 2 | 19 | 3 | 5 |
| Tanytarsini | 5 | 3 | 6 | 5 |
| *Micropsectra* sp. | 2 | 1 | 1 | 1 |
| *Rheotanytarsus* sp. | | 5 | | 2 |
| Empididae | 1 | | | 1 |
| *Clinocera* sp. | | 1 | | |
| *Hemerodromia* sp. | 3 | 4 | | 1 |
| Simulidae | 3 | 1 | 1 | 1 |
| *Simulium* sp. | | | 1 | |
| Tipulidae | | | | |
| *Antocha* sp. | 7 | 10 | 5 | 8 |
| *Tipula* sp. | | | | 1 |

## Little Paint Branch – April 2014

**Table LPB 3. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 $m^2$) at sites in Little Paint Branch on 4 April 2014. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| Taxa | Little Paint Branch Sampling Sites (100 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Turbellaria | 11 | 3 | 3 | 2 |
| Nemotoda | | | 1 | 4 |
| Nemerta | | 4 | | 2 |
| **Annelida** | | | | |
| Oligochaeta | 1 | 1 | 1 | |
| Lumbriculidae | 6 | 19 | 17 | 28 |
| Naidadae | 16 | 6 | 4 | |
| Tubificidae | 2 | 2 | | |
| Gastropoda | 1 | | | |
| Pelycepoda | | | | |
| Sphaeriidae | 1 | 1 | | |
| **Crustaceae** | | | | |
| Amphipoda | | | 1 | |
| Crangonyctidae | | | | |
| Cambaridae | | | | |
| *Cambarus* sp. | | | 1 | |
| **Insecta** | | | | |
| Trichoptera | | | | |
| Hydropsychidae | | 1 | | 1 |
| *Cheumatopsyche* sp. | | 2 | 1 | 3 |
| *Hydropsyche* sp. | 1 | | 1 | 2 |
| *Symphytpsyche* sp. | 1 | | 2 | 1 |
| Hydroptilidae | | | | |
| *Leucotrichia* sp. | | | 2 | 3 |
| Philopotomatidae | | | | |
| *Chimerra* sp. | 3 | | | 3 |
| Coleoptera | | | | |
| Elmidae | | | | |
| *Ancryonyx* sp. | | | 1 | |
| *Ouliminus* sp. | | | | 1 |
| *Stenelmis* sp. | | | | 5 |
| Psephenidae | | | | |
| *Psephenus* sp. | | | | 1 |

**Table LPB 3 (continued).**

| Taxa | Little Paint Branch Sampling Sites (100 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Diptera | | | | |
| Chironomidae | 4 | 8 | 6 | 2 |
| Tanypodinae | | 1 | | |
| Orthocladinae | | 1 | | 2 |
| *Hydrobaenus* sp. | 5 | | 5 | 20 |
| *Orthocaldius* sp. | 53 | 49 | 43 | 16 |
| Chironomini | | 3 | 2 | 1 |
| *Phaenopsectra* sp. | 1 | | | |
| *Polypedilum* sp. | 1 | | 1 | 1 |
| Tanytarsini | | | | |
| *Dicrotendipes* sp. | | | 1 | |
| *Micropsectra* sp. | 1 | | 2 | |
| *Rheotanytarsus* sp. | | | | |
| Empididae | | | | |
| *Chelifera* sp. | | | | 1 |
| *Hemerodromia* sp. | | 1 | | |

**Table LPB 4. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 $m^2$) at sites in Little Paint Branch on 4 April 2014. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| Taxa | Little Paint Branch Sampling Sites (300 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| **Gastropoda** | 1 | | | |
| **Pelycepoda** | | | | |
| Sphaeriidae | 2 | 1 | | |
| **Crustaceae** | | | | |
| Amphipoda | | | | |
| Crangonyctidae | 1 | | 2 | |
| Cambaridae | | | | |
| *Cambarus* sp. | | | 1 | |
| **Insecta** | | | | |
| Odonata | | | | |
| Gomphidae | | | | 1 |
| Trichoptera | | | | |
| Hydropsychidae | | 2 | | 2 |
| *Cheumatopsyche* sp. | | 6 | 1 | 3 |
| *Hydropsyche* sp. | 1 | 1 | 1 | 3 |
| *Symphytpsyche* sp. | 1 | | 2 | 1 |
| *Leucotrichia* sp. | | | 4 | 5 |
| Philopotomatidae | | | | |
| *Chimerra* sp. | 3 | | | 3 |
| Coleoptera | | | | |
| Elmidae | | | | |
| *Ancronyx* sp. | | | 1 | |
| *Oulimnius* sp. | | | | 1 |
| *Stenelmis* sp. | | | | 6 |
| Psephenidae | | | | |
| *Psephenus* sp. | | | | 1 |
| Diptera | | | | |
| Chironomidae | 5 | 15 | 8 | 2 |
| Tanypodinae | | 1 | | |
| Orthocladinae | | 3 | 2 | 7 |
| *Hydrobaenus* sp. | 5 | 5 | 5 | 22 |
| *Orthocaldius* sp. | 91 | 89 | 60 | 24 |
| Chironomini | | 4 | 2 | 1 |
| *Phaenopsectra* sp. | 1 | | | |
| *Polypedilum* sp. | 2 | 1 | 1 | 1 |
| *Stenochironomus* sp. | | 1 | | |
| Tanytarsini | 1 | | | 1 |
| *Dicrotendipes* sp. | | | 1 | 1 |

**Table LPB 4 (continued).**

| Taxa | Little Paint Branch Sampling Sites (300 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| *Micropsectra* sp. | 1 | | 2 | 1 |
| Empididae | | | | |
| *Chelifera* sp. | | 1 | | 1 |
| *Hemerodromia* sp. | | 2 | | |
| Tipulidae | | | | |
| *Antocha* sp. | | | 1 | |

## Long Draught Branch – September 2013

**Table LDB 1. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately ~ 1 $m^2$) at sites in Long Draught Branch on 30 September 2013. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | Long Draught Branch Sampling Sites (100 + subsample) | | | |
|---|---|---|---|---|
| **Taxa** | **Alpha Control** | **Beta control** | **Lower Restoration** | **Middle Restoration** |
| Turbellaria | 7 | | 3 | |
| Nemotoda | 1 | | 1 | |
| Nemerta | 3 | 3 | 1 | 4 |
| **Annelida** | | | | |
| Oligochaeta | | | | |
| Lumbriculidae | 5 | | 4 | 6 |
| **Gastropoda** | | | | |
| Ancylidae | | | | |
| *Ferrissia* sp. | | 2 | | |
| Planorbidae | | 1 | | |
| **Pelycepoda** | | | | |
| Sphaeriidae | 1 | | | |
| **Crustaceae** | | | | |
| Amphipoda | | | | |
| Crangonyctidae | | | 1 | |
| *Crangonyx* sp. | | 1 | | |
| **Insecta** | | | | |
| Colelmbola | | | | |
| Ephemeroptera | | | | |
| Baetidae | 2 | 3 | 5 | 3 |
| *Acentrella* sp. | | | | |
| *Baetis* sp. | 2 | | | |
| Odonata | | | | |
| Coenagrionidae | | | | |
| *Argia* sp. | | 1 | | |
| *Enallagma* sp. | | | | |
| Gomphidae | | | | 1 |
| Trichoptera | | | | |
| Glossosomatidae | | | | |
| *Glossosoma* sp. | | 1 | | |
| Hydropsychidae | 20 | 32 | 22 | 20 |
| *Cheumatopsyche* sp. | 25 | 27 | 9 | 18 |
| *Hydropsyche* sp. | 19 | 4 | 9 | 3 |
| *Symphytpsyche* sp. | 18 | 14 | 21 | 16 |
| Hydroptilidae | | | | |
| *Hydroptila* sp. | | 2 | | |
| *Leucotrichia* sp. | | 2 | 16 | |

**Table LDB 1 (continued).**

| Taxa | Long Draught Branch Sampling Sites (100 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta control | Lower Restoration | Middle Restoration |
| Philopotomatidae | 1 | | 3 | |
| *Chimerra* sp. | 5 | 2 | 22 | 3 |
| Coleoptera | | | | |
| Elmidae | | | 1 | 1 |
| *Macronychus* sp. | | | 1 | |
| *Stenelmis* sp. | 1 | | | 1 |
| Psephenidae | | | | |
| *Psephenus* sp. | 1 | | | |
| Diptera | | | | |
| Chironomidae | 4 | 5 | 7 | 22 |
| Tanypodinae | 2 | 1 | | 3 |
| Orthocladinae | | | 1 | 4 |
| *Corynoneura* sp. | | | 1 | 2 |
| *Eukieferella* sp. | | 1 | | |
| *Orthocaldius* sp. | 6 | 11 | 3 | 5 |
| *Thienemanilla* sp. | 3 | 2 | 1 | 1 |
| *Zalutschia* sp. | | | | |
| Chironomini | 1 | 4 | | |
| Pseudochironomini | 1 | | 1 | |
| *Pseudochironomus* sp. | 3 | 16 | 2 | 1 |
| *Polypedilum* sp. | | | | 1 |
| Tanytarsini | 1 | 2 | 1 | |
| *Micropsectra* sp. | | 1 | | |
| *Rheotanytarsus* sp. | | 2 | | 1 |
| Empididae | | | | |
| *Hemerodromia* sp. | 1 | 3 | | 1 |
| Simulidae | 1 | | 1 | 1 |
| Tipulidae | | | | |
| *Antocha* sp. | 1 | | 3 | 3 |
| *Tipula* sp. | | | | 1 |

**Table LDB 2. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 $m^2$) at sites in Long Draught Branch on 30 September 2013. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | Long Draught Branch Sampling Sites (300 + subsample) | | | |
|---|---|---|---|---|
| **Taxa** | **Alpha Control** | **Beta Control** | **Lower Restoration** | **Middle Restoration** |
| Turbellaria | 22 | 5 | 10 | 7 |
| Nemotoda | | | 1 | |
| Nemerta | 7 | 15 | 4 | 7 |
| **Annelida** | | | | |
| Oligochaeta | | | | |
| Lumbriculidae | 9 | 1 | 9 | 13 |
| **Gastropoda** | | | | |
| Ancylidae | | | | |
| *Ferrissia* sp. | 3 | 5 | 1 | 2 |
| Lymnaeidae | | | | |
| Physidae | | 1 | | |
| Planorbidae | | 1 | | |
| **Pelycepoda** | | | | |
| Sphaeriidae | 1 | | | |
| **Crustaceae** | | | | |
| Amphipoda | | | | |
| Crangonyctidae | | | 4 | 1 |
| *Crangonyx* sp. | | 1 | | |
| *Synurella* sp. | | 6 | | 1 |
| **Insecta** | | | | |
| Ephemeroptera | | | | |
| Baetidae | 7 | 9 | 14 | 7 |
| *Baetis* sp. | 3 | | | |
| Odonata | | | | |
| Coenagrionidae | | | | |
| *Argia* sp. | | 2 | | |
| *Enallagma* sp. | 1 | | | |
| Gomphidae | | | | 1 |
| Trichoptera | | | | |
| Glossosomatidae | | | | |
| *Glossosoma* sp. | | 1 | | |
| Hydropsychidae | 71 | 97 | 49 | 64 |
| *Cheumatopsyche* sp. | 47 | 68 | 25 | 55 |
| *Hydropsyche* sp. | 46 | 8 | 27 | 13 |
| *Symphytpsyche* sp. | 40 | 39 | 49 | 60 |
| Hydroptilidae | | | | 2 |
| *Hydroptila* sp. | | 2 | | |
| *Leucotrichia* sp. | | 5 | 35 | 2 |

**Table LDB 2 (continued).**

| Taxa | Long Draught Branch Sampling Sites (300 + subsample) | | | |
|---|---|---|---|---|
| | **Alpha Control** | **Beta Control** | **Lower Restoration** | **Middle Restoration** |
| Philopotomatidae | 1 | | 4 | 1 |
| *Chimerra* sp. | 11 | 7 | 43 | 11 |
| Coleoptera | | | | |
| Elmidae | 3 | 2 | 3 | 3 |
| *Macronychus* sp. | | | 1 | |
| *Stenelmis* sp. | 1 | 1 | | 5 |
| Psephenidae | | | | |
| *Psephenus* sp. | 1 | | | |
| Diptera | | | | |
| Chironomidae | 14 | 21 | 18 | 43 |
| Tanypodinae | 8 | 3 | 1 | 3 |
| Orthocladinae | 4 | 3 | 1 | 4 |
| *Corynoneura* sp. | | | 1 | 3 |
| *Eukieferella* sp. | | 5 | 2 | |
| *Orthocaldius* sp. | 9 | 24 | 4 | 8 |
| *Thienemanilla* sp. | 4 | 2 | 2 | 3 |
| Chironomini | 1 | 8 | 2 | 1 |
| *Apedilum* sp. | | | | 1 |
| *Polypedilum* sp. | | | 1 | 1 |
| Pseudochironomini | 1 | | 3 | |
| *Pseudochironomus* sp. | 2 | 19 | 3 | 5 |
| Tanytarsini | 5 | 3 | 6 | 5 |
| *Micropsectra* sp. | 2 | 1 | 1 | 1 |
| *Rheotanytarsus* sp. | | 5 | | 2 |
| Empididae | 1 | | | 1 |
| *Clinocera* sp. | | 1 | | |
| *Hemerodromia* sp. | 3 | 4 | | 1 |
| Simulidae | 3 | 1 | 1 | 1 |
| *Simulium* sp. | | | 1 | |
| Tipulidae | | | | |
| *Antocha* sp. | 7 | 10 | 5 | 8 |
| *Tipula* sp. | | | | 1 |

## Long Draught Branch – April 2014

**Table LDB 3. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately ~ 1 $m^2$) at sites in Long Draught Branch on 4 April 2013. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | Long Draught Branch Sampling Sites (100+ subsample) | | | |
|---|---|---|---|---|
| **Taxa** | **Alpha Control** | **Beta Control** | **Lower Restoration** | **Middle Restoration** |
| **Gastropoda** | | | | |
| Ancylidae | | | | |
| *Ferrissia* sp. | | 1 | | |
| Lymnaeidae | | | 4 | 2 |
| Physidae | | | 2 | |
| Planorbidae | 1 | | 1 | 1 |
| **Pelycepoda** | | | | |
| Sphaeriidae | 4 | 1 | 22 | 1 |
| **Insecta** | | | | |
| Collembola | 1 | | | |
| Odonata | | | | |
| Coenagrionidae | | | | |
| *Enallagma* sp. | | | 1 | |
| Trichoptera | | | | |
| Hydropsychidae | | 1 | | 3 |
| *Cheumatopsyche* sp. | | 3 | 2 | 14 |
| Coleoptera | | | | |
| Elmidae | | | | |
| *Stenelmis* sp. | | | | |
| Diptera | | | | |
| Chironomidae | 2 | | 1 | 1 |
| Tanypodinae | | | | |
| Orthocladinae | 8 | | 1 | 3 |
| *Eulieferella* sp. | | | 3 | 1 |
| *Hydrobaenus* sp. | | | 3 | 1 |
| *Orthocaldius* sp. | 67 | 65 | 28 | 19 |
| Chironomini | | | 2 | 1 |
| *Dicrotendipes* sp. | | 5 | | |
| Empididae | | | | |
| *Hemerodromia* sp. | | | | 1 |
| Simulidae | | | | |
| *Prosimulium* sp. | | | | 2 |
| *Simulium* sp. | | | 1 | |
| Tipulidae | | | | |
| *Tipula* sp. | | | | 1 |

**Table LDB 4. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately ~ 1 $m^2$) at sites in Long Draught Branch on 4 April 2013. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | Long Draught Branch Sampling Sites (300+ subsample) | | | |
|---|---|---|---|---|
| **Taxa** | **Alpha Control** | **Beta Control** | **Lower Restoration** | **Middle Restoration** |
| Turbellaria | 19 | | | |
| Nemerta | 21 | 2 | | |
| Nematoda | 4 | 14 | | |
| **Annelida** | | | | |
| Oligochaeta | | | | |
| Lumbriculidae | 2 | 10 | | |
| Naidadae | | 12 | | |
| Tubificidae | 5 | 14 | | |
| Entrachidae | 1 | 2 | | |
| **Gastropoda** | | | | |
| Ancylidae | | | | |
| *Ferrissia* sp. | | 2 | | |
| Planorbidae | 1 | | | |
| **Pelycepoda** | | | | |
| Sphaeriidae | 10 | 4 | | |
| **Insecta** | | | | |
| Odonata | | | | |
| Coenagrionidae | | | | |
| *Enallagma* sp. | | 1 | | |
| Trichoptera | | | | |
| Hydropsychidae | | 3 | | |
| *Cheumatopsyche* sp. | | 8 | | |
| Diptera | | | | |
| Chironomidae | 5 | | | |
| Orthocladinae | 8 | | | |
| *Hydrobaenus* sp. | | 9 | | |
| *Orthocaldius* sp. | 195 | 221 | | |
| Chironomini | | | | |
| *Dicrotendipes* sp. | | 5 | | |
| Empididae | | | | |
| *Chelifera* sp. | | 1 | | |
| *Hemerodromia* sp. | 2 | | | |

## Muddy Bridge Branch – September 2013

**Table MBB 1. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 $m^2$) at sites in Muddy Bridge Branch on 30 September 2013. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | Muddy Bridge Branch (100 + subsample) | |
|---|---|---|
| **Taxa** | **Lower Restoration** | **Middle Restoration** |
| Turbellaria | 4 | 1 |
| **Annelida** | | |
| Oligchaeta | | |
| Lumbriculidae | | 5 |
| Naididae | 1 | |
| Tubificidae | 22 | 9 |
| Hirudinae | | |
| Glossiphoniidae | 2 | |
| **Gastropoda** | | |
| Lymnaeidae | | |
| Physidae | 6 | |
| **Insecta** | | |
| Ephemeroptera | | |
| Baetidae | 2 | 3 |
| Megaloptera | | |
| Corydalidae | | |
| *Nigronia* sp. | | 2 |
| Trichoptera | | |
| Hydropsychidae | 6 | 7 |
| *Cheumatopsyche* sp. | 7 | 15 |
| *Diplectrona* sp. | | |
| *Hydropsyche* sp. | | 3 |
| Coleoptera | | |
| Elmidae | | 1 |
| Diptera | | |
| Chironomidae | 13 | 4 |
| Tanypodinae | 7 | 7 |
| *Ablabesmyia* sp. | | 1 |
| *Thienemannimyia* sp. | | 4 |
| Orthocladinae | | 4 |
| Chironomini | 13 | 25 |
| *Polypedium* sp. | 11 | 19 |
| Tanytarsini | 1 | 3 |
| *Micropsectra* sp. | 2 | 2 |
| Empididae | | |
| Tipulidae | | |
| *Antocha* sp. | | |
| *Pseudolimnophila* sp. | 1 | |

**Table MBB 2. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 $m^2$) at sites in Muddy Bridge Branch on 30 September 2013. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | Muddy Bridge Branch (300 + subsample) | |
|---|---|---|
| **Taxa** | **Lower Restoration** | **Middle Restoration** |
| Turbellaria | 11 | 1 |
| Nematoda | | 1 |
| **Annelida** | | |
| Oligchaeta | | |
| Lumbriculidae | 7 | 18 |
| Naididae | 1 | 1 |
| Tubificidae | 46 | 19 |
| Hirudinae | | |
| Glossiphoniidae | 4 | 1 |
| **Gastropoda** | | |
| Physidae | 11 | 3 |
| Planorbidae | 1 | |
| **Insecta** | | |
| Ephemeroptera | | |
| Baetidae | 8 | 6 |
| *Baetis* sp. | 3 | |
| Odonata | | |
| Calopterygidae | | 1 |
| Megaloptera | | |
| Corydalidae | | |
| *Nigronia* sp. | | 2 |
| Trichoptera | | |
| Hydropsychidae | 16 | 15 |
| *Cheumatopsyche* sp. | 26 | 29 |
| *Hydropsyche* sp. | 4 | 12 |
| *Symphytopsyche* sp. | | 1 |
| Coleoptera | | |
| Elmidae | | 1 |
| Diptera | | |
| Chironomidae | 30 | 25 |
| Tanypodinae | 14 | 16 |
| *Ablabesmyia* sp. | | 1 |
| *Thienemannimyia* sp. | 3 | 7 |
| Orthocladinae | | 4 |
| *Thienemanniella* sp. | 1 | |
| Chironomini | 62 | 42 |
| *Polypedium* sp. | 28 | 82 |
| Tanytarsini | 1 | 3 |
| *Micropsectra* sp. | 2 | 3 |

**Table MBB 2 (continued).**

| Taxa | Muddy Bridge Branch (300 + subsample) | |
|---|---|---|
| | Lower Restoration | Middle Restoration |
| Empididae | | |
| *Hemerodromia* sp. | | 2 |
| Tipulidae | | |
| *Pseudolimnophila* sp. | 1 | |

## Muddy Bridge Branch – April 2014

**Table MBB 3. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 $m^2$) at sites in Muddy Bridge Branch on 4 April 2014. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | Muddy Bridge Branch Sampling Sites (100 + subsample) | | |
|---|---|---|---|
| **Taxa** | **Alpha Control** | **Lower Restoration** | **Middle Restoration** |
| Nematoda | | | 1 |
| **Annelida** | | | |
| Oligchaeta | | | |
| Lumbriculidae | 9 | 2 | 2 |
| Enchytraeidae | 1 | | |
| Naididae | | | |
| Tubificidae | 9 | 1 | 4 |
| Hirudinae | | | |
| Glossiphoniidae | 1 | | |
| **Pelycepoda** | | | |
| Sphaeridae | 5 | | |
| **Insecta** | | | |
| Diptera | | | |
| Chironomidae | 3 | 1 | 3 |
| Tanypodinae | 10 | 4 | 2 |
| *Natarsia* sp. | | 1 | 1 |
| *Rheopelopia* sp. | 3 | | |
| Orthocladinae | | 1 | |
| Chironomini | 1 | 2 | 1 |
| *Demicryptochiromomus* sp. | | | 1 |
| *Dicrotendipes* sp. | 3 | | 1 |
| *Polypedium* sp. | 1 | 2 | 4 |
| *Stenochironomus* sp. | | | 1 |

## Piney Creek – September 2013

**Table PIC 1. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 $m^2$) at sites in Piney Creek on 23 September 2013. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | Piney Creek Sampling Sites (100 + subsample) | | | |
|---|---|---|---|---|
| **Taxa** | **Alpha Control** | **Beta Control** | **Lower Restoration** | **Middle Restoration** |
| Turbellaria | | 1 | | 1 |
| Nemerta | | 1 | | |
| **Annelida** | | | | |
| Oligochaeta | | | | |
| Naididae | 2 | | | |
| Tubificidae | | 1 | | |
| **Insecta** | | | | |
| Ephemeroptera | | | | |
| Baetidae | 8 | 7 | 4 | 9 |
| *Acentrella* sp. | 2 | 2 | 1 | 10 |
| *Baetis* sp. | | | | 1 |
| Heptageniidae | 3 | | | |
| *Stenonema* sp. | | | | 2 |
| Plecoptera | | | | |
| Perlidae | | | | |
| *Acroneuria* sp. | 1 | | | 1 |
| Megaloptera | | | | |
| Corydalidae | | | | |
| *Corydalus* sp. | | 2 | | 1 |
| *Nigronia* sp. | | 2 | 2 | |
| Trichoptera | | | | |
| Glossosomatidae | | | | |
| *Glossosoma* sp. | 3 | 1 | 4 | 2 |
| Hydropsychidae | 5 | 3 | 7 | 6 |
| *Cheumatopsyche* sp. | 1 | 1 | 13 | 7 |
| *Hydropsyche* sp. | 11 | 12 | 3 | 11 |
| *Symphytopsyche* sp. | 14 | 7 | 17 | 10 |
| Hydroptilidae | | | 1 | 1 |
| *Leucotrichia* sp. | | 3 | 3 | 3 |
| Philopotomatidae | | | | |
| *Chimera* sp. | 3 | | 1 | |
| *Dolophilodes* sp. | 1 | | | |
| Rhyacophilidae | | | | |
| *Rhyacophila* sp. | 3 | | | 4 |

**Table PIC 1 (continued).**

| Taxa | Piney Creek Sampling Sites (100 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Coleoptera | | | | |
| Elmidae | 3 | 1 | 1 | |
| *Optioservus* sp. | | 3 | 3 | |
| *Stenelmis* sp. | | | 1 | |
| Psephenidae | | | | |
| *Psephenus* sp. | | | 1 | |
| Diptera | | | | |
| Chironomidae | 11 | 7 | 15 | 3 |
| Tanypodinae | | 1 | | |
| Diamesinae | | | | |
| *Diamesa* sp. | | 1 | | |
| Orthocladinae | 2 | 2 | 1 | |
| *Corynoneura* sp. | | 1 | | |
| *Eukieferella* sp. | 3 | 4 | | 3 |
| *Orthocladius* sp. | 4 | 2 | 3 | 1 |
| *Parametriocnemus* sp. | | | 1 | |
| *Thienemanellia* sp. | 5 | 3 | 2 | 1 |
| *Synorthocladius* sp. | | | 1 | |
| Chironomini | 2 | 2 | 7 | 7 |
| *Apedilum* sp. | | 1 | 5 | 2 |
| *Polypedilum* sp. | 4 | 5 | 1 | 3 |
| *Pseudochironomus* sp, | 1 | 1 | | |
| Tanytarsini | 3 | 3 | 5 | 5 |
| *Micropsectra* sp. | | 1 | | |
| *Rheotanytarsus* sp. | 1 | 2 | | |
| Empididae | | | | |
| *Clinocera* sp. | | 1 | | |
| *Hemerodromia* sp. | | | 1 | |
| Simulidae | | 1 | | |
| *Simulium* sp. | 1 | 1 | | 3 |
| Tipulidae | 2 | | | 1 |
| *Antocha* sp. | 5 | 7 | 5 | 7 |
| *Pseudolimnophila* sp. | | 1 | 4 | |
| *Tipula* sp. | | | 1 | |

**Table PIC 2. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 $m^2$) at sites in Piney Creek on 23 September 2013. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | **Piney Creek Sampling Sites (300 + subsample)** | | | |
|---|---|---|---|---|
| **Taxa** | **Alpha Control** | **Beta Control** | **Lower Restoration** | **Middle Restoration** |
| Turbellaria | | 2 | | 1 |
| Nemerta | 2 | 6 | | 1 |
| **Annelida** | | | | |
| Oligochaeta | | | | |
| Naididae | 4 | 1 | | |
| Lumbriculidae | | | | 1 |
| Tubificidae | | 1 | | |
| **Insecta** | | | | |
| Ephemeroptera | | | | |
| Baetidae | 16 | 15 | 21 | 25 |
| *Acentrella* sp. | 10 | 13 | 1 | 28 |
| *Baetis* sp. | 2 | | 1 | 4 |
| Ephemerellidae | 2 | 1 | | |
| *Ephemerella* sp. | | | 1 | |
| Heptageniidae | 3 | 1 | 4 | 1 |
| *Stenonema* sp. | 8 | 3 | 2 | 3 |
| Isonychidae | | | | |
| *Isonychia* sp. | | 1 | | |
| Odonata | | | | |
| Ashenidae | | | | |
| *Boyeria* sp. | | | 1 | |
| Gomphidae | | | 1 | |
| Plecoptera | | | | |
| Perlidae | | | | |
| *Acroneuria* sp. | 1 | | | 1 |
| Megaloptera | | | | |
| Corydalidae | | | | |
| *Corydalus* sp. | | | 1 | 1 |
| *Nigronia* sp. | | 3 | 2 | |
| Trichoptera | | | | |
| Glossosomatidae | | | | |
| *Glossosoma* sp. | 14 | 3 | 13 | 11 |
| Hydropsychidae | 13 | 12 | 22 | 15 |
| *Cheumatopsyche* sp. | 8 | 14 | 28 | 14 |
| *Diplectrona* sp. | | 1 | | |
| *Hydropsyche* sp. | 30 | 21 | 18 | 32 |
| *Symphytopsyche* sp. | 42 | 29 | 43 | 36 |
| Hydroptilidae | | | 2 | 1 |
| *Leucotrichia* sp. | 1 | 4 | 6 | 8 |

**Table PIC 2 (continued).**

| Taxa | Piney Creek Sampling Sites (300 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Philopotomatidae | | | | |
| *Chimera* sp. | 6 | 2 | 3 | |
| *Dolophilodes* sp. | 2 | | | |
| Rhyacophilidae | | | | |
| *Rhyacophila* sp. | 4 | | | 8 |
| Coleoptera | | | | |
| Elmidae | 7 | 8 | 11 | |
| *Optioservus* sp. | 3 | 9 | 9 | 2 |
| *Stenelmis* sp. | | | 2 | |
| Hydrophilidae | | | | |
| *Hydrobius* sp. | | | 1 | |
| Psephenidae | | | | |
| *Psephenus* sp. | 1 | 1 | 2 | |
| Diptera | | | | |
| *Forcipomyia* sp. | | | | 1 |
| Chironomidae | 33 | 31 | 48 | 14 |
| Tanypodinae | | 1 | | |
| Diamesinae | | | | |
| *Diamesa* sp. | | 2 | 1 | |
| Orthocladinae | 9 | 5 | 4 | 1 |
| *Corynoneura* sp. | | 1 | | |
| *Eukieferella* sp. | 8 | 7 | 1 | 11 |
| *Orthocladius* sp. | 11 | 4 | 8 | 5 |
| *Parametriocnemus* sp. | | 2 | 1 | |
| *Thienemanellia* sp. | 7 | 6 | 3 | 3 |
| *Synorthocladius* sp. | | | 1 | |
| Chironomini | 12 | 17 | 13 | 12 |
| *Apedilum* sp. | | 3 | 26 | 3 |
| *Chironomus* sp. | | | | 1 |
| *Polypedilum* sp. | 11 | 13 | 12 | 7 |
| Pseudochironomini | | | | 2 |
| *Pseudochironomus* sp, | 5 | 10 | 1 | 2 |
| Tanytarsini | 4 | 4 | 6 | 15 |
| *Micropsectra* sp. | | 1 | | |
| *Rheotanytarsus* sp. | 2 | 2 | | |
| Empididae | | 1 | | |
| *Clinocera* sp. | | 1 | 1 | |
| *Hemerodromia* sp. | | 1 | 2 | |

**Table PIC 2 (continued).**

| Taxa | Piney Creek Sampling Sites (300 + subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Simulidae | | 1 | | |
| *Simulium* sp. | 3 | 4 | | 7 |
| Tipulidae | 3 | | | 4 |
| *Antocha* sp. | 18 | 13 | 19 | 11 |
| *Pseudolimnophila* sp. | 1 | 2 | 7 | |
| *Tipula* sp. | | | 2 | |

## Piney Creek – March 2014

**Table PIC 3. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 $m^2$) at sites in Piney Creek on 24 March 2014. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | Piney Creek Sampling Sites (100+ subsample) | | | |
|---|---|---|---|---|
| **Taxa** | **Alpha Control** | **Beta Control** | **Lower Restoration** | **Middle Restoration** |
| Turbellaria | | | | |
| Nemerta | | | | |
| **Annelida** | | | | |
| Nematoda | | | | 1 |
| Oligochaeta | | | | |
| Naididae | | | | |
| Tubificidae | | 1 | | |
| **Insecta** | | | | |
| Ephemeroptera | | | | |
| Baetidae | | | 1 | |
| Ephemerellidae | | | 1 | 1 |
| *Ephemerella* sp. | 29 | 32 | 18 | 24 |
| Heptageniidae | | 1 | | |
| Plecoptera | | | | |
| Nemouridae | | | | |
| *Ostrocerca* sp. | | 1 | 1 | |
| Perlidae | | | | |
| *Acroneuria* sp. | 1 | | 1 | |
| Megaloptera | | | | |
| Corydalidae | | | | |
| Trichoptera | | | | |
| Hydropsychidae | | 4 | 6 | 2 |
| *Cheumatopsyche* sp. | 2 | 6 | 3 | 4 |
| *Diplectrona* sp. | | 1 | | |
| *Hydropsyche* sp. | 2 | 2 | 2 | |
| *Symphytopsyche* sp. | 2 | 4 | 5 | 2 |
| Hydroptilidae | | | | |
| *Leucotrichia* sp. | | 1 | | |
| Philopotomatidae | | | | |
| *Chimarra* sp. | 1 | 1 | 1 | 2 |
| Dolophilodes sp. | | | | |
| Rhyacophilidae | | | | |
| *Rhyacophila* sp. | | | 3 | 1 |
| Uenoidae | | | | |
| *Neophylax* sp. | | | | 1 |
| Coleoptera | | | | |

**Table PIC 3 (continued).**

| Taxa | Piney Creek Sampling Sites (100+ subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Elmidae | | 1 | | 1 |
| *Optioservus* sp. | 1 | 1 | 2 | |
| *Oulimnius* sp. | | | 1 | 1 |
| *Stenelmis* sp. | | 1 | | 1 |
| Psephenidae | | | | |
| *Psephenus* sp. | | | | |
| Diptera | | | | |
| Chironomidae | 7 | 5 | 4 | 10 |
| Tanypodinae | | | | |
| Diamesinae | | | | |
| *Diamesa* sp. | 1 | 1 | | 2 |
| Orthocladinae | 5 | 9 | 6 | 11 |
| *Corynoneura* sp. | | | 1 | |
| *Eukieferella* sp. | 4 | | 1 | |
| *Hydrobaenus* sp. | | 1 | | |
| *Orthocladius* sp. | 11 | 9 | 13 | 15 |
| *Parametriocnemus* sp. | 2 | 1 | | |
| *Thienemanellia* sp. | | | | |
| *Synorthocladius* sp. | | | | |
| Chironomini | 2 | | 2 | 1 |
| *Apedilum* sp. | 1 | | 1 | |
| *Polypedilum* sp. | 8 | 3 | 4 | 8 |
| *Pseudochironomus* sp, | | | 1 | |
| Tanytarsini | 2 | | 2 | |
| *Micropsectra* sp. | | 1 | | |
| *Paratanytrsus* sp. | | | 2 | |
| *Rheotanytarsus* sp. | | | | 5 |
| Empididae | | | | |
| *Chelifera* sp. | 2 | 1 | | |
| *Clinocera* sp. | 3 | 1 | 7 | 8 |
| *Hemerodromia* sp. | | | 1 | 1 |
| Simulidae | 1 | 2 | 1 | 1 |
| *Prosimulim* sp. | 10 | 4 | 9 | 3 |
| *Stegopturna* sp. | 1 | 1 | 1 | |
| Tipulidae | | | | |
| *Antocha* sp. | 3 | 3 | 9 | 4 |
| *Pseudolimnophila* sp. | | | | |
| *Tipula* sp. | | | 1 | |

**Table PIC 4. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 $m^2$) at sites in Piney Creek on 24 March 2014. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| Taxa | Piney Creek Sampling Sites (300+ subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Turbellaria | | | 1 | |
| Nemerta | | | 2 | |
| Annelida | | | | |
| Nematoda | | 1 | | 2 |
| Lumbriculidae | 1 | | | |
| Tubificidae | | 2 | 1 | |
| **Insecta** | | | | |
| Ephemeroptera | | | | |
| Baetidae | 2 | | 1 | 1 |
| Ephemerellidae | 4 | 1 | 1 | 2 |
| *Ephemerella* sp. | 85 | 114 | 76 | 78 |
| Heptageniidae | 2 | 1 | 1 | |
| *Stenonema* sp. | 2 | | 1 | |
| Plecoptera | | | | |
| Leuctridae | 1 | 1 | | |
| Nemouridae | | | | |
| *Amphinemoura* sp. | | 2 | | |
| *Ostrocerca* sp. | 1 | 2 | 2 | |
| Perlidae | | | | |
| *Acroneuria* sp. | 3 | 2 | 1 | 1 |
| Megaloptera | | | | |
| Corydalidae | | | | |
| *Corydalus* sp. | | 1 | 2 | |
| *Nigronia* sp. | | 1 | 1 | |
| Trichoptera | | | | |
| Hydropsychidae | | 10 | 14 | 10 |
| *Cheumatopsyche* sp. | 3 | 9 | 5 | 12 |
| *Diplectrona* sp. | | 2 | 1 | |
| *Hydropsyche* sp. | 5 | 9 | 3 | 1 |
| *Symphytopsyche* sp. | 4 | 9 | 17 | 8 |
| Hydroptilidae | | | | |
| *Leucotrichia* sp. | | 1 | | 4 |
| Philopotomatidae | | | | |
| *Chimarra* sp. | 2 | 1 | 1 | 2 |
| *Dolophilodes* sp. | | | | |
| Rhyacophilidae | | | | |
| *Rhyacophila* sp. | | 3 | 4 | 1 |
| Uenoidae | | | | |
| *Neophylax* sp. | | 1 | 2 | 1 |

**Table PIC 3 (continued).**

| Taxa | Piney Creek Sampling Sites (300+ subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Coleoptera | | | | |
| Elmidae | | 2 | 4 | 5 |
| *Optioservus* sp. | 4 | 1 | 5 | 2 |
| *Oulimnius* sp. | | | 2 | 1 |
| *Stenelmis* sp. | | 1 | | 2 |
| Hydrophilidae | | | | |
| *Hydrobius* sp. | | | | |
| Psephenidae | | | | |
| *Psephenus* sp. | | | 1 | 1 |
| Diptera | | | | |
| Ceratopogonidae | | | | |
| *Probezzia* sp. | | | | 1 |
| Chironomidae | 17 | 12 | 11 | 19 |
| Tanypodinae | 1 | | 1 | 1 |
| Diamesinae | | | | |
| *Diamesa* sp. | 1 | 6 | | 2 |
| Orthocladinae | 9 | 26 | 14 | 22 |
| *Corynoneura* sp. | | | 1 | |
| *Eukieferella* so. | 9 | 1 | 9 | 4 |
| *Hydrobaenus* sp. | | 1 | | |
| *Orthocladius* sp. | 37 | 46 | 17 | 53 |
| *Parametriocnemus* sp. | 2 | 11 | | |
| *Thienemanellia* sp. | 9 | | 8 | 10 |
| *Synorthocladius* sp. | | | | |
| Chironomini | 4 | 6 | 3 | 6 |
| *Apedilum* sp. | 1 | | 2 | |
| *Chironomus* sp. | | | | |
| *Euryhapsis* sp. | 5 | | | |
| *Polypedilum* sp. | 15 | 8 | 6 | 14 |
| *Pseudochironomini* sp. | | | 2 | |
| Tanytarsini | 3 | 1 | 3 | 1 |
| *Micropsectra* sp. | 1 | 1 | | |
| *Paratanytrsus* sp. | | | 10 | 6 |
| *Rheotanytarsus* sp. | 3 | 1 | 12 | 7 |
| *Tanytarsus* sp. | | 1 | | |
| Empididae | | | | |
| *Chelifera* sp. | 3 | 2 | 1 | 2 |
| *Clinocera* sp. | 11 | 9 | 18 | 17 |
| *Hemerodromia* sp. | 1 | | 1 | 1 |

**Table PIC 4 (continued).**

| Taxa | Piney Creek Sampling Sites (300+ subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Lower Restoration | Middle Restoration |
| Simulidae | 3 | 2 | 2 | 2 |
| *Prosimilum* sp. | 31 | 11 | 16 | 3 |
| *Simulium* sp. | | | | |
| *Stegopturna* sp. | 1 | 1 | 3 | |
| Tipulidae | | 1 | | 1 |
| *Antocha* sp. | 8 | 12 | 24 | 30 |
| *Dicronata* sp. | 1 | | 1 | |
| *Pseudolimnophila* sp. | | | | |
| *Tipula* sp. | | | 1 | |

## Plumtree Run – September 2013

**Table PTR 1 . Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 m $^2$) at sites in Plumtree Run on 23 September 2013. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | Plumtree Run Sampling Sites (100+ subsample) | | | |
|---|---|---|---|---|
| **Taxa** | **Alpha Control** | **Beta Control** | **Gamma Control** | **Delta Control** |
| Hoplonemerta | | | | |
| Turbellaria | 1 | | | 1 |
| **Annelida** | | | | |
| Oligochaeta | | | | |
| Naididae | 1 | 1 | 4 | |
| Lumbriculidae | | | 1 | |
| Tubificidae | 3 | | 1 | |
| **Crustaceae** | | | | |
| Amphipoda | | | | |
| Crangonyctidae | 5 | 2 | 1 | |
| *Synurella* sp. | 3 | 3 | | 2 |
| Isopoda | | | | |
| Asellidae | | | | |
| *Caecidotea* sp. | | | | |
| **Insecta** | | | | |
| Ephemeroptera | | | | |
| Baetidae | 5 | 4 | 2 | 3 |
| *Baetis* sp. | 1 | 1 | 2 | 4 |
| Trichoptera | | | | |
| Glossosomatidae | | | | |
| *Glossosoma* sp. | | | 1 | |
| Hydropsychidae | 1 | 8 | 4 | 3 |
| *Cheumatopsyche* sp. | 4 | 12 | 5 | 9 |
| *Hydropsyche* sp. | | 5 | 5 | 3 |
| Philopotomatidae | | 4 | 3 | 2 |
| *Chimera* sp. | 2 | 24 | 6 | 18 |
| Psychomyidae | | | | |
| *Psychomyia* sp. | 1 | | | |
| Coleoptera | | | | |
| Elmidae | | 1 | 3 | 2 |
| *Stenelmis* sp. | 16 | 7 | 4 | 4 |
| Psephenidae | | | | |
| *Psephenus* sp. | 4 | 2 | | 3 |
| Diptera | | | | |
| Ceratopogonidae | | | | |
| *Culicoides* sp. | 1 | | | |

**Table PTR 1 (continued).**

| Taxa | Plumtree Run Sampling Sites (100+ subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Gamma Control | Delta Control |
| Chironomidae | 3 | 3 | 10 | 6 |
| Tanypodinae | | | | 1 |
| Orthocladinae | 13 | 3 | 10 | 1 |
| *Eukiefferiela* sp. | | 2 | | 2 |
| *Orthocladius* sp. | 26 | 4 | 9 | 4 |
| *Parametriocnemus* sp. | | 1 | | 1 |
| *Thienemmaniella* sp. | 6 | | 3 | 4 |
| Chironomini | 2 | | | |
| *Polypedilum* sp. | 1 | 1 | | |
| *Pseudochironomus* sp. | | 1 | 2 | |
| Tanytarsini | 6 | | 10 | 13 |
| *Micropsectra* sp. | | | | 4 |
| *Rheotanytarsus* sp. | | | | 2 |
| *Tanytarsus* sp. | | | 1 | 2 |
| Empididae | | | | |
| *Hemerodromia* sp. | | 1 | 1 | 1 |
| Simulidae | | | | 1 |
| Tipulidae | | | | |
| *Antocha* sp. | 3 | 1 | 2 | 3 |
| *Tipula* sp. | | 2 | | 1 |

**Table PTR 2. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 $m^2$) at sites in Plumtree Run on 23 September 2013. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | Plumtree Run Sampling Sites (300+ subsample) | | | |
|---|---|---|---|---|
| **Taxa** | **Alpha Control** | **Beta Control** | **Gamma Control** | **Delta Control** |
| Hoplonemerta | 1 | 1 | 1 | 2 |
| Turbellaria | 1 | | | 1 |
| **Annelida** | | | | |
| Oligochaeta | | | | |
| Lumbriculidae | 1 | 1 | 3 | 1 |
| Naididae | 1 | 2 | 7 | |
| Tubificidae | 4 | | 1 | |
| **Gastropoda** | | | | |
| Ancylidae | | | | |
| *Ferrissia* sp. | 1 | | | |
| **Crustaceae** | | | | |
| Amphipoda | | | | |
| Crangonyctidae | 21 | 3 | 2 | |
| *Synurella* sp. | 15 | 9 | 4 | 3 |
| Isopoda | | | | |
| Asellidae | | | | |
| *Caecidotea* sp. | 1 | 1 | | 1 |
| **Insecta** | | | | |
| Ephemeroptera | | | | |
| Baetidae | 15 | 9 | 18 | 20 |
| *Baetis* sp. | 4 | 4 | 5 | 7 |
| Megaloptera | | | | |
| Corydalidae | | | | |
| *Nigronia* sp. | 1 | | | |
| Trichoptera | | | | |
| Glossosomatidae | | | | |
| *Glossosoma* sp. | | | 2 | 1 |
| Hydropsychidae | 3 | 23 | 13 | 16 |
| *Cheumatopsyche* sp. | 13 | 33 | 13 | 28 |
| *Diplectrona* sp. | | | | 1 |
| *Hydropsyche* sp. | 2 | 16 | 11 | 5 |
| *Symphytopsyche* sp. | | 11 | 2 | 1 |
| Philopotomatidae | | 14 | 9 | 4 |
| *Chimera* sp. | 5 | 69 | 44 | 52 |
| Psychomyidae | | | | |
| *Psychomyia* sp. | 1 | | 1 | |

**Table PTR 2 (continued).**

| Taxa | Plumtree Run Sampling Sites (300+ subsample) | | | |
|---|---|---|---|---|
| | Alpha Control | Beta Control | Gamma Control | Delta Control |
| Coleoptera | | | | |
| Elmidae | | 2 | 4 | 2 |
| *Stenelmis* sp. | 48 | 19 | 24 | 13 |
| Psephenidae | | | | |
| *Psephenus* sp. | 15 | 10 | 4 | 6 |
| Diptera | | | | |
| Ceratopogonidae | | | | 1 |
| *Attrichopogon* sp. | | | | 1 |
| *Culicoides* sp. | 1 | | | 1 |
| Chironomidae | 15 | 8 | 18 | 17 |
| Tanypodinae | 4 | | | 2 |
| Orthocladinae | 30 | 5 | 11 | 9 |
| *Corynoneura* sp. | | 4 | | 4 |
| E*ukiefferiela* sp. | | 7 | | 1 |
| *Orthocladius* sp. | 47 | 10 | 50 | 27 |
| *Parametriocnemus* sp. | 21 | 16 | | 5 |
| *Thienemmaniella* sp. | 14 | 4 | 17 | 9 |
| Chironomini | 2 | 3 | | 3 |
| *Apedilum* sp. | 1 | | 5 | |
| *Cryptochironomus* sp. | 1 | | | |
| *Polypedilum* sp. | 1 | 5 | 1 | 2 |
| *Pseudochironomus* sp. | | 1 | 7 | 5 |
| Tanytarsini | 10 | 5 | 11 | 29 |
| *Micropsectra* sp. | 4 | 2 | 5 | 6 |
| *Rheotanytarsus* sp. | | | 16 | 3 |
| *Tanytarsus* sp. | | | 1 | 3 |
| Empididae | | | | |
| *Clinocera* sp. | | | | 1 |
| *Hemerodromia* sp. | | 4 | 1 | 2 |
| Ephedridae | | | | |
| *Scatella* sp. | | 1 | | |
| Simulidae | | | | 2 |
| Tipulidae | | | | 1 |
| *Antocha* sp. | 4 | 3 | 3 | 8 |
| *Pseudolimnophila* sp. | | | 1 | |
| *Tipula* sp. | 3 | 2 | | 1 |

## Plumtree Run – April 2014

**Table PTR 3. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 $m^2$) at sites in Plumtree Run on March/May 2014. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | Plumtree Run Sampling Sites (100+ subsample) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Taxa** | **Alpha Control** | **Beta Control** | **Delta Control** | **Sigma Control** | **Upper Control** | **Lower Restoration** | **Middle Restoration** |
| Nematoda | | | 2 | | | | 2 |
| **Annelida** | | | | | | | |
| Oligochaeta | | 1 | | | | | |
| Lumbriculidae | | | | 2 | 2 | 1 | |
| Naididae | | | 2 | | | 24 | 2 |
| Entrichidae | | | | | 1 | 1 | |
| Tubificidae | | | | | 2 | | |
| **Crustaceae** | | | | | | | |
| Amphipoda | | | | | 12 | 4 | |
| Crangonyctidae | | | | | | | |
| *Synurella* sp. | | | | 2 | 13 | 13 | 1 |
| Isopoda | | | | | | | |
| Aesillidae | | | | | | | |
| *Caecidotea* sp. | | | | | 2 | | |
| **Insecta** | | | | | | | |
| Plecoptera | | | | | | | |
| Nemouridae | | | | | | | |
| *Amphinemoura* sp. | | | 1 | | | 1 | |
| Trichoptera | | | | | | | |
| Hydropsychidae | 2 | 1 | | 2 | 1 | | 1 |
| *Cheumatopsyche* sp. | 3 | 2 | | 22 | 1 | | |
| *Hydropsyche* sp. | | | | 9 | 1 | 1 | |
| *Symphytopsyche* sp. | 1 | | | 2 | | | 1 |
| Philopotomatidae | | | | | | | |
| *Chimera* sp. | 18 | 6 | 1 | 7 | 4 | 4 | 1 |
| Coleoptera | | | | | | | |
| Elmidae | | | | 4 | | | |
| *Oulimnius* sp. | | | | 1 | | | |
| *Stenelmis* sp. | 3 | 6 | | 13 | 17 | 7 | 1 |
| Psephenidae | | | | | | | |
| *Psephenus* sp. | | | | 1 | | 1 | |
| Diptera | | | | | | | |
| *Culicoides* sp. | | | 1 | | | | |
| Chironomidae | 4 | 4 | 2 | 4 | 8 | 5 | 1 |

**Table PTR 3 (continued).**

| Taxa | Plumtree Run Sampling Sites (100+ subsample) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Alpha Control | Beta Control | Delta Control | Sigma Control | Upper Control | Lower Restoration | Middle Restoration |
| Diamesinae | | | | | | | |
| *Diamesa* sp. | | | 1 | 2 | | 1 | |
| Tanypodinae | | 1 | | | | 2 | 1 |
| *Thienemannimyia* sp. | 2 | | | | | 3 | 4 |
| Orthocladinae | | 1 | 3 | 2 | 2 | 4 | 4 |
| *Brillia* sp. | | | 5 | | | | |
| *Eukiefferiela* sp. | | 4 | 5 | 1 | | 1 | 9 |
| *Hydrobaenus* sp. | | | | | 3 | | |
| *Orthocladius* sp. | 54 | 44 | 84 | 6 | 25 | 28 | 38 |
| *Parametriocnemus* sp. | 4 | | | 1 | | | 14 |
| *Thienemmaniella* sp. | | 4 | | | | | 5 |
| Chironomini | 7 | 5 | 1 | 3 | | 3 | 3 |
| *Dicrotendipes* sp. | | | | | 2 | 1 | |
| *Polypedilum* sp. | 1 | | | 20 | 5 | 8 | |
| *Pseudochironomus* sp. | | 2 | | | | | 1 |
| Tanytarsini | 1 | 2 | 1 | | 1 | 1 | 1 |
| *Micropsectra* sp. | | 3 | 1 | | | 2 | 4 |
| *Rheotanytarsus* sp. | | | | | | 1 | |
| Empididae | | | | | | | |
| *Chelifera* sp. | | | | 1 | | | |
| *Hemerodromia* sp | | | | 3 | 3 | | |
| Simulidae | | | | 1 | | 1 | |
| *Stegopturna* sp. | | | | | | 1 | |
| Tipulidae | 1 | | 1 | | | | |
| *Antocha* sp. | 7 | 8 | 3 | 4 | | | |
| *Tipula* sp. | | | | | | 2 | |

**Table PTR 4. Numbers of macroinvertebrates collected in benthic samples by combining 9 D-frame aquatic net samplings (total sampling area approximately 1 $m^2$) at sites in Plumtree Run on March/May 2014. Insect quantities represent numbers of larvae or nymphs unless designated otherwise by a P for pupa or A for adult.**

| | **Plumtree Run Sampling Sites (300+ subsample)** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Taxa** | **Alpha Control** | **Beta Control** | **Delta Control** | **Sigma Control** | **Upper Control** | **Lower Restoration** | **Middle Restoration** |
| Hoplonemerta | 1 | | | 2 | 1 | | |
| Turbellaria | | | | 1 | | | |
| Nematoda | 5 | 4 | 2 | | | | 3 |
| **Annelida** | | | | | | | |
| Oligochaeta | | 1 | | | | | |
| Enchytraeidae | | | | | 2 | | |
| Lumbriculidae | | | | 6 | 2 | | |
| Naididae | 3 | | 2 | 3 | | | 3 |
| Tubificidae | | | | | 4 | | |
| **Crustaceae** | | | | | | | |
| Amphipoda | | | | 5 | 41 | | |
| Crangonyctidae | | | | | | | |
| *Synurella* sp. | | 3 | 3 | 8 | 31 | | 2 |
| Isopoda | | | | | | | |
| Asellidae | | | | | 1 | | |
| *Caecidotea* sp. | | | | | 1 | | |
| **Insecta** | | | | | | | |
| Plecoptera | | | | | | | |
| Nemouridae | | | | | | | |
| *Amphinemoura* sp. | | | 1 | 3 | | | |
| Trichoptera | | | | | | | |
| Glossosomatidae | | 1 | | | | | |
| Hydropsychidae | 3 | 1 | 1 | 9 | 1 | | 1 |
| *Cheumatopsyche* sp. | 6 | 5 | 1 | 53 | 3 | | |
| *Hydropsyche* sp. | 6 | 3 | | 13 | 5 | | |
| *Symphytopsyche* sp. | 2 | 1 | | 4 | | | 1 |
| Philopotomatidae | 2 | 1 | | | | | |
| *Chimera* sp. | 46 | 13 | 10 | 13 | 15 | | 1 |
| Psychomyidae | | 2 | | | | | |
| *Psychomyia* sp. | | | | | | | |
| Coleoptera | | | | | | | |
| Elmidae | | | | 10 | 3 | | |
| *Oulimnius* sp. | | | 2 | 2 | | | |
| *Stenelmis* sp. | 4 | 12 | 5 | 41 | 60 | | 1 |
| Psephenidae | | | | | | | |
| *Psephenus* sp. | 2 | 2 | 1 | 7 | | | |

**Table PTR 4 (continued).**

| Taxa | Plumtree Run Sampling Sites (300+ subsample) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Alpha Control | Beta Control | Delta Control | Sigma Control | Upper Control | Lower Restoration | Middle Restoration |
| Diptera | | | | | | | |
| Ceratopogonidae | | | | | 1 | | |
| *Culicoides* sp. | | | 1 | | | | |
| Chironomidae | 7 | 20 | 8 | 10 | 14 | | 1 |
| Diamesinae | | | | | | | |
| *Diamesa* sp. | 2 | 1 | 1 | 4 | | | |
| Tanypodinae | 1 | 1 | | | | | 2 |
| *Thienemannimyia* sp. | | | 1 | | 1 | | 5 |
| Orthocladinae | 1 | 16 | 8 | 6 | 6 | | |
| *Brillia* sp. | | | 5 | | | | |
| *Cricotopus* sp. | 5 | | | | | | |
| *Eukiefferiela* sp. | | 8 | 10 | 5 | | | 16 |
| *Hydrobaenus* sp. | | | | | 3 | | |
| *Krenosmittia* sp. | | | | | 8 | | |
| *Orthocladius* sp. | 179 | 129 | 224 | 15 | 58 | | 49 |
| *Parametriocnemus* sp. | 6 | 4 | 9 | 1 | | | 14 |
| *Thienemmaniella* sp. | | 4 | | | | | 5 |
| Chironomini | 13 | 12 | 8 | 7 | 2 | | 11 |
| *Apedilum* sp. | 1 | 1 | | | | | |
| *Dicrotendipes* sp. | | | | 1 | 9 | | |
| *Polypedilum* sp. | | 1 | | 44 | 13 | | 1 |
| *Pseudochironomus sp.* | | 2 | | | | | 1 |
| *Tanytarsini* | 1 | 7 | 2 | 1 | 3 | | 1 |
| *Micropsectra sp.* | 3 | 4 | 1 | 1 | | | 4 |
| *Rheotanytarsus sp.* | | 3 | | | 1 | | |
| *Tanytarsus sp.* | | | | | 1 | | |
| *Empididae* | 1 | | | | | | |
| *Chelifera sp.* | 1 | | | 3 | | | |
| *Clinocera sp.* | | 1 | 1 | 1 | | | |
| *Hemerodromia sp.* | 1 | 1 | | 5 | 4 | | |
| *Simulidae* | | | | 1 | 1 | | |
| *Tipulidae* | 2 | | 2 | | | | |
| *Antocha sp.* | 15 | 22 | 6 | 11 | | | |
| *Dicranota sp.* | | | 1 | | | | |
| *Pseudolimnophila sp.* | | 1 | | | | | |