National Pollutant Discharge Elimination System
Phase I MS4 Permit No. 99-DP-3313 MD0068276

Permit Term October 2005 to October 2010

Fifth Annual Report
October 21, 2010

Submitted to:
Water Management Administration
Maryland Department of the Environment
1800 Washington Boulevard
Baltimore, MD 21230

Submitted by:
Highway Hydraulics Division
Maryland State Highway Administration
707 North Calvert Street, C-201
Baltimore, MD 21202

SHA State Highway Administration
Maryland Department of Transportation

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

SHA
State Highway
Administration
MARYLAND DEPARTMENT OF TRANSPORTATION

Beverley K. Swaim-Staley, *Secretary*
Neil J. Pedersen, *Administrator*

Date: January 21, 2011

RE: Fifth Annual NPDES MS 4 Phase I Report
Permit term 10/2005 to 10/2010
Permit No. 99-DP-3313 MD0068276

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

Dear Mr. Clevenger:

We are pleased to submit this annual report for the fifth year of the NPDES Phase I MS4 permit. The annual report covers the time period of October 1, 2009 to December 31, 2010. SHA remains committed to the environmental compliance and stewardship even in this difficult budgetary time for furthering the goals of this state towards the preservation and restoration of the Chesapeake Bay. We hope that you find this report presenting the hard work of many individuals throughout the organization and the work achieved through the leadership at much higher levels. We submitted a re-application for the NPDES Phase I Municipal Separate Storm Sewer System (MS4) permit on October 21 2009. We are awaiting a draft permit from MDE. SHA will continue to comply with the existing permit until the new permit is received from MDE.

SHA has made much progress this past year in fulfilling the requirements and purposes of this permit. As discussed previously, SHA has completed impervious surface accounting in all nine counties and is continuing to update our source identification database for our storm drain system accordingly. SHA has worked closely with the MDE over the last year to coordinate efforts with the Bay TMDL and Maryland Watershed Improvement Plan development.

My telephone number/toll-free number is 1-888-320-9346
Maryland Relay Service for Impaired Hearing or Speech 1.800.735.2258 Statewide Toll Free
Street Address: 707 North Calvert Street • Baltimore, Maryland 21202 • *Phone* 410.545.0300 • www.marylandroads.com

As the State of Maryland has recognized the value in source control of stormwater by implementing the requirements of Environmental Site Design, SHA has realized the value of numerous stormwater credits built over the years for which no accounting exists. SHA will continue its efforts to account for those non-structural practices in truly quantifying the impervious surface that is not treated by any stormwater facility. As well as, quantify our pollutant load reductions by structural and non-structural BMPs.

An electronic file of the report and the MDE database tables will be supplied on a CD separately. We look forward to the coming year and continued growth of our program as well as partnership between our agencies. If you have any questions or need any additional information regarding the SHA NPDES MS 4 program, please contact Karen Coffman at 410-545-8407 or contact me at 410-545-8390.

Sincerely

Karuna

Karuna Pujara

Attachment
CC: Karen Coffman
Dana Havlik
Kirk McClelland
Sonal Sanghavi

Phase I National Pollutant Discharge Elimination System
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Executive Summary

The Maryland State Highway Administration (SHA) is submitting this fifth annual report for the NPDES Phase I 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 annual report covers the time period October 2009 to December 2010. A summary of the permit conditions and our work toward meeting them is provided below as a general overview of SHA permit activities for this report period.

Due to budget cutbacks, some of the programs have been adjusted through scheduling delays or projects placed on hold. This has not affected our commitment and ability to meet the requirements of this permit.

Source Identification

Source identification efforts were completed as reported in the 2008 annual report. Updates to the databases for each NPDES county are on-going. Work continues on our NPDES GIS viewer tool that will enable all users to access the data. The impervious accounting condition has been completed for the nine Phase I counties, however the accounting will be recalculated once MDE publishes the forthcoming accounting protocol. Updates to the impervious layers will be completed every five years or when new ortho-photography is developed statewide.

Discharge Characterization

We continue to investigate and research topics in order to maximize water quality in our construction methods, permanent stormwater runoff controls, decisions in design, and location of roadways and maintenance techniques. The grass swale study has been completed and the final progress report is located in Appendix B. This study evaluated the effects of native grass check dams on pollutant removal. Two other studies have also been included in the appendix of this report: One seeks to optimize our bioretention soil media and the second seeks to evaluate the function of infiltration facilities that have transitioned to wetlands in terms of quality and quantity stormwater treatment.

Management Program

Our program continues to effectively incorporate the many permit components. While we have kept our sights on the development of the new environmental site design (ESD) regulations, we have continued to measure our performance in the areas of erosion and sediment control during construction, illicit discharge detection and 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.

The *One Million Tree Initiative* continues toward reaching the goal of a million trees planted in Maryland by the end of 2011. SHA has partnered with MD DNR, FHWA and the Maryland Department of Safety and Correctional Services to plant a million trees in Maryland as part of Governor O'Malley's *Smart, Green and Growing* initiative.

The Design Build Operate and Maintain (DBOM) pilot to place the operations and maintenance responsibilities for permanent stormwater management facilities with a private company continues. The contract was successfully bid and let. The design/build team is working to guarantee the functioning and maintenance of stormwater facilities in Charles County.

Watershed Assessment

Coordination with local NPDES jurisdictions continues. We are also moving forward with watershed restoration sites within the Patuxent River Watershed. With the EPA Green Highway grant, SHA is in the process of developing an implementation framework for watershed-based stormwater design within SHA which could be applicable to any transportation agency.

Watershed Restoration

SHA has added to the restoration projects and increased the number to 112. Our acreage for watershed restoration has increased to 673 acres of impervious surfaces treated by retrofit projects that include upgrading stormwater facilities and stream stabilization or restoration efforts. As we determined that MDE is interested in our maximizing this effort, we are in the process of developing new pavement retrofits that target open medians on our older highways such as I-70 and I-95. This retrofitting effort also is targeted toward meeting the new Chesapeake Bay TMDL and Maryland Watershed Implementation Plan development. We will continue to maximize these efforts in the future.

Assessment of Controls

The Long Draught Branch stream restoration project has been resurrected but with delayed funding until 2014. We will continue the project with the post-construction monitoring when the project is completed. The *Wet Infiltration Basin Transitional Performance Study* will augment data on assessment of controls.

Program Funding

Our NPDES program remains fully funded.

Total Maximum Daily Loads

SHA has worked closely with the MDE over the last year to coordinate efforts with the Bay TMDL and Maryland Watershed Implementation Plan development. In anticipation of the 2017 and 2020 milestones for Maryland compliance we have developed a strategic plan and dedicated funding and engineering resources. We face these fiscal and organizational challenges of compliance with the desire to improve the Bay water quality and demonstrate the SHA commitment to our natural resource preservation and Bay restoration.

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PART ONE

Standard Permit Conditions and Responses

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 one 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 recently expired on October 21, 2010) focused on improving water quality benefits, developing impervious accounting database and developing a watershed-based outlook for stormwater management and NPDES program elements. We submitted a re-application for the NPDES Phase I Municipal Separate Storm Sewer System (MS4) permit on October 21 2009. We are awaiting a draft permit from MDE. SHA will continue to comply with the existing permit until the new permit is received from MDE.

This is the fifth annual report for the recently expired permit. The report covers a reporting period of October 1, 2009 through December 31, 2010. Part One of the report lists the permit conditions and explains SHA activities over the last year in compliance with each condition. Wherever possible, future activities and schedules for completion are provided. In depth discussions for some of the major program components follow this section. Part Two of this report discusses the SHA Stormwater Facility Program in depth. A number of appendices are included at the end of the report that contain research reports, examples of data and other detailed information.

A CD is also included that contains portable document format (PDF) files of the entire report and appendices as well as delivery of database updates for new data collected over the last year. Since we have not processed any new source identification data into our geodatabase, we will not be delivering Tables A, B, or C since the data delivered with the last report is the most current. Database Table D, Watershed Restoration Project Location, Table F, Chemical Monitoring, Table G, Illicit Discharge Detection and Elimination and Table H, Responsible Personnel Certification Information, are delivered with this report. Only the latest data is delivered in these tables and not our full databases. The source identification and impervious surfaces geodatabases are not delivered this year as the data delivered last year is the most current.

A Administration of Permit

Administration responsibilities of the NPDES MS4 permit for SHA is listed below and an organizational chart is attached as Figure 1-1.

Ms. Karen Coffman
SHA NPDES Manager
Highway Hydraulics Division
(410) 545-8407
kcoffman@sha.state.md.us

NPDES Industrial Permits and associated activities are coordinated by:

Ms. Sonal Sanghavi
Director
Office of Environmental Design
(410) 545-8640
ssanghavi@sha.state.md.us

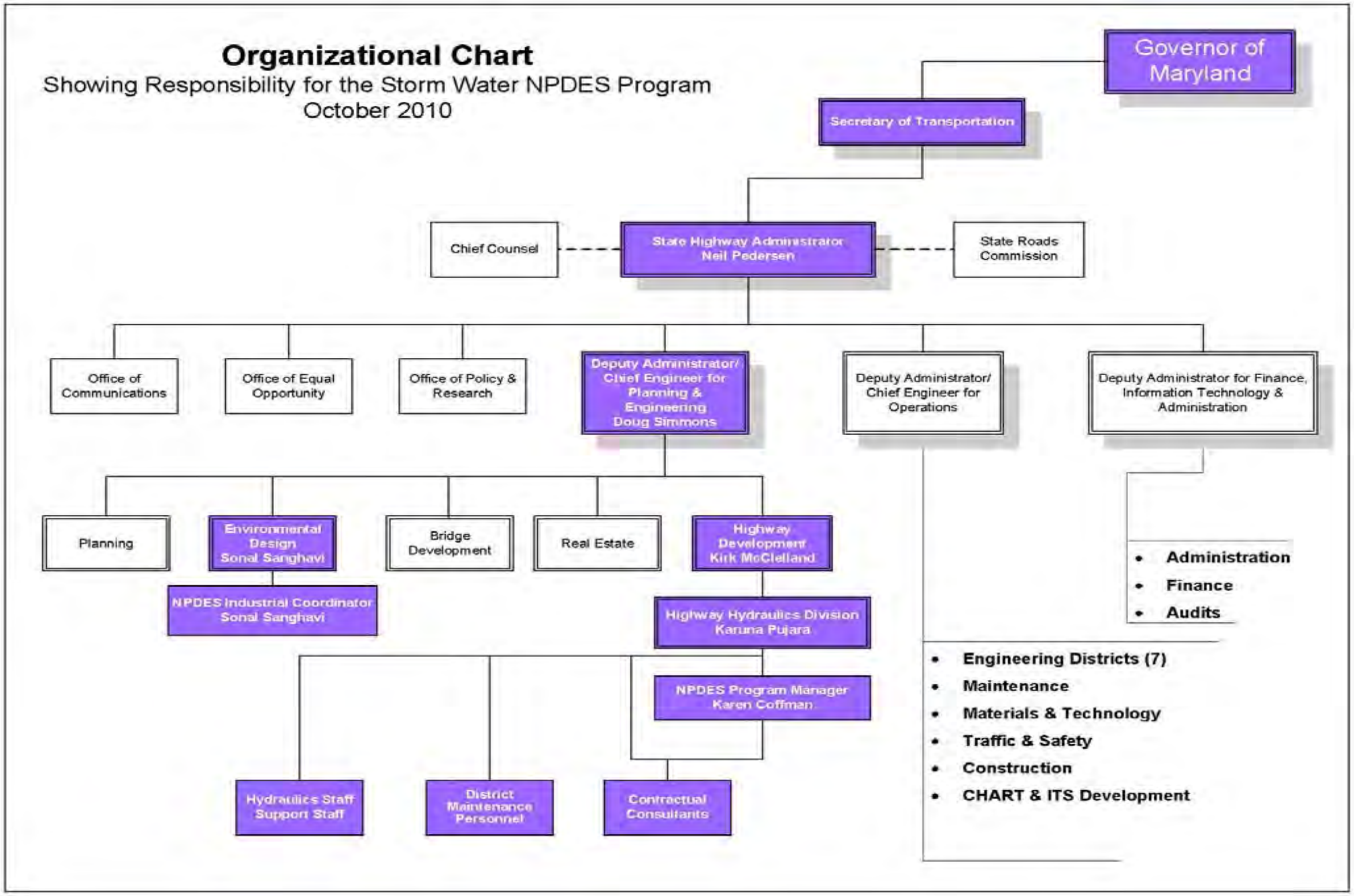


Figure 1-1 Organizational Chart for NPDES Permit Administration

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

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. The geodatabase containing all our hydraulic assets within theses counties as well as inspection data for stormwater management facilities and outfalls is included on the attached CD. Our source identification effort is now focused on periodically updating our geodatabase.

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 all nine counties. Information on source identification updates 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 as well as acquire data from them. The NPDES data generated by SHA is in standard ESRI Geodatabase format and is either natively compatible with other jurisdictions, or can be exported to ESRI shape file format.

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. The geospatial database is deployed using the ESRI Geodatabase data format in an ArcSDE enterprise environment. All of the SHA NPDES data including source identification, BMP inspections, outfall screening, outfall inspections, and impervious area are currently housed in the database. See Figure 1-2 for an example of data displayed in ArcMap.

Updates to the data continue to be performed on a county or district wide basis. The data management and update process is performed using ESRI technology and custom developed applications specific to the SHA data model. SHA has focused on developing a simple data management architecture that allows for the checking out of versioned databases to NPDES team members for updates. The versioned database can be either edited by a custom office editing application, or, deployed to the field with a custom field editing application.

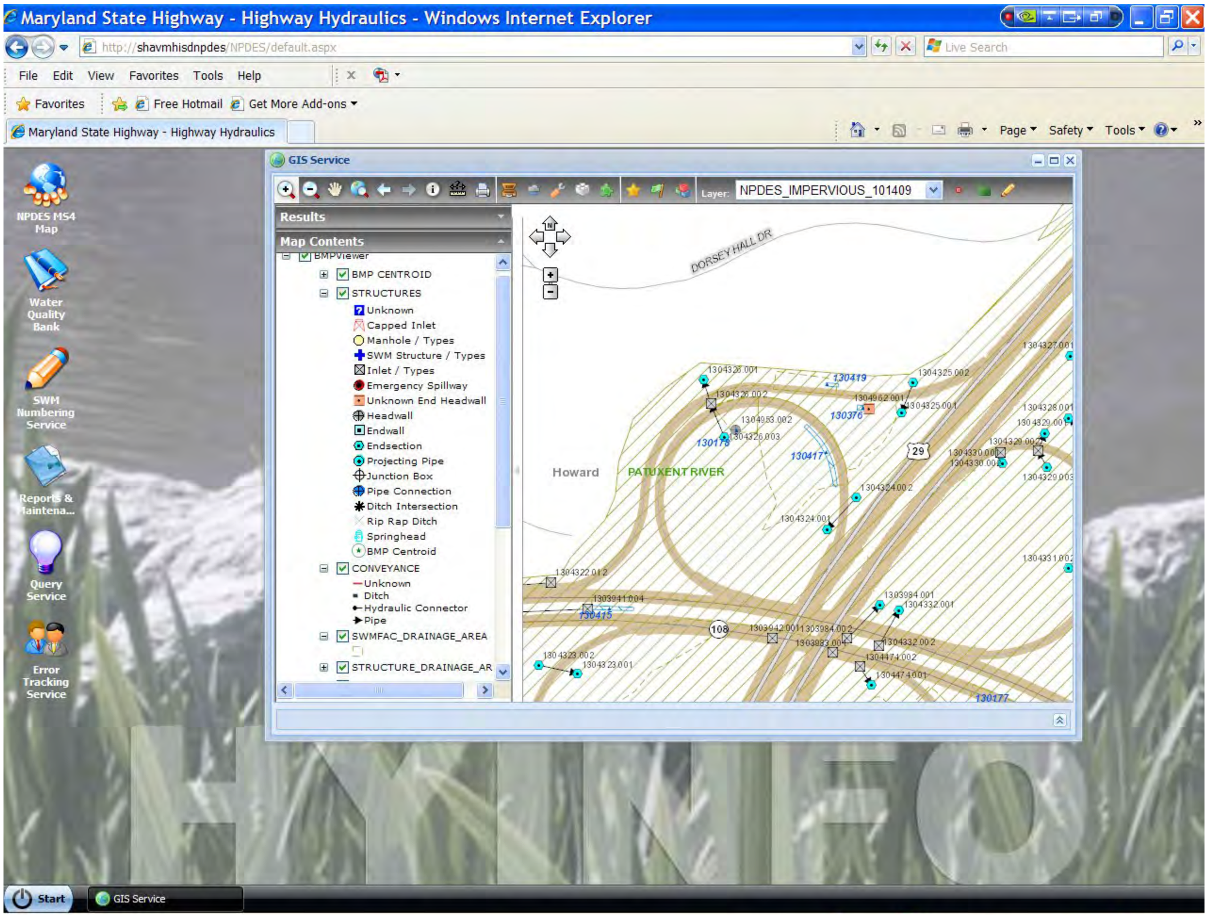


Figure 1-2 NPDES Viewer – HyInfo Screen Shot

NPDES GIS Viewer Application

The SHA NPDES GIS viewer application tool has been developed. The intent of the tool is to utilize the power of the enterprise GIS server to allow SHA to provide general access to the geodatabase information. While the tool platform is complete, many of the modules are currently undergoing final development. Table 1-1 lists percent complete for each module.

- <u>SHA NPDES Viewer</u> – web-based application that will allow SHA personnel, NPDES jurisdictions and other users to access our data. The viewer application will allow SHA staff to view, analyze, and query the storm drain, cross culvert and stormwater facility data. Access to the viewer from outside jurisdictions may not be immediately available as we work through firewall issues.
- <u>Stormwater Facility Program Module</u> – facilitates the management of the BMP inspections, maintenance, remediation or enhancement. Stormwater retrofits that upgrade facilities that were constructed prior to the 2000 Maryland Stormwater Design Manual are also included in the NPDES restoration credits.
- <u>BMP Numbering Module</u> – facilitates generating and maintaining unique BMP numbers in a secure, automated manner. Unique BMP numbers are generated individually or in pre-defined blocks of numbers, depending on the end-users needs.

- Water Quality Bank/ Impervious Accounting Module – tracks impervious areas treated by structural stormwater BMPs for both the SHA/MDE water quality bank and for NPDES restoration credit. This module currently only tracks the SHA/MDE water quality bank balances. We are looking to update our Water Quality Bank agreement and tracking tool.
- Outfall & Storm Drain Inspection & Remediation (SOIRP) Program Module – facilitates the management of the storm drain and outfall inspection data, maintenance, remediation or enhancements. Many of the remediation efforts undertaken here are also NPDES restoration projects.

Table 1-1 NPDES GIS Viewer Development Progress

Phase of Development	% Complete
NPDES GIS Viewer Platform	100
SWM Program Module	90
BMP Numbering Module	100
WQ Bank/Imp. Accounting Module	30
Outfall Program Module	0

GIS Standard Procedures Manual

We are continuing to develop our standard procedures which document data collection, inspection and data management standards for our NPDES data. The outline for the standard procedures is as follows:

Chapter 1	Introduction
Chapter 2	Source Identification & Inventory
Chapter 3	BMP Field Inspections & Data Collection Procedures
Chapter 4	Storm Drain & Outfall Inspection Procedures
Chapter 5	Illicit Discharge, Detection & Elimination Procedures
Chapter 6	Data Management
Chapter 7	BMP Assessment Guidelines for Maintenance & Remediation

Efforts to finalize the standard procedures continue and our goal is to publish a complete document this coming year. The final two chapters, data management standards and BMP remediation standards are currently being finalized.

GIS Development On-Line Instructional Training

In the past, we offered workshops for our field inspectors and GIS developers that explained the many components of the GIS development efforts. Due to budget cuts, we eliminated our workshops; however, we realize that on-line training is a good way to keep inspectors and GIS developers current on our standards, while at the same time, reducing costs. We will begin efforts to develop on-line training for all our GIS development standards in the next year. These self-training tools will enable the field and office personnel to view training material on their own without the need for formal workshops. Certification requirements are also being considered. The training modules include:

- Source ID procedures
- IDDE Field training
- Outfall stability inspection
- BMP inspection
- GIS Data Management.

Work Plan

The approach we will take to develop on-line training for our GIS Standards is detailed below:

1. Create Training Visuals and Narratives – Target date of Oct 2011.
2. Meet with SHA Training Services –Target date of Oct 2011
3. Convert Training Visuals and Narratives into On-line Training Modules – Target date of January 2012.
4. Test On-line Training Modules for Effectiveness –Target date of January 2012.
5. Implementation Of Training to SHA Field Inspectors and GIS Developers – Target date of March of 2012
6. Update and Maintain On-line Training Modules as GIS Standards Change – On going.

Table 1-2. Source ID Update Schedule

County	Source ID Complete	1st Update	2nd Update
Howard	**01/2001-C**	**01/2005-C**	**07/2009-I**
Montgomery	**01/2001-C**	**09/2006-C**	**8/2010-I**
Anne Arundel	**08/2003-C**	*5/2011-C*	
Prince George's	**03/2003-C**	*2/2011-C*	
Baltimore	**03/2004-C**	**7/2009-I**	
Harford	**08/2005-C**	**8/2010-I**	
Frederick	**09/2006-C**	**8/2010-I**	
Carroll	**05/2008-C**	*4/2011-I*	
Charles	**06/2008-C**	*4/2011-I*	

Note: Bold text is actual completion dates (-**C**) or actual initiation dates (-**I**). *Italicized text* is projected initiation (-*I*) or completion (-*C*) dates.

C.1.c Update Source Identification Data

Since the initial source identification is complete for all the NPDES MS4 Phase I counties, the permit activity for this condition now focuses on updating the source data.

Source identification updates are performed every three years or once the maintenance and remediation efforts are complete for a particular county. Last year, we reduced our updates to meet reduced budget constraints. This year we have increased our efforts and initiated three additional counties, Frederick, Montgomery and Harford.

Also, we will be expanding efforts in Baltimore and Howard counties to complete the full MS4. Last year we reduced the scope to inventory and inspect only new BMPs including associated storm drains and screen 150 outfalls for illicit discharges. The reduced work is anticipated to be completed by February but we will expand efforts to inventory and inspect the remaining BMPs, storm drain and outfalls this coming year.

Future updates will be performed according to Table 1-2.

Anne Arundel County – The progress in completing the MS4 update work is listed below:

Phase of GIS Updates	% Complete
Office Research	100
Field Research	100
GIS Development	90

The completed updated GIS development is anticipated by May 2011.

Baltimore County – The progress in completing the MS4 update work is listed below:

Phase of GIS Updates	% Complete
Office Research	100
Field Research	100
GIS Development	90

Completion of the reduced-scope GIS development is anticipated by February 2011. The expanded scope full MS4 update is anticipated to complete by August 2011.

Frederick County – The progress in completing the MS4 update work is listed below:

Phase of GIS Updates	% Complete
Office Research	100
Field Research	84
GIS Development	21

Harford County – The progress in completing the MS4 update work is listed below:

Phase of GIS Updates	% Complete
Office Research	100
Field Research	100
GIS Development	27

Howard County – The progress in completing the MS4 update work is listed below:

Phase of GIS Updates	% Complete
Office Research	100
Field Research	100
GIS Development	90

Completion of the reduced-scope GIS development is anticipated by February 2011.

The expanded scope full MS4 update is anticipated to complete by August 2011.

Montgomery County – The progress in completing the MS4 update work is listed below:

Phase of GIS Updates	% Complete
Office Research	95
Field Research	27
GIS Development	0

Prince George's County – The progress in completing the MS4 update work is listed below:

Phase of GIS Updates	% Complete
Office Research	100
Field Research	100
GIS Development	90

The completed updated GIS development is anticipated by February 2011.

C.1.d Submit Source Identification Data

Examples of the source identification data for Fredrick, Harford and Montgomery counties are included in Appendix A.

C.2 Submit BMP Data

Database tables are included on the enclosed CD for the data that has not been delivered previously. We have delivered our latest our storm drain mapping GIS and database Table A, urban best management practices GIS and database Table B and impervious accounting mapping GIS and database Table C in the previous report. These databases have not changed since last report. We will deliver new GIS mapping and database tables for Baltimore, Anne Arundel, Prince Georges, Howard, Frederick, Harford and Montgomery counties in our next report delivery. With future reports, we will only deliver new or changed data and clarifications on what has changed from the last delivery.

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 have completed the impervious accounting requirement. The current baseline accounting numbers are reflected in Table 1-5. We have added Table 1-6 that includes current restored acreages by county and statewide compared to the untreated impervious baseline acreage. We will continue to update this under the new permit.

Impervious Layers

Several methods exist for developing impervious surface layers ranging from manual digitizing of data from aerial photographs or contract drawings to automated remote sensing applications using satellite or aerial photography. After some study of alternatives, SHA settled on using Feature Analyst with aerial photography. Feature Analyst is a sophisticated computer application that can delineate features of interest in digital imagery. Through a learning process, Feature Analyst is programmed to recognize spectral signatures of impervious area in aerial photography.

Because these layers are generated through a process that reads ortho-photography, there are inaccuracies. But as a general quantity representing the amount SHA owns within an entire county, we feel it is a fair estimate. See Figures 1-3 and 1-4 for an example display and list of data fields. Also, see Tables 1-3 and 1-4 for meta-data on the source information used including ortho-photos and right-of-way files.

Updates to the layers will be performed using the Feature Analyst process unless better methods are developed in the future. Because of the use of ortho-photography as the base data, the process to update the impervious layers will rely on the schedules for updating the statewide ortho-photography. It is anticipated that the next updates will begin in 2011 and is anticipated to take several years to complete statewide coverage. Our impervious surface layers would be updated once the updates on the ortho-photos are completed.

We have also proceeded to develop impervious layers for the Phase II MS4 areas and the non-MS4 counties in Maryland in anticipation of Chesapeake Bay TMDL and Maryland Watershed Implementation Plan compliance.

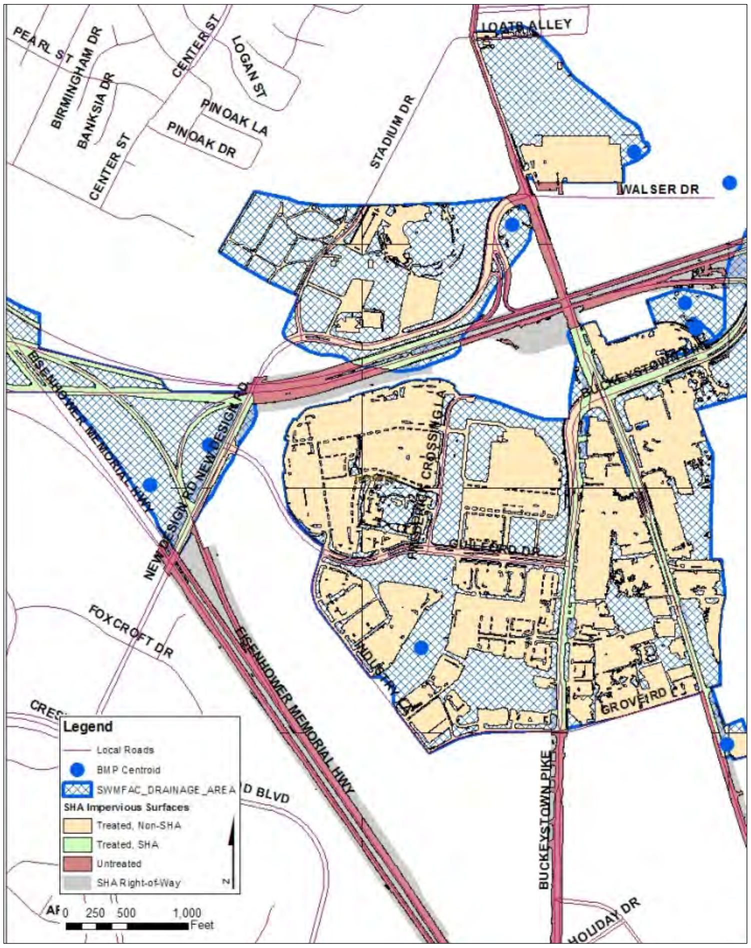
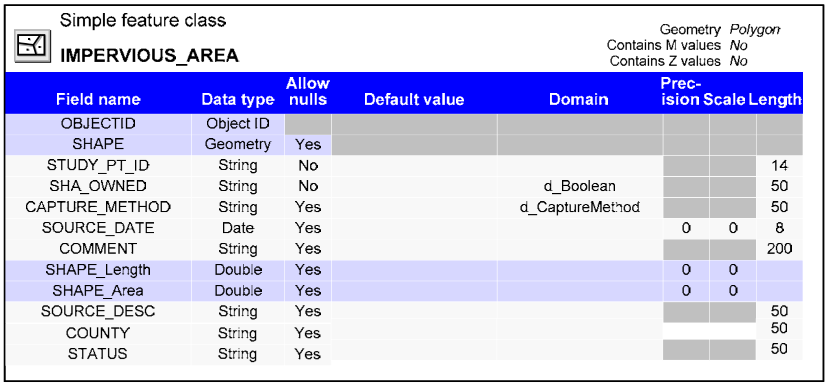


Figure 1-3 Example of Impervious Layer



Simple feature class

IMPERVIOUS_AREA

Geometry *Polygon*
Contains M values *No*
Contains Z values *No*

Field name	Data type	Allow nulls	Default value	Domain	Prec-ision	Scale	Length
OBJECTID	Object ID						
SHAPE	Geometry	Yes					
STUDY_PT_ID	String	No					14
SHA_OWNED	String	No		d_Boolean			50
CAPTURE_METHOD	String	Yes		d_CaptureMethod			50
SOURCE_DATE	Date	Yes			0	0	8
COMMENT	String	Yes					200
SHAPE_Length	Double	Yes			0	0	
SHAPE_Area	Double	Yes			0	0	
SOURCE_DESC	String	Yes					50
COUNTY	String	Yes					50
STATUS	String	Yes					50

Figure 1-4 Data Fields in Impervious Layer Geodatabase

Table 1-3 Meta-Data for Impervious layers

County	Ortho Capture Date	Ortho Source	Pixel Size
Anne Arundel	Spring 2005	County	6 inch
Baltimore	Spring 2005	County	1 foot
Carroll	Spring 2000	County	1 foot
Charles	Spring 2004	County	0.25 meter
Frederick	Spring 2006	County	6 inch
Harford	Spring 2004	County	1 foot
Howard	Spring 2006	County	6 inch
Montgomery	Spring 2006	County	1 foot
Prince Georges	Spring 2007	State	6 inch

Table 1-4 Meta-Data for Right-of-Way (ROW) Layers

County	ROW Source	Property Data Source	Year
Anne Arundel	Vector parcel layer	County	2005
Baltimore	Vector parcel layer	County	2007
Carroll	Spring 2000	County	2007
Charles	Spring 2004	Centerline buffer /MD Property View	2002
Frederick	Vector parcel layer	County	2006
Harford	Vector parcel layer	County	2005
Howard	Vector parcel layer	County	2006
Montgomery	Vector parcel layer	County	2007
Prince Georges	Vector parcel layer	County	2008

Note: Metadata was not available to indicate the year that the ROW Source data was created. The date in the year column is assumed by the date tag of the files provided.

Impervious Accounting

MDE is currently working with the MS4 Phase I jurisdictions to develop an impervious accounting protocol. Once this protocol is finalized, we will adjust our accounting as needed.

Our current criterion for impervious treatment includes any structural stormwater BMP that has SHA impervious surfaces within the drainage area. Pavement being treated by grass swales or other non-structural measures is not accounted for at this time.

In addition to this, many segments of SHA roadways are currently treated by non-structural methods such as swales or street sweeping. We are beginning the process of identifying these segments and treatment types and quantifying the additional impervious that can be designated as treated. While our layers will not be updated annually, our impervious accounting treatment numbers will be updated annually to reflect all of these additions to the accounting.

Table 1-5 SHA Baseline Impervious Accounting[1]

County	Total SHA Impervious in County (AC)	Baseline Untreated SHA Impervious[2] (AC)	Treated SHA Impervious[3] (AC)	Percent SHA Impervious Treated
Anne Arundel	3796	3162	633	16.7%
Baltimore	3954	3718	236	6.0%
Carroll	1330	1286	44	3.3%
Charles	1421	1364	57	4.0%
Frederick	2353	2166	187	7.9%
Harford	2078	1949	129	6.2%
Howard	2211	1982	229	10.4%
Montgomery	3428	2882	546	15.9%
Prince George’s	4187	3792	395	9.4%
Totals	**24,758**	**22,301**	**2,456**	**9.9%**

Notes:
1. Numbers current to 1/21/2011.
2. Baseline acres includes all impervious owned by SHA that is not treated by BMP regardless of pavement construction date.
3. Treatment is by structural BMPs built. The 2002 baseline accounting protocol is under development by MDE and we will adjust our accounting of baseline untreated pavement once this protocol is finalized.
4.

Table 1-6 Pavement Restoration Accounting

County	Baseline Untreated SHA Impervious (AC)	Restored Impervious Acres	Percent Impervious Acres Restored	Adjusted Untreated Impervious (AC)
Anne Arundel	3162	93.5	3.0%	2435
Baltimore	3718	268.7	7.2%	3213
Carroll	1286	0	0%	1242
Charles	1364	1.7	0.1%	1305
Frederick	2166	1.9	0.1%	1977
Harford	1949	20.8	1.0%	1799
Howard	1982	14.6	0.7%	1738
Montgomery	2882	245.6	8.5%	2090
Prince George’s	3792	26.1	0.7%	3371
Totals	**22,301**	**673**	**3%**	**19,170**

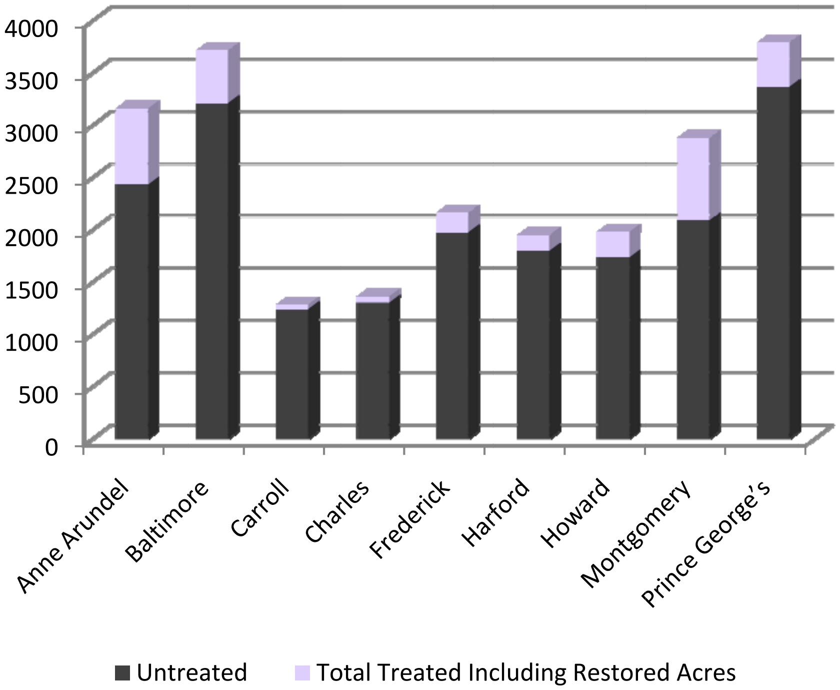


Figure 1-5 SHA-Owned Impervious Surface Treatment in 9 NPDES Counties

D Discharge Characterization

This current permit term looks at scrutinizing the available MDE dataset compiled from eleven NPDES jurisdictions and other research performed nationally to improve stormwater management programs and develop watershed restoration projects. We are continuing our efforts to understand stormwater runoff associated with highways by reviewing available literature and studies on the subject and by conducting studies to further our understanding.

Current Studies by SHA

The following studies are currently under progress by the University of Maryland, Department of Civil Engineering, and progress reports are contained in the appendices as noted:

- *<u>Field Evaluation of Water Quality Benefits of Grass Swale for Managing Highway Runoff.</u>*– This study looks at the affect of installing check dams that are composed of native warm season grasses into the previously studied swales. We are interested in the concept of grassed check dams because of the safety and maintenance implication. They can be run over without much injury or damage to the motorist or vehicle, and only require growth to re-establish the check dam. Because native grasses have extensive root systems and encourage other soil processes, it was deemed useful to analyze the affects these grasses would have on our study swales and pollutant removal. The final progress report is provided as Appendix B, however the results are not conclusive. We will pursue other studies in this vein.

- *<u>Nutrient Removal Optimization of Bioretention Soil Media</u>* – This study was initiated in August 2008. Although new research continues to address arising challenges, bioretention is still a very immature technology and a number of problems and questions remain. One focal point of several questions concerns the media employed in the bioretention facility. The media controls many of the critical performance functions in bioretention (filtration, infiltration, adsorption, microbial substrate, vegetative support), yet we are far from having a good understanding about the critical design and operation components of the media and the resulting performance.

Optimization of media design was investigated for pollutant capture, with a focus on the nutrients phosphorus and nitrogen. A review of current literature and critical analysis of amendment options based on treatment capacity, cost, and local availability led to the selection of aluminum water treatment residual (WTR) as an ideal BSM amendment for phosphorus capture and retention.

This, coupled with other measures such as vigorous facility vegetative cover, is hypothesized to be ideal for nutrient removal from stormwater in bioretention facilities. A copy of the final progress report is included in Appendix D.

<u>Wet Infiltration Basin Transitional Performance Studies</u> – This study was initiated in August 2008. One particular practice of interest to SHA is the infiltration basin. Over the past few decades, a multitude of infiltration basins have been constructed for stormwater management. Inspections have shown that these infiltration basins are no longer functioning as originally intended and designed. These practices have gradually transformed into wetland-like practices that appear to have both water quality and hydrologic management functions. Therefore, rather than a failure, these sites should be classified as functioning stormwater management practices and this study seeks to develop evidence to this end.

Target pollutants to be monitored include total suspended solids (TSS), nitrate, nitrite, total Kjeldahl nitrogen (TKN), total phosphorus, copper, lead, zinc, and chloride. These pollutants are of the greatest concern in roadway runoff because their concentrations often exceed the limits set by anticipated total maximum daily loads (TMDL) requirements.

View of BMP 130348 at Outflow Point – Failed Infiltration Basin Currently Monitored

Instrumentation at Failed Infiltration Basin No. 130348

Totally, 31 storms have been monitored for hydrology. Overall, the results indicate that the BMP is effective in managing the runoff flows. The BMP assimilated the entire inflow volume and did not produce any outflow for 52% of the monitored events. The mean volume reduction achieved through the BMP for 31 events was 67%. Flow delays and peak attenuation (mean peak reduction= 56%) were observed during events with outflow.

The water quality of nine storm events and eleven dry-weather samples has been determined. The event mean concentrations (EMCs) of the measured pollutants in the outflow are lower than those of inflow in all events. Except for total phosphorus, the outflow EMCs of total suspended solids, oxidized nitrogen (nitrite and nitrate), and heavy metals (copper, lead, and zinc) meet the selected water quality criteria for majority of the events monitored. Pollutant removal efficiencies during eight sampled storm events (except one winter event) are: total suspended solids (91-100%), nitrate and nitrite (76-100%), total Kjeldahl nitrogen (38-100%), total phosphorus (60-100%), and total heavy metals, copper (64-100%), lead (29-100%), and zinc (18-100%). Export of nutrients and heavy metals was observed in the winter storm event. Ancillary benefits such as habitat to plants and wildlife are also being recorded. If the "failed" BMP is found to provide hydrology benefits and water quality enhancements in its existing condition, similar sites may be classified as functioning, stormwater management practices.

A copy of the progress report is included in Appendix C.

Previously Completed Studies by SHA

The following studies have been completed by SHA and were included in previous annual reports:

- *Grassed Swale Pollutant Removal Efficiency Studies, Part II* – This study looks at the affect of installing check dams that are composed of native warm season grasses into the previously studied swales
- *Literature Review: BMP Efficiencies for Highway and Urban Stormwater Runoff* – This literature search looked at current available resources for evaluating the effectiveness of stormwater management technologies in removing pollutants and methodologies for evaluating this effectiveness. The report included information on reporting parameters of BMPs, grass swale, bioretention, basins, vegetated buffer strips, sand filters and wetlands.
- *Low Impact Development Implementation Studies at Mt. Rainier, MD,* October 2006.
- *Grass Swale Study – Part II,* October 2006.

The following studies were completed by SHA during the previous permit term:

- *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 Resources

The following additional resources were listed in the 2007 report and SHA is continuing to review and digest the information contained in them in order to improve our processes and to strategically move our program forward:

<u>Highway Runoff Discharge Characterization</u>

- *The National Runoff Data and Methodology Synthesis, Publication No FHWA-EP-03-054 -055, -056, 2003*.

<u>Stormwater Best Management Practices</u>

- *Evaluation of Best Management Practices for Highway Runoff Control*, NCHRP Report 565.
- *Controlling Urban Runoff: Practical Manual for Planning and Designing Urban BMPs*, Metropolitan Washington Council of Governments, 1987.

<u>Deicing Materials</u>

- *Guidelines for Selection of Snow and Ice Control Materials to Mitigate Environmental Impacts*, NCHRP Report 577.

- *Assessing the Role of Road Salt Run-off on the Critical Ecological interactions that Regulate Carbon Processing in Small, Headwter Streams in the Chesapeake Bay Watershed,* Chris Swann, MWRRC, 2006.
- *Pollutant Mass Flushing Characterization of Highway Stormwater Runoff from an Ultra-Urban Area,* Flint and Davis, June 2007.
- *Choosing Appropriate Vegetation for Salt-Impacted Roadways,* Center for Watershed Protection Technical Note # 56.
- *Rating Deicing Agents: Road Salt Stands Firm,* Center for Watershed Protection Technical Note # 55.
- *Increased Salinization of Fresh Water in the Northeastern United States,* Kaushal, Groffman, Likens, Belt, Stack, Kelly, Band and Fisher, August 2005.

Total Maximum Daily Loads

- *Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment*; US EPA, Regions 2 and 3; December 2010.
- *Maryland's Phase I Watershed Implementation Plan for the Chesapeake Bay Total Maximum Daily Load*; MDE, MDP, UMD, MDA, MDNR; December 3. 2010.
- *Estimates of County-Level Nitrogen and Phosphorus Data for use in Modeling Pollutant Reduction – Documentation for Scenario Builder Version 2.2*; Christopher Brosch; September 2010.
- *Developing Best Management Practice Definitions and Effectiveness Estimates for Nitrogen, Phosphorus and Sediment in the Chesapeake Bay Watershed – Final Report*; Thomas Simpson & Sarah Weammert, UMD; December 2009
- *Maryland's 2006 TMDL Implementation Guidance for Local Governments*, Maryland Department of the Environment, 2006.
- *Maryland's Chesapeake Bay Tributary Strategy Statewide Implementation Plan,* Watershed Services Center, Maryland Department of Natural Resources, August 2, 2007.

Illicit Discharges

- *Methods for Detection of Inappropriate Discharges to Storm Drainage Systems*, Robert Pitt, University of Alabama, November 2001.
- *Illicit Discharge, Detection and Elimination: A Guidance Manual for Program Development and Technical Assessments*, Center for Watershed Protection, October 2004.

Watershed-Based Strategies

- *Water Quality Analyses for NEPA Documents: Selecting Appropriate Methodologies*, AASHTO & NCHRP, July 2008
- *A User's Guide to Watershed Planning in Maryland*, Center for Watershed Protection, December 2005.
- *Watershed-Based National Pollutant Discharge Elimination System (NPDES) Permitting Implementation Guidance*, Environmental Protection Agency, December 2003.

Pollutant Load Reductions

- Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs, Metropolitan Washington Council of Governments, July 1987.
- *Pollutant Loadings and Impacts from Highway Stormwater Runoff, Volumes I-IV: Design Procedures, FHWA/RD-88-0006-9,* Driscoll & Strecker, Federal Highway Administration, 1990.

Using the literature and research documented above, we are pursuing further understanding of the pollutant removal capabilities of the various BMPs discussed in the *2000 Maryland Stormwater Design Manual* as well as other innovative stormwater management techniques. We are working to develop our TMDL implementation plan that will be required as part of our next MS4 permit.

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 as part of the May 2010 implementation.

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 design and solution principles. 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

Our National Environmental Policy Act/ Maryland Environmental Policy Act (NEPA/MEPA) design and planning process, includes environmental assessments for any project proposed within SHA right-of-way or utilizing state or federal funding. This includes projects granted Transportation Enhancement Program funds that are carried out by other jurisdictions. The environmental assessments determine the direction environmental documentation must take, whether Categorical Exclusion (CE), Finding of No Significant Impact (FONSI) or Environmental Impact Statement (EIS). Environmental assessments include land use considerations, water use considerations, air use considerations, plants and animals, socio-economic, and other considerations.

Increasingly, SHA is evaluating stormwater needs during the NEPA process. This movement to timing stormwater concepts in planning has affected our development process in several ways. Beginning the stormwater process earlier allows us to present more realistic concepts during public meetings and allows us to more accurately assess 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. This last effect can have negative impacts on our 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 in the 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.

Environmental Research

In addition to the research studies mentioned above in Section D, Discharge Characterization, SHA has also pursued research and development studies to improve our understanding of the impacts certain BMPs have on the environment. Past studies include:

- *Thermal Impact of Underground Stormwater Management Storage Facilities on Highway Stormwater Runoff* – The goal of the study was to identify and document the thermal reduction effects on stormwater in underground storage facilities. The reasons cited include low residency time, limited thermal transfer potential, principal thermal reduction due to reduction in direct solar radiation. No further studies on underground storage and thermal reduction are planned at this time. The final report was included as Appendix F in the 2008 annual report.

- *Mosquito Surveillance/Control Program* – This three-year study conducted by Millersville University for Maryland SHA, investigated the connection between West Nile Virus (WNV) transmission and stormwater management facilities. West Nile viral encephalitis is a zoonosis in which people and horses are incidentally infected by mosquitoes that feed on both bird and mammalian hosts. No further work on mosquito issues is planned at this time as we are referencing the MD Department of Agriculture site for additional information and have consulted with them for eradication efforts. The final report was included as Appendix E of the 2006 annual report.

- *Prediction of Temperature at the Outlet of Stormwater Sand Filters* **–** This study was begun in 2003 and the intent was to create a computer model of a sand filter BMP that will allow prediction of outlet temperature as a function of time. The approach is physics based, depending on energy and mass balances, and heat and mass transfer predictions. Rather than uniform flow, water tends to flow in channels or fingers through sand and other soils and this flow type is called preferential flow. This preferential flow resulted in less contact with sand particles and less transference of heat from the water to the sand. No further work on this predictive model is planned at this time. The final progress report was included as Appendix H in the 2007 report.

E.2 Erosion and Sediment Control

Requirements under this condition include:

a) *Use MDE's 1994 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 ("green card") certification classes to educate highway construction contractors regarding erosion and sediment control requirements. 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 continue to implement the new NPDES Stormwater Construction Activity permit for all our construction projects that impact one acre or more in area. We also anticipate the Draft *2010 Maryland Standards and Specifications for Soil Erosion and Sediment Control* to be formalized this coming year as well as new *Maryland Erosion & Sediment Control Guidelines for State and Federal Projects* to be issued once the new standards are approved.

We are maintaining implementation of the current Guidelines for State and Federal Projects Published January 1990 and Revised January 2004 and the *1994 Standards and Specifications for Soil Erosion* for our projects.

SHA has remained in compliance with the NPDES Construction Activity permit and has implemented changes in our construction inspection to adhere to the new inspection 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 improves field implementation of ESC measures by including an incentive payment to the contractor for excellent ESC performance or imposes liquidated damages on the contractor for poor ESC performance.

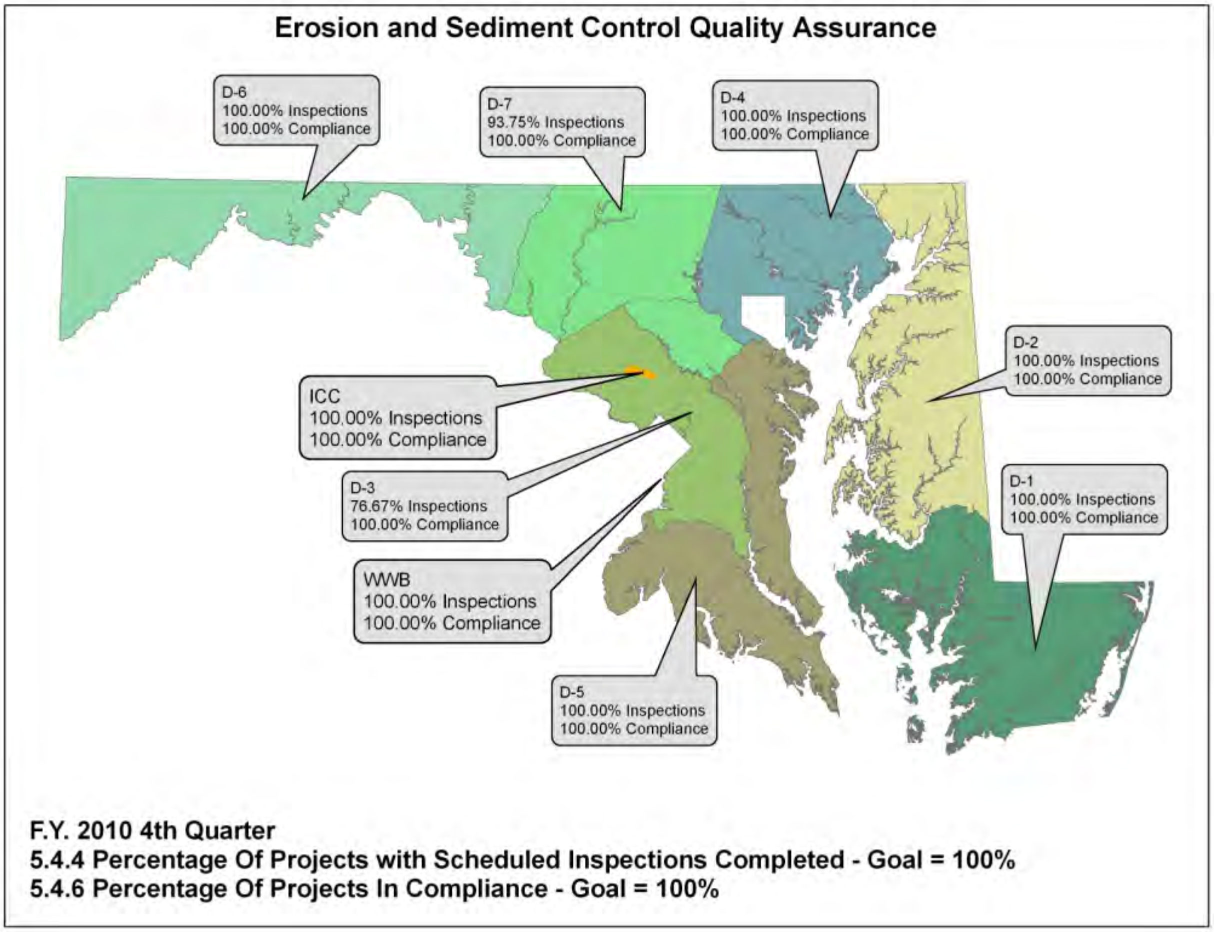


Figure 1-6 Erosion and Sediment Control Quality Assurance for FY2010, Fourth Quarter

SHA tracks QA inspections and ratings for reporting to our business plan (see Figure 1-6) and StateStat. Increased numbers of inspections and better documentation have improved the overall performance of our ESC program. It has also resulted in organizational changes within SHA. The QA inspection team is now housed under the Office of Environmental Design (OED). Incentive payments are made when the contractor receives an ESC rating score of 85 or greater. This incentive payment can be made quarterly (every 3 months) for projects that continue to receive 85 or greater ratings.

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 until they complete and pass the certification training. This system of rewarding good performance and penalizing poor performance is expected to greatly improve contractor responsibility for ESC practices and improve water quality associated with construction activities.

AASHTO Gold Performance Excellence Award

The QA Team received an award from the AASHTO Standing Committee on Performance Management on October 1, 2010 recognizing their accomplishments in training, inspections and high project grades for SHA construction projects statewide.

Limit of Disturbance (LOD) Stationing

Another improvement to our ESC efforts is that we are now requiring designers to provide offsets and stationing on the limit of disturbance (LOD) on ESC design plans. This will give the construction contractor information in order to accurately stake out and place the LOD in the field. Ultimately, this will provide better control of project disturbance.

Turf Acceptance Standard

In order to ensure that quality turf is established along SHA rights-of-way and thereby reduce erosion and improve slope stability, the SHA Landscape Operations Division (LOD) has developed a turf inspection and acceptance process. This process requires contractors to meet minimum turf coverage percentages in order to secure final release of the project for maintenance and final payment to the contractor

At the time of semi-final inspection the turf on the construction project is evaluated according to the criteria below.

- Areas flatter than 4:1 should exhibit:
    - 95% coverage of Permanent Seed Mix or *Sericea lespedeza* or Special Purpose Seed Mix; and
    - Dark green color
- Areas 4:1 and steeper (tracked with a bulldozer) should exhibit:
    - 95% coverage of vegetation with 50% coverage of Permanent Seed Mix or *Sericea lespedeza* or Special Purpose Seed Mix; and
    - Dark green color

SHA ESC Draft Field Guide

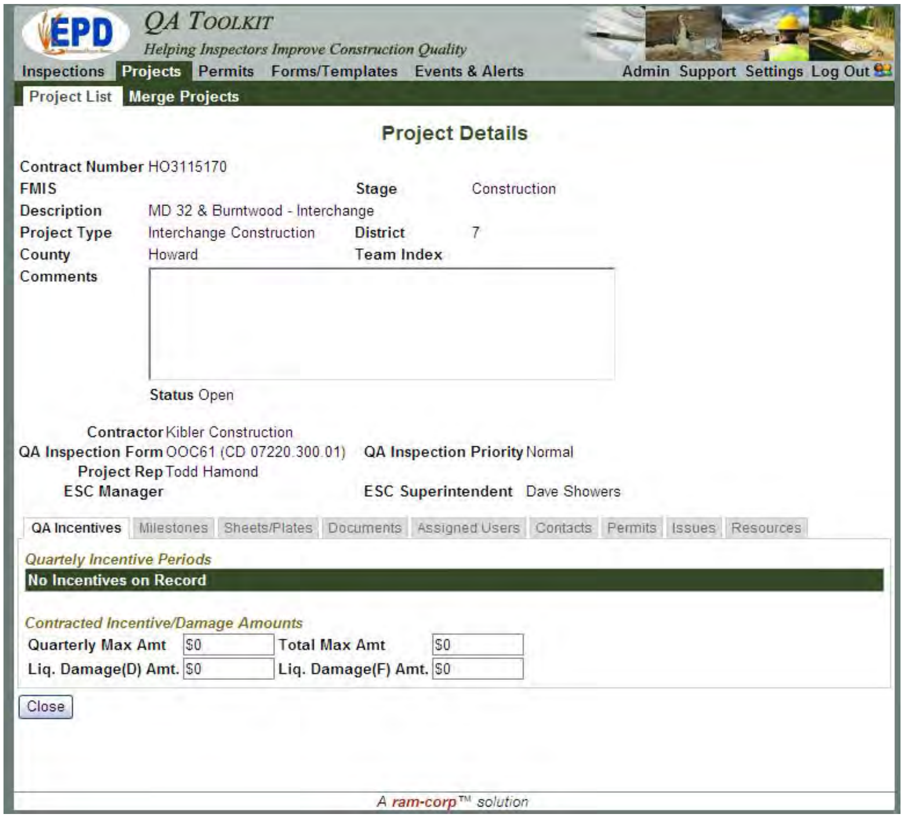
The SHA Draft Field Guide to Erosion and Sediment Control was completed and is being distributed to construction engineers, certified ESC managers and inspectors, and ESC designers. This field guide provides essential information in a format that is easy to access and carry. It will be finalized once Maryland Department of Environment (MDE) issues their new erosion and sedimentation control guidelines.

ESC Quality Assurance (QA) Toolkit

This is a web-based tool that allows SHA ESC compliance field inspectors to capture inspection data directly to the database electronically for use by the HHD and OED for tracking. Prior to the development of this tool, inspections were recorded on paper forms and transferred to a database by a third party. This previous method allowed for inefficiencies and error in report tracking.

With the QA Toolkit, ESC compliance inspectors use wireless ‘tough book’ laptops and input inspection data directly into the database over the worldwide web. This allows SHA to house a centralized database that is accessible to many personnel including inspectors, independent environmental construction monitors, SHA senior management and environmental programs personnel. The dataset that is captured in the field can also include project details such as plan sheets and permit records. The initiative of the ESC QA Toolkit was recognized at the SHA Performance Excellence conference in 2008.

Air-card Equipped Tablet Computer Used to Complete QA Rating Forms Online



Project Details

Contract Number HO3115170
FMIS
Stage Construction
Description MD 32 & Burntwood - Interchange
Project Type Interchange Construction
District 7
County Howard
Team Index
Comments
Status Open

Contractor Kibler Construction
QA Inspection Form OOC61 (CD 07220.300.01)
QA Inspection Priority Normal
Project Rep Todd Hamond
ESC Manager
ESC Superintendent Dave Showers

Quartely Incentive Periods
No Incentives on Record

Contracted Incentive/Damage Amounts
Quarterly Max Amt $0
Total Max Amt $0
Liq. Damage(D) Amt. $0
Liq. Damage(F) Amt. $0

Figure 1-7 Screen Shot of ESC QA Toolkit

E.2.b Responsible Personnel Certification Classes (Green Card Training)

SHA continued to sponsor and perform training for ESC Responsible Personnel Certification Classes over the past year. This training is conducted by SHA for SHA personnel, consultants and contractors.

A copy of the database of trained personnel (MDE Table H, Responsible Personnel Certification Information**)** is included on the CD as an attachment to this report.

SHA Basic Erosion and Sediment Control Training (BEST)

In addition to Green Card Training classes, SHA developed and implemented its own ESC Certification Program at two levels. Level I is known as BEST (Basic Erosion and Sediment Control Training). This day and a half training is aimed at contractors and field personnel and focuses on in-depth discussions of ESC design, construction and permitting requirements. This is also a prerequisite for Level II training.

The Level II training is intended for ESC design professionals. The Level II training began in June 2007.

Table 1-7 ESC Training Held by SHA (10/2009 to 12/2010)

Type of Training	No. of Participants
Responsible Personnel (Green Card)	853
BEST Level I (Yellow Card)	532
BEST Level I (Yellow Card Recertification)	282
BEST Level II (Designer’s Training)	27

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 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. Permitting needs are tracked for projects statewide through our Permit Database that is managed with Microsoft Office Access 2007 software.

E.3.b Implement BMP Inspection & Maintenance Program

Our continuing Stormwater Facility Program (managed by Ms. Dana Havlik) inspects, evaluates, maintains, remediates and enhances SHA BMP assets to maintain and improve water quality and protect sensitive water resources. Inspections are conducted every three years 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 Stormwater 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.

As-Built Certification Process

SHA continues with our SWM facility as-built certification process. This process requires the design engineer to coordinate with MDE on the completion of as-built checklists and tabulations. The contractor is then required to inspect and certify the facility construction according to the approved design plans. SHA has made the delivery of this certification a separate pay item. A copy of the revised As-Built Certification special provision was included the 2006 annual report.

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.

We are finding that compliance by the contractors is not consistent, and we are re-evaluating our process to determine a more effective means to achieve 100% compliance with this requirement.

E.3.c Document Significant BMP Maintenance

See Part 2 for SWM Facility 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 trough 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.

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

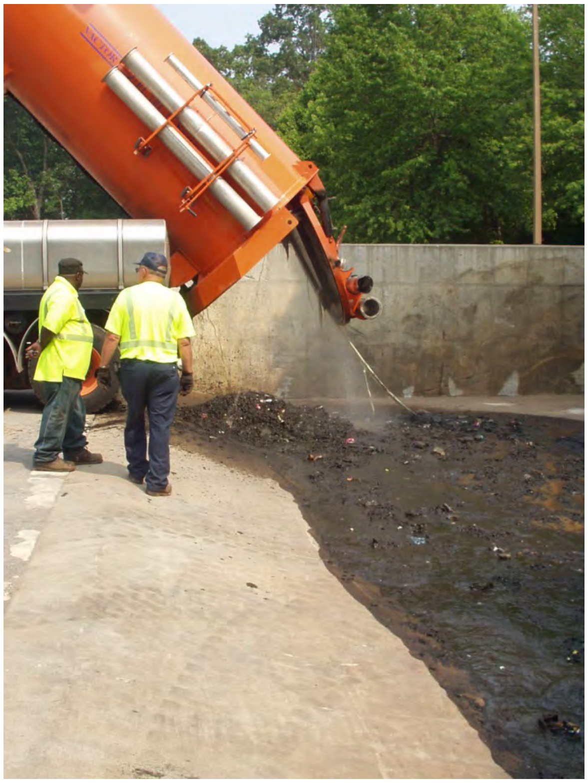
In addition to street sweeping, SHA owns and operates four vacuum pump trucks that routinely clean storm drain inlets along roadways. Sediment and trash make up the majority of the material that is removed. The vacuum trucks operate in central Maryland, spanning the following Counties: Anne Arundel, 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 the pollutants before they enter the waterways.

Pollutant Load Reductions

Sweeping and inlet cleaning are recognized as valid pollutant source reduction BMPs. 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.

SHA Highway Hydraulics Division will be working with the SHA Office of Maintenance 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.

Vacuum Pump Truck



Vacuum Truck at Owings Mills Shop Dewatering Facility

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

SHA has standards for maintaining the highway system. 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

Herbicides are selected based upon their safety to the environment and personnel, as well as for economical performance. In order to ensure that herbicides are applied safely to roadside target species, herbicide supervisory and application personnel are thoroughly trained, registered and/or certified by at least one of the following:

- University of Maryland
- Maryland Department of Agriculture
- SHA.

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 need for Nutrient Management Plans (NMP) is determined by SHA for all roadway projects according to State law (COMAR 15.20.04-08 – Nutrient Management Regulations). NMPs are developed by the Landscape Operations Division (LOD), Technical Resources Team (TRT) and the need for a NMP is at the discretion of the TRT.

The application of fertilizer is performed based upon soil sampling and testing for major plant nutrients such as phosphorus and potash. Once these plant nutrient levels are determined, a NMP is developed for both construction and maintenance. Certain major fertilizer nutrients are reduced due to adequate soil levels.

Mowing Reduction/Native Meadows

A major initiative at the SHA is to reduce the extent of mowed areas within our right-of-way. Along with this initiative, several pilot projects have been completed to install and maintain native meadow areas. Ultimately this practice will further reduce the need for fertilizer and herbicide application.

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 recently initiated a pilot program using a fairly new product called Geo Melt 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. Geo Melt 55 (Beet Juice) also enables the brine to adhere to bridges and road surfaces better and longer, which extends the effectiveness of the deicer.

In addition, SHA has expanded 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 1-8 lists materials used by SHA in winter deicing operations.

Table 1-8 Winter Materials used by SHA

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.
Geo Melt 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 degrees and has proven cost effective in colder regions.
Caliber M-100	A magnesium chloride-based deicer with an agricultural additive. Its very low freeze point makes it ideal for use in Garrett County.
Potassium Acetate	A costly, environmentally friendly, liquid material used at SHA's two automated bridge anti-icing system sites in Allegany County.

Understanding Impacts of Deicing Chemicals

SHA is also pursuing research to understand the impact deicing chemicals have on surrounding ecosystems and organisms. See Section D, Discharge Characterization, for a list of resources we are studying.

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 is currently working toward meeting the deadline and may establish the following items as part of the guidance document:

- Determine Best Management Practices that protect the environment from the negative impacts or road salt,
- Identify all activities that may result in the release of road salt in the environment, including road salt storage, application, and disposal of salt containing road salt,
- Take into consideration of highway safety to the greatest extent possible,
- Establish standards and procedures for identifying areas particularly vulnerable to road salt runoff and additional road salt management practices that need to be implemented in these areas,
- Establish goals for achieving a reduction of the environmental impact of road salt release into the environment,
- Include a training program for all state, local, and contract personnel involved in the performance of winter maintenance activities utilizing road salt,
- Establish response procedures to address uncontrolled release of road salt that may adversely impact the environment, and
- Established record keeping and annual reporting procedures for the quantity of road salt used, where the road salt is used and any training conducted.

E.4.d NPDES Industrial Permit Coverage

As discussed in the previous Annual Report, SHA developed and 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 is being implemented in a phased approach. As stated in previous Annual Reports, Phase I environmental assessments at 29 SHA primary maintenance facilities were completed in the spring of 2007. Phase II compliance assessments, covering 65 satellite facilities, were completed in the summer of 2009. As shown in Table 1-9 below, certain Phase II facilities are currently covered under the General Discharge Permit (02-SW). The permit status of these and other Phase II facilities was evaluated and updated based on the compliance assessments.

SHA has compiled the results of the Phase II assessments and ensured stormwater requirements have been met where applicable, e.g. permit coverage and Stormwater Pollution Prevention Plan (SWPPP) development. The SHA Environmental Compliance Division (ECD) will also begin routine inspections at Phase II facilities through its District Environmental Coordinators (DEC) to ensure stormwater pollution prevention BMPs are implemented. The DECs are responsible for ensuring compliance with applicable permits, plans and regulations at facilities in their region.

Subsequent phases will expand the CFEMS to other SHA facilities and operations. The SHA laboratories (5), landscape depots (2) and sign production shop (1) will be assessed in January 2011. These facilities will be assessed for stormwater permitting needs at this time. 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

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. Beginning in 2008 and continuing through 2009 SHA performed detailed site assessments at 29 primary maintenance facilities to gather information used to update the 2005 SWPPPs and Spill Prevention, Control, and Countermeasure Plans (SPCCP). At of the end of 2009, SHA had completed final versions of SPCCPs for 27 of the primary maintenance facilities and SWPPPs for all 29 primary maintenance facilities.

Throughout 2010, SHA continued to address potential stormwater pollution issues by implementing Best Management Practices (BMPs) and designing / constructing capital improvements. SWPPPs were prepared and implemented at all Phase II satellite facilities, regardless of regulatory requirements, and SPCCPs were developed for all applicable satellite facilities. BMPs were identified during pollution prevention plan updates and routine inspections for Phase I (environmental assessment phasing) facilities (primary maintenance shops) and initial assessments SWPPP / SPCC development of Phase II satellite facilities. The status of BMP implementation for maintenance facilities is tracked by each DEC 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:

- Finalized SWPPP for all satellite facilities
- Finalized SPCCP for all applicable satellite facilities
- Oil/water separator upgrade at Chestertown maintenance facility
- Sanitary sewer floor drain connection at Cambridge maintenance facility
- Petroleum storage tank system upgrades were completed at 36 maintenance facilities
- Battery storage / spill kit procurement for satellite (Phase II) facilities

On-going Projects:

- Statewide oil-water separator maintenance program
- Statewide discharge sampling and reporting program for facilities with Individual Discharge Permits
- Routine compliance inspections at all Phase I facilities (primary maintenance) and Phase II facilities (satellite)
- Second annual multimedia environmental compliance training provided to maintenance shop personnel

Initiated Projects:

- Design initiated to connect storm drain debris dewatering structures at Glen Burnie and Owings Mills maintenance facilities to sanitary sewer system.
- Outfall stabilization project at Prince Frederick maintenance facility
- Grit Chamber assessment and upgrade design at Prince Frederick and Marlboro maintenance facilities

Storm Water Outfall Improvements at SHA Maintenance Shop

Underground Storage Tank System Upgrades

Table 1-9 Industrial NPDES Permit Status

District	Maintenance Facility	Permit Type
1	Berlin[1]	General
	Cambridge	General
	Princess Anne	General
	Salisbury	General
	Snow Hill	General
2	Centreville	Individual – SW
	Chestertown	General
	Denton	General
	Easton	General
	Elkton	General
	Millington[2]	General Terminated 4/22/10
3	Fairland	General
	Gaithersburg	General
	Kensington[2]	General Terminated 8/20/10
	Laurel	General
	Marlboro	General
	Metro/Landover[2]	General Terminated 8/20/10
4	Churchville	Individual – SW
	Golden Ring	General
	Hereford	Individual – SW[3]
	Owings Mills	General
5	Annapolis	General
	Glen Burnie	General
	La Plata	General
	Leonardtown	Individual – SW[3]
	Prince Frederick	General
6	Frostburg[1]	General Terminated 8/20/10
	Hagerstown	General

Table 1-9 Industrial NPDES Permit Status

District	Maintenance Facility	Permit Type
	Hancock	General
	Keyser's Ridge	Individual – GW
	La Vale	General
	Oakland	General
7	Dayton	Individual – SW[3]
	Frederick	General
	Thurmont[1]	General
	Westminster	General
Offices / Other Facilities	Brooklandville Complex[4]	General
	Hanover Auto Shop	Individual – SW[5]

Note: SW = Surface Water, GW = Groundwater

[1] Phase II facility (satellite) where a permit is required due to industrial activity

[2] Phase II facility (satellite) where a determination was made after initial compliance assessment that a permit was not required

[3] All wastewater is collected for pump and treat in a storage tank; no industrial wastewater discharge

[4] Property in the process of being transferred and is no longer used by SHA

[5] Vehicle wash discharge connected to sanitary sewer in 2009, SW provisions of individual permit remain in effect

Table 1-10 shows the SHA capital expenditures towards industrial pollution prevention BMPs from the current and past six fiscal years. Projected expenditures for 2011 are also included.

Table 1-10 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	$ 500,000 – projected

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 of Outfalls

The SHA Storm Drain and Outfall Inspection and Remediation Program (SOIRP) is headed by Mr. Brandon Scott. This program focuses on the physical conditions and structural functionality of major SHA culvert outfalls. Inspections for the SOIRP program will result in developing strategies for maintaining, repairing or otherwise remediating storm drain and outfall stabilization problems. The resulting remediation actions can be constructed through our open-end construction contracts, transportation enhancement program (TEP) funded projects or advertised projects. Projects have been developed to address stabilization issues in Harford and Baltimore counties**.** Preliminary site assessments have been initiated in Anne Arundel County.

E.5.b Document each Outfall's Attributes

SOIRP outfall inspections are currently being conducted on the outfalls in Frederick, Harford and Montgomery counties. Inspections are conducted using the SHA SOIRP Program outfall inspection protocol, Chapter 4 of the *SHA NPDES Standard Procedure*s. SHA is currently in the design phase for Baltimore and Harford County sites. The Baltimore County outfall sites were split into two phases and the first phase, consisting of 10 outfalls, has completed construction. The second phase of Baltimore sites is to be advertised for construction in FY11. The Harford County sites are currently at preliminary design stage.

E.5.c Illicit Connection Investigations

Currently, illicit discharge screenings are being conducted in Frederick, Harford and Montgomery counties. As illicit discharges are found we currently are sending the report to the local NPDES coordinator for elimination. No illicit discharges have been found in these counties for this update season.

E.5.d Use Appropriate Enforcement Procedures

SHA notifies the NPDES coordinator or their IDDE designated contact at the counties or jurisdictions in which the illicit discharges or connections to SHA storm drain system are discovered.

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

Over the reporting period from 10/2009 to 12/2010, 232 outfalls were screened in the Phase I counties for illicit discharges and three illicit connections were discovered. The data is being reviewed and when the illicit discharges have been verified, if they are valid, we will deliver the reports to the County NPDES coordinators.

Table 1-11 below details the illicit discharge efforts for this permit term. Past and current illicit connections to SHA storm drain systems that have been discovered through our field inspection and screening process are included and the jurisdiction and date the reports were delivered for elimination enforcement are also included.

Table 1-11 Illicit Discharge Screenings to Date

County	Outfalls Screened	Illicit Discharge Reports	Delivered to Jurisdiction	Date Delivered
Frederick[1]	46	16	County NPDES Coordinator	9/11/2007
Harford[1]	53	1	No Records	
Howard[2]	244	2	County NPDES Coordinator	01/10/2008
Montgomery[1]	217	3	County NPDES Coordinator	01/10/2008
Charles	74	0		

Table 1-11 Illicit Discharge Screenings to Date

County	Outfalls Screened	Illicit Discharge Reports	Delivered to Jurisdiction	Date Delivered
Carroll	167	10	County NPDES Coordinator	8/14/2008
Anne Arundel[2]	504	2		
Prince Georges[2]	459	0		
Baltimore[2]	77	1	County NPDES Coordinator	10/09/2009
Totals	**1841**	**35**		

Notes: 1. GIS updates currently under development. 2. GIS QA/QC on-going for new data.

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 IPM 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** – As part of its eighth annual event, the SHA Earth Day Team sponsored a weeklong celebration at the SHA headquarters complex beginning April 19, 2010. This annual event is sponsored by the SHA Office of Environmental Design and many volunteers from several offices at SHA Headquarters. This team brings together a diverse group of exhibitors from SHA and the local non-profit community to highlight our resources and how to best manage their use and preservation. Approximately 360 employees or visitors attended the events of the week. The workshops were as follows:
  - April 19th: Rain Barrels – Hands-on rain barrel construction in teams.
  - April 20th: Herb/flower containers – Participants provided their own container and created an herb garden from plants and supplies provided
  - April 21st: Solar Energy 101 – Topics concerning solar energy were discussed and included: energy conservation,

efficiency, money savings, passive solar considerations, photovoltaic modules (electric), hot water systems, sun tubes, Maryland solar grants and federal solar tax credits

- April 22th: Recycling – Focused on new ways to save the environment at SHA, creative ways to reduce waste in the workplace, what can be recycled and where to put it and other educational information and tips on how to be earth friendly and economical
- April 23th: Play and Learn - Participants experienced an interactive game show atmosphere while learning how to contribute to a cleaner environment

Participants in the Earth Week 'Play and Learn' Session

In addition to the Lunch and Learn sessions, a web page was developed that contains additional information including a list of cyber exhibitors, volunteer opportunities, Baltimore Downspout Disconnection Program information, directions for making a rain barrel, herb care information, energy consumption information, recycling information and an earth day video. The website can be accessed at:

http://shavmspweb/2010EarthDay/HOME.aspx

- **Annual Stream Clean-up –** The 2010 Patuxent Clean Up was held April 10th at a tributary to the Little Patuxent in Columbia, MD near MD 175. This was the second year for this site. Seventeen volunteers participated in collecting refuse consisting of five submerged shopping carts, four truck tires and a large wooden shed door, in addition to approximately 1300 lbs. of bagged trash. Volunteers included employees from SHA and the Maryland Department of Transportation (MDOT).

Table 1-12 Adopt-a-Highway Program

County	Groups	No. Bags	Miles Adopted
Anne Arundel	3	112	3
Baltimore	72	983	75
Carroll	36	445	37
Charles	16	339	18
Frederick	19	213	20
Harford	16	34	15
Howard	0	0	0
Montgomery	7	140	7
Prince George's	4	37	5
Totals	173	2303	181

Data extracted from the Adopt-A-Highway database for the period 10/1/09 to 12/31/10

- **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 1-12 lists numbers of groups and bags of trash collected during the reporting period.

Table 1-13 Sponsor-a-Highway Programs

County	Available Miles	Miles Sponsored
Anne Arundel	91.54	50.23
Baltimore	93.89	75.23
Frederick	13.14	5.84
Harford	9.58	2.65
Howard	33.57	17.56
Montgomery	40.38	12.94
Prince George's	79.25	27.64
Totals	361.35	192.09

- **Sponsor-a-Highway Program** – SHA also has a program that allows corporate sponsors to sponsor one-mile sections of Maryland roadways. The Sponsor enters into an agreement with a maintenance provider for litter and debris removal from the sponsored segment.

  Sponsor-A-Highway was not available in Carroll, Charles, Frederick, Harford, and Montgomery Counties as of September 30, 2009. As of October 1, 2009, routes have been added to the Sponsor-A-Highway program through all counties in MD. See Table 1-13 for numbers of currently sponsored miles within the nine Phase I MS4 counties.

- **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 1-14 lists the numbers of plants, counties of participation and numbers of volunteers for the last reporting period.

Table 1-14 Partnership Planting Program

County	No. Trees/Shrubs	No. Volunteers
Howard	170	23

- **Transportation Enhancement Program** – SHA Administers the Federal Highway Transportation Enhancement Program (TEP) for the State of Maryland. In this capacity, SHA looks for opportunities to share the potential benefits of applying for funding under this program with projects that fall under the eligible funding categories.

  For potential projects that fall under the funding category ‘Mitigation of Water Pollution due to Highway Runoff’, SHA Highway Hydraulics Division takes the initiative with watershed groups, local municipalities, community groups and counties to encourage their participation in this program. SHA provides assistance to potential project sponsors by advising on proposal content, reviewing drafts and then providing guidance on Federal Aid requirements for construction document preparation and advertisement process.

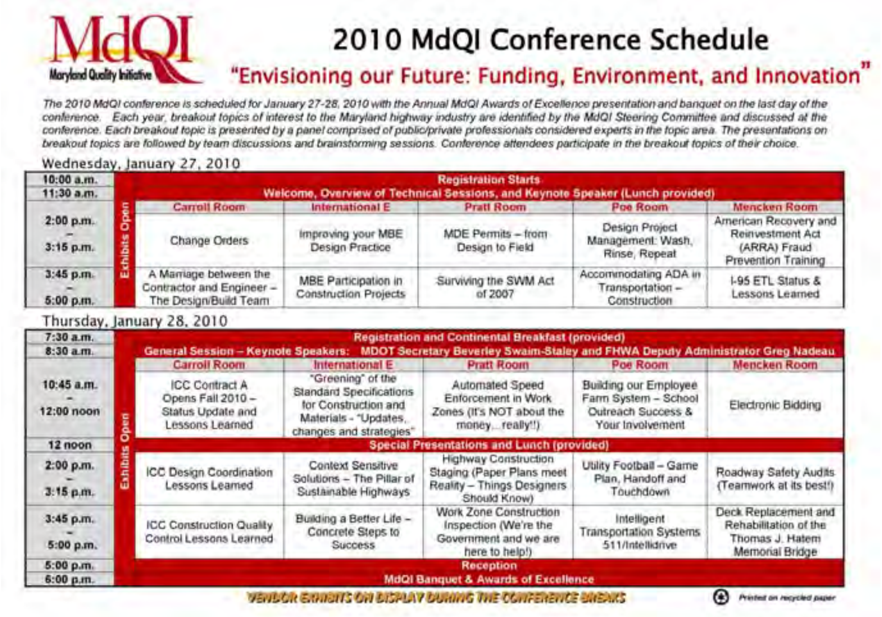
  A supported project that is currently under construction is the Gunpowder Falls Tributaries-Stream Stabilization project located in Baltimore County. This project consists of stabilizing more than 800 LF of stream.

- **Roadside Debris/Safety Campaign TEP Project** – The litter campaign that was developed and reported on in the previous annual reports is completed. However, the SHA Office of Communications is developing another litter campaign to address concerns from litter along Maryland Roadways. This new campaign will look at performing research to develop the most effective target audience and then develop a plan for media coverage to reach that audience. This effort was initiated in May 2008 and has been pursued over the next few years.

- **‘Envisioning Our Future: Funding, Environment, Innovation’, 2010 MdQI (Maryland Quality Initiative) Conference** – SHA co-sponsored and participated in the MdQI Conference held on January 27, 2010 and January 28, 2011. The mission of MdQI is to provide the Maryland highway industry a forum that fosters coordinated and continuous quality improvement in order to ensure safe, efficient, and environmentally sensitive highways which meet the needs of all transportation stakeholders. This industry conference is held annually each winter and brings together public and private highway design and construction industry professionals in a forum of workshops, round table discussions, exhibits and networking. The conference schedule is shown in Figure 1-8.

  Approx 493 engineers, consultants and contractors attended the conference which included public and private participation. There were 64 exhibitors.

The schedule for the upcoming conference to be held February 2-3, 2011 is also available and registration is open. See Figure 1-9 for 2011 conference schedule. Additional information concerning the upcoming MdQI 2011 conference is available at the following web site: http//mdqi.org.



MdQI
Maryland Quality Initiative

2010 MdQI Conference Schedule

"Envisioning our Future: Funding, Environment, and Innovation"

The 2010 MdQI conference is scheduled for January 27-28, 2010 with the Annual MdQI Awards of Excellence presentation and banquet on the last day of the conference. Each year, breakout topics of interest to the Maryland highway industry are identified by the MdQI Steering Committee and discussed at the conference. Each breakout topic is presented by a panel comprised of public/private professionals considered experts in the topic area. The presentations on breakout topics are followed by team discussions and brainstorming sessions. Conference attendees participate in the breakout topics of their choice.

Wednesday, January 27, 2010

10:00 a.m.	Registration Starts					
11:30 a.m.	Welcome, Overview of Technical Sessions, and Keynote Speaker (Lunch provided)					
	Exhibits Open	Carroll Room	International E	Pratt Room	Poe Room	Mencken Room
2:00 p.m. – 3:15 p.m.		Change Orders	Improving your MBE Design Practice	MDE Permits – from Design to Field	Design Project Management: Wash, Rinse, Repeat	American Recovery and Reinvestment Act (ARRA) Fraud Prevention Training
3:45 p.m. – 5:00 p.m.		A Marriage between the Contractor and Engineer – The Design/Build Team	MBE Participation in Construction Projects	Surviving the SWM Act of 2007	Accommodating ADA in Transportation – Construction	I-95 ETL Status & Lessons Learned

Thursday, January 28, 2010

7:30 a.m.	Registration and Continental Breakfast (provided)					
8:30 a.m.	General Session – Keynote Speakers: MDOT Secretary Beverley Swaim-Staley and FHWA Deputy Administrator Greg Nadeau					
	Exhibits Open	Carroll Room	International E	Pratt Room	Poe Room	Mencken Room
10:45 a.m. – 12:00 noon		ICC Contract A Opens Fall 2010 – Status Update and Lessons Learned	"Greening" of the Standard Specifications for Construction and Materials - "Updates, changes and strategies"	Automated Speed Enforcement in Work Zones (It's NOT about the money....really!!)	Building our Employee Farm System – School Outreach Success & Your Involvement	Electronic Bidding
12 noon		Special Presentations and Lunch (provided)				
2:00 p.m. – 3:15 p.m.		ICC Design Coordination Lessons Learned	Context Sensitive Solutions – The Pillar of Sustainable Highways	Highway Construction Staging (Paper Plans meet Reality – Things Designers Should Know)	Utility Football – Game Plan, Handoff and Touchdown	Roadway Safety Audits (Teamwork at its best!)
3:45 p.m. – 5:00 p.m.		ICC Construction Quality Control Lessons Learned	Building a Better Life – Concrete Steps to Success	Work Zone Construction Inspection (We're the Government and we are here to help!)	Intelligent Transportation Systems 511/Intellidrive	Deck Replacement and Rehabilitation of the Thomas J. Hatem Memorial Bridge
5:00 p.m.		Reception				
6:00 p.m.		MdQI Banquet & Awards of Excellence				

VENDOR EXHIBITS ON DISPLAY DURING THE CONFERENCE BREAKS

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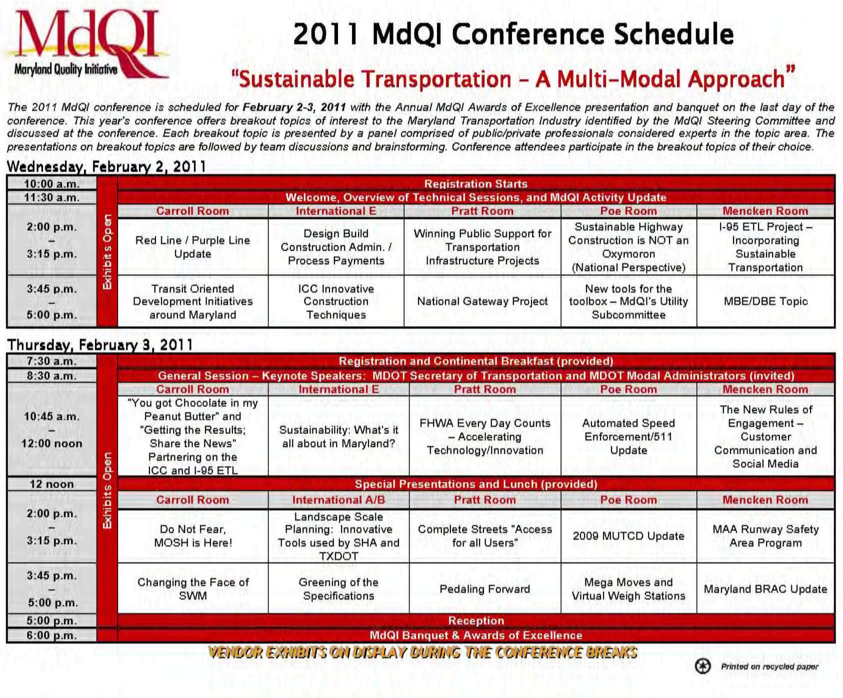
Figure 1-8 – MdQI 2010 Conference Schedule



MdQI
Maryland Quality Initiative

2011 MdQI Conference Schedule

"Sustainable Transportation – A Multi-Modal Approach"

*The 2011 MdQI conference is scheduled for **February 2-3, 2011** with the Annual MdQI Awards of Excellence presentation and banquet on the last day of the conference. This year's conference offers breakout topics of interest to the Maryland Transportation Industry identified by the MdQI Steering Committee and discussed at the conference. Each breakout topic is presented by a panel comprised of public/private professionals considered experts in the topic area. The presentations on breakout topics are followed by team discussions and brainstorming. Conference attendees participate in the breakout topics of their choice.*

Wednesday, February 2, 2011

10:00 a.m.	Registration Starts					
11:30 a.m.	Welcome, Overview of Technical Sessions, and MdQI Activity Update					
	Exhibits Open	Carroll Room	International E	Pratt Room	Poe Room	Mencken Room
2:00 p.m. – 3:15 p.m.		Red Line / Purple Line Update	Design Build Construction Admin. / Process Payments	Winning Public Support for Transportation Infrastructure Projects	Sustainable Highway Construction is NOT an Oxymoron (National Perspective)	I-95 ETL Project – Incorporating Sustainable Transportation
3:45 p.m. – 5:00 p.m.		Transit Oriented Development Initiatives around Maryland	ICC Innovative Construction Techniques	National Gateway Project	New tools for the toolbox – MdQI's Utility Subcommittee	MBE/DBE Topic

Thursday, February 3, 2011

7:30 a.m.	Registration and Continental Breakfast (provided)					
8:30 a.m.	General Session – Keynote Speakers: MDOT Secretary of Transportation and MDOT Modal Administrators (invited)					
	Exhibits Open	Carroll Room	International E	Pratt Room	Poe Room	Mencken Room
10:45 a.m. – 12:00 noon		"You got Chocolate in my Peanut Butter" and "Getting the Results; Share the News" Partnering on the ICC and I-95 ETL	Sustainability: What's it all about in Maryland?	FHWA Every Day Counts – Accelerating Technology/Innovation	Automated Speed Enforcement/511 Update	The New Rules of Engagement – Customer Communication and Social Media
12 noon		Special Presentations and Lunch (provided)				
		Carroll Room	International A/B	Pratt Room	Poe Room	Mencken Room
2:00 p.m. – 3:15 p.m.		Do Not Fear, MOSH is Here!	Landscape Scale Planning: Innovative Tools used by SHA and TXDOT	Complete Streets "Access for all Users"	2009 MUTCD Update	MAA Runway Safety Area Program
3:45 p.m. – 5:00 p.m.		Changing the Face of SWM	Greening of the Specifications	Pedaling Forward	Mega Moves and Virtual Weigh Stations	Maryland BRAC Update
5:00 p.m.		Reception				
6:00 p.m.		MdQI Banquet & Awards of Excellence				

VENDOR EXHIBITS ON DISPLAY DURING THE CONFERENCE BREAKS

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Figure 1-9 – MdQI 2011 Conference Schedule

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.

Tree Plantings at US 13 at US Business 50 for Million Tree Initiative

- **Million Tree Initiative** – In the fall of 2008, the Maryland State Highway Administration (SHA), the Maryland Department of Natural Resources (MDNR), Federal Highway Administration (FHWA), and the Maryland Department of Safety and Correctional Services (DPSCS) formed a partnership to plant trees along Maryland roadsides and in State right-of-way. The tree-planting program directly supports Governor Martin O’Malley’s *Smart, Green and Growing* initiative. SHA is funding the trees and materials; MDNR is funding the labor, which is provided by inmates from DPSCS. As of December 31, 2010 over 500,000 trees have been planted with close to 200,000 of them being planted within the Phase I NPDES counties. Trees are being planted during spring and fall months so the young plants can survive hot, dry summers and harsh winters.

Funds for the purchase of the trees, support stakes and tree shelters are made possible from the FHWA Transportation Enhancement Program (TEP) along with State funding. The total TEP funding and match for the SHA participation in the *One Million Tree* initiative increased from $800,000 in 2010 to $1,600,000 in 2011. The Million Tree Initiative will continue through December 31, 2011.

- **SHA Environmental Advisory Committee** – A committee was formed by SHA in order to seek expert level, environmental advice from pronounced experts and practitioners in various fields and industries. This committee meets several times a year to advise SHA senior management on initiatives ranging from clean air, wind power, water quality and recycle/reuse.

- **Graduate Engineers Training Program (GETP)** – SHA continues to provide environmental awareness training to its personnel and is committed to continuing these efforts in the future. The two-year GETP provides training to over 100 new engineers and includes modules concerning the National Environmental Policy Act (NEPA) and Introduction to the Office of Environmental Design. The GETP hosted the revised Introduction to Environmental Design module to the GETP Class of 2010 on August 10, 2010.

- **OHD University** – This is an annual, internal training program for the Office of Highway Development that provides technical training for new engineers and others who desire to take refresher courses. In addition to highway engineering and technical issues, detailed information is presented for SWM, ESC and environmental permitting issues, including NPDES concerns. The number of people trained during 2010 was 128.

- **Statewide Pesticide/Vegetation Management Training** – There are several types of internal training sessions for pesticide management that SHA provides annually. They include re-certification, right-of-way pre-certification, aquatic pre-certification, herbicide update and an annual vegetation management conference. The numbers of participants at each of these training sessions are listed in Tables 1-15 to 1-17. There was no Pesticide Aquatic Certification (ENV600) training held in 2010.

Table 1-15 Pesticide Applicator Training (ENV100)

SHA District	Number Trained
3 (MO, PG)	25
4 (BA. HA)	6
5 (AA, CH)	9
7(CL,FR, HO)	16
Totals	56

Table 1-16 SHA Vegetation Management (Re-certification) Conference (ENV200)

SHA District	Number Trained
3 (MO, PG)	8
4 (BA. HA)	19
5 (AA, CH)	14
7(CL,FR, HO)	12
Totals	53

Table 1-17 Pesticide Core and Right-of-Way Pre-Certification (ENV210)

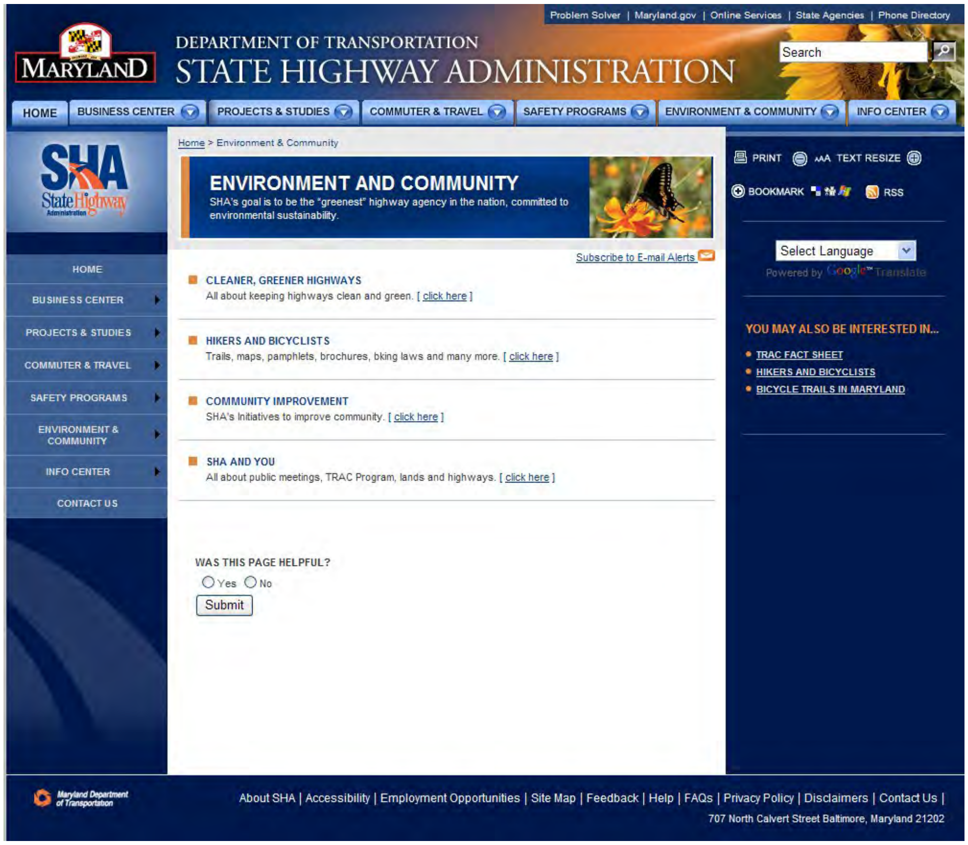
SHA District	Number Trained
3 (MO, PG)	7
4 (BA. HA)	0
5 (AA, CH)	4
7(CL,FR, HO)	0
Totals	11

- **Annual Vegetation Management Conference –** This annual conference is sponsored by the Office of Environmental Design and the Maryland SHA Statewide Vegetation Management Team. It provides a forum for disseminating current information on topics such as invasive species eradication, nutrient management, stormwater management facility vegetation management, turf establishment, forest conservation, native meadow establishment, and herbicide application. Each SHA maintenance shop sends people to these conferences. The 2010 conference was held on October 20, 2010 and numbers of attendees was 79.

- **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 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 environmental resources such as environmental stewardship in the 2009 MD Transportation Plan and the 2010 Annual Attainment Report on Transportation System Performance; and an information brochure for the MDOT Office of Environment.

- **SHA Environment and Community Web Page** – SHA has developed an environmental awareness web page that is located on the SHA internet site at the following link: http://www.marylandroads.com/index.aspx?PageId=675

  Topics include the following programs: Transportation Enhancement Program (TEP), Adopt-a-Highway, Sponsor-a-Highway, Partnership Plantings, Green Highways Partnership and the Million Tree Initiative.



ENVIRONMENT AND COMMUNITY

SHA's goal is to be the "greenest" highway agency in the nation, committed to environmental sustainability.

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Figure 1-10 - SHA Internet 'Environment and Community' Web Page

- **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.

  Finally, employee ID badges allow 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 SHA Administrator, Neil Pedersen, issued a policy regarding 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.

F Watershed Assessment

The watershed assessment effort described by the permit includes continuing to provide available geographic information system (GIS) highway data to permitted NPDES municipalities and MDE; completing the impervious surface accounting by the fourth annual report; select sites for retrofitting impervious areas with poor or no control infrastructure; and working with NPDES municipalities to maximize water quality improvements in areas of local concern.

F.1 GIS Highway Data to NPDES Jurisdictions and MDE

SHA continues to make the SHA GIS storm drain and BMP data available to NPDES jurisdictions (when requested) and MDE.

We periodically coordinate with the MDE Science Services Administration on data issues for the Bay and local TMDL modeling.

F.2 Complete Impervious Accounting by Fourth Annual Report

SHA completed the Impervious Accounting for the all phase I counties, by the fourth annual report, October 2009. Adjustments to the accounting will be undertaken when the MDE Impervious Accounting protocol is developed. Issues to be addressed by the protocol such as pro-rating treatment associated with BMPs by era of development and impervious equivalencies for BMPs that are not urban stormwater BMPs will be evaluated and the accounting recomputed for future SHA treatment requirements.

F.3 Impervious Area Retrofits

We will continue to identify sites that prove suitable for developing as stormwater facilities to treat additional impervious surfaces in these counties. These efforts will be coordinated within both Chesapeake Bay and local TMDL priorities and within local water resources elements (WREs) for the individual counties and municipalities where possible and to the extent our resources allow.

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

As part of this permit condition, MDE required that we not only implement restoration efforts, but that we adhere to the watershed restoration goals and priorities established by local NPDES jurisdictions. Past performance over this permit term concerning this condition was discussed in detail in the last four reports. They include:

- US 301 Watershed-based SWM Assessment, and
- EPA Green Highways Grant – Framework for Watershed Based SWM.

With the TMDL requirements anticipated for the next permit term focused on waste load reductions for urban stormwater, our first focus in the future will be on the Chesapeake Bay segmentsheds and local TMDL watersheds where SHA is named as a contributor to the waste load allocation (WLA). This includes setting and meeting the 2-year milestones for the Bay TMDL as well as demonstrating compliance in local TMDL watersheds.

G Watershed Restoration

Requirements for this permit condition include developing and implementing twenty-five significant stormwater management retrofit projects, contributing to local watershed restoration activities by constructing or funding retrofits within locally targeted watersheds, and submitting annual reports on watershed activities that contain proposals, costs, schedules, implementation status and impervious acres proposed for management.

G.1 Implement 25 Significant SWM Retrofit Projects

The requirement that twenty-five projects be completed was met and reported on in past annual reports. We are continuing our efforts to maximize treatment of our baseline untreated impervious in anticipation of a percentage treatment requirement for our next permit term.

BMP Upgrade Retrofits

These projects were developed outside of roadway development stormwater management requirements and consist of upgrading stormwater BMPs to current regulations, stream stabilization and restoration, and outfall stabilization projects. Table 1-18 lists these projects to date which total 112 and amount to approximately 673 acres of treated impervious surfaces. We have also summarized progress in treating the SHA baseline untreated impervious surfaces in Table 1-6 on page 1-10 in Section C.3, Create Impervious Surface Account. Our current level of treatment of treatment is 3%. This is before adjustments that will be required by the upcoming impervious accounting protocol that MDE is developing, so the 3% is subject to change.

Two additional projects have been added this year in Montgomery County:

- BMP 150059 with 4.67 acres treated, and
- BMP 150556 with 5.65 acres treated.

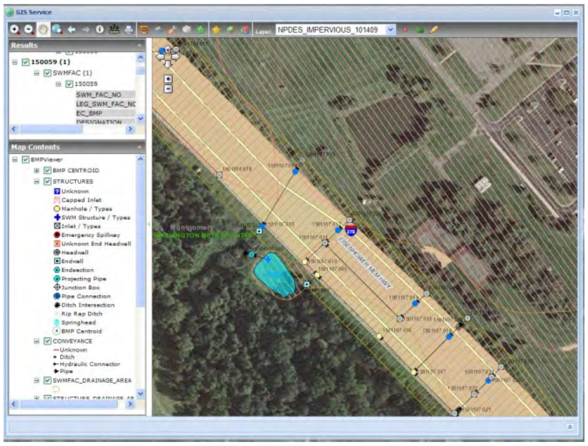


Figure 1-11 - BMP 150059 at I-270 in Montgomery County – Under Design

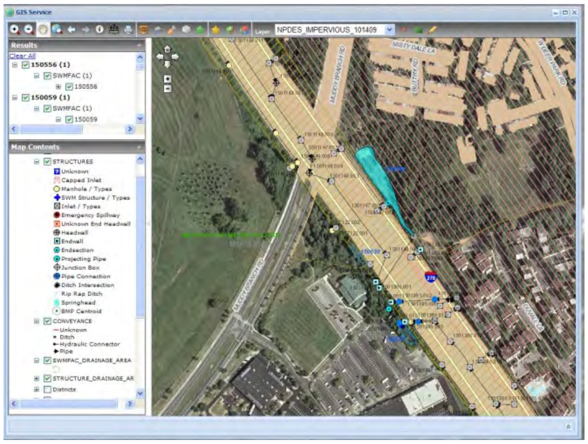


Figure 1-12 - BMP 150556 at I-270 and Muddy Branch Rd – Under Design

Table 1-18 Watershed Restoration Projects

Projects by Watershed	Retrofit Type	Status	Restored Impervious Acres
Lower Susquehanna River – 02-12-02			
1. BMP 120076	BMP retrofit	Complete	2.82
Chester River Area – 02-13-05			
2. BMP 170011*	BMP retrofit	Design	0.41
3. BMP 170012*	BMP Retrofit	Design	0.23
Bush River Area – 02-13-07			
4. BMP 120069	BMP Retrofit	Complete	4.16
5. BMP 120072	BMP Retrofit	Complete	4.68
6. BMP 120073	BMP Retrofit	Complete	3.99
7. BMP 120075	BMP Retrofit	Complete	1.77
8. BMP 120081	BMP Retrofit	Complete	2.39
9. BMP 120082	BMP Retrofit	Complete	1.00
Gunpowder River – 02-13-08			
10. I-83 Outfall Stabilization of Tributaries to Gunpowder Falls	Stream	On-Hold	7.85
Patapsco River – 02-13-09			
11. BMP 020120	BMP Retrofit	Complete	17.73
12. BMP 020121	BMP Retrofit	Complete	0.96
13. BMP 020122	BMP Retrofit	Complete	0.92
14. BMP 020625*	BMP Retrofit	Design	2.46
15. BMP 030281	BMP Retrofit	Complete	8.35
16. MD 139 Tributary to Towson Run Stabilization	Stream Stabilization	Complete	260.30
17. BMP 020111	BMP Retrofit	Complete	6.04
18. BMP 020112	BMP Retrofit	Complete	0.56
19. BMP 020098	BMP Retrofit	Construction	0.68
20. BMP 020099	BMP Enhancement	Construction	0.75
21. BMP 020476	BMP Retrofit	Construction	3.79
22. BMP 020477	BMP Retrofit	Construction	Combined with 020476

Table 1-18 Watershed Restoration Projects

Projects by Watershed	Retrofit Type	Status	Restored Impervious Acres
23.BMP 130197	BMP Retrofit	Complete	0.44
24.BMP 130207	BMP Retrofit	Complete	1.57
25.BMP 130221	BMP Retrofit	Complete	0.17
26.BMP 130210	BMP Retrofit	Complete	0.24
27.BMP 130217	BMP Retrofit	Complete	0.10
West Chesapeake Bay – 02-13-10			
28.BMP 020019	BMP Retrofit	Construction	1.22
29.BMP 020022	BMP Retrofit	Complete	1.06
30.BMP 020027	BMP Retrofit	Complete	1.59
31.BMP 020029	BMP Retrofit	Complete	0.88
32.BMP 020031	BMP Retrofit	Complete	2.29
33.BMP 020088	BMP Retrofit	Complete	3.53
34.BMP 020481	BMP Retrofit	Complete	2.09
35.BMP 020522	BMP Retrofit	Complete	1.70
36.BMP 020273	BMP Retrofit	Construction	1.18
37.BMP 020491	BMP retrofit	Complete	1.79
38.BMP 020185	BMP Retrofit	Construction	0.48
39.BMP 020198	BMP Retrofit	Construction	0.68
40.BMP 020201	BMP retrofit	Construction	1.01
41.BMP 020205	BMP Retrofit	Construction	1.16
42.BMP 020206	BMP Retrofit	Construction	0.49
43.BMP 020210	BMP Retrofit	Construction	0.36
44.BMP 020220	BMP Retrofit	Construction	0.72
45.BMP 020258	BMP Retrofit	Design	3.27
46.BMP 020260	BMP Retrofit	Design	1.41
47.BMP 020268	BMP Retrofit	Design	7.08
48.BMP 020393	BMP Retrofit	Design	4.35
49.BMP 020394	BMP Retrofit	Design	3.27
50.BMP 020014	BMP Retrofit	Design	2.20
51.BMP 020015	BMP Retrofit	Design	1.22
52.BMP 020016	BMP Retrofit	Design	0.95
53.BMP 020017	BMP Retrofit	Design	0.44
54.BMP 020018	BMP Retrofit	Design	0.89

Table 1-18 Watershed Restoration Projects

Projects by Watershed	Retrofit Type	Status	Restored Impervious Acres
Patuxent River – 02-13-11			
55. BMP 160059	BMP Retrofit	Complete	3.2
56. BMP 020488	BMP Retrofit	Complete	5.56
57. BMP 160217	BMP Retrofit	Complete	0.64
58. BMP 160219	BMP Retrofit	Complete	0.91
59. BMP 160380	BMP Retrofit	Complete	3.42
60. Unnamed Tributary to Rocky Gorge Reservoir adjacent US 29	Stream Stabilization	Cancelled	
61. BMP 020301	BMP Retrofit	Design	2.30
62. BMP 020311	BMP Retrofit	Design	0.28
63. BMP 020437	BMP Retrofit	Design	4.13
64. BMP 130149	BMP Retrofit	Complete	0.48
65. BMP 130150	BMP Retrofit	Complete	1.02
66. BMP 130154	BMP Retrofit	Complete	0.47
67. BMP 130159	BMP Retrofit	Complete	0.02
68. BMP 130160	BMP Retrofit	Complete	0.52
69. BMP 130162	BMP Retrofit	Complete	0.66
70. BMP 130179	BMP Retrofit	Complete	2.10
71. BMP 130180	BMP Retrofit	Complete	0.43
72. BMP 130187	BMP Retrofit	Complete	0.13
73. BMP 130188	BMP Retrofit	Complete	0.12
74. BMP 130189	BMP Retrofit	Complete	0.03
75. BMP 130190	BMP Retrofit	Complete	0.03
76. BMP 130191	BMP Retrofit	Complete	0.05
77. BMP 130192	BMP Retrofit	Complete	0.05
78. BMP 130193	BMP Retrofit	Complete	0.10
79. BMP 130194	BMP Retrofit	Complete	0.22
80. BMP 130232	BMP Retrofit	Complete	0.03
81. BMP 130242	BMP Retrofit	Complete	0.72
82. BMP 130243	BMP Retrofit	Complete	3.49
83. BMP 150228	BMP Retrofit	Complete	0.13
84. BMP 150331	BMP Retrofit	Complete	0.23

Table 1-18 Watershed Restoration Projects

Projects by Watershed	Retrofit Type	Status	Restored Impervious Acres
85. BMP 130047	BMP Retrofit	Complete	1.39
Lower Potomac River – 02-14-01			
86. BMP 160456	BMP Retrofit	Completed	1.70
87. BMP 080014	BMP Retrofit	Construction	0.24
88. BMP 080039	BMP Retrofit	Construction	0.10
89. BMP 080040	BMP Retrofit	Construction	0.10
90. BMP 080041	BMP Retrofit	Construction	0.12
91. BMP 080042	BMP Retrofit	Construction	0.11
92. BMP 080043	BMP Retrofit	Construction	0.28
93. BMP 080044	BMP Retrofit	Construction	0.20
94. BMP 080083	BMP Retrofit	Construction	0.06
95. BMP 080095	BMP Retrofit	Construction	0.48
Washington Metropolitan-02-14-02			
96. BMP 160607	BMP Retrofit	Complete	0.41
97. BMP 160609	BMP Retrofit	Complete	Combined with 160607
98. BMP 160653	BMP Retrofit	Complete	15.80
99. Long Draught Branch Restoration/ Stabilization	Stream Stabilization	Delayed Due to Agency Comments	228
100. BMP 150002	BMP Retrofit	Complete	0.31
101. BMP 150003	BMP Retrofit	Complete	1.69
102. BMP 150004	BMP Retrofit	Complete	Combined with 150003
103. BMP 150005	BMP Retrofit	Complete	Combined with 150003
104. BMP 150301	BMP Retrofit	Complete	0.28
105. BMP 150362	BMP Retrofit	Complete	1.03
106. BMP 150380	BMP Retrofit	Complete	1.05
107. BMP 150550	BMP Retrofit	Complete	1.26
108. BMP 150076	BMP Retrofit	Complete	1.25
109. BMP 150059*	BMP Retrofit	Design	4.67
110. BMP 150556*	BMP Retrofit	Design	5.65
Middle Potomac River – 02-14-03			
111. Tributary to Tuscarora Creek	Stream Stabilization	Complete	1.94

Table 1-18 Watershed Restoration Projects

Projects by Watershed	Retrofit Type	Status	Restored Impervious Acres
Stabilization at US 340 and US 15			
112. BMP 150270	BMP retrofit	Complete	0.08

* Projects added since last report.

Pavement Retrofit Projects

We have worked closely with MDE to determine Bay TMDL requirements for SHA in order to establish funding and resource needs for the future 2-year milestones. As a result, in addition to the stormwater upgrade projects we are currently pursuing, we have established funding sources for the next three years to provide management, design and construction resources to implement new BMPs to meet both the future waste load reductions and impervious treatment requirement. Future projects include median treatment at existing open section roadways and include sites in all nine Phase I counties.

Stream Project Assessments

In order to assess the success of SHA stream restoration and stabilization projects, SHA has contracted with Dr. R. P. Morgan at UMD Center for Environmental Service, Appalachian Laboratory, to perform stream assessments on completed projects. Three assessment protocols are undertaken: benthic macroinvertebrates, fish and habitat.

Assessments investigate the presence of benthic macroinvertebrates and the quality of habitats using MBSS sampling protocols for the purpose of quantitatively describing the community composition, determining relative abundance in favorable habitat at each sampling station and assessing habitat categories. Fish are sampled using the Fish Indices of Biotic Integrity (FIBI).

A copy of the report, *Assessment of SHA Stream Restoration Projects in Maryland: 1998-2010,* is included in Appendix E.

Retrofit Database Delivery

The database for Table D from Attachment A of the permit is included on the attached CD and includes only the two additional projects added this year. The full list was provided to MDE in the 2009 annual report.

G.2 Contribute to Local NPDES Watershed Restoration Activities

SHA often participates in and supports watershed interest groups and local jurisdictions in their activities. In addition, SHA has participated directly or indirectly in developing watershed plans as well as providing funding. The Maryland Department of Transportation's State Highway Administration oversees the Federal Transportation Enhancement Program (TEP) and encourages the use of these funds by local jurisdictions and interest groups to fund water quality projects associated with roadway runoff.

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

- **I-695 at Minebank Run Stream Restoration and Water Quality Improvements – SHA.** This is a new project that will provide outfall stabilization, stream restoration and reforestation. The Minebank Run watershed is a priority targeted by Baltimore County for restoration. The design work on this project has been initiated and no schedule has been developed at this time. This project will also provide pollutant load reductions for the Gunpowder River watershed.

Figure 1-13 - Minebank Run Project Area – I-695 and Cromwell Bridge Road Interchange

- **Westminster SWM Regional Pond – Carroll County.** This is a project that Carroll County is sponsoring and SHA has approved for TEP funding. The project provide stormwater management for a currently untreated impervious are and provide pollutant load reductions. SHA will provide guidance for navigating the Federal Aid approval process and will receive a percentage of the reduced loads credited to us.

Figure 1-14 - Carroll County Westminster Pond Project

- **Laurel Lakes Task Force** – **PG County**. The I-95/Contee Road project recently received design funding (after being put on hold for a number of months) and is currently scheduled for advertisement as a Design/Build contract in spring 2010. The project will be designed in accordance with the Stormwater Management Act of 2007, implementing ESD features.

- **South River Federation – AA County.** The BMP upgrade projects mentioned in the last annual report were delayed to address in-stream issues.

- **Whitehall Creek Watershed – AA County.** This is a Transportation Enhancement Program (TEP) funded project being undertaken by Anne Arundel County. SHA is supporting this project through the TEP review process and has previously recommended it for award. SHA worked with the county to prepare a watershed assessment study and actively participated in a multi-agency effort to address water quality concerns in this watershed. The project proposes construction of various stream segments at the head of the watershed as well as significant stabilization from the US 50 interchange at MD 279 up to the point of tidal influence. Currently, the project is under design by the county.

- **MD 213 Stormwater Retrofit for Gravel Run South – (Corsica River, not Phase 1)** Although not a phase I jurisdiction, the Corsica watershed is a special initiative by the Governor to implement tributary strategies and a Watershed Restoration Action Strategy (WRAS). This project is sponsored by the Town of Centreville and SHA supported funding. TEP funding was subsequently granted. Funding support was also provided by MDE through Section 319 grant initiatives.

  The project objective is to provide stormwater management treatment to a significant amount of impervious surface from MD 213. The project has progressed through the design process in 2008 and is now entering the construction phase.

G.3 Report and Submit Annually

SHA completed and submited information on our twenty-five required watershed restoration projects and other activities to meet the permit requirement in past reports including retrofit proposals, costs, schedules, implementation status and impervious acres proposed for management.

Documentation in the form of construction plans, cost estimates and schedule for these additional projects can be provided to MDE at their request.

H Assessment of Controls

This condition requires that SHA develop a proposal and receive approval for a watershed restoration project by October 21, 2006; develop and receive approval for a monitoring plan that should include chemical, biological and physical monitoring according to parameters specified in the permit and submit data annually.

H.1 Restoration Site Approved by October 21, 2006

The Long Draught Branch restoration project was previously approved as our restoration site. This project has undergone difficulties in obtaining the joint permit approval for construction. SHA is investigating the possibility of altering the proposed design in order to address agency concerns and is continuing to pursue this project. However, the current budget cuts have caused us to delay construction funding until 2014. We will continue to provide monitoring on this project in accordance with the permit requirements.

H.2 Monitoring Plan

Based on the previous approval of the Long Draught Branch project by MDE-WMA, significant monitoring (physical, chemical and biological) was performed. The final report for the pre-construction monitoring data was included in the 2008 annual.

The pre-construction monitoring was completed on this project. Since the project has been delayed, the post-construction monitoring data will not be available until after the construction is completed.

In the interim, we are pursuing monitoring of a failed infiltration basin and these monitoring results are included in Appendix C.

H.3 Annual Data Submittal

Monitoring data has been included in the formats requested as Tables E and F in Attachment A of the Phase I permit. These are included on the attached CD.

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.

Available Funding

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 in the amount of $18 million for five years to continue our efforts for the future.

In addition to the funding commitment from this office we also use State Planning and Research funds (SPR), Transportation Enhancement Program (TEP) funds and SHA Operations and Maintenance funds in completing NPDES requirements.

Required Fiscal Analysis Data

Currently, SHA tracks spending for the NPDES program as a whole and breaks out a few items such as NPDES Stormwater Facility Program and industrial activities. We do not currently track many of the requested areas such as street sweeping, inlet cleaning or database maintenance as separate expenditures.

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.

Table 1-19 SHA Capital Expenditures for NPDES

Fiscal Year	Expenditure (Millions)
2005	$ 3.40
2006	$ 7.26
2007	$ 5.74
2008	$ 5.73
2009	$ 6.42
2010	$ 8.68

J Total Maximum Daily Loads

The permit states that MDE has determined that owners of storm drain systems that implement the requirements of this permit will be controlling stormwater pollution to the maximum extent practicable. Therefore, satisfying the conditions of this permit will meet waste load allocations specified in Total Maximum Daily Loads (TMDL) developed for impaired water bodies.

However, we are aware that the next permit term will have greater TMDL involvement with waste load allocation requirements. To this end, SHA is working to develop a TMDL implementation strategy for our agency that will encompass many facets of our organization on many levels. We are also working closely with MDE on the Maryland WIP I and II development.

PART TWO
Stormwater Management Facilities Program

2.1 Introduction

This section of the report summarizes the Maryland SHA Stormwater Management (SWM) Facilities Program activities between October 2009 and December 2010.

Based on the latest estimates SHA owns about 2,025 stormwater management (SWM) facilities statewide that were constructed since the mid 1970's. Since 1999, SHA has managed a comprehensive program to locate, inspect, evaluate, maintain and remediate BMPs to sustain their functionality, improve water quality, and protect sensitive water resources.

The program's primary goal is to maintain SHA's stormwater facilities to operate as designed and to strategically enhance their functions to meet today's stormwater standards. The SWM Facilities Program consists of four major components:

- Identification, inspection and database development to manage SHA assets,
- Maintenance and Remediation of BMPs,
- Visual , functional and environmental quality enhancements, upgrades and retrofits,
- Monitoring, research and technology tools development.

The program focuses on the remediation and enhancement of BMPs. This effort requires continuous improvement of the BMP inspection procedures, data management system, tools to track the performance and remediation actions. SHA has developed a prioritization system for remedial activities, and to develop new technologies for repairing or retrofitting BMPs including visual and functional enhancement projects. A part of the SWM Facilities Program is research on performance and efficiency of commonly used BMPs.

2.2 Inventory and Inspection

The following section summarizes the inspection system and inventory results to provide a status of SHA-owned SWM facilities.

2.2.1 Inspection Protocol

In order to perform consistent inspection assessment, SHA continues to update the Chapter 3 of the *Maryland State Highway Administration Stormwater NPDES Program Standard Procedures*

Performance Rating

The initial assessment of a SWM facility is a field inspection where individual parameters are *scored* (on a scale 1 to 5) then used to establish an overall BMP performance rating:

A **No Issues** – BMP functioning as designed with no problem conditions identified. There are no signs of impending deterioration.

B **Minor Problems** are observed, however, BMP is functioning as designed.

C **Moderate Problems** are observed, however BMP is functioning as designed, but some parameters indicate the performance and functionality are compromised.

D **Major Problems** are observed, and the facility is not functioning as designed. Several issues may exist that have compromised the BMP performance or indicate failure

E **Severe Problems** exist, and the facility is not functioning as designed with several critical parameters having problem conditions. BMP facility shows signs of deterioration and/or failure. Remedial action should be performed immediately.

The remedial inspection protocol is summarized in the recently updated guidance document - Chapter 7 of *"Maryland State Highway Administration Stormwater NPDES Program, Standard Procedures*, dated November 2008, updated November 2010. This document is entitled Best Management Practice Assessment Guidelines for Maintenance and Remediation . This chapter describes methodologies used in the field for assessing the current functionality of a SWM facility and provides guidance for remedial actions. SHA protocol includes criteria for visual quality, maintenance relationships, and overall health of the SWM system. Inspections and assessment enable SHA to properly allocate funding mechanism to ensure the SWM system has a high level of functionality.

SHA Remediation Rating

SHA performs qualitative evaluation for maintenance and remediation by assigning the remedial rating. The assessment process and guidelines are detailed in the Best Management Practice Assessment Guidelines for Maintenance and Remediation .This is based on the overall initial inspection rating, performance, functionality, integrity and visual appearance; and also scope and complexity of the potential remedial work:

I **No Response Required** – schedule for multi-year inspection. These facilities are functioning as designed

II **Minor Maintenance** – perform preventative maintenance to sustain facility performance. Activities can typically be performed within an 8-hour workday by an average maintenance crew. These facilities are functioning as designed

III **Major Maintenance or Repair** – Maintenance or repair is needed to return the site to original functionality within the existing footprint of the facility. Remediation is more significant than just preventative maintenance and will likely require heavy equipment mobilization, construction material and possible Maintenance of Traffic.

IV **Retrofit Design -** Remedial design and construction is required since the facility cannot be returned to its original functionality within its existing footprint. It involves the construction of new type of facility in the vicinity of the existing facility.

V **Immediate Response** – Public safety hazards exist that require immediate correction.

VI **Abandonment** – the facility is not maintainable and will not provide sufficient benefit to justify remedial design.

2.2.2 Inventory

BMP Inventory is being performed countywide on SHA's roadways in Maryland jurisdictions with Phase I and II MS4 permits, and on a district-level. Table 2-1 summarizes the total number of SHA maintained BMPs identified in each County and SHA District.

Table 2-1
Current SHA Maintained SWM Facilities

District	County	No. BMPs	Totals
1	Dorchester	28	174
	Somerset	11	
	Wicomico	50	
	Worchester	85	
2	Caroline	4	134
	Cecil	15	
	Kent	6	
	Queen Anne's	102	
	Talbot	7	
3	Montgomery	264	445
	Prince George's	181	
4	Baltimore	160	271
	Harford	111	
5	Anne Arundel	420	564
	Calvert	31	
	Charles	97	
	St. Mary's	16	
6	Allegany	41	71
	Garrett	12	
	Washington	18	
7	Carroll	47	366
	Frederick	67	
	Howard	252	
Statewide			**2025**

BMP inventories are being constantly updated as remediation and retrofit projects are completed. In some instances, SWM may be replaced, consolidated, retrofitted, constructed or re-constructed by a private developer to serve as a Joint Use facility. In order to track pending changes in BMP inventory, SHA keeps improving the internal process and database management tools. As the inventory spans statewide, major efforts of inspection and maintenance are strategically expedited in NPDES counties.

2.2.3 Field Inspection

The initial BMP inspections and inventories are completed for all counties, including non-MS4 counties. BMPs that provide water quality and/ or quantity control for SHA impervious surfaces are included. The statewide inventory is continuously being updated on a cyclical basis. Remedial actions are established and based on the field inspections and/ or subsequent field investigations.

2.3 Maintenance & Remediation

This section summarizes the status of SHA maintenance and remedial responses to deficiencies identified through the inspections of SWM facilities. The program's primary goal is to keep SHA stormwater facilities functioning as designed and (when the opportunity arises) to enhance their functions. The responses are separated between routine maintenance major maintenance and retrofit projects. Table 2-2 shows the status of the remediation responses by either maintenance or retrofit/enhancement design

Table 2-2 – Remediation Responses

District 1 -Responses	I	II	III	IV	Total
Dorchester County	0	25	1	2	**28**
Somerset	5	5	1	0	**11**
Wicomico	22	16	11	1	**50**
Worcester County	47	28	9	1	**85**
Totals	**74**	**74**	**22**	**4**	**174**

District 2 - Responses	I	II	III	IV	Totals
Cecil County	1	8	6	0	15
Kent County	1	4	1	0	6
Queen Anne's County	31	63	6	2	102
Talbot County	5	1	0	1	7
Totals	**38**	**76**	**13**	**3**	**130**

District 3 - Responses	I	II	III	IV	TOTAL
Montgomery County	240	10	8	6	**264**
Prince George's Co.	153	10	16	2	**181**
Totals	**393**	**20**	**24**	**8**	**445**

District 4 - Responses	I	II	III	IV	TOTAL
Baltimore County	122	15	11	12	**160**
Harford County	82	21	1	7	**111**
Totals	**204**	**36**	**12**	**19**	**271**

District 5 - Responses	I	II	III	IV	TOTAL
Anne Arundel County	311	43	15	51	**420**
Calvert County	4	19	8	0	**31**
Charles County	82	4	2	9	**97**
St. Mary's	1	13	1	1	**16**
Totals	**398**	**79**	**26**	**61**	**564**

District 6- Responses	I	II	III	IV	TOTAL
Allegany County	29	3	6	3	**41**
Garrett County	9	3	0	0	**12**
Washington County	14	4	0	0	**18**
Totals	**52**	**10**	**6**	**3**	**71**

District 7- Responses	I	II	III	IV	TOTAL
Carroll County	42	4	1	0	**47**
Frederick County	63	4	0	0	**67**
Howard County	222	6	11	13	**252**
Totals	**327**	**14**	**12**	**13**	**366**

2.3.1 Routine Maintenance

Routine maintenance or preventive maintenance is generally considered a repair activity that addresses minor issues such as mowing, vegetative maintenance, trash and debris removal. The objective is to maintain performance of a BMP and/or to avoid deterioration of specific BMP elements. SWM facilities that require routine maintenance are assigned "II" rating by SHA.

SHA is currently performing most of the routine maintenance using two (2) HHD Open Ended Maintenance contracts and Design, Operate and Maintain Project (DBOM) for Charles County. These maintenance crews perform both routine and major/remedial maintenance. These performance vehicles are structured using time and materials contracting method.

Since the completion of the statewide inventory, routine maintenance activities are scheduled based on the local needs and geospatial data. Roadway corridors are typically completed within a few weeks.

Figures 2-1 and 2-2 show the typical vegetative management activities at SWM ponds in Charles County.

Figure 2-1 Minor Maintenance Activities BMP 080069 Before Maintenance

Figure 2-2 Minor Maintenance Activities BMP 080069 After Maintenance

2.3.2 Major Maintenance

SHA performs major maintenance tasks that address significant deficiencies at BMPs through the time & material open ended contract lead by Highway Hydraulics Division. The intent is to restore performance of a BMP and/or to avoid failure of specific elements. SWM facilities that require major or remedial maintenance are assigned a "III" rating by SHA. Figure 2-3 shows an example of SWM Facility requiring major maintenance in terms of excavating of accumulated sediments in infiltration trench and replacing the media to restore its functionality.

Figure 2-3 Removal of Sediment from Infiltration Trench and Media Replacement in Harford County (BMP 120063)

SHA continues performing detailed field assessments for BMPs identified for major maintenance. A workorder and a summary report is prepared for each BMP that provides sketches using as-built plans, photographs, cost estimate, repair recommendations, specifications and MOT.

Major maintenance is underway in all inspected counties but the focus in the past year has been on Anne Arundel, Baltimore, Howard, Harford, and Charles Counties. Table 2-3 lists the total number of facilities requiring major maintenance and the total number that were maintained with the associated cost between October 2009 and December 31, 2010.

Table 2-3 BMP Maintenance Summary

County	District	BMPs Maintained 10/2009 to 12/2010
Anne Arundel	5	23
Baltimore	4	10
Charles	5	87
Harford	4	17
Howard	7	10
Montgomery	3	8
Prince George’s	3	43
Note” Cost of Remedial Construction Activities from 10/2009 to 12/2010: $1,984,993		

2.3.3 Infiltration Facilities Remediation

SHA continues remedial actions for infiltration trenches and infiltration basins since they represent major part of SHA BMP inventory. Most of the constructed infiltration practices in the inventory were originally designed to provide water quality treatment for the first ½ in runoff. This is an MDE design standards that was used prior to 2000 MDE SWM Manual.

Most components of an infiltration trench are underground; many problems associated with this type of facility are not readily observable. Therefore, when an infiltration trench has failed due to high levels of water within the observation well, a general recommendation to replace the media is sometimes made. For some cases, maintenance may not always be the best option, such as when there are several facilities constructed in a series and all have failed. Under these circumstances, it may be more cost effective to redesign one facility instead of rebuilding several failed facilities. For most instances, maintaining as infiltration trench as designed is the preferred recommendation. Maintenance can include replacement of the stone media in-kind when the water level in the observation well is greater than 50%. Other maintenance recommendations for trenches can include replacing broken observation wells, installing new observation wells for trenches with no well, clearing of invasive vegetation, and repairing erosion around the media.

There are several reasons for a trench failure including a high groundwater table, poor drainage in the surrounding soils, poor construction of the trench, or internal blockage within the facility due to sedimentation or vegetative debris. If there are no indications that the facility was improperly designed or constructed, it is assumed that the facility has become blocked due to sedimentation. Indications of a high groundwater level would include a nearby stream, wetland or saturated channel with a water surface elevation above the bottom of the infiltration trench. Figure 2-7 shows the remedial activities of an Infiltration Trench replacement in Harford County. Before and after photos are shown in Figure 2-4 and 2-5, respectively.

Figure 2-4 Infiltration Trench Replacement in Harford County (BMP120039)

Figure 2-5 Infiltration Trench Replacement in Prince Georges County (before)

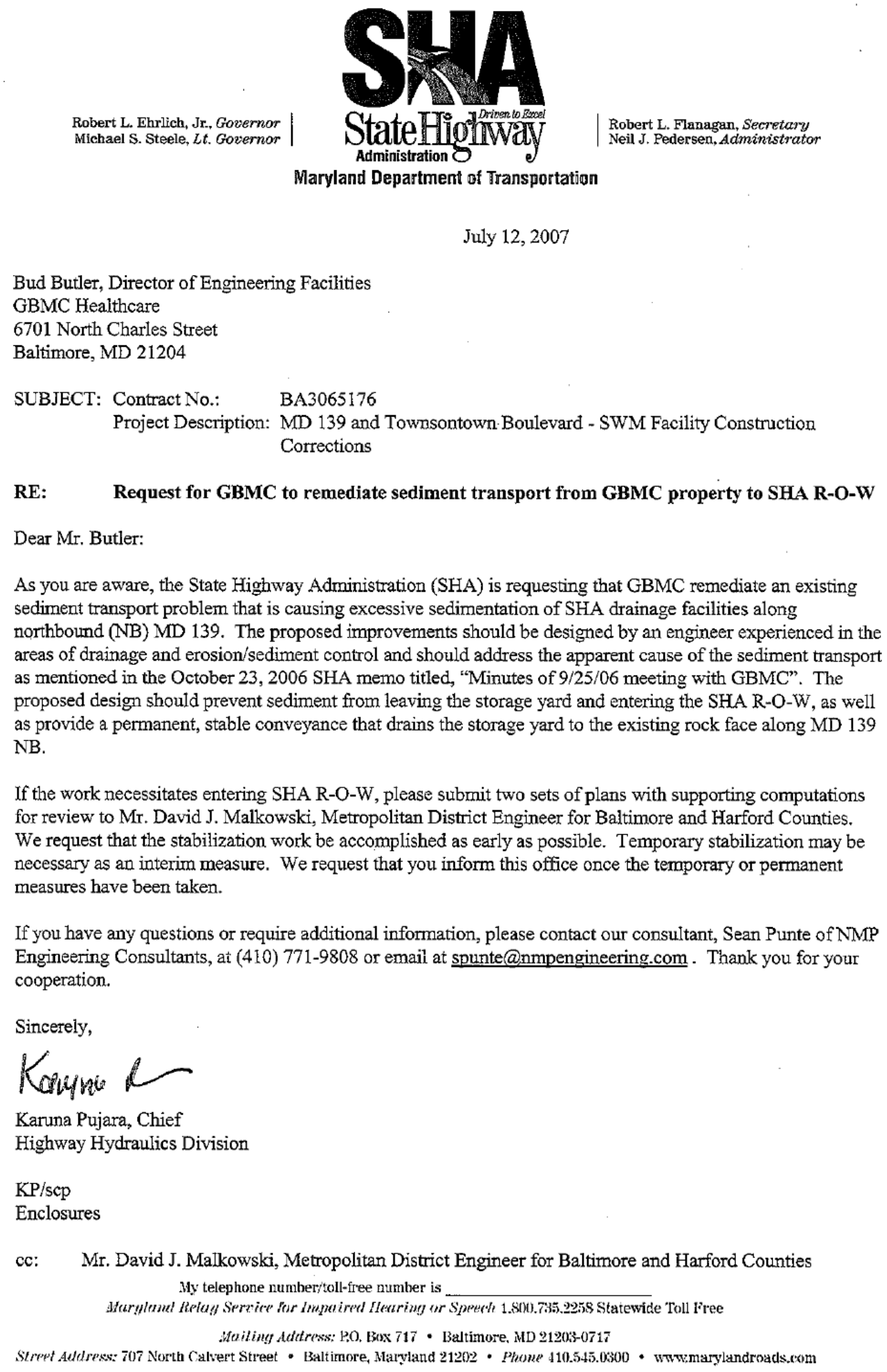
Figure 2-6 Infiltration Trench Replacement in Prince Georges County (after)

Infiltrations basins are generally considered failed when retain permanent pool more than 72 hours. The purpose of an infiltration basin is to temporarily store a volume of water to infiltrate through the bottom of the facility. The infiltration basin can include both a water quality volume and a water quantity volume. On construction plans, the facility may also be identified as an infiltration pond. The primary problem with infiltration basins is siltation of the facility bottom which prevents infiltration and leads to excessive ponding. This adds a different dimension to the investigation of an infiltration basin. Since the most obvious indication of siltation is a ponded facility, additional investigation will usually only confirm that the bottom of the facility needs to be dredged. Under these circumstances, care is taken to locate any sources of sediment that may contribute to a blockage and should investigate any control structures within the facility. Often times, the sources for the sedimentation are outside of SHA's Right-of-Way and requests for corrective actions are forwarded to the assumed responsible party.

Several sites that were designed as infiltration basins near existing natural wetlands and streams floodplains (some even within the stream channel) evolved into wetland systems, shallow marshes and retention or pocket ponds mostly due to the presence of high ground water table. Most of them established good vegetative cover including variety of local wetland species. Many provide good wildlife habitat.

SHA continues monitoring study of "failed" infiltration basin to evaluate water quality treatment potential in terms of nutrient pollutant removal efficiency. The detailed study report is included in the appendix of this report. The intent of the study is to demonstrate the value of leaving these natural systems in place to prevent disturbance to well established natural systems, and instead change their functionality in the inventory database. SHA recently approached MDE with proposal for modification of BMP type at specific BMP sites referring to them as "retrofits by nature". Examples of the infiltration basins "retrofitted by nature" are shown in Figure 2-7.

Figure 2-7 Infiltration Basins in Howard and Anne Arundel County Functioning as Wetland/ Wet SWM Facilities - Suggested Retrofits by Nature



Robert L. Ehrlich, Jr., *Governor*
Michael S. Steele, *Lt. Governor*

SHA
State Highway Administration
Driven to Excel
Maryland Department of Transportation

Robert L. Flanagan, *Secretary*
Neil J. Pedersen, *Administrator*

July 12, 2007

Bud Butler, Director of Engineering Facilities
GBMC Healthcare
6701 North Charles Street
Baltimore, MD 21204

SUBJECT: Contract No.: BA3065176
Project Description: MD 139 and Townsontown Boulevard - SWM Facility Construction Corrections

RE: Request for GBMC to remediate sediment transport from GBMC property to SHA R-O-W

Dear Mr. Butler:

As you are aware, the State Highway Administration (SHA) is requesting that GBMC remediate an existing sediment transport problem that is causing excessive sedimentation of SHA drainage facilities along northbound (NB) MD 139. The proposed improvements should be designed by an engineer experienced in the areas of drainage and erosion/sediment control and should address the apparent cause of the sediment transport as mentioned in the October 23, 2006 SHA memo titled, "Minutes of 9/25/06 meeting with GBMC". The proposed design should prevent sediment from leaving the storage yard and entering the SHA R-O-W, as well as provide a permanent, stable conveyance that drains the storage yard to the existing rock face along MD 139 NB.

If the work necessitates entering SHA R-O-W, please submit two sets of plans with supporting computations for review to Mr. David J. Malkowski, Metropolitan District Engineer for Baltimore and Harford Counties. We request that the stabilization work be accomplished as early as possible. Temporary stabilization may be necessary as an interim measure. We request that you inform this office once the temporary or permanent measures have been taken.

If you have any questions or require additional information, please contact our consultant, Sean Punte of NMP Engineering Consultants, at (410) 771-9808 or email at spunte@nmpengineering.com . Thank you for your cooperation.

Sincerely,

Karuna Pujara, Chief
Highway Hydraulics Division

KP/scp
Enclosures

cc: Mr. David J. Malkowski, Metropolitan District Engineer for Baltimore and Harford Counties

My telephone number/toll-free number is ____________________
Maryland Relay Service for Impaired Hearing or Speech 1.800.735.2258 Statewide Toll Free
Mailing Address: P.O. Box 717 • Baltimore, MD 21203-0717
Street Address: 707 North Calvert Street • Baltimore, Maryland 21202 • *Phone* 410.545.0300 • www.marylandroads.com

Figure 2-8 Example of Request for Off-site Corrective Actions

05/24/2010 10:04

Figure 2-9 Example of SHA Actions to Prevent Off-site sedimentation source from contaminating downstream Infiltration Practice

09/15/2010

Figure 2-10 Existing Infiltration Basin

10/27/2010

Figure 2-11 Existing Infiltration Basin during Remedial Activities

10/16/2010

Figure 2-12 Infiltration Basin Remedial Activites completed

2.4 SWM Retrofits, Visual and Functional Enhancement Projects

MD SHA has actively continued design as well as construction phases of *SWM Functional Enhancement and Retrofit Projects* funded through State Fund for drainage improvements. When appropriate, SHA seeks partial funding match from the Transportation Equity Act for the 21st Century (TEA-21) Enhancement Funds. The projects have been initiated with the intention to improve the pollutant removal efficiency and bring the functional parameters up to the current standards required by the MDE 2000 *Maryland Stormwater Design Manual*, Volumes I and II and MDE *Guidelines for State and Federal Projects*, dated July 1, 2001. The new design criteria include groundwater recharge volume, and water quality volume. In addition to the functionality upgrades, the enhancement projects are intended to improve aesthetic value, provide refuge to local wildlife and increase the water quality benefits.

Locations for enhancement projects are evaluated based on feasibility, permitting process, and overall net benefit. Other items that may influence a project decisions are overall health and need of the watershed. Concepts are developed and feasibility studies are conducted for many sites. The status of the currently active SWM Enhancement and Retrofit projects is summarized in Table 2-4.

Table 2-4: BMP Enhancement and SWM Retrofit Projects Summary

Project	County	No. of BMPs	Contract Number	Total Cost (PE, R/W, Constr.)	Status
1. MD 28 – Retrofit of SWM Facility 150344	MO	1	MO247A21	$120,000	Will be constructed through T&M Contract
2. US 50 –Retrofit of Infiltration Basins	AA	3	AA822A21	Preliminary Estimate $800,000	Survey completed, Development of concept design
3. MD 8 - Drainage Improvement and SWM Retrofit	QA	2	QA2835174	$711,000	Advertisement 02/22/11
4. I-97/ MD100 SWM Facilities Functional Upgrades	AA	12	AA5355174	$1,180,000	Under Construction (to be completed in spring 2011)
5. SWM Retrofit and Drainage Improvements at Sawmill Creek	AA	1	AA2735174	$550,000	Under Construction (to be completed in summer 2011)
6. MD 235 – BMP Retrofit and Drainage Improvements	SM	1	SM3565174	SF Estimate $611,000	Under Design Semi- Final Review
7. MD 4 – Enhancement of SWM Facilities	AA	3	AA5515174	$720,000	Advertisement 02/08/11
8. MD 355 – Retrofit of SWM Facility 150012	MO	1	MO410A21	$70,000	Will be constructed through T&M Contract
9. MD 32 Infiltration Basins Retrofit	AA	8	AX931B21	Preliminary $1,500,000	Field Investigation, Concept design
10. I-270 SWM Retrofit of BMP 150059 and 150556	MO	2	MO106A21	Preliminary $510,000	Survey completed, Development of concept design
Totals		**34**		**$6,772,000**	

Figure 2-13 Construction of Retrofit of Failed Infiltration Trenches into Dry Swales at I-97

Figure 2-14 Construction of Retrofit of Failed Infiltration Trenches into Dry Swales at I-97

SHA advertised SWM Functional Upgrades project in Anne Arundel County – 12 failed infiltration trenches along I-97 and MD 100 and the project's construction should be completed in Spring 2011.

SWM retrofit project of failed bioretention into sand filter at SHA Glen Burnie maintenance shop includes drainage improvements and 3 outfalls stabilization. The project has been advertised and is currently under construction Figure 2-15 and Figure 2-16 show the preconstruction condition of the project site. Figures 2-17 and 2-18 show the construction progress of the outfall and new facility. The improvements are scheduled to be completed in the Summer of 2011.

Figure 2-15 Failed Bioretention at SHA Glen Burnie Maintenance Shop

Figure 2-16 Deteriorated outfall at SHA Glen Burnie Maintenance Shop

Figure 2-17 Improved outfall at SHA Glen Burnie Maintenance Shop

Figure 2-18 Construction progress of Sand Filter Installation at SHA Glen Burnie Maintenance Shop

In summary, the proposed SWM retrofit and enhancement projects are designed to contribute towards the improvement of water quality of highway runoff in the environmentally sensitive watersheds of Chesapeake Bay. These retrofits address original water quality capacity, but also upgrade them to the most recent standards for water quality volume requirements.

2.4 Other Topics

2.4.1 Data Management

To-date SHA has performed inventory of SWM drainage infrastructure in all NPDES counties and BMP inspections in all twenty-three counties with the intent to finalize statewide BMP inventory database by June 2011. SHA has preceded with the second cycle re-inspection in four counties. This effort involves continuous creation and updating of GIS data for source identification and database records for inspections and remediation activities.

SHA has finalized the structure of 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 when needed. The database format resulted in improved data intelligence and integrity. SHA plans to integrate geodatabase with other SHA initiatives to improve communication between offices.

SHA and its consultant partners use two custom software to collect and store geospatial information. The Office Tool is used to input data, as well as integrity assurance (QA) checks. In addition, a Field Tool is used with coordination with GPS units to collect and edit field data.

Along with the database format, a data viewer tool – NPDES Viewer- has been enhanced. The functionality of this tool allows the user to view the spatial information as well as digital images associated with each BMP including as-built plans, photographs, inspection reports and other documents. BMP Viewer is used to view data from various levels such as a highway corridor, MSHA district, County, or watershed.

A component for BMP maintenance tracking called Remediation Tool has been added to the NPDES Viewer. This application will allow tracking maintenance activities, and associated cost as well retrofit project progress and current functionality of SHA owned SWM facilities. It also allows the reporting of data to managers and administrators.

The most recent tool incorporating BMP geodatabase that is used for quick data viewing, reporting and spatially displaying is a web application named iMap. (Screen captures are shown on Figure 2-19). The application can be found at http://www.mdimap.com/sha/

This tool was developed by SHA primarily for reporting the current status and progress of SHA Business Plan objectives to StateStat Committee. This tool was also used to present SHA SWM program at the Lt. Governor's meeting in July 2010.

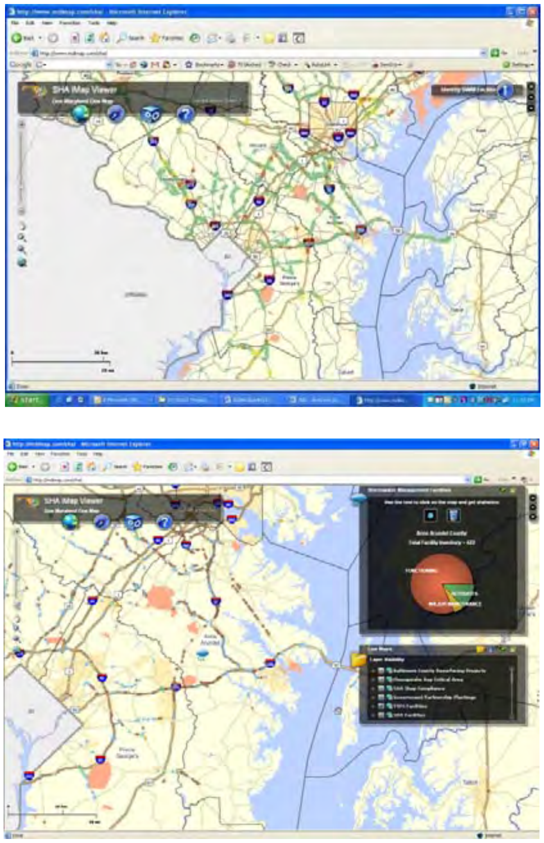


Figure 2-19 iMap Screen Captures

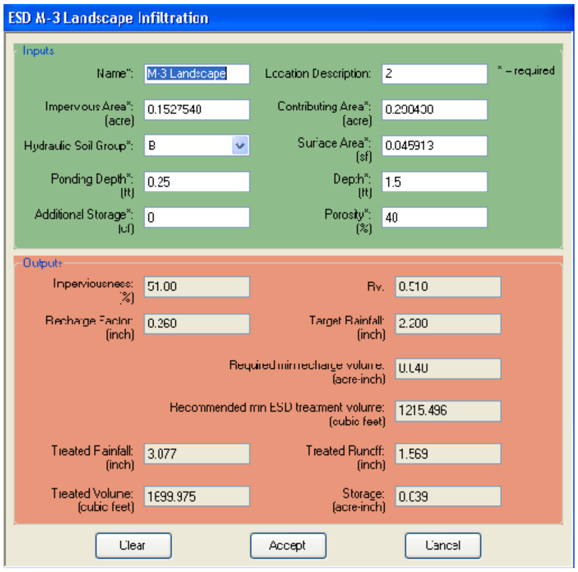
2.4.2 Standard Procedures

In order to maintain consistency and compatibility of the data collected during source identification and BMP inspections, SHA continues conducting NPDES Standard Procedures Workshop for outfall inspections, BMP inspections and illicit discharge screening.

Chapter 7 of NPDES Standard Procedures for SWM maintenance work order development has been updated to include knowledge gained over the last few years. The chapter describes the procedure for field assessment of BMPs previously designated as requiring remediation after an Initial Inspection or at any time throughout the inspection cycle. After the preventative cyclical inspections and database updates, final performance ratings and level of functionality are evaluated. BMPs 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. The procedures that are outlined in the chapter assists the decision making process for maintenance, repair, and remediation of SWM facilities. It also provides standardization in the assessment process, instructions to inspect BMP facilities statewide, examples for identifying and assessing the causes of the deficiencies, and to recommend repairs with relatively consistent results. The intent of the document is not to be an all-inclusive resource manual and other resources are consulted in conjunction with the document. Cost estimating and common causes for facility failure are the updated key portions. Examples of work action are included for common facility types.

SWM Processor

MD SHA is developing comprehensive SWM design software that will enable design engineers to optimize water quality needs for a roadway improvement. Figure 2-20 shows a screen capture of the interface. SWM Processor is developed for engineers to manage the stormwater management design process as listed in MDE Stormwater Management Design Manual. The program has a built-in computation model with flexible user interface and report generator. It enables the design engineer to perform calculations efficiently with several error checking mechanisms. The engineer can save the project data including project information and calculation data to a centralized database or XML file. The program generates standardized reports including the computational procedures as seen in the examples in the Design Manual. The database catalogs all projects that have been entered. External users may install the software without the cataloging and forward computations to be imported into system. Consistent computational policies for stormwater management are needed for long-term success of any comprehensive SWM program.



Name*: M-3 Landscape
Location Description: 2
Impervious Area*: (acre) 0.1527540
Contributing Area*: (acre) 0.290430
Hydraulic Soil Group*: B
Surface Area*: (sf) 0.045913
Ponding Depth*: (ft) 0.25
Depth*: (ft) 1.5
Additional Storage*: (cf) 0
Porosity*: (%) 40

Imperviousness: (%) 51.00
Rv. 0.510
Recharge Factor: (inch) 0.260
Target Rainfall: (inch) 2.200
Required min recharge volume: (acre-inch) 0.040
Recommended min ESD treatment volume: (cubic feet) 1215.496
Treated Rainfall: (inch) 3.077
Treated Runoff: (inch) 1.569
Treated Volume: (cubic feet) 1699.975
Storage: (acre-inch) 0.039

Figure 2-20 Screen Shot of SWM Processor

2.5 Summary

The SHA continues improving protocols and standard procedures for inventorying and inspecting SMW facilities. This leads to the development of a responsive maintenance program to sustain BMP performance, and also includes functional and visual enhancements to upgrade SWM to the today's standards. The SHA researches SWM facilities performance through monitoring and research studies. The SHA continues development of data management technology to manage and utilize BMP data more efficiently. Tools are being developed to facilitate timely decisions on remedial actions, and meet NPDES permit requirements.

The SHA Business Plan goes beyond the NPDES permit jurisdiction by promoting the statewide inventory and a high-level of BMPs performance. The goal is to bring 90 percent of all SHA owned SWM facilities to their functionality by FY 2012. Currently 88.8 % of SHA inventoried facilities function as designed. Figure 2-21 summarizes the progress.

SWM Facilities Program has shown environmental stewardship in the areas of innovative state-of-the-art inspection and data management technology as well as BMP remediation techniques. The program components and structure demonstrate strategic approach to meet the NPDES Permit requirements and enhance the performance efficiency of SWM facilities to improve water quality in the sensitive watersheds of Chesapeake Bay.

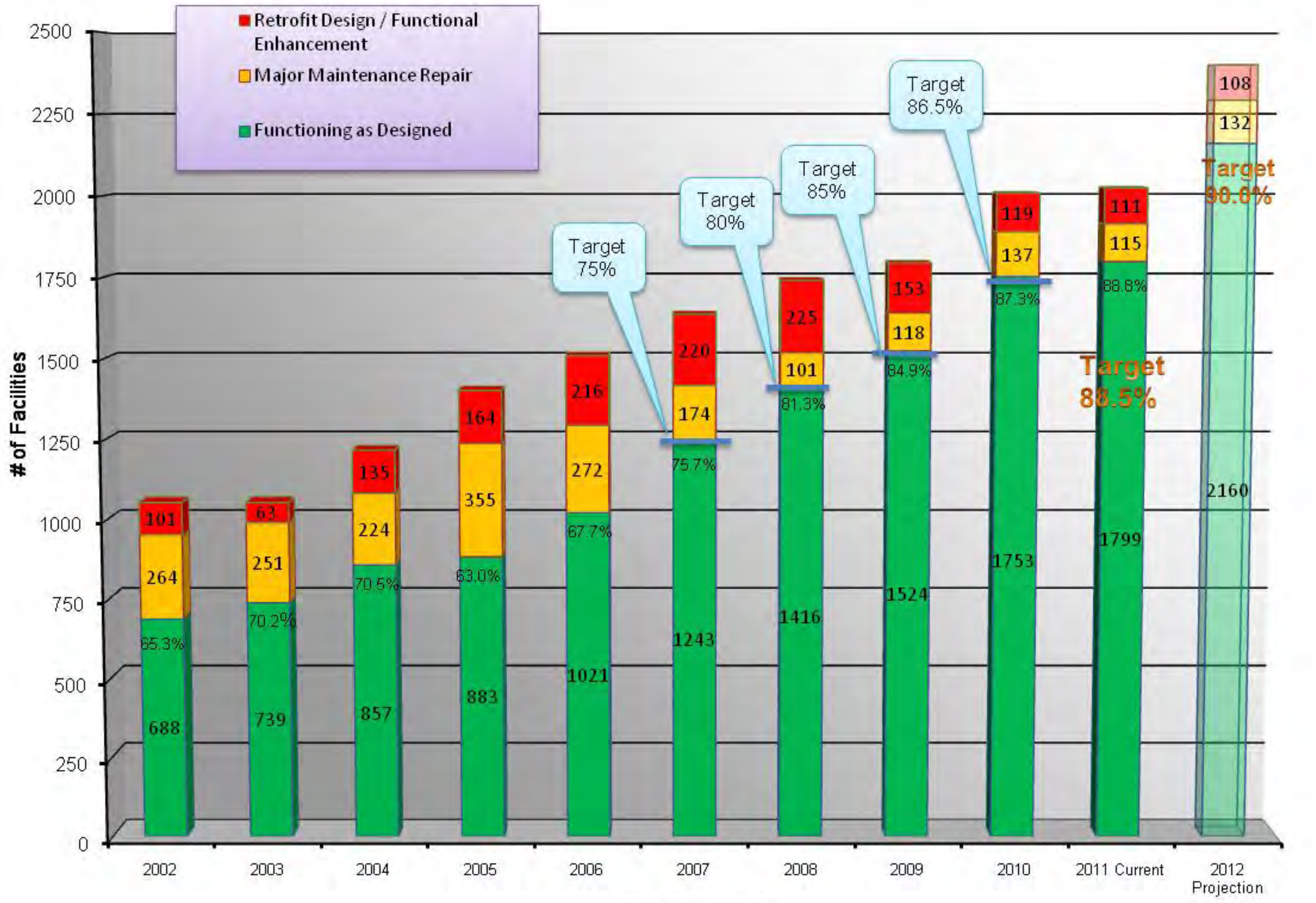


Figure 2-21 Progress in SWM Facilities Program

APPENDIX A

Examples of Source Identification

Frederick County
Harford County
Montgomery County

SOURCE ID EXAMPLES

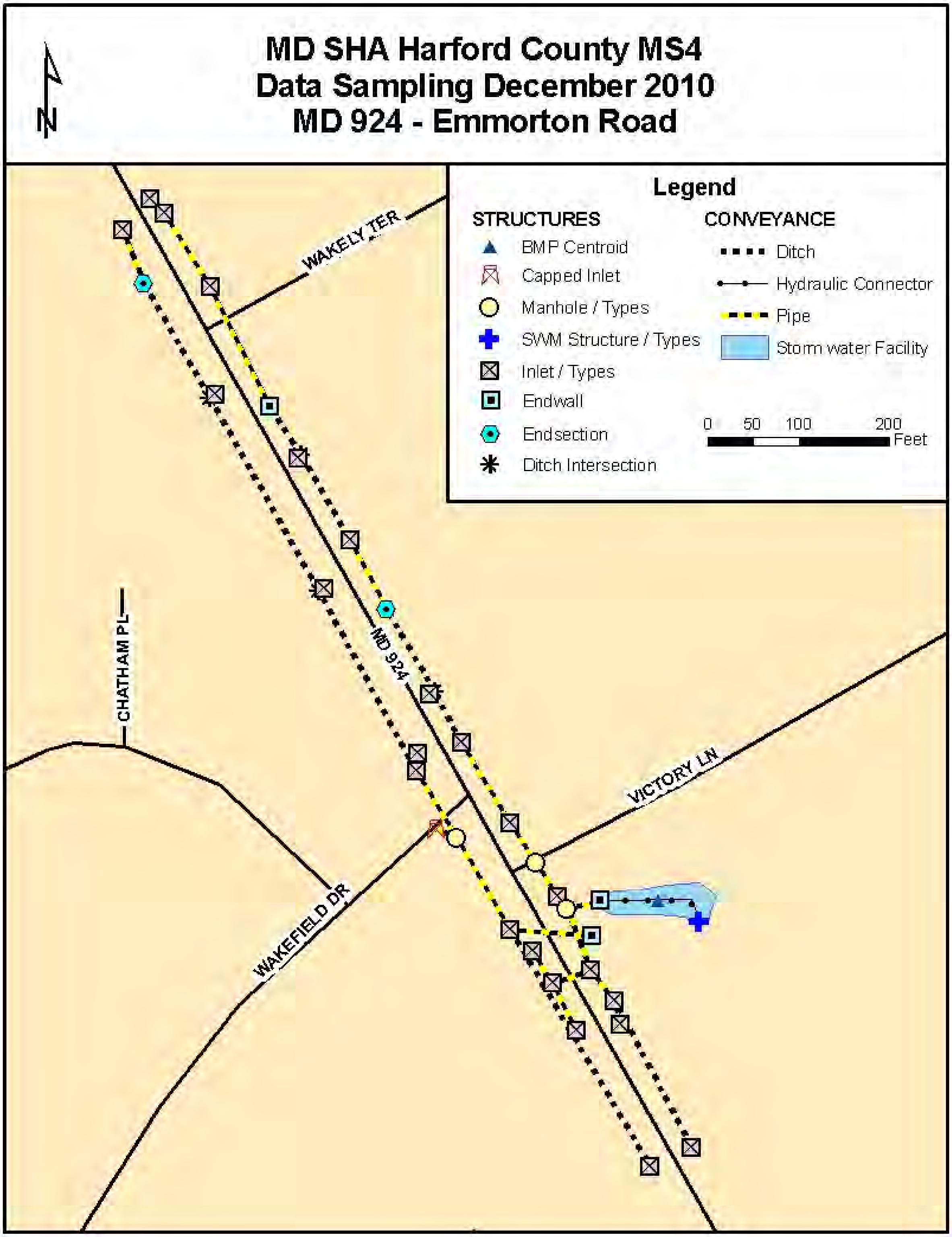
SOURCE ID EXAMPLES

Frederick County Source ID Example

SOURCE ID EXAMPLES

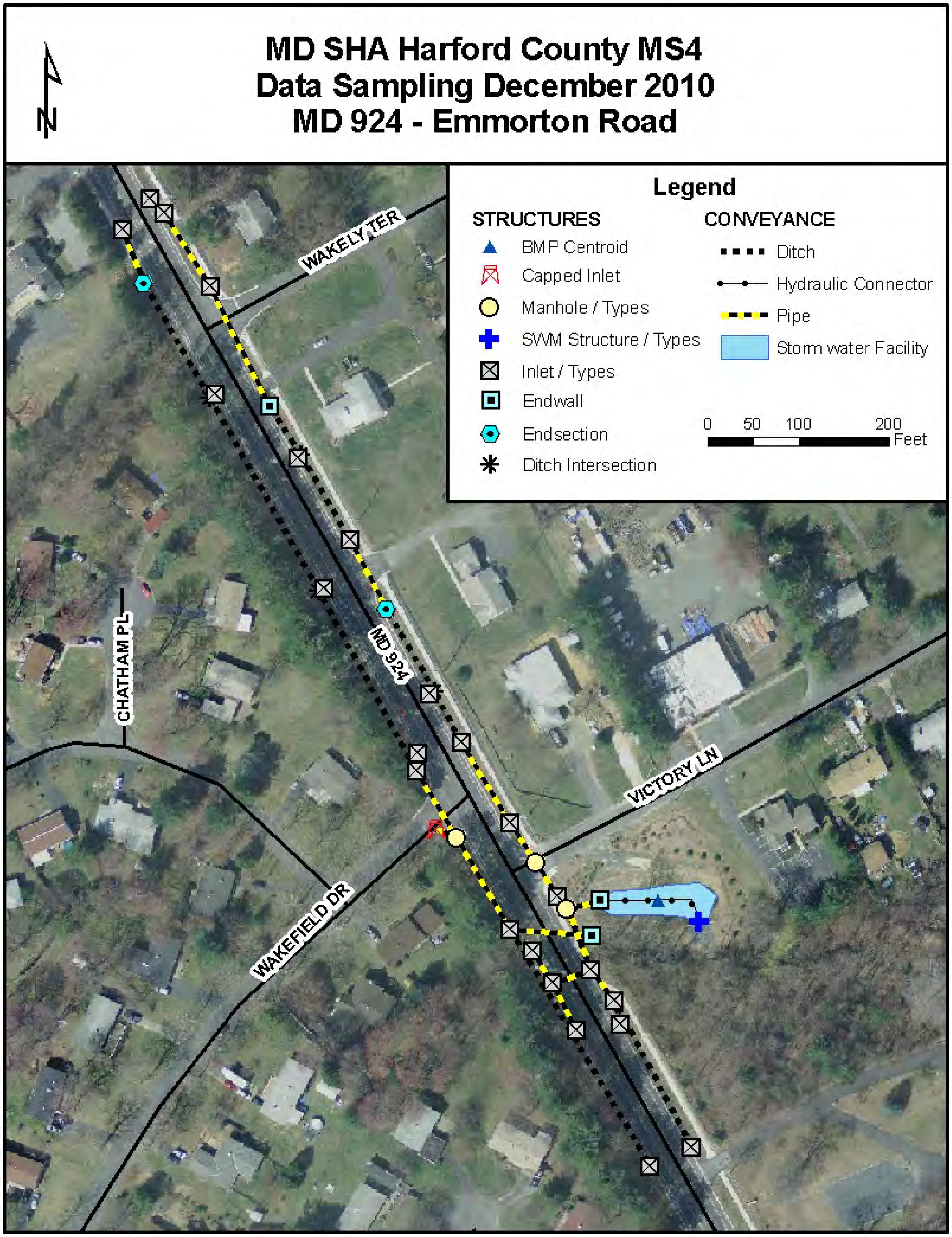
Frederick County Source ID Example

SOURCE ID EXAMPLES



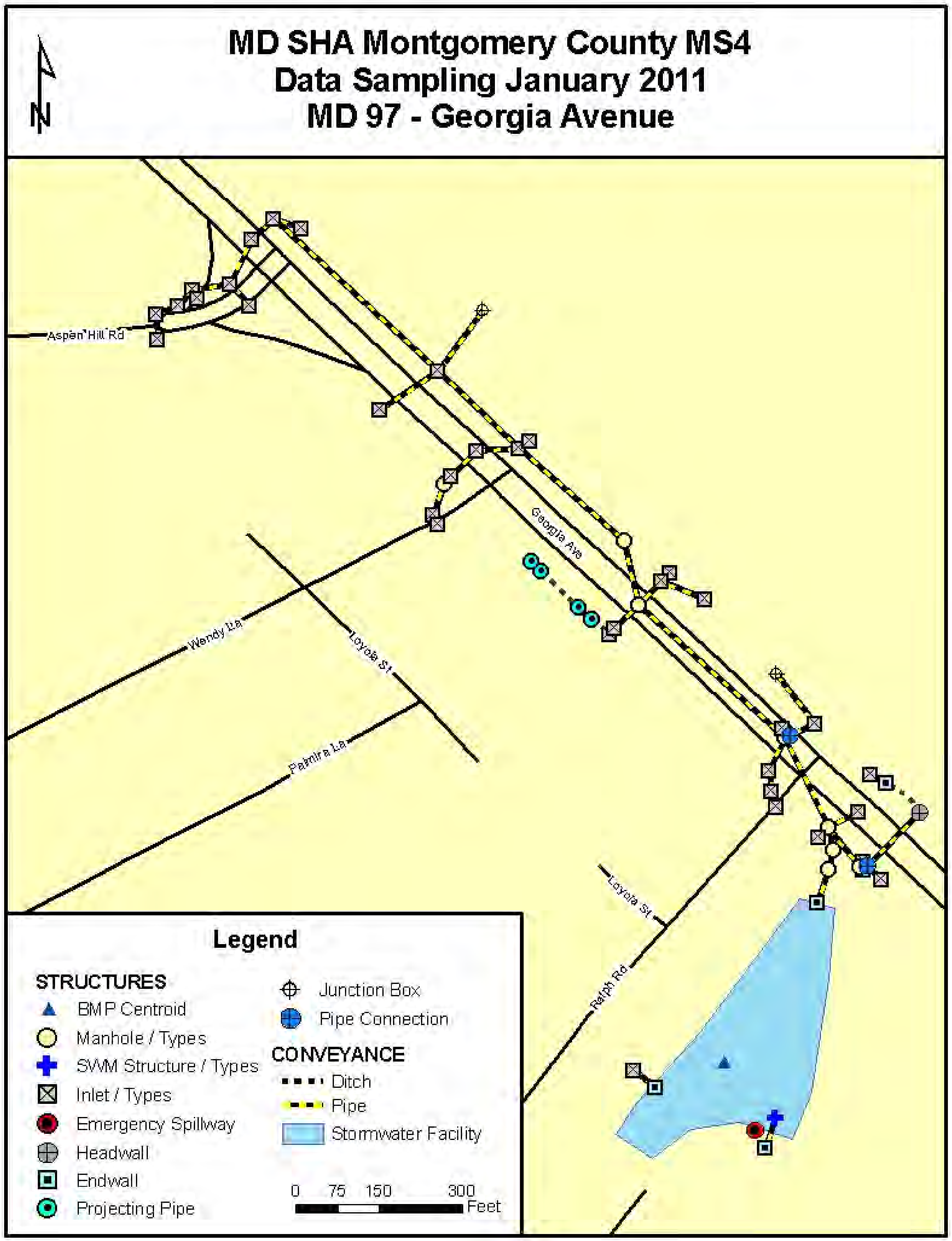
Harford County Source ID Example

SOURCE ID EXAMPLES



Harford County Source ID Example

SOURCE ID EXAMPLES



Montgomery County Source ID Example

SOURCE ID EXAMPLES

Montgomery County Source ID Example

APPENDIX B:

Progress Report:

Field Evaluation of Water Quality Benefits of Grass Swale for Managing Highway Runoff

FIELD EVALUATION OF WATER QUALITY BENEFITS OF GRASS SWALE FOR MANAGING HIGHWAY RUNOFF

Progress Report: Field Evaluation of Water Quality Benefits of Grass Swale for Managing Highway Runoff

Project Duration: February 2009 – July 2009

Project Sponsor: Maryland State Highway Administration (SHA)

Project Coordinators:

Allen P. Davis, PhD, P.E
Professor
Hunho Kim
Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Maryland
College Park, MD 20742

Date: July 24th, 2009

FIELD EVALUATION OF WATER QUALITY BENEFITS OF GRASS SWALE FOR MANAGING HIGHWAY RUNOFF

FIELD EVALUATION OF WATER QUALITY BENEFITS OF GRASS SWALE FOR MANAGING HIGHWAY RUNOFF

EXECUTIVE SUMMARY

Water pollution caused by storm water runoff from paved areas and road ways has been increased drastically as urbanization and land development proceed rapidly. Due to relatively easy design and maintenance coupled with cost effectiveness and aesthetic benefits, grass swales have been adapted by the Maryland State Highway Administration (SHA) as Low Impact Development (LID) technologies to address roadway stormmwater runoff management. However, few data and references are available to prove the performance and efficiency of grass swale in terms of water quality as well as hydrologic benefits.

Two individual swales were constructed in the median of a four-lane (two in each direction) on Maryland Route 32 near savage, Maryland, to treat runoff from the southbound roadway lanes. Four different storm events were monitored during April to July 2009 at three different sampling point; direct channel, a swale with pretreatment area (MDE swale), and a swale without pretreatment area (SHA swale). Event mean concentrations (EMCs) of most contaminants from swales were lower than EMCs from direct channel except Cl^- from both swales on both June 3rd and July 1s, TSS from MDE swale on June 3rd, and NO_2^- from MDE swale on June 3rd. The water quality results during the sampling period demonstrate that grass swales can be efficient in treating highway storm water runoff as LID technologies with hydrologic benefits, especially with unsaturated soil condition.

FIELD EVALUATION OF WATER QUALITY BENEFITS OF GRASS SWALE FOR MANAGING HIGHWAY RUNOFF

FIELD EVALUATION OF WATER QUALITY BENEFITS OF GRASS SWALE FOR MANAGING HIGHWAY RUNOFF

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FIELD EVALUATION OF WATER QUALITY BENEFITS OF GRASS SWALE FOR MANAGING HIGHWAY RUNOFF

Introduction

Stormwater runoff is a major contributor to water pollution in the United States (Line et al., 1996; Wu et al., 1998). Specifically, water pollution caused by storm water runoff from paved areas and roadways has been increased drastically as urbanization and land development proceed rapidly. Furthermore, urbanization and land development have increased impervious areas and reduced vegetation, and therefore, worsen water quality due to altered hydrology of runoff flow.

Due to relatively easy design and maintenance coupled with cost effectiveness and aesthetic benefits, grass swales have been adapted by the Maryland State Highway Administration (SHA) as Low Impact Development (LID) technologies to address stormmwater runoff management by water filtration, evapotranspiration and infiltration through grass and soil. However, few data and references are available to prove the performance and efficiency of grass swale in terms of water quality as well as hydrologic benefits. Therefore, field monitoring for grass swales is needed to monitor water quality and hydrologic characteristics of swales.

Two individual swales were constructed in the median of a four-lane (two in each direction) high way on Maryland Route 32 near savage, Maryland (near Exit 38A of I-95N), to treat runoff from the southbound roadway lanes. The first swale (the one to the south) was constructed based on Maryland Department of the Environment (MDE) guidelines, while the second swale known as the SHA swale was identically constructed but without the pretreatment area.

Three sampling points; discharge from both swales as well as one direct concrete channel, which had essentially identical roadway drainage areas, were previous monitored by Stagge (2006) and Eluziea Jamil (2009). The concrete channel that collects runoff directly from the highway was constructed south of the swales in order to obtain instantaneous flow input and water quality from the highway surface and compare it to swale performance. Specific design parameters for the swales and direct concrete channel are shown in Table 1. More detailed information regarding the grass swale site can be found in Stagge (2006) and Eluzieal Jamil (2009).

Table 1. Design parameters for MDE, SHA swales and direct channel (partially adapted from Eluzieal Jamil, 2009).

	Direct	MDE Swale with Check Dams	SHA Swale with Check Dams
Roadway Area (ha)	0.271	0.225	0.224
Swale Area (ha), As	0	0.431	0.312
Total Area (ha), AT	0.271	0.656	0.393
Channel Material	Concrete	Grass	Grass
Channel Slope	0.2%	1.2%	1.6%

	Direct	MDE Swale with Check Dams	SHA Swale with Check Dams
Channel Length (m)	168	137	198
Pretreatment Slope	-	6%	-
Pretreatment Width (m)	-	15.2 *	-
Number of Check Dam Rows	-	3	3
Thickness of each check dam (m)	-	0.914	0.914
Bottom width of Check Dam (m)	-	0.610	0.610
Total width of Check Dam (m)	-	variable	variable
Distance between two check dams (m)	-	60.5	59.8

* from roadway to channel center

This research is a extended study of the two previous filed monitoring research studies on the two grass swales. In this research, ten different water quality parameters as major pollutants in roadway runoff; Total Suspended solids (TSS), NO_3^-, NO_2^-, Total Kjeldahl Nitrogen (TKN), Total Phosphorus (TP), Cl^- and heavy metals including lead (Pb), copper (Cu), zinc (Zn), and cadmium (Cd) were measured and analyzed from the samples collected from all three sampling points. Precipitation and runoff flow data were also collected and analyzed to monitor hydrologic characteristics and performance of the swales.

Materials and Methods

Four different storm events were monitored during April to July 2009 (on April 29th, May 16th, June 3rd, and July 1st 2009) at three different sampling points; direct channel, discharge of swale with pretreatment area (MDE swale), and swale without pretreatment area (SHA swale).

During the storm events, rainfall was measured with 0.0254 cm sensitivity using a rain gauge (ISCO 674 Tipping Bucket Rain Gauge) and the data were recorded in 2 minute increments. Runoff flow from each sampling point was measured by an ISCO 730 bubbler flow module installed at a 125° V-notch wooden weir located at the end of each swale and the concrete channel. A tubing line connected to the bubbler flow module was installed at the bottom end of the V-notch to measure the water head level and the flow data were recorded by each sampler.

ISCO Model 6712 Portable Samplers were used in each sampling point with twenty-four 300 mL glass bottles installed inside. Sampling was triggered by water level at the V-notch greater than 0.254 cm (0.1 inch) and sampling was performed based on sampling times as shown in Table 2

Table 2. Sampling times for storm events (adapted from Eluzieal Jamil, 2009)

Sampling bottle ID	Direct (Time from start)	Both Swales (Time from start)
1, 2	zero minutes	zero minutes
3, 4	20 minutes	20 minutes
5, 6	40 minutes	40 minutes
7, 8	1 hour	1 hour
9, 10	1 hr 20 min	1 hr 20 min
11, 12	2 hr	1 hr 40 min
13, 14	2 hr 40 min	2 hr
15, 16	3 hr 20 min	2 hr 20 min
17, 18	4 hr 20 min	2 hr 40 min
19, 20	5 hr 20 min	3 hr 40 min
21, 22	6 hr 20 min	4 hr 40 min
23, 24	8 hr	6 hr

As soon as sampling was completed from each sampling point, all samples were collected (within 24 hours) and transported to the University of Maryland Environmental Laboratory for water quality analysis. Nutrients analyses including NO_3^-, NO_2^- and TP, and TSS were immediately measured. The samples were filtered through 0.2 μm membrane filter to analyze NO_3^-, NO_2^- and Cl^-. Around 100 mL of sample was preserved for metal analyses using six drops of concentrated trace level HNO_3 and a 200 mL sample was preserved for TKN analysis using 12 drops of concentrated H_2SO_4.

Heavy metal concentrations (Pb, Cu, Cd, and Zn) of the samples were measured using flame or graphite furnace atomic absorption spectrophotometry (Perkin Elmer 5100PC with Perkin Elmer Zeeman Furnace module 5100ZL) after nitric acid digestion of samples. Analytical methods used in this study are summarized in Table 3.

Table 3. Summary of the Analytical Method and detection limit for each analysis (Adapted from Eluzieal Jamil, 2009)

Pollutant	**Standard Method (APHA et al. 1995)**	**Detection Limit (mg/L)**
Total Suspended Solids (TSS)	2540 D	1
Total Phosphorus (TP)	4500-P	0.025
Total Kjeldahl Nitrogen (TKN)	4500-N0rg	0.14
Copper	3030 E	0.005
Lead	3030 E	0.005
Cadmium	3030 E	0.0002

Pollutant	**Standard Method (APHA et al. 1995)**	**Detection Limit (mg/L)**
Zinc	3030 E	0.025
Chloride	Dionex DX-100 ion chromatograph	1
Nitrate	Dionex DX-100 ion chromatograph	0.05 as N
Nitrite	4500-NO2- B	0.005 as N

Results and Discussion

Event mean concentrations (EMC) of each contaminant from swale and direct samples for four monitored storm events are shown in Table 4. Two storm events, on April 29th and May 16th, did not produce outflow from both swales due to low rainfall (see figure 4 and 5 in Appendix 2: total 0.12 inch and 0.33 inch for April 29th and May 16th, respectively). One notable observation from direct samples collected from the April 29th storm is that a relatively high TKN EMC (9.3 mg/L –N) was observed in the direct runoff samples. The first flush sample, especially, demonstrated 21 mg/L –N TKN concentration. This high TKN likely originated mainly from high pollen content in runoff samples washed from roadways and air during the precipitation. High pollen content in runoff water through the direct channel during and after rainfall was observed (Figure 1a). Pollen in collected samples was also observed as shown in Figure 1b.

Table 4. EMC of each storm event during the monitoring study.

Storm Event	Sampling Point	Solids (mg/L)	Nutrients (mg/L)				Heavy metals (µg/L)				Cl^- (mg/L)
		TSS	NO_3^--N	NO_2^--N	TKN	TP	Pb	Cu	Zn	Cd	Cl^-
April 29	Direct	139	0.65	0.18	9.3	0.54	17	60	320	0.4	NA
	MDE					No outflow					
	SHA					No outflow					
May 16	Direct	68	1.05	0.03	1.4	0.39	11	32	250	0.2	56
	MDE					No outflow					
	SHA					No outflow					
June 3	Direct	145	0.76	0.04	3.7	0.99	21	64	650	1.0	16
	MDE	**162**	0.34	**0.05**	1.9	0.36	21	18	24	0.2	**45**
	SHA	45	0.38	0.02	1.9	0.24	6.5	10	45	0.5	**29**
July 1	Direct	183	0.67	0.03	6.8	1.1	19	48	1200	0.9	26
	MDE	80	0.36	0.03	1.5	0.20	9.5	9.0	28	0.2	**127**
	SHA	15	1.95	0.04	2.2	0.28	4.8	8.1	16	0.3	**65**

Figure 1. Pollens from storm water runoff on April 29th; (a) Pollen in direct channel, and (b) Pollens in the first flush sample.

EMCs of most contaminants from the swales were lower than EMCs from the direct channel, except for Cl^- from both swales on both June 3rd and July 1st, TSS from the MDE swale on June 3rd, and NO_2^- from the MDE swale on June 3rd, as indicated in bold in Table 4. The higher EMC of Cl^- from both swales is likely due to salt accumulation on the swales by salt application on roadways for deicing during winter seasons. The salts are captured by the swales during storm events and the accumulated salts are slowly released during later storm events. Therefore, the swales perform as buffers to release salts gradually, which prevents sudden and significant increase of Cl^- concentrations in water bodies during the winter season.

The higher TSS EMC from the MDE swale on June 3rd is probably due to intense rainfall and some bare spots on the pretreatment area as shown in Figure 2. Most of the TSS in the MDE swale samples likely originated from soils and clays which were washed and mobilized during intense storm events. This was observed by comparing captured total suspended solids by grass fiber filter from MDE swales with that from direct channel (Figure 3).

Figure 2. Bare spots on pretreatment area of MDE swale.

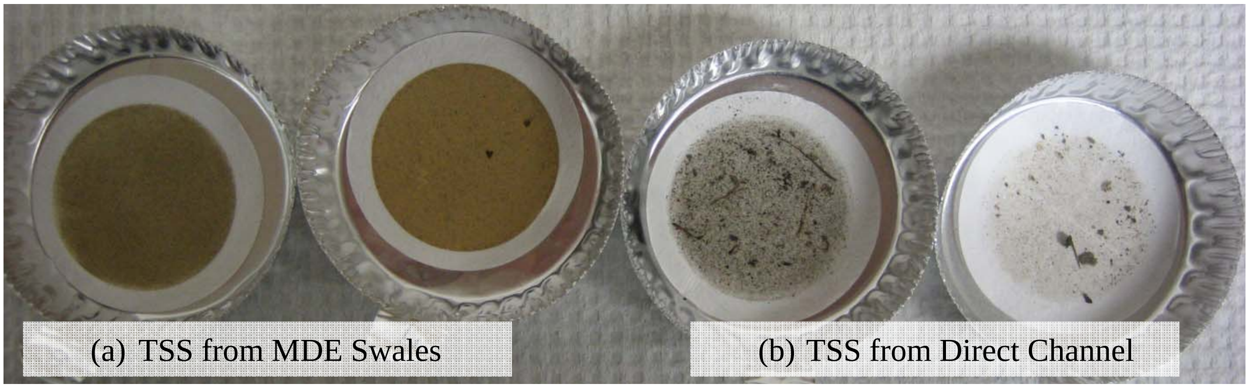

Figure 3. Captured suspended solids on grass fiber filter (a) from MDE swales, and (b) from direct channel.

Table 5 indicates total mass of each contaminant discharged to drainage and percent removal in mass by swales. As shown in bold in Table 5, mass of some contaminants was higher from the swales than the direct channel. Furthermore, some contaminants show higher release from swales than direct channel, although the EMCs of the contaminants from swales were lower than that from the direct channel. This is because higher flows from both swales were produced than that from the direct channel, due to the greater total water receiving areas, including pretreatment areas, as well as saturated soil conditions on June 3rd (Figure 6 in Appendix 2).

Table 5. Total mass of each contaminant discharged to drainage and percent removal efficiency of each swale compared to direct channel for (a) June 3rd Storm event and (b) July 1st Storm event.

(a) June 3rd Storm event

Total Mass discharged		Nutrients (g)				TSS (kg)	$\mathrm{Cl^-}$ (kg)	Heavy metals (g)			
		NO_2^--N	NO_3^--N	TKN-N	TP	TSS	$\mathrm{Cl^-}$	Zn	Cu	Pb	Cd
Direct	Mass	7.2	133	642	174	25.5	2.8	115	11.3	3.6	0.17
MDE	Mass	**14.6**	122	605	116	**51.9**	**14**	7.8	5.6	**6.7**	0.077
	% Removal	**-103***	8.5	5.9	33.0	**-1037**	**-407**	93.2	50.1	**-83.5**	55.4
SHA	Mass	**10.7**	**181**	**1026**	127	24.0	**15**	24	5.5	3.4	**0.25**
	% Removal	**-49.2**	**-35.5**	**-59.7**	26.7	5.9	**-444**	79.1	51.7	5.4	**-43.7**

(b) July 1st Storm event

Total Mass discharged		Nutrients (g)				TSS (kg)	$\mathrm{Cl^-}$ (kg)	Heavy metals (g)			
		NO_2^--N	NO_3^--N	TKN-N	TP	TSS	$\mathrm{Cl^-}$	Zn	Cu	Pb	Cd
Direct	Mass	1.15	22.7	233	35.8	6.2	0.88	41	1.6	0.63	0.032
MDE	Mass	0.34	4.30	18.1	2.47	0.97	1.5	0.34	0.11	0.11	0.0019
	% Removal	70.1	81.1	92.2	93.1	84.3	**-73.3**	99.2	93.4	81.7	93.9
SHA	Mass	0.34	16.5	18.3	2.33	0.12	0.55	0.13	0.068	0.040	0.0022
	% Removal	70.3	27.6	92.1	93.5	98.0	37.8	99.7	95.8	93.6	93.0

* Negative percent removal indicates percent production (increase) of contaminants compared to that from direct channel.

Among the metals studied, zinc shows the greatest percent removal by the swales, while much higher Zn EMCs (ranging from 250 to 1200 µg/L) than Cu (32 to 60 µg/L), Pb (11 to 21 µg/L) and Cd (0.2 to 1.0) EMCs were observed from direct channel (Table 4). The percent removal of all the contaminants by the swales for July 1st storm was much greater than that for June 3rd (Table 5). This is because high unsaturated condition of swale soils on July 1st makes large portion of runoff flows infiltrate into soil. Therefore, significant decrease of outflows to drainage (see Figure 6 in Appendix 2) resulted less release of contaminants to water bodies.

The water quality results during the sampling period demonstrate that grass swales can be efficient in treating highway storm water runoff as LID technologies with hydrologic benefits, especially with unsaturated soil condition.

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APPENDIX 1. Water Quality Data of outflow samples from Direct channel, MDE swale, and SHA swale.

(a) April 29th Storm

Direct		Average Flow	Nitrite-N	Nitrate-N	TKN-N	TP	TSS	Chloride	Zinc	Copper	Lead	Cadmium
Bottles	*Sampling Date*	*(L/s)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	(mg/L)	(ug/L)	*(ug/L)*	*(ug/L)*	*(ug/L)*
1,2	4/29/09 8:56	0.94	0.298	1.11	21	1.362	549	NA	649.1	104.0	0.7	0.37
3,4	4/29/09 9:16	1.39	0.198	0.94		0.611	234	NA	407.5	70.1	40.5	0.52
5,6	4/29/09 9:36	1.91	0.171	0.73	6.72	0.677	147	NA	389.0	58.5	6.1	0.25
7,8	4/29/09 9:56	0.94	0.124	0.62		0.669	45	NA	337.0	55.6	36.4	0.62
9,10	4/29/09 10:16	1.27	0.245	0.37	2.8	0.219	43	NA	172.7	45.5	5.3	0.47
11,12	4/29/09 10:56	0.79	0.065	0.33		0.129	32	NA	93.2	51.0	6.5	0.41

(b) May 16th Storm

Direct		Average Flow	*Nitrite-N*	*Nitrate-N*	*TKN-N*	*TP*	*TSS*	*Chloride*	*Zinc*	Copper	Lead	Cadmium
Bottles	*Sampling Date*	*(L/s)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	(mg/L)	(ug/L)	*(ug/L)*	*(ug/L)*	*(ug/L)*
1,2	5/16/09 21:28	3.85	0.170	0.52	7.98	0.740	569	55.25	1781.0	162.0	37.5	1.31
3,4	5/16/09 21:48	2.59	0.068	0.58		0.553	270	26.11	905.3	77.0	18.8	0.81
5,6	5/16/09 22:08	1.96	0.051	0.92	1.54	0.393	98	54.82	460.4	48.1	19.9	0.49
7,8	5/16/09 22:28	0.94	0.037	1.13		0.370	33	102.48	224.5	24.4	8.1	0.17
9,10	5/16/09 22:48	1.41	0.046	1.82	1.54	0.275	27	120.47	199.2	22.8	6.9	0.24
11,12	5/16/09 23:28	3.11	0.031	1.41		0.310	29	55.60	146.1	21.3	11.8	0.16
13,14	5/17/09 0:08	3.21	0.017	0.54	0.56	0.345	35	26.53	147.9	22.0	8.8	0.15
15,16	5/17/09 0:48	2.50	0.018	1.24		0.444	20	72.94	136.4	22.5	8.3	0.19
17,18	5/17/09 1:48	1.89	0.014	1.03	0.7	0.428	34	58.78	79.8	20.6	4.6	0.10
19,20	5/17/09 2:48	1.24	0.011	1.29		0.155	27	27.27	78.0	14.2	12.9	0.01
21,22	5/17/09 3:48	0.73	0.012	0.81	0.56	0.504	32	63.63	54.3	39.2	5.2	0.11
23,24	5/17/09 5:28	0.42	0.011	0.87		0.481	16	61.38	73.7	15.4	6.1	0.10

(c) June 3rd Storm

Direct		Average Flow	Nitrite-N	Nitrate-N	TKN-N	TP	TSS	Chloride	Zinc	Copper	Lead	Cadmium
Bottles	Sampling Date	(L/s)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)
1,2	6/3/2009 20:10	9.60	0.204	1.92	3.36	0.272	136	15.0	655	176.4	19.7	0.59
3,4	6/3/2009 20:30	36.27	0.045	0.72		1.085	347	13.2	1362	137.4	51.2	1.44
5,6	6/3/2009 20:50	19.89	0.019	0.44	4.62	4.733	175	13.9	1168	46.9	26.2	1.32
7,8	6/3/2009 21:10	0.94	0.025	1.07		0.383	76	31.5	325	37.9	19.3	0.69
9,10	6/3/2009 21:30	2.14	0.027	1.06	1.31	0.222	30	29.2	188	50.0	10.1	0.33
11,12	6/3/2009 22:10	24.62	0.022	0.69		0.188	71	12.2	184	29.3	1.4	0.66
13,14	6/3/2009 22:50	6.62	0.019	0.49	5.88	0.232	131	9.1	915	44.7	20.3	1.61
15,16	6/3/2009 23:30	2.90	0.062	0.36		0.705	195	14.9	99	12.7	15.1	1.47
17,18	6/4/2009 0:30	1.49	0.007	0.61	0.42	0.099	31	21.1	67	16.0	10.5	0.13
19,20	6/4/2009 1:30	1.08	0.004	0.66		0.150	18	27.3	271	15.7	21.6	0.30
21,22	6/4/2009 2:30	0.69	0.004	0.63	3.5	0.075	12	28.8	111	16.1	9.5	0.15
23,24	6/4/2009 4:10	0.41	0.004	0.62		0.123	27	30.3	90	15.3	12.3	0.16

MDE Swale		Average Flow	Nitrite-N	Nitrate-N	TKN-N	TP	TSS	Chloride	Zinc	Copper	Lead	Cadmium
Bottles	Sampling Date	(L/s)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)
1,2	6/3/2009 20:22	3.13	0.373	0.42	3.92	0.775	267	45.03	75.1	27.3	27.4	0.56
3,4	6/3/2009 20:42	89.47	0.024	0.6		0.683	279	48.48	46.0	23.9	31.6	0.39
5,6	6/3/2009 21:02	35.21	0.015	0.41	1.4	0.294	99	23.56	2.9	15.1	20.7	0.16
7,8	6/3/2009 21:22	6.27	0.014	0.23		0.176	28	35.55	1.3	9.7	14.6	0.13
9,10	6/3/2009 21:42	1.68	0.012	0.14	0.84	0.128	20	55.67	8.1	8.6	10.6	0.10
11,12	6/3/2009 22:22	2.26	0.010	0.21		0.193	35	97.14	2.9	7.6	8.8	0.05
13,14	6/3/2009 22:22	59.01	0.016	0.4	1.4	0.263	289	68.08	47.5	25.7	29.3	0.33
15,16	6/3/2009 22:42	42.94	0.008	0.36		0.205	102	17.99	1.4	14.7	15.3	0.12
17,18	6/3/2009 23:02	10.33	0.007	0.2	1.82	0.157	39	26.96	2.4	9.6	8.2	0.09
19,20	6/4/2009 0:02	2.64	0.005	0.05		0.116	13	66.14	2.1	2.1	1.2	0.01
21,22	6/4/2009 1:02	0.19	0.005	0.05	0.42	0.097	6	84.07	1.6	7.0	5.8	0.04
23,24	6/4/2009 2:22	0.00	0.005	0.05		0.058	17	94.64	1.4	6.9	3.8	0.02

SHA swale		**Average Flow**	***Nitrite-N***	***Nitrate-N***	***TKN-N***	***TP***	***TSS***	**Chloride**	***Zinc***	**Copper**	**Lead**	**Cadmium**
Bottles	***Sampling Date***	*(L/s)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	(ug/L)	*(ug/L)*	*(ug/L)*	*(ug/L)*
1,2	6/3/2009 20:24	6.11	0.113	0.85	4.48	0.871	138	75.42	138.4	22.3	11.6	0.89
3,4	6/3/2009 20:44	89.65	0.016	0.62		0.332	73	76.06	81.4	15.8	10.9	0.44
5,6	6/3/2009 21:04	83.14	0.022	0.38	2.24	0.258	44	20.48	33.4	8.9	5.2	0.34
7,8	6/3/2009 21:24	28.11	0.021	0.36		0.263	44	10.15	36.3	8.3	5.2	1.14
9,10	6/3/2009 21:44	7.80	0.019	0.28	1.26	0.169	26	14.24	25.9	8.4	4.2	0.13
11,12	6/3/2009 22:04	6.21	0.017	0.25		0.222	25	17.54	35.0	11.4	9.7	0.34
13,14	6/3/2009 22:24	61.84	0.014	0.36	0.84	0.123	43	27.78	40.9	10.0	4.8	0.09
15,16	6/3/2009 22:44	83.60	0.011	0.17		0.135	28	15.24	23.0	7.0	4.9	0.40
17,18	6/3/2009 23:04	27.19	0.007	0.14	1.68	0.135	28	10.5	21.8	7.7	5.3	0.87
19,20	6/4/2009 0:04	6.35	0.009	0.05		0.159	16	12.62	18.7	7.5	5.7	0.13
21,22	6/4/2009 1:04	0.85	0.009	0.09	0.98	0.131	18	18.72	24.5	9.1	5.0	0.10
23,24	6/4/2009 2:24	0.00	0.010	0.05		0.131	42	26.53	26.0	9.6	6.0	0.09

(d) July 1st Storm

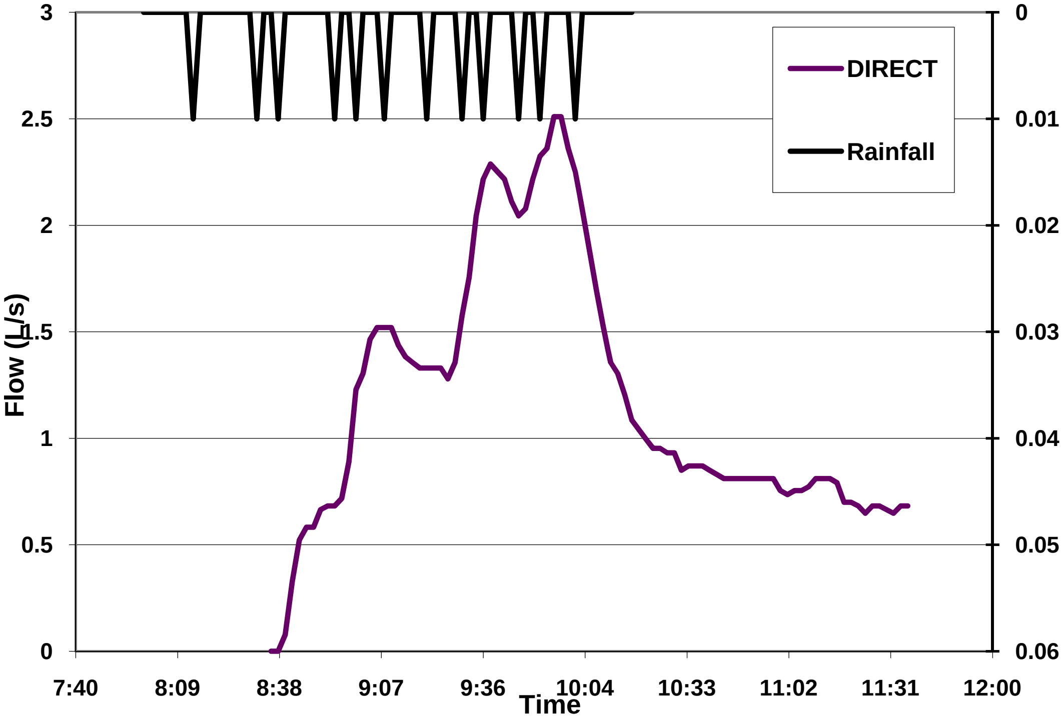
Direct		**Average Flow**	***Nitrite-N***	***Nitrate-N***	***TKN-N***	***TP***	***TSS***	***Chloride***	***Zinc***	**Copper**	**Lead**	**Cadmium**
Bottles	***Sampling Date***	*(L/s)*	*Conc (mg/L)*	*Conc (mg/L)*	*Conc (mg/L)*	*Conc (mg/L)*	*Conc (mg/L)*	Conc (mg/L)	Conc (ug/L)	*Conc (ug/L)*	*Conc (ug/L)*	*Conc (ug/L)*

1,2	7/1/2009 21:02	16.43	0.047	0.47	12.04	2.602	396	17.22	1972.0	92.9	44.4	1.78
3,4	7/1/2009 21:22	16.53	0.029	0.45		0.560	127	20.31	1307.0	40.9	9.0	0.84
5,6	7/1/2009 21:42	1.77	0.030	1.23	1.4	0.161	25	45.12	126.7	10.6	5.5	0.17
7,8	7/1/2009 22:02	0.94	0.025	1.64	0.56	0.249	40	55.72	219.9	9.3	6.5	0.16
9,10	7/1/2009 22:22	1.35	0.021	1.37	0.84	0.053	131	48.76	71.3	8.1	6.3	0.17

MDE Swale		**Average Flow**	***Nitrite-N***	***Nitrate-N***	***TKN-N***	***TP***	***TSS***	**Chloride**	***Zinc***	**Copper**	**Lead**	**Cadmium**
Bottles	***Sampling Date***	*(L/s)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	(ug/L)	*(ug/L)*	*(ug/L)*	*(ug/L)*
1,2	7/1/2009 21:16	2.33	0.0254	0.41	1.68	0.321	94	131.84	52.4	10.1	10.9	0.18
3,4	7/1/2009 21:36	5.66	0.0272	0.38	1.54	0.166	126	135.6	35.4	11.2	12.4	0.18
5,6	7/1/2009 21:56	2.97	0.0309	0.31	1.4	0.197	26	111.26	10.8	6.3	6.1	0.14
7,8	7/1/2009 22:16	0.28	0.0321	0.28	1.26	0.146	19	124.69	1.3	5.5	4.5	0.10
9,10	7/1/2009 22:36	0.00	0.0290	0.22	0.98	0.148	28	138.5	1.0	6.3	3.1	0.14

SHA Swale		**Average Flow**	***Nitrite-N***	***Nitrate-N***	***TKN-N***	***TP***	***TSS***	**Chloride**	***Zinc***	**Copper**	**Lead**	**Cadmium**
Bottles	***Sampling Date***	*(L/s)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	(ug/L)	*(ug/L)*	*(ug/L)*	*(ug/L)*
1,2	7/1/2009 21:18	3.58	0.0434	1.65	2.24	0.236	19	75.42	24.4	7.2	5.1	0.44
3,4	7/1/2009 21:38	5.10	0.0294	2.13	2.1	0.277	13	76.06	15.8	8.5	5.1	0.15
5,6	7/1/2009 21:58	0.26	0.0641	1.98	2.24	0.344	11	20.48	1.1	8.4	3.4	0.28

Appendix 2. Flow charts with rainfall graphs



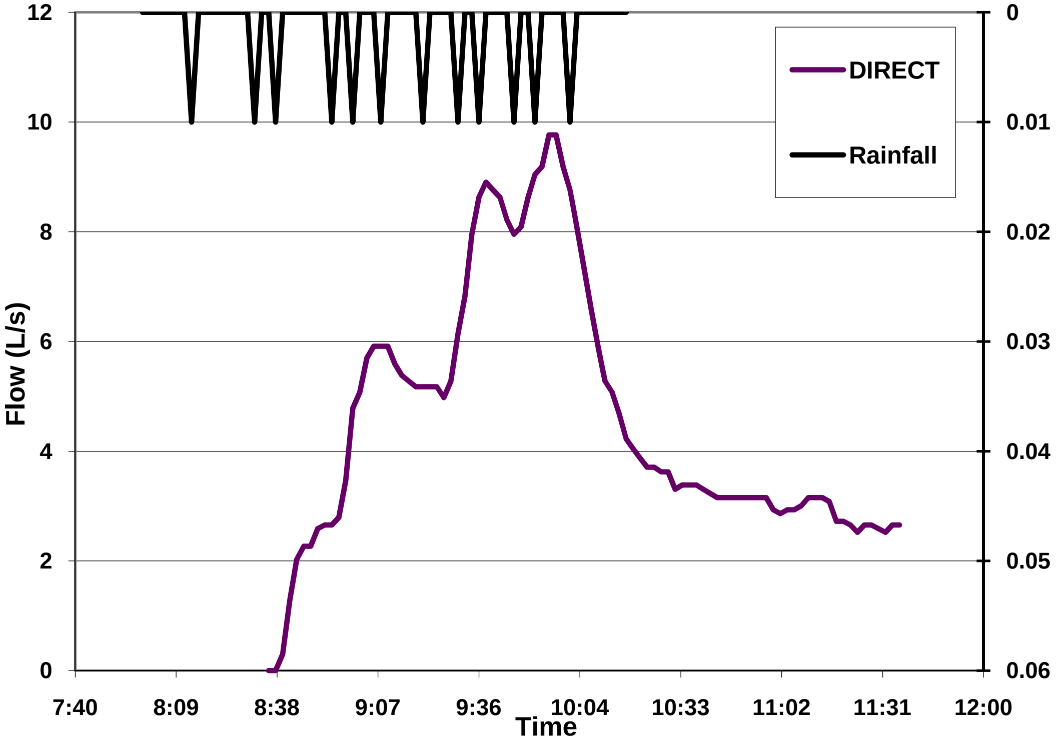


Figure 4. Flow chart with rainfall graph for April 29th storm event; (a) Flow chart, and (b) normalized flow chart (Total Rainfall=0.12 inch).

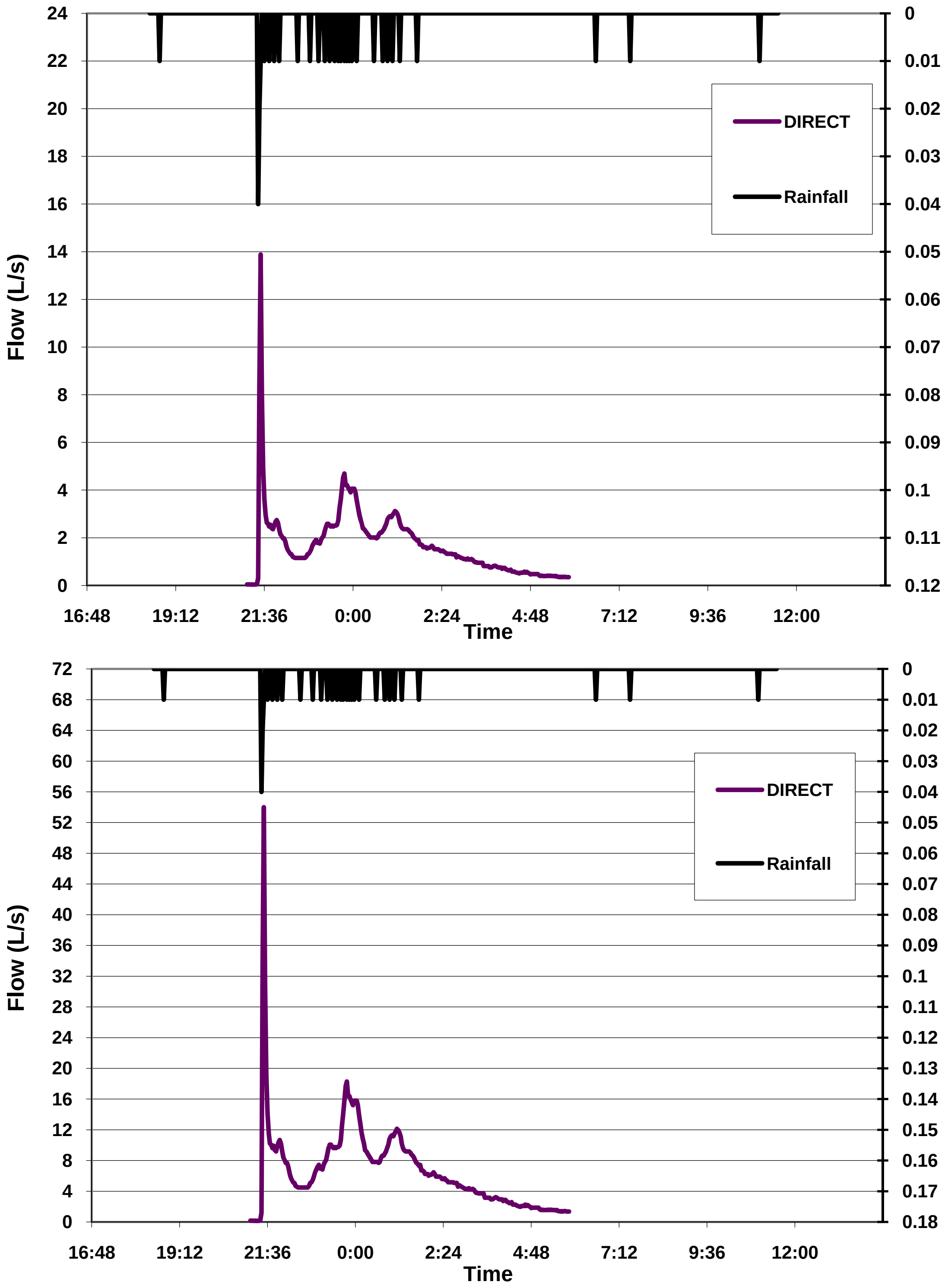


Figure 5. Flow chart with rainfall graph for May 16th storm event; (a) Flow chart, and (b) normalized flow chart (Total Rainfall=0.33 inch).

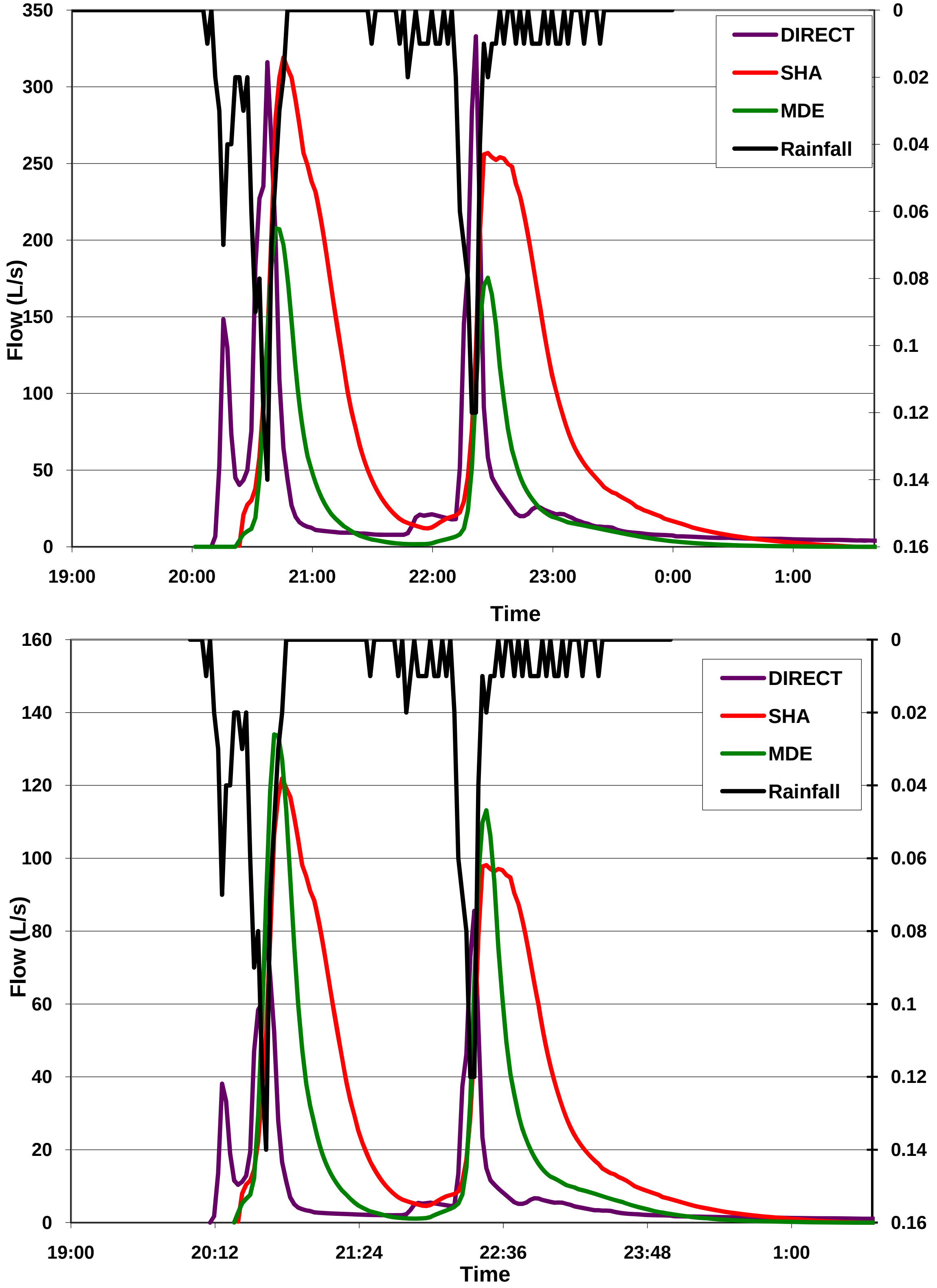


Figure 6. Flow chart with rainfall graph for May 16th storm event; (a) Flow chart, and (b) normalized flow chart (Total Rainfall=1.75 inch).

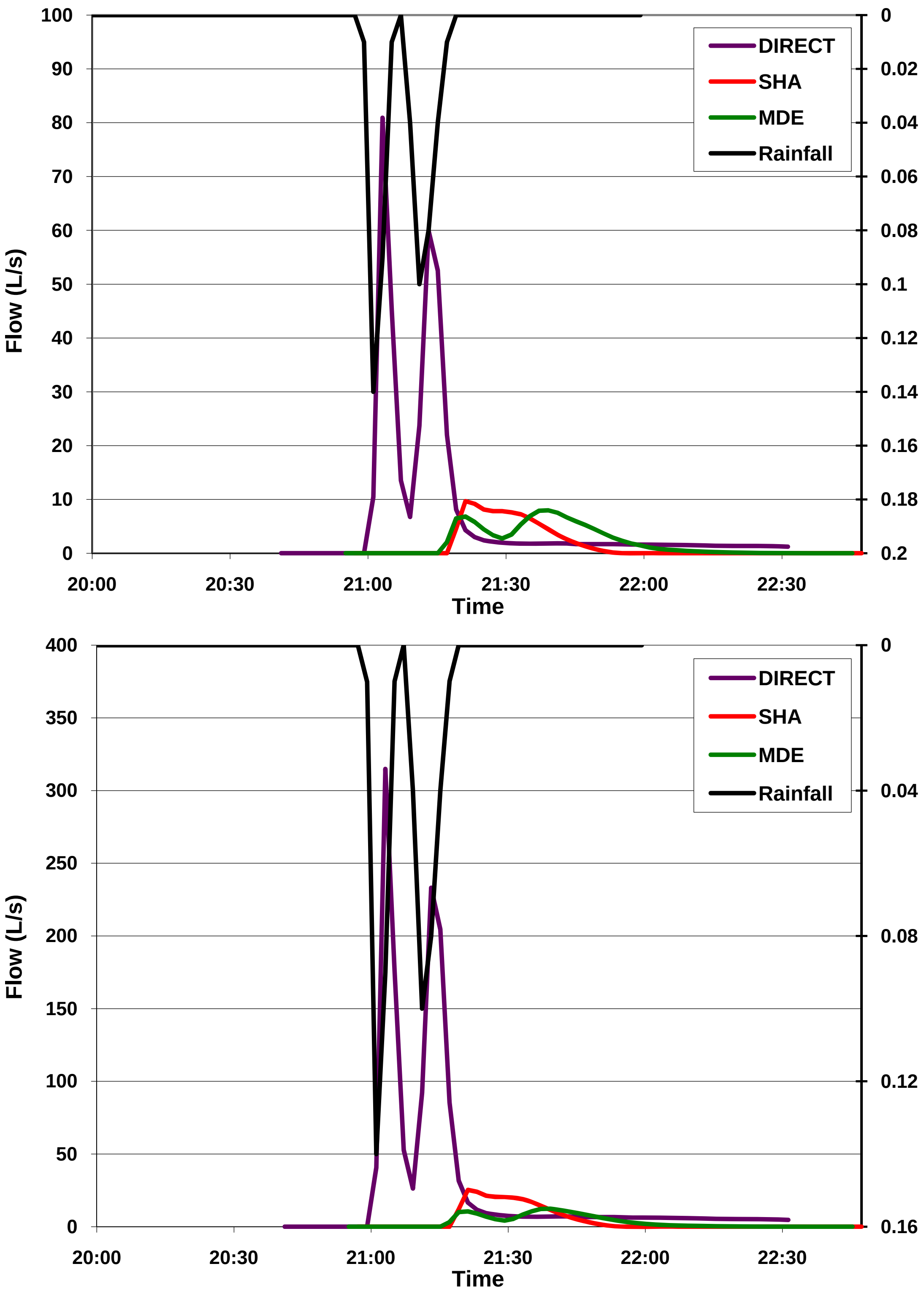


Figure 7. Flow chart with rainfall graph for July 1st storm event; (a) Flow chart, and (b) normalized flow chart (Total Rainfall=0.52 inch).

Appendix 3. Swale Site photos

(a) MDE Swale

(b) SHA Swale

Figure 8. Surface condition of the sampling points of; (a) MDE swale with some bare spots, and (b) SHA swale with well vegetated surface.

(a) MDE Swale

(b) SHA Swale

Figure 9. Check dam for; (a) MDE swale, and (b) SHA swale.

Figure 10. *Pits caused by erosion near direct channel*

APPENDIX C

Progress Report

Field Evaluation of Wet Infiltration Basin Transitional Performance

FIELD EVALUATION OF WET INFILTRATION BASIN TRANSITIONAL PERFORMANCE

Progress Report: Field Evaluation of Wet Infiltration Basin Transitional Performance

Project Duration:	June 2009 - July 2010
Project Sponsor:	Karen Coffman Highway Hydraulics Division Maryland State Highway Administration 707 North Calvert Street C-201 Baltimore, MD 21202
Project Coordinators:	Allen P. Davis, PhD, P. E Professor Poornima Natarajan Graduate Research Assistant Department of Civil and Environmental Engineering University of Maryland College Park, MD 20742

FIELD EVALUATION OF WET INFILTRATION BASIN TRANSITIONAL PERFORMANCE

FIELD EVALUATION OF WET INFILTRATION BASIN TRANSITIONAL PERFORMANCE

Executive Summary

This research study is systematically quantifying the performance of a "failed" wet infiltration basin that has naturally transformed into a functional stormwater wet pond or wetland site. The study site, located in Howard County, Maryland, is being monitored for flow characteristics and water quality during and periods subsequent to storm events. Totally, 31 storms have been monitored for hydrology. Overall, the results indicate that the BMP is effective in managing the runoff flows. The BMP assimilated the entire inflow volume and did not produce any outflow for 52% of the monitored events. The mean volume reduction achieved through the BMP for 31 events was 67%. Flow delays and peak attenuation (mean peak reduction= 56%) were observed during events with outflow.

The water quality of nine storm events and eleven dry-weather samples has been determined. The event mean concentrations (EMCs) of the measured pollutants in the outflow are lower than those of inflow in all events. Except for total phosphorus, the outflow EMCs of total suspended solids, oxidized nitrogen (nitrite and nitrate), and heavy metals (copper, lead, and zinc) meet the selected water quality criteria for majority of the events monitored. Pollutant removal efficiencies during eight sampled storm events (except one winter event) are: total suspended solids (91-100%), nitrate and nitrite (76-100%), total Kjeldahl nitrogen (38-100%), total phosphorus (60-100%), and total heavy metals, copper (64-100%), lead (29-100%), and zinc (18-100%). Export of nutrients and heavy metals was observed in the winter storm event. Ancillary benefits such as habitat to plants and wildlife are also being recorded. If the "failed" BMP is found to provide hydrology benefits and water quality enhancements in its existing condition, similar sites may be classified as functioning, stormwater management practices.

FIELD EVALUATION OF WET INFILTRATION BASIN TRANSITIONAL PERFORMANCE

FIELD EVALUATION OF WET INFILTRATION BASIN TRANSITIONAL PERFORMANCE

1.0 Introduction

Land use changes induced by urbanization decrease the perviousness of a watershed, leading to a decrease in infiltration and increase in surface runoff (Dunne and Leopold 1978). Such hydrologic modification in a watershed can affect the physical, chemical, and biological conditions of the receiving waters (Paul and Meyer 2001; Wang et al. 2003). Impervious surfaces such as roads, driveways, parking lots, sidewalks, and rooftops accumulate pollutants, including suspended solids, metals, nutrients, pesticides, pathogenic microorganisms, and other contaminants, which are washed off during storm events and eventually delivered to the receiving waters (Barrett *et al.* 1998; Davis *et al.* 2001b; Paul and Meyer 2001). *The National Water Quality Inventory: 2000 Report to Congress* has identified urban runoff as one of the leading sources of water quality impairment in surface waters (USEPA 2005).

Over the past few decades, a multitude of wet infiltration basins have been constructed for stormwater management. An infiltration basin is a shallow impoundment on permeable soil that is designed to capture, temporarily store, and infiltrate stormwater runoff into the ground water over a period of days (Pennsylvania Stormwater Management Manual 2005). In addition to providing water quantity benefit, these best management practices (BMPs) remove pollutants through detention and filtration of runoff (USEPA 1999). Birch *et al.* 2005 studied the efficiency of an infiltration basin located in Sydney (Australia) in removing pollutants from urban stormwater runoff and reported reduction in total suspended solids (TSS) (50%), total phosphorus (TP) (51%), total Kjeldahl nitrogen (TKN) (65%), trace metals, and fecal coliforms (96%), but increases in oxidized nitrogen species (NO_x) and total nitrogen (TN).

Over the years, inspections have shown that wet infiltration basins constructed in Maryland may no longer be functioning as originally intended and designed (Lindsey *et al.* 1992). The facilities exhibit inappropriate ponding of water, reduced infiltration rates, excessive sedimentation, clogging, and failure with time (Lindsey *et al.* 1992; Dechesne *et al.* 2005).

Nonetheless, a separate ecological function may develop in the failed infiltration basins. These practices can gradually transform into a wet pond or wetland-like practice. Functionality of wet ponds and wetlands in providing hydrologic benefits and in removing pollutants from stormwater runoff is well documented (Wu *et al.* 1996; USEPA 1999; Carleton *et al.* 2000; Birch *et al.* 2004; Brydon *et al.* 2006). Hence, it can be hypothesized that the transformed infiltration basin BMPs will have both water quality and hydrologic management function.

The overall goal for this research is to systematically quantify, through field scale research and monitoring, the performance of a "failed" wet infiltration basin that has naturally transformed into a functional stormwater wet pond or wetland site. Both water quality and flow characteristics will be monitored during storm events and for time periods directly subsequent to storm events. The performance of these systems, as functional stormwater BMPs, will be appropriately documented. Ancillary benefits such as wildlife habitat will also be recorded if possible. If the "failed" BMP is found to provide water quality enhancements, similar sites may be classified as functioning, stormwater management practices.

2.0 Background

Watershed imperviousness has been increasing due to expanding urbanization. This has led to increased surface runoff volume, decreased lag time, increased peak flows, and lower dry weather flow in streams. This modification of the hydrologic regime (rate, timing, and delivery) of streamflow has potential effects on the structure and composition of the lotic communities (Konrad and Booth 2005). The term "urban stream syndrome" has been used to describe the consistently observed ecological degradation of streams draining urban land (Walsh *et al.* 2005). Urban-induced flashy hydrographs, decreased baseflow, channel instability, elevated levels of sediments, metals, nutrients, pesticides, pathogens and other contaminants, stream warming, riparian deforestation, and decline in biodiversity in streams have been well documented by various researchers.

Infiltration basins are structural BMPs that are designed to capture and retain runoff until it infiltrates into the ground over a period of few hours or days. These BMPs are located on areas with relatively undisturbed (uncompacted), permeable soils, which may or may not be vegetated. Their main purpose is to simply convey the surface water flow into ground water and to remove pollutants through mechanisms such as filtration, adsorption and biological conversion as the water percolates through the underlying soil (USEPA 1999). Infiltration basins can be considered to provide 100% surface water pollutant removal, since the inflow runoff completely infiltrates into the soil.

Infiltration basins are not designed to hold a permanent pool of water. Regular maintenance activities, such as mowing, removing debris and litter, and scraping off the sediment to restore the original infiltration rate, are critical to the performance for these BMPs (Stormwater Center, Stormwater fact sheet). Lindsey *et al.* (1992) have published results of a field survey conducted on certain stormwater facilities in Maryland that included infiltration basins. About 48 facilities were inspected in both1986 and 1990. The study showed that the facilities were not functioning as designed and were considered failed; 52% of the infiltration basins were inappropriately ponded due to clogging by sediment input and needed to be rehabilitated.

Although infiltration BMPs may not function as originally designed, such failed facilities holding a permanent pool of water may be transforming into a wet pond or a wetland. Both stormwater ponds and wetlands are widely employed stormwater management practices for flood control and pollutant removal. Wet ponds and wetlands intercept and store runoff, thereby mitigate and delay the flow peaks, and provide runoff volume reduction (USEPA 1999).

Figure 1 depicts the possible components of the hydrological inputs to and outputs from the wet basin system. Water input to the basin is from runoff (as concentrated inflow or sheet flow) and precipitation on the surface area of the basin. Runoff stored in the basin will be discharged as outflow depending on the total volume of runoff received (function of rainfall amount and drainage area) and the basin storage capacity. Losses from the basin are by evaporation driven by solar radiation and transpiration from vegetation in the basin, and by infiltration into the soil underneath.

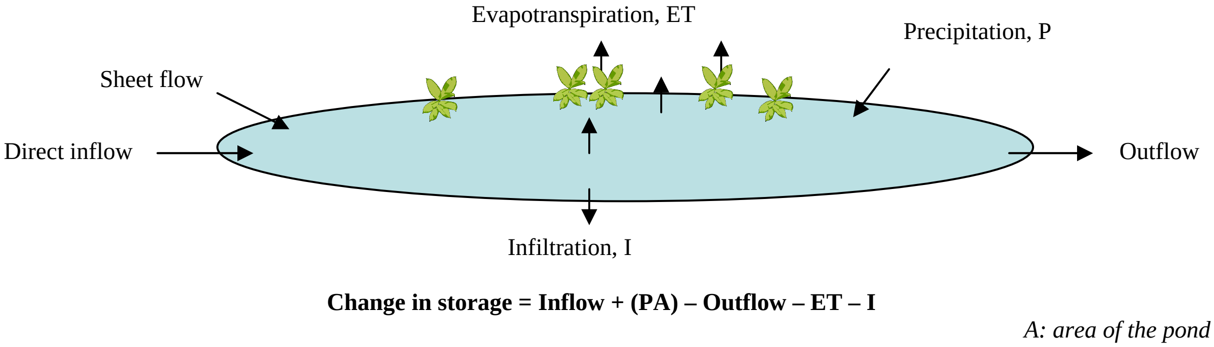
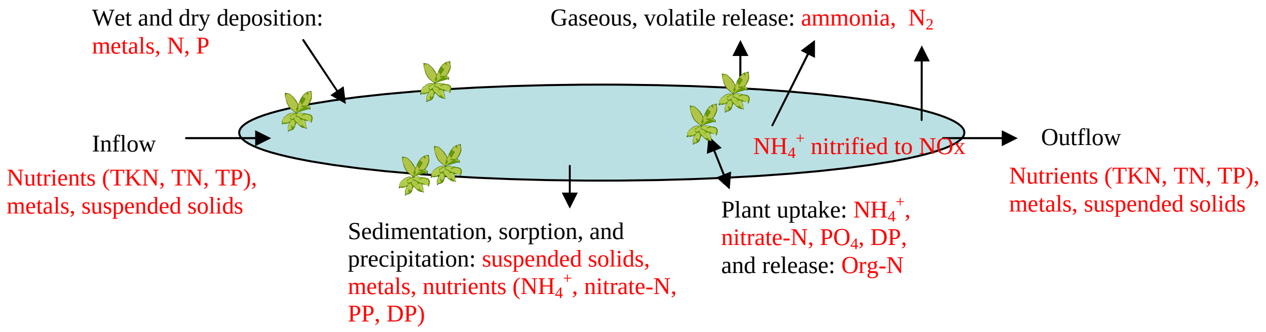


Figure 1. Schematic of flow balance in a wet infiltration basin.

Considering water quality, both wet ponds and wetlands have been found to be effective in removing pollutants from urban stormwater runoff. Removals in the range of 80-90% for TSS, 21-50% TKN, 22-58%, NO_x, 16-48% TN, and 35-65% TP have been reported (Wu *et al.* 1996; Carleton *et al.* 2000; Birch *et al.* 2004; Brydon *et al.* 2006). Removal efficiencies for metals are usually good; Cr (64%), Cu (45-65%), Pb (33%-75%), Zn (31-61%). These BMPs usually show highly variable removal efficiencies of nutrients, nitrogen and phosphorus, generally <50%. Removal of soluble reactive phosphorous (SRP) of -12%, and even -50% (phosphorus export) has been reported (Comings *et al.* 2000). However, the performance of stormwater ponds has been observed to be poor during winter than in summer (German *et al.* 2003; Semadeni-Davies 2006; Vollertsen *et al.* 2009). The formation of ice cover changes the pond hydrology by reducing the available detention volume, arresting biological activity due to cold temperatures, and thus impairing the pollutant removal efficiency. Also, snow accumulates contaminants from the highway and subsequent snowmelt introduces large flow volumes and high pollutant loads to the BMP, thereby affecting the overall performance of the BMP (Sansalone and Glenn 2002; Glenn and Sansalone 2003; Vollertsen *et al.* 2009).

The removal of many stormwater pollutants in a wet pond, wetland or detention basin is a function of residence time, which is defined as the mean time spent by a flow parcel in the basin (Walker 1998). Extended residence time provides opportunity for solids to settle and dissolve, and for components to be acted upon either biologically or chemically. All reactions are governed by the presence of aerobic or anaerobic condition in the basin, which creates redox gradients in the soil and water columns. Redox conditions are influenced by hydrological fluctuations, presence of electron acceptors (O_2, NO_3^-, SO_4^{2-}), and transport of oxygen by plants into the root zones (Reddy and D'Angelo 1997). Figure 2 illustrates the possible transformations that the pollutants (solids, nutrients, and metals) can undergo in a wet pond or wetland-like system.



Total N = TKN (organic and ammonium-N) + NOx –N (nitrate and nitrite)

$$\text{Org-N} \xrightarrow{\text{Ammonification}} \text{Ammonium} - \text{N} \xrightarrow{\text{Nitrification}} \text{NO}_2\text{-N} \rightarrow \text{NO}_3\text{-N} \xrightarrow{\text{Denitrification}} \text{N}_2$$

Total P = Particulate P (PP) + Dissolved P (DP)

Figure 2. Schematic of possible pollutant transformations in a wet basin.

Suspended solids in road runoff originate from pavement wear, vehicles, atmospheric deposition, maintenance activities, and wash off from local soils (Sansalone *et al.* 1998). The particle size distribution is of hetero-disperse nature in highway runoff, with particle sizes ranging from 1 μm to greater than 24,500 μm (Kim and Sansalone 2008). High levels of suspended solids in runoff are attributed to coarser fractions (Furumai *et al.* 2002). Suspended solids are pollutants themselves and also contain nutrients and heavy metals associated with particles. Sedimentation is the primary removal mechanism of suspended solids in the runoff.

Nutrients (nitrogen and phosphorus) are introduced in urban runoff through decomposing organic matter, human and pet wastes, fertilizers, and atmospheric deposition. The various chemical species of nitrogen and phosphorus exist in dissolved and particulate forms. The dissolved forms are of greater importance since they are readily available for uptake by organisms and may lead to eutrophication if present in excessive amounts (Galloway *et al.* 2003). Nitrogen in runoff is speciated into various forms: ammonium, nitrate, nitrite, and organic nitrogen. Taylor *et al.* (2005) characterized the composition of nitrogen in urban stormwater runoff in a study conducted in Australia and found that total dissolved nitrogen is a larger portion (~80%) of total nitrogen (TN) of the runoff. The study also revealed that organic nitrogen is the major (>50%) and ammonia is the least-abundant (~11%) constituent of TN in stormwater runoff which is in agreement with other international studies.

In a wet pond and wetland environment, nitrogen and phosphorus are utilized via complex biogeochemical cycling, which involves many pathways, sinks and sources (Kadlec and Knight

1995). The species are partitioned into particulates, dissolved in water, sorbed, and exist in biomass phases. The nitrogen species transform from organic to inorganic and vice-versa via chemical and biologically-mediated transformations as shown in Figure 2. Ammonium nitrogen (NH_4^+-N) is transformed into oxidized nitrogen forms (NO_x) of nitrite and nitrate by nitrifying bacteria. Some NH_4^+-N is lost through volatilization. Under anaerobic condition, denitrifying bacteria can transform the NO_x species to nitrogen gas. Plants serve as source of organic nitrogen and uptake ammonia and nitrate nitrogen for growth.

In a wetland-like environment, phosphorus is regulated via various abiotic and biotic processes such as sedimentation, adsorption, plant uptake, and microbial reactions. Mineralization of plant litter and soil organic-P can release P into the water. Precipitation and dissolution of the nitrogen and phosphorus species are influenced by factors such as redox potential, presence of electron acceptors and donors, pH and temperature of the sediment and water (Reddy and D'Angelo 1997).

Metals are introduced in the runoff from vehicles, tires, brake wear, and by atmospheric deposition (Davis *et al.* 2001a). Metals are present in both dissolved and particulate forms in runoff. A study conducted by Furumai *et al.* (2002) observed higher particle-bound fractions of Zn, Pb, and Cu than their dissolved forms in runoff from a highway in Switzerland. Particle-size distribution studies of highway runoff found that most metals have a greater affinity for smaller particles and hence metal concentrations generally increase with decreasing particle size (Furumai *et al.* 2002; Herngren *et al.* 2005). Removal mechanisms of heavy metals within wetlands include sedimentation, filtration, chemical precipitation and adsorption, microbial interactions, and uptake by vegetation (Walker and Hurl 2002; Yeh 2008).

To summarize, a wet basin, transforming into wet pond- or wetland-like system, is expected provide possible volume reduction via evapotranspiration and infiltration, peak attenuation through runoff capture and detention, and water quality enhancement by various pollutant removal mechanisms. In addition, these BMPs may support varied flora and fauna, thereby providing secondary functionality of habitat for plants and animals.

3.0 Methodology

3.1 Site Description

From the MD State Highway Administration (SHA) inventory, five failed infiltration basins located in Howard County were identified as potential study sites and were investigated through field visits to determine their suitability for inclusion in this study. The BMPs were evaluated based on the drainage area, number of inflow and outflow points, accessibility and ease of instrumentation at the inlet and outlet points, and safety at the site. Also, the traffic density and other parameters representative of the State of Maryland were considered during the selection process.

BMP 13348, located along MD 175 eastbound (EB) between Dobbin Road and Snowden River Parkway in Columbia, Howard County (Figures 3, 4, and 5), was chosen for the study. The BMP is located within the Maryland SHA right-of-way. The BMP was originally constructed as an infiltration basin built in-stream. Currently, the facility is inundated and has been classified as a failed BMP (SHA failure rating IV). Total drainage area to the BMP is 7.2 acre, which is 33% impervious. The BMP has one inflow and one outflow point. The source of inflow is sheet flow from MD-175 and ramp to Snowden River Parkway south, along with culvert and swale flow; all of these flows concentrate within a vegetated swale as the input to the BMP (Figure 4).

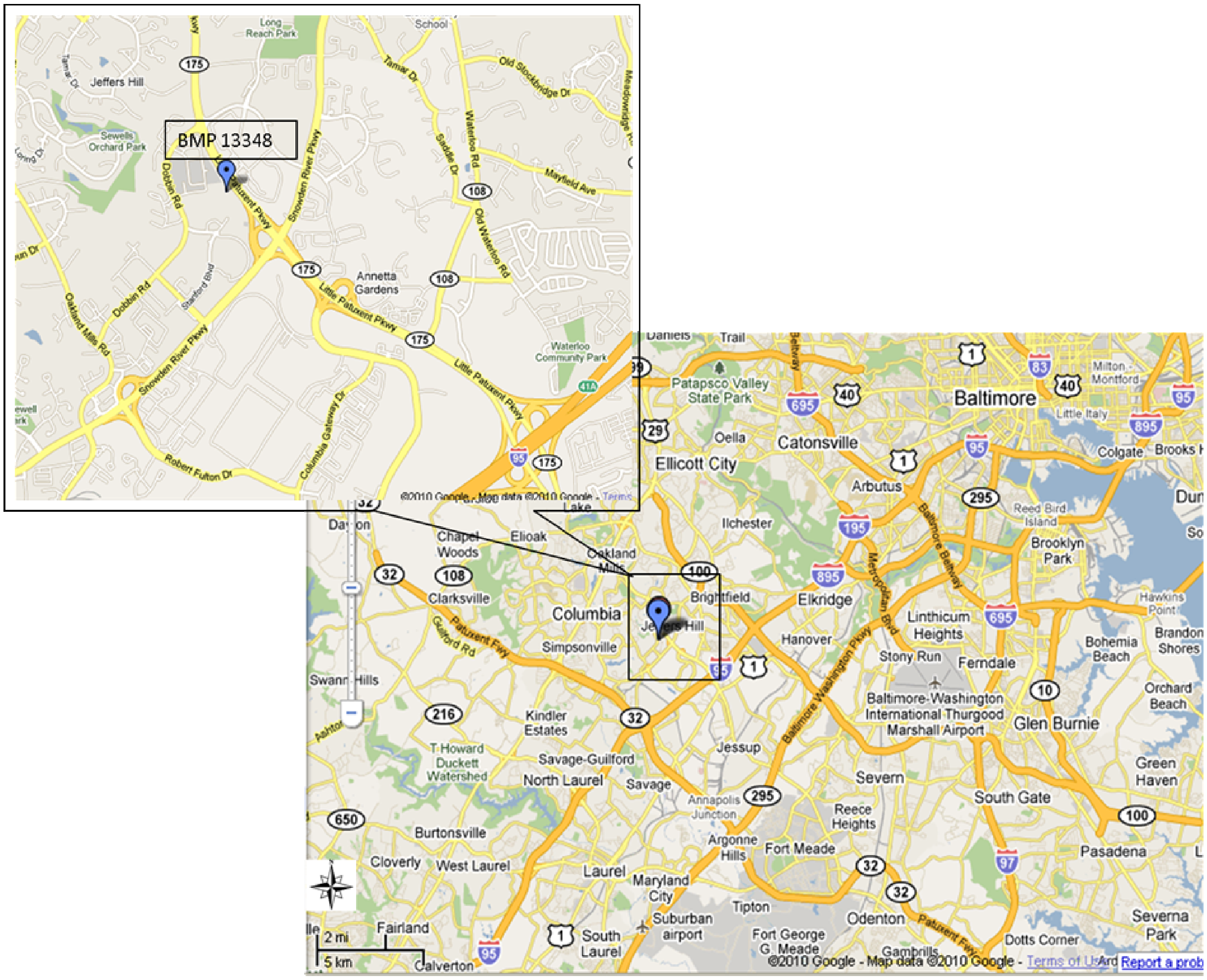


Figure 3. Map location of BMP 13348 along MD 175 EB. (Source: <www.maps.google.com>)

April 9, 2009

Figure 4. BMP 13348 located along MD 175 EB. Photo, looking west, shows single concentrated inflow point to the BMP. Some additional flow will occur from sides of the BMP.

Figure 5. BMP 13348 at outflow point, looking east.

April 9, 2009

3.2 Monitoring

An input/output monitoring approach is employed to evaluate the BMP effectiveness. The BMP is monitored for flows and water quality samples are collected for targeted storm events. The goal of the project is to evaluate one event for water quality per month, for an overall goal of 24 or more events. Hydrology data (rainfall and flows) will be collected for as many events as possible. Attempts will be made to monitor a distribution of rainfall events consistent with those expected in Maryland (e.g., many small, short-duration events; fewer high intensity, long duration storms).

3.2.1 Instrumentation and Sampling

Runoff flows are directed through calibrated weirs. Automated portable samplers (ISCO 6712) are used for flow monitoring and sample collection at the inlet and the outlet (Figure 6). Each sampler contains 12 glass bottles and the sampling program is set to collect 12 samples per event. Based on the expected rainfall amount and duration, either a six-, eight-, ten- or twelve-hour period sampling program is employed to collect samples representative of the event. An example for the sample timing is presented in Table 1. Emphasis is placed on obtaining more samples in the early part of the precipitation event. The discharge flow is spread over a longer duration due to the expected flow attenuation through the facility.

Figure 6. Photo showing the sampler and weir installed at the inlet side of the BMP.

Table 1. Example sampling times for automated collection during storm events.

	Time	
Sample Number	**Input**	**Output**
1	zero minutes	zero minutes
2	20 minutes	20 minutes
3	40 minutes	40 minutes
4	1 hour	1 hour
5	1 hour, 20 min	1 hour, 20 min
6	1 hour, 40 min	2 hours
7	2 hours	2 hr, 40 min
8	2 hr, 20 min	3 hr, 20 min
9	2 hr, 40 min	4 hr, 20 min
10	3 hr, 40 min	5 hr, 20 min
11	4 hr, 40 min	6 hr, 20 min
12	6 hr	8 hr

The glass bottles are cleaned, acid washed, and labeled before placement in the sampler. Filled sample bottles are sealed, placed in an iced cooler, and transported to the Environmental Engineering Laboratory, College Park, MD within 12 hours after a rainfall event.

In addition to collecting stormwater runoff samples during rainfall events, water samples are collected from the BMP during selected dry-weather periods. Samples are collected at multiple locations in the BMP prior to and following target events or on a monthly basis as suitable. This dry-weather monitoring will provide useful information to interpret the possible physical, chemical, and biological transformations occurring in the BMP.

Rainfall depth measurements are taken on a 2-minute increment basis using a tipping bucket rain gauge with 0.01 inch sensitivity, installed on top of one of the sampler vaults and connected to the sampler. A water level probe was installed in the basin at the end of March 2010. The probe continuously records the water level and temperature at 10-minute intervals. Air temperature, pressure, relative humidity, wind speed, and wind direction data are available from a weather station located about 3 miles from the study site, which can be accessed through the website (<http://www.wunderground.com/cgi-bin/findweather/getForecast?query=21045>). These weather parameters are required to estimate the evapotranspiration component of the water balance of the system.

3.2.2 Water Quality Parameters

Pollutants monitored include total suspended solids (TSS), nitrate, nitrite, total Kjeldahl nitrogen (TKN), total phosphorus, total copper, total lead, total zinc, and chloride. These pollutants are of the greatest concern in roadway runoff because their concentrations often exceed the limits set by anticipated total maximum daily loads (TMDL) requirements. The performance of the BMP will be evaluated by comparing the water quality during each event with the selected water quality criteria listed in Table 2.

Table 2. Criteria for various water quality parameters (Source: Li and Davis 2009). All concentrations are in mg L^{-1}.

Pollutant	TSS	TP	Nitrate (as N)	Nitrite (as N)	TKN (as N)	TN (as N)	Lead	Copper	Zinc	Chloride
Water quality criterion	25^a	0.05^a	0.20^a	1^c	-	-	0.065^b	0.013^b	0.12^b	250^c

[a] Criteria for excellent water quality in the Potomac River Basin (Davis and McCuen 2005)
[b] Acute toxicity level (COMAR 2006)
[c] Secondary drinking water regulation (US EPA 2009)

The selected water quality criteria in Table 2 are based on the water quality goals outlined in the bioretention research study by Li and Davis (2009). The criteria have been derived from various local, state, and federal regulations; threshold levels of TSS, TP, and nitrate are local quantitative water quality designations (Davis and McCuen 2005); total heavy metal criteria are acute toxicity levels for freshwaters in Maryland [Code of Maryland Regulations (COMAR) 2006]; and the threshold nitrite and chloride levels are federal secondary drinking water regulation (US EPA 2009).

3.3 Analytical Methodology

All pollutant concentrations are determined based on *Standard Methods* (APHA *et al.* 1995).

3.3.1 Solids

Solids in the water samples are measured following Standard Method 2540 (APHA *et al.* 1995). The sample is well mixed and 100 mL of the sample is evaporated to a constant weight at 105°C, cooled, weighed, and the total solids (TS) computed. A well-mixed sample of 100 mL is filtered through a pre-weighed standard glass-fiber filter with 47 *mm* diameter (Pall Corporation). The residue retained on the filter is dried to a constant weight at 221°F, cooled, weighed, and the total suspended solids (TSS) is computed. The difference between total solids and total suspended solids is the total dissolved solids concentration in the sample. The TS and TSS residues are ignited at 1022°F for one hour to determine the amounts of fixed and volatile TS and TSS.

3.3.2 Total Phosphorus

Phosphorus analysis is performed following Standard Method 4500-P (APHA *et al.* 1995). Total phosphorus (TP) in the sample is determined by a) conversion of the phosphorus to dissolved orthophosphate by persulfate digestion, and b) colorimetric determination of dissolved orthophosphate by the ascorbic acid method, using a spectrophotometer (Shimadzu model UV160U) at 880 nm. Fraction of total dissolved phosphorus and dissolved reactive phosphorus are determined in samples filtered through 0.2 *μm* pore diameter membrane following the same principle. Samples containing high TSS were observed to contain some suspended material after persulfate digestion. These samples were centrifuged or filtered to remove all suspended material before proceeding to the ascorbic method in order to avoid interferences during the photometric measurements.

3.3.3 Nitrite

Nitrite analysis follows Standard Method 4500-NO_2^- B (APHA *et al.* 1995). 50 mL samples are filtered through 0.2 *μm* filters and are subjected to the colorimetric method. Formation of a reddish purple azo dye on mixing NO_2^- with diazotized sulfanilamide (J. T. Baker) and NED dihydrochloride (Fisher Scientific) is the principle of the method. Spectrophotometric measurement of the azo dye is performed at 543 *nm*.

3.3.4 Total Kjeldahl Nitrogen (TKN)

TKN analysis is performed using Standard Methods 4500-NH_3 and 4500-N_{org} Macro-Kjeldahl method (APHA *et al.* 1995) in three steps: a) digestion of 250 mL of sample diluted to 300 mL after addition of 50 mL of digestion reagent, b) distillation of digested sample, after dilution to 300 mL and treatment with 50 mL of sodium hydroxide-sodium thiosulfate ($NaOH$-$Na_2S_2O_3 \cdot 5H_2O$) reagent, into boric acid indicating solution, and (c) titration of distillate with standard 0.02 *N* H_2SO_4 titrant. Dissolved TKN is determined in samples filtered through 0.2 *μm* filters following the same procedure.

3.3.5 Nitrate and Chloride

Nitrate, chloride, and sulfate analyses are performed by ion chromatography. Samples are filtered through 0.2 *μm* filters. Analysis is performed using a Dionex ion chromatograph (model DX-100) using a 1.3 *mM* Na_2CO_3/1.5 *mM* $NaHCO_3$ eluent at 2.0 mL min^{-1} flow rate with AS-4A-SC separator column and an AG-5 guard column. The scale and standard concentrations are selected based on the ions and expected concentration levels; the conductivity detection level is 10 *μS* for nitrate, and 100 or 300 *μS* for chloride.

3.3.6 Total Metals

Metals analysis involves three steps a) digestion of samples by evaporation of 50 mL of sample after addition of 5 mL of trace metal grade concentrated HNO_3. b) filtration and dilution to 50 mL of digested samples and c) analysis of Pb and Cu on the furnace module of a Perkin Elmer Model 5100PC Atomic Absorption Spectrophotometer (AAS) (Standard Method 3110), and Zn on the flame module of the AAS (Standard Method 3111) (APHA *et al.* 1995).

3.3.7 *Loss on Ignition*

The loss on ignition method is utilized to determine the approximate organic matter content of solids (Standard Method 2540) (APHA *et al*. 1995). At least 200 *mg* of the wet sediment sample is placed in a pre-weighed Gooch crucible and weighed. The sample is dried to a constant weight in an oven at 221°F, cooled, dessicated, weighed, and the water content computed. The residue produced is ignited in a muffle furnace at a temperature of 1022°F for one hour, cooled, dessicated, and weighed. The cycle of igniting, cooling, dessicating, and weighing is repeated until a constant weight is obtained and the percent organic content in the sediment is computed.

3.3.8 *Analytical Detection Limits*

The laboratory analytical detection limit (D.L.) of each target water quality parameter is summarized in Table 3.

Table 3. Analytical detection limits (D.L.) of the target water quality parameters. All concentrations are in mg L^{-1}.

Pollutant	TSS	TP	Nitrate (as N)	Nitrite (as N)	TKN (as N)	Lead	Copper	Zinc	Chloride
D.L.	1	0.01	0.1	0.002	0.14	0.005	0.002	0.025	2

3.3.9 *Quality Assurance/Quality Check*

Field blanks (or laboratory blanks) were subjected to the same analytical procedure as the samples during each pollutant analysis. Standard calibration curves were validated by checking at least one standard during each pollutant analysis. For ion chromatographic determination of nitrate and chloride concentrations, at least two standards were run along with the samples. During metal analysis, standard concentration were checked after every ten samples. If the error in standard concentration check exceeded ±10%, a new standard calibration curve was created.

3.4 Data Handling

For each event, the total flow volume is calculated by a simple numerical integration of the flow measurements over time:

$$V = \int_{0}^{T_d} Q \, dt \qquad (1)$$

For each pollutant, the total mass (M) present in each storm event is calculated as:

$$M = \int_0^{T_d} Q\,C\,dt \tag{2}$$

In Equations 1 and 2, Q is the measured stormwater flow rate, C is the pollutant concentration for each sample during the event, and T_d is the event duration. The interval between samples (or measurements) is dt. Substituting corresponding values of Q and C for inflow and outflow in Equations 1 and 2, the inflow and outflow total flow volumes and mass loadings can be obtained, respectively. In cases where the concentration of a pollutant is below the laboratory analytical detection limit (Table 3), a value equal to one-half of the detection limit is used for calculation and statistical purposes.

Mass removal efficiency for a pollutant is calculated as:

$$M_R = \frac{(M_{in} - M_{out})}{M_{in}} \tag{3}$$

The event mean concentration (EMC) is calculated as:

$$EMC = \frac{M}{V} = \frac{\int_0^{T_d} C\,Q\,dt}{\int_0^{T_d} Q\,dt} \tag{4}$$

The EMC represents the concentration that would result if the entire storm event discharge were collected in a single container. EMC weights discrete concentrations with flow volumes; therefore it is generally used to compare pollutant concentrations among different events.

Metrics and tools such as peak reduction ratio, peak delay ratio, probability exceedence distributions for flows and peak flows (Davis 2008), flow volume reduction ratio, and flow duration curves will be employed in assessing the hydrologic performance of the BMP. Pollutant removal efficiency, expressed as a percent removal, may not be an accurate representation of performance of a BMP (Strecker *et al.* 2001). Therefore, in addition to percent pollutant mass removal efficiency, the wet infiltration basin will be evaluated based on effluent pollutant concentrations, statistical characterizations of the inflow and outflow concentrations through probability exceedence distributions with appropriate water quality targets, and total loads in and out of the BMP. Performance will be related to storm characteristics. Also, the distribution of storms studied (intensity, duration) will be compared to expected storm distributions for Maryland.

4.0 Research Progress

The study site has been monitored since June 2009. Figure 7 is a collage of photographs of the BMP from June 2009 to July 2010. Totally, 35 rainfall events have been recorded between June 2009 and July 2010. However, four rainfall events in summer 2010 did not produce any inflow to the site and were excluded in all analyses. Hence, the hydrology performance of the BMP has been evaluated for 31 rainfall events. Nine rainfall events have been sampled for water quality and eleven dry-weather sampling excursions have been performed to date. The pond was completely frozen from late Dec 2009 through early Mar 2010 (Jan 4, 2010 photo in Figure 7). Except for one event on Jan 18, 2010, no hydrology and water quality data are available for this period. All rainfall events and flows at the site have been recorded for the period Oct 15 to Dec 4, 2009, and Mar 25 to July 31, 2010. Details of antecedent dry period, rainfall depth and duration, and inflow and outflow volumes recorded during each event are summarized in Table 4.

For the purpose of definition, a new rainfall event is defined as an event occurring six hours after the preceding event. Occasionally, outflow from the BMP continued for extended periods overlapping the next rainfall event. In such cases, flow volumes of the two events were combined during analysis. In some instances, the rainfall duration exceeded the sampling period. For such events, the hydrology data reported include flows to and from the BMP from the start of the rainfall event until the flows cease. While performing pollutant mass loading calculations, concentration of the unsampled volume will be assumed to be equal to half the concentration of the last sample collected for conservative estimation. This assumption is applicable to both inflow and outflow mass loading calculations. In the event that the rainfall duration was much longer than the sampling duration, judgment will be used regarding the inclusion of the water quality data towards quantitative determinations.

The hydrology and water quality performances of the BMP have been evaluated on an event basis as well as on seasonal basis. The months have been classified as: Sep to Nov as fall, Dec to Feb as winter, March to May as spring, and June to Aug as summer.

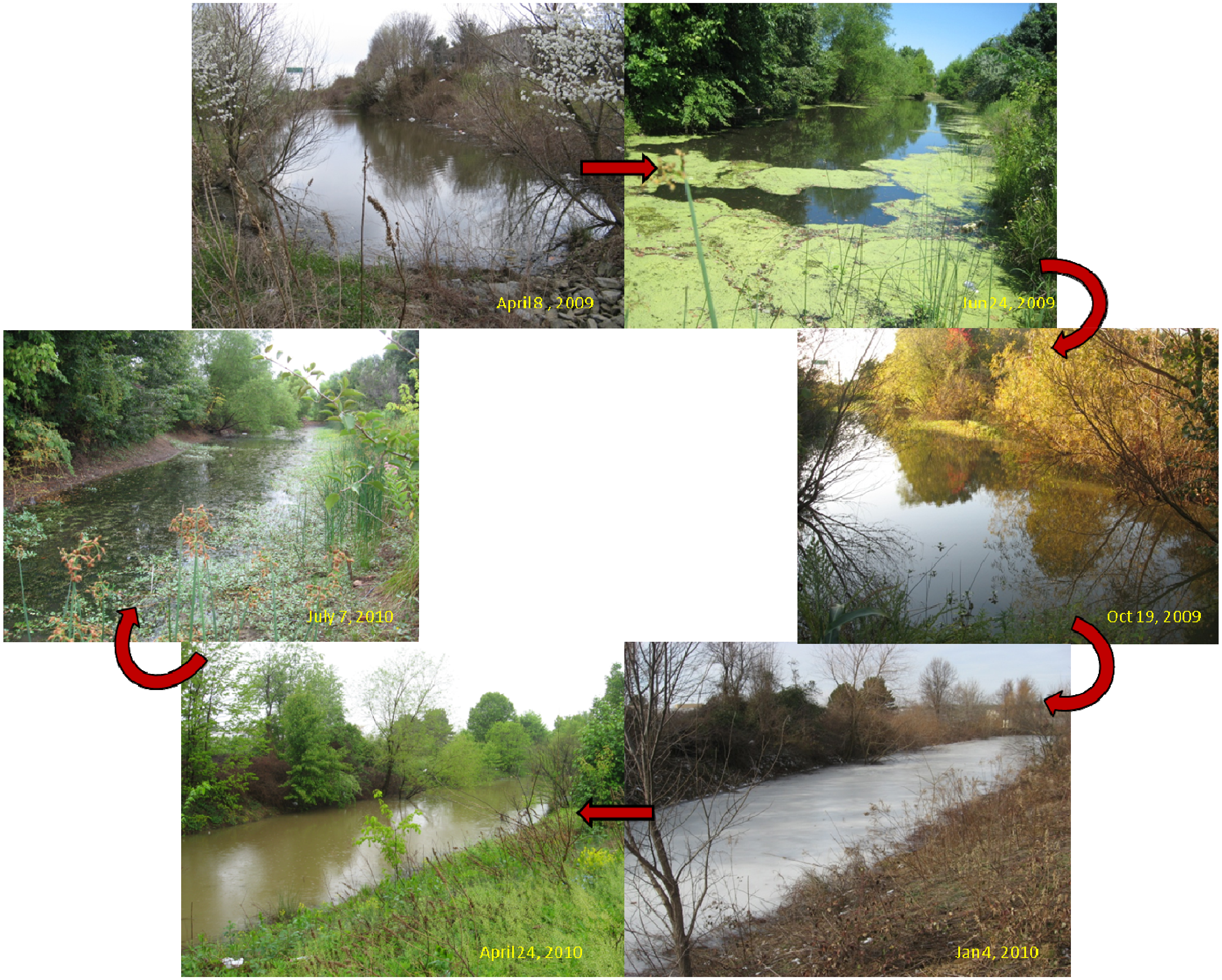


Figure 7. Study BMP from June 2009 through July 2010.

Table 4. Hydrology data recorded at the study site from June 2009 to July 2010.

Event	**Antecedent dry period (days)**	**Rainfall depth (inch)**	**Rainfall duration (hours)**	**Inflow volume $(\times 10^3 gal)$**	**Outflow volume $(\times 10^3 gal)$**
8/13/2009	2	0.94	1.13	28	0
8/21/2009	2	0.64	14.9	11	0
9/26/2009	1	1.28	16.6	47	21
10/15/2009 [a]	17	2.87	71.6	171	133
10/24/2009 [a]	6.3	0.40	8.1	14	12
10/27/2009 [a]	2.1	1.82	33.4	125	146
11/1/2009 [a]	3.4	0.45	12.3	31	17
11/11/2009 [a]	10	1.12	36.6	68	36
11/13/2009 [a]	0.7	0.36	1.93	17	10
11/19/2009	6	0.61	8.5	33	35
11/23/2009 [a]	3	0.83	22.1	86[++]	78[++]
11/25/2009 [a]	0.7	0.17	10.8		
11/26/2009 [a]	0.9	0.12	5.0		
11/30/2009 [a]	3.3	0.22	7.1	9	0
12/2/2009 [a]	1	0.82	19.3	52	63
1/18/2010	16	0.63	13.4	52	73
3/26/2010	3.3	0.31	11.7	9	0
3/28/2010 [a]	2.4	0.5	11	26	13
3/30/2010 [a]	1.3	0.1	3.5	5	0
4/25/2010	4	0.96	15.4	40	13
5/3/2010 [a]	6	0.23	2.7	2	0
5/11/2010 [a]	7	0.20	1.67	0	0
5/12/2010 [a]	1	0.47	1.6	15	0
5/18/2010 [a]	0.5	0.18	9.83	1	0
5/23/2010	4	0.40	3.47	7	0
5/27/2010 [a]	4	0.37	2.3	6	0
6/3/2010 [a]	2	0.25	0.9	0	0
6/28/2010 [a]	19	0.48	0.53	0	0
7/10/2010 [a]	10	0.32	5.37	0	0
7/12/2010 [a]	2	0.55	0.80	3	0

Event	**Antecedent dry period (days)**	**Rainfall depth (inch)**	**Rainfall duration (hours)**	**Inflow volume** ($\times 10^3 gal$)	**Outflow volume** ($\times 10^3 gal$)
7/12/2010	0.25	0.96	1.57	14	0
7/13/2010 [a]	0.75	1.70	7.37	94[++]	51[++]
7/14/2010 [a]		0.11	1.17		
7/18/2010 [a]	4.5	0.17	0.67	0	0
7/25/2010 [a]	6.5	0.39	0.33	0.21	0

[a] Only hydrology data

[++] Flows have been combined since continuous flows occurred during this period.

4.1 Hydrology performance

Hydrology data is available for a total of 31 events to date (Table 4). Typical inflow and outflow hydrographs for the BMP for different storm sizes and seasons are shown in Figure 8. The time of concentration varies between 30 and 40 minutes. The runoff responds to temporal changes in the rainfall intensity during an event.

Overall, the results indicate that the BMP provides hydrological benefits. The BMP assimilated the entire inflow volume and did not produce any outflow for 52% of the monitored events. Peak flow attenuation was observed during several events. The maximum inflow and outflow during an event were compared using the flow peak ratio (R_{peak}) (Davis 2008), which was computed as:

$$R_{peak} = \frac{q_{peak-out}}{q_{peak-in}} \tag{5}$$

For the 31 events monitored, outflow was produced for 14 events only. R_{peak} for these 14 events ranged between 0.05 and 1.2; the mean R_{peak} for these events is 0.56 and the median is 0.52.

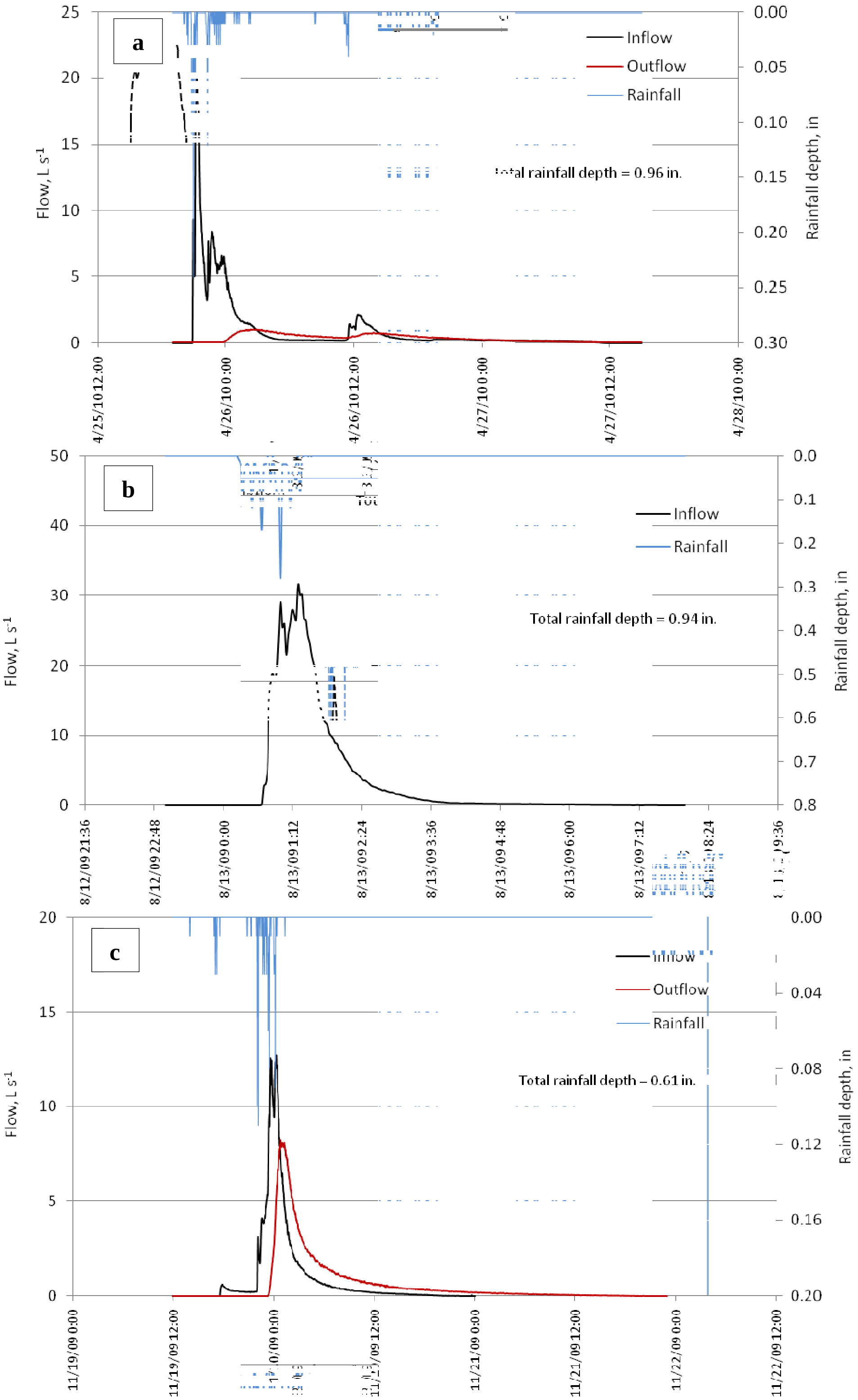


Figure 8. Hydrographs recorded during rainfall events on **a.** April 25, 2010 **b.** Aug 13, 2009 (No outflow) **c.** Nov 19, 2009 at the study site.

The mean reduction in volume achieved through the BMP for 31 rainfall events was 67%. The BMP is capable of detaining the runoff for a period depending on the pre-event storage volume and the inflow volume. Smaller runoff volumes were completely retained in the facility. For events in which outflow occurred, the outflow volumes were lower than the inflow volume for 27 events. The reduction in volume ranged between 9 and 100% for these 27 events. The outflow volumes exceeded the inflow volumes for 4 events. This occurred specifically during large rainfall events and extended wet periods (Oct 26, 2009), or due to snow melt (Jan 17, 2010). For instance, the outflow during the Jan 17, 2010 event exceeded the inflow volume by 28% due to the melting of the frozen water by the runoff flowing through the BMP during this event. The total inflow and outflow volumes for 31 events were 967,926 gal and 702,434 gal, respectively, which is a total volume reduction of 27%.

For the events in which outflow occurred, the BMP was capable of delaying the discharge from the BMP, ranging from four hours up to more than one day after the onset of inflow. The outflow is spread over several hours at low flow rates after the inflow ceases. The decrease in peak flow, delayed outflow, reduced volume leaving the system, and longer outflow recession limb can be seen in the sample hydrographs in Figure 8.

The influence of factors such as rainfall intensity and duration, antecedent dry period, and season on the hydrological behavior of the BMP have been observed throughout the monitoring period. The volumetric flow rates to the system depend on the drainage area characteristics, antecedent dry period, and the rainfall intensity and duration. Figure 11 shows the relation between the rainfall depths and runoff volumes recorded during the 35 monitored events. As expected, there is a strong correlation between the rainfall depth and runoff to the site. The antecedent dry period and season influence the volume of runoff to the site for a given rainfall depth. For instance, few rainfall events, especially June and July 2010 events, produced smaller or no runoff flows to the facility due to long dry periods between events.

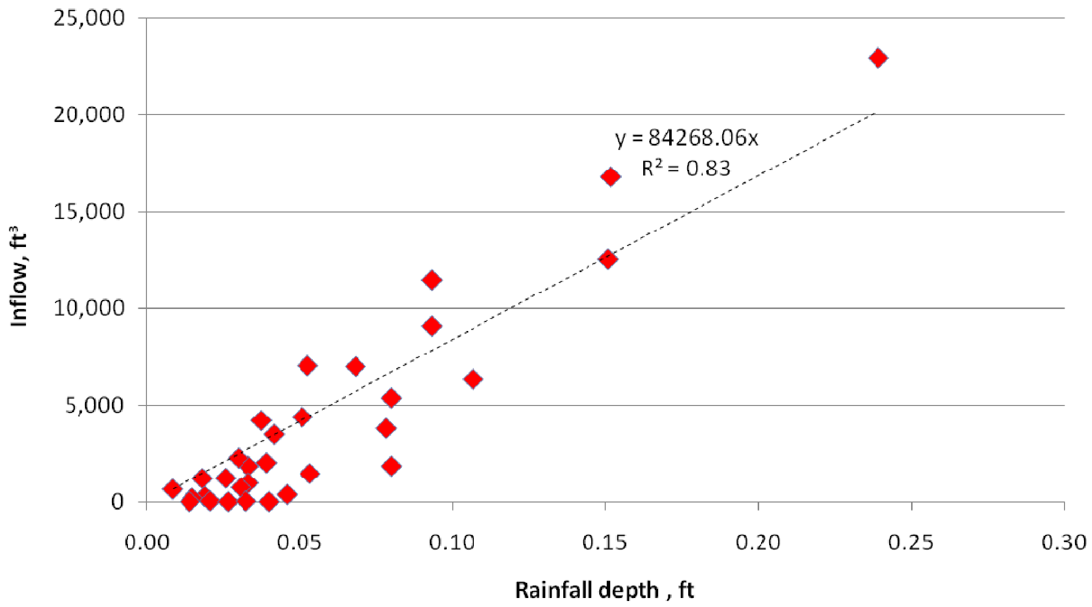


Figure 11. Rainfall-runoff characteristics for the rainfall events recorded at the study site from June 2009 to July 2010.

The dry duration between two events, combined with the effects of evapotranspiration and infiltration from the system influence the volume of water detained in the system. Loss of water by evapotranspiration and infiltration can be important seasonally, especially in summer. Evaporation rates increase as temperatures go up. Higher infiltration rates are expected during warmer periods compared to other seasons (Braga *et al.* 2007). The water level in the BMP was lowered significantly (~ average water level in the basin ~ 1 foot only) owing to very high air temperatures and scant rainfall during summer 2010. Any inflow to the BMP was thus completely captured (Table 4).

The combined effects of the factors discussed can be observed in the hydrographs in Figure 8. Figure 8b is a hydrograph for a late summer event and Figure 8c is the hydrograph of a storm event in winter. While the entire inflow volume was captured for a large event in summer (Figure 8b), outflow occurred for a relatively small event in winter (Figure 8c).

The overall hydrology performance of the BMP was assessed based on the inflow-outflow characteristics during rainfall events of different depths and durations, and seasons. Figure 9 is a plot showing the inflow and outflow volumes recorded during the 31 monitored events. A 1:1 line is also plotted in the figure. The events have been differentiated with different colors based on seasons.

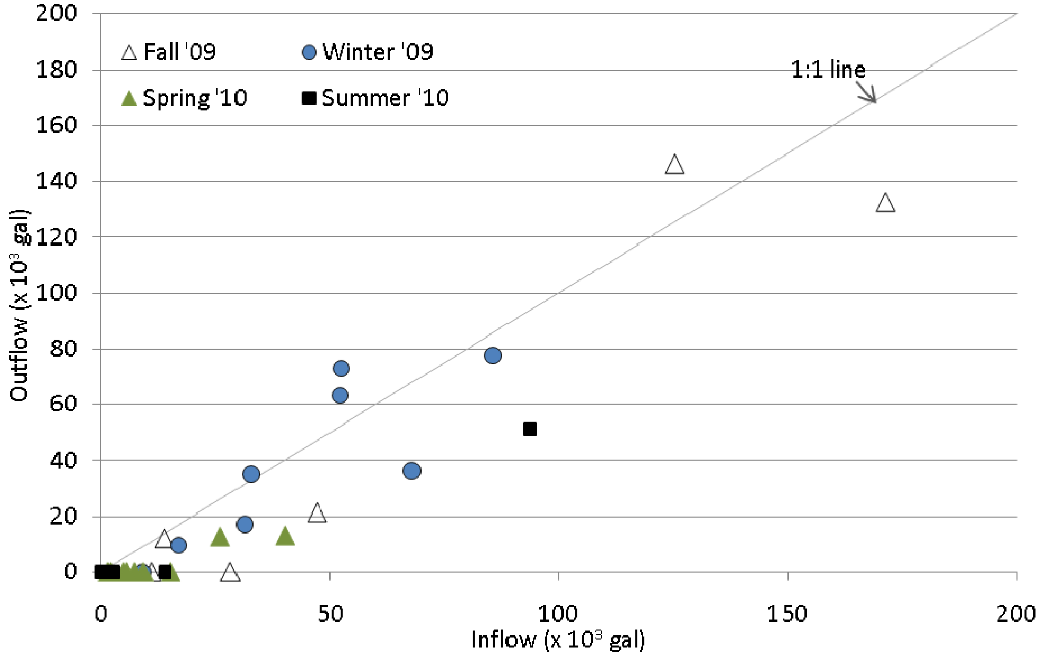


Figure 9. Inflow-outflow characteristics for the rainfall events recorded at the study site from June 2009 to July 2010.

Most of the points lie below the 1:1 line suggesting that reduction of runoff volume was achieved for those events. As expected, the entire runoff volume from smaller rainfall events was detained in the BMP. For the same inflow runoff volume, the reduction in discharge achieved in spring and summer was higher than that in late fall or winter. As mentioned earlier, the outflow volumes exceeded the inflow volumes during certain large rainfall events (1.82 *in* rainfall depth with 33-hour duration) or due to snow melt.

4.1.1 Flow Volume Balance

Accounting for all the water flows and losses in the basin, the volume balance for the system (Figure 1) at any time *t* is:

$$\text{Change in storage}_{(t)} = \text{Inflow}_{(t)} + (PA)_{(t)} - \text{Outflow}_{(t)} - ET_{(t)} - \text{Infiltration}_{(t)} \qquad (6)$$

where, *A* is the surface area of the basin. Inflow, precipitation (*P*), and outflow components are being measured directly at the study site. Evapotranspiration and infiltration losses are required to be estimated.

For simplicity, the ET component is estimated using the Blaney-Criddle formula (Hargreaves and Samani 1982):

(7)

where, ET_0 (mm/day) is reference crop evapotranspiration as an average for a period of one month; p is the mean daily percentage of annual daytime hours, and T_{mean} (°C) is the mean daily temperature. Approximate values of p for the BMP location are tabulated (Table 5). The mean daily temperature can be obtained via web (<http://www.wunderground.com/cgi-bin/findweather/getForecast?query=21045>).

Table 5. Mean daily percentage of annual daytime hours (p) for the study site location.

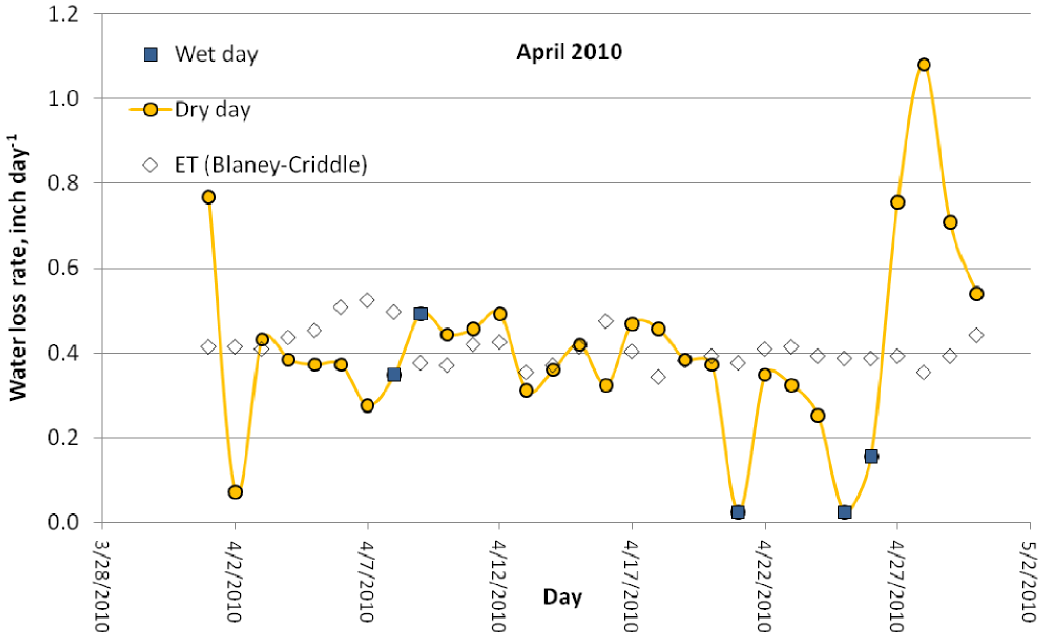
Latitude	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
39.24 N	0.22	0.24	0.27	0.30	0.32	0.34	0.33	0.31	0.28	0.25	0.22	0.21

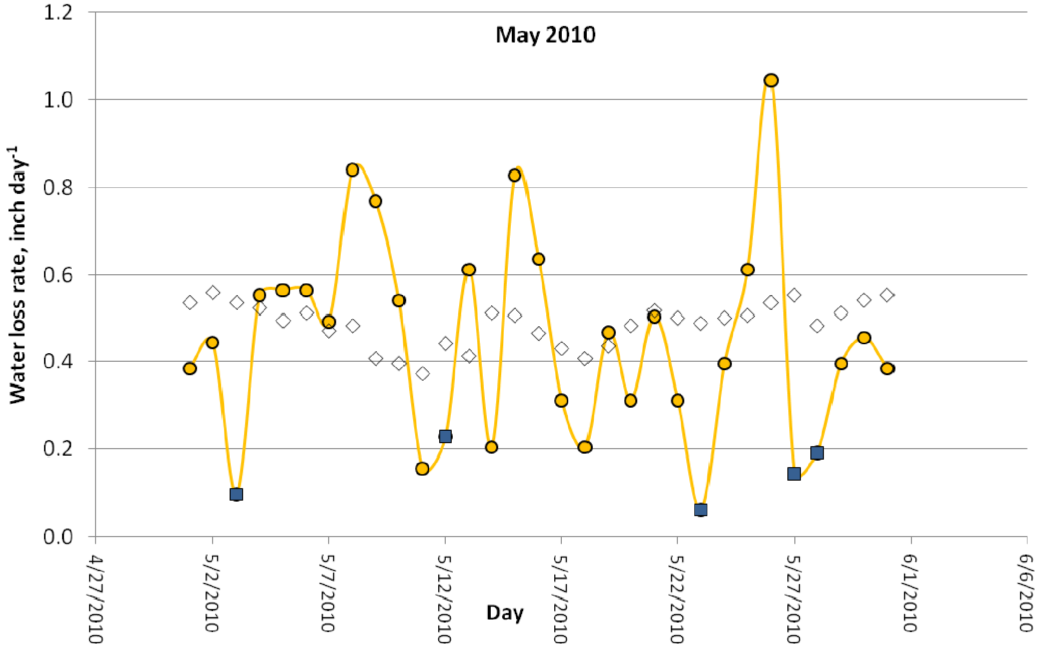
(Source: <http://www.fao.org/docrep/s2022e/s2022e07.htm>)

Currently, all estimates of ET have been performed utilizing the Blaney-Criddle formula. It is proposed to utilize equations developed based on energy balance or mass balance or a combined approach for a more accurate estimation of ET at the study site.

Continuous basin water level data is available from Mar 29 through July 2010, except for a brief period in June when the water level in the pond dropped below the probe until the probe was re-installed at a different location within the basin. The daily rate of water loss from the pond can be determined using the water level data. This total water loss computed is inclusive of ET and infiltration at the site. Since a direct measure of infiltration is not available, the total water loss and ET values can be compared to determine if the infiltration rate is significant in the facility.

The available water level data was utilized to compute the daily rate of loss of water from the BMP. The daily water loss rate is calculated as the drop in water level in 24 hours for a dry day. Figure 10 shows the rate of water loss for April, May, and July, 2010. The evapotranspiration (estimated using Blaney-Criddle formula in Equation 7) is also plotted in the figure. The water loss on a wet day has been differentiated from the dry days (darker square markers in the plot). For a wet day, the water loss is computed prior to the event or after both inflow and outflow cease.


April 2010
Wet day
Dry day
ET (Blaney-Criddle)
Water loss rate, inch day^{-1}
1.2
1.0
0.8
0.6
0.4
0.2
0.0
3/28/2010
4/2/2010
4/7/2010
4/12/2010
4/17/2010
4/22/2010
4/27/2010
5/2/2010
Day


May 2010
Water loss rate, inch day^{-1}
1.2
1.0
0.8
0.6
0.4
0.2
0.0
4/27/2010
5/2/2010
5/7/2010
5/12/2010
5/17/2010
5/22/2010
5/27/2010
6/1/2010
6/6/2010
Day

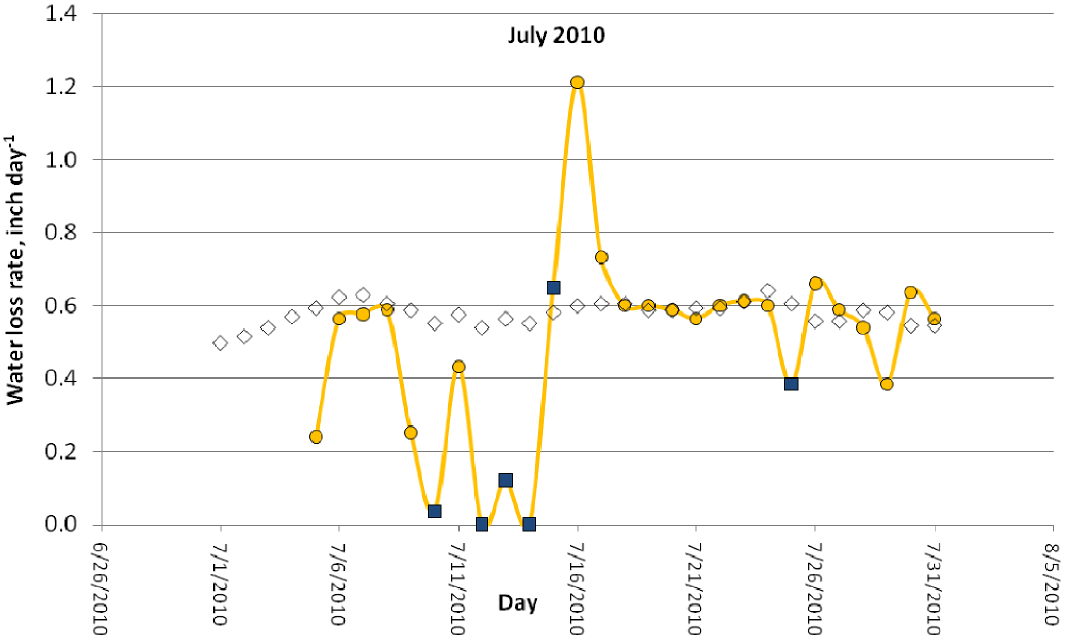


Figure 10. Daily water loss rate in the BMP in April, May, and July, 2010.

The mean of the computed daily loss rates for the dry days were similar for the months in summer; 0.45 inch day^{-1} in April, 0.5 inch day^{-1} in May, and 0.57 inch day^{-1} in July, 2010. The dry-day water loss totals were 11.2 inch in April (30 days), 13 inch in May (31 days), and 11.6 inch in July (27 days). The estimated ET totals (using Equation 7) during the dry periods were 10.3 inch in April, 12.6 inch in May, and 11.9 inch in July. Hence, ET contributed to 92%, 96%, and 100% of the total water loss from the basin during these three months, respectively. Comparing the estimates of monthly total water loss and ET values, it appears that evaporation is the major component of water loss during the dry periods.

Currently, the surface area and side slopes of the basin are not accurately known. Two approaches were used to estimate the area of the BMP, assuming linear length and width (rectangle), and straight (90°) side slopes. First, the water level data were utilized to estimate the approximate surface area of the BMP.

(8)

In Equation 8, is the total volume of water contributed by inflow runoff and rainfall (over the surface area) until outflow occurs. This is divided by the measured increase in the water level in the basin within that period to estimate the approximate area (*A*) of the basin. For no-outflow events, total volume of runoff received (along with rainfall contribution) divided by the corresponding increase in water level was used. The estimated area of the BMP based on seven events is around 0.10 acre (standard deviation, S.D = 0.02 acre).

Secondly, the dimensions of the basin along its length and maximum width were measured using a tape and the area was computed as 0.12 acre. Based on these two estimates, a value of 0.11 acre was used for all calculations involving area of the BMP. This value is approximate and will be updated as more hydrology and survey data becomes available. The water balance computations are subject to change if the value of BMP area changes.

With more hydrology data available, the storage capacity of the basin can be estimated. For a given rainfall amount, the runoff to the site can be estimated a using simple rational formula or curve number. Knowing the water level in the basin prior to an event, the volume of water in the basin can be computed. It can thus be predicted if a given rainfall event will produce outflow from the BMP. The hydrologic behavior of the BMP during different rainfall depths and durations, and seasons can thus be characterized. The hydrologic behavior can then be related to the water quality performance of the BMP.

4.2 Water Quality Performance

The performance of the BMP in treating stormwater runoff has been characterized based on nine storm event and eleven dry-weather samplings. For each event, the sampling program is designed to collect samples spread over the entire hydrograph. Figure 12 shows the hyetograph and hydrographs recorded for the Nov 19, 2009 rainfall event. Also included in the figure are the sampling points and a photograph showing the inflow and outflow samples collected.

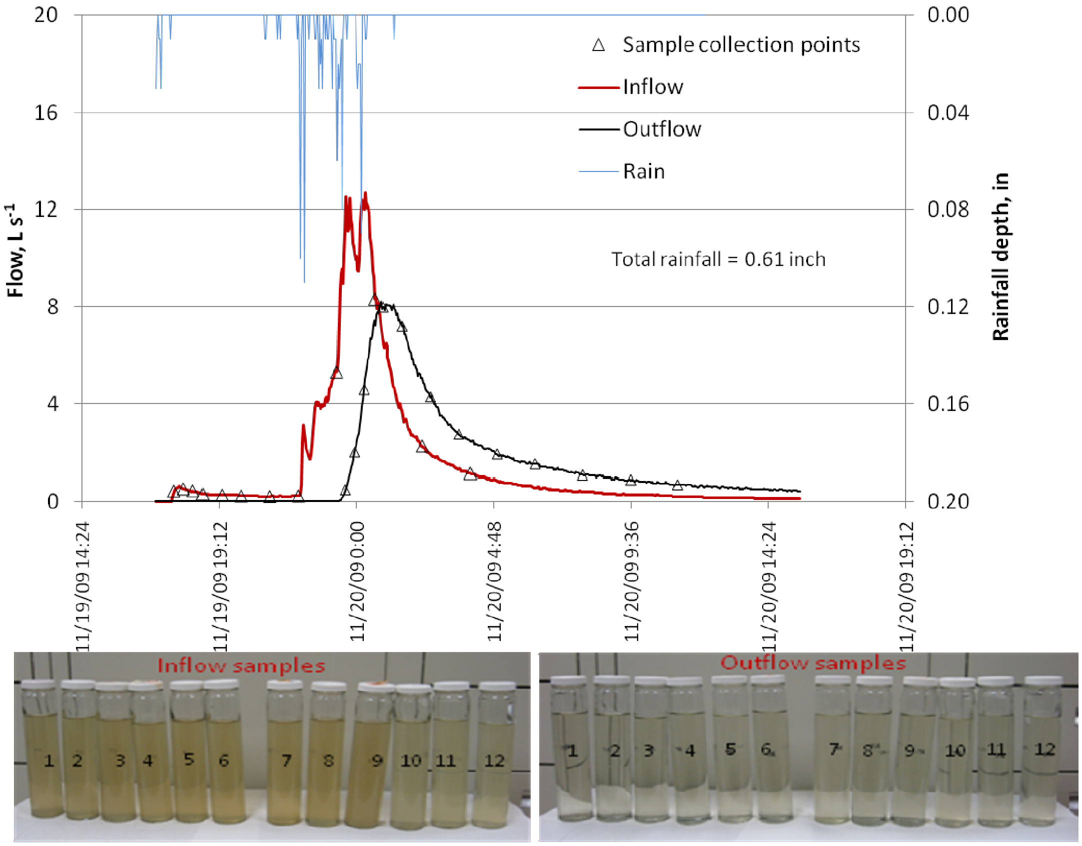


Figure 12. Inflow and outflow hydrographs recorded at the study site during Nov 19, 2009 event. Inlet sampling duration= 10 hours and outlet sampling duration= 12 hours. Photograph shows the inflow and outflow samples collected.

Dry weather samples have been collected from the basin periodically. Samples are collected from different locations in the basin using a swing sampler. At each location, samples are collected from the water column with efforts not to disturb the sediment bottom. Although care was taken to avoid algae or weeds at the pond surface while taking a sample, some samples were found to have some plant material. All water samples were analyzed for the target pollutants. Periodically, the organic content of the collected sediment is also determined. Figure 13 depicts the sampling locations and the samples collected on June 24, 2009.

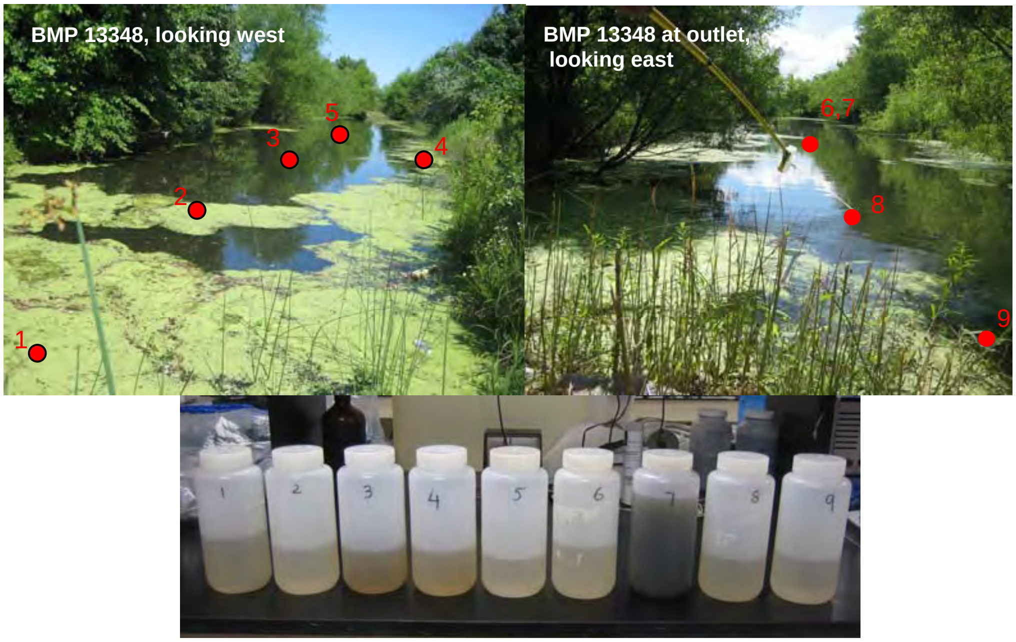


Figure 13. Sampling locations and samples collected during the 24 June, 2009, grab sampling. (Samples 1-6, 8, and 9 are water samples and sample 7 is sediment)

Eight samples were collected from the basin during the first dry-weather sampling conducted in June 2009. Due to the fairly uniform concentration of most water quality parameters in the eight samples, it was decided to collect five or four samples in the following sets.

Of the nine wet-weather sampled events, outflow was produced during four events only. Water quality enhancements during these four events that produced outflow will be discussed in detail. In cases where the entire inflow volume is assimilated by the BMP, the removal efficiency for all target pollutants is 100% for that event. For such events, performance of the BMP will be quantified using results of runoff sampling and grab samples collected from the basin after the event.

The calculated EMCs and percent pollutant mass removal for all target pollutants are summarized for all events in Table 7. Table 2 summarizes the water quality criteria for the target water quality parameters for comparison. For the dry-weather samples, the average concentration in the collected samples, along with the standard deviation has been reported in Table 7.

Table 7. Water quality data of the sampled storm events and dry-weather samples at the study site.

Event	**TSS**			**TP**			**TKN (as N)**			**Nitrite + Nitrate (as N)**		
	EMC$_{in}$ (mg L^{-1})	EMC$_{out}$ (mg L^{-1})	M$_R$ (%)	EMC$_{in}$ (mg L^{-1})	EMC$_{out}$ (mg L^{-1})	M$_R$ (%)	EMC$_{in}$ (mg L^{-1})	EMC$_{out}$ (mg L^{-1})	M$_R$ (%)	EMC$_{in}$ (mg L^{-1})	EMC$_{out}$ (mg L^{-1})	M$_R$ (%)
6/24/2009 Dry-weather	65 ± 75			0.32 ± 0.23			2.5 ± 1.7			0.06 ± 0.0		
8/10/2009 Dry-weather	126 ± 107			0.45 ± 0.16			6.6 ± 4.1			0.08 ± 0.06		
8/13/2009 Storm event	181	0*	100	0.52	0*	100	1.5	0*	100	0.58	0*	100
8/21/2009 Storm event	44	0*	100	0.42	0*	100	2.6	0*	100	0.38	0*	100
9/26/2009 Storm event	39	1	98	0.43	0.06	93	1.5	0.93	72	0.96	0.05	97
10/04/2009 Dry-weather	7.6 ± 2.1			0.10 ± 0.06			1.5 ± 0.3			0.06 ± 0.0		
11/19/2009 Storm event	110	9	91	0.25	0.09	60	1.2	0.70	38	0.26	0.06	76
01/18/2010 Storm event	n/a~	n/a~		0.22	0.19	-16	1.3	0.92	-0.32	0.58	0.34	20
3/25/2010 Dry-weather	14 ± 2.1			0.08 ± 0.0			0.95 ± 0.08			0.07 ± 0.02		
3/26/2010 Storm event	72	0*	100	0.22	0*	100	2.1	0*	100	0.46	0*	100
4/24/2010 Dry-weather	16 ± 3.6			0.08 ± 0.0			1.4 ± 0.14			0.11 ± 0.03		
4/25/2010 Storm event	185	29	95	0.28	0.10	91	1.9	1.1	83	0.29	0.14	85
5/2/2010 Dry-weather	9 ± 1.5			0.08 ± 0.0			1.2 ± 0.3			0.22 ± 0.03		
5/22/2010 Dry-weather	15 ± 11			0.11 ± 0.06			0.49 ± 0.3			0.07 ± 0.03		
5/23/2010 Storm event	52	0*	100	0.34	0*	100	1.3	0*	100	0.18	0*	100
5/23/2010 Dry-weather	11 ± 6.6			0.12 ± 0.05			0.98 ± 0.2			0.06 ± 0.0		
6/15/2010 Dry-weather	6 ± 2.5			0.09 ± 0.01			0.89 ± 0.08			0.10 ± 0.05		
6/27/2010 Dry-weather	17 ± 3.3			0.14 ± 0.03			1.1 ± 0.06			0.06 ± 0.0		
7/9/2010 Dry-weather	44 ± 48			0.19 ± 0.07			2.1 ± 0.43			0.06 ± 0.0		
7/12/2010 Storm event	54	0*	100	0.58	0*	100	0.99	0*	100	0.86	0*	100

Event	Total Pb			Total Cu			Total Zn			Chloride		
	EMC$_{in}$ (μg L^{-1})	EMC$_{out}$ (μg L^{-1})	M$_R$ (%)	EMC$_{in}$ (μg L^{-1})	EMC$_{out}$ (μg L^{-1})	M$_R$ (%)	EMC$_{in}$ (μg L^{-1})	EMC$_{out}$ (μg L^{-1})	M$_R$ (%)	EMC$_{in}$ (mg L^{-1})	EMC$_{out}$ (mg L^{-1})	M$_R$ (%)
6/24/2009 Dry-weather	7 ± 2.7			6 ± 4			23 ± 13			13 ± 0.1		
8/10/2009 Dry-weather	4 ± 2.1			2 ± 2.8			13 ± 0.0			21 ± 0.14		
8/13/2009 Storm event	7	0*	100	11	0*	100	n/a~	0*		22	0*	100
8/21/2009 Storm event	5	0*	100	13	0*	100	55	0*	100	44	0*	100
9/26/2009 Storm event	2	2	48	10	2	93	47	11	90	79	19	89
10/04/2009 Dry-weather	3 ± 0.0			2 ± 0.0			n/a~			22 ± 0.55		
11/19/2009 Storm event	6	4	29	11	4	64	56	43	18	15	12	10
01/18/2010 Storm event	2	2	-28	5	4	-8	43	35	-13	647	522	-10
3/25/2010 Dry-weather	3 ± 0.0			3 ± 0.72			17 ± 9.1			444 ± 19		
3/26/2010 Storm event	6	0*	100	13	0*	100	58	0*	100	449	0*	100
4/24/2010 Dry-weather	3 ± 0.0			1 ± 0.7			13 ± 0.0			562 ± 86		
4/25/2010 Storm event	6	2	90	20	5	93	54	10	94	120	303	21
5/2/2010 Dry-weather	3 ± 0.0			1 ± 0.7			13 ± 0.0			427 ± 33		
5/22/2010 Dry-weather	3 ± 0.0			1 ± 0.93			21 ± 16			339 ± 14		
5/23/2010 Storm event	3	0*	100	16	0*	100	51	0*	100	113	0*	100
5/23/2010 Dry-weather	3 ± 0.0			1 ± 0.6			13 ± 0.0			320 ± 20		
6/15/2010 Dry-weather	n/a*			n/a*			n/a*			297 ± 6		
6/27/2010 Dry-weather	n/a*			n/a*			n/a*			392 ± 10		
7/9/2010 Dry-weather	n/a*			n/a*			n/a*			436 ± 13		
7/12/2010 Storm event	n/a*			n/a*			n/a*			42		100

EMC = Event mean concentration (as defined in Equation 4); M$_R$ = Mass removal efficiency (as defined in Equation 3)

*Entire inflow runoff volume assimilated
n/a Not applicable
n/a~ No data due to lab accident
n/a* Analysis not complete

4.2.1 Total suspended solids

Total suspended solids (TSS) are washed into the basin mainly from the road and by erosion of local soil. During periods immediately after the weir installation and seeding of the soil, it appeared that the TSS load flowing into the BMP was predominantly eroded soil particles from the upstream channel and bare soil on the inlet side of the BMP than particles from the road. The soil erosion has reduced with the subsequent establishment of plant cover.

Figure 14 shows the inflow and outflow sample TSS concentrations for the Nov 19, 2009 rainfall event. Figure 14 shows that the outflow TSS levels were much lower than the inflow levels, which was a common observation during all events. While the EMC of the inflow was 112 mg L^{-1}, the outflow EMC was 10 mg L^{-1} for this event. Outflow occurred six hours after the onset of inflow and during this detention period; most of the solids in the influent runoff should have settled, resulting in a total mass removal efficiency of 90% for this event. As can be seen in Table 7, the outflow EMCs are much lower than those of inflow and the removal of TSS mass through the BMP is significant, ranging from 91 to 100%, for eight rainfall events.

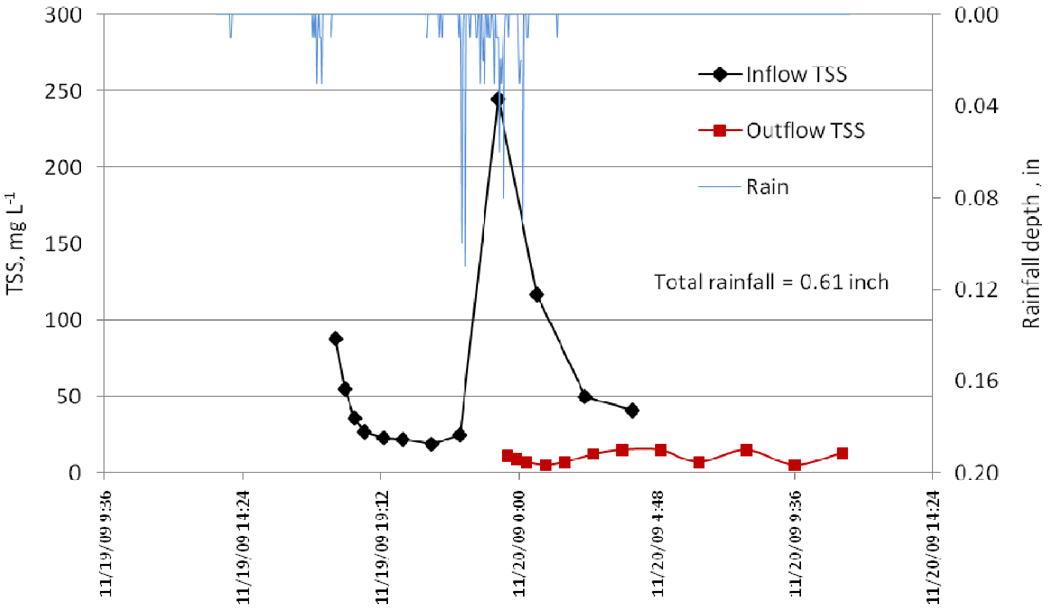


Figure 14. Sample total suspended solids concentrations recorded during the Nov 19, 2009 event at the study site. Figure 12 shows the inflow and outflow hydrographs of this event.

The removal of suspended solids from the runoff by sedimentation is supported by the TSS levels in the grab samples. Based on the data collected so far, water stored in the basin for a relatively long dry period (~10 days) contains a TSS concentration of about 10 mg L^{-1}

(Table 7). The highest inflow EMC of 185 mg L^{-1} was recorded during the April 25, 2010 event. Comparing the pre-event (16 mg L^{-1}), outflow EMC (29 mg L^{-1}), and post-event (9 mg L^{-1}) TSS levels, it can be deduced that some mixing occurred during the event and given enough detention time (one week), the solids settled within the basin.

One observation common to a majority of the rainfall events is the correlation between the inflow TSS concentrations and the rainfall intensity profiles. The solids are flushed when the rainfall intensity and flow rate increase. In all sampled events, the maximum inflow TSS concentration coincides with the peak flow. The flushing effect can be observed in Figures 12 and 14, where inflow sample #9 was collected during a high flow period and contained the highest TSS concentration. No notable flushing of solids is produced in the effluent from the BMP; the TSS concentrations are mostly similar in all samples.

It should be mentioned that some variability were observed in the grab samples on few occasions. The presence of algae or other plant debris seemed to introduce variation in the TSS levels within a sample set (65 ± 75 mg L^{-1} on June 24, 2010). In an another instance, the pond TSS level was relatively high compared to other dry weather concentrations (44 ± 48 mg L^{-1} on July 9, 2010); this was because true water column samples could not be collected as the water level in the pond was less than one foot. Samples with such discrepancies were carefully used towards quantifying the BMP performance.

4.2.2 Nitrogen and Phosphorus

Of most interest is the nutrient (nitrogen and phosphorus) loading to the BMP during various rainfall events and efficiency of the BMP in reducing the loads to acceptable levels. Firstly, inflow NO_x (nitrite- and nitrate-nitrogen) and TKN do not show any particular trend with respect to change in flow rate in the sampled events. The highest concentration in the influent does not necessarily correspond to the peak flow. In some events, the maximum concentration was recorded at the beginning of the inflow to the BMP, before the peak flow occurred. A few other events contained the highest NO_x and TKN concentrations at the peak inflow. No trend was visible in the outflow TN concentration profiles in all the events and the concentrations in all the outflow samples were uniform during an event.

In general, concentrations of the oxidized nitrogen species (nitrate and nitrite) in the runoff were low. In the inflow, individual sample concentrations of nitrite-N ranged between 0.01 and 0.09 mg L^{-1}; nitrate-N concentrations ranged between 0.3 and 1.4 mg L^{-1}, and TKN-N levels ranged between 6 and 0.5 mg L^{-1}. Outflow nitrite-N were always below 0.1 mg L^{-1} and nitrate-N concentrations were around the laboratory detection limit of 0.1 mg L^{-1} in the samples collected during most events (except two events; Jan 18 and April 26, 2010). The outflow samples did contain TKN, mostly less than 1 mg L^{-1} and also lower than the inflow TKN levels.

Figure 15 shows the nitrogen loading to the BMP for a sample event. Total nitrogen (TN) is determined as the sum of nitrogen species: nitrate, nitrite, and TKN (TN = NO_3-N + NO_2-N + TKN-N). Based on the concentration profiles of inflow NO_x and TKN in Figure 15 and the remaining eight sampled events, it can be deduced that TKN (organic and ammonia nitrogen) is the dominant fraction of total nitrogen to the BMP. TKN was found to be the major constituent (~70%) of total nitrogen in urban stormwater runoff by Taylor *et al.* (2005). The outflow TN was predominantly TKN as well in all events.

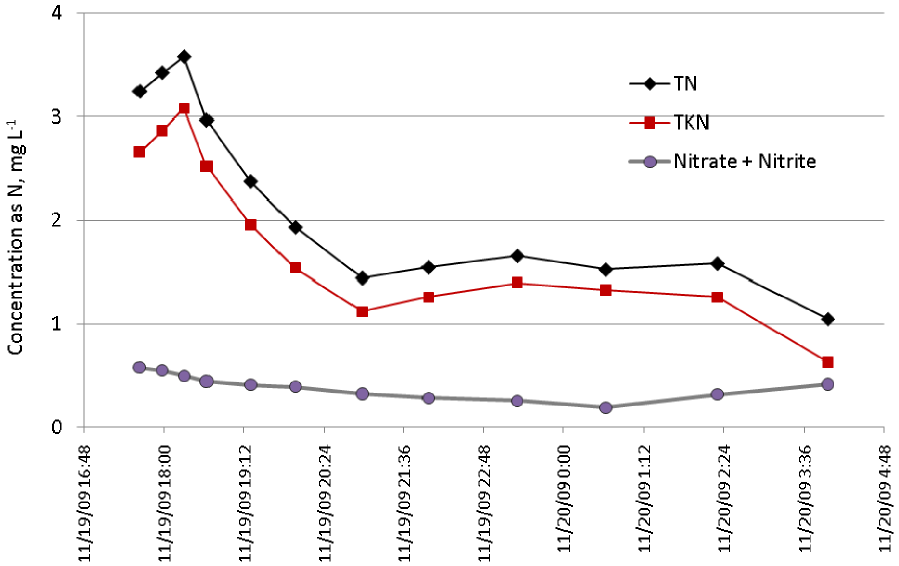


Figure 15. Nitrogen loading to the BMP during the Nov 19, 2009 rainfall event.

Figure 16 shows the profiles of the total nitrogen concentrations in the inflow and outflow on the Nov 19, 2009 event. For this event, the EMC of NO_x of inflow was 0.8 mg L^{-1} and that of outflow was 0.07 mg L^{-1}. TKN was the largest portion of TN in both inflow (~81%) and outflow (~91%). The TN mass removal efficiency for this event was about 44%.

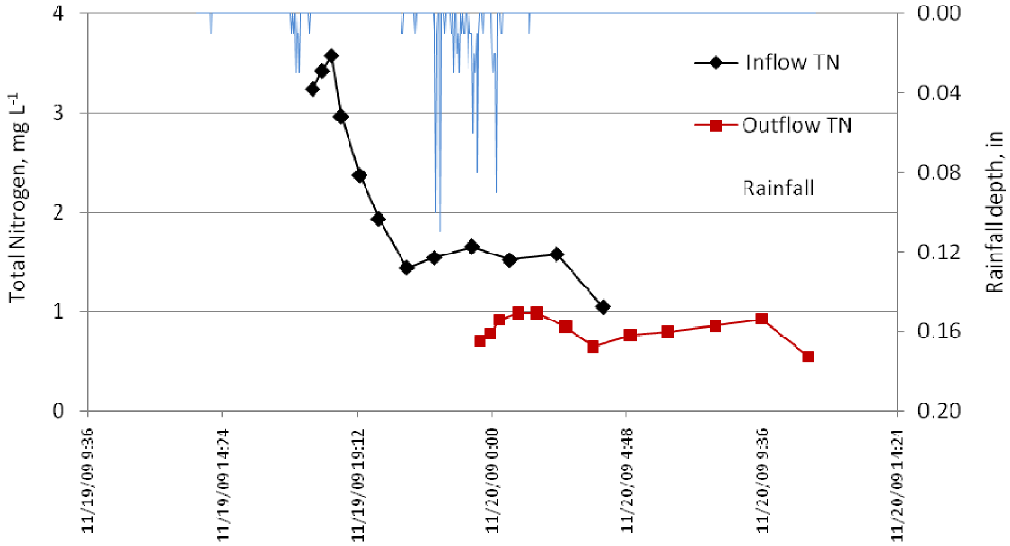


Figure 16. Sample concentrations of total nitrogen during the Nov 19, 2009 event. Figure 12 shows the hydrographs of this event.

Table 7 shows that the NO_x outflow EMCs are much lower than the inflow EMCs. The percent mass removal efficiency for NO_x ranges between 76 and 100% for 8 rainfall events. TKN removal efficiency ranges between 38 and 100%. In eight of the nine sampled events, the inflow EMCs exceeded the water quality criterion of nitrate (0.2 mg L^{-1}) but not nitrite (1 mg L^{-1}) in any event. The outflow EMCs of both nitrate and nitrite are lower than their respective water quality criteria.

The worst removal of the nitrogen species was observed during the winter event Jan 18, 2010. About 23% of the inflow nitrate-N was removed by the BMP, the least removal observed among the nine sampled events. This was the only event during which export of TKN (0.32%) and nitrite-N (25%) was observed. Also, the highest outflow EMCs for NO_x-N was recorded during this event.

The ability of the BMP to process oxidized nitrogen species is supported by the grab sampling data. NO_x levels in the grab samples collected from the BMP before and after an event were below 0.1 mg L^{-1} (Table 2). Following a rainfall event, the runoff mixes with the stored water containing very low NO_x, resulting in low outflow concentrations. The NO_x concentration of the detained water appears to further decrease in the following dry days. Thus, the effluent from the BMP is expected to meet the water quality criteria for NO_x on most occasions. TKN levels in the pond are about the same before and following an event. From these observations, it can be deduced that the BMP receives low NO_x loads and is capable of removing most of the incoming load. However, only moderate removal of TKN is observed.

In the nine storm events, the runoff TP levels were often less than 1 mg L^{-1} which is the lower range of the expected runoff TP levels of 0.5 to 20 mg L^{-1} (Stagge 2006). Figure 17 shows the total phosphorus (TP) concentrations of the inflow and outflow samples collected on the April 24, 2010 rainfall event. A first flush is observed in the inflow runoff. All outflow samples contained lower and similar TP concentration of 0.11 mg L^{-1}. The inflow and outflow TP EMCs were 0.28 and 0.10 mg L^{-1}, respectively, both exceeding the water quality criterion of 0.05 mg L^{-1}. The TP mass removal efficiency of the BMP was 83% for this event.

Table 7 shows the computed TP EMCs for all events. Although the outflow EMCs were lower than inflow EMCs, both inflow and outflow samples exceeded the stringent water quality criterion of 0.05 mg L^{-1} for all storm events. The efficiency of the BMP in removing the TP mass varied between 2 and 100%. Similar to nitrogen, the phosphorus export occurred during the winter storm event (Jan 18, 2010). Also, this event recorded the maximum outflow EMC of 0.19 mg L^{-1}.

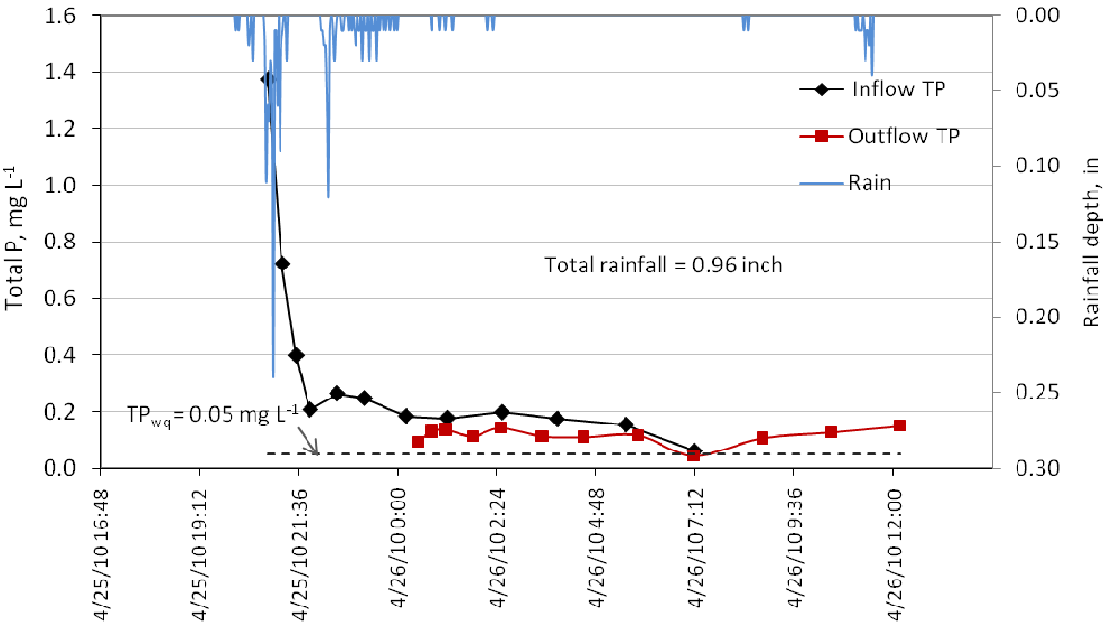
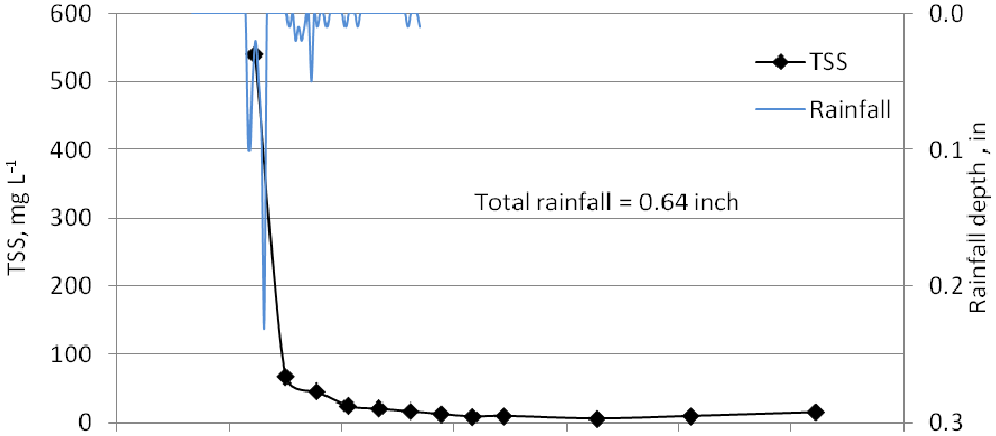


Figure 17. Sample concentrations of inflow and outflow total phosphorus (TP) at the BMP during the Apr 24, 2009 event. Subscript "*wq*" denotes "water quality".

Another observation was that the profiles of total phosphorus (TP) concentrations matched with that of TSS for most events (Figure 18). One possible explanation is that most of the phosphorus is associated with particles rather than being in dissolved forms. Total dissolved phosphorus (TDP) levels have been determined since the April 24, 2010 event only. For this event, no particular trend was noticeable in the runoff TDP profile; the TDP levels were very similar in all inflow samples (~0.08 mg L^{-1}). Outflow TDP levels were below the detection limit of 0.01 mg L^{-1}. More data are required to conclude if most of the TP is particulate.



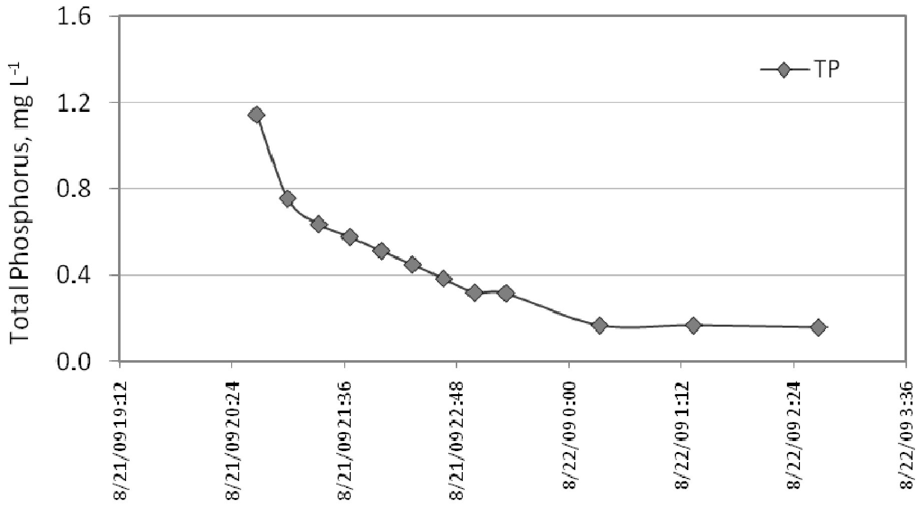


Figure 18. Inflow total suspended solids (TSS) and total phosphorus (TP) concentration profiles recorded during the Aug 21, 2009 event.

The observed outflow EMCs and the background concentration of TP in the BMP during dry weather were about the same (~0.1 mg L^{-1}). Based on the available data set, it can be inferred that most of the particulate TP in runoff was removed during the detention period before outflow began. Subsequent detention should allow other physical and biological actions to remove phosphorus from the water.

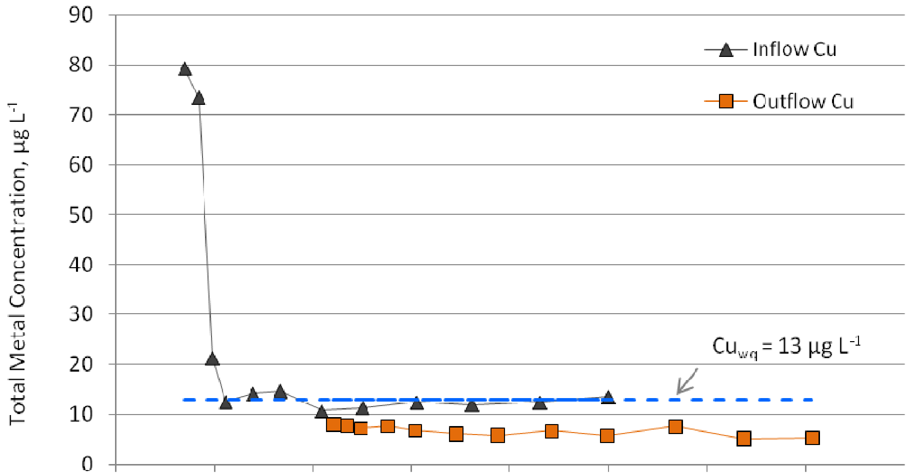
Total dissolved phosphorus (TDP) concentrations were measured in samples from April 2010 (not reported in Table 7). The dissolved forms of phosphorus are the biologically available P species. The grab samples collected showed that the pond TDP levels were almost 50% of the TP levels (between 0.03 and 0.1 mg L^{-1}). As more data are available, the trends of TP and TDP levels in the BMP can be quantified.

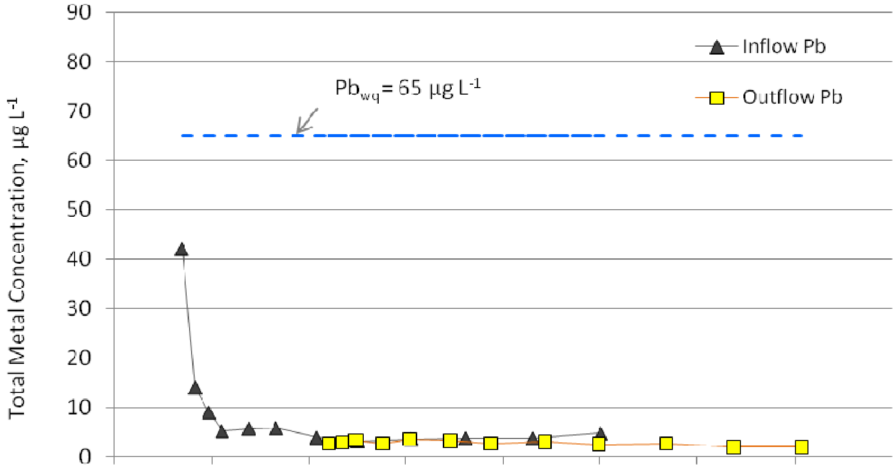
4.2.3 Heavy metals

The total concentrations of the heavy metals copper (Cu), lead (Pb), and zinc (Zn) were determined for all storm event and dry weather sampling. In general, the heavy metal concentrations were low in the runoff. A first-flush behavior was observed in several events (Figure 19). For a given storm event, only the first few samples contained detectable levels of metals (first flush effect), especially lead and copper. The outflow lead and copper concentrations were around or below their detection limits in a majority of the events. Zinc was detected in all inflow and outflow samples (except outflow on Sep 26, 2010).

In the events sampled, although individual sample concentrations (first flush samples only) exceeded the water quality criteria, the inflow and outflow EMCs were lower than the water quality criteria for all three heavy metals, except total Cu EMC of inflow on two events (Apr 25 and May 23, 2010). Runoff sampled during winter and early Spring 2010 contained relatively higher metal concentrations than other events. Accretion of metals in the snow and their subsequent wash off in snowmelt runoff have been observed (Sansalone and Glenn 2002; Glenn and Sansalone 2003). The inflow EMCs were below the water quality criteria for lead and zinc, but not copper during these events. However, the outflow EMCs never exceeded the water quality criteria for any metal. The heavy metals loadings to the BMP were removed during all rainfall events, except on the Jan 18, 2010 event, during which export of metals was observed (Table 7).

It was also observed that the concentration profiles of total copper, lead, and zinc correlated with that of TSS. This is because most of the heavy metals are associated with the suspended solids and can settle out with the solids (Guo 1997; Herngren *et al.* 2005). Removal of metals by sedimentation is supported by the water column concentrations of total metals in the dry-weather samples (Table 7).





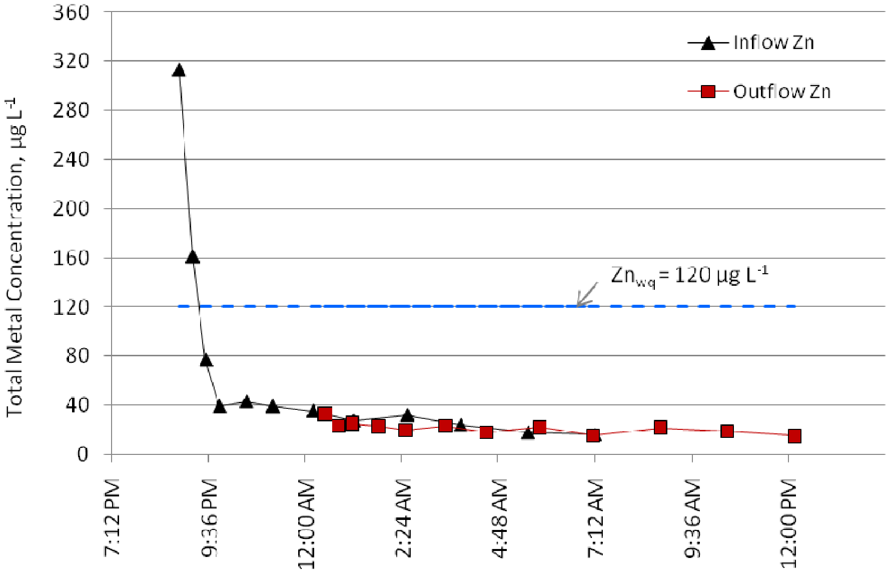


Figure 19. Sample concentrations of total copper, lead, and zinc during the April 25, 2010 event at the study site. The dashed line represents the water quality criteria for each heavy metal (acute; COMAR 2006) (denoted by subscript "*wq*").

4.2.4 Chloride

The chloride concentrations of the inflow, outflow, and dry-weather samples were determined. On an event basis, flushing of chloride at higher inflow flow rates was observed during some rainfall events. However, no such trends were noticeable in the outflow samples, which contained a uniform and lower chloride concentration compared to that of inflow.

The chloride levels in all runoff and grab samples exhibited seasonal trends, as expected (Table 7). From August through December 2009, the inflow chloride concentrations ranged between 20 and 120 mg L^{-1}. Such relatively low concentrations are expected during summer and fall. The chloride concentration profiles were very different during the winter storm events and the following periods. In winter, freezing temperatures and application of road salts for deicing are common. Stormwater runoff from the road surfaces contained high levels of chloride in the January 18, 2010 event (maximum sample concentration = 2445 mg L^{-1}) (Figure 20). Photographs of the frozen BMP and the adjoining highway with applied salt, one day prior to the rainfall event, are also included in the figure. The highest chloride concentrations were recorded during this event; inflow and outflow EMCs were 766 and 631 mg L^{-1}, respectively. The runoff chloride levels decreased in the following seasons as the residual chloride in the soil adjoining the highway were washed off during subsequent rainfall events.

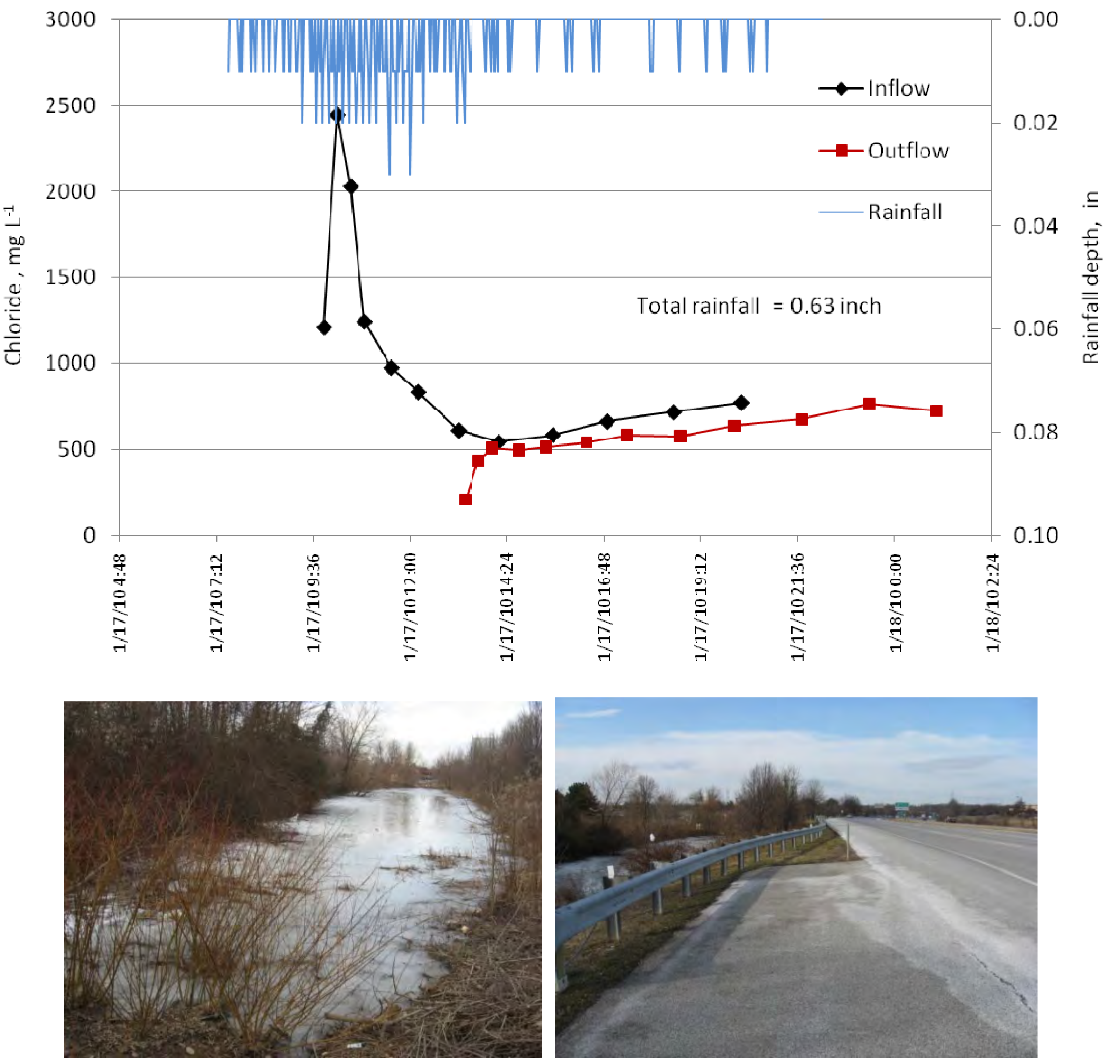


Figure 20. Sample chloride concentrations during the Jan 17, 2010 event at the study site. Photographs show the frozen BMP (left) and adjoining highway (right), one day prior to the event.

Chloride ions remain dissolved in the water and the concentration is expected to decrease by dilution and wash off during subsequent storm events. Chloride retained in the BMP after the winter event was exported during the April 24, 2010 event, as indicated by the higher outflow EMC (Table 7). In summer 2010, the chloride ions concentrated in the water as water was lost from the pond due to evaporation. Figure 21, which shows the chloride levels in the BMP as a function of calendar dates, illustrates these observations. For wet days, the outflow EMC is plotted as the pond chloride concentration.

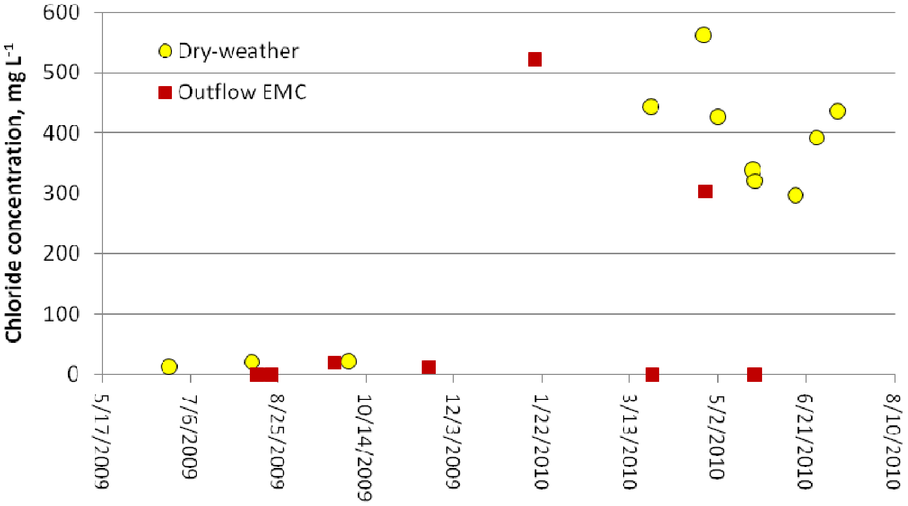


Figure 21. Chloride concentrations in the outflow and dry-weather samples from the BMP from June 2009 to July 2010.

The chloride concentration of the water can be important seasonally, especially during winter. Research by Kaushal *et al.* (2005) has shown long-term increase in chloride concentrations in urban and rural streams of the northeastern US. Stream chloride concentrations as high as 25% of sea water concentrations were reported in this study. The chloride pollution can have several human and ecological implications including potential threats to availability of freshwater for consumption and degradation of aquatic habitat (Kaushal *et al.* 2005).

Due to the relatively high chloride concentrations in the grab samples collected during summer 2010, the total dissolved solids (TDS) levels were determined in the samples collected from the BMP during May, June, and July, and compared to the drinking water standards. TDS in water include inorganic ions such as carbonates, chlorides, sulfates, sodium, calcium, magnesium, etc, and is a secondary measure of the quality of the water. The allowable levels of chloride and TDS in drinking water are 250 mg $L^{-1}$and 500 mg L^{-1}, respectively (National secondary drinking water regulation, US EPA). The mean chloride concentration was 360 mg $L^{-1}$and that of TDS was 700 mg L^{-1} in the samples. The TDS concentrated in the water as water was lost from the BMP by evaporation and no input runoff was received and is expected to be diluted during subsequent runoff flows, i.e., as shown for chloride in June 2010 Figure 21.

4.2.5 Pollutant Mass Load Reductions

The pollutant mass input and output to the BMP was computed for a rainfall event using Equation 9:

$$Mass = EMC \times Flow\ volume \tag{9}$$

The total pollutant mass into and out of the BMP during the entire monitoring period (9 events) is summarized in Table 8. Table 8 shows that the input pollutant loads were removed by the BMP for all the pollutants. The mass removal efficiencies for the entire monitoring duration are TSS 96%, TP

75%, NO_x 76%, TKN 65%, total Cu 80%, total Pb 63%, total Zn 56%, and chloride 14%. Part of this removal is attributed to 39% volume reduction during the 9 monitored storm events.

The annual pollutant mass load per unit drainage area (L_{in}, in *lb ac*$^{-1}$ *yr*$^{-1}$) can be estimated as:

$$L_{in} = \frac{M_{in}}{A} \times \frac{P_{average}}{P_{observed}} \tag{10}$$

In Equation 10, M_{in} is the overall input pollutant mass (in *lb*), A is the drainage area of the BMP (in *acre*), $P_{average}$ is the average annual precipitation [42 in yr^{-1} for the State of Maryland; MDE 2000], and $P_{observed}$ is the observed cumulative precipitation during the monitoring events (in *inches*). The annual pollutant mass discharge (L_{out}) from the BMP can be obtained using output pollutant mass in Equation 10. The annual mass load and discharge for all the water quality parameters are summarized in Table 8.

Table 8. Pollutant mass removal in the BMP for nine storm events and annual pollutant loads and discharge from June 2009 to July 2010.

Pollutant	TSS	TP	Nitrate + Nitrite (as N)	TKN (as N)	Lead	Copper	Zinc	Chloride
Mass in (*lb*)	160	0.61	0.99	2.9	8.0	21	81	399
Mass out (*lb*)	5.9	0.15	0.24	1.0	3.0	4.3	36	342
Annual pollutant mass load, L_{in} (*lb ac*$^{-1}$ *yr*$^{-1}$)	148	0.57	0.92	2.7	7.4	19	75	369
Annual pollutant mass discharge, L_{out} (*lb ac*$^{-1}$ *yr*$^{-1}$)	5.5	0.14	0.22	0.9	2.7	3.9	33	316

The difference between annual input and output masses ($L_{in} - L_{out}$) is the effect of the BMP in reducing the annual pollutant loads. Table 8 shows that the annual pollutant mass discharged from the BMP is much lower than the annual pollutant load to the BMP for all parameters to date. As more data become available, the long-term pollutant mass removal performance of the BMP can be assessed.

4.3 Other Observations

As can be seen in Figure 7, productivity of the BMP changes as the seasons change. In summer 2009, a filamentous algae bloom covered a portion of the pond. Partially and fully submerged plants, and floating macrophytes and other aquatic weeds cover the basin in fall and spring. The pond was completely frozen in winter devoid of any aquatic vegetation. Photographs of the flora and fauna at the site are shown in Figure 22.

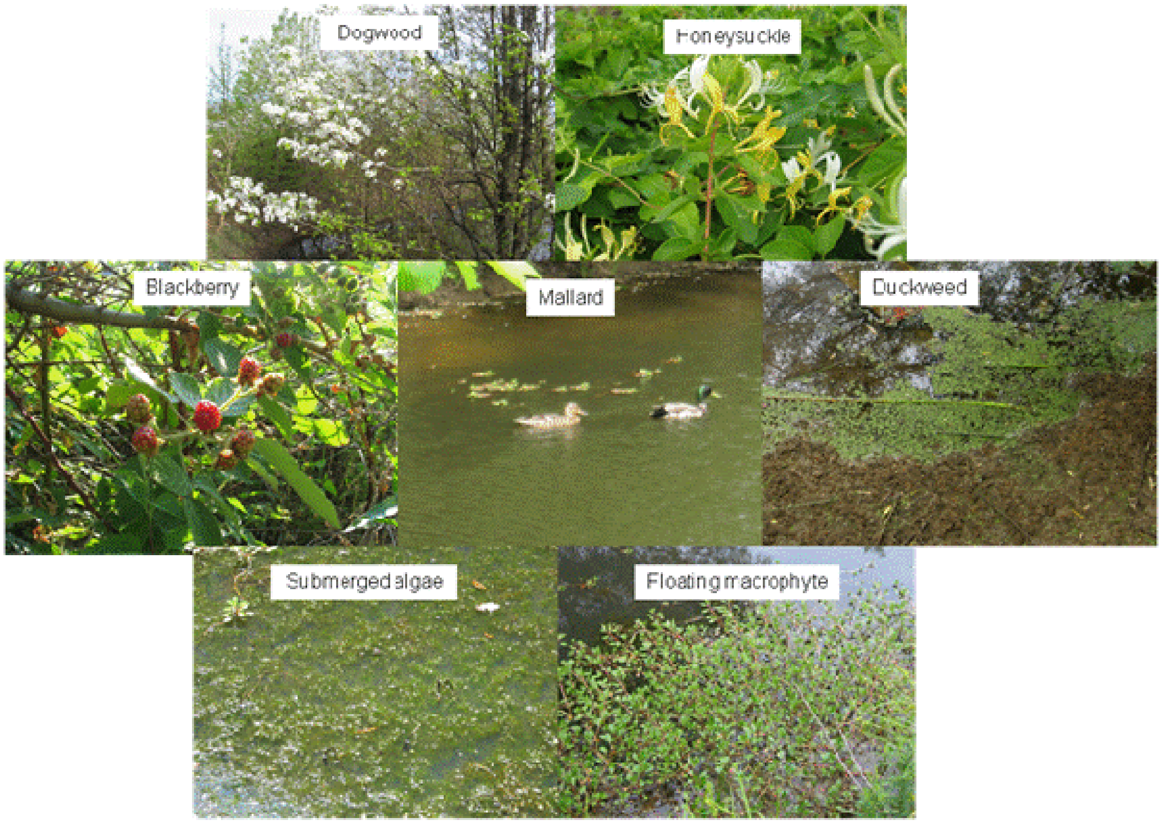


Figure 22. Photos showing the flora and fauna at the site.

Some of the vegetation identified at the site include blackberry, honeysuckle, and dogwood (common names). Macroinvertebrates, frogs, insects, ducks, and birds are some of the fauna observed so far. Photographs of the flora and fauna at the site are shown in Figure 22. Several other woody vegetation and aquatic species are yet to be identified by their names. These observations suggest that the BMP holds habitat value.

4.4 Discussion

The hydrologic behavior of the wet infiltration basin was quantified for 31 rainfall events. Overall, the results indicate that the BMP is capable of mitigating the hydrologic impacts of urban stormwater runoff. The BMP attenuates peak flows, delays outflow, and reduces the discharge volume through detention. The available hydrology data suggest that the response of the BMP to a rainfall event is influenced by factors such as the size and duration of the rainfall event, available storage volume in the basin, incoming runoff rate and volume, combined with the effects of evapotranspiration and infiltration, which can be significant depending on the season.

Improvements in water quality through the BMP are observable during both storm events and dry–weather periods. For most pollutants, the detention time enables mixing and dilution of incoming water with the stored water until outflow occurs. The detention period provides opportunity for the pollutants to undergo transformations via physical, chemical, and biological processes. Wind can also play a role in the mixing of water, especially during non-flow periods.

Settleable and suspended solids in the water are removed via sedimentation during the detention period. Particulate-associated fractions of other pollutants, including phosphorus and heavy metals, are also removed via settling. Further settling will occur during the dry periods between rainfall events.

Nitrogen species in the runoff exist in particulate and dissolved organic and inorganic (NH_4^+ and NO_3^-) forms. Particulates are removed via settling and dissolved forms are removed via biogeochemical reactions in the soil and water column. The runoff samples contained low concentrations of nitrate and almost no nitrite. Most of the incoming NO_x were removed during and after storm events. Under saturated conditions, reducing (anoxic) conditions likely develop in the soil and diffusion of the water into the anaerobic soil favors denitrification to convert the NO_x species to N_2 or NH_4^+-N (Reddy and D'Angelo 1997). Additionally, plants can assimilate N into their tissues and microbes can uptake N for carrying out energy-generating reactions, and hence remove inorganic nitrogen from the water.

While the BMP is effective in removing the inorganic nitrogen species (NO_x), organic portions (TKN = ammonia -N + organic nitrogen) are only partially removed. Since the inflow and outflow inorganic fractions were usually low in concentration, the TN in the samples is mainly in the form of organic nitrogen. Under aerobic conditions, the organic and ammonium nitrogen species are processed to inorganic nitrogen via nitrification. The predominance of organic nitrogen in the water suggests that conditions in the basin limit ammonification and nitrification from occurring at a considerable rate compared to denitrification. Also, decomposition of biomass can contribute organic nitrogen in the basin.

In the samples collected, outflow total phosphorus concentrations were usually lower than the inflow levels, but both exceeded the selected water quality criterion. Phosphorus occurs in dissolved and particulate forms in the runoff. Since a relation between solids and TP concentration profiles was observed in most events, it is possible that the particulate-affiliated P, formed by adsorption and precipitation reactions, settled. The TP and TDP levels in the inflow and outflow phosphorus are available for one storm event only. More TP and TDP data are needed to interpret the main removal mechanism of phosphorus in the BMP.

Phosphorus can also be removed via plant uptake and microbial reactions. Mineralization of plant litter and soil organic-P can release P into the water. Precipitation and dissolution of the nitrogen and phosphorus species are influenced by factors such as redox potential, presence of electron acceptors and donors, pH and temperature of the sediment and water.

Based on the data collected to date, the BMP is effective in removing metals from the runoff. It should also be noted that the incoming runoff carries relatively low concentrations of the metals itself (EMCs of total Cu < 20 µg L^{-1}; total Pb < 7 µg L^{-1}; total Zn < 58 µg L^{-1}). Metal removal is mainly by binding to sediments and soils, precipitation as insoluble salts, and uptake by plants and bacteria. The data suggest that sedimentation is the predominant mechanism of metal removal in the BMP.

Chloride concentrations are of most interest in winter, when high levels are expected due to regular application of deicers to melt ice and snow on the highway. As expected, high chloride levels were sampled during winter and subsequent rainfall events. Chloride data can be utilized to determine the detention time and mixing characteristics of the basin. The results can be applied to investigate dissolved forms of other pollutants of interest.

The hydraulics and treatment efficiency of the BMP showed seasonal difference. Evidence of reduced performance of stormwater ponds during winter compared to summer can be found in several research studies (Oberts 1994; Marsalek 2003; German *et al.* 2003; Semadeni-Davies 2006; Vollertsen *et al.* 2009). The BMP will be biologically more active in warmer periods. As temperatures drop, biological activity tends to slow down. During freezing temperatures, the BMP is expected to act as a flow-through system and providing least benefits. The poor removal efficiency, especially nutrients, was evident in the winter storm event.

5.0 Summary

The goal of this research study is to qualitatively and quantitatively evaluate through field study the performance of a failed wet infiltration basin in treating highway stormwater runoff. The study BMP has been selected and the site has been equipped with instruments to monitor and record rainfall, flows to and from the BMP, and to collect runoff samples during and subsequent to rainfall events. Hydrology data are available for 31 rainfall events, of which 9 events have been sampled for water quality. Additionally, dry-weather samples have been collected periodically.

The hydrology data indicate that the BMP has the ability of mitigate stormwater runoff flows. Peak flow attenuation, delayed outflow response and reduced discharge volumes are observed during all events. As more hydrology data become available, responses of the BMP to varying rainfall intensities, antecedent dry periods, and seasons will be characterized. Relationships between hydrology and pollutant treatment can thus be established.

Storm event samples and dry-weather samples have been analyzed for TSS, nutrients, and heavy metals concentrations. Based on the results obtained, outflows from the BMP meet the selected criteria for most water quality parameters. The BMP is effective in removing TSS, nitrate, nitrite, and metal loads. While the outflow mean pollutant concentrations of TSS, nitrate, nitrite, and total metals satisfy their respective water quality criterion, total phosphorus concentrations exceed the selected water quality criterion during all events.

High removal efficiency of the total suspended solids from the runoff suggests removal of particulate-bound fractions of nutrients and metals as well. Sedimentation appears to be the main removal mechanism based on this observation. However, more flow and water quality data are needed to determine the characteristics of the pollutants (dissolved vis-a-vis particulate), main removal mechanisms, and hence characterize the BMP treatment potential.

Thus, research and performance information obtained from this study will determine the functionality of these wet infiltration basins in managing roadway runoff. If these basins are found to be providing adequate water quality improvement and controlling the hydrology as they exist, then they need not be treated as "failed" BMPs. As long as their performance is acceptable from a stormwater management perspective, these systems should be permitted to remain.

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FIELD EVALUATION OF WET INFILTRATION BASIN TRANSITIONAL PERFORMANCE

APPENDIX D

Final Progress Report:

Nutrient Removal Optimization of Bioretention Soil Media

NUTRIENT REMOVAL OPTIMIZATION OF BIORETENTION SOIL MEDIA

Final Progress Report: Nutrient Removal Optimization of Bioretention Soil Media

Project Duration:	August 2008 – September 2010
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Project Sponsor:

Karen Coffman
Highway Hydraulics Division
Maryland State Highway Administration
707 North Calvert Street C-201
Baltimore, MD 21202

Project Coordinators:

Allen P. Davis, PhD, P.E
Professor
Sean W. O'Neill
Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Maryland
College Park, MD 20742

NUTRIENT REMOVAL OPTIMIZATION OF BIORETENTION SOIL MEDIA

NUTRIENT REMOVAL OPTIMIZATION OF BIORETENTION SOIL MEDIA

EXECUTIVE SUMMARY

Specifications for bioretention soil media (BSM) vary markedly among jurisdictions, even within the state of Maryland. Optimization of media design was investigated for pollutant capture, with a focus on the nutrients phosphorus and nitrogen. A review of current literature and critical analysis of amendment options based on treatment capacity, cost, and local availability led to the selection of aluminum water treatment residual (WTR) as a candidate BSM amendment for phosphorus capture and retention. Use of WTR amendment, coupled with other measures such as vigorous facility vegetative cover, is hypothesized to be ideal for nutrient removal from stormwater in bioretention facilities.

Sorption isotherms were first developed to determine the appropriate BSM amendment content for effective and long term phosphorus capture, found to be approximately 5% WTR by weight. Hardwood bark mulch (HBM) was investigated as an organic matter amendment and shown to potentially increase BSM P capture further. Media were further investigated under both continuous and intermittent flow conditions in small (6 in.) columns to more accurately characterize P adsorption as expected to occur within a bioretention system. These studies supported the conclusions formed during the batch studies, although total media P adsorption capacity was reduced under the column flow conditions. Additionally, adsorption was further decreased when media were subject to intermittent flow.

Final tests involved media investigation utilizing a mesoscale (3 ft. height) vegetated column. Final selected experimental media consisted of 75% sand, 10% silt, 5.8% clay, 5.2% WTR, and 3.4% bark mulch (air dry mass basis).This media showed excellent P removal relative to a non-WTR-amended control media. Whereas the control media leached P (71.1% increase in mass), the experimental media adsorbed 85.7% of the P mass applied, displaying a cumulative effluent EMC of 16.1 μg/L, below the selected 25 μg/L goal.

It is recommended that media should have a measured oxalate ratio of at least 20 to 40 (PSI ≤ 2.5 to 5%) to achieve the desired P adsorption capacity. Based on average reported WTR characteristics, this should be equivalent to an amendment of approximately 5 to 10% (air dry mass). Amending the BSM may be accomplished during initial bioretention cell installation or via the retrofit of existing systems. Retrofits are envisioned to be possible through the surface application and incorporation by rototilling of WTR into the soil to a depth of ⅓ to 1 ft. Assuming a BSM bulk density of 93.6 lb/ft^3, this is equivalent to an application of 1.54 to 9.22 lb/ft^2 (air dry mass).

NUTRIENT REMOVAL OPTIMIZATION OF BIORETENTION SOIL MEDIA

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Chapter 1: Introduction

Non-point source pollution continues today to be a challenge that needs addressing by engineers, scientists, and regulators. As land development continues and the size of urban conurbations continues to increase, so do the associated impervious areas such as roads, parking lots, and roofs. Urban stormwater runoff from such areas, and the concomitant flux of pollutants to surface water bodies, is an especially pressing issue that requires attention because of the negative impact pollution from such sources has on receiving water bodies. Low Impact Development (LID) is a development ideology whereby these increases in impervious areas are counterbalanced by providing for on-site green spaces and other areas that attempt to maintain the pre-development hydrology of an area. One LID technology, which also happens to be an EPA Best Management Practice (BMP), that is implemented as a means to reduce runoff pollution discharges is bioretention. Also known as biofiltration or rain gardens, these facilities are effectively shallow depressions filled with sandy media into which runoff is directed (Figure 1-1). This interception of runoff prevents direct stormwater migration to surface waterways, increases groundwater infiltration, and improves water quality.

Although ongoing research concerning the design and performance of bioretention facilities leads to continued improvement, bioretention remains an immature technology with a number of concerns and issues still to be resolved. Prominent among these is the development of a bioretention soil medium (BSM) locally optimized to reach treatment goals, as specifications are inconsistent jurisdictionally. Even within the state of Maryland there is little consensus.

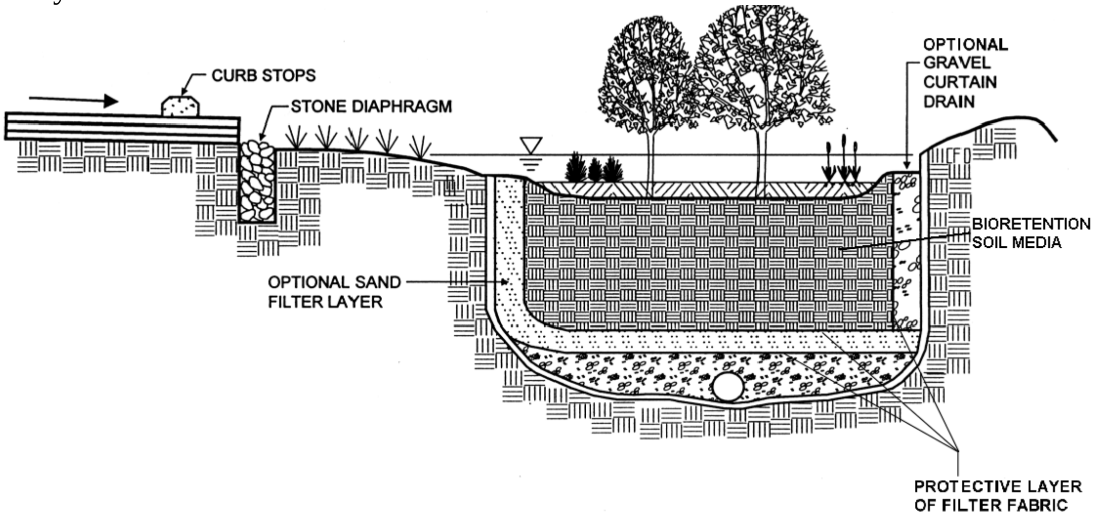


Figure 1-1. Schematic representation of a typical bioretention facility. Adapted from MDE, 2000.

Regardless of the medium employed, previous bioretention research has shown effective removal of suspended solids, oil and grease, and particulate metal species (e.g., Davis et al., 2001; Bratieres et al., 2008). While some work has already been undertaken, a means of improving the highly variable removal of dissolved phosphorus and nitrogen species is still necessary. This is because these nutrients lead to the development of eutrophic conditions in surface waters; when excess nutrients produce explosive growth of photoautotrophic organisms such algae, the death and decomposition of which leads to dissolved oxygen depletion with concomitant negative ecosystem impacts. Eutrophication is estimated to cost the United States over $2.2 billion every year from recreational and drinking water losses, decreased waterfront property values, and expenses related to threatened/endangered species habitat recovery (Dodds et al., 2009).

1.1. Research Goals

In many surface water ecosystems, P is the limiting nutrient (Schindler et al., 2008; Smolders et al., 2010). Therefore, it is believed that eutrophication may be reduced or even eliminated in some systems by effective control of this nutrient. Bioretention may be used as one means of reducing the P load to urban runoff-impacted waters through the development of a BSM to efficiently capture P. Research has shown that traditional BSM performs adequate to poor for P removal from incoming stormwater (Hunt et al., 2006; Bratieres et al., 2008; Li and Davis, 2009). Because P mobility is controlled by Al and Fe species in acidic soils (McGechan and Lewis, 2002), the addition of sufficient Al or Fe to the BSM is expected to produce a media with the ability to adequately remove P from stormwater. This BSM will be a sandy loam, loam, or loamy sand amended with aluminum-based drinking water treatment residual (Al-WTR) and possibly an appropriate organic amendment.

It is hypothesized that Al-WTR will perform ideally in the relatively acidic soil environment of the east coast of the United States (Elliott et al., 2002). Greatly improved P retention capacity in BSM may be provided without compromising media hydraulic conductivity by augmentation with WTR, a byproduct of drinking water treatment. Al-WTR is generated when alum (aluminum sulfate) or a similar compound is added to drinking water as a coagulant. The sulfate and aluminum dissociate in solution and the aluminum forms aluminum (hydr)oxide. Aluminum (hydr)oxide interacts with suspended colloidal material to alter particle net surface charge and mitigate repulsive forces, leading to the formation of flocs which precipitate from the water column. This settled material, upon removal from the settling tank and dewatering, is classified as WTR. It has a very high potential for P adsorption because of its large amorphous (i.e., poorly crystalline) aluminum (hydr)oxide content.

Many other materials were reviewed as potential BSM amendments, including coal combustion fly ash and steel slag, but were decided to be inappropriate because they operate mainly through Ca-P complexation, which performs optimally in an alkaline environment. Also, iron-based WTR was considered, but rejected because of the scarcity of use in the Baltimore-Washington corridor, as well as the potential for iron to release all adsorbed P under subsurface reducing conditions.

An organic amendment is also necessary as such organic matter imparts important qualities to the medium. While some organic materials may mineralize and release P, others have been noted in the literature to enhance P adsorption (Borggaard et al., 2005; Guan et al., 2006; Kang et al., 2009), probably by serving to retain moisture and prevent crystallization of amorphous metal oxides (i.e., aluminum hydroxide). An organic matter with high carbon content and relatively small amounts of N and P is hypothesized to be ideal for moisture retention without ultimately leading to increased nutrient leaching. Additionally, this material will provide a carbon source for microbiological activity within the bioretention cell, further enhancing stormwater nutrient treatment.

A small but carefully selected group of organic materials including shredded hardwood bark mulch, wood chips, leaf compost, and newspaper was reviewed with respect to their ability to retain soil moisture and the effect of their addition on P adsorption. Bark mulch was selected as an ideal organic amendment as it was expected to minimally affect P adsorption due to its high C:N:P ratio (see Section 2.4.1). Leaf compost, conversely, should have a very low C:N:P ratio, ultimately causing reduced phosphorus adsorption, and was chosen for investigation to provide a negative control for the effect of organic matter amendments on the P adsorption capacity of BSM.

Development of the enhanced-P BSM progressed in three phases. Initially, P sorption isotherms for mixtures containing various amounts of WTR, sand, and differing organic amendments were derived to determine the optimal component ratio for P capture. Pure aluminum hydroxide was also used as an amendment for comparison purposes. The specific focus for all isotherms was on equilibrium with P at low solution concentration (120 μg/L), because of the low P concentrations typically found in urban stormwater. This differs from the main body of published research in the field of stormwater P capture using soil amendments, which primarily are focused on situations in agriculture subject to much higher P concentrations. These concentrations depend on fertilizer types and application rates, but may be upwards of 3 mg P/L (Sharpley et al., 2003).

Based on the results of the phase 1 isotherm studies, selected mixtures were investigated in small-scale (6 in.) sealed upflow columns undergoing continuous flow or intermittent (wet/dry) cycling. The third and final phase involved the selection of an optimal BSM mixture based on Phase 2 results. Performance of this mixture was evaluated in a vegetated mesoscale (3 ft.) gravity-flow column fed a suite of nutrients. Additionally, in an effort to develop BSM performance criteria with respect to P adsorption capacity, operationally defined amorphous Al and Fe extracts of all media were taken and analyzed for Al, Fe, and P.

Chapter 2: Literature Review

Much work already exists concerning the evaluation of hydrologic and pollutant treatment capabilities of bioretention facilities. Additionally, a large body of work has been published concerned with improving these capabilities through media and configuration adjustments.

2.1. Hydrologic Performance

Contributing toward maintaining or returning a site's hydrology to a predevelopment state through increased infiltration of stormwater is one of bioretention's major advantages. Accordingly, this necessitates media which provides a high hydraulic conductivity (Hsieh and Davis, 2005). Storage is also a benefit of bioretention. Storm events of sufficiently small size may produce no outflow from the system, leading to reduced loading of the receiving waterbodies (Davis, 2008). Through increased infiltration and reduced surface runoff, bioretention as a technology helps to mitigate waterway peak flows by delaying the peak and redistributing the stormwater volume more equally over a given time period. This more closely mimics the behavior of undeveloped land, where water flows are slowed by natural meandering, infiltration, and vegetation, leading to reductions in stream erosion (Davis, 2008).

2.2. Pollutant Removal

2.2.1. Particulates

Excellent removal of particulate and particulate-bound pollutants has been shown, including total suspended solids (TSS); metals such as Pb, Cu, Zn, and Cd; particulate organic nitrogen (PON), and phosphorus (P). TSS has been shown to be removed predominantly in the surface mulch layer and upper soil profile of bioretention cells (Li and Davis, 2008a; 2008b). Both metals and P, when particulate associated, are captured via the filtration mechanism of the soil and mulch much the same as TSS. In fact, work has shown that effective removal of particulate contaminants takes place in approximately the top 8 in (20 cm) of the bioretention media (Li and Davis, 2008a; 2008b). In this same research, Li and Davis (2008a) recommend a media depth of only 8 to 16 in (20 to 40 cm) to effectively remove particulate-associated pollutants.

2.2.2. Dissolved Species

Capture of dissolved species within bioretention media often depends on adsorption and complexation mechanisms to immobilize pollutants. Dissolved metals are often captured within a bioretention cell when they bind to organic material such as the mulch top dressing and organics within the BSM (Davis et al., 2001).

Dissolved organic nitrogen (DON) and ammonium (NH_4^+) may be removed by adsorption to charged soil particles. However, these compounds are microbially degraded in aerobic environments to the oxidized nitrogen (NOx) species nitrite (NO_2^-) and nitrate (NO_3^-), and may even be produced through breakdown of the organic portion of the BSM. These NOx species are soluble and readily leach through soils (Dietz and Clausen, 2005; Hsieh et al., 2007b; Bratieres et al., 2008). NOx leaching has been prevented through the establishment of effective vegetative cover (Bratieres et al., 2008; Read et al., 2008), and by installing saturated anoxic zones in the media to promote denitrification of NOx to nitrogen gas (Kim et al., 2003; Hunt et al., 2006; Zinger et al., 2007). Additionally, research has shown that such saturated zones contribute to improved metals retention. They maintain a higher soil moisture content, thereby lessening organic matter (OM) mineralization and soil aggregate drying. This leads to reduced metal loss by preventing the generation and washout of particulate OM and fine soil particle associated metals (Blecken et al., 2009).

Dissolved P, similarly, is often not just uncaptured but may be produced through the degradation of organic material associated with the bioretention media (Hsieh et al., 2007a; Bratieres et al., 2008), leading to inconsistent removal among different facilities. Additional variables may also impact bioretention media performance such as the available media capacity to adsorb P (see Section 2.4.2). Davis et al. (2006) reported effluent TP concentration reductions for two field sites in MD of 65 and 87%. Hunt et al. (2006) reported TP mass loading reductions of 65 and -240% for two field sites in NC. For two sites in Melbourne, Victoria, Australia and McDowell, Queensland, Australia, Hatt et al. (2008) reported TP mass loading reductions by the facilities of -398 and 86%, respectively. These results exemplify the extreme variability in P removal from stormwater by bioretention facilities.

Sufficient vegetative coverage and the selection of appropriate plant species have been found to greatly control P and N mobility through uptake. Significant differences in nutrient uptake have been found among plant species, making selection of utmost importance (Lucas and Greenway, 2007; Read et al., 2008). For instance, Lucas and Greenway observed unvegetated bioretention mesocosoms retaining 14 to 56% of the applied P mass, depending on the media employed. The same experiments conducted with vegetated media displayed P mass retention of 44 to 92%, an increase in retention relative to the unvegetated media of 28 to 36%. Media amendments also have been investigated to promote P capture within facilities. Zhang et al. (2008) investigated the incorporation of coal combustion fly ash into a sand-based BSM (98% sand) for P immobilization. They reported mass load reductions of 66 and 85% for BSM amended with 2.5 and 5% fly ash (air dry mass).

2.3. Pollutant Concentrations

The U.S. EPA Nationwide Urban Runoff Program reported an average urban stormwater concentration of 0.33 mg/L phosphorus (TP), of which 120 μg/L is soluble (SP). This equates to 64% of phosphorus in stormwater being in particulate form (US

EPA, 1983). They also reported that stormwater, on average, contains 1.5 mg/L total Kjeldahl nitrogen (TKN) and 0.68 mg/L oxidized nitrogen species (NOx). The Metropolitan Washington Council of Governments (MWCOG) reported ranges for total P and N of 0.10 – 0.66 mg/L and 0.25 – 1.4 mg/L, respectively, in urban stormwater runoff in the Washington area (MWCOG, 1983). Average concentrations of the most commonly found stormwater contaminants are given in Table 2-1.

Table 2-1. Commonly found urban stormwater contaminants and their average concentrations. Adapted from US EPA, 1983 (U.S. national average) and Duncan, 1999 (Global average).

Contaminant	**Average Concentration**	
	US EPA, 1983	Duncan, 1999
Total Suspended Solids (mg/L)	80	330
Total P (mg/L)	0.3	0.5
Total N (mg/L)	2.1	2.6
Zinc (Zn; µg/L)	60	430
Copper (Cu; µg/L)	5	100
Nickel (Ni; µg/L)	30	40
Lead (Pb; µg/L)	15	260
Cadmium (Cd; µg/L)	1	7

2.4. Soil-Phosphorus Interactions

Effective P removal within soil systems is a complicated challenge, as there is conflicting evidence of which factors promote and diminish P retention. The primary mechanisms of P capture involve interactions with iron (Fe), aluminum (Al), and calcium (Ca), and these interactions are highly pH dependent. Immobilization in calcareous environments is primarily through (co)precipitation reactions with Ca and Ca-containing compounds like $CaCO_3$ and hydroxyapatite. Primary mechanisms in acidic environments are sorption to Fe and Al (hydr)oxides such as goethite, ferrihydrite, gibbsite, as well as phyllosilicates and other hydroxylated mineral surfaces (Ann et al., 2000; Arai and Sparks, 2007; Zhao et al., 2007). Ann et al. (2000) reported that adsorption to Fe and Al (hydr)oxides is optimal at pH 5.6 to 7.7, while for Ca phosphate precipitation the optimal pH range is 6 to 8.5.

2.4.1. Organic Matter

2.4.1.1. Organophosphorus Release

As mentioned above, OM contains P, the concentration of which varies depending on the specific source. Breakdown of OM is implicated in reduced bioretention performance through increases in leaching of the soluble organic fraction of P (Hsieh et al., 2007a; Bratieres et al., 2008). This occurs as soil microorganisms, plant roots, and mycorrhizae release phosphohydrolase, enzymes that mobilize P to allow for uptake by the organisms. Significant release of organic P (P_o) from soil organic matter (SOM) has been observed to only occur when inorganic P (P_i), such as the predominant orthophosphate [PO_4(-III)] found in runoff, is limited in supply (McGill and Cole, 1981). A very coarse means of determining whether P_o will mineralize from OM or remain immobilized is through the ratio of organic carbon (org-C) to P_o. When org-C:$P_o \leq 200$, mineralization will occur; when org-C:$P_o \geq 300$, it will not (Dalal, 1977). While this is an imprecise measure, it does allow some quantification for the potential of P_o release from OM in soil and bioretention media.

2.4.2. Competition for and Contribution of Sorption Sites

Dissolved organic matter has been shown to possibly compete with P for sorption sites on Fe and Al compounds in acidic environments, and in this way may reduce P capture in bioretention. Borggaard et al. (2005) observed that P will outcompete OM for $Al(OH)_3$ adsorption sites (as well those of iron (oxyhydr)oxides) if provided with sufficient contact time. Unfortunately, sufficient time was show to be at least 2 days (Borggaard et al., 2005), well beyond the time permitted in bioretention systems. Because of this, mixing order is important. P will control the sorption sites when OM is not present, while if OM and the sorption sites are associated first, it will take time for P to exchange with the OM and become sorbed to the media active sites (Borggaard et al., 2005).

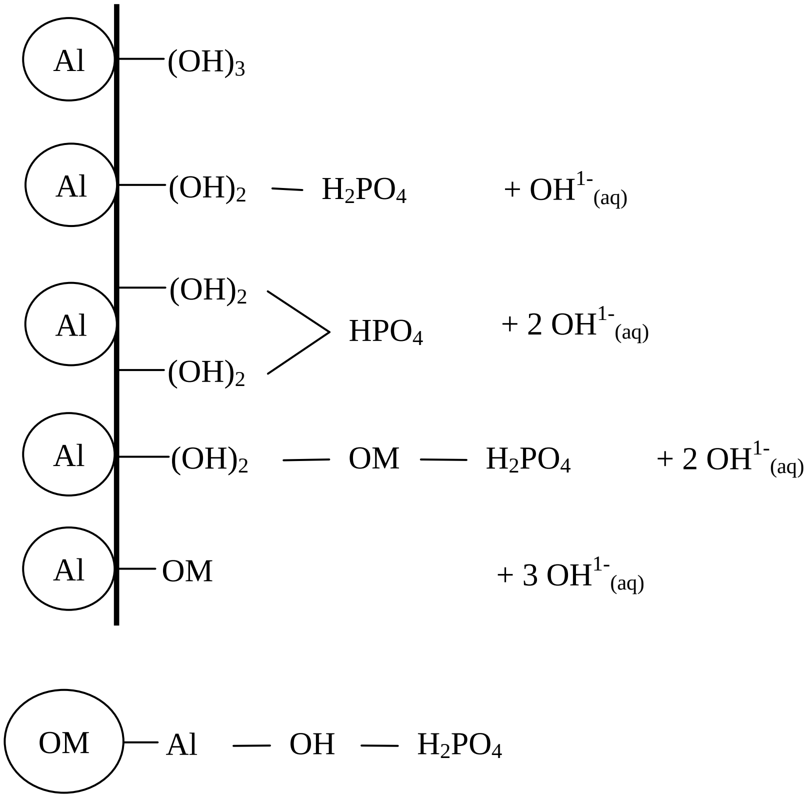


Figure 2-1. Schematic of potential interactions between the Al-WTR surface and inorganic P species in solution. Additionally, interactions may also potentially occur on the surface of OM.

Other research has shown increased rather than competitive P sorption in OM rich soils (Kang et al., 2009). This has been attributed to the formation of metal-OM complexes (Figure 2-1) in the soil that can provide sites for increased P retention. Obviously these results are contradictory with those above, and the matter is still under investigation. Ultimately, evidence suggests that if sorption sites are present in sufficient abundance, there will be no competition and both organic material and P will sorb (Guan et al., 2006).

A statistical path analysis was conducted on soils from North Carolina by Kang et al. (2009). The interactions between P adsorption in the soils and various soil parameters, including oxalate-extractable Al (Al_{ox}) and OM contents, were analyzed. Results show a direct effect of Al_{ox} content on P adsorption, and an indirect effect of OM content on P adsorption via Al content. This suggests there is some manner of interaction between Al_{ox} and SOM, resulting in soil P adsorption. Furthermore, their findings show a steep positive correlation between increasing OM content and P adsorption, up to a certain point deemed the change point (Figure 2-2). This change point was observed at approximately 5% OM content. The correlation between P adsorption and OM had a slope one order of magnitude lower when SOM content was above this change point (greater than 5%), suggesting that beyond this change point the benefit of increased P adsorption provided by increasing OM content is greatly reduced.

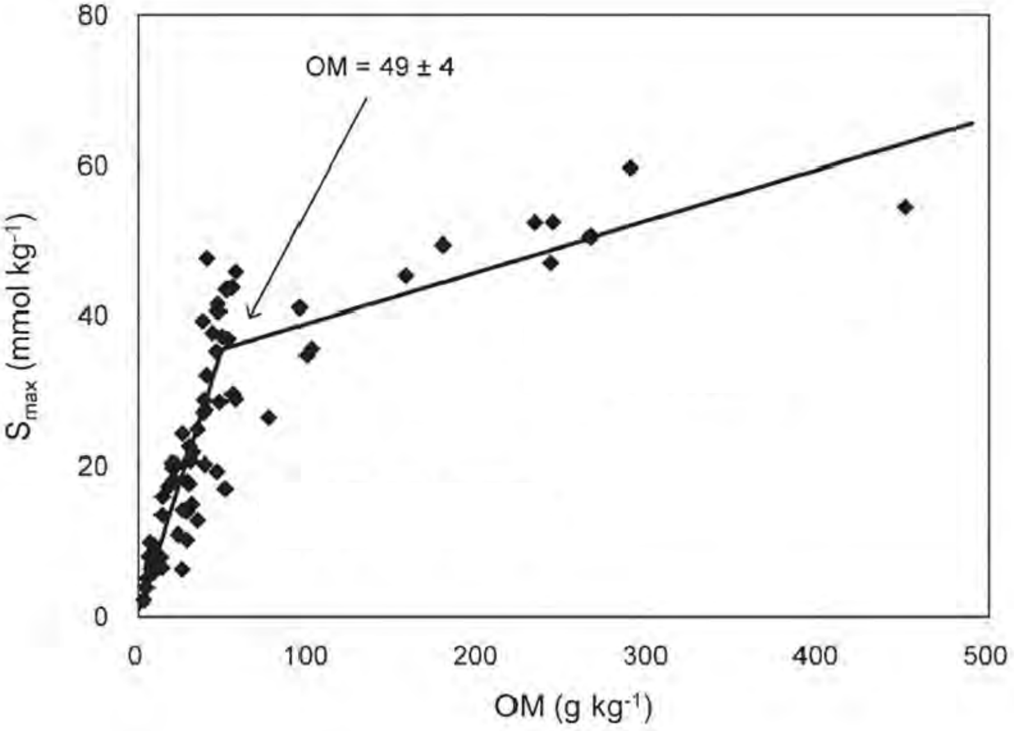


Figure 2-2. Depiction of experimentally determined relationship between soil OM content and S_{max}, the fitted Langmuir isotherm maximum media P adsorption capacity. A change point is evident at approximately 5% OM content. Adapted from Kang et al., 2009.

2.4.3. Wetting and Drying

Soil drying is another important mechanism for P mobilization. Even minor drying of soils has been shown to dramatically increase the amount of soluble P that may readily leach because of the resultant crystallization of mineral compounds, soil aggregate breakdown, and disruption of clay OM coatings (Worsfold et al. 2005; Styles and Coxon, 2006). However, OM may also play an important role in minimizing P loss through retention of soil moisture. This prevents soil drying and the concomitant crystallization of P-sorbing metal compounds (Borggaard et al., 1990). Amorphous (i.e., poorly crystalline) compounds have a vastly superior ability

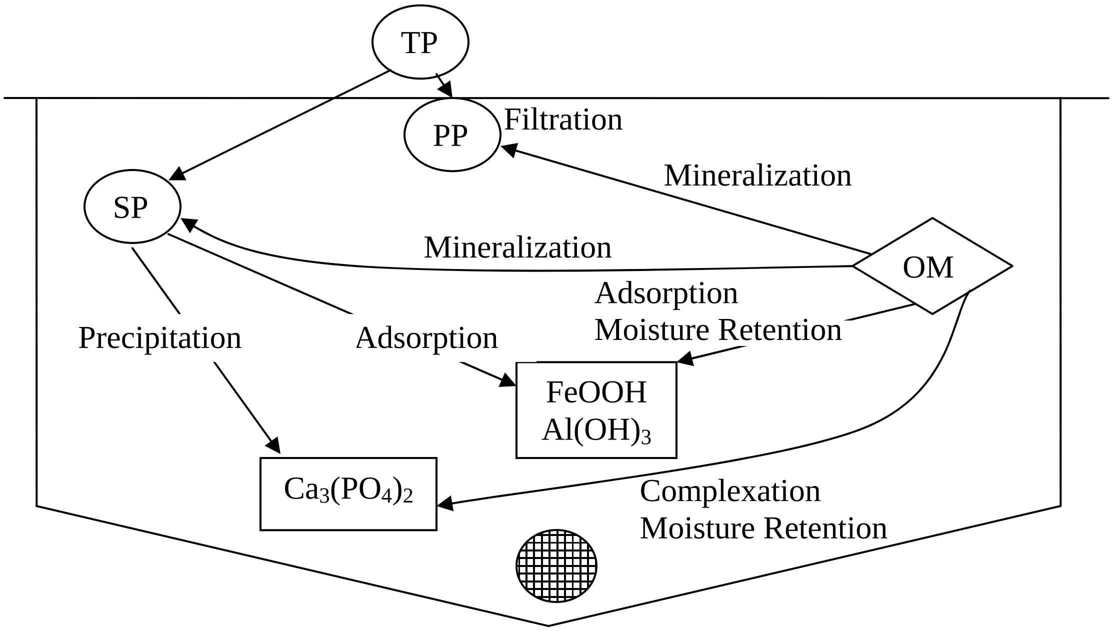


Figure 2-3. Phosphorus interactions in a bioretention cell. TP – total phosphorus, SP – soluble phosphorus, PP – particulate phosphorus, OM – organic matter. $Ca_3(PO_4)_2$, FeOOH, and $Al(OH)_3$ exemplify calcium phosphates, iron (oxyhydr)oxides, and aluminum (hydr)oxides, respectively.

to bind phosphorus compared to crystallized, attributed to their appreciably larger surface area (Darke and Walbridge, 2000). Therefore OM such as that found within bioretention media and as the surface mulch layer may ultimately lead to greater P retention through increased sorption capacity, brought about by maintaining P complexing compounds in an amorphous state. This OM will also provide a carbon source in the event of saturated conditions, ideally resulting in biological denitrification reactions in the subsurface. A graphical representation of P interactions in a bioretention cell is presented in Figure 2-3.

2.5. Bioretention Soil Media Amendments

2.5.1. Organic Matter

Numerous organic amendments have been used in bioretention facilities, including bark, wood or woodchips, sawdust, peat moss, and leaf mulch/yard waste compost. An important parameter to consider for evaluation of organic matter amendments is the C:N:P ratios of their constituents. These ratios vary greatly among components and depend on the specific species of plant or tree from which the material is derived, as well as the conditions under which it was grown. A compilation of such ratios from relevant literature (Byard et al., 1996; Yarie and Van Cleve, 1996; Antikainen et al., 2004; Beauchamp et al., 2006; Sardans et al., 2008) may be found in Table 2-2. In addition to potentially high labile nutrient content, concerns have been raised regarding the input to soils of toxic pollutants which are incorporated into the OM amendments.

For example, some research has shown increased bark heavy metal content from trees grown in areas subject to increased air or soil metal content, such as near metal smelters (Saarela et al., 2005; Baptista et al., 2008). However, the small proportion of OM amended to the total BSM makes the contribution of significant amounts of toxics from such sources highly unlikely.

In general, wood based organics such as bark have a higher C:N:P ratio than that of many other organic materials as they contain less N and P per unit of C, as shown in Table 2-2. A high C:N:P ratio for an organic amendment is theorized to be desirable, as it will minimize the mass of added N and P and reduce the potential for their mineralization and possible leaching from the organic matter. Making the assumption that 50% of the total C reported in Table 2-2 is organic, and all of the P is organic, org-C:P_o ratios can be determined. Only one material, birch leaves, reported an org-C:P_o ratio < 200 (org-C:P_o 181). Three others reported indeterminate ratios between 200 and 300. *Strypnodendron microstachyum* leaves had a ratio of 289,

Table 2-2. C:N:P ratios of various organic amendments on a molar basis. All reported C contents ranged from 45.0 – 50.4% (w/w). Therefore, C content was estimated to be 47% (w/w) and ratio calculated accordingly when not reported in the references. †: C content estimated as 47% (w/w), ×: Data not reported. References: [1] Beauchamp et al., 2006; [2] Antikainen et al., 2004; [3] Sardans et al., 2008; [4] Byard et al., 1996; [5] Yarie and Van Cleve, 1996. Data from [5] calculated from the average of all control samples across all sample years.

Bark	C	N	P	**Leaves**	C	N	P
Fresh [1]	6587 †	26.5	1	*Quercus ilex* L. [3]	1145	26.3	1
Young [1]	6771 †	29.8	1	*Phillyrea latifolia* [3]	1029	21.6	1
Light brown [1]	5611 †	36.9	1	*Arbutus unedo* L. [3]	949	19.8	1
Brown [1]	7215 †	49.3	1	*Strypnodendron microstachyum* [4]	577 †	20.4	1
Black [1]	12243 †	77.7	1	*Callophylum brasiliense* [4]	1347 †	26.8	1
Pine [2]	2020 †	14.7	1	*Jacaranda copaia* [4]	673 †	20.9	1
Spruce [2]	2204 †	19.3	1	*Vochysia guatemalensis* [4]	866 †	22.6	1
Birch [2]	2424 †	20.8	1	Birch [5]	362	12.3	1
Aspen [2]	2020 †	34.6	1	Aspen [5]	557	18.8	1
Eucalyptus [2]	404 †	3.17	1	Poplar [5]	725	20.3	1
Wood				Alder [5]	869	38.1	1
Pine [2]	22037 †	24.1	1	White Spruce [5]	871	14.4	1
Spruce [2]	12121 †	17.7	1	**Leaf Litter**			

Birch [2]	12121 †	17.7	1	*Quercus ilex* L. [3]	1576	28.0	1
Aspen [2]	13467 †	4.91	1	*Phillyrea latifolia* [3]	1573	23.4	1
Eucalyptus [2]	3910 †	7.85	1	*Arbutus unedo* L. [3]	2058	22.2	1
Quercus ilex L. [3]	611	6.53	1				
Phillyrea latifolia [3]	3022	13.7	1				
Arbutus unedo L. [3]	2112	10.7	1				
Sawdust [5]	4198	10	×				

aspen leaves had a ratio of 278, and eucalyptus bark had a ratio of 202. This gives some indication that OM amendments produced from sources like leaves, such as leaf and yard waste compost, may be at greater risk for mineralization of P_o compared to those make from bark or wood, such as bark mulch.

2.5.2. Aluminum-based Drinking Water Treatment Residual

2.5.2.1. Mechanisms of Action

Al-WTR is a byproduct of alum addition for the removal of colloidal material during the drinking water treatment process (see Section 1.1). Because of this, Al-WTR contains large amounts of Al (hydr)oxides, adsorbing P through mono and/or bidentate ligand exchange mechanisms (Figure 2-1; Goldberg and Sposito, 1985; Stumm and Morgan, 1996). This has been verified through measured release of hydroxide and other ions after P adsorption (Goldberg and Sposito, 1985; Yang et al., 2006). Yang et al. (2006), upon investigating an Al-WTR, observed ligand exchange between P and OH^-, Cl^-, SO_4^{2-}, and humic substances (OM); as well as additional releases of Cl^-, SO_4^{2-}, and OM due to dissolution and hydrolysis.

As stated in Section 2, such sorption mechanisms with Al predominate in acidic environments and are dependent on pH. Results from Agyin-Birikorang and O'Connor (2007) indicate that soil amended with Al-WTR show maximized P adsorption at pH 4 within an investigated range of 3 through 9. Yang et al. (2006) investigated the effects of pH on P adsorption to an Al-WTR in the range of 4.3 to 9 and found a decline in adsorption as pH increased, with this decline greatly increasing above pH 6. These studies correspond well with the known zero point of charge (pH_{zpc}) and solubility of $Al(OH)_3$, whereby surface charge becomes positive at approximately pH 9 and shows a continued positive increase with decreasing pH until approximately pH 4.0, below which hydroxylated Al is no longer the thermodynamically preferential form but rather free Al (Al^{3+}) is (Stumm and Morgan, 1996).

2.5.2.2. Al Toxicity

Al is a heavy metal toxic to both aquatic and terrestrial organisms in sufficient quantities. As such, there is reasonable concern over potential leaching of elemental Al from Al-WTR when used as a BSM amendment. $Al(OH)_3$, the dominant Al species in Al-WTR is sparingly soluble at approximately $4 \leq pH \leq 11$, with greatly increasing solubility beyond these pH values (Figure 2-4). Natural soils tend to maintain $pH \geq 5$ because of their buffering capacity, and urban stormwater has a circumneutral pH due to the buffering capacity of impervious surfaces such as concrete. Because of this, the pH of any bioretention system is expected to maintain a pH well within the pH range of $Al(OH)_3$ insolubility, and significant Al(III) will not be released to solution except under very extreme conditions.

Numerous studies have investigated the impacts of Al-WTR application on crops, which gives an indication of the impact of Al-WTR on a bioretention system. Many have reported increased soil Al concentrations, and some have reported increased plant Al concentrations, although this appears to depend on the plant species (e.g., Mahdy et al., 2009; Oladeji et al., 2009). Mahdy et al. (2009) reported increased plant Al concentrations, but noted they remained well below the level which could be harmful if ingested (90.7 – 454 mg/lb, 200 – 1000 mg/kg). No

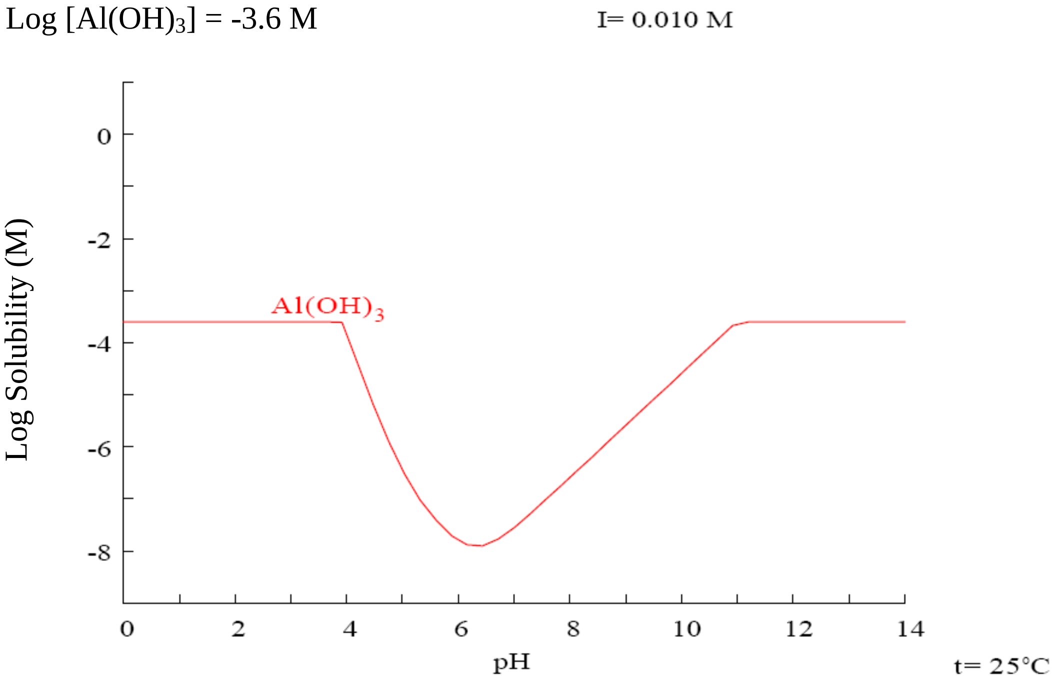


Figure 2-4. Solubility diagram of aluminum hydroxide. Generated using HYDRA/MEDUSA, KTH Royal Institute of Technology, Stockholm, Sweden.

indications of Al phytotoxicity were reported, but in many cases crop yields were negatively correlated with increasing WTR application rates (Oladeji et al., 2007; Mahdy et al., 2009; Oladeji et al., 2009). This is likely the result of a plant available P deficiency (Lombi et al., 2010). Additionally, Sotero-Santos et al. (2005) investigated the toxicity of Al-WTR using *Daphnia similis* as a bioassay. They found no acute toxicity and minimal impacts on *Daphnia* fecundity, suggesting little Al toxicity of WTR at the investigated pH (7.0-7.3).

While soils applied with Al-WTR have been observed with slightly elevated Al contents, the greatest concern involved mobilization of elemental Al from the WTR. Agyin-Birikorang et al. (2009) investigated Al leaching from Al-WTR treated field plots at various depths. While measurable concentrations of Al were found in the groundwater, they were not significantly different between control and experimental (Al-WTR applied) plots. Summarily, the reported Al concentrations in experimental plots were 70 – 120 μg/L in shallow wells and 140 – 250 μg/L in deep wells, vis-à-vis concentrations in control plots of 70 – 110 μg /L in shallow wells and 170 – 210 μg/L in deep wells.

Chapter 3: Materials and Methodology

Initial P batch studies for determination of adsorption isotherms were conducted to determine adsorption properties of various BSM mixtures, which allowed prediction of adsorption behavior under various conditions and were ultimately used to determine the best performing BSM at this stage. The most promising mixtures investigated were then used in small column studies receiving a P solution to determine their adsorption behavior under dynamic flow conditions. Mixture performance could be verified with these studies and adequate hydraulic conductivity of the media estimated. Performance under wet/dry cycling (i.e., intermittent flow) was also investigated at this stage in an attempt to better simulate actual bioretention conditions. Larger, vegetated columns were then studied using a mixture based on that which was the best performing to date. These larger columns received a complete suite of pollutants, including orthophosphate, ammonium, nitrogen oxides, and organic nitrogen as glycine to determine BSM performance for nutrient pollutant removal. Plant survival was observed to determine possible toxicity or other negative effects of WTR addition. Effluent samples were also analyzed for potential leaching of free aluminum, as this metal is toxic to many aquatic and terrestrial organisms in sufficient concentrations. All mixtures and BSM components were subjected to acid ammonium oxalate extraction and analyzed for oxalate-extractable P, Al, and Fe content. These data were compiled for use as a measure to determine P adsorption potential for BSM mixtures.

3.1. Media Performance Benchmark

Performances of all media were measured against a target adsorption of 15.4 mg/lb (oven dry mass basis) soluble P. This adsorption benchmark was calculated as:

$$\frac{V_{P,1} \cdot C_{SP} \cdot t}{V_C \cdot \rho} \tag{3-1}$$

where $V_{P,1}$ is the volume of precipitation per annum, C_{SP} is the concentration of soluble P, t is time, V_C is the volume of the bioretention cell, and ρ is the bioretention media bulk density. The Washington Metropolitan Area receives approximately 40 in (102 cm) of rain per year, and the average stormwater soluble P concentration is 120 µg P/L (US EPA, 1983; Bratieres et al., 2008). The media adsorption benchmark was determined for a bioretention facility sized at 5% of catchment area and having 20 years capacity. Therefore, a BSM mixture must be able to adsorb at least 15.4 $\text{mg}_\text{P}/\text{lb}_\text{media}$ (34 mg/kg) at 120 µg/L soluble P to provide the necessary stormwater treatment.

3.2. Media Characterization

3.2.1. Bioretention Soil Media and Al-WTR

BSM was obtained pre-mixed from a local landscape supplier and passed through a 2-mm sieve. A sample was sent to the University of Delaware Soil Testing Program for particle size analysis. The media contained 77% sand, 14% silt, and 8% clay, and was classified as a sandy loam per USDA soil texture classification. The media was stored in water tight containers, and before use was air dried for at least 1 week. Loss on ignition at 550°C (LOI), a measure of OM content, measured 2.1%. pH was measured with a pH meter (Mettler Toledo MA235) using a glass electrode probe. A mixture of air dried BSM and deionized water (1:2 w/v) resulted in a pH measured as 6.0. A conductance probe (YSI Model 35) measured the electrical conductance (EC) of a deionized water saturated media paste (1:1 w/v) as 0.8 mmohs/cm (Table 3-1).

Table 3-1. Media component characteristics. EC: electrical conductance; WC: water content; OM: Organic matter; †: Data reported by manufacturer; ×: Data not collected.

	pH		EC (mmohs/cm)		WC [moist] (%)		WC [air dry] (%)		OM (%)	
	Avg.	**S.D.**	**Avg.**	**S.D.**	**Avg.**	**S.D.**	**Avg.**	**S.D.**	**Avg.**	**S.D.**
BSM	**6.03**	**(0.20)**	**0.79**	**(0.04)**	**8.19**	**(0.28)**	**0.64**	**(0.11)**	**2.11**	**(0.32)**
WTR	**7.53**	**(0.04)**	**1.35**	**(0.05)**	**85.9**	**(0.24)**	**42.6**	**(0.44)**	**36.4**	**(3.35)**
HBM	**6.90**	**(0.03)**	**0.20**	**(0.02)**	**49.9**	**(6.33)**	**6.22**	**(0.93)**	**74.5**	**(6.90)**
LC	×	×	×	×	**57.1**	**(0.93)**	×	×	**47.1**	**(1.79)**
Sand	**6.5 †**	×	×	×	**0**	**(0)**	×	×	**0.19**	**(0.04)**

Al-WTR was secured from the Rockville Drinking Water Treatment Plant in Potomac, MD. Until use it was stored in water tight covered containers to retain moisture. The work of Yang et al. (2008) showed that the phosphorus adsorption capacity of Al-WTR stored in such containers is not affected by ageing for at least 18 months, and so the material used is expected to be representative of fresh Al-WTR. Agyin-Birikorang and O’Connor (2009) came to a similar conclusion with regard to the effect of ageing on WTR 0.2 M acid ammonium oxalate extractable P, Fe, and Al contents. Prior to use as a BSM amendment, the WTR was crushed by hand, sieved < 2 mm, and then air dried for at least 1 week. WTR LOI was measured 36.4%. The high organic matter content of the WTR is somewhat misleading, as this is not representative of typical surface water OM content. It is believed to have two causes: additionally released water from hydrous oxides upon ignition (Elliott et al., 2002); and the use of a nonionic organic polymer (Praestol N3100 LTR; Ashland, Inc.) in the drinking water coagulation process (Vern Simmons, Rockville Drinking Water Treatment Plant, personal communication). The pH of a 1:2 (w/v) water:media mixture measured was 7.5. EC of a saturated paste (1:2 w/v) measured 1.4 mmohs/cm (Table 3-1).

3.2.2. Low-fines BSM

Influence of clay content on P adsorption was investigated by the addition of sand to the BSM to reduce the net fines (silt and clay) content. Concurrently, this also provided an estimation of the performance of a media mixture of a different textural class. The BSM was amended with angular, white quartz sand (Mystic White® II, U.S. Silica Co.). This produced a media textural profile of 85% sand, 10% silt, and 5% clay; rated as a loamy sand per the USDA soil textural classification. Organic content was measured via LOI as 1.6%, and the pH was 6.2 as calculated from a mass weighted average of the sand and BSM pH values. Henceforth, this media mixture is referred to as low-fines bioretention soil media (LFBSM).

3.2.3. Organic Matter Amendments

The WTR amended BSM was further amended with organic material to investigate its effects on media P adsorption capacity. The investigated materials were triple-shredded hardwood bark mulch (HBM) and leaf and yard waste compost (LC). The HBM was purchased from a local landscaping supply company in the Washington, DC area, and the LC was obtained from the College Park, MD Department of Public Works and is their screened Smartleaf® Compost. The pH (1:4 w/v) and EC (1:4 w/v saturated paste) of HBM was found to be 6.9 and 0.2 mmohs/cm, respectively. HBM was 74.5% OM and LC was 47.1% OM as measured by LOI (Table 3-1).

3.2.4. Aluminum Hydroxide

Aluminum hydroxide [$Al(OH)_3$] was synthesized and used as an amendment to provide a comparison between the effectiveness of Al-WTR and pure $Al(OH)_3$ in terms of P adsorption. $Al(OH)_3$ was synthesized by mixing aluminum sulfate ($Al_2(SO_4)_3 \cdot 14 H_2O$; Fisher Scientific) and NaOH (Fisher Scientific) in a molar ratio of 1:3 Al:OH. Both compounds were mixed in deionized water under vigorous stirring for 1 hour, allowed to settle for 1 hour, and then the pH was adjusted to approximately 7 with HCl. After pH adjustment, the solution was centrifuged at 4200 rpm for 10 minutes. The supernatant was than decanted and the pellet filtered and collected on a glass fiber filter (Whatman No. 40) under vacuum. It was washed three times with ethanol and once with acetone to remove excess sulfate and sodium ions, and air dried overnight (Borggaard et al., 2005).

3.3. Phosphorus Adsorption Isotherms

P isotherms were determined for unamended BSM as well as BSM amended with Al-WTR, triple-shredded hardwood bark mulch (HBM), yard and leaf waste compost (LC), quartz sand, and/or pure aluminum hydroxide ($Al(OH)_3$), using a modified method based on that reported by Nair et al. (1984). In this study, NaH_2PO_4 was used to make 0.3, 0.9, 3.0, and 9.0 mg/L P solutions with a 0.01 M KCl background electrolyte concentration. Isotherms were prepared as follows: 1.8 g of media mixture was weighed and placed in each of 5 centrifuge tubes of 50 mL volume. To these was added 45 mL P solution, for a media:solution ratio of 1:25 (w/v). A sixth centrifuge tube containing no media, but 45 mL of appropriate P solution was carried through all procedures with the samples as a control. Each media mixture had phosphorus solution addition at concentrations of 0.3, 0.9, and 3.0 mg P/L as NaH_2PO_4. In addition, any mixture containing 10% WTR (air dry mass basis) underwent addition of 9.0 mg P/L as NaH_2PO_4, and these data were included in the isotherm. Due to the high adsorption capacity of the mixture, this was necessary to extend the isotherm and provide for comparison of all treatments.

For each treatment and P solution addition, investigation was then undertaken to observe the effects of varying pH on P adsorption. Three samples were acidified to approximately pH 4.00, 4.25, and 4.50 using 0.05 – 0.2 mL 0.1 M HCl, and to one sample 0.05 – 0.1 mL 0.1 M NaOH was added to produce a pH of approximately 7.5 to 8.5. The final sample as well as the control underwent no pH adjustment. Samples were then shaken on an end-over-end shaker for 24 hours, after which they were centrifuged at 2000 rpm for 13 minutes and the supernatant decanted and filtered through a 0.22 µm membrane filter. Final pH was measured and then the samples were analyzed for soluble reactive phosphorus (SRP) by the ascorbic acid molybdenum blue method (4500-P E) as presented in Standard Methods (APHA, 1992). A 5 cm pathlength cuvette was employed to provide a detection limit of 0.01 mg/L P. The final data were fitted with Freundlich isotherms using nonlinear regression in Microsoft® Excel®. Freundlich isotherms are of the form:

$$q = K \cdot C^{1/n} \qquad (3\text{-}2)$$

where C is the equilibrium P concentration in solution (mg/L), q is the equilibrium media adsorption capacity (mg/kg), and both K and n are fitting constants. The value of q is calculated as the difference between the initial and final P solution concentrations normalized by the media mass (oven dry mass).

Adjustments to the method proposed by Nair et al. (1984) include the use of KCl as the background electrolyte, as well as the decision to use a media mass of 1.8 g and 1.5 oz. (45 mL) P solution instead of 1 g and 0.8 oz. (25 mL), respectively. It was decided not to use $CaCl_2$ as a background electrolyte as the method recommends because at the higher pH values encountered in these analyses the precipitation of calcium phosphates may result, which would misrepresent the phosphorus adsorption capacity of the media. Also, alterations in the sample mass, solution volume, and consequently the equilibration vessel headspace, stemmed from the use of a 2.0 in. (5 cm) pathlength cuvette for spectrophotometric P concentration determination. It was desired to maximize sorption characterization ability, and so the lowest detection limit was necessary. Because of the large volume of the cuvette, a larger volume of solution (1.5 oz.) was necessary. To maintain the desired soil:solution ratio, 1.8 g media was used.

Phosphorus adsorption isotherms were determined for BSM and BSM amended with 2, 4, and 10% Al-WTR on an air dried mass basis (1.2, 2.4, and 6.0% WTR on an oven dried mass basis, respectively; Tables 3-2 and 3-3). Amended BSM mixtures were prepared by weighing the necessary amounts of BSM, WTR, and any other amendments, placing together in a sealed bag, and homogenizing through vigorous shaking.

Table 3-2. Composition of investigated bioretention media. †: Air dry mass; ‡: Field moist weight; *: Percent weight of $Al(OH)_3$, analogous to 0.5% WTR with respect to amorphous Al content.

Media	BSM † (%)				WTR † (%)	HBM/LC ‡ (%)
		Sand	Silt	Clay		
BSM	100	77.3	14.4	8.30	0	0
BSM + 2% WTR	98.0	75.8	14.1	8.13	2	0
BSM + 4% WTR	96.0	74.2	13.8	7.97	4	0
BSM + 10% WTR	90.0	69.6	13.0	7.47	10	0
LFBSM	100	85.2	9.40	5.40	0	0
LFBSM + 3% WTR	97.0	82.6	9.12	5.24	3	0
LFBSM + 4% WTR	96.0	81.8	9.02	5.18	4	0
LFBSM + 6% WTR	94.0	80.1	8.84	5.08	6	0
LFBSM + 10% WTR	90.0	76.7	8.46	4.86	10	0
BSM + HBM	94.2	72.8	13.6	7.82	0	5.84
BSM + 2% WTR + HBM	92.3	71.3	13.3	7.66	1.88	5.84
BSM + 4% WTR + HBM	90.4	69.9	13.0	7.50	3.77	5.84
BSM + LC	88.5	68.4	12.7	7.35	0	11.5
BSM + 4% WTR + LC	85.6	66.1	12.3	7.10	2.95	11.5
BSM + 4% WTR + LC [OM+]	71.0	54.8	10.2	5.89	2.95	26.1
Sand + 4% WTR	96.0	96.0	0	0	4	0
BSM + 0.5% AH	99.9	77.2	14.4	8.29	0.12^{*}	0

LFBSM P adsorption isotherms were also determined. LFBSM, in contrast to BSM, was amended with Al-WTR at rates of 0 (unamended), 3, 6, and 10% WTR on an air dried mass basis (0, 1.8, 3.5, and 6.0% WTR on an oven dried mass basis, respectively; Table 3-2).

HBM was amended to media containing 0, 2, and 4% WTR (air dry mass; Table 3-2). For LC, amendments were made only to 0 and 4% WTR media (Table 3-2). Additionally, 4% WTR amended BSM was augmented with an increased mass of LC to further investigate the negative effects of LC on P adsorption, termed the OM+ treatment (Table 3-2).

The organic amendments provided increased OM to the BSM, as did the WTR. Because of the high measured OM content of the WTR, noticeable increases in BSM OM content were observed with increasing WTR content. Therefore, it was decided to amend all media treatments with an equal proportion of organic material (either mulch or compost). In accordance with the findings of Kang et al. (2009) who showed greatly diminished improvement in soil P adsorption when SOM exceeded 5%, it was decided to amend treatments with the mass necessary to produce 5% OM content in the 2% WTR amended treatment. The organic amendments were mechanically shredded and sieved < 2 mm, then added at field moisture (49.9% and 56.5% water content for HBM and LC, respectively) to air dried WTR amended BSM (BSM+WTR) at a ratio of 1:16.1 (w/w) HBM:(WTR+BSM) and 1:7.7 (w/w) LC:(WTR+BSM). For the LC OM+ mixture, LC addition occurred at approximately 2.5 times the mass with which other mixtures were amended, having a ratio of addition of 1:2.8 (w/w) LC:(WTR+BSM).. Organic amendments were added at field

Table 3-3. Aluminum based water treatment residual (WTR) and organic matter (OM) content of investigated BSM mixtures during batch studies. † : Per air dry mass basis; ‡ : Per oven dry mass basis; * : Measured by loss on ignition at 550°C.

Organic Material Amendment	**WTR Content (%)**[†]				
	0	2	4	4 [OM+]	10
None					
% WTR[‡]	-	1.2	2.4	×	6.0
% OM*	2.2	2.7	3.1	×	4.5
Hardwood Bark Mulch					
% WTR[‡]	-	1.1	2.3	×	×
% Bark Mulch[‡]	3.2	3.2	3.2	×	×
% OM*	5.6	4.0	5.7	×	×
Leaf Compost					
% WTR[‡]	-	×	1.9	1.9	×
% Leaf Compost[‡]	5.2	×	5.3	12.0	×
% OM*	4.6	×	5.4	8.8	×

moisture vis-à-vis air dried mass to prevent uncharacteristic P leaching that would result upon rewetting, similar to the release of additional P from the mineralization of SOM upon rewetting (Worsfold et al., 2005; Styles and Coxon, 2006). The addition of the organic amendments to WTR-amended BSM resulted in a net reduction in WTR content, but this was minimal (≤ 0.5% gross change in WTR content of the mixtures on an oven dry mass basis). Tables 3-2 and 3-3 detail the proportions of constituents in the majority of mixtures investigated in this study on an air dry mass and oven dry mass basis, respectively.

For $Al(OH)_3$-amended mixtures, the oxalate-extractable (i.e., amorphous) aluminum content of the constituents and mixes were investigated, as described in Section 3.6. With this information, $Al(OH)_3$ was amended to BSM at a rate analogous to the amorphous Al content of 0.5%, 2% and 4% WTR, utilizing the assumptions that the $Al(OH)_3$ did not include any significant impurities, and was completely amorphous. These mixes are referred to hereafter as 0.5%, 2%, and 4% AH, respectively. In actuality, the mixes were 0.12%, 0.50%, and 0.98% $Al(OH)_3$ on an air dry mass basis, respectively.

3.4. Minicolumn Adsorption Experiment

Adsorption studies using small sealed upflow columns were conducted to investigate the behavior and P adsorption capabilities of the various media mixes.

3.4.1. Column Setup

Columns were constructed as detailed in Figure 3-1. A 6 in.(15.2 cm) tall, 1 in.(2.5 cm) inner diameter (0.79 in^2 cross-sectional area) Plexiglass cylinder was attached to a base chamber. The cylinder and base chamber were separated by a base plate containing drilled holes, and was overlaid with a metal screen intended to prevent media movement into the base chamber. Influent was pumped horizontally into the base chamber and redirected vertically through the base plate to evenly distribute flow radially throughout the column.

During installation, the media was allowed to naturally settle within the column by slowly filling the column with deionized water as the media was being placed. This allowed the particles to settle before sealing the column and helped to remove possible air bubbles. Prior to placement in the column, media was manually homogenized through vigorous shaking and stirring with a laboratory spatula.

Media was placed in the column to a height of 4.73 in. (12.0 cm) and then a 0.39 in. (1.0 cm) washed quartz sand layer was placed on top to prevent washout of fines. This provided for a total bed volume of 4.0 in^3 (66.0 mL). A rubber stopper with an outlet port was inserted 0.88 in. (2.22 cm) into the top of the column and sealed using

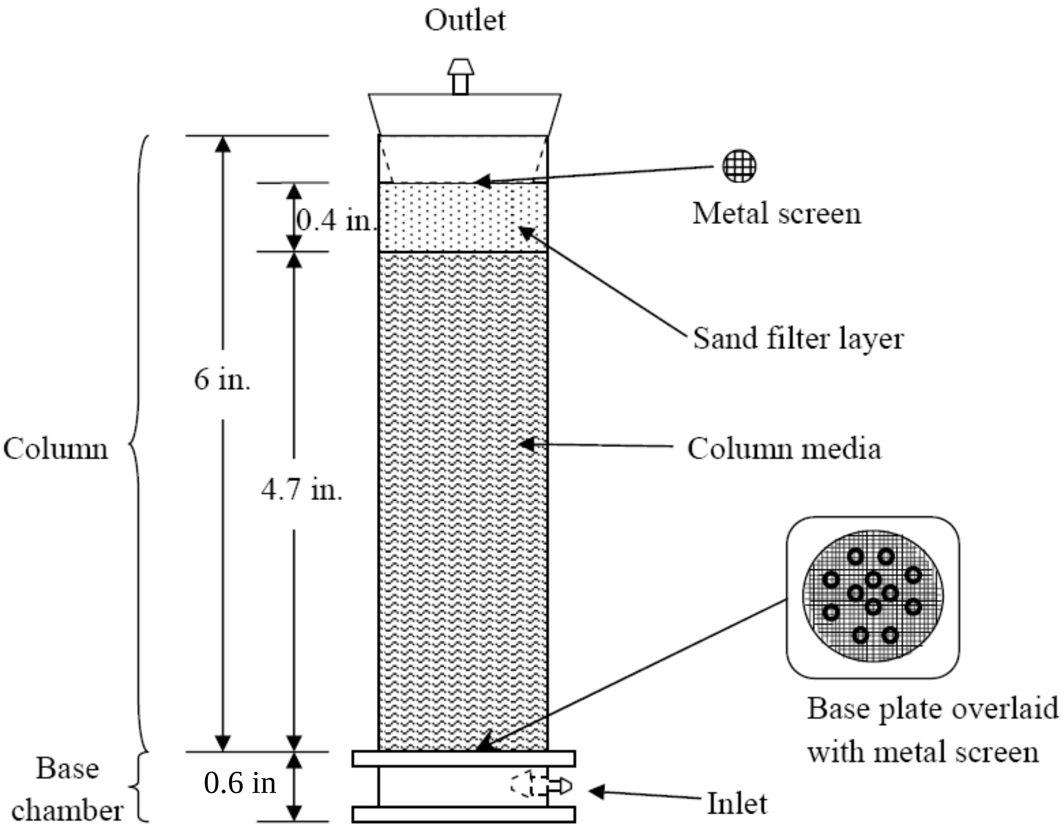


Figure 3-1. Upflow column schematic for minicolumns.

silicone and epoxy. A small metal mesh screen was installed in the column stopper to further prevent the washout of material.

3.4.2. Media, Influent, and Flow Characteristics

Column experiments were initiated with six different media or flow characteristics at a time (Table 3-4). All media had been previously investigated to determine batch adsorption isotherms with the exception of the LFBSM + 4% WTR and Sand + 4% WTR mixes. 4% WTR was chosen in both cases to maintain a constant proportion of WTR among all columns. After LFBSM amended with WTR produced greater P adsorption in both batch and column studies, a column of the

Table 3-4. Media and flow regimes for minicolumn experimental groups I and II.

Experimental Group	Column Media	Flow Regime
1	Unamended BSM	Continuous
	BSM + 2% WTR	Continuous
	BSM + 4% WTR	Continuous

	BSM + HBM + 2% WTR	Continuous
	BSM + HBM + 4% WTR	Continuous
	LFBSM + 4% WTR	Continuous
2	Unamended BSM	Continuous
	BSM + 4% WTR	Continuous
	Sand + 4% WTR	Continuous
	BSM + HBM + 4% WTR	Intermittent
	BSM + 4% WTR	Intermittent
	LFBSM + 4% WTR	Intermittent

same washed quartz sand used as a filter layer was amended with WTR to further investigate the effect of reduced fines content on WTR P adsorption.

Two experimental groups of six columns each were tested, for a total of twelve column experiments. Select experiments were duplicated to verify results. Influent solution was pumped into each column via a peristaltic pump from a continuously stirred influent batch to assure homogeneity. Two continuously stirred influent tanks were used and connected in series through a siphon, providing at total batch volume of 38 L when full. Column flowrates were calibrated by using a stopwatch to time the duration to fill a 5 mL volumetric flask. Each column was individually calibrated to within 5% of the desired flowrate. Figure 3-2 depicts the experimental setup.

Influent for the experiment was a solution of 120 μg/L dissolved P, using NaH_2PO_4, and 0.01 M KCl as a background electrolyte. 1 N NaOH was added to the solution to adjust the pH to approximately 7. Over the course of the column experiments, column flowrates were systematically increased in an attempt to force

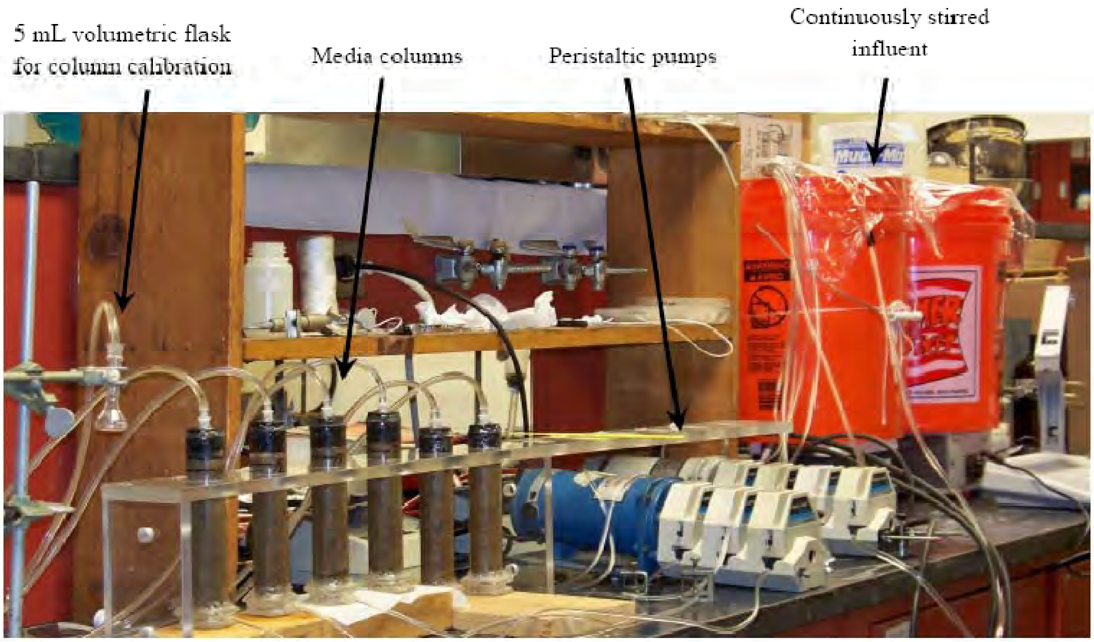


Figure 3-2. Column experimental setup. Influent is continually drawn from the stirred influent batches and pushed through the columns. Column effluent was sampled daily for pH, turbidity, and total phosphorus (TP).

breakthrough. All columns began at an inflow rate of 4.7 in^3/hr (6 in/hr; 1.29 mL/min), at which they were run for exactly 28 days. After that time, flow was doubled to 9.4 in^3/hr (12 in/hr; 2.57 mL/min) and run for an additional 21 days. Finally, after 49 days of total run time, flow was again doubled to 19 in^3/hr (24 in/hr; 5.15 mL/min) at which rate the columns were run until completion of the experiment. While flow greater than 6 in/hr is not representative of that seen in actual, gravity driven bioretention cells in the field, such high flows were needed to provide the mass loading necessary to force column breakthrough.

Within both experimental sets, nine columns were operated under continuous flow for at least eight weeks. Samples were collected from all columns primarily daily, except when this was logistically infeasible. In all instances continuously running columns were never unsampled for more than two consecutive days, and samples were collected on four out of every seven days at a minimum. The percent of sampled days on a number-of-days-run weighted average basis was 89% for set I and 73% for set II.

Three columns from experimental set II were operated intermittently to simulate a rain-induced wetting/drying regime. These columns underwent throughflow for approximately 24 to 36 hours, during which time two sets of samples were collected: one for initial performance and one to analyze for performance immediately prior to shutdown. After shutdown, columns were disconnected from the influent tanks and the column pumps slowly operated in reverse to drain the columns and continuously pull ambient air through the media. Columns were operated dry for four days in between flow events on average.

3.5. Mesoscale Vegetated Column Experiments

Larger (3 ft.) columns were constructed with the final selected BSM mixture and periodically subjected to 6-hour synthetic storms. These storm events allowed measurement of media performance with regard to the removal of PO_4(-III), NH_4^+, NO_3^-, and DON.

3.5.1. Column Setup

The large vegetated columns were constructed of 3.6 ft. (1.1 m) of clear Plexiglas pipe affixed to a base plate which was bolted to a stand. The column had a cross-sectional area of 44 in^2 (284 cm^2). The column drained vertically through an outlet valve and outflow was redirected horizontally via Tygon® tubing (Saint-Gobain Corp.). A fiberglass filter (1 mm mesh) was placed inside the columns at the base to prevent media washout. Atop the filter was a 2 in. (5 cm) angular quartz sand layer to further minimize media washout. The majority of the remaining column space (2.8 ft., 86 cm) contained the final BSM mixture. Ultimately both the sand and BSM were 3 ft. (0.9 m) in height, characteristic of a bioretention cell. This resulted in a bed volume of 26 L. The columns were left with 6.0 in. (15 cm) of freeboard to allow for ponding, above which the ponded water would drain through an overflow structure. Figure 3-3 details the column schematic and experimental setup.

3.5.2. Column Vegetation

Vegetation for column planting was selected based on species status as a native to the Chesapeake Bay region, tolerance to drought and anaerobic conditions, moisture use, minimum root depth, and local availability. Based on these constraints (largely due to availability upon commencing the experiment in January) Narrowleaf Blue-eyed grass (*Sisyrinchium angustifolium*) was purchased for use. Planting media was gently washed from the plants roots as completely as possible before transplantation to columns. Four mature plants were installed along with the column media, two plants per column. Total plant mass was approximately equal between each columns. Each planted column was illuminated by a grow light (Phillips 50 W 120 V Agro-lite plant light), which were place on a timer set to provide the plants with a 12 hour light period.

3.5.3. Media, Influent, and Flow Characteristics

Media composition was selected based on the results of minicolumn studies; initially determined to be 5% Al-WTR (air dry w/w), 3.3% HBM (air dry w/w), and the remainder BSM. HBM was amended at a rate of 3.3% as this was the mass

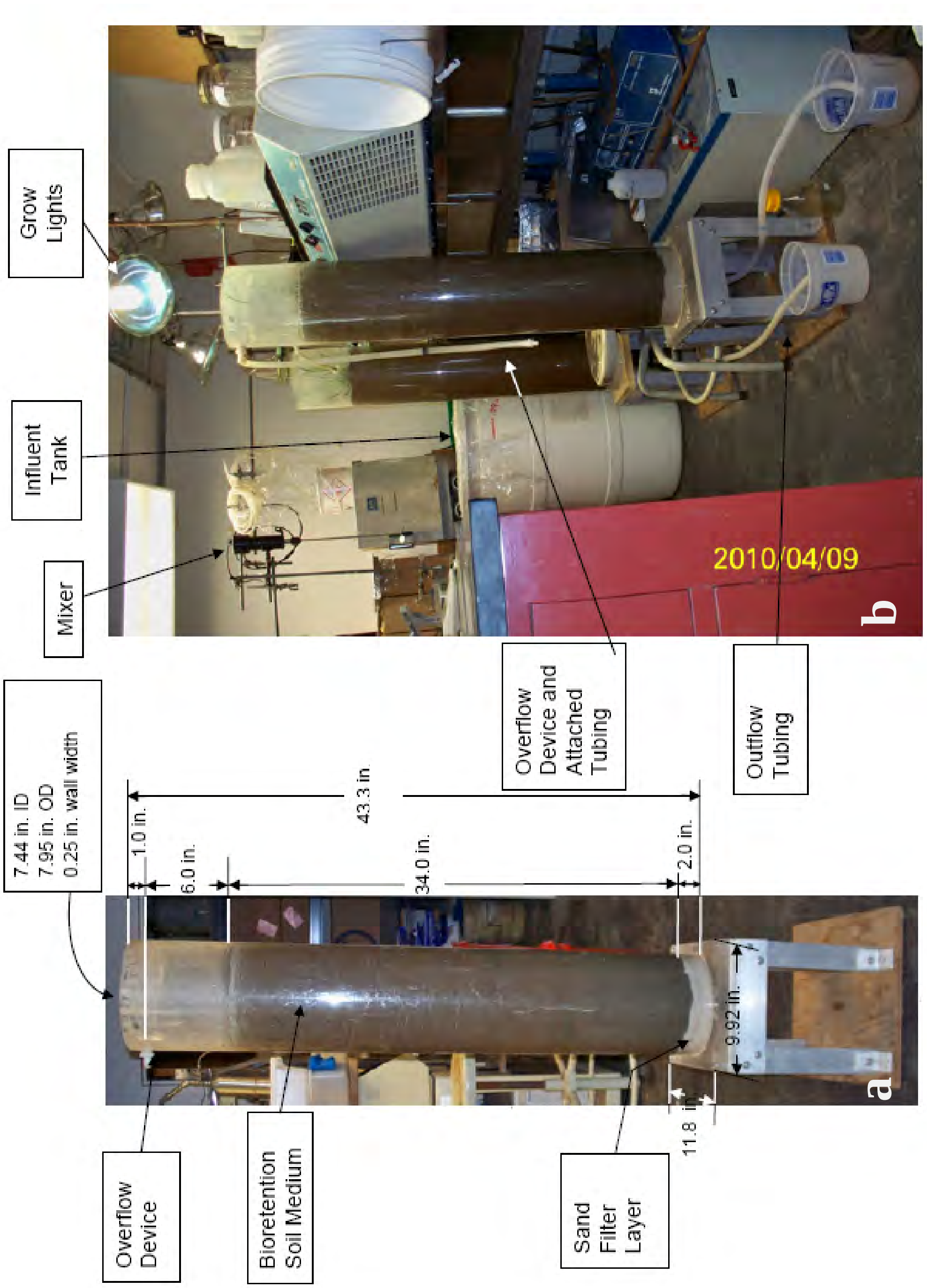


Figure 3-3. Detail of (a) gravity driven vegetated column schematic and (b) experimental setup.

Table 3-5. Relative proportions of vegetated column BSM mixture media constituents.

	Experimental			Control		
	Moist	Air Dry	Oven Dry	Moist	Air Dry	Oven Dry
BSM	59.8%	69.2%	70.7%	73.7%	74.4%	74.4%
WTR	17.3%	5.15%	3.12%	0.00%	0%	0%
HBM	5.04%	3.30%	3.18%	5.79%	3.30%	3.12%
Sand	17.8%	22.3%	23.0%	20.5%	22.3%	22.5%

necessary to produce a 5% OM content in a 2% WTR amended mixture. All non-organic media was sieved < 2 mm, HBM was shredded and sieved < 2.36 mm, and the components were combined at field moist water content. However, upon setup of the columns the measured infiltration rate, while sufficient for the majority of specifications (≥ 0.52 in/hr, ≥ 1.33 cm/hr), did not meet the Prince George's County requirement of ≥ 2.0 in/hr (≥ 5.1 cm/hr). Consequently, media was removed from the columns, air dried for 1 week, and amended with sand as well as additional WTR and HBM (both field moist) to maintain the desired concentrations of each. After the decision to amend the media with sand, the media OM content was reduced because of the low sand OM content. Therefore, the amount of HBM necessary to produce 5% OM in a 2% WTR amended media was altered. Ultimately, the experimental BSM consisted, on an air dry mass basis, of 69% BSM, 5% WTR, 22% additional sand, and 3% HBM. Control BSM consisted of 74% BSM, 22% additional sand, and 3% HBM on an air dry mass basis. Final media composition may be seen in Table 3-5.

Influent composition was based on average stormwater concentrations (US EPA, 1983; Maestre and Pitt, 2005; Bratieres et al., 2008). All pollutants were applied as dissolved species, as particulate species are treated well through the filtration mechanism of the BSM and so were deemed unnecessary to include (Li and Davis, 2008b). Summarily, pollutant concentrations were 120 µg/L PO_4^{3-}-P, 700 µg/L

Table 3-6. Concentration (µg/L) and source compounds for vegetated column synthetic stormwater influent solution. †: Contaminant; ‡: Concentration (µg/L).

Contam.[†]	Conc.[‡]	Contam.[†]	Conc.[‡]	Contam.[†]	Conc.[‡]	Source
TP/TDP	120					NaH_2PO_4
TN	1700	NO_3^-	700			NH_4NO_3 $NaNO_3$
		TKN	1000	NH_4^+	300	NH_4NO_3
				DON	700	Glycine

NO_3^--N, 300 μg/L NH_4^+-N, and 700 μg/L DON. This resulted in total N (TN) input of 1.3 mg/L, and TKN of 1.0 mg/L. Table 3-6 details pollutant concentrations and species source compounds.

Both columns were subjected primarily to a standard hydrologic regime, being a constant inflow rate (i.e., uniform distribution) of approximately 11.1 in^3/min (15.2 in/hr) for a continuous 6 hour period, providing a total storm volume of 17.2 gal (65 L) per column. This flowrate is equivalent to a rainfall rate of 0.75 in/hr (1.91 cm/hr) over the entire catchment area, assuming a bioretention cell sized at 5% of catchment. Such a storm duration and flowrate is a typical medium-to-large sized storm for that duration in the Washington, DC region (Kreeb, 2003). These synthetic storms were applied to the columns once per week, providing an antecedent dry period of 6 days.

Table 3-7. Testing regime for vegetated bioretention columns. Uniform hydrologic regime influent P concentration was 120 μg/L. Log-normal hydrologic regime influent P concentration ranged from 69 to 175 μg/L. Standard antecedent dry period was 6 days.

Test No.	Hydrologic Distribution	Influent Concentration	Antecedent Dry Period
1 - 5	Uniform	100%	Standard
6	Log-normal	100%	Standard
7	Uniform	250%	Standard
8	Uniform	100%	Standard
9	Log-normal	250%	2x
10	Uniform	60%	Standard
11	Uniform	100%	Standard
12	Uniform	100%	1/2x
13	Uniform	100%	Standard

Table 3-8. Vegetated column study detail of test flowrates and applied *o*-phosphate concentrations.

	Flow				PO_4^{3-}
	Step No.	Duration (min)	Rate (in^3/min)	Rate (in/hr)	Concentration (μg/L)
Standard Test	-	360	11.1	15.1	120
Test 6	1	16	3.97	5.41	175
	2	24	14.2	19.4	153
	3	57	20.3	27.7	131
	4	80	15.3	20.8	109
	5	90	9.15	12.5	88.5
	6	93	3.97	5.41	68.5
Test 7	-	360	11.1	15.1	313
Test 9	1	16	3.97	5.41	476
	2	24	14.2	19.4	437

	3	57	20.3	27.7	373
	4	80	15.3	20.8	329
	5	90	9.15	12.5	250
	6	93	3.97	5.41	201
Test 10	-	360	11.1	15.1	68.4
Tests 11 & 12	-	180	11.1	15.1	120

Periodically, the columns were subjected to variations in influent hydrologic regime, pollutant loading, and antecedent dry period. This testing regime is outlined in Tables 3-7 and 3-8. Test 6 subjected the columns to an altered hydrologic regime, consisting of 6 “steps” of varying flowrate and pollutant concentration to more closely simulate actual rainfall. The flowrate followed an approximate log-normal distribution, being typical for stormwater runoff. It must be noted that the influent was not statistically log-normally distributed as it failed the Kolmogorov–Smirnov one sample test for a log-normal distribution. The applied pollutant concentration decreased step-wise with time. The applied flowrate and pollutant concentration were calculated to provide each column over the course of the 6 hour test with the same total influent volume and pollutant mass as the standard tests (17.2 gal/column, 7.8 mg P). It should be noted that across all tests, all pollutants were applied at a constant ratio relative to P. Figure 3-4 provides a graphic representation of the flowrate and pollutant concentration for test 6.

Test 7 subjected the columns to a standard uniformly-distributed hydrologic regime with a 2.5-fold increase in the influent pollutant concentration. Test 9 again subjected the columns to a log-normally distributed hydrologic regime with a 2.5-fold increase in the concentration of each “step”. Additionally, the antecedent dry period for this test was doubled to 13 days. Test 10 had a standard hydrologic regime with a reduced influent concentration of approximately 60% of standard. Tests 11 and 12 subjected the columns to a reduced antecedent dry period. Test 11 was a standard experiment run for only 3 hours instead of 6. Test 12 was a replicate of test 11 run 4 days later, providing an antecedent dry period of 3 days. It was chosen to run both tests at ½ duration (3 hours) due to the logistical impossibility of analyzing all samples from a full duration test provided the reduced time period between runs.

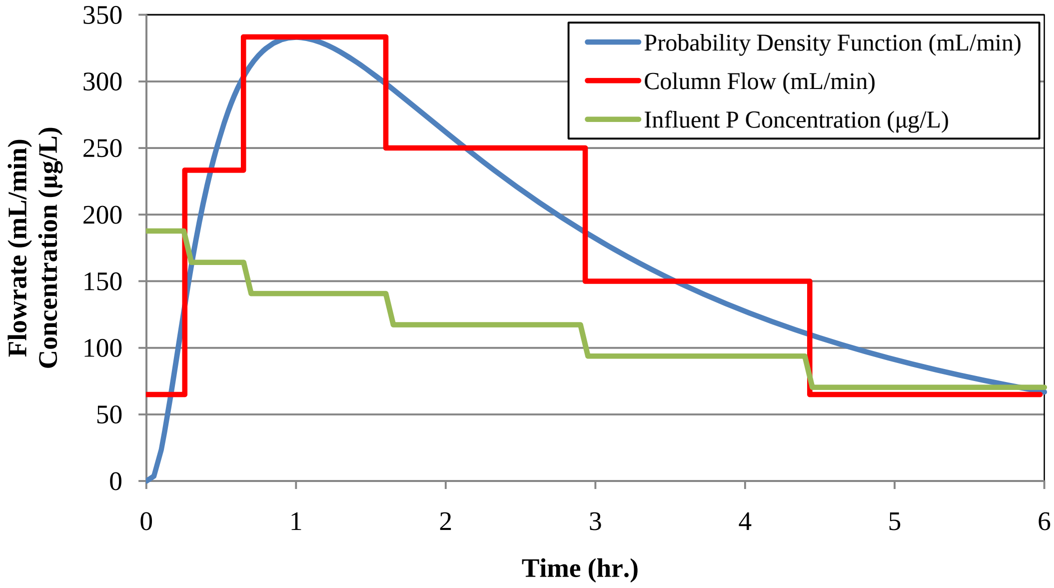


Figure 3-4. Hydrologic and pollutant concentration regime for Test 6, as well as the hydrologic regime for Test 9.

3.6. Analytical Procedures

Numerous analytical procedures were performed on the column effluents and batch study solutions. The batch study solution was analyzed for SRP per Standard Method 4500-P E. Additionally, pH was determined using a glass electrode pH meter (Mettler Toledo MA235). Total phosphorus (TP) was determined using potassium persulfate digestion (4500-P B.5) and colorimetric determination by the ascorbic acid method (4500-P E) at 880 nm as described in Standard Methods (APHA, 1992). Samples were also analyzed for turbidity using a turbidimeter (Hach 2100N). Electrical conductance was measured using a conductance meter (YSI Model 35). Total dissolved phosphorus (TDP) samples were filtered through a 0.22 µm membrane filter and analyzed using methods identical to TP analysis. Samples for NO_3^- determination were filtered (0.22 µm membrane) and analyzed by ion chromatograph (Dionex DX-100) per Standard Method 4110 (APHA, 1992). TKN was analyzed using 300 mL sample volume and the macro-Kjeldhal digestion method and titration per Standard Method techniques 4500-N_{org} B and 4500-NH_3 C, respectively (APHA, 1992). Samples for SO_4^{2-} were filtered (0.22 µm membrane) and analyzed by ion chromatograph (Dionex DX-100) per Standard Method 4110 (APHA, 1992). NO_2^- was analyzed colorimetrically in compliance with Standard Method 4500- NO_2^- B. Summarily, 2 mL of color reagent was added to 1.7 oz. (50 mL) filtered sample (0.22 µm) and analyzed after 10 minutes via spectrophotometer (Shimadzu, UV-160) at 543 nm.

Water extraction of various media and media components was performed per the method outlined in *Methods of Soil Analysis* (Kovar and Pierzynski, 2009). 4 g of media (oven dry mass basis) were placed in a 1.7 oz. (50 mL) centrifuge tube along with 1.4 oz. (40 mL) deionized water, to provide a 1:10 media:solution ratio. A tube containing solely deionized water was also carried through all analyses as a blank. Centrifuge tubes were then placed on an end-over-end shaker for 1 hour. After shaking, all samples were centrifuged at 4000 rpm for 13 minutes and then filtered through a 0.22 µm membrane filter. Water-extractable phosphorus (WEP) was determined by the ascorbic acid method (4500-P E; APHA, 1995). Anions such as NO_3^- and SO_4^{2-} were determined by ion chromatography per Standard Method 4110 (APHA, 1992).

Both BSM and WTR were digested per EPA Method 3050B (Acid Digestion of Sediments, Sludges, and Soils) and analyzed by atomic absorption spectrophotometry (AAS) (Perkin-Elmer 5100PC) for total content of metals, including: Al, Fe, Ca, and Mg. This method releases most elements that may become environmentally available. By design, this method generally does not release those elements bound by silicates, as these are predominantly non-mobile in the environment. In brief, Method 3050B involved digesting 1 g (oven dry mass) of sieved media (< 2 mm) with concentrated HNO_3 for two hours or until a final volume of 5 mL was reached, with HNO_3 addition sufficient for all organic material to be oxidized as evidenced by the cessation of brown fume generation (an indicator of oxidation of organic material). Then, 2 mL water and 2-10 mL H_2O_2 was added, 1 mL at a time, until effervescence was minimal or the maximum 10 mL added. Again, the mixture was digested for 2 hours or to a final volume of 5 mL. Finally, 10 mL concentrated HCl was added and the mixture heated for 15 minutes. It was then filtered through a glass fiber filter (Whatman No. 40), diluted to 3.4 oz. (100 mL), and analyzed by AAS.

Effluent total metals content was determined by AAS after digestion per Standard Method 3030 E (APHA, 1992). 5 mL of concentrated HNO_3 was added to 50 mL of column effluent in an erlenmeyer flask, which was heated until the total solution volume was reduced to approximately 10 mL. The flask was then removed from the heat, allowed to cool, and rediluted to 1.7 oz. (50 mL). This solution was then analyzed by AAS. Prior to analysis, collected samples were acidified < pH 2 with HNO_3 and stored at 4°C. Digestion and analysis was conducted within 6 months of sample collection.

Determination of oxalate extractable elements; namely iron (Fe), aluminum (Al), and phosphorus (P), was also undertaken. An acid ammonium oxalate solution was used as an extractant to selectively dissolve the amorphous (non-crystalline) fraction of certain soil compounds; namely (hydr)oxides of Al and Fe (McKeague and Day, 1966; 1993). A number of studies have shown a strong correlation between oxalate-extractable aluminum and iron (Al_{ox} + Fe_{ox}) and P sorption capacity or, conversely, risk of soil P leaching (Dayton and Basta, 2005). Specifically, the Phosphorus Saturation Index (PSI) is often used as a measure of P adsorption/leaching potential, and is defined as:

$$\mathrm{PSI} = \frac{\mathrm{P_{ox}}}{(\mathrm{Al_{ox}} + \mathrm{Fe_{ox}})} \tag{3-3}$$

where P_{ox}, Al_{ox}, and Fe_{ox} are oxalate-extractable P, Al, and Fe in mmol/kg, respectively. Work has shown that in general, a PSI above 0.1 greatly increases the risk for P leaching from a soil (Agyin-Birikorang and O'Connor, 2007, Kleinman et al., 2000).

In this research, a modified method of McKeague and Day (1993) was utilized, with a 0.275 M acid ammonium oxalate (0.175 M Ammonium Oxalate + 0.1 M Oxalic Acid) solution used as an extractant, this solution having a pH of approximately 3.4. The pH was adjusted to 3.0 ± 0.1 using 1 M HCl. A 1:40 w/v ratio of media to oxalate solution was used. The single exception to this was the determination of the oxalate-extractable content for WTR alone, for which was used a 1:100 w/v ratio per the recommendation of Dayton and Basta (2005), who showed that a greater ratio is necessary to accurately characterize WTRs because of their much greater amorphous aluminum content.

The oxalate solution was both added to the media and shaken on an orbital shaker for 2 hours in the dark. Samples were centrifuged for 13 minutes at 2000 rpm after shaking and filtered through a 0.22 µm membrane filter. This filtrate was then analyzed by AAS for Fe and Al within 1 week.

P was analyzed using the method of Wolf and Baker (1990), a modification of the method of Murphy and Riley (1962), with the addition of excess ammonium molybdate. This addition is necessary as oxalate binds molybdate, resulting in insufficient concentration in solution to react with P to form the phosphomolybdic acid which is ultimately measured. This method calls for the use of 0.275 M acid ammonium oxalate solution, and is the impetus behind the use of this higher-than-standard concentration in this work. As with Fe and Al, oxalate extraction samples were analyzed colorimetrically for P within 1 week.

3.7. Statistical and Numerical Analyses

3.7.1. Media Adsorption Capacity

Media adsorption capacity for column studies was calculated by the equation:

$$q = \frac{T_{P,in} - T_{P,out}}{M_{media}} \tag{3-4}$$

where q is the total media P adsorption capacity (mg_P/kg_{media}), $T_{P,in}$ is the total mass of P which entered the column (mg P), $T_{P,out}$ is the total mass of P which exited the column (mg P), and M_{media} is the oven-dried mass of media within the column at the outset of the experiment (kg media). $T_{P,in}$ and $T_{P,out}$ were calculated as:

$$T_P = \int_{t_0}^{t_i} C \cdot Q \, dt \tag{3-5}$$

where T_p is the total mass of P either entering or exiting the column (mg P). C is the concentration of P (mg/L) and Q the volumetric flowrate (L/min), integrated with respect to time from the beginning of column flow (t = 0 min) to the cessation of the experiment (t = i min). The media adsorption capacity, q, defines the mass of a pollutant that can be adsorbed or otherwise immobilized per unit of treatment media under specific environmental conditions (i.e., pH, pollutant concentration, ionic strength, temperature, etc.).

Predominantly, TP and TDP were used independently to calculate media adsorption of total and dissolved P species. However, when TDP measured greater than TP for a given sample (one occurrence for the vegetated control column), the result was rejected as irrational and erroneous, and TP used for all calculations.

3.7.2. Event Mean Concentration

Synthetic storm event mean concentrations (EMCs) were calculated for a number of tests and pollutants, specifically during the vegetated column experiments. The EMC is calculated from a composite of discrete samples, and used to estimate the flow-weighted mean outflow concentration for the entire storm. The EMC may be visualized as the concentration of the outflow if the entire runoff volume could be captured in a single container. It is calculated by using integration to determine the entire influent pollutant mass divided by the entire flow volume, or:

$$\mathrm{EMC} = \frac{\int_{t_0}^{t_i} C \cdot Q \, dt}{\int_{t_0}^{t_i} Q \, dt} \qquad (3\text{-}6)$$

where C is the concentration, Q is the flowrate, and t_0 and t_i are the initial and final times, respectively. The EMC is used as a means to compare mean pollutant concentrations between events and to compare average influent and effluent pollutant concentrations.

3.7.3. The Kolmogorov-Smirnov One Sample Test

The Kolmogorov-Smirnov one sample test is a hypothesis test to analyze for the probability density function (PDF) of a sample population. The test involves calculation of the test statistic, |D|, which is the absolute maximum difference between the cumulative probability distribution of the sample and that of the hypothesized PDF. The analysis tests the null hypothesis (H_0) that the sample population has the given PDF against the alternative hypothesis (H_A) that is does not. A critical value (D_α) is calculated at the 5% level of significance, and if $|D| > D_\alpha$, H_0 is rejected and sample population does not have the hypothesized PDF.

3.7.4. The Dixon-Thompson Test

The Dixon-Thompson Test is an analysis for the determination of outliers from a given sample population. The test assumes that the sample data are independent measurements from a normal population, and that a datum that tests positive as an outlier is in fact from another population having either a different mean or a larger variance. The analysis tests the null hypothesis (H_0) that all data point are from the same population, against the alternative hypothesis (H_A) that the most extreme point in the sample is not from the same normal population as all other sample points.

The test is only valid for the analysis of a single outlier of either extreme (i.e., upper or lower outlier). All data are sorted in descending order and the most extreme value is used in the calculation of the test statistic (R). The calculation for R is dependent on sample size. R is evaluated against the critical value (R_α) at the 5% level of significance, and the null hypothesis is rejected if $R > R_\alpha$. Upon rejection of the null hypothesis, the potential outlying point was assessed to determine if there was an empirical reason for the extreme value (e.g., excessive release of particulate matter from the media after flowrate increase). If there was such an identifiable cause for the event, the outlier was removed from further calculations.

3.7.5. T-test

The t-test was used as means of determining if two sample means are statistically the same. A test statistic, t, is calculated to analyze the degree of variation between each sample relative to that within a sample. The value of t is calculated as:

$$t = \frac{x_1 - x_2}{S_p \cdot \left(\frac{1}{n_1} + \frac{1}{n_2}\right)^{0.5}} \tag{3-7}$$

where x_i is a sample mean, n_i is the number of data points within a sample, and S_p is the standard deviation of the paired means, calculated as:

$$S_p^2 = \frac{(n_1 - 1) \cdot S_1^2 + (n_2 - 1) \cdot S_2^2}{n_1 + n_2 - 2} \tag{3-8}$$

where S_i is the standard deviation of a given the sample. It was assumed that all sample populations were normally distributed and had equal variances. This analysis was used to test the null hypothesis (H_0: $\mu_1 = \mu_2$) that the two sample population means compared are equal, against the alternate hypothesis that they are not (H_A: $\mu_1 \neq \mu_2$). The calculated t value was compared against a critical value, t_α, at a 1% level of significance.

Chapter 4: Batch and Column Experiments

Phosphorus adsorption batch studies were undertaken to investigate the impact of various media amendments on BSM and their effectiveness on the removal of P from solution. These studies provided an initial estimate of the proportion of these amendments in the BSM, as well as gave evidence of the impact of certain environmental variables on media performance, such as pH.

4.1. Media Characterization

Characterization of the materials used in this study was necessary to provide insight on the nature of these components. The results of 0.275 M acid ammonium oxalate extraction and WEP for BSM, WTR, HBM, and LC are found in Table 4-1. Additionally, the results of a 3050B digestion and metal analysis for BSM and WTR are also included. From Table 4-1, it is seen that LC contains 5.29 mg WEP/lb (11.7 mg/kg), followed by HBM with 1.29 mg WEP/lb (2.85 mg/kg), BSM with 0.162 mg WEP/lb (0.358 mg/kg), and WTR which measured below the detection limit of 0.05 mg WEP/lb (0.1 mg/kg). Clearly the organic amendments, and LC in particular, contain the largest amount of very labile WEP.

Interestingly, P_{ox} does not follow a similar order of increasing P content. WTR contains by far the largest P_{ox} content with 0.820 g P_{ox}/lb (1.81 g/kg). LC contains the second largest amount with 0.223 g P_{ox}/lb (0.492 g/kg), followed by BSM with 0.057 g P_{ox}/lb (0.125 g/kg), and HBM with 0.053 g P_{ox}/lb (0.116 g/kg). Therefore the percent fraction of very labile P (WEP/P_{ox}) is 2.46% for HBM, 2.37% for LC, 0.286% for BSM, and < 0.006% for WTR. This ratio shows the proportion of a component's P which is in the most labile state. The strong adsorption of P by the WTR is clear as effectively none of its P is labile. Similarly, the inherent P in the BSM appears to be predominantly adsorbed to Fe and Al species and not released until dissolution by oxalate. Both organic amendments show similar proportions of very labile P, however the magnitude of P in each material is different, which may partly explain their different P adsorption behavior.

Table 4-1. Media component characterization. ‡: Water-extractable phosphorus, ×: Data not collected.

	Oxalate Extractable (g/kg)			WEP	Total Elements (g/kg)			
	P	Fe	Al	(mg/kg)	Ca	Mg	Fe	Al
BSM	0.125	0.871	0.286	0.358	2.24	2.58	20.4	21.9
WTR	1.81	3.67	155	< 0.1	0.038	0.778	8.80	169
HBM	0.116	3.04	0.343	2.85	×	×	×	×
LC	0.492	2.20	0.369	11.7	×	×	×	×

Among the four materials, Fe_{ox} content is fairly consistent. WTR contains the most with 1.67 g Fe_{ox}/lb (3.67 g/kg), HBM contains 1.38 g Fe_{ox}/lb (3.04 g/kg), LC contains 0.999 g Feox/lb (2.20 g/kg), and BSM contains the least with only 0.395 g Fe_{ox}/lb (0.871 g/kg). Additionally, total Fe was determined for both the BSM and WTR, which showed 9.25 g Fe_{Tot}/lb (20.4 g/kg) and 3.99 g Fe_{Tot}/lb (8.80 g/kg), respectively. This indicates that of the Fe in the BSM, 4.27% is amorphous, while the WTR Fe is 41.7% amorphous. A much larger proportion of the Fe in the BSM is crystalline.

For Al_{ox}, the WTR shows a clearly larger amount compared to the other materials with 70.2 g Al_{ox}/lb (155 g/kg). The LC contains 0.167 g Al_{ox}/lb (0.369 g/kg), HBM contains 0.156 g Al_{ox}/lb (0.343 g/kg), and BSM contains 0.130 g Al_{ox}/lb (0.286 g/kg). The total Al content for the BSM and WTR are 9.95 g Al_{Tot}/lb (169 g/kg) and 76.5 g Al_{Tot}/lb (21.9 g/kg), respectively. This equates to 1.30 and 91.8% of the Al being amorphous in the BSM and WTR, respectively. Again, this indicates that the majority of Al in the BSM is crystalline, while nearly the entire Al contained in the WTR is amorphous.

Having analyzed all four materials for oxalate-extractable P, Fe, and Al, the media PSI may be determined. Each media PSI measures 1.00, 5.58, 15.4, and 29.9% for the WTR, HBM, WTR, and LC, respectively. Research has shown that media P leaching greatly increases with a PSI > 10% (Agyin-Birikorang and O'Connor, 2007). This indicates that, as expected, the WTR has a very large capacity for P adsorption. The HBM also shows some capacity on account of its low P_{ox} content relative to its $(Al+Fe)_{ox}$ content, which may explain the improved P adsorption capacity of the BSM when amended with both HBM and WTR (see Sections 4.3 and 4.4.3). Conversely, the LC PSI indicates it is as risk for P leaching, which may again explain its poor P adsorption performance. The BSM also indicates it is at risk for P leaching. This is because it has low $(Al+Fe)_{ox}$ content, which appears to be nearly or completely saturated with P as suggested by its relatively high P_{ox} content.

Aluminum-based WTR can be a highly variable material, and the implications this has on its use as a BSM amendment requires addressing. The physical and chemical characteristics of WTR will conceivably be affected by a number of parameters. For instance, the amount of alum added to remove colloidal material in the flocculation basin during drinking water treatment will have some impact on the resulting mass of aluminum hydroxide in the WTR, and likely affect its P adsorption capabilities.

A number of references have discussed WTR Al_{ox} content. Elliott et al. (2002) reported 32.6 g Al_{ox}/lb (71.9 g/kg) in a WTR used in a column study as a soil amendment to measure its impact on soil P leachability. In a field study in Florida to assess the impact of surface-applied WTR and manure on soil P leaching, Agyin-Birikorang et al. (2009) reported a WTR Al_{ox} content of 38.2 ± 2.8 g Al_{ox}/lb (84.3 ± 6.2 g/kg). Dayton and Basta (2005) reported on 18 WTRs from Pennsylvania and Oklahoma, having a mean Al_{ox} content of 33.2 ± 20.0 g Al_{ox}/lb (73.1 ± 44.2 g/kg), and a median content of 26.7 g Al_{ox}/lb (58.8 g/kg). The WTR used in the present study measured 70.3 ± 3.38 g Al_{ox}/lb (155 ± 7.45 g/kg; Table 4-1).

These data show quite a large amount of variation in WTR characteristics. The WTR used in this work trends toward the high end in terms of typical Al_{ox} content, and this must be taken into account when considering P adsorption results. However, this should have no effect on the use of Al-WTR as a BSM amendment. Ultimately, recommendations in Sections 6.4 and 7.1 are based on the measure of P_{ox}, Al_{ox}, and Fe_{ox} in a BSM mixture, not by percent mass of WTR. This should adequately account for the variability seen in the oxalate-extractable contents of WTRs.

4.2. Media Adsorption pH Effects

Results of investigation into pH effects on WTR adsorption capacity were encouraging. WTR acted as a buffer upon pH adjustment, which should be expected because of the chemicals routinely added to drinking water during treatment. This resulted in approximately neutral pH after equilibration in most instances. The final pH of solutions containing WTR ranged from approximately 5.9 to 7.4, trending higher with increasing WTR content. Mixtures unamended with WTR had a range of final pH values that was shifted somewhat lower, as these did not benefit from the buffering capacity provided by the WTR, ranging from 4.6 to 7.2. Minimal pH effect on P adsorption capacity was observed in this pH range, as exemplified in Figures 4-1 and 4-2 (note the variations in both the ordinate and abscissa axes between the plots). Therefore, changes in pH within this range are not expected to produce large differences in media P adsorption and minor fluctuations in pH are not expected to significantly impact results.

4.3. Media P Adsorption Isotherms

Sorption isotherms for each amendment mixture were plotted as the P concentration remaining in solution after equilibration and the mass of adsorbed P per mass of media. Table 4-2 shows the Freundlich equation constants for each isotherm, and details each media's P adsorption capacity at equilibrium with a 120 μg/L P

solution as calculated from the isotherms. The effect of WTR content on BSM sorption capacity is summarized in Figure 4-3, and its effect on LFBSM is seen in Figure 4-4. BSM and LFBSM media having the same WTR content are compared in Figure 4-5. These data clearly show that increasing the WTR content of the media increases its P adsorption capabilities, as does the estimated media adsorption capacities predicted utilizing the fitted Freundlich isotherms, seen in Table 4-1.

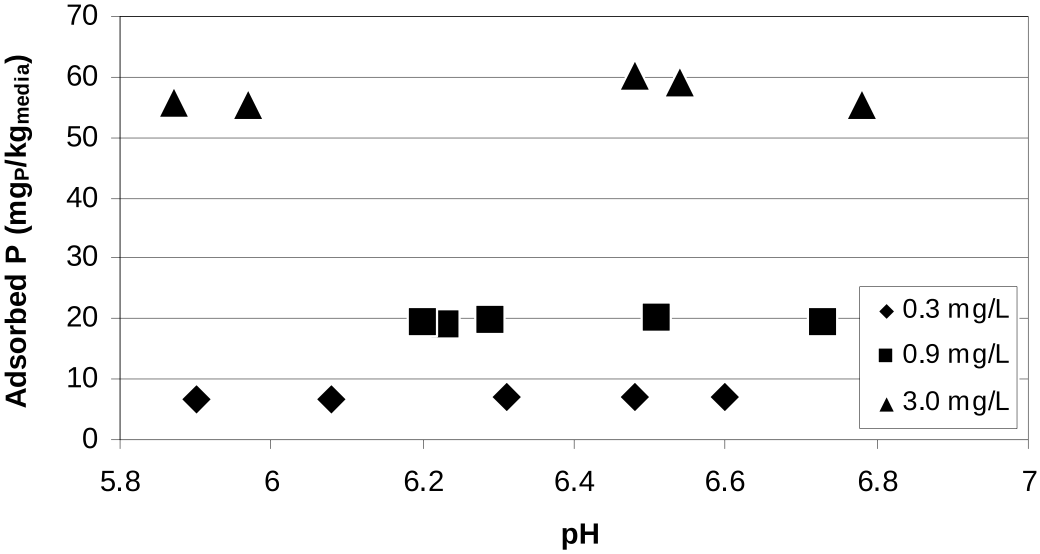


Figure 4-1. P sorption capacity of BSM + 2% WTR as affected by variation in pH after equilibration with P solutions of 0.3, 0.9, and 3.0 mg/L initial concentration.

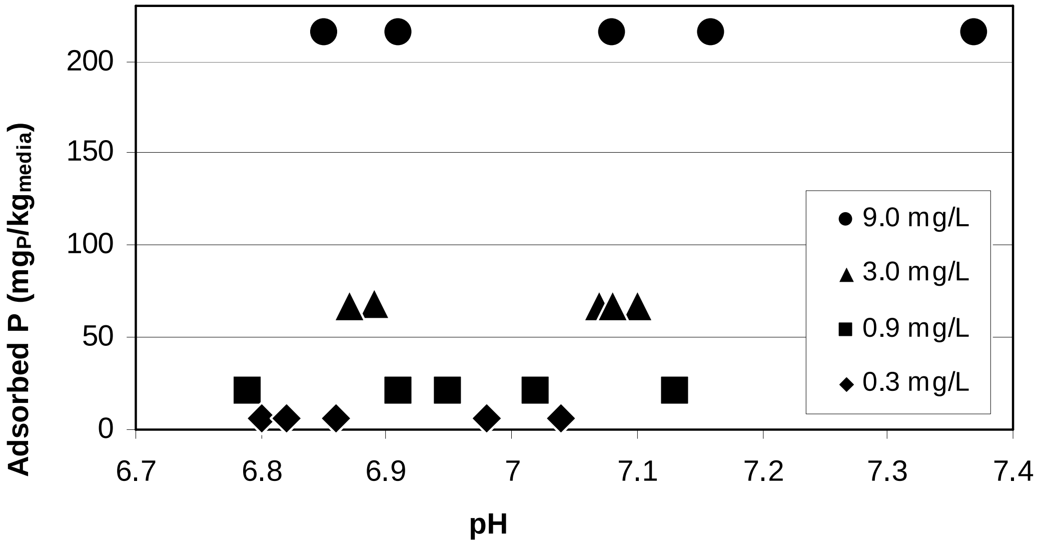


Figure 4-2. P sorption capacity of BSM + 10% WTR as affected by variation in pH after equilibration with P solutions of 0.3, 0.9, 3.0, and 9.0 mg/L initial concentration.

Table 4-2. Freundlich equation constants for the investigated BSM mixtures. 0.3, 0.9, 3.0, and 9.0 mg P/L solution additions were used containing 0.01 M KCl as a background electrolyte and at pH 4.6 to 7.4. A media to solution ratio of 1:25 was used.

Mixture	**K**	**n**	**Adsorption Capacity at 120 µg P/L (mg/kg)**
BSM	46.0	1.69	13.1
2% WTR	69.3	1.61	18.6
4% WTR	106	1.50	25.6
10% WTR	361	1.49	81.9
LFBSM	21.0	1.37	4.49
3% WTR	90.4	1.62	24.4
6% WTR	271	1.35	56.1
10% WTR	1786	1.02	225
BSM + HBM	61.0	1.36	12.8
2% WTR + HBM	183	1.25	33.4
4% WTR + HBM	256	1.22	45.0
BSM + LC	17.5	0.778	1.14
4% WTR + LC	326	0.857	27.4
4% WTR + LC [OM+]	273	0.580	7.07
0.5% AH	244	1.23	43.7

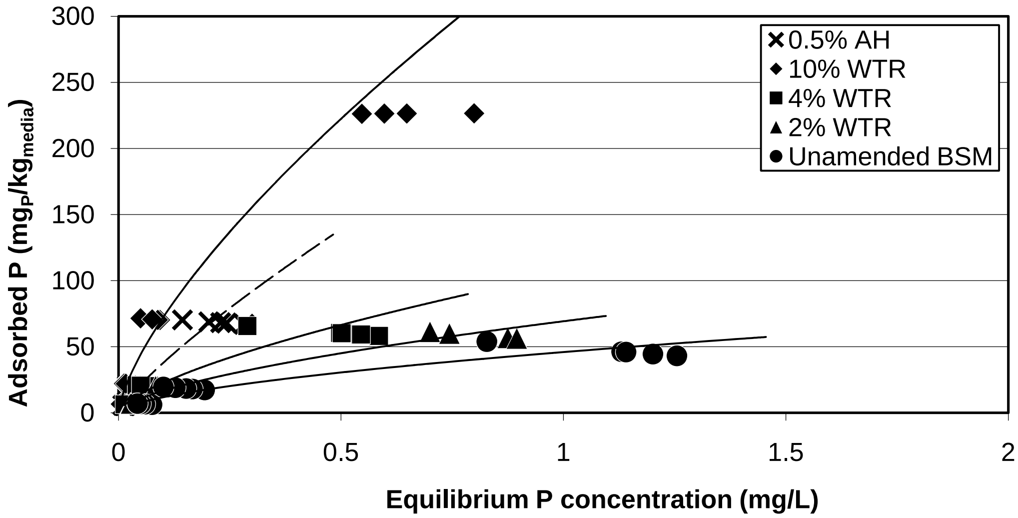


Figure 4-3. Comparison of P adsorption isotherms for BSM amended with various amounts of Al-WTR as well as 0.5% Al_{ox} WTR-equivalent as $Al(OH)_3$ at a pH range of approximately 4.2 to 7.4. Data produced using 0.01 M KCl as a background electrolyte and a media to solution ratio of 1:25. Lines are fitted Freundlich isotherms.

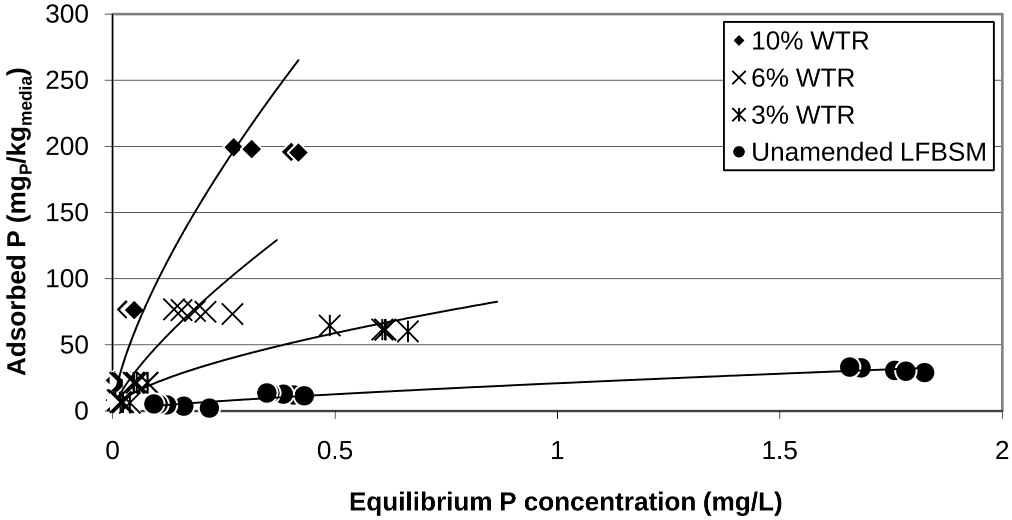


Figure 4-4. Comparison of P adsorption isotherms for LFBSM amended with various amounts of Al-WTR at a pH range of approximately 4.6 to 7.3. Data produced using 0.01 M KCl as a background electrolyte and a media to solution ratio of 1:25. Lines are fitted Freundlich isotherms.

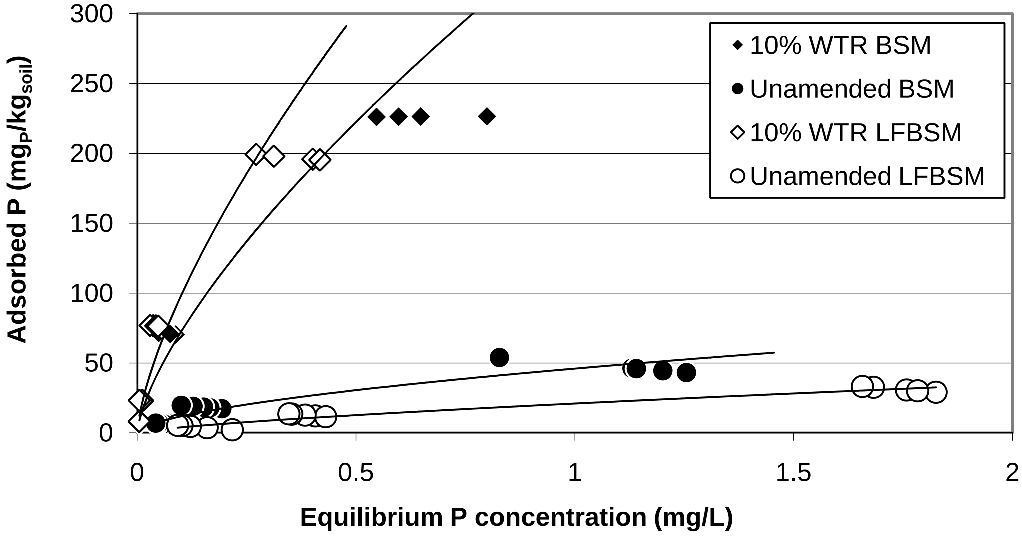


Figure 4-5. Comparison of P adsorption isotherms for BSM and LFBSM both unamended and amended with 10% Al-WTR (air dry wt.) at a pH range of

approximately 4.6 to 7.4. Data produced using 0.01 M KCl as a background electrolyte and a media to solution ratio of 1:25. Lines are fitted Freundlich isotherms.

The unamended LFBSM media clearly shows a decreased adsorption capacity compared to the BSM, which is attributed to the lower clay content (and associated Al and Fe (hydr)oxides). However, increased adsorption for the low-fines media was observed when comparing the LFBSM and BSM amended with an equal proportion of WTR. The reason for this behavior is unknown, but may be explained by occlusion of WTR surfaces by fines in the media. As many soil minerals and especially clays have negative surface charges (Sposito et al., 1999), upon mixing with WTR the complementary surface charges of the clays and WTR may lead to surficial interactions (Goldberg, 1990). This results in decreased exposed surface area available for P adsorption. This phenomenon was further investigated through scanning electron microscopy (SEM) analysis of various media, but differences between mixtures were not overtly apparent. Fines addition may also improve adsorption because BSM is nearly saturated with P, as indicated by its 15.4% PSI. Addition of BSM adds significantly to the P_{ox} of the mixture, while the addition of sand reduces this source of P while maintaining a high Al_{ox} content as the proportional mass of WTR in the mixture is unchanged. This results in a greater P adsorption capacity. It is believed that both mechanisms account for the increased adsorption of low-fines media.

The addition of fines may only improve sorption capacity where BSM is no longer a sink for P. Consequently, use of BSM containing higher contents of clay not saturated with P may show decreasing P adsorption with addition of sand. However, electrostatic interactions between the complementarily charged clay and WTR surfaces are believed to be possible, and clays with a high net negative surface charge may compete with P for available adsorptive surface sites based on evidence of competition between P and other anionic compounds (Goldberg and Sposito, 1985).

Effects of organic amendments on P adsorption may be seen in Figures 4-6 and 4-7. HBM improved adsorption, shown in Figure 4-6. This may possibly be due to the formation of metal-OM complexes which provide additional reactive sites for P adsorption (Darke and Walbridge, 2000; Kang et al., 2009; Figure 2-2).

As hypothesized, LC addition to the BSM resulted in decreased P adsorption, as seen in Figure 4-7. BSM + LC performed worse than BSM when unamended in all respects. When amended with WTR, though, this was not necessarily the case. The media amended with both WTR and LC performed better than without LC at higher P concentrations. This held true even for the 4% WTR amended BSM mixture with additional LC, referred to hereafter as the OM+ mix. However, the 4% WTR + LC performed better only above 0.1 mg P/L, and the OM+ mix performed better only above 0.5 mg P/L when utilizing the fitted trend lines. Therefore, at the concentrations of P found in most urban stormwater, it is expected that LC will have a detrimental effect on adsorption. It is believed that this loss of adsorptive capacity is caused by leachable P inherent in the LC, which may be released into solution and adversely affect adsorption to the WTR. By its nature, LC is in a greater state of decomposition than HBM and so is expected to have greater labile P content. This is supported by Gressel et al. (1996), who found that the extent of P mineralization and P_i content is positively correlated with the breakdown of OM (leaf litter) in forest soils. By corollary, the advanced state of decomposition of LC is reason to expect a high labile P_i content, which may explain the reduced media P adsorption capacity when LC is used as an amendment.

Pure $Al(OH)_3$ was also amended to the BSM to allow comparison with WTR. As explained in Section 4.4, $Al(OH)_3$ was amended on an amorphous Al basis analogous to 0.5%, 2% and 4% WTR. Both 2% AH and 4% AH additions completely or nearly completely removed all added phosphate, resulting in P concentrations after equilibration below the method detection limit (10 μg/L). In both instances an adsorption isotherm could not accurately be constructed because of this.

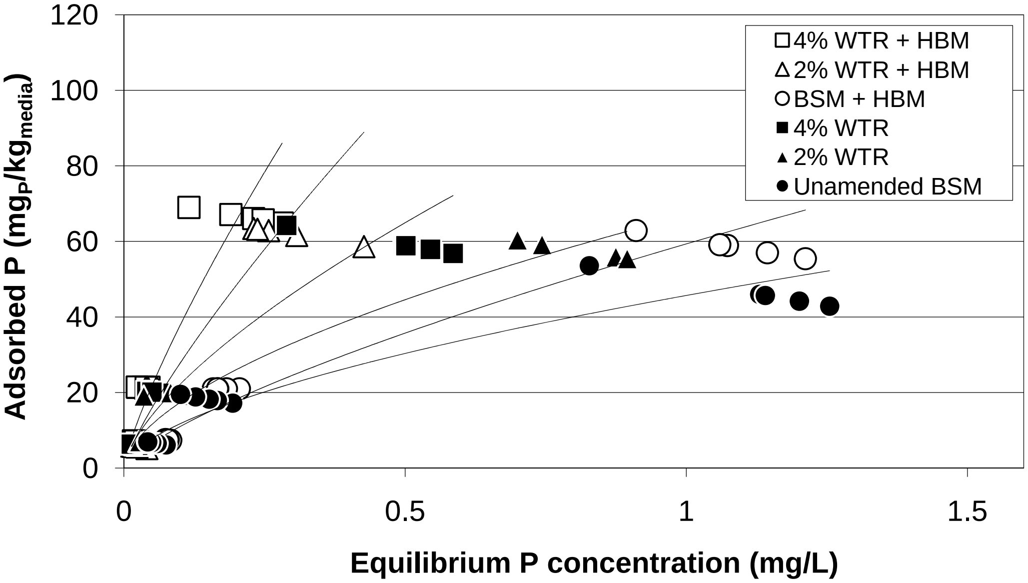


Figure 4-6. Comparison of P adsorption isotherms for BSM and BSM + HBM, both unamended and amended with 2% and 4% Al-WTR (air dry wt.) at a pH range of approximately 4.8 to 7.4. Data produced using 0.01 M KCl as a background electrolyte and a media to solution ratio of 1:25. Lines are fitted Freundlich isotherms.

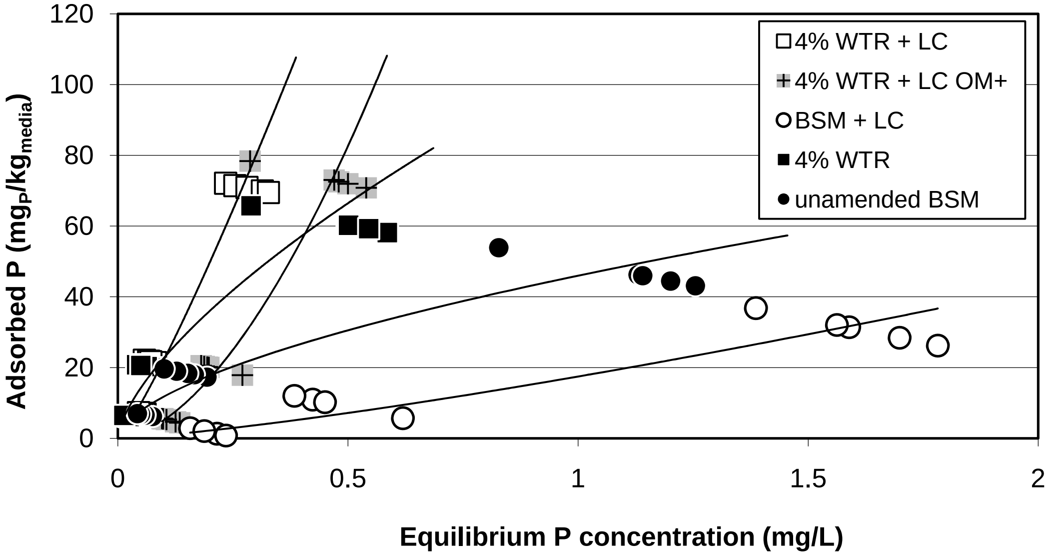


Figure 4-7. Comparison of P adsorption isotherms for BSM and BSM + LC, both unamended and amended with 4% Al-WTR (air dry wt.), plus 4% WTR with additional LC content (OM+ treatment). The pH range of the data is approximately 4.8 to 7.4., and was produced using 0.01 M KCl as a background electrolyte and a media to solution ratio of 1:25. Lines are fitted Freundlich isotherms.

The 0.5% AH addition produced adsorption results from which an isotherm could be constructed. In comparison with BSM amended solely with WTR, it performed between the 4% and 10% mixtures (Figure 4-3). Although the WTR and AH amendments contain the same amount of amorphous $Al(OH)_3$, the AH amendment adsorbs P much more efficiently. A number of possibilities exist that may explain this phenomena. It may be that the AH amendment possesses a much greater surface area compared to the WTR, as it is a powder. Also, oxalate extraction is operationally defined as a measure of amorphous metals content. It may therefore be that some portion of the extracted Al is not actually amorphous, as oxalate extraction is only an operational definition of amorphous content. This would again cause the WTR to possess less surface area relative to the AH when compared on the basis of measured oxalate-extractable Al content.

It may also be that the fresh AH contains a greater percentage of highly reactive Al (hydr)oxides. Agyin-Birikorang and O'Connor (2009) investigated the effect of aging on extractable Al content of WTR using 0.2 M acid ammonium oxalate and 0.005 M acid ammonium oxalate. The former is intended to be a measure of complete oxalate-extractable content, while the latter is a measure of the most reactive oxalate-extractable Al forms. They concluded that over the course of 2 years the total oxalate Al content did not significantly change, while the highly reactive oxalate-extractable Al content steadily decreased over the first 6 months after WTR generation, stabilizing thereafter. The freshly generated AH may contain a greater highly-reactive oxalate-extractable Al content than the WTR, resulting in the disparate P adsorption capacity. It should be noted, however, that Agyin-Birikorang and O'Connor (2009) did not correlate 0.005 M oxalate-extractable Al with P adsorption capacity of the WTR, and other studies (Yang et al., 2008) showed no aging effect on WTR P adsorption capacity when stored in a watertight container as was the WTR used in this study.

The strong positive correlation between % WTR (air dry weight) and media P adsorption for these batch tests is clearly seen in Figure 4-8. It is evident that as WTR content increases, so does the media adsorption capacity. Additional amendments may enhance or reduce mixture P adsorption. HBM increases adsorption, apparently because it contains a relatively low P content in relation to its Fe_{ox} content. Conversely, the addition of LC results in lower media P adsorption relative to media without LC addition. This appears to stem from its high P and low $(Al+Fe)_{ox}$ content. The addition of quartz sand to create low-fines media also improved P adsorption. This may be due in part because the addition of sand reduces the overall media fines content. Fines, including clays, often have a net negative surface charge because of isomorphically substituted elements within the mineral lattice structure, which may undergo interactions with the positively charged WTR surface, thereby competing with P in solution for adsorption sites. It is also feasible that these small particulates are blocking WTR micropores, preventing P interactions was large

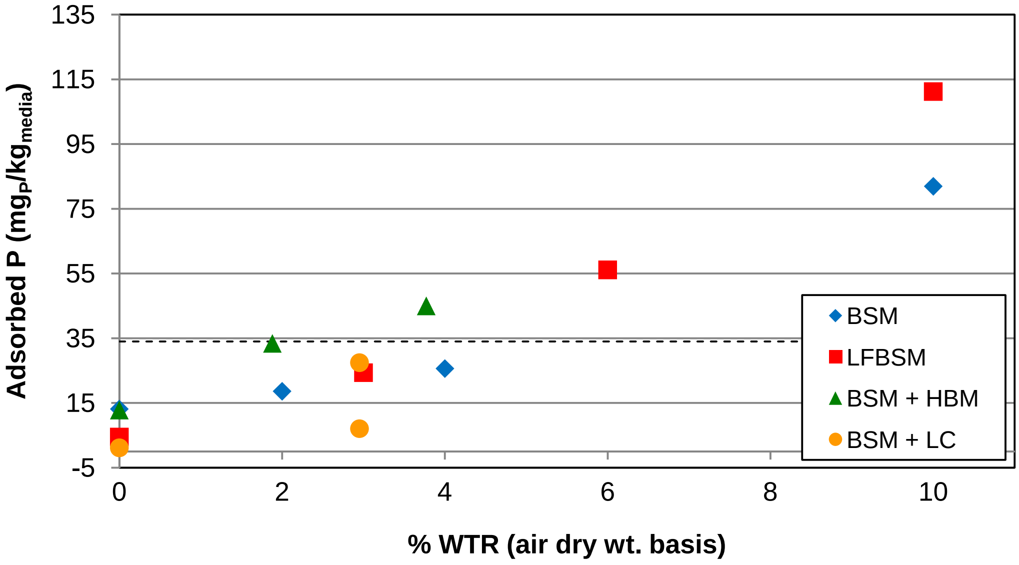


Figure 4-8. Batch data detailing increased P adsorption (at equilibrium with 120 µg/L P) with increasing WTR content (air dry weight basis). Batch adsorption data calculated from Freundlich isotherms. The dotted line represents the media adsorption benchmark of 15.4 mg P/lb (34 mg/kg).

portions of the WTR surface. Thirdly, the BSM used is nearly saturated with respect to P, and is at risk for P leaching as indicated by its PSI > 10%. So while reducing fines content in this media increases overall P adsorption, other media which are not saturated with P and contain significant Fe and Al (hydr)oxides may present increasing adsorption with increasing fines content. Also, these batch investigations only characterized the system under static conditions. Shorter reactions times and the removal of any formed complexes or leached ions in solution will occur under dynamic flow conditions, which are expected to present a different indication of media adsorption capabilities.

4.4. Minicolumn P Adsorption Study

Small (approximately 6 in. length) column studies were undertaken to determine amended BSM P adsorption capacity under flow conditions. Experiments were set up and run as described in Section 3.7, including the calculation of media P adsorption capacity by Equation 3-4. Influent P concentration for set I averaged 124 ± 8.9 µg/L (± SD), and pH average 6.57 ± 0.29 (± SD). For set II, influent P concentration averaged 122 ± 2.2 µg/L and pH averaged 6.60 ± 0.55. Table 3-3 details the media and flow regimes investigated.

Ideally, exhaustion of the media was desired during the course of these experiments to determine total media adsorption capacity when in equilibrium with the influent P solution. Exhaustion was defined as two consecutive days where the TDP concentration was at or above the influent P concentration. However, column capacity was generally depleted very slowly over time and due to constraints on allowable run time, columns were taken offline prior to complete exhaustion occurring. However, in every case media capability to remove P from the influent solution significantly diminished with time. The only media to show true exhaustion was the unamended BSM after 14.5 and 16.7 ft. (4.41 and 5.08 m) of inflow for sets I and II, respectively (Figure 4-9). This is equivalent to 8.7 and 10 in. (22.1 and 25.4 cm) over the entire catchment assuming a cell sized at 5%, or approximately 0.23 years of rain in Maryland.

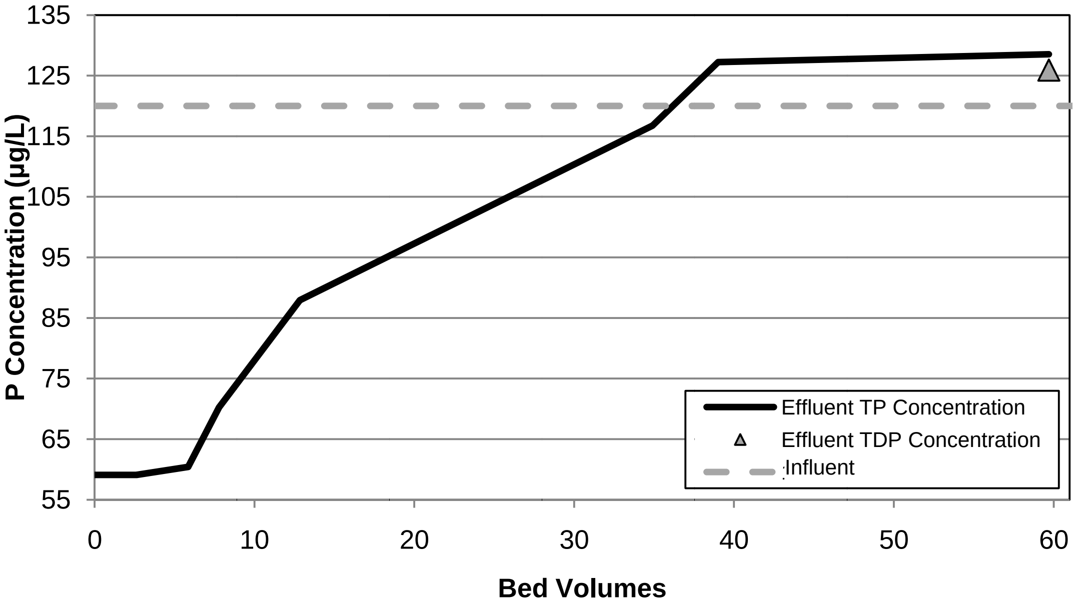


Figure 4-9. Breakthrough curve for continuously run unamended BSM media from set II. Mean influent TP concentration was 124 µg/L and pH was 5.58. The column ran for a total of 2 days at an inflow rate of 6 in/hr. Total inflow was equivalent to 10 in. of rain over the entire catchment.

In terms of P adsorption, media were expected to perform approximately as well as during batch studies, and so column results were compared against batch results to evaluate performance. As seen with the batch tests, increasing the proportion of WTR in the media was expected to yield increasing media P adsorption capacity. Based on the results of the batch studies, the addition of HBM at approximately 3% oven dry weight along with WTR was expected to increase the adsorptive capacity of the media. Additional sand was expected to increase media adsorption as well by reducing the amount of fines which occlude WTR surfaces.

Intermittent flow studies were also conducted on three different media, as detailed in Tables 3-3 and 4-3, to more accurately replicate bioretention field conditions. The addition of HBM under such conditions was expected to yield further increases in media P adsorption over the long term as such organic material retains

Table 4-3. Media adsorption capacity at equilibrium with 120 µg P/L, in mg P/kg. Set I and Set II are experimental column results for media adsorption. Expected capacity is the calculated media adsorption with 120 µg P/L based on batch adsorption isotherms (Table 4-2). ×: Data not collected; ‡: Outlier excluded; †: Intermittent flow regime.

	Set I		Set II		Expected
Media	Total	Dissolved	Total	Dissolved	Capacity
BSM	-1.00	0.422	0.706	×	13.1

BSM + 2% WTR	13.2	57.7	×	×	18.6
BSM + 4% WTR	[‡] 14.4	84.0	43.7	62.2	25.6
BSM + 4% WTR [†]	×	×	[†] 8.14	[†] 27.2	25.6
BSM + 2% WTR + HBM	10.6	43.0	×	×	33.4
BSM + 4% WTR + HBM	57.5	62.3	[†] 37.6	[†] 52.7	45.0
LFBSM + 4% WTR	124	133	[†] 52.2	[†] 65.4	×
Sand + 4% WTR	×	×	132	×	×

water and reduced media drying (Borggaard et al., 2005). As media dries, P adsorbing amorphous metal (hydr)oxides crystallize, reducing their surface area and limiting the sites available for P adsorption (Borggaard et al., 2005). It was also expected that under intermittent flow, media would show temporary improvements in adsorption upon the reestablishment of flow following dry periods (Hsieh et al., 2007a). This is because of the biphasic nature of WTR and specifically Al (hydr)oxides; whereby after the cessation of flow, "fast" adsorption reactions no longer occur and "slow" reactions continue. During these "slow" reactions P molecules diffuse deeper into the WTR particles via pores (McGechan and Lewis, 2002; Makris et al., 2004), providing increased available adsorptive surfaces for P capture upon the recommencement of flow.

4.4.1. WTR-amended BSM

Column breakthrough curves show column effluent P concentration (µg/L) as a function of the cumulative number of bed volumes (BV) treated, which is the ratio of cumulative influent to the column media volume of 2.23 oz. (66.0 mL; L influent/L column media). The reduction in media P treatment can clearly be seen by the increasing effluent P concentrations as the experiments progress, such as for the unamended BSM from set II (Figure 4-9). Additionally, sharp increases in particulate P (PP) can be seen at points when there are large differences between TP and TDP, most notably after flowrate increases, for example with 4% WTR + BSM (4% BSM) in Figure 4-10. This is due to the migration of media from the column, which is discussed in greater detail below. In all instances, data tended to have a large amount of interdiurnal variability, attributed to particulate release and the combined impact of minor changes in influent P concentration and flowrate from day to day. Table 4-3 details the calculated media P adsorption capacity based on equations 3-4 and 3-5. The P adsorption capacity was calculated based on both column effluent TP measurements, as well as TDP measurements for columns that exhibited significant effluent turbidity. In many cases, media TDP adsorption capacity was significantly greater than that found for TP (Table 4-3). While this is predominantly because of PP losses from the column media, it must be noted that calculations based on TDP are a much more coarse measure of adsorption as TDP was analyzed for less consistently.

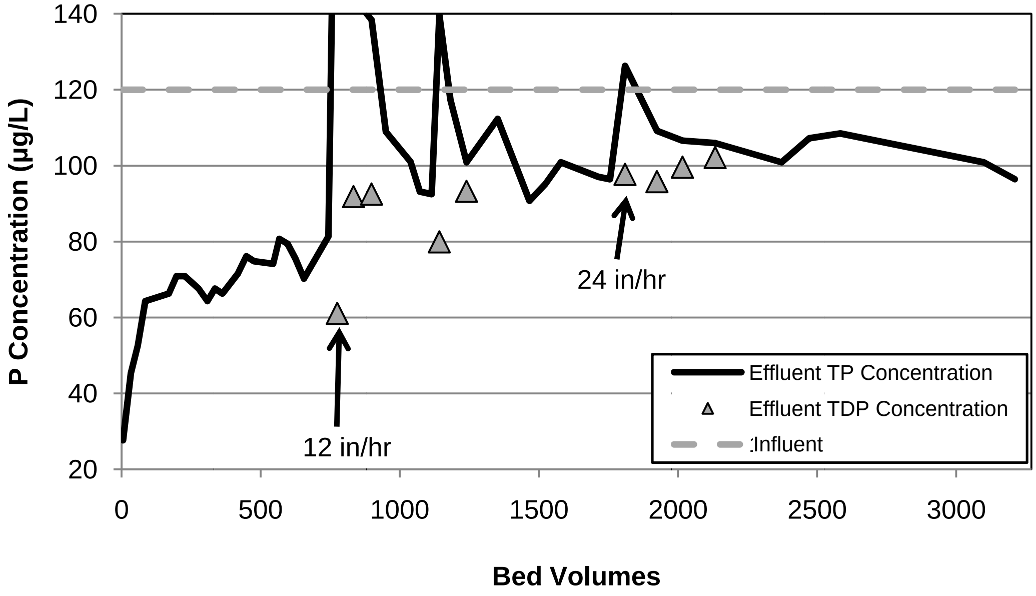


Figure 4-10. Breakthrough curve for continuously run BSM + 4% WTR from set II. Mean influent TP concentration was 122 µg/L and mean pH was 6.60. The column ran for a total of 64 days. Labeled arrows indicate increases in column flowrate from an initial rate of 6 in/hr. Total inflow was equivalent to 68.6 ft. of rain over the entire catchment.

As stated previously, increasing WTR content produced increasing P adsorption capacity. However, column results were more mixed in terms of the magnitude of expected adsorption compared to batch studies. Subject to continuous flow, both unamended BSM and 2% WTR amended media (2% BSM) adsorbed less P to varying degrees relative to what was expected based on Freundlich isotherms (Table 4-2) from the batch studies. For instance, unamended BSM was expected to adsorb 5.94 mg P/lb (13.1 mg/kg) based on batch study Freundlich isotherms (Table 4-2), but instead exported 0.454 mg P/lb (1.00 mg/kg). 2% BSM displayed adsorption of only 5.99 mg P/lb (13.2 g/kg), which is somewhat lower than the predicted P adsorption capacity of 8.53 mg P/lb (18.8 g/kg) based on Freundlich isotherms. 4% BSM showed adsorption capacity of 19.8 mg P/lb (43.7 g/kg) during set II, better than the Freundlich isotherm-based expectation of 11.6 mg P/lb (25.6 g/kg). Conversely, TP adsorption for 4% BSM from set I performed significantly worse (Table 4-3), with equilibrium P adsorption of only 6.53 mg P/lb (14.4 g/kg). This may likely be explained by PP releases, which reflected poorly in calculating media adsorption capacity. As a result of flowrate increases, column effluents often experienced an increase, in some cases a very significant increase, in turbidity and a concomitant release of PP. For example, the 2% BSM column from set I saw a turbidity increase of 6.27 to 61.4 NTU and a concomitant TP increase of 117 to 271 μg P/L upon flowrate increase to 24 in/hr from 12 in/hr. The 4% BSM under continuous flow from set II experienced an increase in turbidity from 5.47 to 85.4 NTU along with an increase from 81.4 to 233 μg P/L in TP after increasing the

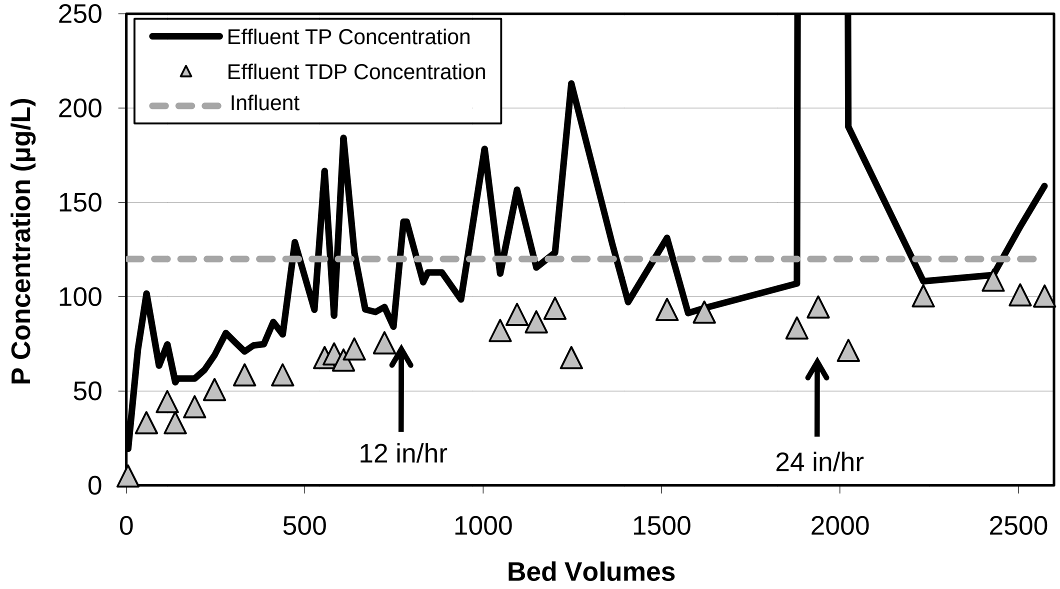


Figure 4-11. Breakthrough curve for continuously run BSM + 4% WTR from set I. Mean influent TP concentration was 124 μg/L and mean pH was 6.57. The column ran for a total of 57 days. Labeled arrows indicate increases in column flowrate from an initial rate of 6 in/hr. Total inflow was equivalent to 54.8 of rain over the entire catchment.

flowrate from 6 in/hr to 12 in/hr. In the majority of cases these increases did not have excessive influence on the calculated media adsorption capacity. The 4% BSM from set I, seen in Figure 4-11, was an exception to this. When the flowrate was increase to 24 in/hr, sample turbidity increased to 3357 NTU. TP measured 5.20 mg/L, more than 40 times the influent P concentration. TDP at the same time, however, measured only 71.6 μg/L.

To account for this extreme event, the Dixon-Thompson test was performed, confirming that this sample point measuring 5.20 mg P/L was an outlier ($p < 0.05$) of the population of all column effluent samples. PP and turbidity levels did not return to normal, stable levels until the fourth day of increased flow. However, as only this single point was statistically an outlier, no additional data were excluded from media adsorption calculations. When all results were included in the media P adsorption calculations, TP capacity of -116 mg P/lb (-255 mg P/kg) resulted. Excluding the outlier, TP capacity was 6.53 mg P/lb (14.4 mg/kg). It is believed that this estimated capacity is still negatively impacted by the elevated PP losses from the column because of the aforementioned continued residual PP losses after this event, leading to this low measure of capacity compared to batch and other column studies (Table 4-3).

In addition to continuous flow, 4% BSM was investigated under an intermittent flow regime (Figure 4-12). Over the course of the experiment, media P adsorption was only 3.69 mg P/lb (8.14 mg/kg), much worse compared to aforementioned batch or continuous flow studies (Table 4-3). This is believed to be the result of media drying during periods without inflow (Borggaard et al., 2005),

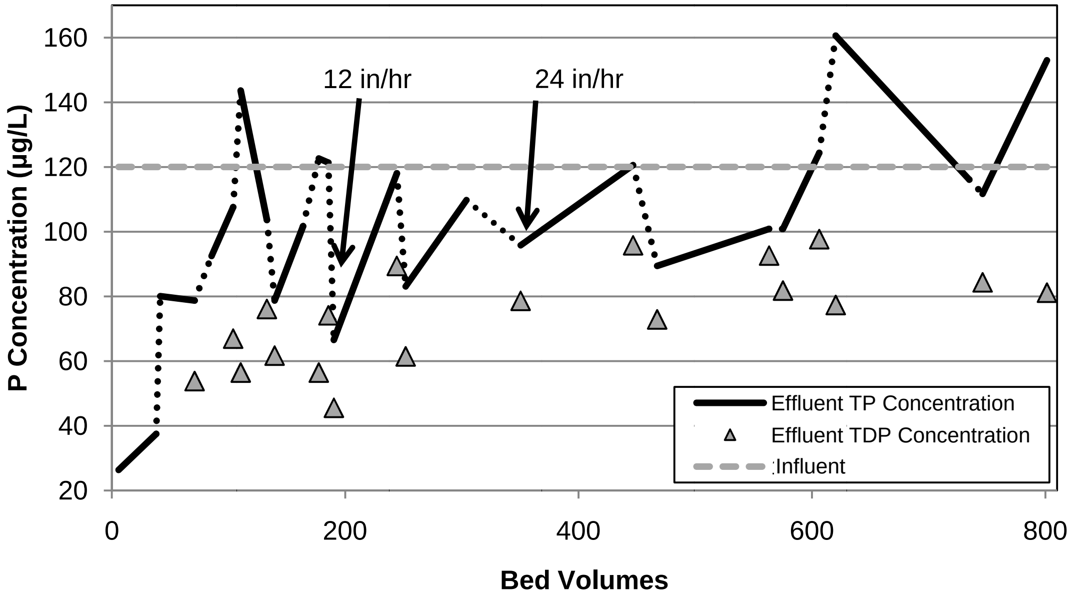


Figure 4-12. Breakthrough curve for intermittently run BSM + 4% WTR from set II. Mean influent TP concentration was 120 μg/L and mean pH was 6.63. The column ran 13 cycles (approx. 24 hours each) over a total of 86 days. Labeled arrows indicate increases in column flowrate from an initial rate of

6 in/hr. Total inflow was equivalent to 17.1 ft of rain over the entire catchment.

which is assumed to have occurred as air was actively pumped through the column. As hypothesized, a localized renewal or improvement in adsorption was observed after flow was reestablished following dry periods. This improvement was short lived and the media showed rapid decline in P adsorption, creating a sawtooth pattern for the effluent concentration. This supports the theory that during dry periods, secondary "slow" reactions are occurring, which free reactive surface sites for sorptive interactions with P. As flow continues, these newly re-exposed sites are quickly occupied, leading to the rapid decline in P adsorption.

4.4.2. Low-fines Media

LFBSM + 4% WTR (4% LFBSM) is presented to exemplify a LFBSM media breakthrough curve (Figure 4-13). Similar to BSM media, temporarily increased particulate release and turbidity were observed for LFBSM media after the flowrate

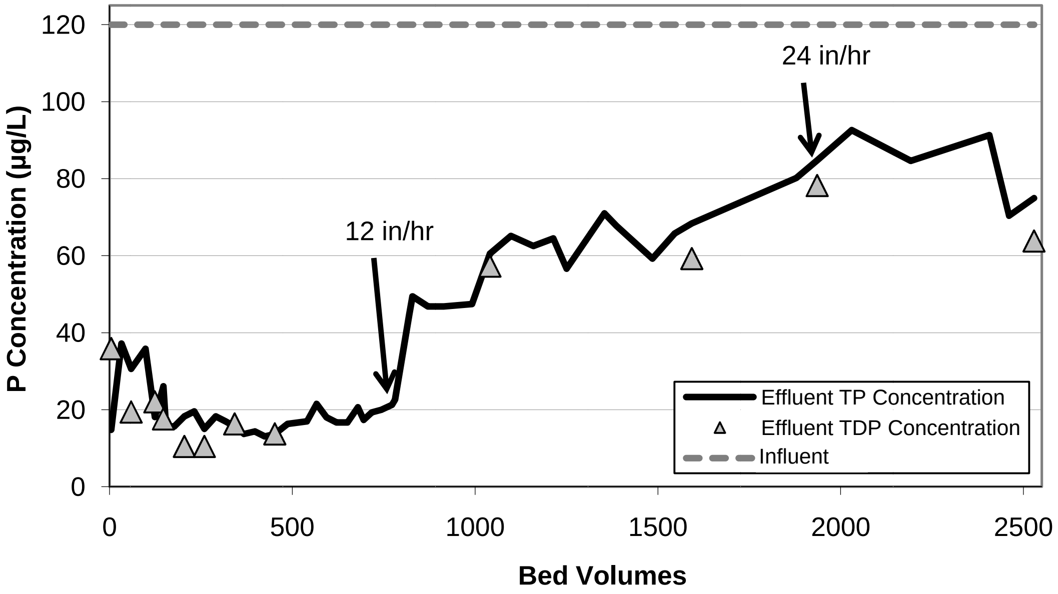


Figure 4-13. Breakthrough curve for continuously run LFBSM + 4% WTR from set I. Mean influent TP concentration was 124 µg/L and mean pH was 6.57. The column ran for a total of 57 days. Labeled arrows indicate increases in column flowrate from an initial rate of 6 in/hr. Total inflow was equivalent to 54.1 ft of rain over the entire catchment.

was increased, although to a lesser extent. By the second day after increasing the inflow rate from 6 in/hr to 12 in/hr, the 4% LFBSM media experienced an increase in turbidity from 7.39 to 15.3 NTU, along with an effluent TP increase of 20.0 to 49.4 μg P/L. This behavior was not observed for the 4% WTR amended sand media, although rapid increases in effluent P concentrations did occur. For instance, while turbidity dropped from 0.9 to 0.5 NTU after increasing the inflow rate from 6 in/hr to 12 in/hr, within two days after the flowrate increase, the effluent TP concentration had increased from 29.0 to 59.8 μg P/L. Similar to the reduced performance of media during column studies compared to batch, this increase in effluent P concentration from the amended sand column is attributed to further reduced contact time between the media and influent solution. The jump in effluent concentration was followed by periods of leveling off as a steady state was reestablished.

Neither low fines media (4% LFBSM, Sand + 4% WTR) had batch isotherms determined to allow for a direct comparison with column studies. However, batch isotherms for LFBSM + 10% WTR and LFBSM + 3% WTR were determined and those media were expected to have adsorption capacities of 50.3 and 11.1 mg P/lb (111 and 24.4 mg/kg), respectively. Comparatively, both of the low fines column media far outperformed these batch results under continuous flow, with adsorption capacities of 56.2 and 59.9 mg P/lb (124 and 132 mg/kg) for amended LFBSM and Sand, respectively (Table 4-3). Comparing the low-fines media results to the 4% BSM results, the low-fines media performed well, with the 4% BSM subject to continuous flow during set II displaying adsorption of only 19.8 mg P/lb (43.7 mg/kg). It is interesting that the low-fines media continued to display greater media P adsorption relative to analogous BSM mixtures for both batch and column experiments. For instance, WTR-amended LFBSM batch media unexpectedly showed higher P adsorption compared to WTR-amended BSM, contrary to initial hypotheses. Similarly, WTR-amended low-fines media exhibited greater media P adsorption than amended BSM under flow conditions as just detailed (Table 4-3). This suggests that decreases in fines content lead to further increases in media P adsorption in the presence of WTR, implying the need for increased WTR application to agricultural fields and bioretention media containing higher fines contents.

4% LFBSM was also investigated under intermittent flow to evaluate the performance of the media compared to BSM under more realistic bioretention conditions. Media adsorption dropped under intermittent flow compared to continuous from 56.2 to 23.7 mg P/lb (124 to 52.2 mg/kg), but maintained greater media adsorption relative to 4% BSM also subjected to intermittent flow, which showed adsorption of 8.14 mg P/L. In fact, intermittent 4% LFBSM showed greater adsorption than continuous flow 4% BSM, which had measured P adsorption capacity of 19.8 mg P/lb (43.7 mg/kg) during set II (Table 4-3). This further supports the conclusion that decreases in media fines content yield increases in P adsorption.

4.4.3. Hardwood Bark Mulch Amended BSM

BSM amended with both WTR and HBM showed increased P adsorption under batch conditions. Under column conditions results were not as consistent. BSM amended with HBM and 2% WTR (2% HBM) adsorbed only 5.99 mg P/lb (13.2 mg/kg) compared to the 18.6 mg P/lb (18.6 mg/kg) expected media P adsorption capacity calculated from Freundlich isotherms conducted during batch studies (Table 4-3). The media also showed worse P adsorption than 2% BSM during column experiments, as 2% BSM measured adsorption of 5.99 mg P/lb (13.2 mg/kg) and 2% HBM demonstrated an adsorption capacity of only 4.81 mg P/lb (10.6 mg/kg; Table 4-4). This was not expected as batch study Freundlich isotherms predicted 2% BSM to have a media P adsorption capacity of only 8.44 mg P/lb (18.6 mg/kg), while 2% HBM was predicted by Freundlich isotherms to have a greater P adsorption capacity of 15.1 mg P/lb (33.4 mg/kg). In contrast, BSM + HBM + 4% WTR (4% HBM) showed greater media P adsorption than it had during batch studies or compared to 4% BSM column studies (Table 4-4). 4% HBM had a measured P adsorption capacity of 26.1 mg P/lb (57.5 mg/kg), while the batch study Freundlich isotherm predicted an adsorption capacity of only 20.4 mg P/lb (45.0 mg/kg), and 4% BSM media under continuous flow conditions measured adsorption of 19.8 mg P/lb (43.7 mg/kg) during set II.

The increased adsorption of 4% HBM and decreased adsorption of 2% HBM relative to batch studies cannot be attributed to a direct release of P from the HBM. Because both media (2% and 4% HBM) were amended with the same proportion of mulch, a release of P would have caused a unified increase or decrease in adsorption relative to media unamended with HBM, not the divergent behavior observed. It is believed that this observed behavior is the result of the formation of an insoluble, possibly colloidal, Al-OM-P complex. Conceivably, some portion of the Al contained in the WTR, dissolved or colloidal OM that contains P_o (OM_P), and P in solution may have resulted in the formation of this complex when all three components were present in the same system (Figures 4-14 and 4-15). The formation of such complexes in soil systems have been reported by numerous authors (e.g., Sinha, 1971; Gerke and Hermann, 1992; Dolfing et al., 1999; Hens and Merckx, 2001). The formation of such a complex may have resulted in increased measured adsorption by providing additional reaction sites for the adsorption of P from solution.

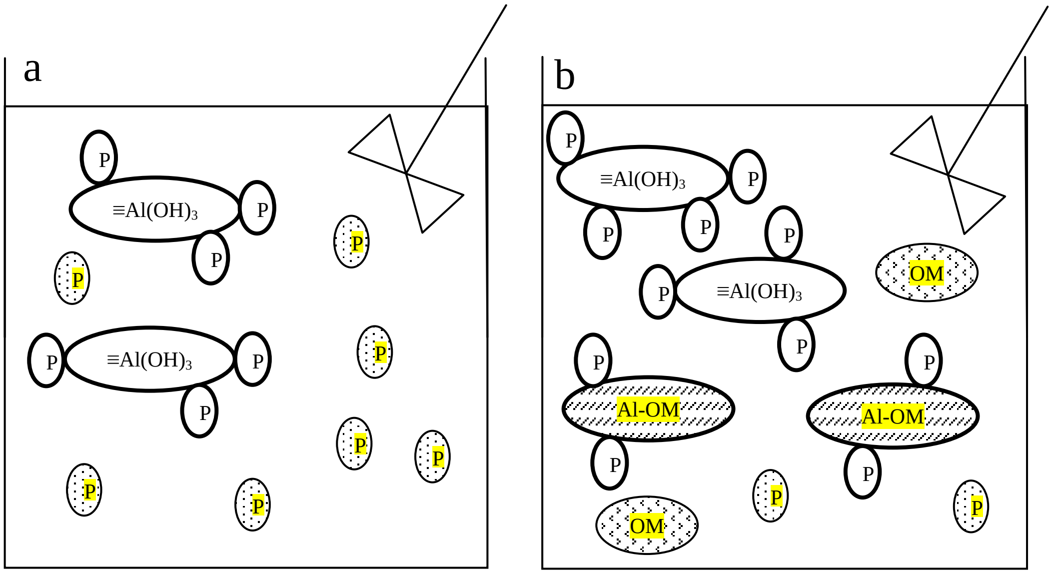


Figure 4-14. Representation of Al, OM, and P interactions in HBM-amended and - unamended batch systems. The reactors display (a) BSM + WTR batch system and (b) BSM + WTR + HBM batch system. The figures explain that HBM amended media exhibited increased P adsorption relative to the media without HBM in batch systems because of increased sequestration of P in an Al-OM-P complex.

The disparate behavior of the HBM media relative to the non-HBM is believed to be caused by a limitation in reaction time and available surface adsorption reactive sites in the 2% HBM column system. The longer reaction time in the batch studies (24 hrs) may have allowed Al to complex with both P and OM_P, preventing the solubilization of OM_P as well as removing a significant portion of P from solution via adsorption to the OM itself (Figure 4-14). This would have resulted in greater measured adsorption for the HBM mixtures relative to the non-HBM mixtures.

In the column experiments (Figure 4-15), the Al-OM-P complex may have formed initially but not completely because of reduced reaction time, which was a byproduct of P and OM_P being flushed from the system with throughflow. At the

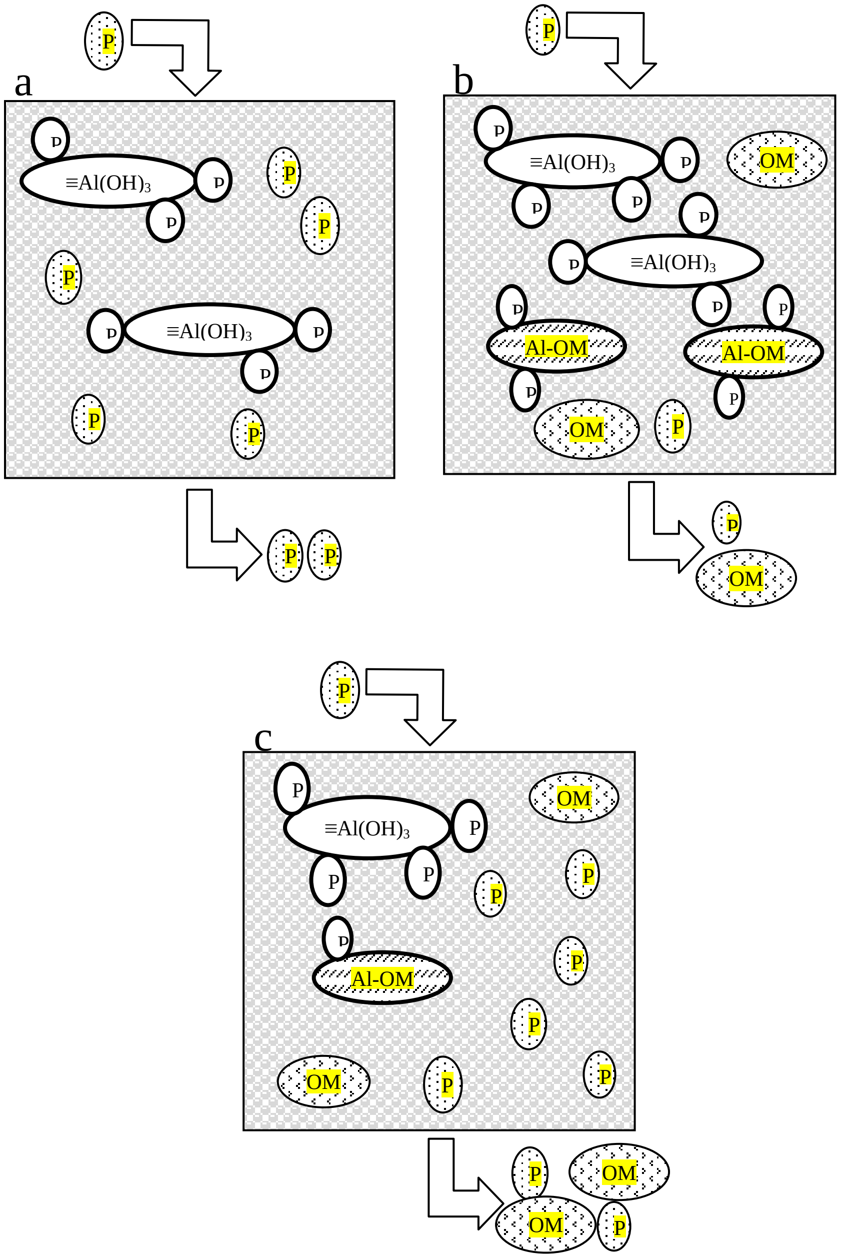


Figure 4-15. Representation of Al, OM, and P interactions in HBM-amended and - unamended column systems. The reactors display (a) BSM + WTR column system, (b) 4% HBM column system, and (c) 2% HBM column system. The figures explain that when HBM amended media exhibited increased P adsorption relative to the media without HBM, it was though sequestration of P in an Al-OM-P complex. The 4% HBM column experienced the formation of this complex, leading to increased adsorption relative to 4% BSM by sequestration of both P and $OM_{D\text{-}C}$. The 2% HBM media did not show increased adsorption relative to 2% BSM column media because the

system WTR concentration was insufficient for both P and OM capture under flow conditions.

lower WTR concentration of the 2% HBM mixture, the system Al concentration may have been small enough that Al-OM-P complex formation was insufficient to manifest as increased media adsorption. Instead, more influent P exited the column relative to the batch system because flow limited the reaction time with adsorbents. Also, OM_P may have leached from the column (Figure 4-15c), which upon effluent sample digestion would have been measured as P exiting the system, negatively impacting the measured column media P adsorption. This is supported by Guppy et al. (2005), who explain that the increased P in soil solution upon application of OM amendments is not from reduced adsorption capabilities of the soil or competition for adsorption sites between OM and P, but instead results from additional P supplied to solution by the OM amendments themselves.

Comparatively, the 4% HBM media had greater WTR mass, possibly providing sufficient Al content for Al-OM-P formation and minimal release of P and OM_P (Figure 4-15b). The 4% HBM column was subject to limited reaction time, just as was the 2% HBM column. However, unlike the 2% HBM column, the 4% HBM column showed increased adsorption relative to the non-HBM because the available reactive surface sites provided by the Al-WTR were sufficient to adsorb both P and OM_P from solution. By capturing this OM_P fraction, the column media measured increased adsorption relative to both the 4% BSM column and batch study 4% HBM (Figure 4-16). However, while the occurrence of Al-OM-P complexes in soil solution have been previously reported, little data could be found on formation constants or kinetic impacts (i.e., soil water flow) on the formation and P adsorption capabilities of

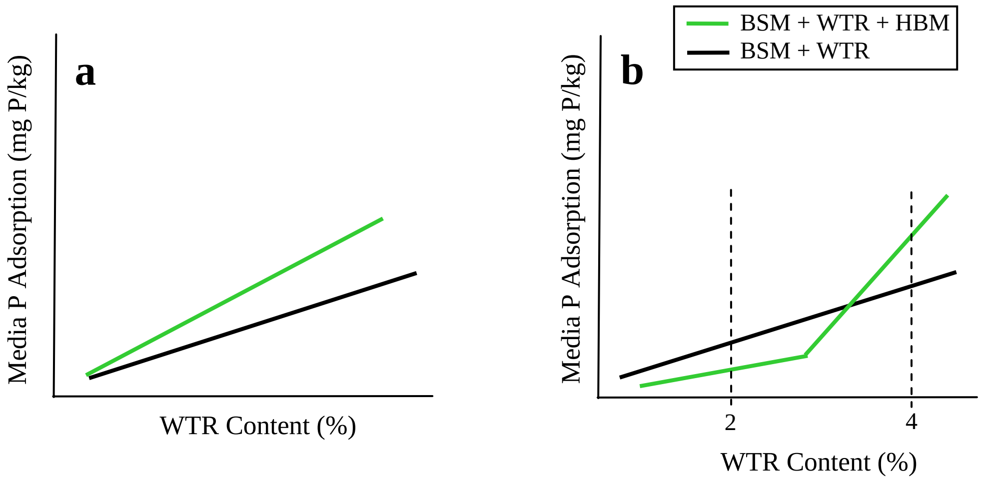


Figure 4-16. Comparison of relative media adsorption capacity trends under (a) batch and (b) continuous flow column conditions, assuming consistent P concentrations in solution, uniform flow conditions, and uniform HBM contents for HBM-amended media.

these compounds. Consequently, further research is necessary to characterize this complex P removal mechanism within the BSM system.

Similar to both BSM- and LFBSM-amended media, HBM-amended media demonstrated a reduction in media P adsorption under intermittent flow conditions (Figure 4-17). The 4% HBM media showed the smallest % drop in total P adsorption density for intermittent media relative to its continuous flow counterpart among all 3 media tested under both flow regimes (34.6% drop compared to 57.9%, 43.5%, and 81.4% for 4% LFBSM, 4% WTR set I, and 4% WTR set II, respectively).

HBM-amended media did not exhibit elevated turbidity or significant particulate releases as other media did, but problems with clogging were observed, especially during experimental set I. During the first set, both the 2% HBM and 4% HBM media experienced irreversible and complete clogging after increasing the flowrate to 12 in/hr but prior to the increase to 24 in/hr. In the case of both columns, the pumping rate was increased in an attempt to reach the desired flowrate but to no avail. After continually decreasing throughflow even with sustained, elevated pumping rates,

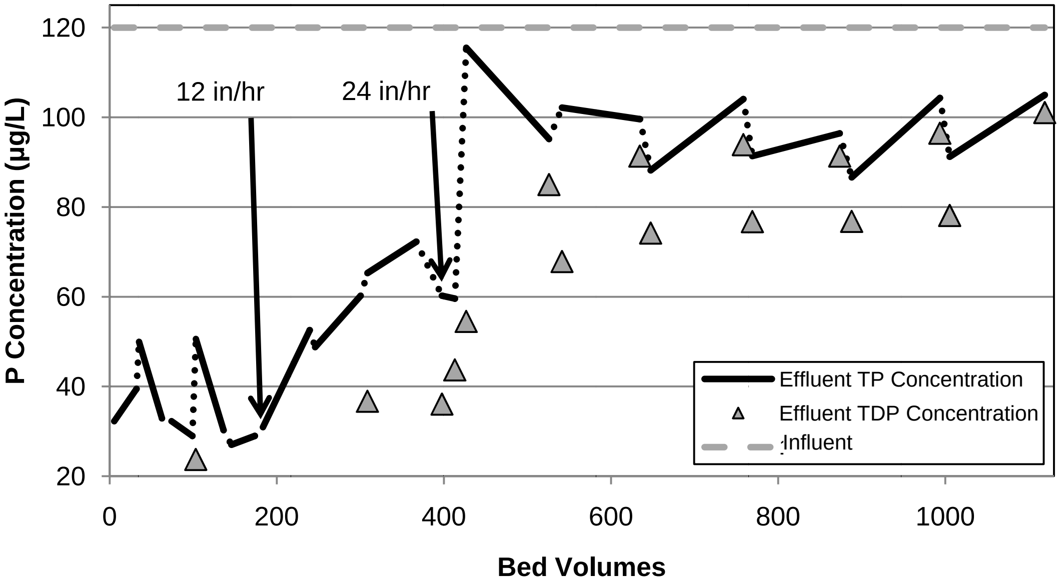


Figure 4-17. Breakthrough curve for intermittently run BSM + 4% WTR + HBM under intermittent flow from set II. Mean influent TP concentration was 120 µg/L and mean pH was 6.63. The column ran 15 cycles (approx. 24 hours each) over a total of 97 days. Labeled arrows indicate increases in column flowrate from an initial rate of 6 in/hr. Total inflow was equivalent to 23.9 ft. of rain over the entire catchment.

the columns were ultimately taken offline prematurely. This may reflect negatively on the calculated media adsorption because the media is not at true equilibrium with the influent. Most of the columns were taken offline prior to breakthrough, though, so the early cessation of these experiments is not extraordinary.

As clogging was observed only with media amended with HBM, it was concluded that this phenomenon was a result of HBM addition. To counteract this and prevent clogging during experimental set II (Figure 4-17) the HBM was not only sieved to < 2 mm but also to > 300 µm to prevent possible clogging by HBM fines material. Regardless, upon attempting to increase the flowrate for this column to 24 in/hr, the desired throughflow was unable to be achieved even with a drastically increased pumping rate. However, throughflow did not steadily deteriorate over time as observed with the set I columns, and the set II column was allowed to continue at a reduced flowrate (2.75 in^3/hr; 0.75 mL/min; 3.5 in/hr). Over a short pumping time (approximately 36 hours) the column flowrate gradually increased and reached the target flow. However, it is not known if this is a direct result of removing the HBM fines, or if the intermittent flow regime of the column also played some part in the alleviation of clogged conditions. Regardless, the use of HBM as a soil amendment at the field level is not expected to lead to media clogging because clogging was not observed at 16 in/hr flow, which is the only tested flowrate within the typical bioretention range.

4.5. Column Media Behavior

Overall, media adsorption behavior agreed with that of the batch studies in that increasing WTR content resulted in increasing adsorption capacity (Figure 4-18). However, media P adsorption was generally much lower for column studies than that calculated from batch study isotherms. This is likely caused by the reduced contact time between the P in solution and the media surface. Similar to batch results, HBM addition and decreasing fines content led to increasing P adsorption, although these parameters were only investigated in the presence of WTR. Batch studies suggested a decrease in adsorption with HBM addition and decreasing fines content when no WTR was present.

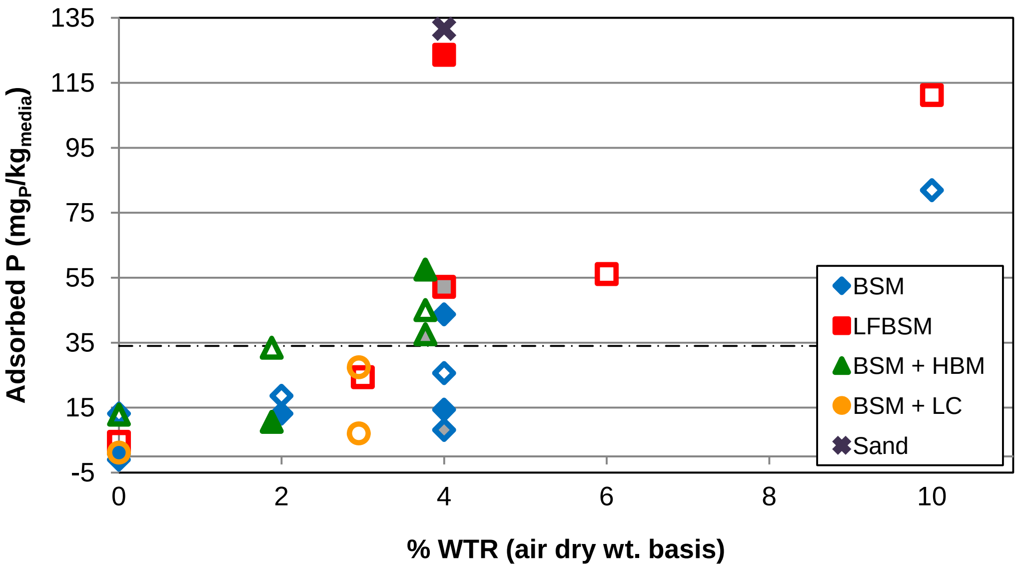


Figure 4-18. Batch and column data detailing P adsorption at equilibrium with 120 µg P/L solution as a function of WTR content (air dry weight basis). Batch adsorption data was calculated from Freundlich isotherms. Open marks represent batch data, closed marks represent data from columns subject to continuous flow, and open grey-filled marks represent intermittent column data. The dotted line represents the media adsorption benchmark of 15.4 mg P/lb (34 mg/kg).

LFBSM showed greater P adsorption relative to other batch and column media. Even under intermittent flow, gross media P adsorption was greatest of all 3 media subjected to this flow regime. The even greater adsorption of the sand + 4% WTR media suggests that with the specific media components used in this study fines content and P adsorption are negatively correlated. This relationship may likely exist for other media components as well.

2% HBM media for column studies showed decreased adsorption compared to 2% BSM media, while 4% HBM still exhibited greater media P adsorption than 4% BSM. In conjunction with the behavior of these media mixtures during batch studies, this suggests the formation of an Al-OM-P complex from constituents of the WTR and HBM, which may yield reduced losses of P and P-containing OM molecules. This complex may have formed within the 2% HBM column but been insufficient to prevent leaching of OM_{D-C}, resulting in a reduced measure of media P adsorption.

The 4% HBM media also was the least impacted by drying during intermittent flow, as evidenced by this media having the smallest decrease in P adsorption relative to its continuous flow counterpart. The development of a characteristic sawtooth pattern in intermittent column effluent P concentrations across all 3 intermittent flow studies also gives support to the hypothesis that “slow” adsorption interactions continue to occur after flow has stopped and “fast” adsorption is no longer taking place.

These preliminary media studies illuminate media behavior under static and dynamic flow conditions. They also give an indication of the ideal BSM mixture for optimal P adsorption and treatment. The performance of such an ideal mixture is not known, however, especially under conditions typical of a bioretention facility.

Chapter 5: Vegetated Column Pollutant Treatment Study

Two vegetated columns were constructed to replicate conditions experienced in a full scale bioretention system. Each column contained a different media, one typical of a standard bioretention cell (control media), and the other consisting of the control mix amended with 5% Al-WTR (experimental media), as described in Section 3.8.3. The column vertical dimensions were of actual bioretention scale (3 ft), and hydraulic loading was applied at a surface loading rate to again be typical of a bioretention cell (15.2 in/hr). Across all experiments, influent solution pH was 5.8 ± 0.6, turbidity was ≤ 1.3 NTU, and conductance was 1.3 ± 0.04 mmho/cm. Influent P concentrations averaged 144 ± 79.1 μg/L, with standard runs averaged 117 ± 3.7 μg/L. Cumulatively, the experimental column received 91.9 ft (210 gal) of influent, while the control column received 88.9 ft (204 gal). This 4% difference was caused by slight variations in flowrate throughout the life of the columns. These surface loading rates are equivalent to approximately 1.3 years worth of rain for the Washington region, assuming a bioretention cell sized at 5% of catchment.

5.1. Vegetation Mortality

Plants were originally purchased from a local nursery in January 2010 to acclimate to the laboratory environment before transplantation to the bioretention column. While they were provided with sufficient light and water, the plants became infested with an unidentified species of winged insect, and despite all best efforts the four individuals died within a matter of weeks.

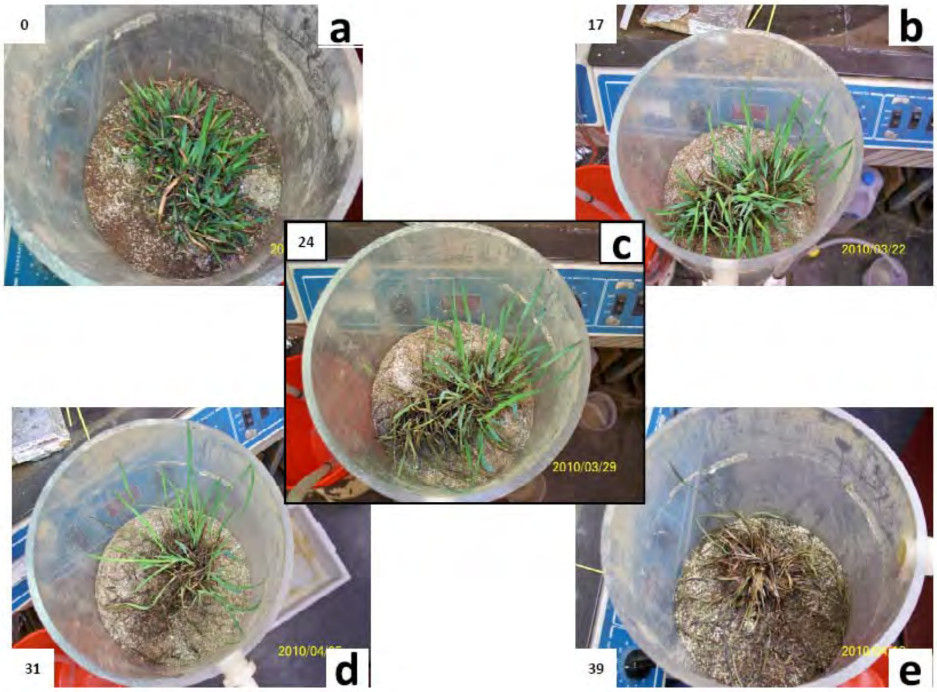


Figure 5-1. Chronosequence of control column *S. angustifolium* development. Numbers in the upper/lower corners identify days of growth after planting.

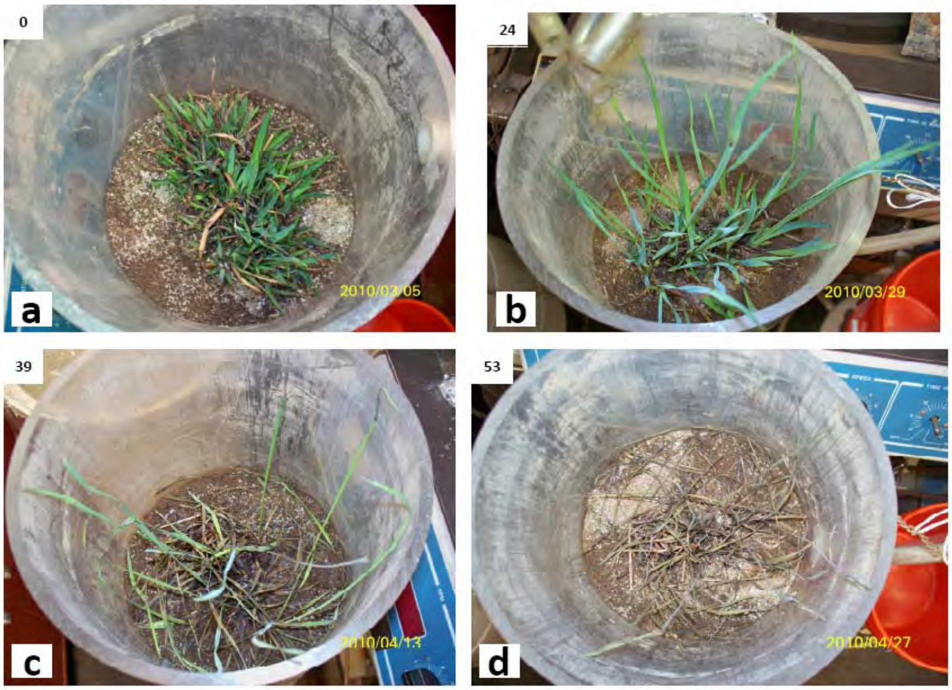


Figure 5-2. Chronosequence of experimental column *S. angustifolium* development. Numbers in the upper corners identify days of growth after planting.

Additional plants were purchased just prior to construction of the columns, and on 5 March, 2010 (day 0) two individual *Sisyrinchium angustifolium* were planted in each bioretention column (Figures 5-1a and 5-2a). Plants in both columns appeared to fare well initially (Figures 5-1b and 5-2b). However, an initial plant in the control column began to show signs of stress around day 24 (Figure 5-1c), becoming brown and languishing. This individual died by day 31 (Figure 5-1d). The second surviving individual in the control column began to show stress almost immediately after the first perished, and was dead by day 39 (Figure 5-1e).

Plants in the experimental column fared better, although ultimately succumbed to the same fate. While initially appearing to thrive (Figure 5-2b), both plants began to show signs of stress around day 39 (Figure 5-2c), beginning to wither and appear brittle, although remaining green in color. Gradually, color faded and both individuals expired around day 53 (Figure 5-2d).

It must be noted that, as had occurred previously, there was an issue with winged insect infestation in both columns. Photographs were attempted, but the small size of this particular species made pictures indistinct. Additionally, plant stress may have been caused by other variables, such as excessive water from large weekly "storms", or light being provided via artificial sources rather than natural sunlight. Regardless, as plants in both columns ultimately perished, it is not believed that WTR or Al phytotoxicity is the cause of their demise.

5.2. General Column Trends

Data for all experimental runs can be seen in Figure 5-3, detailing TP and TDP effluent concentrations for both the experimental and control columns. Influent concentrations differed between runs, but in all cases effluent behavior was similar. The control column discharged P greater than the influent concentration at the beginning of each experiment, but the concentration dropped with continued flow and eventually P removal from the influent was found. Primarily, however, net P was released by the media. This drop in P concentrations led to an exponential decay-shaped curve. TDP followed the same pattern as TP, although the degree of difference between the two (i.e., PP) differed between and within runs. Head buildup never developed in the control column.

The experimental column behaved very differently from the control with respect to P. Effluent TP was much lower, and in most instances the majority of P in the influent was removed. Generally, removal was high at the beginning of flow addition and worsened for the next 15 to 30 minutes, gradually dropping thereafter. This created a pattern of a TP peak around the second or third sample (15 – 30 minutes). This behavior produced a pollutograph with a rising limb and a falling limb that was strongly skewed to the right. The approximately horizontal portion of the falling limb was often not particularly consistent, but fluctuated over a range of about 10 to 15 μg/L. TDP, similar to the control column, started relatively high (approximately 10 to 20 μg/L) and dropped with flow, although in almost all instances effluent TDP concentrations were below detection limit (10 μg/L) within one hour. In several instances the experimental column developed head, but the head

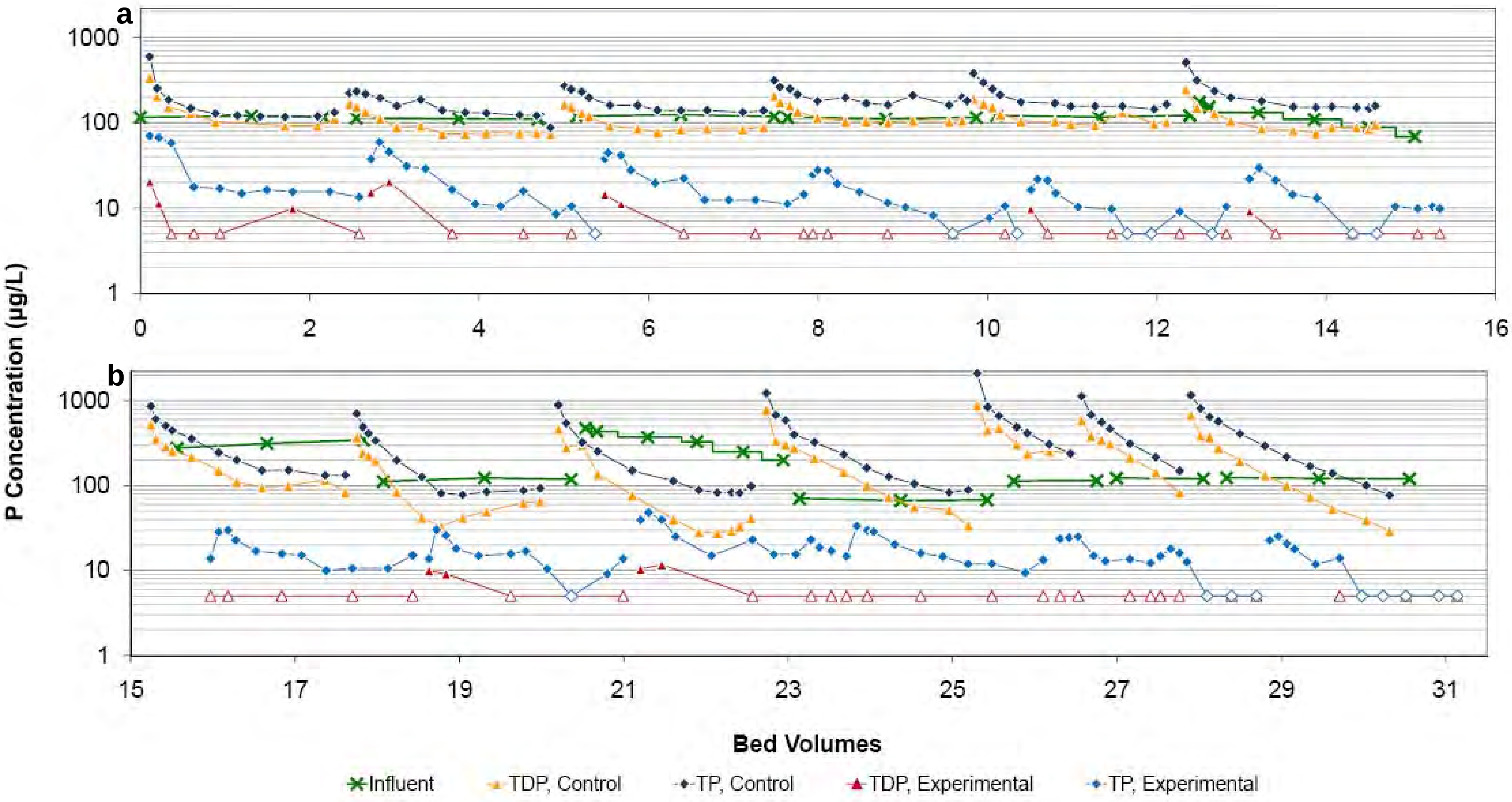


Figure 5-3. Effluent P concentration as a function of cumulative column bed volumes of flow for both the control and experimental columns runs (a) numbers 1-6 and (b) numbers 7-13. Influent P concentration varied by experiment but ranged from 68.4 – 476 µg/L. Mean pH was 5.8. Samples that measured below the method detection limit are estimated as 5 µg/L, and are indicated by open symbols.

remained < 6 in (15.2 cm). Influent EMCs and effluent EMCs for both columns across all runs and pollutants are presented in Table 5-1.

5.3. Standard Condition Experiments

Standard runs (nos. 1 – 5, 8, and 13) where the columns were subjected to a constant flowrate of 15.2 in/hr (11.1 in^3/min; 182 mL/min) and concentration of 120 µg P/L are compared for TP, TDP, and PP in Figure 5-4. Initially for the experimental column one can see a 73.6% (17.3 to 4.6 µg/L) drop in effluent PP EMC from the first to the fifth replicate, while TDP EMC remains low and more consistent (6.7 ± 1.5 µg/L; Table 5-1). This shows the stabilization of the column by the fifth replicate as initial soluble materials are flushed, and it is the fifth run (10.4 to 12.9 BV) that is used as a baseline against which other experimental runs are compared. Run 8 (6.3 and 7.5 µg/L TDP and PP, respectively) shows a slight increase in both TDP and PP EMCs relative to run 5 (5.5 µg/L TDP and 4.6 µg/L PP), but a small decrease relative to the previous run 7 (5.0 µg/L TDP and 10.1 µg/L PP). This behavior is believed to show that the column is still returning to a steady state after the elevated flowrate and concentrations encountered in the seventh run. For run 13 (5.0 and 5.3 µg/L TDP and PP, respectively), the experimental column results are nearly identical to those of run 5 (5.5 and 4.6 µg/L TDP and PP, respectively), providing further evidence that this behavior is the typical, stable behavior of the column when subjected to the standard flow and concentration conditions.

Table 5-1. Experimental and control column effluent EMCs and influent EMCs. Influent TDP is not listed as it is the same as TP because all influent P was soluble. NO_2^--N is not listed as it was not a pollutant included in the influent.

	Experimental Column							Control Column							Influent			
Test No.	TP (µg/L)	TDP (µg/L)	PP (µg/L)	NO_3^--N (mg/L)	NO_2^--N (µg/L)	TKN (mg/L)	TN (mg/L)	TP (µg/L)	TDP (µg/L)	PP (µg/L)	NO_3^--N (mg/L)	NO_2^--N (µg/L)	TKN (mg/L)	TN (mg/L)	TP (µg/L)	NO_3^--N (mg/L)	TKN (mg/L)	TN (mg/L)
1	25.1	7.8	17.3	0.928	13.2	0.889	1.83	167	127	40.1	0.719	24.1	1.23	1.95	117	0.740	0.980	1.72
2	20.0	8.4	11.6	0.691	6.32	0.468	1.16	156	93.2	62.6	0.618	4.86	0.885	1.51	111	0.703	1.07	1.78
3	19.6	6.8	12.8	0.547	5.08	0.349	0.901	164	97.2	66.6	0.504	6.24	1.08	1.59	120	0.800	1.06	1.86
4	12.1	5.0	7.1	0.493	4.87	0.397	0.895	189	120	68.9	0.533	11.3	1.01	1.55	114	0.743	1.10	1.84
5	10.0	5.5	4.6	0.458	4.98	0.383	0.846	186	117	69.0	0.667	22.7	1.20	1.88	119	0.743	1.03	1.77
6	12.9	5.6	7.3	0.521	4.39	0.541	1.07	220	114	106	0.724	12.3	1.22	1.95	105	0.740	1.09	1.83
7	15.1	5.0	10.1	1.88	6.60	0.712	2.60	273	170	103	2.01	18.8	1.62	3.65	313	2.21	2.60	4.81
8	13.8	6.3	7.5	0.936	3.89	0.709	1.65	180	94.3	86.2	1.02	10.0	1.44	2.47	118	0.700	1.25	1.95
9	23.5	7.4	16.1	2.12	4.82	0.838	2.96	237	126	111	2.26	18.9	1.74	4.02	326	2.37	2.62	4.99
10	16.5	5.0	11.5	0.692	1.00	0.373	1.07	292	177	115	1.05	14.1	1.02	2.09	68.4	0.520	0.809	1.33
11	17.3	5.0	12.3	0.775	1.00	0.327	1.10	640	378	262	0.827	21.0	1.41	2.26	114	1.41	1.03	2.44
12	8.9	5.0	3.9	0.658	1.00	0.327	0.986	427	258	170	0.792	19.1	1.26	2.07	122	0.830	1.12	1.95
13	10.3	5.0	5.3	0.712	1.00	0.281	0.994	322	158	164	0.734	19.2	0.912	1.67	122	0.703	1.04	1.75
Cumulative	16.1	6.1	10.0	0.891	4.80	0.524	1.42	245	144	102	0.978	13.3	1.22	2.22	146	0.880	1.31	2.19

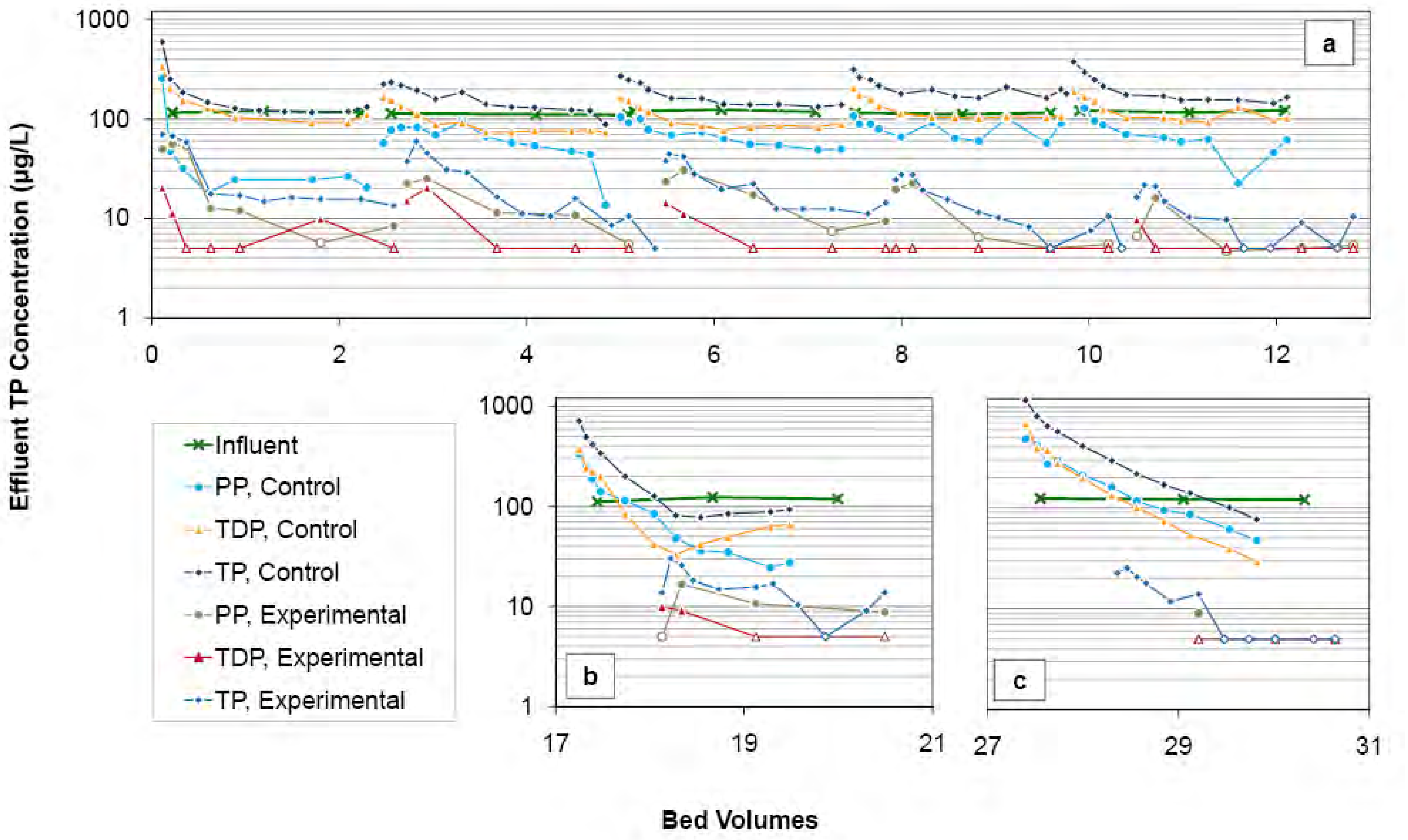


Figure 5-4. Effluent TP concentration for standard condition runs (a) numbers 1-5, (b) number 8, and (c) number 13, as a function of cumulative column bed volumes of flow for both the control and experimental columns. Influent P concentration measured 117 ± 4.4 µg/L. Mean pH was 5.9. Samples that measured below the method detection limit are estimated as 5 µg/L, and are indicated by open symbols.

The control column exhibits very different behavior during the standard runs. After an initial drop in TP effluent EMC from runs 1 to 2 (167 to 156 μg/L), concentrations increased with each experiment (156 to186 μg/L). This shows that the

media's adsorption capacity was exhausted during the first two runs. This same pattern of increasing TP EMCs continues with runs 8 (181 μg/L) and 13 (322 μg/L), although the climb in EMC magnitude is not linear because of the varying experimental conditions. This same pattern of consistently increasing effluent EMCs is followed by both TDP and PP, ranging from 93.2 to 158 μg/L TDP and 40.1 to 164 μg/L PP. This increasing release of P must have a source to comply with the law of mass conservation. A proportion of this may be attributed to degradation of the HBM and *S. angustifolium* from the media, as evidenced by the increasing PP effluent EMCs and the turbid, tea-colored column outflow. Also, the increasing P releases from the column are believed to be washout of previously adsorbed P from runs 7 and 9, which both utilized a higher influent P concentration and subsequently were the only experiments to produce net adsorption in the control column (see Section 5.5).

Ultimately, under standard conditions (15.2 in/hr, 120 μg/L) the experimental column far out performed the control column. The experimental column showed consistent removal of P from solution, with EMCs ranging from 10.0 to 25.1 μg/L, while the control column exported P for all standard runs. Control TP EMCs ranged from 156 to 322 μg/L. Experimental TP effluent EMCs were an 85.0 to 96.8% reduction compared to the control column TP EMCs under standard condition, and the experimental column consistently treated influent via adsorption to maintain effluent concentrations ≤ 25 μg/L, the EPA recommended limit for freshwater lakes and reservoirs (US EPA, 1986).

5.4. Hydropollutograph Experiments

Experimental runs 6 and 9 were deemed 'hydropollutograph' experiments, whereby the columns were subjected to variable influent flowrate and pollutant concentrations in an attempt to replicate the behavior of an actual runoff event. Run 6 followed a 'standard' run, so column behavior was not impacted by previous non-standard conditions. In both figures, influent concentration is plotted as the mean cumulative BVs of both columns for a given time. A more proper depiction of influent concentration relative to effluent may be seen in Figure 5-5b where concentration is plotted as a function of time for run 9.

One can see from Figure 5-6 that the experimental column shows very little exceptional behavior compared to all other column pollutographs, exhibiting a pollutograph with an initial peak that was skewed to the right and a falling limb that becomes nearly horizontal, but with a slightly fluctuating concentration. The TP effluent EMC was slightly elevated relative to the previous 'standard' run (12.9 vis-à-vis 10.0 μg/L), but this was caused by an increase in effluent PP as the TDP EMC is nearly unchanged (Table 5-1, Figure 5-7a). This additional PP release is likely the result of the increased flowrate experienced by the column for this experiment.

The control column followed previous trends. Peak effluent concentration increased 34.7% relative to the previous experiment (from 378 to 509 µg/L), as did TP (186 to 220 µg/L) and PP (69.0 to 106 µg/L) EMCs, with the highest concentrations found initially. TDP was relatively unchanged (114 vis-à-vis 117 µg/L, 2.82% decrease),

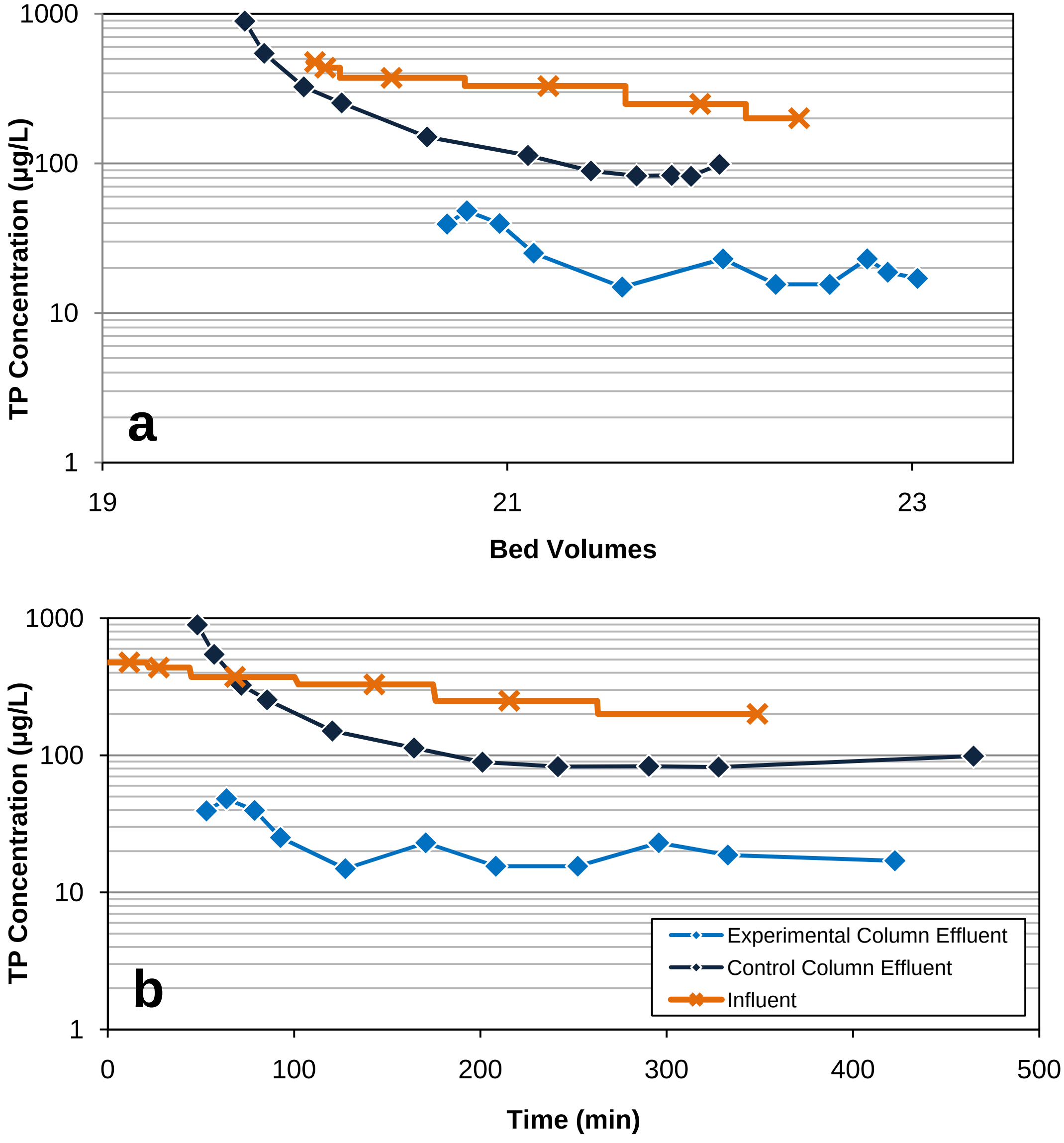


Figure 5-5. Run number 9. Experimental and control column effluent concentrations plotted against (a) column cumulative bed volumes of flow, and (b) run time. Columns were subjected to variable influent flow rates of 50.3 to 345 mL/min, and TP concentrations ranging from 201 to 476 µg /L. Influent solution contained 0.01 M KCl as a background electrolyte and had pH of 5.9 ± 0.7. This experiment also investigated an extended antecedent dry period of 13 days.

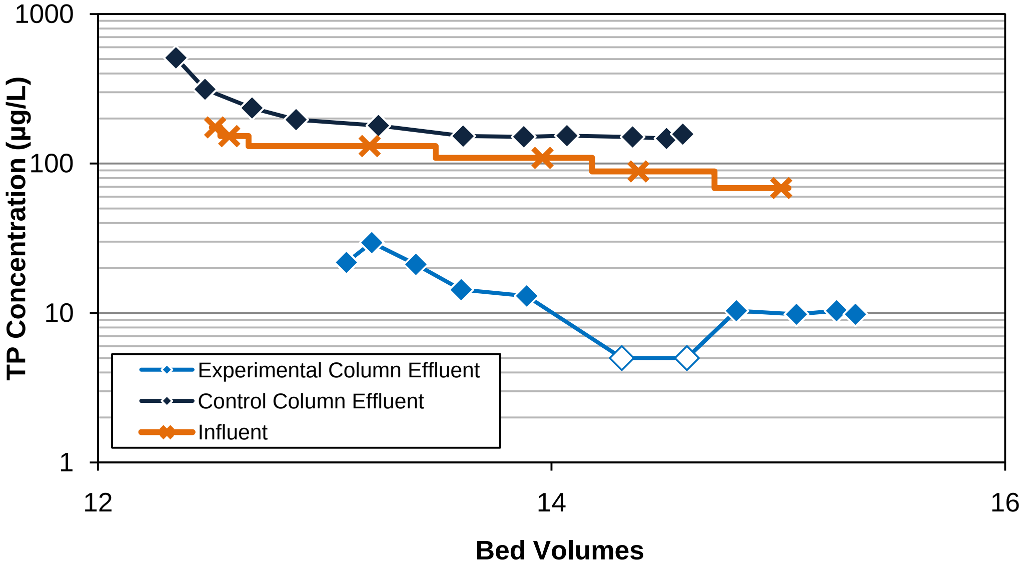


Figure 5-6. Run number 6. Experimental and control column effluent concentrations plotted against column cumulative bed volumes of flow. Columns were subjected to variable influent flow rates of 64 to 327 mL/min, and TP concentrations ranging from 69 to 175 µg/L. Influent solution contained 0.01 M KCl as a background electrolyte and had pH of 5.7 ± 0.5.

and like the experimental column the increased release of P was the result of released PP (Table 5-1, Figure 5-7b). Again, this is attributed to increased inflow rate.

Run 9 (Figure 5-5) subjected the columns to the same inflow rates as run 6, but increased the concentration of each hydropollutograph ‘step’ by a factor of approximately 2.5 to 476 and 201 µg/L for the initial and final concentrations, from 175 and 68.5 during run 6 (Table 3-8). Additionally, this experiment was also conducted after a doubled antecedent dry period of 13 days. Consequently, the experimental column effluent experienced an increase in both TDP and especially PP relative to run 6 (from 5.6 and 7.3 µg/L to 7.4 and 16.1 µg/L for TDP and PP, respectively) as well as the immediately previous run (6.3 µg/L TDP and 7.5 µg/L PP). TDP did not significantly increase during other experiments when inflow rate

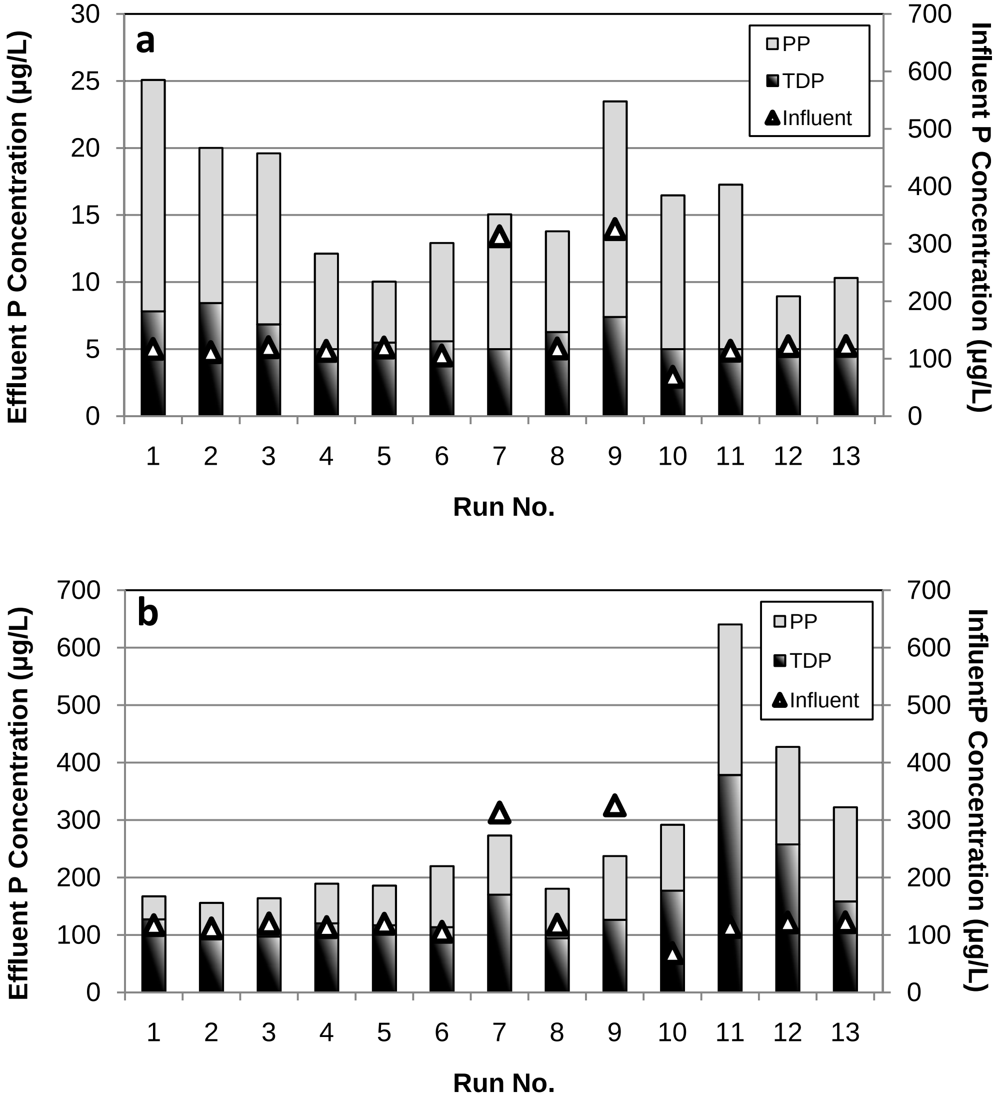


Figure 5-7. Effluent PP and TDP EMCs for the (a) experimental and (b) control columns by run number. Note the differing ordinate axes.

(run 6) or pollutant concentration (run 7) were elevated, which suggests the increased TDP for this run was caused by the combined impact of increasing both variables, leading to decreased reaction time between the media and increased P in solution. Decreased water content of the media after extended drying may also have contributed to the increased TDP concentration by causing some initial limitation in P diffusion. The elevated PP concentration is more convoluted because of the multiple experimental variables. Elevated PP was experienced for both runs 6 and 7, but both were approximately half the concentration seen in this run (Table 5-1). It is therefore believed that the high PP release observed during this run is the combined result of both an extended dry period and increased flowrate.

Control column run 9 experienced a TP effluent peak (894 μg/L) approximately the same as that of the other elevated concentration run (number 7; 864 μg/L), but had a depressed TP EMC (273 μg/L vis-à-vis 237 μg/L; Figure 5-7b). PP was approximately the same for runs 6, 7, and 9 (106, 103, and 111 μg/L, respectively); it is, in fact, the result of increased TDP releases that led to the elevated effluent TP (Table 5-1). Removal was found to be greater for run 9 than for similar runs, actually showing net adsorption (0.155 mg/kg). It may be that the extended dry period allowed for the oxidation of previously reduced Fe-containing minerals in the media, leading to increased adsorption.

Interestingly, this experiment and the previous run (number 8) also saw an alteration in the TDP column behavior. In previous experiments, column TDP had behaved similar to the experimental column and exhibited a right-skewed pollutograph with an extended, nearly horizontal falling limb. However, these two experiments saw an almost parabolic curve of the effluent TDP (Figure 5-3) which is not explainable. After these two experiments, the column TDP began to show a third type of TDP behavior (see Section 5.5).

Ultimately, it would appear that varying the inflow rate and concentration within a storm event has little impact on the general shape and behavior of the effluent pollutograph for either media. However, varying the magnitude of flow or concentration elicited distinct responses in media P adsorption behavior, with differing directions for the relationship between either of these variables and media adsorption. Flowrate appears to have a positive correlation with effluent PP concentrations, and increases in antecedent dry time seem to further increase these PP concentrations. Additionally, increased influent concentrations lead to increased effluent TDP concentrations for the control column, and also for the experimental column when these elevated concentrations were coupled with increased flowrate. Also, adsorption was observed for the control media when subjected to elevated concentrations because of the increased concentration gradient between the media surface and bulk solution.

5.5. Additional Investigated Variables

Application of an increased pollutant concentration (~ 2.5 × standard) with a constant flowrate was investigated with experimental run 7 (Figure 5-8). In the

experimental column, effluent did not show an elevated TDP EMC relative to run 5 (5.5 and 5.0 μg/L, respectively), but did contain additional PP (4.6 vis-à-vis 10.1 μg/L; 122% increase). The reason for this behavior is not know, although it is possible this additional particulate release was because the column had not returned to a stable condition after the elevated inflow rate it was subjected to in the previous run (number 6; up to 20.0 in^3/min vis-à-vis 11.1 in^3/min for run 7), and these were residual particulate materials being flushed.

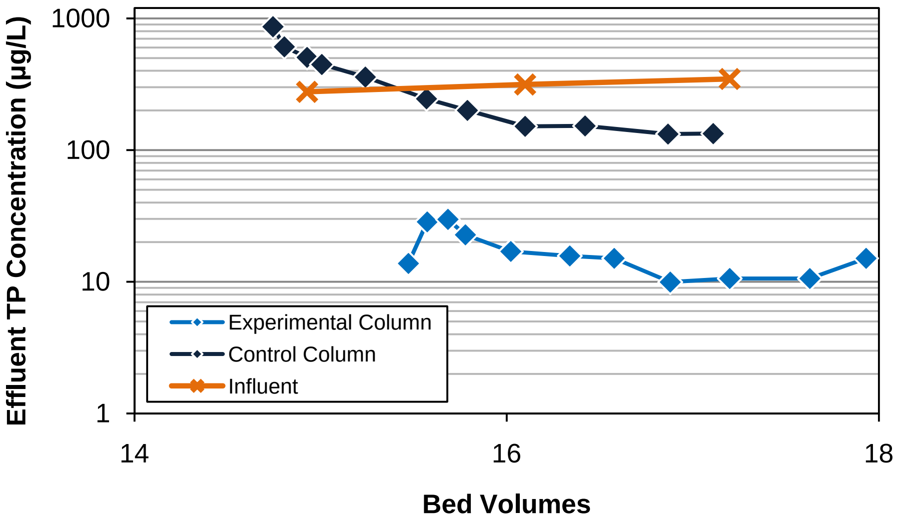


Figure 5-8. Run number 7 showing the effects of elevated influent concentration (313 µg/L) on the media. Experimental and control column effluent concentrations plotted against column cumulative bed volumes of flow. TP concentration was 313 ± 35 µg/L. Influent solution contained 0.01 M KCl as a background electrolyte and had pH of 5.4 ± 1.1

The control column exhibited both elevated TDP and PP releases relative to run 5 (170 µg/L TDP and 103 µg/L PP, up from 69.0 µg/L TDP and 117 µg/L PP during run 5; Table 5-1), although effluent PP was not significantly greater than the previous run (106 µg/L). Elevated TDP is simply throughflow of the influent solution, while PP is believed to again be further washout of particulates dislodged by the elevated flowrate of run 6. Because of the elevated inflow concentration, there was some minimal retention of P by the media (0.062 mg/kg).

Run number 10 (Figure 5-9) investigated the effect of decreased influent concentration on column behavior, applying influent at 60% of the standard concentration (68.4 µg/L). The experimental column behaved mostly as expected, showing effluent TDP below the method detection limit. Elevated PP relative to the

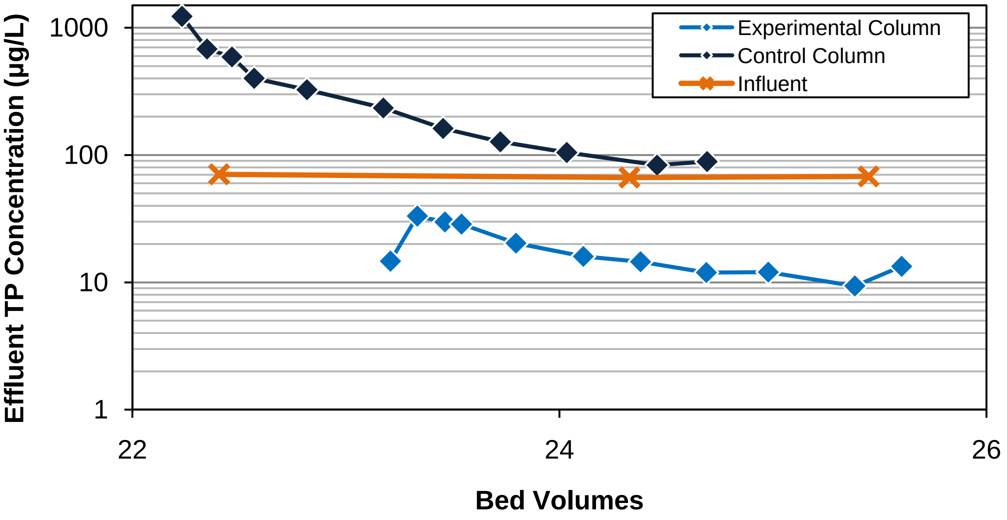


Figure 5-9. Run number 10 showing the effects of decreased influent concentration (68.4 µg/L) on the media. Experimental and control column effluent concentrations plotted against column cumulative bed volumes of flow. TP concentration was 68.4 ± 2.0 µg/L. Influent solution contained 0.01 M KCl as a background electrolyte and had pH of 6.0 ± 0.1.

standard runs was observed (11.5 µg/L vis-à-vis 4.55 µg/L), but again this is believed to be further particulate washout from the elevated flowrates of the previous run (number 9).

The control column showed behavior similar to previous runs, with greatly elevated initial effluent TP concentrations that dropped over the course of the experiment, and unexpectedly this experiment had an increased, not reduced, TP EMC relative to standard run 5 (292 µg/L vis-à-vis 186 µg/L). The PP EMC for this experiment was nearly identical to run number 9 (115 and 111 µg/L, respectively), and so was elevated compared to the standard runs. Again, this was attributed to residual media flushing from the previous experiment. The increased TP was the result of excess release of TDP from the media. It would appear that adsorbed P from run number 9 was partially released during this experiment. This phenomenon will be discussed in more detail further on. Also, the effluent P profile changed with this experiment from that discussed in Section 6.4. From run 10 through the demobilization of the columns, the column no longer reached a constant effluent concentration but showed continuously dropping P concentrations throughout the duration of the experiment. While the reason for this behavior is not know, it may be that after the elevated influent concentration and double antecedent dry period of run 9 in which column showed net adsorption of P, the column did not reach a steady state but exhibited continued leaching of adsorbed P over the course of several experimental runs until the adsorbed P was flushed from the media.

Runs 11 and 12 (Figure 5-10) were performed to investigate shortened antecedent dry time on the columns. Experiment 11 was a truncated standard run, as was experiment 12, applied to the columns after a dry period of only 3 days. The experimental column acted during run 11 as if its adsorption of P was negatively impacted by the elevated P and inflow conditions encountered during run number 9, showing effective TDP removal but having elevated PP release relative to run 5 (5.0 µg/L TDP and 12.3 µg/L PP EMCs compared to 5.5 µg/L TDP and 4.6 µg/L PP). However, the issue causing this elevated particulate release seemed to be

addressed before run 12, because column performance was actually better than previous standard runs, exhibiting both effective TDP removal and reduced PP concentrations (5.0 µg/L TDP and 3.9 µg/L PP EMCs).

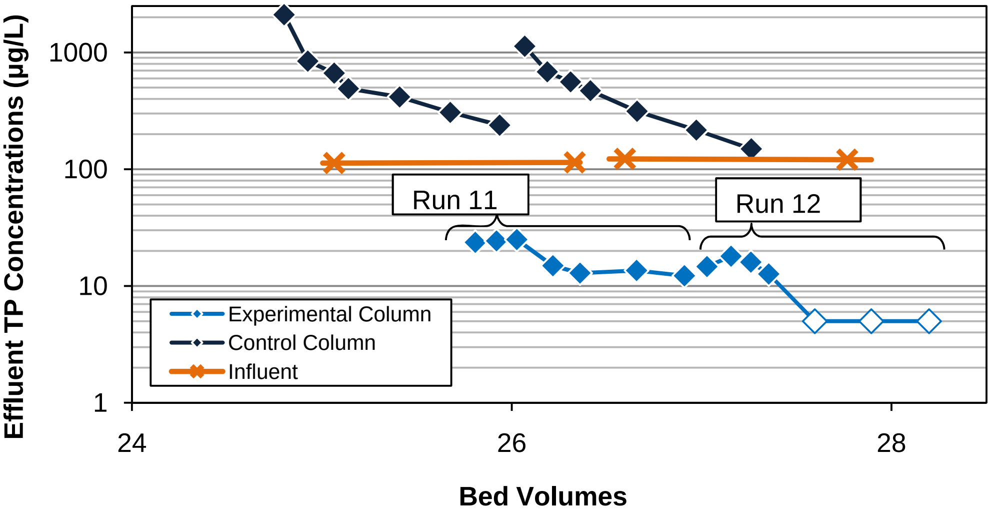


Figure 5-10. Runs number 11 and 12 showing the effects of reduced antecedent dry period (3 days) on the media. Experimental and control column effluent concentrations plotted against column cumulative bed volumes of flow. TP concentration was 118 ± 4.7 µg/L. Influent solution contained 0.01 M KCl as a background electrolyte and had pH of 5.7 ± 0.5.

The control column showed its worst performance during run 11 relative to standard run 5, with high peak release (2.11 mg/L) and elevated TP, TDP, and PP EMCs (640 µg/L, 378 µg/L. and 262 µg/L, respectively; Table 5-1). Performance improved for run 12 (427 µg/L TP, 257 µg/L TDP, and 170 µg/L PP, respectively), but only relative to run 11. It was hypothesized that the relatively high P retention observed for run 9 may be partly explained by newly oxidized Fe components following the extended dry period. If this is the case, the gradual release of large quantities of TDP over the following three experiments (runs 10 to 12) may be the results of the re-reduction of these Fe minerals as the column remains more saturated.

However, the elevated PP releases for these three experiments is not explained by this hypothesis.

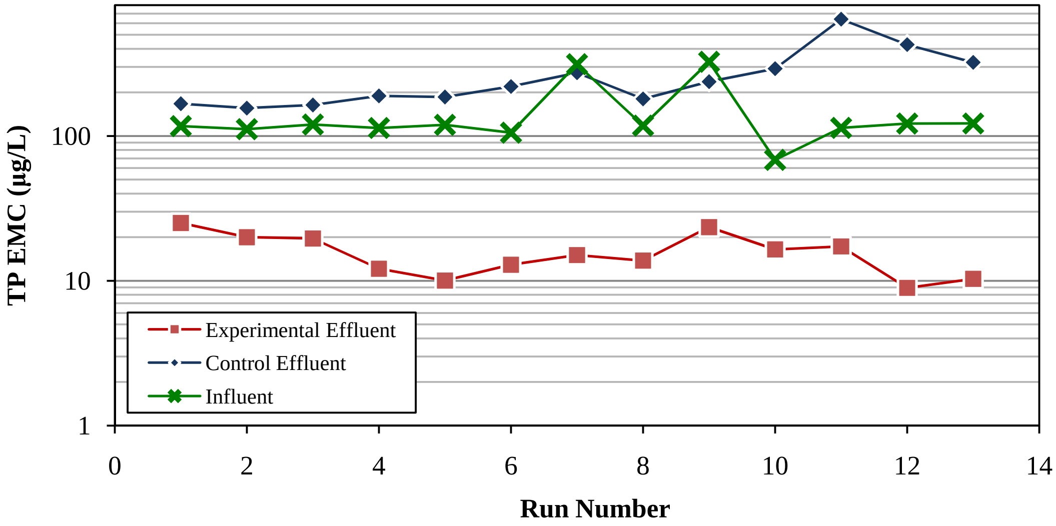


Figure 5-11. Influent and effluent TP EMC of both columns for each run. Influent pH was 5.8 ± 0.6, influent P concentration varied from 68.4 to 572 µg/L, and inflow rate varied from 4.17 to 28.7 in/hr (3.06 to 21.0 in^3/min).

Control media performance for runs 11 and 12 are somewhat obscured because of previous experiments. Media EMCs continued to decrease from run 11 through 13, and this improvement may be partially a benefit of the shortened drying time between runs 11 and 12. However, because performance improved quite markedly after having a standard antecedent dry time prior to run 13, it is likely that the media was experiencing negative effects due to previous experiments (e.g., leaching of previously sorbed P) and this continued improvement indicates the column media is still working towards reaching a stable state.

The trends in effluent TP EMCs for each column and the effects of influent EMC can be seen in Figure 5-11. A drop in TP EMC from 25.1 to 10.0 µg/L is shown for the experimental column for runs 1 to 5 as the column establishes a steady state, followed by an increase in EMC from 10.0 to 23.5 µg/L as higher influent concentrations and flow rates are used (runs 6, 7, and 9). Being thereafter subjected to reduced or standard inflow concentrations (approximately 70 to 120 µg/L) and standard inflow rates, the column effluent begins to move toward its original steady state as typified by run 5 (10.0 µg/L TP EMC), showing a final TP EMC for run 13 of 10.3 µg/L. The control column, in comparison, shows a near continuous increase in effluent EMC. Run 1 showed a TP EMC of 167 µg/L and subsequent runs showed ever increasing EMCs until a peak of 640 µg/L was reached during run 11. Thereafter the column showed a slight drop in effluent EMC through run 13 which had an EMC of 322 µg/L. The experimental column clearly performed better under all conditions to which it was subjected, showing removal as opposed to the P export of the control column.

Looking at the entire population of synthetic storm events applied to the columns, the probability of the EMC to exceed a given value may be calculated and plotted, as seen in Figure 5-12. This plot indicates that 95.3% of the influent storms exceeded 68.4 µg/L EMC, while 50% exceeded 118 µg/L, and approximately 12.3% exceeded 313 µg/L.

Statistically, the control column will export TP at all inflow concentrations. 95.3% of TP EMCs exceeded 156 µg/L, 50% exceeded 220 µg/L, and 4.72% exceeded 640 µg/L. This data also appears to exhibit a change point, a distinct point on either side of which the data show different behaviors. For the control column, effluent EMC shows a steady increase as influent concentration increases. It appears that when influent storms exceed the 50% percentile in terms of TP EMC, the control column EMC shows a distinctly steeper slope. This may indicate that as influent concentration increases beyond this change point (118 µg/L), there are increasingly greater releases of TP from the column.

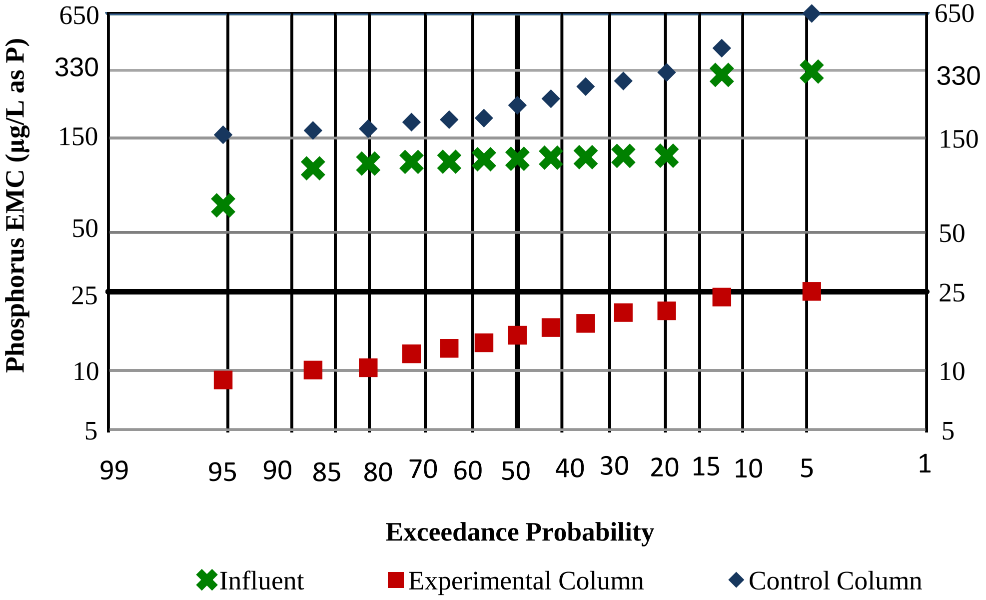


Figure 5-12. Probability plot of influent and effluent TP EMCs. The abscissa indicates the probability that an inflow event will exceed a given P concentration.

The experimental column exhibited much greater P adsorption, showing consistent low TP EMCs. Figure 5-12 indicates that 95.3% of TP EMCs exceeded 8.9 µg/L, 50% exceeded 15.1 µg/L, and only 4.72% exceeded 25.1 µg/L. This indicates that the experimental media possesses the capability to adequately treat P-containing stormwater, reducing the effluent concentration below the EPA recommended limit of 25 μg/L for freshwater lakes for the majority of storms.

These experiments show that increasing influent P concentrations lead to increasing effluent TP and TDP for the control media, but when applied at 15.2 in/hr (11.1 in^3/min) the experimental column is still able to treat all influent to ≤ 20 μg/L TP EMC and keep peak effluent concentration ≤ 35 μg/L. However, as stated previously, reduced experimental media performance was observed when both influent flowrate and concentration were increased. The media maintained effluent EMCs at or below the 25 μg/L EPA recommendation regardless of inflow concentration or flowrate. Similarly, reduced influent concentration resulted in reduced effluent TP and TDP concentrations. Also, shortened antecedent dry time produced enhanced removal for the experimental media, just as the extended dry period led to reduced performance. It may therefore be concluded that WTR-amended media P performance should be maximized when subjected to small volume, more frequent storm events. However, this conclusion cannot be supported with minicolumn data as intermittent flow minicolumn experiment showed no correlation between antecedent dry time and P adsorption. However, dry time was not varied significantly throughout the minicolumn experiments, and the impact of antecedent dry time on column P adsorption may have been confounded by other variables such as flowrate increase.

Over the life of the columns, in every instance, WTR amended media far exceeded control media performance with respect to P adsorption. Experimental media treatment also met or surpassed the recommended concentration limit for fresh waters set by the EPA of ≤ 25 μg/L (US EPA, 1986). From all experiments, the control column received 204 gal of influent, containing a total mass of 111 mg P. The experimental column received 210 gal of influent, containing a total mass of 112 mg P. The mass of P in the effluent was 190 mg and 12.8 mg for the control and experimental columns, respectively. This equates to an 88.5% reduction in P mass in the stormwater by the experimental column media relative to the influent, and a 93.3% reduction in total effluent mass relative to the control column. These reductions in mass are similar to those observed in some studies for BSM. Davis et al. (2006) reported TP mass reductions ranging from 52 to 96% for laboratory media studies, and field results of 70 – 80%. Hsieh et al. (2007) reported mass TP reductions by two media mixture and column configuration combinations of 63 and 85%. Other studies report much poorer removal of P from the influent. Hatt et al. (2009) reported a 398% increase in effluent TP mass relative to influent at a field site in Australia, and a concomitant increase in SRP mass of 1271%. Similarly, Hunt et al. (2006) reported effluent mass increases at a North Carolina field site relative to influent of 240% and 9.3% for TP and SRP, respectively. This indicates that, similar to our control media, many BSM are poorly suited to removing P from stormwater, and may release P. The use of WTR as a media amendment may be useful to transform a media which poorly adsorbs P to one that reduces effluent P concentrations to within acceptable limits.

Normalized by media mass, the experimental media exhibited adsorption of 1.44 mg P/lb (3.18 mg/kg), while the control media exported P (1.08 mg P/lb, 2.38 mg/kg). This calculated measure of media adsorption for the experimental column media is not representative of the true media adsorption capacity, as oxalate extractions indicate the media capacity is not exhausted (see Chapter 6). Clearly, based on reductions in mass loading, effluent concentration reductions, and calculated media adsorption, the experimental media far out performs the control media at removal of P from the influent. It consistently produced effluent EMCs below 25 μg/L as recommended by the U.S. EPA, while the control column exported P. Additionally, the reductions in TP mass provided by the experimental column are similar to those reported by others (Davis et al., 2006; Hsieh et al., 2007). This is a vast improvement over the control media, which showed a large export of P (78 mg net). This suggests that the use of WTR as a BSM amendment will produce even greater P adsorption when integrated into a media that shows even moderate ability to bind P.

5.6. Nitrogen Species Removal

Throughout the course of the experiment, mass loading to both columns included 678 mg NO_3^--N, 1.01 g TKN, and no NO_2^-. The control column released 759 mg NO_3^--N, 11.8 mg NO_2^--N, and 951 mg TKN in its effluent. The experimental column, conversely, released 710 mg NO_3^--N, 3.82 mg NO_2^--N, and 417 mg TKN in its effluent. These are 11.9 and 4.72% increases in effluent NO_3^--N mass compared to the influent for the control and experimental columns, respectively. For TKN, mass in the effluent decreased by 5.65 and 58.6% relative to the influent for the control and experimental columns.

Comparatively, mass of effluent TN for the experimental and control columns measured 1.13 and 1.72 g N, respectively, relative to an influent mass of 1.69 g N. This equates to a 32.9% reduction in TN mass loading by the experimental column and a 2.16% increase in mass loading by the control column. This shows that, apart from reductions in TKN mass by the experimental column, treatment of N species by either column was minimal (Table 5-1).

The WTR amended column retained or exported NO_3^- depending on the experiment, but over the course of the entire life of the column all the NO_3^- that entered the column simply flushed out with little additional production (0.499 g N/lb , 1.1 g N/kg). The same may be said for the control media, although there was greater production of NO_3^- (1.13 g N/lb, 2.5 g N/kg). Similarly, there was some production of NO_2^- by both columns; 0.05 and 0.2 g N/lb (0.1 and 0.4 g/kg) for the experimental and control columns, respectively. This production of oxidized N species from both columns suggests that nitrification is taking place.

Unlike the NOx species, there was some removal of TKN (NH_4^+ + glycine) in both columns. The control column removed 0.77 g N/lb (1.7 g/kg). The removal of TKN is less than the sum of the NOx species produced, suggesting that the NOx are being produced by organic matter in the media. Removal of TKN by the experimental column was much greater than that of the control column, measuring 9.25 g N/lb (20.4 g/kg). This is much greater than the NOx species produced, indicating that the ammonium and/or glycine are being retained by the WTR-containing media. It is likely that the WTR is adsorbing the glycine component of the TKN, because glycine will exist as a zwitterion ($pK_{a1} = 2.4$, $pK_{a2} = 9.8$) and at the pH encountered in the column soil system the anionic carboxyl moiety could likely undergo some manner of sorption to the positively charged WTR surface (Lambert, 2008). However, this cannot be conclusively determined as neither NH_4^+ nor organic N were measured individually.

5.7. Leaching

Experimental column effluent was digested and analyzed for Al(III) as described in Section 3.10. All samples analyzed were below the method detection limit of 5 mg/L. However, both EPA and Maryland Department of the Environment have established a drinking water MCL of 50 – 200 μg/L and a criterion continuous concentration (CCC) for freshwater organisms of 87 μg/L. Unfortunately, that renders our results inconclusive with regards to the degree of elemental Al leaching.

As previously discussed, there were also measurable releases of dissolved and particulate materials from both columns. Throughout all the column experiments, WTR-containing media effluent maintained turbidity < 8 NTU, and except for a single sample turbidity was < 2 NTU. The control column, on the contrary, had high effluent turbidity ranging from 2.5 to 155 NTU with a cumulative average of 32.4 ± 20.1 NTU. Turbidity within runs often exhibited the same behavior trends as P species, showing a large initial peak and a near exponential decay with flow. This high turbidity was not exclusively particulate species either. Most samples from the control column remained tea-colored even after filtering, suggesting that the column was leaching dissolved organic matter (DOM). The amount of P that effluent DOM was contributing to TDP was measured by comparing SRP and TDP for the control column. Undigested and filtered samples measured for P by the ascorbic acid method (APHA, 1995) are an operational measure of PO_4(-III). The difference between SRP and TDP is often used as a measure of P_o in solution (Dr. Bruce James, personal communication). For all control column samples, P_o analyzed in this way measured $\leq$ 10 μg/L, suggesting that the DOM is either not exporting P or the P species are Mo reactive.

It was also observed during ion chromatograph (IC) analysis for anions that a large amount of an unknown ion was leaching from the media, especially the experimental BSM. It was theorized to be sulfate (SO_4^{2-}), and this was confirmed by performing a sample matrix spike. Unfortunately, little SO_4^{2-} data are available, and such large amounts were leached from the WTR-containing media that the initial concentrations exceeded the upper measurement limit of 25 mg SO_4^{2-}/L. Effluent concentrations gradually diminished over time, but the results from runs 1 through 3 were lost due to these circumstances. However, all EMCs that are available ranged from 2.12 to 14.6 mg SO_4^{2-}/L. Including all available results, SO_4^{2-} leaching from each column was measured as 53.5 and 12.3 mg SO_4^{2-}/lb (118 and 27.2 mg/kg) from the experimental and control columns, respectively.

To account for the lost samples, a media water extraction per Section 3.9 was performed on the WTR-containing media, resulting in a labile media SO_4^{2-} content of 118 mg SO_4^{2-}/lb (261 mg/kg). It can be assumed this is the content of the media as a whole, and as this concentration is not significantly larger than what was measured during column operation it may be concluded that the experimental column media may be nearly exhausted with respect to SO_4^{2-}. Therefore, SO_4^{2-} leaching should not be of concern, although the possibility of H_2S formation if the media becomes anoxic may lead to nuisance odors. The leaching of SO_4^{2-} is likely to result from the WTR because of the

$Al_2(SO_4)_3$ used during drinking water coagulation. The minimal losses from the control media also suggest there is some inherent in the BSM itself. However, studies have previously suggested ligand exchange to be the primary P adsorption process occurring at the WTR surface (Yang et al., 2006), and it is likely that some of the leaching SO_4^{2-} in this study is the result of the exchange of SO_4^{2-} for PO_4(-III) at the BSM-water interface.

Similar to SO_4^{2-} leaching, an increase in column effluent pH may be an indication of hydroxyl leaching caused by P adsorptive ligand exchange (Yang et al., 2006). The control column exhibited little change in effluent pH across all experiments, averaging 6.3 ± 0.1 for the first run to 5.9 ± 0.1 for the final run, with a mean and median for all samples of 6.1 ± 0.1 and 6.1, respectively. Conversely, the experimental column showed a steady, much more pronounced decrease in effluent pH over time. Effluent pH averaged 7.1 ± 0.3 for the first run to 6.2 ± 0.2 for the last run, with a global mean and median of 6.6 ± 0.3 and 6.5, respectively. While both media showed some buffering of the influent pH and a gradual effluent pH drop with flow, the WTR-containing BSM traversed a pH range twice as great as that of the control column. If hydroxyl ions were in fact being released through ligand exchange, an increase in pH would be expected, suggesting that either ligand exchange for hydroxyl ions is not occurring, or some other process is obscuring this phenomenon. Possibly SO_4^{2-} is being released from residual alum in the media, allowing –OH groups to react with newly exposed Al in the formation of $Al(OH)_3$. Alternatively, it may simply be the leaching or neutralization of pH adjustment chemicals that had been used during the drinking water treatment process, which as they migrate from the media lead to a general decrease in effluent pH.

NUTRIENT REMOVAL OPTIMIZATION OF BIORETENTION SOIL MEDIA

Chapter 6: Media Oxalate Extractions and Phosphorus Saturation Indices

Oxalate extractions and calculation of the PSI for each media were conducted as per Section 3.10. Additionally, PSI was determined for column media both pre- and post-experiment. For the mesoscale vegetated columns this allowed determination of the degree of media saturation with depth. These data also allowed for a comparison of media adsorptive capacities from batch and column studies, and allowed for the development of media specification requirements for effective P capture.

6.1. Amendment Contributions to Oxalate-extractable Elements

6.1.1. Water Treatment Residual

The addition of increasing WTR content to BSM led to small increases in media P_{ox} and Fe_{ox} contents and much more pronounced increases in Al_{ox} content. For example, in the batch studies 0, 2, 4, and 10% WTR amended BSM showed P_{ox} contents of 1.83, 2.34, 2.86, and 3.35 mmol P_{ox} /lb (4.04, 5.15, 6.30, and 7.39 mmol/kg), respectively. Similarly, Fe_{ox} measured 7.08, 6.89, 7.80, and 10.0 mmol Fe_{ox}/lb (15.6, 15.2, 17.2, and 22.1 mmol/kg), and Al_{ox} measured 4.81, 22.0, 42.1, and 180 mmol Al_{ox}/lb (10.6, 48.4, 92.9, and 396 mmol/kg) for each mixture, respectively (Table 6-1). These increases were from the WTR itself, as it possesses P_{ox}, Fe_{ox}, and Al_{ox} content greater than the BSM (Table 4-1), and clearly as the WTR content of the mixture increased almost uniformly so did all measured oxalate-extractable contents. A similar general trend of increasing oxalate-extractable content with increasing mixture WTR proportion was also seen among media amended with other

Table 6-1. Oxalate-extractable P, Fe, and Al contents of BSM mixtures from batch studies. A 0.275 M acid ammonium oxalate extractant was used with pH 3.0 ± 0.1. PSI is defined as per Section 4.5.

	P_{ox}	Fe_{ox}	Al_{ox}	PSI
		mmol/kg		%
BSM	4.04	15.6	10.6	15.4
2% WTR	5.15	15.2	48.4	8.10
4% WTR	6.30	17.2	92.9	5.72
10% WTR	7.39	22.1	396	1.77
LFBSM	1.74	8.86	5.62	12.0
3% WTR	2.55	11.5	66.7	3.26
6% WTR	3.32	11.2	193	1.63
10% WTR	4.60	15.0	338	1.30
BSM + HBM	3.85	17.4	9.35	14.4
2% WTR + HBM	6.88	22.8	54.8	8.87
4% WTR + HBM	5.16	15.4	118	3.87

BSM + LC	5.52	18.5	11.8	18.2
4% WTR + LC	5.59	9.64	62.6	7.74
4% WTR + LC [OM+]	8.79	22.3	53.4	11.6

Table 6-2. Oxalate-extractable P, Fe, and Al contents of media, initially and after column experimentation. PSI is defined as per Section 4.5. †: Intermittent column flow regime.

	P_{ox}	Fe_{ox}	Al_{ox}	Initial PSI (%)	Final PSI (%)
	Initial (Final) content; mmol/kg				
Experimental Set I:					
BSM	4.02 (4.30)	14.0 (15.0)	12.3 (10.5)	15.3	16.9
BSM + 2% WTR	6.18 (5.51)	17.7 (12.8)	91.7 (70.8)	5.65	6.59
BSM + 4% WTR	6.33 (6.77)	16.7 (12.9)	181 (125)	3.19	4.91
BSM + 2% WTR + HBM	5.04 (6.93)	15.9 (15.4)	119 (99.3)	3.75	6.04
BSM + 4% WTR + HBM	5.95 (6.50)	19.4 (17.3)	217 (196)	2.52	3.05
LFBSM + 4% WTR	4.86 (10.3)	11.2 (14.6)	161 (192)	2.83	5.00
Experimental Set II:					
BSM	4.13 (3.56)	7.85 (11.0)	13.3 (8.82)	19.5	18.0
BSM + 4% WTR	7.75 (8.59)	19.8 (12.9)	101 (164)	6.43	4.86
Sand + 4% WTR	2.35 (5.35)	2.12 (1.04)	222 (148)	1.05	3.58
†BSM + 4% WTR + HBM	5.88 (8.76)	12.8 (17.6)	183 (179)	3.00	4.50
†BSM + 4% WTR	9.24 (6.71)	19.1 (13.4)	228 (202)	3.74	3.10
†LFBSM + 4% WTR	5.26 (7.36)	12.3 (12.3)	218 (182)	2.28	3.80

components such as HBM and quartz sand, from both batch and minicolumn studies (Tables 6-1 and 6-2). While the WTR does contribute to an increased P_{ox} measure in the mixtures, the addition of P to the mixture by WTR is nearly two orders of magnitude less than Al_{ox} addition (58.4 mmol P_{ox}/kg vis-à-vis 5.74 mol Al_{ox}/kg) and so a net increase in P adsorption capacity results from amending media with WTR.

6.1.2. Low-fines BSM

LFBSM amended with WTR showed reduced oxalate-extractable elements compared to equivalent WTR-amended BSM mixtures. For example, 4% LFBSM measured 2.20 mmol P_{ox}/lb (4.86 mmol/kg), 5.08 mmol Fe_{ox}/lb (11.2 mmol/kg), and 73.0 mmol Al_{ox}/lb (161 mmol/kg) from the set I minicolumn study (Table 6-2). Comparatively, the 4% BSM from the same minicolumn set measured 2.87 mmol P_{ox}/lb (6.33 mmol/kg), 7.57 mmol Fe_{ox}/lb (16.7 mmol/kg), and 82.1 mmol Al_{ox}/lb (181 mmol/kg; Table 6-2). A similar, more exaggerated trend is seen for the WTR amended sand investigated in minicolumn set II where P_{ox} and Fe_{ox} were even less abundant and measured 1.07 mmol P_{ox}/lb (2.35 mmol/kg) and 0.962 mmol Fe_{ox}/lb (2.12 mmol/kg; Table 6-2). This is logical as the fines in the BSM mixture contain Fe and Al and associated adsorbed P. When the fines content is reduced by the addition of sand to create the LFBSM, these oxalate-extractable media elements will also be reduced.

In a few instances, however, LFBSM and sand amended with WTR measured greater Al_{ox} content compared to analogous WTR-amended BSM mixtures. The amended sand media contained 101 mmol Al_{ox}/lb (222 mmol/kg), greater than the measured Al_{ox} contents of either 4% amended BSM or LFBSM from minicolumn set I (82.1 and 73.0 mmol Al_{ox}/lb, respectively). The continuous and intermittent 4% BSM mixtures from minicolumn set II measured 45.8 and 103 mmol Al_{ox}/lb (101 and 228 mmol/kg), while the intermittent 4% LFBSM media from the same set measured 98.9 mmol Al_{ox}/lb (218 mmol/kg; Table 6-2). This apparent variability of Al_{ox} contents in media containing the same proportion of WTR is difficult to explain, but may simply be the result of sample variation. T-tests on the mean Al_{ox} contents for the 4% WTR amended BSM, LFBSM, and sand media failed to reject the null hypothesis that these average media Al_{ox} contents were equal ($p > 0.16$), indicating that no two of the amended media have statistically different average Al_{ox} contents.

6.1.3. Organic Amendments

The organic amendments (HBM and LC) both contributed a small amount of Fe_{ox} and Al_{ox} to the overall media mixture. HBM contained 24.7 mmol Fe_{ox}/lb (54.4 mmol/kg) and 5.76 mmol Al_{ox}/lb (12.7 mmol/kg), while LC contained 17.9 mmol Fe_{ox}/lb (39.4 mmol/kg) and 6.21 mmol Al_{ox}/lb (13.7 mmol/kg). These differing oxalate extractable metals contents may partially be the cause of the two very different impacts the amendments have on media P adsorption. The major difference between the two based on P performance results because of their respective contributions of P_{ox}. While HBM added no additional P to the overall mixture (1.70 mmol P_{ox}/lb, less than the content of BSM or WTR; Table 4-1), LC added a measureable amount (7.21 mmol P_{ox}/lb). Therefore, while HBM added some Fe and Al with no P and thereby increased the media oxalate ratio and improved adsorption, the addition of P from LC outweighed its minimal Fe and Al contribution and lead to decreased adsorption and a lower oxalate ratio. This can be seen in various media mixtures. 4% HBM from minicolumn set I had 2.70 mmol P_{ox}/lb (5.95 mmol/kg), 8.80 mmol Fe_{ox}/lb (19.4 mmol Fe_{ox}/kg), and 98.4 mmol Al_{ox}/lb (217 mmol/kg), resulting in an oxalate ratio of 39.7 (Table 6-2). The same media from the batch studies contained 2.86 mmol P_{ox}/lb (6.30 mmol/kg), 7.80 mmol Fe_{ox}/lb (17.2 mmol/kg), and 42.1 mmol Al_{ox}/lb (92.9 mmol/kg), producing an oxalate ratio of 17.4 (Table 6-1). Comparatively, the BSM + 4% WTR + LC mixture from the batch studies contained 2.54 mmol P_{ox}/lb (5.59 mmol/kg), 4.37 mmol Fe_{ox}/lb (9.64 mmol/kg), and 28.4 mmol Al_{ox}/lb (62.6 mmol/kg), having an oxalate ratio of 12.9. Regardless of the differing Al_{ox} contents, the increase in P_{ox} of the LC-containing media is evident and negatively impacted the mixture's oxalate ratio (Tables 6-1 and 6-2). As oxalate ratio is positively correlated with media P adsorption capacity (see Section 6.2), the reduced P adsorption capacity observed after the addition of LC is explainable.

6.2. Correlation of Oxalate Extraction with P Adsorption

As show in previous work, media P adsorption (e.g., Q_{max}) is correlated with PSI and oxalate extractable Al and Fe (Dayton and Basta, 2005). All media investigated in this study were analyzed for oxalate extractable Al, Fe, and P to quantify their relationship with media P adsorption capacity. The control media from the vegetated column study was included in these analyses. This is because an equilibrium P adsorption capacity could be estimated for the media as it ceased showing adsorption in contact with a 120 µg P/L solution, indicating the media and solution were at equilibrium. The experimental media from the vegetated column study was not included as it was not at equilibrium with the influent and still had

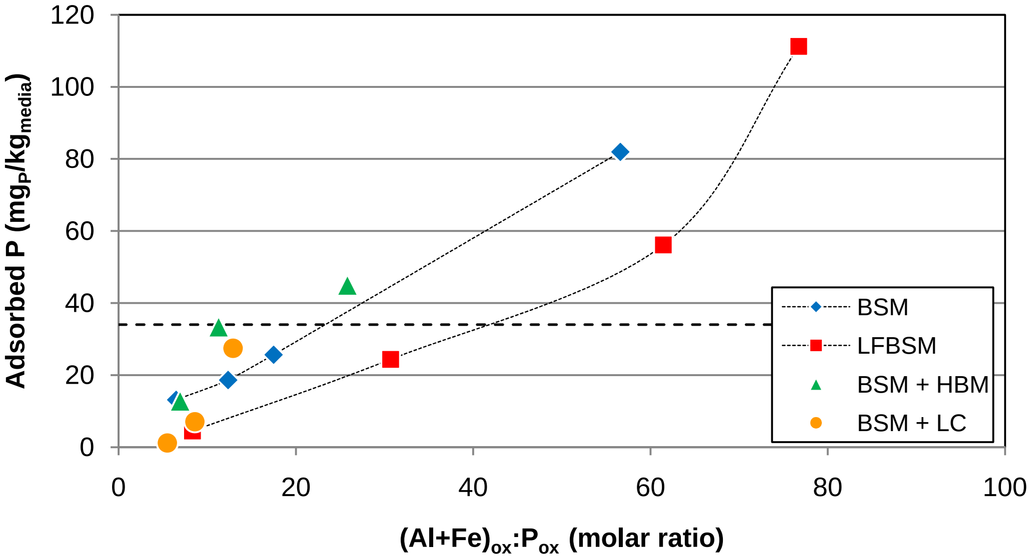


Figure 6-1. Batch adsorption study measured oxalate ratio for each media mixture, and the interpolated media equilibrium adsorption content. The media equilibrium is calculated for a soluble P concentration of 120 µg/L, within a pH range of 4.6 – 7.4. The horizontal dashed line represents the media adsorption benchmark of 15.4 mg P/lb (34 mg/kg).

available capacity. Because of this, a media adsorption capacity could not be determined.

In Figures 6-1 to 6-3, points increasing along the abscissa have increasing amorphous Al and Fe content, produced mainly through increasing Al in each mixture caused by greater WTR content. The ordinate axis in all figures is a measure of the equilibrium P adsorption of a mixture with a 120 µg P/L solution. This value was determined by the Freundlich fitted isotherms calculated from the batch adsorption data (Section 4.3) or from the column adsorption studies, as discussed in Sections 4.4 and 5.5.

Figure 6-1 shows the increasing effectiveness of a given media for adsorption of P correlated with increasing $(Al+Fe)_{ox}:P_{ox}$ ratio (Oxalate ratio; PSI^{-1}) for the batch study results. Each mixture of the four amendment types (WTR, LFBSM+WTR, WTR+HBM, WTR+LC) are shown, with each individual point correlating to the expected media P adsorption based on Freundlich isotherms from the batch adsorption studies and oxalate extractions for a given amendment content (0, 2, 4% WTR, etc.). Under batch conditions, BSM amended with only WTR performed at the threshold requirement (15.4 mg P/lb, 34 mg P/kg) when the oxalate ratio was approximately 23, which correlates to a WTR content of about 5% on an air dry weight basis. Similarly, the LFBSM amended with WTR straddled the threshold with oxalate ratios of 30 and 61, representing a necessary WTR content of between 3% and 6%. BSM amended with both WTR and HBM crossed the threshold between oxalate ratios of 11 and 26, correlating to 2% and 4% WTR. The strong correlation between media P adsorption and oxalate ratio is clear, especially for the BSM and LFBSM media, which exhibit nearly linear relationships.

Figure 6-2 again shows media P adsorption correlated with oxalate ratio, detailing the relationship for column as well as batch studies. The addition of the column data provides a more varied indication of minimum WTR content under conditions invoked by the continuous and intermittent treatments compared to the batch studies (Table 6-1, Figures 6-2). This can be attributed to the fluctuating Al_{ox} content. In some cases, Al_{ox} content for the column media more than doubled that measured for batch media of the same WTR mass. For example, the 4% BSM mixture used for the batch study measured 42.1 mmol Al_{ox}/lb (92.9 mmol/kg), while media mixed in the same proportions and used for the set I minicolumn study measured 82.1 mmol Al_{ox}/lb (181 mmol/kg; Tables 6-1 and 6-2). However, even with greater Al_{ox} contents the column data often showed reduced media P adsorption, likely because of reduced contact time between the media and P in solution compared to batch conditions. For example, although 2% BSM from the batch studies had an oxalate ratio of 12.3 and a P adsorption capacity of 8.44 mg P/lb (18.6 mg/kg), from the set I minicolumn study the analogous media had a higher oxalate ratio of 17.7.

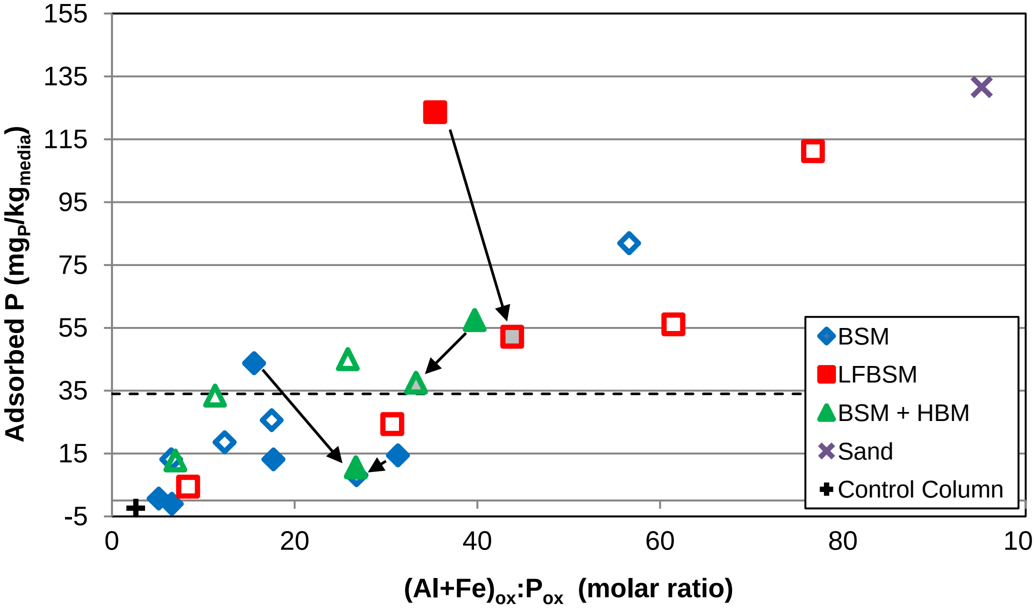


Figure 6-2. Measured oxalate ratio for media from both batch and column studies and the expected or actual TP media equilibrium adsorption capacity. The media equilibrium is for a soluble P concentration of 120 µg/L, within a pH range of 4.6 – 7.4. Open marks represent batch data, closed marks represent data from columns subject to continuous flow, and open grey-filled marks represent intermittent column data, with arrows originating from the equivalent continuous column data. The horizontal dashed line represents the media adsorption benchmark of 15.4 mg P/lb (34 mg/kg).

This high oxalate ratio suggests greater media P adsorption capacity, but measured capacity for the media was only 5.99 mg P/lb (13.2 mg/kg). This phenomena was even more pronounced in the intermittent flow columns. For instance, the 4% LFBSM media used in the set I minicolumn study had an oxalate ratio of 35.3 and a media P adsorption capacity of 56.2 mg P/lb (124 mg/kg). An identical media

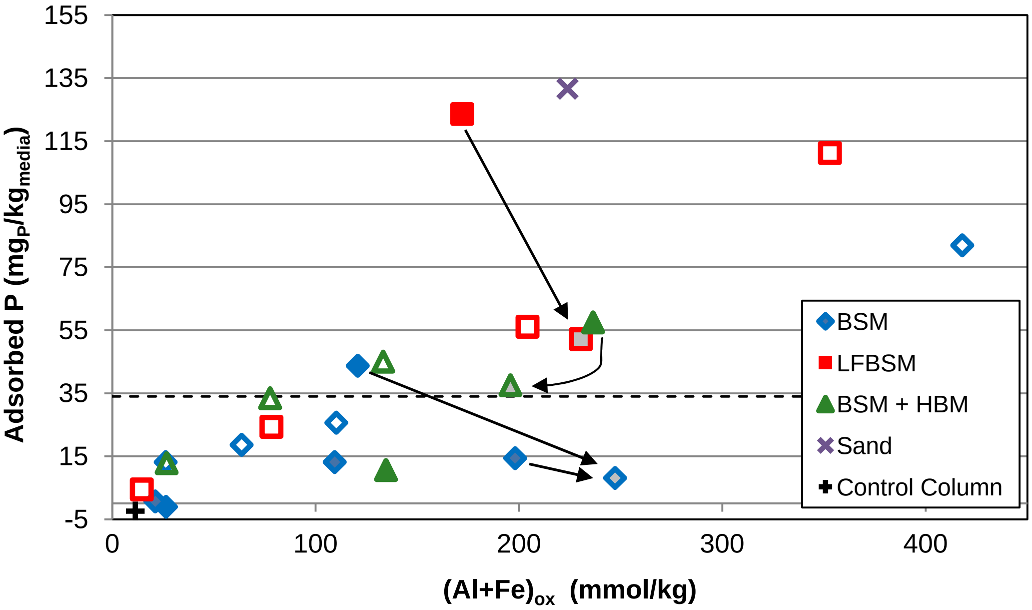


Figure 6-3. Oxalate-extractable Al and Fe for media from both batch and column studies and the expected or actual TP media equilibrium adsorption capacity. The media equilibrium is for a soluble P concentration of 120 µg/L, within a pH range of 4.6 – 7.4. Open marks represent batch data, closed marks represent data from columns subject to continuous flow, and open grey-filled marks represent intermittent column data, with arrows originating from the equivalent continuous column data. The horizontal dashed line represents the media adsorption benchmark of 15.4 mg P/lb (34 mg/kg).

mixture used for set II had an oxalate ratio of 43.9, but only had an adsorption capacity under intermittent flow of 23.7 mg P/lb (52.2 mg/kg; Table 6-2). In addition to the reduced contact time with flow experienced in the column experiments, the drying of the media subjected to intermittent flow is believed to be the source of this further reduction in media P adsorption capacity. Drying causes the crystallization of WTR, which reduces its surface area and consequently its P adsorption capacity by limiting available adsorption sites (Yang et al., 2008; Agyin-Birikorang and O'Connor, 2009). Even with the complex interactions between flow regime and media adsorption, the strong positive correlation that exists between oxalate ratio and media P adsorption capacity can clearly be seen (Figure 6-2)

Figure 6-3 again shows both media P adsorption capacity for batch and column data on the ordinate axis, but the abscissa expresses the media molar oxalate-extractable Al + Fe content instead of the oxalate ratio. These data also show a general trend of increasing media P adsorption, however the scatter of the data is much greater, and consequently the correlation between media P adsorption capacity and $(Al+Fe)_{ox}$ is much more poorly defined than the correlation between oxalate ratio and media P adsorption capacity. This figure illustrates the need to include a measure of media P content in a predictor for media P adsorption capacity, such as is done with the PSI or the oxalate ratio.

Along with the variability in measured Al_{ox} contents of the media, a similar observed phenomenon involved the changes in media oxalate-extractable contents from pre- to post-adsorption. It was expected that P_{ox} would increase after experimentation as P adsorbed on media Fe and Al. Similarly, a drop in media Fe_{ox} and/or Al_{ox} was expected due to media drying and crystallization, as well as washout of fines and other media components that contribute to Fe and Al content. However, in a number of instances behavior was contrary to that expected. The 4% LFBSM media from the set I minicolumn study saw an increase of both Fe_{ox} and Al_{ox}, from 5.08 to 6.62 mmol Fe_{ox}/lb (11.2 to 14.6 mmol/kg) and 73.0 to 87.1 mmol Al_{ox}/lb (161 to 192 mmol/kg). The 4% BSM from minicolumn set II also saw an increase in its Al_{ox} content from 45.8 to 74.4 mmol Al_{ox}/lb (101 to 164 mmol/kg; Table 6-2). This increase was so large that the oxalate ratio for the media from pre- to post-adsorption actually increased, from 15.6 to 20.6, which suggests increasing capacity for P adsorption. 4% BSM subjected to intermittent flow from minicolumn set II experienced a decrease in P_{ox}, from 4.19 to 3.04 mmol P_{ox}/lb (9.24 to 6.71 mmol/kg). This also resulted in the media oxalate ratio increasing after adsorption, from 26.7 to 32.3 (Table 6-2).

These decreases in P_{ox} and increases in Fe_{ox} were attributed to poor sample homogenization and sampling variation, as the magnitude of the changes were relatively small (approximately 0.5 to 1.5 mmol/lb). However, in the two instances where this occurred for Al_{ox}, the magnitude of the unexpected increase was much greater (14 and 29 mmol/lb). Al-WTR, especially that used in this study, has a very high Al density (2.60 mol Al_{ox}/lb; 2.83 mol Al_{Tot}/lb), so significant variation can result if the media is improperly homogenized, to produce huge swings in measured Al_{ox} content. This high degree of variability for WTR-amended media is further exemplified by the measured Al_{ox} content of the 4% BSM media from the minicolumn set II (Table 6-2). The same media was used in two columns and one each subjected to continuous and intermittent flow. However, a single batch of media was mixed for the construction of both columns and an oxalate extraction was performed on the media on two separate occasions. Table 6-2 shows that the difference in the measured “virgin” media Al_{ox} content was 57 mmol Al_{ox}/kg (45.8 vis-à-vis 103 mmol Al_{ox}/kg), a factor of approximately 2.3. Additionally, the measured post-adsorption Al_{ox} contents converged somewhat, with the continuous flow media measuring 74.4 mmol Al_{ox}/lb (164 mmol/kg) and the intermittent flow media measuring 91.6 mmol Al_{ox}/lb (202 mmol/kg), reducing the measured difference to 17.2 mmol Al_{ox}/lb (38 mmol/kg). These differences may have been more fully understood by analyzing the different media’s P adsorption capacity, except each column was subjected to different flow regime treatments, and hence comparison is not valid. Ultimately, the reason for this variation is not known, but because the difference in measured contents converged on measuring post-adsorption, this phenomenon is attributed to sampling variation. This exemplifies the need to carefully and thoroughly mix amended media when sampling.

Regardless, because Al (hydr)oxides such as the $Al(OH)_3$ in WTR adsorb P, increasing their content in the media will result in greater P adsorption. This held true in general, as seen in Figure 6-2. Specifically, however, even with a greater Al_{ox} content in the column media, in many instances media adsorption capacity was lower than that of batch media because of reduced media/solution contact time. Furthermore, this trend is exacerbated with media subject to an intermittent flow regime, where such columns adsorbed less P per media mass than the same media subjected to continuous flow (Section 4.4), even when the media have similar oxalate ratios. This is because of media drying, as explained in Section 2.2. Therefore, while WTR content has a strong impact on oxalate ratio and P adsorption capacity, the flow conditions to which the media are subject are an important variable to consider when using WTR as a stormwater management amendment. Also, when using the oxalate ratio as a metric, it must be remembered that adsorption to Fe and Al (hydr)oxides is only the dominant P control mechanism under acidic to neutral soil conditions. The oxalate ratio is therefore not expected to be a valid predictor of adsorption capacity under alkaline conditions or in soils with a large Ca content, which can sequester P as Ca-P precipitates, because Ca content and Ca-P interactions are not accounted for using this metric (Kovar and Pierzynski, 2009). Regardless, the use of the oxalate ratio appears to be a fairly reliable and informative metric in predicting the P adsorption capacity of a medium for stormwater treatment.

6.3. Media Capacity Exhaustion with Depth

Changes in media oxalate extractions with depth for the media used in the vegetated columns was investigated. Table 6-3 shows the oxalate-extractable contents for unused media and used media collected at 0-0.8 in (0-2 cm, surface layer), 4.3-4.7 in (11-12 cm, ⅛ column length), 8.3-8.7 in (21-22 cm, ¼ column length), and 16.9-17.3 in (43-44 cm, ½ column length) depths for the mesoscale vegetated column experiments. Figure 6-4 visually represents media oxalate from Table 6-3. With the control media, little variation is seen in the media with depth or compared to unused media. One minor exception to this is the surface layer sample,

Table 6-3. Oxalate extractable contents of control and experimental media from vegetated columns pre- and post-experimentation. 0.275 M acid ammonium oxalate extraction fluid (pH = 3.0 ± 0.1) at 1:40 w/v was used.

Depth (cm)	P_{ox} (mmol/kg)	Al_{ox} (mmol/kg)	Fe_{ox} (mmol/kg)	$(Al+Fe)_{ox}$ (mmol/kg)	PSI (%)	Oxalate Ratio
Control						
Unused	4.20	9.74	1.26	11.0	37.9	2.62
0 - 2	2.91	7.44	0.896	8.33	36.3	2.87
11-12	4.94	10.2	1.31	11.5	42.8	2.32
21-22	5.70	11.7	1.59	13.3	42.6	2.34
43-44	4.47	11.0	1.28	12.3	36.4	2.74

Experimental						
Unused	7.88	180	1.30	182	4.32	23.1
0 - 2	13.4	193	1.55	195	6.90	14.5
11-12	9.99	191	1.59	193	5.27	19.3
21-22	8.19	162	1.44	163	5.05	19.9
43-44	7.99	181	1.41	182	4.41	22.8

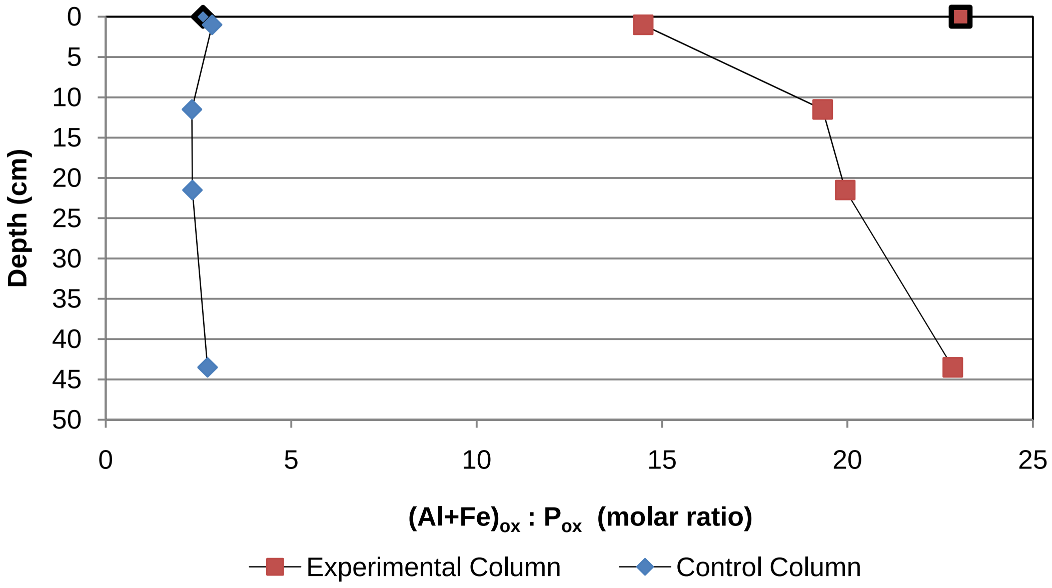


Figure 6-4. Post-adsorption vegetated column oxalate ratios at various depths. 0.275 M acid ammonium oxalate extraction fluid (pH = 3.0 ± 0.1) at 1:40 w/v was used. Marks with black trim represent unused, "virgin" media.

which showed reduced oxalate-extractable contents for P, Fe, and Al (1.31 mmol P_{ox}/lb, 0.406 mmol Fe_{ox}/lb, and 3.37 mmol Al_{ox}/lb) compared to the unused media (1.91 mmol P_{ox}/lb, 0.572 mmol Fe_{ox}/lb, and 4.42 mmol Al_{ox}/lb) and other depths. This surface portion was observed to have suffered heavily from fines migration, having a clearly greater content of quartz sand relative to other media constituents, and it is believed that this is the reason for the reduced oxalate-extractable contents. Also, the 8.3-8.7 in. layer showed a slight increase in all oxalate components (2.59 mmol P_{ox}/lb, 0.721 mmol Fe_{ox}/lb, and 5.31 mmol Al_{ox}/lb) compared to the unused, 4.3-4.7 in. layer (2.24 mmol P_{ox}/lb, 0.594 mmol Fe_{ox}/lb, and 4.63 mmol Al_{ox}/lb), and the 16.9-17.3 in. layer (2.02 mmol P_{ox}/lb, 0.581 mmol Fe_{ox}/lb, and 4.99 mmol Al_{ox}/lb). This is believed to be caused by heterogeneities in the media, because the slight increase in the Fe_{ox} and Al_{ox} of this layer was accompanied by a measured increase in P_{ox}. A slight increase in clay or HBM content at that depth in the column media would cause a greater measure of oxalate extractable elements, and explain this occurrence. Because this difference is small and the media at all depths measured nearly identical oxalate ratios, the media being relatively the same throughout is implied, and suggests that the slight increase in oxalate measurements at this depth are not caused by an impurity in the media.

All fresh and unused control media showed very low oxalate ratios, indicating it will be a very poor sink for P and verifying experimental adsorption results (Section 4.4). Agyin-Birikorang and O'Connor (2007) report that the P leachability of a soil greatly increases with a PSI > 10%, which is analogous to an oxalate ratio of < 10. The unused control media has an oxalate ratio of 2.62 (PSI 37.9%), which falls well within this region of P leachability and corroborates the observed poor media P adsorption behavior (-1.08 mg P/lb). The control media is plotted on Figures 6-2 and 6-3, on which it shows behavior consistent with the overall trend in the data, having both a low oxalate ratio and low media P adsorption capacity relative to the other media.

The experimental media, conversely, showed well defined reductions in media capacity near the surface (Figure 6-4, Table 6-3). At 16.9-17.3 in. (½ column length) the media oxalate extractions measured nearly the same as the unused media (22.8 vis-à-vis 23.1), indicating that P carried into the column by the influent had been nearly completely adsorbed and removed from solution by this depth.

Exhaustion of the surface media may be determined by comparison with the minicolumn post-adsorption oxalate-extractable contents (Tables 6-2 and 6-3, respectively), although the media are not directly comparable because they differ in WTR and fines contents. However, the experimental column surface media sample and minicolumn media having similar WTR and fines contents had approximately the same oxalate-extractable contents post-use. For example, the experimental surface layer measured 3.62 mmol P_{ox}/lb (7.99 mmol/kg), 0.640 mmol Fe_{ox}/lb (1.41 mmol/kg), and 82.1 mmol Al_{ox}/kg (181 mmol/kg). Comparatively, the set II intermittent 4% LFBSM media measured 3.34 mmol P_{ox}/lb (7.36 mmol/kg), 5.58 mmol Fe_{ox}/lb (12.3 mmol/kg), and 82.6 mmol Al_{ox}/lb (182 mmol/kg) post-adsorption. Also, the 4% WTR + sand media measured oxalate-extractable contents post-adsorption of 2.43 mmol P_{ox}/lb (5.35 mmol/kg), 0.472 mmol Fe_{ox}/lb (1.04 mmol/kg), and 67.1 mmol Al_{ox}/lb (148 mmol/kg). One can see that the P_{ox} and Al_{ox} for the experimental media are nearly identical to that measured for the LFBSM mixture, while its Fe_{ox} content is more akin to the amended sand mixture. The sand itself should have little to no Fe_{ox} content, and that which was measured is believed to come from the WTR amendment. Consequently, this may indicate that the Fe content of the experimental (and control) media may be crystallized. Also, the similar measurements for the surface layer of the experimental media and these post-adsorption minicolumn experiments may suggest that the experimental media at the surface is in fact exhausted. If such is the case, it may be concluded that the media at greater depths still retain capacity for P adsorption as they have a higher measured oxalate ratio. Therefore, because only the surface layer of the vegetated column has exhausted its capacity, the majority of the experimental media in the column is not exhausted and the media still retains a large proportion of its adsorptive capacity. The media that has reached capacity for P adsorption is between 0.8 and 4.7 in. (2 and 12 cm), or approximately 2.2 to 13% of the media by depth, and nearly half the column (> 17.3 in. depth) retains most to all of its adsorption capacity. Overall, the experimental column media adsorbed 99.4 of 112 mg P from the influent, compared to the control column which produced 79.0 mg P (see Section 5.5).

A linear regression was performed for media adsorption capacity dependence on the oxalate ratio (Figure 6-2). This regression ($R^2 = 0.7148$) resulted in the equation

$$q = 1.35889 \cdot \mathrm{OR} - 0.841644 \qquad (6\text{-}1)$$

where q is the media adsorption capacity (mg P/kg), and OR is the oxalate ratio (molar basis). This predicts for the experimental media an adsorption capacity of 30.5 ± 20.3 mg P/kg (± SE) for OR = 23.1. While this is only 90% of the necessary 15.4 mg P/lb, when the magnitude of the standard error is considered, this suggests the media has a sufficient capacity for P adsorption.

6.4. Recommended Media Specifications and Procedures

Figure 6-3 indicates that a minimum oxalate-extractable Al and Fe content of approximately 68.0 to 113 mmol/lb (150 to 250 mmol/kg) is necessary for satisfactory P capture as defined by 120 μg/L soluble P. It must be noted that this is a very coarse predictor of media adsorption, as exemplified by the high degree of variability in the data. The oxalate ratio data presented in Figure 6-2 show a much stronger linear trend and indicate that for any media an oxalate ratio of at least 20 to 40 is necessary for adequate stormwater treatment. This is equivalent to a PSI of no more than 2.5 to 5%. Based on a linear regression ($R^2 = 0.5627$) of percent WTR on media oxalate ratios utilizing all available data, this is equivalent to 2.6 to 4.3 ± 1.7 % WTR (± SE) for the specific WTR used in this study. Lower WTR contents in this range are more appropriate as P_{ox} content of the unamended media or fines content diminishes. Conversely, unamended media with higher P_{ox} contents or the use of WTR with a lower Al_{ox} content may require higher additions.

WTR-amended media must meet these requirements to perform adequately, but procedures should be followed to correctly prepare the amended BSM for use (Figure 6-5). Al-WTR should be collected dewatered from the drinking water treatment plant. Air dried materials may be used, but those which have aged in the open air for more than 6 months or have been subjected to higher temperatures (> 45°C) may have reduced Al_{ox} contents and reactivity (Agyin-Birikorang and O’Connor, 2009). This same study, however, also implicated such “fresh” Al-WTR (aged < 6 mo.) as having increased risk of Al leaching. Therefore, while reduced reactivity may lead to the need for greater volumes of residual to achieve the desired media P adsorption, this must be counter-balanced with Al leaching potential.

Drinking water plants often produce dewatered sludge as either pellets or large cakes. If possible, the WTR should be fed through an impact crusher, ball mill, grinding mill, or other device well suited for crushing soft materials, especially if the WTR is acquired as cakes. Particles of WTR should be as small as possible to maximize surface area while large enough so as to not migrate within the larger soil

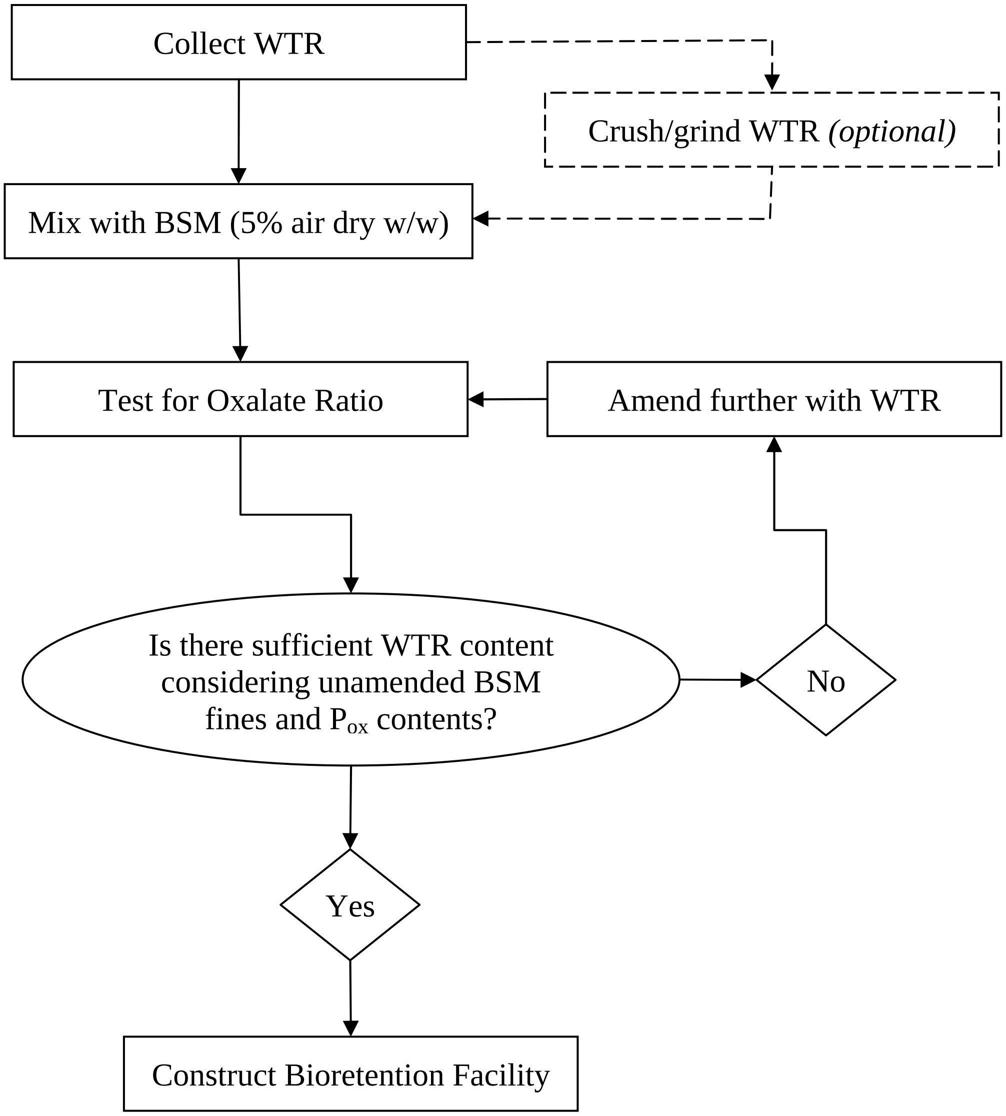


Figure 6-5. Flow chart for amended BSM mixing.

matrix or contribute to media clogging. Ostensibly this should be approximately 2 mm. Crushing the WTR is not mandatory, however it should improve performance by maximizing the available surface area for P adsorption.

The collected residual must be mixed thoroughly with the BSM. This may be done mechanically such as with a cement mixer or other tumbling device. As explained in Section 4.1, the literature has reported mean WTR Al_{ox} content to be approximately 32 to 41 g/lb (70 to 90 g/kg). Therefore, the WTR should be amended at a rate of 5 to 10% of total media mass (air dried weight), trending upwards as fines content or the unamended media P_{ox} content increases. Solids content of the dewatered residual is often obtainable from the source drinking water plant to allow for calculation of the air dry mass equivalent of the moist WTR. After mixing, test the media and determine the oxalate ratio. If necessary, further amend the media. For the period when the BSM is mixed but samples are being analyzed in the laboratory, or in any instance where the amended BSM must sit before installation in the bioretention cell, cover the media with a tarp or other impervious material and attempt to make it as water tight as possible. Prevention of media drying will help to maintain a high oxalate ratio. Once the media meets specifications it should be installed as normal.

Additionally, thought must be given to plant survivorship with WTR-amended facilities. The addition of WTR at the recommended application rates will lead to some stunted plant growth and may cause the death of some individual plants (Oladeji et al., 2007; Mahdy et al., 2009; Lombi et al., 2009; Oladeji et al., 2009). However, healthy plants should not be severely negatively impacted. If plant survivorship is of particular importance and some degree of media performance may be compromised, a ½ - 1 ft. (15 – 30 cm) unamended surface layer may be used for planting. The soil used for this planting layer should have an oxalate ratio of at least 10 to prevent leaching of P to the amended media below.

Retrofitting of established bioretention facilities may be undertaken by rototilling WTR into the soil surface, as surface application of WTR has been shown effective in the agriculture literature. In many agricultural studies (Oladeji et al., 2007; Agyin-Birikorang et al., 2009; Mahdy et al., 2009; Oladeji et al., 2009), no negative plant effects were reported when surface applying WTR at a rate of approximately 20 – 25 Mg WTR/ha (8.92-11.2 tons/acre) along with a P source (i.e., biosolids, manure, inorganic fertilizer). At 4 – 6 in. (10 – 15 cm) depth, this is equivalent to 1 to 1.7% WTR (w/w) assuming a soil bulk density of 90.5 lb/ft^3 (1.45 g/cm^3). Amending the soil with WTR at a rate of 5% and to a depth of at least ⅓ ft. (10 cm) should be sufficient to adsorb stormwater P. However, greater application rates and depths will provide greater capacity for P adsorption. During rototilling, established plants may be avoided or non-woody species may be tilled under and the facility replanted with little foreseeable impact on media performance.

NUTRIENT REMOVAL OPTIMIZATION OF BIORETENTION SOIL MEDIA

Chapter 7: Conclusions and Recommendations

Investigation into the use of Al-WTR as a BSM amendment provided an encouraging indication as to the capability of Al-WTR to control the movement of P through bioretention cells. Batch studies showed only a minimal effect of pH on media P adsorption capacity within the investigated range of both pH and P concentration. Increasing WTR content yielded increasing media P adsorption capacity. Pure $Al(OH)_3$ provided increased P adsorption relative to an equivalent proportion of Al_{ox} provided by WTR. This is believed to be caused by the greater surface area of the $Al(OH)_3$ powder and diffusional limitations of the WTR. Unexpectedly, increasing fines content also yielded increasing media P adsorption capacity. Potential reasons for this behavior are that: sand addition led to a reduction in overall P_{ox} content of the mixture by "diluting" the BSM (PSI > 10%) while maintaining a high Al_{ox} content because the proportion of WTR was kept constant; reduced fines content led to a reduction in competitive adsorption by negatively charged clay particles and P for positively charged WTR reactive sites; and reduced fines content minimized the blocking of WTR micropores by clay particles, helping to maintain a high available WTR surface area. HBM addition (~ 3% dry wt.) yielded increasing media P adsorption capacity in most cases. This is believed to result from the formation of Al-OM-P complexes, which bind P as well as dissolved/colloidal OM. This OM has the capacity to leach from the media and appear as reduced media P adsorption capacity upon effluent digestion. LC addition (~ 5 % wt.) yielded decreased media P adsorption capacity, likely because of P leaching by the LC.

Minicolumn experiments examined the behavior of media under flow conditions. For equivalent media, equilibrium P adsorption capacity generally decreased from: batch > continuous column flow > intermittent column flow. For the investigated media subjected to intermittent flow, the HBM-amended media displayed the least reduction in media P adsorption capacity relative to its continuous flow counterpart. This suggests that the HBM helped to reduce drying and concomitant crystallization of the amended WTR, maintaining a higher amorphous Al content. Also, increased media P adsorption was observed in the intermittent flow column media upon the resumption of flow following dry periods. Media P adsorption rapidly declined thereafter. This suggests that "slow" reactions continue after the cessation of flow, providing some additional reactive surface sites for P adsorption when flow resumes.

Throughout all experiments for the mesoscale vegetated columns, the WTR-amended experimental media showed greatly improved adsorption relative to the control media. Experimental media exhibited a total effluent TP EMC of 16.1 μg/L from an input of 120 μg/L, far superior to the 266 μg/L displayed by the non-WTR-amended control media and sufficient to meet the EPA recommended surface water limit of 25 μg/L.

The vegetated columns generally showed consistent effluent pollutographs throughout all experiments. The experimental media exhibited initial high adsorption which rapidly declined over the course of approximately 15 to 30 minutes. Thereafter, media P adsorption began to improve again, creating a localized peak in P adsorption. Conversely, the control media displayed poor P adsorption initially which increased with continued flow, creating a exponential-like effluent concentration curve.

Increased flowrate resulted in increased PP releases from both media. The magnitude of these releases were quite different for each column, though, with the experimental column showing EMC increases of 3-8 μg/L relative to the previous run, while the control column increases were 25-36 μg/L. Similarly, increased drying time further exacerbated the release of PP. Total PP EMC for the experimental column measured 10.0 μg/L, while that for the control column measured 102 μg/L.

Increased influent P concentrations led to increased effluent TDP (and concomitantly TP) for the control column. The experimental column only displayed significantly increased effluent TDP when increased influent P concentrations were applied in conjunction with an elevated flowrate. Ultimately, the experimental column total effluent TDP EMC was 6.1 μg/L, while the control column value was 144 μg/L.

Increased drying time, as previously mentioned, induced increased PP release from both columns. However, in the control column it also resulted in decreased effluent TDP, while in the experimental column it resulted in increased effluent TDP. The TDP increase observed in the control column is consistent with the intermittent flow results from the minicolumn experiments, and is attributed to the freeing of surface reactive sites through the occurrence of "slow" reactions during dry periods. Conversely, the reduced P adsorption seen in the experimental column is attributed to media drying, which may have resulted in reduced media adsorptive surface area. Conversely, reduced antecedent dry time resulted in improved P adsorption in the experimental column. The control column results after reduced antecedent dry time were obscured by the aftereffects of previous runs and no definitive conclusion could be drawn.

Both columns showed minimal releases of NOx, with total effluent EMCs of 0.896 and 0.991 mg NO_3^-+NO_2^-/L for the experimental and control columns, respectively, relative to the influent EMC of 0.880 mg/L. Conversely, there was some removal of TKN from the influent, with the experimental and control columns displaying effluent EMCs of 0.524 and 1.22 mg TKN/L relative to an influent EMC of 1.31 mg/L. The TKN species used were NH_4^+ and organic N as glycine. The removal of TKN from the influent is attributed to the adsorption of glycine to the media, as glycine exists as a zwitterion within the pH range of the experiments.

Some leaching of SO_4^{2-} was observed from the experimental media, attributed to release from the WTR because $Al_2(SO_4)_3 \cdot 14\ H_2O$ was used as a coagulant during its generation. Media SO_4^{2-} density was measured as 118 mg SO_4^{2-}/lb (261 mg/kg). This is not expected to be environmentally significant or a potential danger to human health, although nuisance odors as a result of H_2S formation may occur if reducing conditions are encountered in the bioretention cell.

Oxalate extractions were used to characterize the media and to develop a metric to predict adsorption performance. Media oxalate ratio $[(Al+Fe)_{ox}:P_{ox}]$ was found to positively correlate with media P adsorption capacity. WTR addition improved P adsorption by increasing media measured Al_{ox} content. Sand addition improved media P adsorption by reducing media P_{ox} content while maintaining a high Al_{ox} content via added WTR. HBM improved media P adsorption by contributing Fe_{ox} to the media mixture along with little to no P_{ox} relative to the BSM. Conversely, LC depressed media P adsorption by contributing increased P_{ox} to the media mixture.

In the vegetated mesocolumn studies, control media exhibited an oxalate ratio of 2.62 (PSI 37.9%). This corroborates the leaching behavior observed in the media, as an oxalate ratio < 10 (PSI > 10%) indicates a media that is at risk of P leaching. Conversely, the experimental media had a measured oxalate ratio of 23.1 (PSI 4.32%). This supports the excellent P adsorption observed in the media. A decreasing oxalate ratio nearer the surface after the 13 experiments also suggests that the P adsorption capacity of the media is not exhausted. A linear regression of media P adsorption capacity on the oxalate ratio ($R^2 = 0.7148$) predicts the P adsorption capacity of the experimental media to be 13.8 ± 9.21 mg P/lb (30.5 ± 20.3 mg/kg; ± SE).

For future use, media amended with WTR are suggested to have an oxalate ratio of at least 20 to 40 (PSI $\leq$ 2.5 to 5%) to remove sufficient P from influent stormwater. This should be equivalent to approximately 5 to 10% WTR by air dry mass. Oxalate ratios toward the higher end of this range will be required for media with higher fines contents, higher P-content OM amendments (i.e., compost, etc.), and lower Al_{ox}-content WTR.

It is recommended that WTR is collected from the drinking water treatment plant, crushed to approximately 2 mm if possible, and thoroughly mixed with BSM. The WTR will retain maximum adsorption capacity by minimizing ageing and drying prior to and during installation, although very "fresh" WTR has been suggested to be at risk for Al leaching (Agyin-Birikorgan and O'Connor, 2009). Therefore, WTR aged less than one month should not be used, and the risk for Al leaching must be considered for those residuals aged less than six months. The WTR amended BSM may be installed in the bioretention cell per standard operating procedure. In the end, combining both Al-WTR and an organic amendment such as HBM with an increased nitrogen removal measure such as carefully selected vigorous plant coverage and/or a raised underdrain (anoxic denitrification sump) is theorized to lead to dramatically increased removal efficiency in a bioretention system without sacrificing hydrologic performance. The installation of such a raised underdrain in an amended facility will be ideal to promote N removal by the bioretention cell through denitrification in conjunction with P sequestration. The possible generation of nuisance odors must be considered though. The addition of WTR at the recommended concentrations is also expected to lead to stunted plant growth. An unamended BSM surface layer (15 – 30 cm) may be use to diminish any negative effects on vegetation. However, doing so will reduce the total capacity of the cell for P adsorption.

The retrofitting of established bioretention cells may be undertaken by rototilling WTR into the BSM surface *in situ*. The necessary content of WTR amended to the soil will depend on P treatment goals, but increasing the concentration and depth of amendment will result in improved overall P adsorption. WTR may be applied around vegetation, or non-woody vegetation may be rototilled into the soil along with the WTR and then the bioretention cell replanted with little expected impact on adsorption performance. The surface application of WTR at 5 to 10% (air dry mass) of BSM should be to a depth of ⅓ - 1 ft. (10 to 30 cm). Assuming a BSM bulk density of 93.6 lb/ft^3 (1.5 g/cm^3), this is analogous to 1.54 – 9.22 lb/ft^2 (7.5 – 45 kg/m^2, 75 - 450 Mg/ha).

Future research needs are many. It is necessary to attempt to verify these results using different BSM and WTR, possibly one that does not contain a secondary polymer coagulant or that uses a different Al-based coagulant such as polyaluminum chloride (PAC) or polyaluminum chlorosulfate (PACS). Additionally, validation of oxalate extraction as a means of predicting media P adsorption capacity is needed using field core oxalate extractions and monitoring data to verify the robustness of this metric.

Probing into the nature of HBM and the mechanisms by which it interacts with WTR to improve P adsorption in the amended BSM is also of interest. The variable and somewhat inconsistent results between batch and column studies indicate mechanisms are operating which are not fully understood.

An attempt to construct a cell and/or perform a retrofit is necessary to verify the construction specifications outlined. Additionally, this would allow for monitoring to ensure media specifications provide for adequate stormwater P adsorption and verification of plant survivability in a WTR-amended bioretention cell. It may also be beneficial to perform a laboratory or field study to investigate native and local vegetation which provide for maximal nutrient uptake in both WTR-amended and non-amended bioretention cells.

Appendices

Appendix A: Batch Data

Table A-1. Unamended BSM P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH_0 is the sample pH before adjustment. pH_i is the adjusted pH before equilibration. pH_f is the sample pH after the 24 hour equilibration period.

	ID	Mass (g)	Vol (mL)	pH_0	pH_i	pH_f	Equilibrium Concentration (mg/L)	Adsorption Capacity (mg P/kg)
0.3 mg P/L solution	Control	-	45	5.39	5.39	5.38	0.320	-
	BK0-1-1	1.787	45	5.86	3.87	4.79	0.075	6.16
	BK0-1-2	1.790	45	5.83	4.08	5.38	0.059	6.55
	BK0-1-3	1.791	45	5.85	4.63	5.68	0.049	6.79
	BK0-1-4	1.788	45	5.85	5.85	5.94	0.042	6.99
	BK0-1-5	1.792	45	5.8	8.63	6.48	0.042	6.96
0.9 mg P/L solution	Control	-	45	5.18	5.18	5.22	0.881	-
	BK0-2-1	1.792	45	5.72	3.77	5.11	0.193	17.28
	BK0-2-2	1.790	45	5.67	4.14	5.65	0.166	17.98
	BK0-2-3	1.789	45	5.74	4.69	5.65	0.152	18.36
	BK0-2-4	1.790	45	5.75	5.75	6.01	0.128	18.96
	BK0-2-5	1.791	45	5.73	8.21	6.29	0.101	19.62
3.0 mg P/L solution	Control	-	45	5.14	5.14	5.08	2.969	-
	BK0-3-1	1.789	45	5.71	3.85	5.23	1.255	43.12
	BK0-3-2	1.789	45	5.61	4.24	5.5	1.130	46.25
	BK0-3-3	1.790	45	5.59	4.43	5.67	1.201	44.45
	BK0-3-4	1.790	45	5.65	5.65	6.1	1.140	45.97
	BK0-3-5	1.788	45	5.66	8.07	6.51	0.828	53.90

Table A-2. BSM + 2% WTR P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH_0 is the sample pH before adjustment. pH_i is the adjusted pH before equilibration. pH_f is the sample pH after the 24 hour equilibration period.

	ID	Mass (g)	Vol (mL)	pH$_0$	pH$_i$	pH$_f$	Equilibrium Concentration (mg/L)	Adsorption Capacity (mg P/kg)
0.3 mg P/L solution	Control	-	45	5.35	5.35	5.11	0.310	-
	BK0-1-1	1.777	45	5.84	3.93	5.9	0.035	6.96
	BK0-1-2	1.775	45	5.86	4.34	6.08	0.038	6.88
	BK0-1-3	1.776	45	5.86	4.57	6.31	0.026	7.18
	BK0-1-4	1.777	45	5.91	5.91	6.48	0.028	7.13
	BK0-1-5	1.774	45	5.92	8.73	6.6	0.028	7.15
0.9 mg P/L solution	Control	-	45	5.2	5.2	5.23	0.881	-
	BK0-2-1	1.775	45	5.97	4.17	6.23	0.118	19.36
	BK0-2-2	1.776	45	5.84	4.31	6.2	0.104	19.70
	BK0-2-3	1.775	45	5.92	4.61	6.29	0.087	20.13
	BK0-2-4	1.771	45	5.82	5.82	6.51	0.083	20.29
	BK0-2-5	1.773	45	5.79	8.64	6.73	0.110	19.57
3.0 mg P/L solution	Control	-	45	5.14	5.14	5.16	3.112	-
	BK0-3-1	1.774	45	5.79	3.98	5.97	0.895	56.25
	BK0-3-2	1.774	45	5.74	4.22	5.87	0.875	56.76
	BK0-3-3	1.771	45	5.8	4.67	6.48	0.700	61.30
	BK0-3-4	1.775	45	5.75	5.75	6.54	0.744	60.05
	BK0-3-5	1.773	45	5.79	8.29	6.78	0.895	56.28

Table A-3. BSM + 4% WTR P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH$_0$ is the sample pH before adjustment. pH$_i$ is the adjusted pH before equilibration. pH$_f$ is the sample pH after the 24 hour equilibration period.

	ID	Mass (g)	Vol (mL)	pH$_0$	pH$_i$	pH$_f$	Equilibrium Concentration (mg/L)	Adsorption Capacity (mg P/kg)
0.3 mg P/L solution	Control	-	45	5.28	5.28	5.29	0.266	-
	BA4-1-1	1.758	45	5.9	8.9	6.94	0.020	6.31
	BA4-1-2	1.761	45	5.98	5.98	6.47	0.023	6.20
	BA4-1-3	1.759	45	5.94	3.93	5.92	0.024	6.18
	BA4-1-4	1.760	45	5.93	4.2	6.14	0.025	6.17
	BA4-1-5	1.759	45	5.98	4.63	6.59	0.013	6.47
0.9 mg P/L solution	Control	-	45	5.26	5.26	5.24	0.855	-
	BA4-2-1	1.759	45	5.92	3.98	6	0.074	19.97
	BA4-2-2	1.757	45	5.91	4.23	6.29	0.059	20.38

	BA4-2-3	1.757	45	5.91	4.64	6.34	0.064	20.26
	BA4-2-4	1.762	45	5.92	5.92	6.82	0.041	20.79
	BA4-2-5	1.760	45	5.92	8.41	6.66	0.050	20.58
3.0 mg P/L solution	Control	-	45	5.25	5.25	5.26	2.860	-
	BA4-3-1	1.758	45	5.83	3.94	6.06	0.498	60.46
	BA4-3-2	1.760	45	5.81	4.09	6.46	0.289	65.73
	BA4-3-3	1.760	45	5.82	4.59	6.5	0.585	58.16
	BA4-3-4	1.762	45	5.81	5.81	6.43	0.501	60.24
	BA4-3-5	1.758	45	5.81	7.97	6.77	0.545	59.26

Table A-4. BSM + 10% WTR P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH_0 is the sample pH before adjustment. pH_i is the adjusted pH before equilibration. pH_f is the sample pH after the 24 hour equilibration period. Highlighted yellow data are those measured below the MDL of 10 μg P/L, and consequently 5 μg P/L was used in media P adsorption capacity calculations

	ID	**Mass (g)**	**Vol (mL)**	**pH_0**	**pH_i**	**pH_f**	**Equilibrium Concentration (mg/L)**	**Adsorption Capacity (mg P/kg)**
0.3 mg P/L solution	Control	-	45	6.05	6.05	6.03	0.259	-
	BA2-1-1	1.714	45	6.23	3.99	6.86	0.007	6.67
	BA2-1-2	1.712	45	6.25	4.15	6.8	0.007	6.68
	BA2-1-3	1.713	45	6.31	4.68	6.82	0.007	6.67
	BA2-1-4	1.713	45	6.23	6.23	6.98	0.007	6.67
	BA2-1-5	1.712	45	6.3	8.33	7.04	0.002	6.68
0.9 mg P/L solution	Control	-	45	5.8	5.8	5.78	0.856	-
	BA2-2-1	1.713	45	6.12	3.85	6.79	0.010	22.21
	BA2-2-2	1.713	45	6.17	4.27	6.95	0.018	22.03
	BA2-2-3	1.712	45	6.25	4.96	6.91	0.011	22.20
	BA2-2-4	1.714	45	6.25	6.25	7.02	0.012	22.16
	BA2-2-5	1.713	45	6.19	8.58	7.13	0.016	22.06
3.0 mg P/L solution	Control	-	45	5.16	5.16	5.19	2.767	-
	BA2-3-1C	1.710	45	6.06	3.86	6.89	0.049	71.50
	BA2-3-2C	1.713	45	6.02	4.16	6.87	0.093	70.24
	BA2-3-3C	1.712	45	6.03	4.58	7.07	0.076	70.72
	BA2-3-4C	1.714	45	6.02	6.02	7.1	0.088	70.32
	BA2-3-5C	1.712	45	6.04	8.53	7.08	0.075	70.73

9.0 mg P/L solution	Control	-	45	5.1	5.1	5.12	8.646	-
	BA2-4-1	1.716	45	5.9	3.87	6.91	0.547	226.14
	BA2-4-2	1.714	45	5.89	4.29	6.85	0.597	226.34
	BA2-4-3	1.716	45	5.9	4.76	7.08	0.547	226.14
	BA2-4-4	1.713	45	5.96	5.96	7.16	0.648	226.41
	BA2-4-5	1.711	45	5.89	7.9	7.37	0.799	226.50

Table A-5. Unamended LFBSM P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH$_0$ is the sample pH before adjustment. pH$_i$ is the adjusted pH before equilibration. pH$_f$ is the sample pH after the 24 hour equilibration period.

	ID	**Mass (g)**	**Vol (mL)**	**pH$_0$**	**pH$_i$**	**pH$_f$**	**Equilibrium Concentration (mg/L)**	**Adsorption Capacity (mg P/kg)**
0.3 mg P/L solution	Control	-	45	5.28	5.28	5.15	0.306	-
	LF0-1-1	1.801	45	5.56	3.83	4.6	0.217	2.22
	LF0-1-2	1.800	45	5.5	3.98	4.91	0.160	3.66
	LF0-1-3	1.799	45	5.54	4.36	5.06	0.121	4.62
	LF0-1-4	1.800	45	5.53	5.53	5.67	0.102	5.10
	LF0-1-5	1.795	45	5.56	8.92	6.43	0.093	5.36
0.9 mg P/L solution	Control	-	45	5.4	5.4	5.24	0.892	-
	LF0-2-1	1.797	45	5.55	3.98	4.81	0.407	12.13
	LF0-2-2	1.797	45	5.52	4.12	4.78	0.431	11.54
	LF0-2-3	1.799	45	5.55	4.48	5.33	0.384	12.70
	LF0-2-4	1.801	45	5.54	5.54	5.52	0.353	13.45
	LF0-2-5	1.797	45	5.55	8.81	6.12	0.347	13.64
3.0 mg P/L solution	Control	-	45	5.09	5.09	5.16	2.986	-
	LF0-3-1	1.800	45	5.39	3.99	4.82	1.758	30.69
	LF0-3-2	1.798	45	5.44	4.13	4.99	1.825	29.04
	LF0-3-3	1.799	45	5.46	4.45	5.21	1.783	30.07
	LF0-3-4	1.797	45	5.48	5.48	5.75	1.682	32.63
	LF0-3-5	1.800	45	5.45	7.88	6.32	1.657	33.21

Table A-6. LFBSM + 3% WTR P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH$_0$ is the sample pH before adjustment.

pH$_i$ is the adjusted pH before equilibration. pH$_f$ is the sample pH after the 24 hour equilibration period.

	ID	Mass (g)	Vol (mL)	pH$_0$	pH$_i$	pH$_f$	Equilibrium Concentration (mg/L)	Adsorption Capacity (mg P/kg)
0.3 mg P/L solution	Control	-	23.5	5.15	5.15	5.12	0.281	-
	LF2-1-1	1.776	45	5.55	4.01	6.31	Sample dropped	
	LF2-1-2	1.778	45	5.54	4.14	6.34	0.018	6.66
	LF2-1-3	1.777	45	5.61	4.36	6.57	0.018	6.68
	LF2-1-4	1.777	45	5.63	5.63	6.53	0.023	6.53
	LF2-1-5	1.775	45	5.61	8.41	6.71	0.039	6.16
0.9 mg P/L solution	Control	-	45	5.13	5.13	5.19	0.843	-
	LF2-2-1	1.778	45	5.55	3.95	6.33	0.047	21.33
	LF2-2-2	1.776	45	5.6	4.13	6.48	0.054	21.36
	LF2-2-3	1.776	45	5.61	4.31	6.47	0.048	21.37
	LF2-2-4	1.778	45	5.6	5.6	6.51	0.079	21.33
	LF2-2-5	1.775	45	5.51	7.84	6.69	0.078	21.38
3.0 mg P/L solution	Control	-	45	5.24	5.24	5.24	3.038	-
	LF2-3-1	1.774	45	5.5	4.05	6.39	0.613	61.53
	LF2-3-2	1.776	45	5.48	4.22	6.47	0.488	64.63
	LF2-3-3	1.777	45	5.52	4.47	6.48	0.606	61.56
	LF2-3-4	1.775	45	5.53	5.53	6.44	0.664	60.21
	LF2-3-5	1.776	45	5.55	7.83	6.86	0.613	61.43

Table A-7. LFBSM + 6% WTR P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH$_0$ is the sample pH before adjustment. pH$_i$ is the adjusted pH before equilibration. pH$_f$ is the sample pH after the 24 hour equilibration period.

	ID	Mass (g)	Vol (mL)	pH$_0$	pH$_i$	pH$_f$	Equilibrium Concentration (mg/L)	Adsorption Capacity (mg P/kg)
0.3 mg P/L solution	Control	-	45	5.25	5.25	5.28	0.326	-
	LF3-3-1	1.755	45	5.77	3.9	6.69	0.014	8.02
	LF3-3-2	1.753	45	5.77	4.15	6.76	0.015	7.98
	LF3-3-3	1.753	45	5.7	4.4	6.89	0.011	8.09
	LF3-3-4	1.752	45	5.85	5.85	6.87	0.012	8.08
	LF3-3-5	1.753	45	5.83	8.44	7	0.012	8.07
mg P/L solu	Control	-	45	5.21	5.21	5.18	0.844	-

	LF3-2-1	1.753	45	5.71	3.93	6.7	0.018	21.23
	LF3-2-2	1.754	45	5.66	4.1	6.73	0.022	21.11
	LF3-2-3	1.752	45	5.74	4.44	6.84	0.023	21.10
	LF3-2-4	1.754	45	5.9	5.9	6.87	0.027	20.98
	LF3-2-5	1.753	45	5.79	8.93	7.08	0.017	21.24
3.0 mg P/L solution	Control	-	45	5.13	5.13	5.22	3.129	-
	LF3-1-1	1.753	45	5.64	4.07	6.65	0.185	75.58
	LF3-1-2	1.755	45	5.64	4.36	6.84	0.155	76.28
	LF3-1-3	1.753	45	5.74	4.55	6.87	0.209	74.98
	LF3-1-4	1.751	45	5.77	5.77	7.02	0.138	76.88
	LF3-1-5	1.755	45	5.7	7.83	7	0.269	73.30

Table A-8. BSM + 10% WTR P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH_0 is the sample pH before adjustment. pH_i is the adjusted pH before equilibration. pH_f is the sample pH after the 24 hour equilibration period. Highlighted yellow data are those measured below the MDL of 10 µg P/L, and consequently 5 µg P/L was used in media P adsorption capacity calculations

	ID	**Mass (g)**	**Vol (mL)**	**pH_0**	**pH_i**	**pH_f**	**Equilibrium Concentration (mg/L)**	**Adsorption Capacity (mg P/kg)**
0.3 mg P/L solution	Control	-	45	5.18	5.18	5.26	0.320	-
	LF1-1-1	1.725	45	6.09	3.94	6.92	0.007	8.21
	LF1-1-2	1.722	45	6.04	4.11	6.82	0.008	8.22
	LF1-1-3	1.723	45	6.01	4.55	7.1	0.006	8.22
	LF1-1-4	1.725	45	6.16	6.16	7.01	0.008	8.21
	LF1-1-5	1.720	45	5.93	8.86	7.29	0.009	8.23
0.9 mg P/L solution	Control	-	45	5.25	5.25	5.42	0.895	-
	LF1-2-1	1.721	45	5.91	3.88	6.98	0.010	23.14
	LF1-2-2	1.723	45	5.96	4.23	7.05	0.011	23.08
	LF1-2-3	1.721	45	5.99	4.71	7.13	0.012	23.07
	LF1-2-4	1.721	45	6.1	6.1	7.18	0.011	23.10
	LF1-2-5	1.726	45	6.04	8.65	7.24	0.010	23.08
3.0 mg P/L solution	Control	-	45	5.16	5.16	4.94	2.969	-
	LF1-3-1	1.723	45	5.96	4.13	7.14	0.037	76.59
	LF1-3-2	1.721	45	5.92	4.33	7.17	0.030	76.86
	LF1-3-3	1.720	45	5.99	4.82	7.11	0.043	76.56
	LF1-3-4	1.725	45	5.98	5.98	7.19	0.044	76.31

	LF1-3-5	1.722	45	5.94	8.35	7.29	0.048	76.33
9.0 mg P/L solution	Control	-	45	4.99	4.99	4.93	8.246	-
	LF1-5-1	1.725	45	5.81	3.96	6.82	0.418	204.23
	LF1-5-2	1.724	45	5.84	4.31	6.98	0.401	204.77
	LF1-5-3	1.722	45	5.84	4.58	7.03	0.272	208.38
	LF1-5-4	1.725	45	5.84	5.96	7.08	0.312	206.97
	LF1-5-5	1.725	45	5.81	7.63	7.29	0.418	204.23

Table A-9. BSM + HBM P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH$_0$ is the sample pH before adjustment. pH$_i$ is the adjusted pH before equilibration. pH$_f$ is the sample pH after the 24 hour equilibration period.

	ID	**Mass (g)**	**Vol (mL)**	**pH$_0$**	**pH$_i$**	**pH$_f$**	**Equilibrium Concentration (mg/L)**	**Adsorption Capacity (mg P/kg)**
0.3 mg P/L solution	Control	-	45	5.24	5.24	5.29	0.376	-
	HM3-1-1	1.755	45	5.81	3.89	5.34	0.074	7.75
	HM3-1-2	1.753	45	5.97	4.1	5.79	0.083	7.52
	HM3-1-3	1.753	45	6.01	4.57	6.04	0.079	7.63
	HM3-1-4	1.755	45	6.15	6.15	6.38	0.078	7.64
	HM3-1-5	1.752	45	5.99	8.47	6.48	0.067	7.94
0.9 mg P/L solution	Control	-	45	5.13	5.13	5.22	0.840	-
	HM3-2-1	1.754	45	5.9	3.97	5.27	0.205	21.54
	HM3-2-2	1.753	45	5.88	4.19	5.82	0.182	21.55
	HM3-2-3	1.755	45	5.87	4.39	5.71	0.159	21.53
	HM3-2-4	1.753	45	5.92	5.92	6.31	0.167	21.55
	HM3-2-5	1.754	45	5.95	8.15	6.45	0.167	21.54
3.0 mg P/L solution	Control	-	45	5.1	5.1	5.19	3.427	-
	HM3-3-1	1.752	45	5.88	3.88	5.46	1.212	56.90
	HM3-3-2	1.751	45	5.8	4.16	5.81	1.073	60.49
	HM3-3-3	1.756	45	5.86	4.35	5.9	1.144	58.50
	HM3-3-4	1.755	45	5.88	5.88	6.25	1.060	60.70
	HM3-3-5	1.754	45	5.81	8.07	6.43	0.911	64.56

Table A-10. BSM + 2% WTR + HBM P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH_0 is the sample pH before adjustment. pH_i is the adjusted pH before equilibration. pH_f is the sample pH after the 24 hour equilibration period.

	ID	Mass (g)	Vol (mL)	pH_0	pH_i	pH_f	Equilibrium Concentration (mg/L)	Adsorption Capacity (mg P/kg)
0.3 mg P/L solution	Control	-	45	5.11	5.11	4.95	0.247	-
	HM4-1-1	1.733	45	6.19	3.91	6.08	0.041	5.36
	HM4-1-2	1.732	45	6.24	4.47	6.26	0.023	5.82
	HM4-1-3	1.734	45	6.22	4.81	6.32	0.016	5.99
	HM4-1-4	1.732	45	6.14	6.14	6.43	0.014	6.06
	HM4-1-5	1.730	45	6.19	8.21	6.57	0.020	5.92
0.9 mg P/L solution	Control	-	45	5.05	5.05	4.99	0.849	-
	HM4-2-1	1.732	45	5.8	3.81	5.92	0.040	22.04
	HM4-2-2	1.734	45	5.86	4.19	6.01	0.043	22.02
	HM4-2-3	1.734	45	5.86	4.21	6	0.040	22.02
	HM4-2-4	1.734	45	6.02	6.02	6.45	0.039	22.02
	HM4-2-5	1.731	45	5.95	8.64	6.62	0.059	22.05
3.0 mg P/L solution	Control	-	45	4.93	4.93	5.05	2.769	-
	HM4-3-1	1.732	45	5.75	3.96	6.17	0.231	65.93
	HM4-3-2	1.730	45	5.78	4.09	6.2	0.257	65.35
	HM4-3-3	1.733	45	5.75	4.31	6.38	0.237	65.72
	HM4-3-4	1.730	45	5.87	5.87	6.52	0.427	60.94
	HM4-3-5	1.730	45	5.74	7.85	6.71	0.307	64.01

Table A-11. BSM + 4% WTR + HBM P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH_0 is the sample pH before adjustment. pH_i is the adjusted pH before equilibration. pH_f is the sample pH after the 24 hour equilibration period.

	ID	Mass (g)	Vol (mL)	pH_0	pH_i	pH_f	Equilibrium Concentration (mg/L)	Adsorption Capacity (mg P/kg)
0.3 mg P/L solution	Control	-	45	5.2	5.2	5.27	0.305	-
	HM2-1-1	1.733	45	6.03	4.1	6.65	0.017	7.48
	HM2-1-2	1.733	45	5.94	4.32	6.78	0.025	7.27
	HM2-1-3	1.734	45	6.04	4.5	6.83	0.020	7.40
	HM2-1-4	1.734	45	6.16	6.16	6.91	0.021	7.38
	HM2-1-5	1.733	45	6.11	8.5	7.22	0.021	7.38
mg P/L solu	Control	-	45	5.03	5.03	5.24	0.857	-

	HM2-2-1	1.733	45	5.92	3.99	6.4	0.034	22.24
	HM2-2-2	1.736	45	5.94	4.2	6.71	0.025	22.20
	HM2-2-3	1.734	45	5.96	4.58	6.72	0.045	22.22
	HM2-2-4	1.733	45	5.91	5.91	7.05	0.024	22.24
	HM2-2-5	1.737	45	5.95	8.55	6.95	0.040	22.19
3.0 mg P/L solution	Control	-	45	5.37	5.37	5.39	2.877	-
	HM2-3-1	1.736	45	6.16	4.12	6.43	0.190	69.64
	HM2-3-2	1.735	45	6.24	4.35	6.47	0.281	67.31
	HM2-3-3	1.737	45	6.23	4.56	6.55	0.231	68.55
	HM2-3-4	1.735	45	6.35	6.35	7.1	0.116	71.61
	HM2-3-5	1.735	45	6.27	8.06	7.26	0.248	68.19

Table A-12. BSM + LC P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH_0 is the sample pH before adjustment. pH_i is the adjusted pH before equilibration. pH_f is the sample pH after the 24 hour equilibration period.

	ID	**Mass (g)**	**Vol (mL)**	**pH_0**	**pH_i**	**pH_f**	**Equilibrium Concentration (mg/L)**	**Adsorption Capacity (mg P/kg)**
0.3 mg P/L solution	Control	-	45	5.29	5.29	5.07	0.264	-
	LC2-1-1	1.679	45	6.41	4.23	6.64	0.215	1.30
	LC2-1-2	1.681	45	6.38	4.04	6.6	Outside range	
	LC2-1-3	1.683	45	6.42	4.44	6.69	0.235	0.78
	LC2-1-4	1.679	45	6.54	6.54	6.81	0.157	2.87
	LC2-1-5	1.681	45	6.43	8.08	7.2	0.188	2.04
0.9 mg P/L solution	Control	-	45	5.23	5.23	5.17	0.832	-
	LC2-2-1	1.680	45	6.43	3.91	6.32	0.619	5.69
	LC2-2-2	1.680	45	6.38	4.2	6.58	0.423	10.94
	LC2-2-3	1.682	45	6.46	4.34	6.7	0.450	10.22
	LC2-2-4	1.680	45	6.58	6.58	-	Sample dropped	
	LC2-2-5	1.681	45	6.48	8.57	6.9	0.384	12.00
3.0 mg P/L solution	Control	-	45	5.21	5.21	5.12	2.761	-
	LC2-3-1	1.682	45	6.41	4.06	6.77	1.699	28.41
	LC2-3-2	1.679	45	6.28	4.23	6.4	1.589	31.40
	LC2-3-3	1.682	45	6.34	4.32	6.65	1.782	26.19
	LC2-3-4	1.680	45	6.43	6.43	6.85	1.387	36.81
	LC2-3-5	1.683	45	6.43	8.25	6.89	1.563	32.04

Table A-13. BSM + 4% WTR + LC P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH_0 is the sample pH before adjustment. pH_i is the adjusted pH before equilibration. pH_f is the sample pH after the 24 hour equilibration period.

	ID	Mass (g)	Vol (mL)	pH_0	pH_i	pH_f	Equilibrium Concentration (mg/L)	Adsorption Capacity (mg P/kg)
0.3 mg P/L solution	Control	-	45	5.12	5.12	5.03	0.311	-
	LC1-1-1	1.649	45	6.42	3.91	6.41	0.059	6.86
	LC1-1-2	1.650	45	6.36	4.42	6.77	0.057	6.92
	LC1-1-3	1.648	45	6.35	4.35	6.71	0.052	7.05
	LC1-1-4	1.649	45	6.53	6.53	7.03	0.045	7.24
	LC1-1-5	1.648	45	6.45	8.47	7.08	0.045	7.26
0.9 mg P/L solution	Control	-	45	5.14	5.14	5.02	0.865	-
	LC1-2-1	1.647	45	6.2	3.9	6.41	0.082	21.40
	LC1-2-2	1.647	45	6.13	4.67	6.82	0.058	22.06
	LC1-2-3	1.647	45	6.17	4.32	6.88	0.067	21.80
	LC1-2-4	1.652	45	6.39	6.39	6.92	0.071	21.63
	LC1-2-5	1.652	45	6.35	8.42	7.04	0.072	21.62
3.0 mg P/L solution	Control	-	45	5.13	5.13	4.99	2.877	-
	LC1-3-1	1.649	45	6.26	4.28	6.74	0.234	72.11
	LC1-3-2	1.652	45	6.18	3.96	6.96	0.254	71.45
	LC1-3-3	1.647	45	6.17	4.45	6.91	0.281	70.92
	LC1-3-4	1.649	45	6.24	6.24	6.8	0.314	69.93
	LC1-3-5	1.651	45	6.27	8.15	7.07	0.327	69.49

Table A-14. BSM + 4% WTR + LC [OM+] P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH_0 is the sample pH before adjustment. pH_i is the adjusted pH before equilibration. pH_f is the sample pH after the 24 hour equilibration period.

	ID	Mass (g)	Vol (mL)	pH_0	pH_i	pH_f	Equilibrium Concentration (mg/L)	Adsorption Capacity (mg P/kg)
0.3 mg P/L solution	Control	-	45	5.23	5.23	5.1	0.281	-
	LC1-1-1	1.492	45	6.91	3.84	6.58	0.125	4.68
	LC1-1-2	1.492	45	6.88	4.16	6.63	0.098	5.50
	LC1-1-3	1.492	45	6.77	4.49	6.88	0.134	4.41
	LC1-1-4	1.492	45	7.17	7.17	7.27	0.096	5.57
	LC1-1-5	1.488	45	6.97	8.72	7.3	0.105	5.30

0.9 mg P/L solution	Control	-	45	5.19	5.19	5.1	0.862	-
	LC1-2-1	1.492	45	6.79	3.75	6.66	0.188	20.33
	LC1-2-2	1.491	45	6.79	4.29	6.77	0.181	20.54
	LC1-2-3	1.490	45	7.8	4.59	6.91	0.271	17.86
	LC1-2-4	1.491	45	6.95	6.95	7.22	0.194	20.15
	LC1-2-5	1.491	45	6.86	8.6	7.31	0.198	20.04
3.0 mg P/L solution	Control	-	45	5.16	5.16	4.96	2.885	-
	LC1-3-1	1.491	45	6.81	3.84	6.65	0.500	71.97
	LC1-3-2	1.491	45	6.77	4.37	6.99	0.287	78.38
	LC1-3-3	1.492	45	6.65	4.52	6.87	0.480	72.53
	LC1-3-4	1.488	45	6.91	6.91	7.21	0.470	73.03
	LC1-3-5	1.491	45	6.94	8.22	7.21	0.540	70.81

Table A-15. BSM + 0.5% Al(OH)$_3$ (WTR Alox equivalent) P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH$_0$ is the sample pH before adjustment. pH$_i$ is the adjusted pH before equilibration. pH$_f$ is the sample pH after the 24 hour equilibration period.

	ID	**Mass (g)**	**Vol (mL)**	**pH$_0$**	**pH$_i$**	**pH$_f$**	**Equilibrium Concentration (mg/L)**	**Adsorption Capacity (mg P/kg)**
0.3 mg P/L solution	Control	-	45	5.18	5.18	5.13	0.239	-
	AH3-1-1	1.803	45	5.51	3.88	5.06	0.013	5.64
	AH3-1-2	1.801	45	5.52	4.08	5.24	0.012	5.69
	AH3-1-3	1.799	45	5.55	4.41	5.01	0.013	5.67
	AH3-1-4	1.802	45	5.69	5.69	5.61	0.009	5.74
	AH3-1-5	1.799	45	5.65	8.03	6.4	0.015	5.60
0.9 mg P/L solution	Control	-	45	5.28	5.28	5.12	0.837	-
	AH3-2-1	1.802	45	5.39	3.8	5	0.053	19.59
	AH3-2-2	1.802	45	5.45	4.2	4.85	0.036	20.01
	AH3-2-3	1.802	45	5.44	4.5	5.27	0.031	20.13
	AH3-2-4	1.801	45	5.57	5.57	5.62	0.020	20.43
	AH3-2-5	1.801	45	5.43	8.35	6.37	0.043	19.83
3.0 mg P/L solution	Control	-	45	4.95	4.95	4.98	2.960	-
	AH3-2-1	1.802	45	5.42	3.92	4.62	0.203	68.85
	AH3-2-2	1.801	45	5.47	4.09	4.79	0.229	68.22
	AH3-2-3	1.800	45	5.47	4.38	4.57	0.282	66.94

AH3-2-4	1.803	45	5.48	5.48	5.55	0.143	70.29
AH3-2-5	1.800	45	5.43	8.23	6.33	0.243	67.93

Table A-16. BSM + 2% $Al(OH)_3$ (WTR Alox equivalent) P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH_0 is the sample pH before adjustment. pH_i is the adjusted pH before equilibration. pH_f is the sample pH after the 24 hour equilibration period. Highlighted yellow data are those measured below the MDL of 10 µg P/L, and consequently 5 µg P/L was used in media P adsorption capacity calculations

	ID	Mass (g)	Vol (mL)	pH_0	pH_i	pH_f	Equilibrium Concentration (mg/L)	Adsorption Capacity (mg P/kg)
0.3 mg P/L solution	Control	-	45	5.13	5.13	5.12	0.269	-
	AH2-1-1	1.802	45	5.65	4.26	5.66	0.026	6.07
	AH2-1-2	1.803	45	5.76	4.01	5.36	0.004	6.59
	AH2-1-3	1.798	45	5.79	4.19	5.5	0.002	6.61
	AH2-1-4	1.803	45	5.81	5.81	5.79	0.002	6.59
	AH2-1-5	1.797	45	5.7	7.95	6.27	0.003	6.61
0.9 mg P/L solution	Control	-	45	5.24	5.24	5.15	0.844	-
	AH2-2-1	1.800	45	5.61	3.83	5.16	0.012	20.79
	AH2-2-2	1.801	45	5.69	4.15	5.43	0.006	20.96
	AH2-2-3	1.799	45	5.71	4.62	5.57	0.005	20.98
	AH2-2-4	1.798	45	5.78	5.78	5.69	0.005	20.99
	AH2-2-5	1.799	45	5.62	8.31	6.23	0.006	20.98
3.0 mg P/L solution	Control	-	45	5.11	5.11	5.08	2.720	-
	AH2-3-1	1.802	45	5.55	3.95	5.2	0.017	67.50
	AH2-3-2	1.800	45	5.59	4.22	5.44	0.015	67.64
	AH2-3-3	1.801	45	5.62	4.58	5.53	0.027	67.29
	AH2-3-4	1.801	45	5.72	5.72	5.95	0.007	67.85
	AH2-3-5	1.802	45	5.56	8.13	6.22	0.011	67.66

Table A-17. BSM + 4% $Al(OH)_3$ (WTR Alox equivalent) P adsorption isotherm data. Sample mass is adjusted for water content. Volume is the volume of the respective P solution with a 0.01 M KCl background electrolyte. pH_0 is the sample pH before adjustment. pH_i is the adjusted pH before equilibration. pH_f is the sample pH after the 24 hour equilibration period. Highlighted yellow data are those measured below the MDL of 10 µg P/L, and consequently 5 µg P/L was used in media P adsorption capacity calculations

	ID	Mass (g)	Vol (mL)	pH_0	pH_i	pH_f	Equilibrium Concentration (mg/L)	Adsorption Capacity (mg P/kg)
0.3 mg P/L solution	Control	-	45	5.38	5.38	5.22	0.269	-
	AH1-1-1	1.802	45	5.91	3.99	5.61	0.016	6.32
	AH1-1-2	1.801	45	5.93	4.27	4.93	0.004	6.60
	AH1-1-3	1.802	45	6.05	4.6	5.37	0.003	6.59
	AH1-1-4	1.799	45	6.18	6.18	5.98	0.002	6.60
	AH1-1-5	1.799	45	5.93	8.13	6.43	0.002	6.60
0.9 mg P/L solution	Control	-	45	5.31	5.31	5.33	0.814	-
	AH1-2-1	1.802	45	5.81	3.95	5.06	0.001	20.20
	AH1-2-2	1.803	45	5.9	4.67	5.38	0.002	20.19
	AH1-2-3	1.800	45	5.92	4.3	5.41	0.002	20.22
	AH1-2-4	1.802	45	6.14	6.14	5.94	0.007	20.20
	AH1-2-5	1.801	45	5.87	8.31	6.44	0.003	20.21
3.0 mg P/L solution	Control	-	45	5.3	5.3	5.1	2.960	-
	AH1-3-1	1.802	45	5.76	4.29	5.3	0.002	73.79
	AH1-3-2	1.801	45	5.73	3.96	5.21	0.004	73.83
	AH1-3-3	1.802	45	5.77	4.4	5.61	0.002	73.79
	AH1-3-4	1.802	45	6.06	6.06	5.93	0.002	73.79
	AH1-3-5	1.802	45	5.81	8.19	6.7	0.004	73.79

Appendix B: Minicolumn Data

Table B-1. Unamended BSM media results from the minicolumn experiment, set I. Media mass in the column was 92.58 g. Media was subject to continuous flow of an approximately 120 µg P/L solution. ID is the sample identifier, provided as the date of collection. pH, turbidity, TP, and TDP are the measured effluent sample values. BV is the cumulative bed volumes of flow that had passed through the media at the time of sample collection. Initial Q is the volumetric flowrate before calibration. Calibrated Q is the volumetric flowrate as calibrated prior to sample collection.

ID	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/L)	BV	Initial Q (mL/min)	Calibrated Q (mL/min)
6/24/2009	5.69	5.6	0.045	0.033	4.8	-	1.327
6/25/2009	5.82	149.0	> 0.25	-	33.9	1.376	1.310
6/26/2009	6.13	62.6	0.251	0.193	59.5	1.277	1.277

6/27/2009	6.13	50.1	0.250	-	97.0	1.266	1.266
6/28/2009	6.01	52.0	0.193		121.5	1.255	1.255
6/29/2009, #1	-	-	-	-	144.5	1.250	1.250
6/29/2009, #2	-	-	0.211	-	150.8	1.250	1.250
6/30/2009	-	-	-	-	172.3	1.042	1.235
7/3/2009	6.39	34.7	0.198	0.139	254.9	1.288	1.288

Table B-2. Unamended BSM media results from the minicolumn experiment, set II. Media mass in the column was 100.7 g. Media was subject to continuous flow of an approximately 120 µg P/L solution. ID is the sample identifier, provided as the date of collection. pH, turbidity, TP, and TDP are the measured effluent sample values. BV is the cumulative bed volumes of flow that had passed through the media at the time of sample collection. Initial Q is the volumetric flowrate before calibration. Calibrated Q is the volumetric flowrate as calibrated prior to sample collection.

ID	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/L)	BV	Initial Q (mL/min)	Calibrated Q (mL/min)
9/8/2009, #1	5.66	6.8	0.059	-	2.6	-	1.327
9/8/2009, #2	-	-	0.060	-	5.9	1.327	1.327
9/8/2009, #3	-	-	0.070	-	7.8	1.327	1.327
9/8/2009, #4	-	-	0.088	-	12.8	1.327	1.327
9/9/2009, #1	4.54	4.1	0.117	-	34.9	1.261	1.261
9/9/2009, #2	-	-	0.127	-	39.0	1.261	1.261
9/10/2009	6.49	4.0	0.129	0.126	59.7	1.277	1.277

Table B-3. BSM + 2% WTR media results from the minicolumn experiment, set I. Media mass in the column was 86.35 g. Media was subject to continuous flow of an approximately 120 µg P/L solution. ID is the sample identifier, provided as the date of collection. pH, turbidity, TP, and TDP are the measured effluent sample values. BV is the cumulative bed volumes of flow that had passed through the media at the time of sample collection. Initial Q is the volumetric flowrate before calibration. Calibrated Q is the volumetric flowrate as calibrated prior to sample collection.

ID	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/L)	BV	Initial Q (mL/min)	Calibrated Q (mL/min)
6/24/2009	6.40	5.0	0.046	0.048	4.8	-	1.282
6/25/2009	6.33	25.8	0.100	-	33.5	1.376	1.376
6/26/2009	6.25	33.2	0.116	0.057	60.1	1.316	1.316
6/27/2009	6.11	13.1	0.079	-	99.9	1.382	1.382
6/28/2009	6.22	12.3	0.071	0.071	130.5	1.389	1.357

6/29/2009, #1	6.24	11.2	0.096	0.075	155.5	1.402	1.271
6/29/2009, #2	-	-	0.090	-	162.0	1.402	1.271
6/30/2009	6.39	19.3	0.103	-	184.4	1.339	1.266
7/1/2009	6.53	9.1	0.092	0.092	212.6	1.389	1.261
7/2/2009	6.43	9.8	0.103	-	239.5	1.261	1.261
7/3/2009	6.56	9.6	0.101	0.089	267.4	1.304	1.304
7/4/2009	6.19	10.9	0.112	-	299.9	1.310	1.310
7/5/2009, #1	6.61	24.6	0.118	-	328.7	1.322	1.322
7/5/2009, #2	-	-	0.117	-	332.3	1.322	1.322
7/6/2009, #1	6.41	11.3	0.112	0.097	355.0	1.339	1.339
7/6/2009, #2	-	-	0.107	-	361.3	1.339	1.339
7/7/2009, #1	6.71	32.3	0.109	-	381.6	1.389	1.310
7/7/2009, #2	-	-	0.113	-	389.1	1.389	1.310
7/8/2009	6.40	22.5	0.117	-	412.0	1.351	1.288
7/9/2009, #1	6.44	12.9	0.119	0.104	439.7	1.322	1.322
7/9/2009, #2	-	-	0.117	-	448.4	1.322	1.322
7/10/2009, #1	6.56	20.5	0.111	0.100	467.2	1.345	1.345
7/10/2009, #2	-	-	0.107	-	477.2	1.345	1.345
7/11/2009	6.41	9.8	0.112	-	503.9	1.389	1.345
7/13/2009	6.74	11.5	0.116	-	560.3	1.357	1.250
7/14/2009	6.62	10.0	0.111	0.100	587.2	1.293	1.293
7/15/2009	6.66	13.8	0.102	-	615.1	1.310	1.310
7/16/2009	6.65	8.6	0.103	-	643.3	1.327	1.327
7/17/2009	6.65	26.2	0.111	-	674.0	1.357	1.293
7/18/2009	6.63	12.0	0.113	-	703.8	1.271	1.271
7/19/2009	6.39	9.7	0.102	-	731.8	1.255	1.255
7/20/2009	6.56	26.3	0.114	0.095	759.4	1.351	1.282
7/21/2009	6.49	24.7	0.111	-	785.3	1.277	1.277
7/22/2009, #1	6.44	203.0	> 0.25	0.089	815.2	1.304	2.542
7/22/2009, #2	-	-	0.106	-	824.6	1.304	2.542
7/23/2009, #1	-	-	0.142	-	877.0	3.093	2.679
7/23/2009, #2	6.34	16.2	0.133	-	892.0	3.371	2.703
7/24/2009	6.43	41.4	0.182	0.099	936.3	3.000	2.655
7/25/2009	6.60	5.7	0.116	-	996.7	3.226	2.586
7/26/2009	6.57	31.2	0.153	-	1047.7	2.885	2.564
7/27/2009	6.56	7.5	0.114	0.104	1090.4	2.362	2.564
7/28/2009	6.74	5.8	0.114	0.106	1143.0	2.586	2.564
7/29/2009	6.33	4.5	0.109	-	1199.6	2.564	2.542
7/30/2009	6.52	4.1	0.110	-	1247.0	1.911	2.564
7/31/2009	6.36	3.1	0.113	-	1309.2	3.093	2.679

8/2/2009	6.34	2.9	0.123	-	1446.3	3.261	3.061
8/3/2009	6.57	3.5	0.116	-	1501.1	3.704	2.564
8/5/2009	6.62	5.5	0.119	-	1596.3	2.586	2.752
8/6/2009	6.35	4.2	0.112	-	1662.1	3.333	2.632
8/7/2009	6.32	7.7	0.123	0.097	1713.0	3.061	2.479
8/11/2009	6.68	6.3	0.117	0.116	1933.6	2.564	2.564
8/12/2009	6.54	61.4	0.271	0.114	1990.6	2.469	5.455
8/13/2009	6.67	6.8	0.174	0.120	2083.9	2.597	5.455
8/15/2009	6.89	7.8	0.123	0.106	2212.9	0.312	5.128
8/17/2009	6.51	7.2	0.115	0.115	2403.8	3.822	5.217
8/18/2009	6.50	0.7	0.117	0.116	2493.5	3.947	5.000
8/19/2009	6.52	17.1	0.139	0.102	2553.6	3.015	4.545

Table B-4. BSM + 4% WTR media results from the minicolumn experiment, set I. Media mass in the column was 89.23 g. Media was subject to continuous flow of an approximately 120 µg P/L solution. ID is the sample identifier, provided as the date of collection. pH, turbidity, TP, and TDP are the measured effluent sample values. BV is the cumulative bed volumes of flow that had passed through the media at the time of sample collection. Initial Q is the volumetric flowrate before calibration. Calibrated Q is the volumetric flowrate as calibrated prior to sample collection.

ID	**pH**	**Turbidity (NTU)**	**TP (mg/L)**	**TDP (mg/L)**	**BV**	**Initial Q (mL/min)**	**Calibrated Q (mL/min)**
6/24/2009	6.42	4.3	0.019	0.005	4.9	-	1.322
6/25/2009	6.70	22.9	0.072	-	32.5	1.255	1.250
6/26/2009	6.49	44.6	0.102	0.033	56.5	1.136	1.245
6/27/2009	6.60	22.3	0.064	-	91.7	1.154	1.186
6/28/2009	6.73	35.0	0.075	0.044	115.0	1.176	1.255
6/29/2009, #1	6.45	10.5	0.055	0.033	137.3	1.172	1.266
6/29/2009, #2	-	-	0.057	-	143.7	1.172	1.266
6/30/2009	6.50	14.4	0.057	-	165.2	1.240	1.224
7/1/2009	6.53	15.1	0.057	0.042	191.6	1.245	1.230
7/2/2009	6.60	13.5	0.061	-	219.0	1.333	1.333
7/3/2009	6.30	11.7	0.069	0.051	247.4	1.277	1.277
7/4/2009	6.37	16.1	0.081	-	278.9	1.261	1.261
7/5/2009	6.47	13.9	0.076	-	306.4	1.261	1.261
7/6/2009	6.57	8.3	0.071	0.059	331.5	1.271	1.271
7/7/2009	6.74	32.6	0.074	-	356.3	1.261	1.261
7/8/2009	6.58	12.6	0.075	-	385.2	1.240	1.240
7/9/2009	6.55	15.2	0.087	-	411.6	1.277	1.277
7/10/2009	6.57	20.0	0.080	0.059	438.2	1.255	1.255

7/11/2009	6.53	32.7	0.129	-	472.2	1.282	1.282
7/13/2009	6.80	18.9	0.093	-	526.9	1.327	1.327
7/14/2009	6.77	52.2	0.167	0.068	555.8	1.364	1.299
7/15/2009	6.62	14.9	0.090	0.070	582.4	1.240	1.240
7/16/2009	6.64	55.5	0.184	0.066	608.8	1.163	1.339
7/17/2009	6.73	27.3	0.123	0.072	639.1	1.327	1.327
7/18/2009	6.51	8.3	0.093	-	669.7	1.322	1.322
7/19/2009	6.68	9.2	0.092	-	698.5	1.288	1.288
7/20/2009	6.62	22.1	0.095	0.076	723.5	1.163	1.266
7/21/2009	6.52	16.1	0.084	-	748.6	1.083	1.266
7/22/2009, #1	6.44	23.9	0.140	-	776.9	1.119	2.479
7/22/2009, #2	-	-	0.140	-	785.9	1.119	2.479
7/23/2009, #1	-	-	0.108	-	831.9	2.344	2.632
7/23/2009, #2	6.62	16.6	0.113	-	844.8	2.500	2.521
7/24/2009	6.57	9.4	0.113	-	884.3	2.419	2.703
7/25/2009	6.45	5.3	0.099	-	937.9	2.500	2.500
7/26/2009	6.71	46.4	0.178	-	1004.0	2.239	2.542
7/27/2009	6.49	12.6	0.112	0.082	1047.8	2.459	2.459
7/28/2009	6.60	29.5	0.157	0.091	1095.0	2.128	2.609
7/29/2009	6.47	13.2	0.116	0.087	1149.0	2.256	2.703
7/30/2009	6.50	14.9	0.123	0.094	1201.3	2.222	2.564
7/31/2009	6.59	69.5	0.213	0.068	1247.4	1.554	2.564
8/2/2009	6.32	15.7	0.128	-	1361.8	1.402	2.941
8/3/2009	6.67	4.6	0.097	-	1406.3	2.479	2.655
8/5/2009	6.58	16.1	0.131	0.093	1515.5	2.521	2.655
8/6/2009	6.24	0.3	0.091	-	1574.6	2.778	2.679
8/7/2009	6.29	0.2	0.094	0.083	1619.8	2.381	2.857
8/11/2009	6.60	7.5	0.107	0.095	1879.3	2.609	2.609
8/12/2009	6.48	3357.0	5.204	0.072	1939.0	2.553	5.128
8/13/2009	6.53	27.3	0.190	0.100	2023.5	2.113	4.918
8/15/2009	6.51	3.1	0.108	0.109	2233.5	4.878	4.878
8/17/2009	6.60	0.4	0.112	0.101	2429.5	3.488	4.959
8/18/2009	6.46	14.4	0.137	0.100	2504.9	2.643	5.085
8/19/2009	6.55	24.5	0.159	0.092	2573.3	0.538	4.959

Table B-5. BSM + 4% WTR media results from the minicolumn experiment, set II. Media mass in the column was 91.87 g. Media was subject to continuous flow of an approximately 120 μg P/L solution. ID is the sample identifier, provided as the date of collection. pH, turbidity, TP, and TDP are the measured effluent sample values. BV is the cumulative bed volumes of flow that had passed through the media at the time of sample collection. Initial Q is the volumetric flowrate before calibration. Calibrated Q is the volumetric flowrate as calibrated prior to sample collection.

ID	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/L)	BV	Initial Q (mL/min)	Calibrated Q (mL/min)
9/8/2009	6.91	5.4	0.028	-	5.6	-	1.261
9/9/2009	6.26	4.3	0.045	-	33.7	1.245	1.245
9/10/2009	6.65	4.4	0.053	-	58.2	1.255	1.255
9/11/2009	6.85	3.8	0.064	-	85.4	1.224	1.304
9/14/2009	6.79	2.2	0.066	-	169.7	1.255	1.255
9/15/2009	6.83	2.3	0.071	-	197.5	1.255	1.266
9/16/2009	6.56	2.7	0.071	-	227.3	1.245	1.245
9/18/2009	6.73	3.8	0.068	-	276.8	1.220	1.351
9/19/2009	6.83	3.4	0.064	-	308.4	1.299	1.299
9/20/2009	6.88	3.9	0.068	-	335.8	1.310	1.310
9/21/2009	6.72	4.8	0.066	-	362.7	1.293	1.293
9/23/2009	6.57	4.2	0.072	-	417.9	1.282	1.282
9/24/2009	6.78	5.4	0.076	-	448.6	1.282	1.282
9/25/2009	6.54	3.4	0.075	-	476.3	1.245	1.322
9/28/2009	6.64	3.5	0.074	-	545.2	0.718	1.351
9/29/2009	6.60	3.0	0.081	-	566.9	0.867	1.316
9/30/2009	6.81	3.0	0.079	-	596.9	1.339	1.339
10/1/2009	6.61	3.8	0.075	-	625.1	1.339	1.339
10/2/2009	6.62	4.6	0.070	-	655.6	1.351	1.351
10/5/2009	6.62	5.5	0.081	-	743.3	1.327	1.327
10/6/2009	6.50	85.4	0.233	0.061	775.4	1.339	2.752
10/7/2009	6.54	26.7	0.144	0.092	833.8	2.970	2.679
10/8/2009	6.29	23.0	0.138	0.093	898.6	3.000	2.479
10/9/2009	6.50	9.0	0.109	-	950.3	2.655	2.655
10/12/2009	6.60	10.5	0.101	-	1038.9	0.000	2.521
10/13/2009	6.68	10.4	0.093	-	1071.8	0.144	2.564
10/14/2009	6.60	2.6	0.093	-	1114.6	1.415	2.586
10/15/2009	6.67	23.9	0.140	0.080	1142.3	2.655	1.911
10/16/2009	6.69	3.3	0.117	-	1181.7	0.293	2.679
10/17/2009	6.58	2.2	0.101	0.093	1239.9	2.586	2.752
10/19/2009	6.66	3.7	0.112	-	1351.9	2.500	2.655
10/21/2009	6.59	1.6	0.091	-	1466.2	2.885	2.632
10/22/2009	6.57	1.8	0.095	-	1523.2	2.655	2.655
10/23/2009	6.61	1.8	0.101	-	1579.2	2.609	2.609
10/25/2009	6.69	1.8	0.097	-	1713.7	2.830	2.542
10/26/2009	6.52	1.1	0.096	-	1755.4	2.857	2.679

10/27/2009	6.66	14.7	0.126	0.098	1809.8	1.807	5.128
10/28/2009	6.60	6.8	0.109	0.096	1924.5	5.310	4.286
10/29/2009	6.52	3.3	0.107	0.100	2016.2	5.357	4.082
10/30/2009	6.73	1.6	0.106	0.102	2133.7	6.250	5.455
11/2/2009	6.56	3.6	0.101	-	2372.1	0.259	4.959
11/3/2009	6.58	3.1	0.107	-	2471.9	5.217	5.042
11/4/2009	6.59	2.5	0.109	-	2583.3	3.125	5.263
11/6/2009	6.54	1.2	0.105	-	2797.0	4.800	4.286
11/9/2009	6.42	1.5	0.101	-	3098.5	5.000	3.061
11/10/2009	6.53	1.5	0.096	-	3210.8	5.042	5.128

Table B-6. BSM + 4% WTR media results from the minicolumn experiment, set II. Media mass in the column was 83.30 g. Media was subject to intermittent flow of an approximately 120 µg P/L solution. ID is the sample identifier, provided as the date of collection. pH, turbidity, TP, and TDP are the measured effluent sample values. BV is the cumulative bed volumes of flow that had passed through the media at the time of sample collection. Initial Q is the volumetric flowrate before calibration. Calibrated Q is the volumetric flowrate as calibrated prior to sample collection.

ID	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/L)	BV	Initial Q (mL/min)	Calibrated Q (mL/min)
9/8/2009	6.77	0.2	0.026	-	5.9	1.327	1.327
9/9/2009	6.02	9.8	0.037	-	38.0	1.796	1.796
9/14/2009	7.18	31.7	0.080	-	41.5	1.676	1.255
9/15/2009	7.04	17.7	0.079	0.054	70.9	1.395	1.435
9/19/2009	7.22	38.2	0.093	-	85.5	2.000	1.304
9/20/2009	7.07	47.1	0.108	0.067	104.0	0.503	0.997
9/24/2009	7.08	57.9	0.144	0.056	110.5	2.419	1.402
9/25/2009	6.88	19.2	0.104	0.076	132.9	1.923	1.796
9/30/2009	6.86	13.5	0.079	0.062	139.5	1.205	1.345
10/1/2009	6.77	6.9	0.102	-	163.9	1.158	1.230
10/6/2009	6.97	42.4	0.123	0.056	177.4	7.895	2.564
10/7/2009	6.66	28.3	0.121	0.074	185.6	2.521	2.344
10/16/2009	6.77	15.8	0.067	0.046	190.3	2.128	2.459
10/17/2009	6.75	14.4	0.118	0.089	244.2	2.500	2.542
10/22/2009	6.74	15.6	0.083	0.061	251.8	2.479	2.479
10/23/2009	6.72	8.4	0.110	-	303.9	2.479	2.479
10/28/2009	6.66	8.9	0.096	0.079	350.3	6.452	5.263
10/29/2009	6.56	11.0	0.121	0.096	446.7	5.172	4.762
11/2/2009	6.72	7.1	0.089	0.073	467.3	5.128	5.505

11/3/2009	6.67	9.4	0.101	0.093	563.2	4.959	5.042
11/12/2009	6.69	16.3	0.101	0.082	575.1	5.357	6.000
11/13/2009	6.71	10.4	0.124	0.098	606.2	6.316	6.186
11/20/2009	6.67	42.0	0.161	0.077	620.3	5.217	6.977
11/21/2009	6.70	7.0	0.116	0.133	734.8	6.122	6.383
12/1/2009	6.55	12.9	0.112	0.084	746.2	5.556	5.263
12/2/2009	6.92		0.153	0.081	801.3	5.217	6.383

Table B-7. BSM + 2% WTR + HBM media results from the minicolumn experiment, set I. Media mass in the column was 87.01 g. Media was subject to continuous flow of an approximately 120 µg P/L solution. ID is the sample identifier, provided as the date of collection. pH, turbidity, TP, and TDP are the measured effluent sample values. BV is the cumulative bed volumes of flow that had passed through the media at the time of sample collection. Initial Q is the volumetric flowrate before calibration. Calibrated Q is the volumetric flowrate as calibrated prior to sample collection.

ID	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/L)	BV	Initial Q (mL/min)	Calibrated Q (mL/min)
6/24/2009	6.90	2.3	0.025	0.013	4.8	-	1.322
6/25/2009	6.27	19.3	0.064	-	33.1	1.304	1.282
6/26/2009	6.45	31.9	0.093	0.048	57.9	1.200	1.310
6/27/2009	6.53	27.4	0.102	-	92.8	1.060	1.339
6/28/2009	6.38	17.5	0.083	0.063	118.6	1.322	1.322
6/29/2009, #1	6.47	16.1	0.083	0.059	142.6	1.293	1.293
6/29/2009, #2	-	-	0.076	-	149.1	1.293	1.293
6/30/2009	6.69	15.1	0.074	-	170.9	1.224	1.271
7/1/2009	6.55	16.0	0.076	0.059	197.5	1.220	1.310
7/2/2009	6.52	8.9	0.075	-	222.8	1.034	1.271
7/3/2009	6.40	7.1	0.078	0.067	249.9	1.224	1.255
7/4/2009	6.08	6.5	0.087	-	282.7	1.376	1.376
7/5/2009	6.17	11.0	0.087	-	312.3	1.333	1.333
7/6/2009	6.39	23.7	0.088	0.075	339.2	1.310	1.288
7/7/2009	6.56	21.8	0.077	-	363.5	1.271	1.271
7/8/2009	6.33	7.7	0.078	-	392.6	1.240	1.240
7/9/2009	6.32	16.6	0.083	-	420.4	1.415	1.310
7/10/2009	6.68	16.8	0.081	0.074	448.3	1.327	1.327
7/11/2009	6.20	6.2	0.077	-	482.8	1.250	1.250
7/13/2009	6.55	9.0	0.078	-	536.6	1.327	1.327
7/14/2009	6.41	4.2	0.078	-	564.0	1.215	1.261
7/15/2009	6.46	15.2	0.078	-	589.8	1.176	1.316
7/16/2009	6.69	25.4	0.095	-	620.5	1.604	1.250

7/17/2009	6.39	12.9	0.079	-	648.2	1.158	1.293
7/18/2009	6.21	9.1	0.093	-	664.2	0.000	1.266
7/19/2009	6.55	11.6	0.092	-	696.5	1.508	1.316
7/20/2009	6.53	3.6	0.087	-	716.4	0.987	1.277
7/21/2009	6.28	7.2	0.090	-	739.7	0.862	1.351
7/22/2009, #1	6.75	18.6	0.095	-	769.1	1.167	2.752
7/22/2009, #2	-	-	0.094	-	781.2	1.167	2.752
7/23/2009, #1	-	-	0.751	-	820.0	1.442	2.542
7/23/2009, #2	6.42	121.0	> .25	-	832.1	2.239	2.586
7/24/2009	6.50	43.6	0.160	0.091	859.7	0.497	2.941
7/25/2009	6.14	11.1	0.123	-	896.2	1.935	2.542
7/26/2009	6.55	0.3	0.105	-	963.0	2.256	2.500
7/27/2009	6.39	4.4	0.106	0.103	1006.0	2.381	2.655
7/28/2009	6.50	4.3	0.108	0.106	1056.2	2.256	2.521
7/29/2009	6.44	4.3	0.112	-	1113.7	2.679	2.679
7/30/2009	6.43	0.4	0.103	-	1171.3	2.778	2.703
7/31/2009	6.26	3.9	0.112	-	1228.0	2.459	2.586
8/2/2009	6.15	4.1	0.116	-	1351.2	2.344	2.609
8/3/2009	6.51	3.1	0.112	-	1387.6	1.695	2.655
8/5/2009	6.73	16.5	0.123	0.106	1475.0	1.449	1.796

Table B-8. BSM + 4% WTR + HBM media results from the minicolumn experiment, set I. Media mass in the column was 85.67 g. Media was subject to continuous flow of an approximately 120 µg P/L solution. ID is the sample identifier, provided as the date of collection. pH, turbidity, TP, and TDP are the measured effluent sample values. BV is the cumulative bed volumes of flow that had passed through the media at the time of sample collection. Initial Q is the volumetric flowrate before calibration. Calibrated Q is the volumetric flowrate as calibrated prior to sample collection.

ID	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/L)	BV	Initial Q (mL/min)	Calibrated Q (mL/min)
6/24/2009	6.87	2.6	0.019	0.013	4.7	-	1.266
6/25/2009	6.76	13.5	0.038	-	34.0	1.456	1.370
6/26/2009	6.67	14.8	0.035	0.017	59.7	1.215	1.370
6/27/2009	6.58	15.5	0.035	-	99.0	1.293	1.293
6/28/2009	6.65	9.8	0.031	0.054	125.9	1.370	1.370
6/29/2009, #1	6.62	9.2	0.035	0.018	150.4	1.310	1.310
6/29/2009, #2	-	-	0.025	-	157.1	1.310	1.310
6/30/2009	6.76	9.4	0.025	-	179.9	1.327	1.327
7/1/2009	6.72	10.9	0.024	0.015	207.6	1.293	1.293

7/2/2009	6.64	8.0	0.029	-	235.6	1.304	1.304
7/3/2009	6.46	5.0	0.025	0.014	263.0	1.224	1.224
7/4/2009	6.31	3.9	0.028	-	293.4	1.220	1.220
7/5/2009	6.29	4.3	0.025	-	319.9	1.195	1.316
7/6/2009	6.33	4.7	0.025	0.023	345.4	1.176	1.261
7/7/2009	6.41	3.6	0.022	-	370.7	1.408	1.304
7/8/2009	6.28	4.8	0.023	-	397.7	1.027	1.327
7/9/2009	6.31	3.7	0.028	-	426.5	1.408	1.310
7/10/2009	6.09	3.8	0.025	0.020	455.7	1.449	1.316
7/11/2009	6.23	0.2	0.022	-	490.5	1.288	1.288
7/13/2009	6.70	18.8	0.025	-	537.4	0.952	1.327
7/14/2009	6.36	3.9	0.031	-	569.2	1.630	1.288
7/15/2009	6.48	0.2	0.027	-	596.2	1.282	1.282
7/16/2009	6.28	4.0	0.032	-	623.1	1.245	1.351
7/17/2009	6.45	5.8	0.030	-	656.0	1.523	1.357
7/18/2009	6.46	3.2	0.034	-	687.8	1.261	1.370
7/19/2009	6.38	5.2	0.032	-	703.8	0.000	1.322
7/20/2009	6.63	6.4	0.028	-	724.1	0.962	1.364
7/21/2009	6.64	26.4	0.032	-	738.9	0.000	1.288
7/22/2009	6.76	2.9	0.057	-	769.9	1.370	2.542
7/22/2009	-	-	0.034	-	779.9	1.370	2.542
7/24/2009	6.59	159.0	0.166	0.025	791.1	0.534	0.293

Table B-9. BSM + 4% WTR + HBM media results from the minicolumn experiment, set II. Media mass in the column was 77.64 g. Media was subject to intermittent flow of an approximately 120 µg P/L solution. ID is the sample identifier, provided as the date of collection. pH, turbidity, TP, and TDP are the measured effluent sample values. BV is the cumulative bed volumes of flow that had passed through the media at the time of sample collection. Initial Q is the volumetric flowrate before calibration. Calibrated Q is the volumetric flowrate as calibrated prior to sample collection.

ID	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/L)	BV	Initial Q (mL/min)	Calibrated Q (mL/min)
9/8/2009	6.94	4.2	0.032	-	5.5	1.250	1.250
9/9/2009	4.25	9.6	0.039	-	32.2	1.339	1.339
9/14/2009	7.15	18.4	0.050	-	35.2	1.408	1.266
9/15/2009	6.98	10.9	0.033	-	62.6	1.220	1.224
9/19/2009	6.96	9.8	0.032	-	74.0	0.962	1.345
9/20/2009	6.81	8.2	0.029	-	99.0	1.167	1.299
9/24/2009	6.87	16.4	0.051	0.024	103.1	0.838	1.370
9/25/2009	6.61	5.3	0.030	-	136.4	1.357	1.149

9/30/2009	6.57	6.1	0.027	-	145.6	0.743	1.299
10/1/2009	6.57	3.9	0.029	-	173.7	1.293	1.075
10/6/2009	6.45	5.5	0.031	-	183.5	5.660	2.586
10/7/2009	6.42	2.5	0.053	-	239.4	2.727	2.564
10/16/2009	6.59	7.9	0.049	-	246.0	2.174	2.609
10/17/2009	6.41	3.9	0.060	-	300.4	2.564	2.655
10/22/2009	6.42	14.5	0.065	0.037	308.5	2.752	2.727
10/23/2009	6.37	2.5	0.072	-	366.9	2.830	2.778
10/28/2009	6.45	17.8	0.060	0.036	397.7	3.846	0.746
10/29/2009	6.25	14.7	0.060	0.044	413.1	0.833	1.310
11/2/2009	6.38	27.8	0.115	0.054	426.7	4.615	5.357
11/3/2009	6.18	4.7	0.095	0.085	525.8	5.310	5.505
11/12/2009	6.45	18.4	0.102	0.068	541.3	4.545	5.217
11/13/2009	6.48	4.7	0.100	0.091	634.5	5.660	5.714
11/20/2009	6.57	7.9	0.088	0.074	647.4	4.878	5.714
11/21/2009	6.53	5.1	0.104	0.094	758.3	5.769	5.714
12/1/2009	6.54	8.0	0.091	0.077	769.1	4.511	5.128
12/2/2009	6.54	4.2	0.096	0.091	873.7	5.310	5.263
12/7/2009	6.52	4.3	0.087	0.077	888.0	4.688	6.061
12/8/2009	6.56	3.3	0.104	0.096	993.5	5.172	5.505
12/12/2009	6.46	6.7	0.091	0.078	1005.3	4.959	5.607
12/13/2009	6.57	2.8	0.105	0.101	1119.0	5.357	5.607

Table B-10. LFBSM + 4% WTR media results from the minicolumn experiment, set I. Media mass in the column was 92.44 g. Media was subject to continuous flow of an approximately 120 µg P/L solution. ID is the sample identifier, provided as the date of collection. pH, turbidity, TP, and TDP are the measured effluent sample values. BV is the cumulative bed volumes of flow that had passed through the media at the time of sample collection. Initial Q is the volumetric flowrate before calibration. Calibrated Q is the volumetric flowrate as calibrated prior to sample collection.

ID	**pH**	**Turbidity (NTU)**	**TP (mg/L)**	**TDP (mg/L)**	**BV**	**Initial Q (mL/min)**	**Calibrated Q (mL/min)**
6/24/2009	6.82	2.3	0.015	0.036	4.8	-	1.339
6/25/2009	6.79	9.3	0.037	-	32.7	1.240	1.310
6/26/2009	6.73	9.4	0.031	0.019	59.2	1.376	1.376
6/27/2009	6.48	7.8	0.036	-	98.5	1.271	1.271
6/28/2009	6.75	4.5	0.018	0.022	124.1	1.261	1.261
6/29/2009, #1	6.71	5.9	0.026	0.018	147.5	1.310	1.310
6/29/2009, #2	-	-	0.016	-	154.3	1.310	1.310

6/30/2009	6.76	5.5	0.016	-	177.1	1.327	1.327
7/1/2009	6.76	4.2	0.018	0.010	204.8	1.288	1.288
7/2/2009	6.77	4.2	0.020	-	232.0	1.255	1.255
7/3/2009	6.54	3.2	0.015	0.010	259.5	1.271	1.271
7/4/2009	6.19	4.6	0.018	-	290.6	1.224	1.224
7/5/2009	6.46	4.2	0.017	-	317.5	1.240	1.240
7/6/2009	6.75	3.5	0.016	0.016	342.4	1.190	1.327
7/7/2009	6.78	7.2	0.014	-	367.7	1.316	1.316
7/8/2009	6.63	5.1	0.014	-	397.4	1.271	1.271
7/9/2009	6.57	3.9	0.013	-	424.4	1.293	1.293
7/10/2009	6.40	4.1	0.014	0.014	452.2	1.322	1.322
7/11/2009	6.38	6.1	0.016	-	487.0	1.299	1.299
7/13/2009	6.62	5.3	0.017	-	540.2	1.245	1.245
7/14/2009	6.64	3.5	0.022	-	566.7	1.190	1.316
7/15/2009	6.72	8.2	0.018	-	593.5	1.250	1.250
7/16/2009	6.54	4.4	0.017	-	621.3	1.357	1.339
7/17/2009	6.70	5.6	0.017	-	650.9	1.250	1.250
7/18/2009	6.40	5.1	0.021	-	679.6	1.124	1.316
7/19/2009	6.39	4.1	0.017	-	695.2	0.000	1.339
7/20/2009	6.63	5.6	0.019	-	717.3	1.111	1.299
7/21/2009	6.27	7.4	0.020	-	743.2	1.091	1.266
7/22/2009, #1	6.57	2.5	0.021	-	772.7	1.014	2.679
7/22/2009, #2	-	-	0.023	-	781.0	1.014	2.679
7/23/2009, #1	-	-	0.045	-	820.2	1.415	3.093
7/23/2009, #2	6.62	15.3	0.049	-	828.7	0.000	2.500
7/24/2009	6.62	3.9	0.047	-	871.3	2.609	2.679
7/25/2009	6.55	6.3	0.047	-	914.6	1.639	2.586
7/26/2009	6.66	0.2	0.047	-	991.7	2.970	2.586
7/27/2009	6.54	5.2	0.061	0.057	1040.7	3.030	2.679
7/28/2009	6.59	0.5	0.065	-	1098.2	2.970	2.609
7/29/2009	6.54	0.5	0.063	-	1159.4	2.941	2.679
7/30/2009	6.33	0.2	0.064	-	1214.0	2.439	3.191
7/31/2009	6.45	3.2	0.057	-	1250.5	0.000	2.586
8/2/2009	6.33	3.8	0.071	-	1353.6	1.351	2.679
8/3/2009	6.68	3.5	0.068	-	1386.7	1.215	2.970
8/5/2009	6.67	7.6	0.059	-	1485.0	0.000	2.703
8/6/2009	6.35	0.4	0.066	-	1545.9	2.913	2.586
8/7/2009	6.37	0.2	0.068	0.059	1592.8	2.609	3.061
8/11/2009	6.53	0.3	0.080	-	1878.8	2.703	2.703
8/12/2009	6.44	0.3	0.085	0.078	1935.7	2.326	5.455
8/13/2009	6.52	0.5	0.093	-	2030.4	2.655	5.263

8/15/2009	6.36	0.2	0.085	-	2192.0	1.662	5.128
8/17/2009	6.48	0.2	0.091	-	2406.8	2.941	5.042
8/18/2009	6.53	8.0	0.070	-	2460.9	0.000	6.061
8/19/2009	6.58	5.7	0.075	0.064	2528.8	0.612	2.885

Table B-11. LFBSM + 4% WTR media results from the minicolumn experiment, set II. Media mass in the column was 90.48 g. Media was subject to intermittent flow of an approximately 120 µg P/L solution. ID is the sample identifier, provided as the date of collection. pH, turbidity, TP, and TDP are the measured effluent sample values. BV is the cumulative bed volumes of flow that had passed through the media at the time of sample collection. Initial Q is the volumetric flowrate before calibration. Calibrated Q is the volumetric flowrate as calibrated prior to sample collection.

ID	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/L)	BV	Initial Q (mL/min)	Calibrated Q (mL/min)
9/8/2009	6.99	4.2	0.022	-	5.3	1.266	1.266
9/9/2009	6.77	16.1	0.040	-	34.3	1.515	1.515
9/14/2009	7.15	23.3	0.052	-	37.3	1.442	1.357
9/15/2009	7.01	9.6	0.030	-	57.3	1.293	1.304
9/19/2009	7.05	15.4	0.043	0.017	70.8	1.796	1.316
9/20/2009	7.11	10.0	0.027	-	90.3	0.616	1.948
9/24/2009	7.12	19.5	0.049	0.015	98.4	2.174	0.785
9/25/2009	6.89	8.3	0.039	-	127.1	1.176	1.200
9/30/2009	6.90	11.9	0.036	0.017	138.6	2.752	1.261
10/1/2009	6.98	4.7	0.033	-	159.4	0.811	1.210
10/6/2009	6.93	9.6	0.034	-	169.5	6.000	2.500
10/7/2009	6.58	3.4	0.053	-	223.0	2.586	2.308
10/16/2009	6.86	10.4	0.037	0.014	227.9	2.143	2.586
10/17/2009	6.81	4.9	0.054	-	284.6	2.632	2.703
10/22/2009	6.73	9.0	0.034	0.020	292.6	2.609	2.632
10/23/2009	6.87	3.7	0.060	-	348.1	2.655	2.679
10/28/2009	6.67	3.6	0.042	0.037	392.7	4.724	1.130
10/29/2009	6.52	5.1	0.078	0.067	494.9	5.128	6.122
11/2/2009	6.51	3.5	0.044	-	515.5	5.357	5.172
11/3/2009	6.56	2.2	0.073	-	609.9	5.217	5.263
11/12/2009	6.74	5.9	0.050	0.042	625.2	4.317	5.941
11/13/2009	6.75	2.0	0.075	-	710.8	4.959	5.085
11/20/2009	6.67	3.0	0.079	-	722.7	4.918	5.263
11/21/2009	6.73	1.8	0.049	-	820.3	5.085	5.042
12/1/2009	6.71	3.6	0.061	0.056	830.5	4.800	5.263

12/2/2009	6.81	2.8	0.077	-	939.8	5.556	5.405
12/7/2009	6.70	1.4	0.053	-	957.2	7.229	5.882
12/8/2009	6.77	0.8	0.084	-	1067.6	5.660	5.455
12/12/2009	6.63	4.6	0.058	0.048	1079.4	5.505	3.750
12/13/2009	6.69	5.0	0.098	0.087	1193.2	5.607	5.455

Table B-12. Sand + 4% WTR media results from the minicolumn experiment, set II. Media mass in the column was 85.93 g. Media was subject to continuous flow of an approximately 120 µg P/L solution. ID is the sample identifier, provided as the date of collection. pH, turbidity, TP, and TDP are the measured effluent sample values. BV is the cumulative bed volumes of flow that had passed through the media at the time of sample collection. Initial Q is the volumetric flowrate before calibration. Calibrated Q is the volumetric flowrate as calibrated prior to sample collection.

ID	**pH**	**Turbidity (NTU)**	**TP (mg/L)**	**TDP (mg/L)**	**BV**	**Initial Q (mL/min)**	**Calibrated Q (mL/min)**
9/8/2009	7.69	0.2	0.007	-	5.6	-	1.271
9/9/2009	7.48	1.0	0.009	-	33.8	1.240	1.240
9/10/2009	7.18	1.2	0.009	-	58.1	1.240	1.240
9/11/2009	7.41	1.5	0.009	-	85.3	1.250	1.299
9/14/2009	7.26	0.3	0.010	-	170.2	1.277	1.277
9/15/2009	7.23	0.3	0.011	-	197.5	1.190	1.255
9/16/2009	6.80	0.3	0.009	-	222.9	1.245	1.245
9/18/2009	7.05	0.5	0.009	-	277.0	1.235	1.327
9/19/2009	7.25	0.6	0.015	-	308.6	1.316	1.316
9/20/2009	7.16	0.3	0.015	-	336.1	1.304	1.304
9/21/2009	6.84	0.3	0.013	-	363.0	1.304	1.304
9/23/2009	6.96	0.3	0.015	-	418.6	1.288	1.288
9/24/2009	6.92	0.2	0.017	-	449.0	1.250	1.250
9/25/2009	6.82	0.3	0.020	-	475.9	1.210	1.288
9/28/2009	6.86	0.2	0.024	-	553.8	1.010	1.288
9/29/2009	7.03	0.3	0.015	-	573.4	0.711	1.316
9/30/2009	6.93	1.0	0.027	-	603.1	1.322	1.322
10/1/2009	6.83	0.3	0.028	-	631.1	1.316	1.316
10/2/2009	6.78	0.7	0.026	-	660.7	1.316	1.316
10/5/2009	6.78	0.9	0.029	-	746.7	1.310	1.310
10/6/2009	6.72	0.5	0.041	-	777.3	1.299	2.500
10/7/2009	6.69	0.9	0.060	-	829.3	2.479	2.479
10/8/2009	6.44	0.4	0.048	-	886.4	2.439	2.632
10/9/2009	6.49	0.2	0.052	-	938.4	2.586	2.586
10/12/2009	6.79	0.6	0.060	-	1086.1	1.899	2.479

10/13/2009	6.67	0.7	0.068	-	1142.4	2.206	2.632
10/14/2009	6.71	0.3	0.072	-	1191.4	2.174	2.542
10/15/2009	6.81	0.4	0.075	-	1236.7	1.657	1.744
10/16/2009	6.75	0.8	0.061	-	1270.0	0.337	2.521
10/17/2009	6.76	0.6	0.078	-	1324.4	2.326	2.586
10/19/2009	6.68	0.4	0.091	-	1439.3	2.679	2.655
10/21/2009	6.67	0.3	0.066	-	1553.8	2.778	2.542
10/22/2009	6.65	0.4	0.062	-	1608.5	2.500	2.586
10/23/2009	6.65	0.5	0.079	-	1663.0	2.632	2.564
10/25/2009	6.75	0.8	0.077	-	1792.2	2.564	2.830
10/26/2009	6.73	0.2	0.071	-	1831.7	2.362	2.609
10/27/2009	6.55	1.8	0.090	-	1892.0	5.310	5.357
10/28/2009	6.72	0.5	0.095	-	2005.5	5.172	5.042
10/29/2009	6.65	0.3	0.099	-	2107.9	4.380	5.941
10/30/2009	6.64	1.2	0.096	-	2217.5	5.217	5.128
11/2/2009	6.60	0.5	0.089	-	2500.5	4.511	5.455
11/3/2009	6.72	1.0	0.089	-	2598.3	1.700	5.085
11/4/2009	6.45	0.4	0.096	-	2711.7	4.196	4.138
11/6/2009	6.53	0.3	0.091	-	2921.5	1.519	4.138
11/9/2009	6.51	0.5	0.086	-	3150.7	4.196	5.128
11/10/2009	6.49	0.6	0.088	-	3292.2	5.042	5.128

Table B-13. Influent solution measurements from the minicolumn experiment, set I. ID is the sample identifier, provided as the date of collection. pH, turbidity, and TP are the measured influent sample values.

ID	pH	Turbidity (NTU)	TP (mg/L)
6/24/2009	6.47	0.5	0.108
6/25/2009	6.08	0.3	0.123
6/26/2009	5.99	0.8	0.114
6/27/2009	6.12	1.6	0.112
6/28/2009	6.19	0.1	0.110
6/29/2009, #1	6.24	0.1	0.118
6/29/2009, #2	-	-	0.109
6/30/2009	6.41	0.2	0.108
7/1/2009	6.24	0.3	0.109
7/2/2009	6.33	4.0	0.141
7/3/2009	6.39	0.2	0.133
7/4/2009	6.39	0.2	0.138
7/5/2009	6.31	0.2	0.141

7/6/2009	6.35	0.3	0.146
7/7/2009	6.47	0.2	0.138
7/8/2009	6.68	7.7	0.143
7/9/2009	6.40	3.3	0.140
7/10/2009	6.61	3.2	0.130
7/11/2009	6.36	3.5	0.124
7/13/2009	6.70	7.1	0.119
7/14/2009	6.69	0.2	0.121
7/15/2009	6.57	0.2	0.120
7/16/2009	6.56	0.3	0.119
7/17/2009	6.76	0.1	0.121
7/18/2009	6.77	0.3	0.122
7/19/2009	6.68	7.3	0.120
7/20/2009	6.73	0.5	0.124
7/21/2009	6.55	9.1	0.124
7/22/2009, #1	6.57	0.5	0.122
7/22/2009, #2	-	-	0.121
7/23/2009, #1	-	-	0.122
7/23/2009, #2	6.67	0.2	0.124
7/24/2009	6.65	4.6	0.120
7/25/2009	6.89	0.2	0.124
7/26/2009	6.71	0.1	0.120
7/27/2009	6.55	0.1	0.120
7/28/2009	6.66	0.3	0.120
7/29/2009	6.63	0.3	0.120
7/30/2009	6.56	0.1	0.116
7/31/2009	6.53	0.4	0.126
8/2/2009	7.77	0.1	0.123
8/3/2009	6.74	0.3	0.129
8/5/2009	6.52	0.4	0.120
8/6/2009	7.23	0.1	0.129
8/7/2009	7.04	0.2	0.119
8/11/2009	6.58	0.1	0.131
8/12/2009	6.74	0.1	0.123
8/13/2009	6.51	0.1	0.128
8/15/2009	6.56	0.3	0.121
8/17/2009	6.54	2.0	0.121
8/18/2009	6.40	4.2	0.122
8/19/2009	6.61	0.4	0.117

Table B-14. Influent solution measurements from the minicolumn experiment, set II. ID is the sample identifier, provided as the date of collection. pH, turbidity, and TP are the measured influent sample values.

ID	pH	Turbidity (NTU)	TP (mg/L)
9/8/2009	5.81	0.3	0.123
9/9/2009	4.40	1.6	0.123
9/10/2009	6.53	1.3	0.126
9/11/2009	6.81	1.0	0.122
9/14/2009	6.27	0.4	0.121
9/15/2009	6.46	1.1	0.123
9/16/2009	6.14	1.8	0.126
9/18/2009	6.49	0.9	0.123
9/19/2009	5.88	0.4	0.123
9/20/2009	6.48	0.3	0.121
9/21/2009	6.57	0.7	0.126
9/23/2009	6.27	0.5	0.121
9/24/2009	6.59	1.9	0.121
9/25/2009	6.58	0.3	0.123
9/28/2009	6.71	0.3	0.122
9/29/2009	6.70	0.5	0.120
9/30/2009	6.60	0.4	0.123
10/1/2009	6.59	0.4	0.125
10/2/2009	6.50	0.4	0.120
10/5/2009	6.56	0.5	0.125
10/6/2009	6.45	0.3	0.122
10/7/2009	6.54	0.9	0.122
10/8/2009	6.22	0.7	0.118
10/9/2009	6.57	0.6	0.119
10/12/2009	6.88	0.3	0.121
10/13/2009	6.75	0.5	0.121
10/14/2009	6.60	0.3	0.123
10/15/2009	6.80	0.3	0.117
10/16/2009	6.64	0.8	0.115
10/17/2009	6.62	0.5	0.119
10/19/2009	8.23	1.0	0.115
10/21/2009	6.48	0.2	0.112
10/22/2009	6.64	0.5	0.117
10/23/2009	6.62	0.7	0.119
10/25/2009	6.82	0.9	0.119
10/26/2009	6.58	0.4	0.120

10/27/2009	6.57	3.0	0.118
10/28/2009	6.74	0.7	0.119
10/29/2009	6.54	0.2	0.118
10/30/2009	6.64	0.6	0.113
11/2/2009	6.62	0.3	0.117
11/3/2009	6.39	0.2	0.117
11/4/2009	6.49	1.2	0.121
11/6/2009	6.45	0.6	0.114
11/9/2009	7.47	1.9	0.115
11/10/2009	6.42	0.4	0.114
11/12/2009	7.78	0.6	0.119
11/13/2009	6.62	1.3	0.117
11/20/2009	8.27	0.7	0.117
11/21/2009	6.61	1.1	0.121
12/1/2009	9.06	0.9	0.117
12/2/2009	6.53	0.7	0.116
12/7/2009	6.59	0.2	0.118
12/8/2009	6.66	0.3	0.117
12/12/2009	6.55	0.5	0.118
12/13/2009	6.71	1.0	0.119

Appendix C: Vegetated Column Flow Data

Table C-1. Influent flow measurements of both vegetated columns for run 1. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Exp. Flow and Ctrl. Flow are the measured flowrates at a given time for the experimental and control column, respectively. V_e In and V_c In are the cumulative volume of influent applied to the experimental and control columns, respectively.

Sample ID	Runtime (min)	Exp. Flow (mL/min)	V_e In (mL)	Ctrl. Flow (mL/min)	V_c In (mL)
	0	190.5	-	181.8	-
0	11	-	2166.3	-	2031.3
	106	203.4	20874.9	187.5	19573.9
3	181	-	36002.0	-	33528.2
	220	200.0	43868.1	184.6	40784.4
	299	203.4	59802.0	187.5	55483.0
5.5	323	-	64683.4	-	59983.0

Table C-2. Effluent flow measurements of both vegetated columns for run 1. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Flow is the measured flowrate at a given time. Cum. V is the cumulative volume of effluent that the column produced. †: Volume of effluent collected between column runs.

Experimental Column				**Control Column**			
Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)	Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)
	22	150.0	1650.0		27	136.4	1840.9
0	30	162.2	2898.6	0	34	157.9	2870.8
0.3	44	240.0	5713.8	0.3	48	166.7	5142.7
0.7	64	142.9	9542.4	0.7	69	166.7	8642.7
1	84	181.8	12789.1	1	90	176.5	12245.7
1.3	103	193.5	16355.1	1.3	108	176.5	15422.2
2	147	171.4	24384.6	2	151	176.5	23010.4
2.7	184	187.5	31024.8	2.7	189	176.5	29716.3
3.3	225	187.5	38712.3	3.3	229	176.5	36775.1
4	268	181.8	46652.6	4	273	166.7	44324.1
5	330	181.8	57925.3	5	331	176.5	54275.1
	344	62.5	59635.6		351	27.9	56318.9
6	579	0	66979.3	6	579	0	59500.3
		† ~ 0.6 L	67579.3			† ~ 1.1 L	60600.3

Table C-3. Influent flow measurements of both vegetated columns for run 2. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Exp. Flow and Ctrl. Flow are the measured flowrates at a given time for the experimental and control column, respectively. V_e In and V_c In are the cumulative volume of influent applied to the experimental and control columns, respectively.

Sample ID	Runtime (min)	Exp. Flow (mL/min)	V_e In (mL)	Ctrl. Flow (mL/min)	V_c In (mL)
	0	187.5	-	171.4	-
0	15	-	2881.7	-	2629.0
	56	196.7	10758.2	179.1	9814.9
	65	187.5	12487.2	166.7	11370.9
	69	200.0	13262.2	179.1	12062.4
	81	184.6	15569.9	-	14165.6
	115	184.6	21846.8	171.4	20124.7

3	185	-	34769.9	-	32301.2
	200	184.6	37539.1	176.5	34910.4
	333	184.6	62093.0	-	-
	334	157.9	62264.2	176.5	58557.5
5.5	339	190.5	63135.1	-	59439.8
	347	-	64659.0	-	60851.6
	355	-	66182.8	-	62263.4

Table C-4. Effluent flow measurements of both vegetated columns for run 2. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Flow is the measured flowrate at a given time. Cum. V is the cumulative volume of effluent that the column produced. †: Volume of effluent collected between column runs.

Experimental Column				**Control Column**			
Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)	Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)
	26	157.9	2052.6		27	150.0	2025.0
0	35	187.5	3606.9	0	36	176.5	3494.1
0.25	46	176.5	5608.7	0.25	48	176.5	5611.8
0.5	61	222.2	8598.9	0.5	63	187.5	8341.5
0.75	85	222.2	13932.3	0.75	86	200.0	12797.8
1	92	230.8	15517.7	1	94	187.5	14347.8
1.3	111	206.9	19675.6	1.3	113	187.5	17910.3
	134	176.5	24084.3		136	157.9	21882.3
	143	176.5	25672.5		145	162.2	23322.6
2	154	230.8	27912.3	2	155	222.2	25244.5
	157	166.7	28508.5		158	150.0	25802.8
	182	187.5	32935.6		192	171.4	31267.1
2.7	191	250.0	34904.3	2.7	195	222.2	31857.6
	194	187.5	35560.6		195	162.2	31857.6
	212	166.7	38748.1		213	176.5	34905.3
	228	176.5	41493.2		228	176.5	37552.4
3.3	234	230.8	42714.9	3.3	235	206.9	38894.1
	238	187.5	43551.4		238	162.2	39447.7
	263	176.5	48101.1		263	171.4	43617.6
4	271	206.9	49634.5	4	272	206.9	45320.1
	289	171.4	53039.5		289	166.7	48495.4
	326	157.9	59131.9		326	171.4	54750.1
5	329	193.5	59659.1	5	330	214.3	55521.6
	345	139.5	62323.8		345	171.4	58414.4

	357	146.3	64039.0		357	150.0	60343.0
6	359	230.8	64416.1	6	359	200.0	60693.0
	367	139.5	65897.4		369	65.2	62019.1
7	446	5.9	71642.3	7	451	5.6	64922.5
		† ~ 0.7 L	72322.3			† ~ 0.9 L	65817.5

Table C-5. Influent flow measurements of both vegetated columns for run 3. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Exp. Flow and Ctrl. Flow are the measured flowrates at a given time for the experimental and control column, respectively. V_e In and V_c In are the cumulative volume of influent applied to the experimental and control columns, respectively.

Sample ID	Runtime (min)	Exp. Flow (mL/min)	V_e In (mL)	Ctrl. Flow (mL/min)	V_c In (mL)
	0	193.5	-	193.5	-
	2	179.1	372.7	179.1	372.7
	5	-	914.0	-	914.0
0	16	-	2899.1	-	2899.1
	143	181.8	25817.7	181.8	25817.7
3	191	-	35234.0	-	35234.0
6	338	210.5	64071.3	210.5	64071.3

Table C-6. Effluent flow measurements of both vegetated columns for run 3. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Flow is the measured flowrate at a given time. Cum. V is the cumulative volume of effluent that the column produced. †: Volume of effluent collected between column runs.

Experimental Column				**Control Column**			
Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)	Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)
	31	11.9	184.5		24.0	55.6	666.7
	37	25.5	296.8		27.0	133.3	950.0
	40	136.4	539.7		28.0	187.5	1110.4
0	52	150.0	2257.9		32.0	200.0	1885.4
	53	181.8	2423.8	0	39.0	222.2	3363.2
0.25	57	222.2	3231.8		47.0	181.8	4979.4
	65	230.8	5043.8	0.25	50.0	181.8	5524.8

0.5	74	250.0	7207.3		58.0	187.5	7002.1
	80	250.0	8707.3	0.5	67.0	193.5	8716.8
0.75	86	250.0	10207.3		72.0	181.8	9655.2
	95	230.8	12370.7	0.75	79.0	181.8	10927.9
1	103	193.5	14068.0		88.0	176.5	12540.2
	115	187.5	16354.3	1	93.0	181.8	13436.0
1.3	122	193.5	17688.0		110.0	187.5	16575.2
	141	187.5	21307.9	1.3	114.0	181.8	17313.8
2	168	193.5	26452.1		140.0	187.5	22114.9
	181	187.5	28928.9	2	160.0	176.5	25754.6
2.6	202	187.5	32866.4		180.0	181.8	29337.5
	225	181.8	37113.6	2.6	194.0	176.5	31845.6
3.3	242	187.5	40252.8		219.0	181.8	36324.2
	261	181.8	43761.3	3.3	234.0	181.8	39051.4
4	286	181.8	48306.7		260.0	176.5	43709.2
	321	171.4	54488.6	4	279.0	171.4	47014.2
5	343	162.2	58158.1		319.0	181.8	54079.2
	354	61.9	59390.2	5	340.0	187.5	57957.0
6	467	4.5	63138.0		352.0	52.6	59397.8
	546	2.6	63416.5	6	535.0	1.2	64321.6
		† ~ 1.0 L	64416.5			† ~ 1.1 L	65421.6

Table C-7. Influent flow measurements of both vegetated columns for run 4. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Exp. Flow and Ctrl. Flow are the measured flowrates at a given time for the experimental and control column, respectively. V_e In and V_c In are the cumulative volume of influent applied to the experimental and control columns, respectively.

Sample ID	Runtime (min)	Exp. Flow (mL/min)	V_e In (mL)	Ctrl. Flow (mL/min)	V_c In (mL)
	0	181.8	-	184.6	-
	2	184.6	366.4	184.6	369.2
	4	174.5	725.6	173.3	727.1
0	29	-	5137.9	-	5124.7
	71	178.4	12550.6	178.5	12512.5
	119	177.1	21084.0	175.3	21003.2
	186	174.0	32846.2	174.6	32725.1
3	188	-	33196.0	-	32725.1
	221	175.8	38967.9	172.4	38452.0
	231	174.6	40720.2	173.5	40181.5

	233	178.3	41069.4	177.2	40528.4
	298	179.2	52687.0	177.5	52057.5
	340	177.7	60181.6	177.2	59507.1
6	355	-	62847.0	-	62165.1

Table C-8. Effluent flow measurements of both vegetated columns for run 4. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Flow is the measured flowrate at a given time. Cum. V is the cumulative volume of effluent that the column produced. †: Volume of effluent collected between column runs.

Experimental Column				**Control Column**			
Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)	Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)
	34	3.3	55.6		22	8.7	95.4
	35	117.6	116.0		26	163.4	439.5
0	44	193.5	1516.4	0	36	193.5	2224.2
0.25	52	187.5	3040.6		39	193.7	2805.2
	56	181.8	3779.2	0.25	45	179.3	3924.2
0.5	68	205.5	6103.4		53	177.9	5353.0
	76	201.5	7731.5	0.5	62	184.3	6982.9
0.75	82	198.3	8931.0		66	176.8	7705.0
	90	204.3	10541.6	0.75	75	175.7	9291.2
1	96	203.0	11763.4		83	182.0	10721.9
	110	189.3	14509.5	1	91	180.5	12171.7
1.3	117	183.5	15814.6		105	180.8	14700.3
	140	175.5	19943.5	1.3	109	180.8	15423.5
2	165	182.1	24414.0		139	182.7	20876.5
	173	173.6	25837.0	2	156	184.4	23997.3
2.6	197	158.3	29820.1		169	184.4	26395.1
	218	172.8	33296.9	2.6	191	173.9	30337.0
3.3	247	173.6	38320.0		219	177.4	35255.5
	261	176.0	40766.9	3.3	229	172.0	37002.7
4	280	197.3	44312.9		252	174.9	40992.0
	302	193.9	48616.4	4	272	184.3	44583.5
5	337	197.9	55473.1		303	189.0	50368.9
6	371	87.2	60319.3	5	332	177.1	55677.7
	374	57.1	60535.8	6	374	13.8	59687.7
	474	6.0	63692.7		377	22.8	59742.5
7	546	3.2	64024.3		484	2.9	61113.7

† ~ 725 mL	64024.3	7	548	0.0	61205.3
				† ~ 855 mL	61205.3

Table C-9. Influent flow measurements of both vegetated columns for run 5. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Exp. Flow and Ctrl. Flow are the measured flowrates at a given time for the experimental and control column, respectively. V_e In and V_c In are the cumulative volume of influent applied to the experimental and control columns, respectively.

Sample ID	Runtime (min)	Exp. Flow (mL/min)	V_e In (mL)	Ctrl. Flow (mL/min)	V_c In (mL)
	0	185.8	-	180.8	-
	2	185.1	370.9	179.0	359.8
0	9	-	2476.3	-	1622.5
	14	165.8	3353.6	-	2524.4
	16	181.1	3700.5	181.7	2885.1
	39	185.2	7912.9	182.9	7078.8
	53	186.5	10514.5	182.6	9637.4
	80	185.7	15539.0	183.9	14585.2
	95	175.6	18248.5	184.9	17351.0
	98	192.5	18775.2	-	17907.6
	105	185.1	20122.7	186.2	19206.5
	127	183.9	24182.1	184.0	23278.8
	170	183.8	32088.3	183.2	31173.6
3	194	-	36459.6	-	35562.2
	204	180.5	38281.0	182.5	37390.7
	239	177.6	44547.2	179.4	43724.6
	284	177.3	52532.5	181.1	51835.3
	287	178.1	53065.5	180.3	52377.3
	319	175.8	58728.2	178.4	58115.7
	339	179.5	62281.8	177.2	61671.3
6	341	-	62640.8	-	62025.7

Table C-10. Effluent flow measurements of both vegetated columns for run 5. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Flow is the measured flowrate at a given time. Cum. V is the cumulative volume of effluent that the column produced. †: Volume of effluent collected between column runs.

Experimental Column				**Control Column**			
Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)	Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)
	28	167.6	2346.4		23	33.8	388.9
	29	198.9	2529.6		26	149.1	274.3
0	37	212.6	4175.9		27	199.1	448.4
	45	176.2	5731.0	0	34	237.6	1977.1
0.25	48	178.3	6262.7		42	191.8	3694.8
	57	178.3	7867.2	0.25	49	184.3	5011.2
0.5	65	190.8	9343.5		56	182.3	6294.2
	72	193.2	10687.6	0.5	64	189.2	7780.1
0.75	78	189.7	11836.2		71	176.8	9060.9
	87	202.1	13599.2	0.75	77	179.6	10130.0
1	91	203.0	14409.3		86	167.4	11691.5
1.3	113	181.8	18642.1	1	90	184.1	12394.5
	124	182.7	20647.0	1.3	112	188.2	16490.0
2	168	195.9	28975.9		123	190.1	18570.7
	185	189.7	32253.4	2	167	188.6	26902.9
2.6	193	180.8	33735.3		183	195.6	29976.4
	225	178.4	39482.3	2.6	192	193.0	31724.9
3.3	234	179.6	41093.3		224	177.8	37657.1
	256	184.8	45101.4	3.3	233	173.4	39237.5
4	281	185.7	49732.5		255	177.6	43098.8
	308	190.7	54813.3	4	280	178.9	47555.8
5	335	166.9	59641.0		307	180.3	52405.5
	346	157.0	61422.6	5	334	178.9	57255.1
	351	125.1	62127.7		345	133.7	58974.6
	354	77.0	62430.9		349	77.2	59396.4
6	389	15.7	64054.2		353	57.2	59665.2
		† ~ 1.8 L	65859.2	6	395	7.7	61029.3
						† ~ 1.2 L	62286.3

Table C-11. Influent flow measurements of both vegetated columns for run 6. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Exp. Flow and Ctrl. Flow are the measured flowrates at a given time for the experimental and control column, respectively. V_e In and V_c In are the cumulative volume of influent applied to the experimental and control columns, respectively.

Experimental Column **Control Column**

Sample ID	Runtime (min)	Exp. Flow (mL/min)	V_e In (mL)	Runtime (min)	Ctrl. Flow (mL/min)	V_c In (mL)
	0.0	0.0	-	0.0	0.0	-
	1.8	65.7	59.1	3.2	63.6	101.9
	3.6	-	178.1	3.6	-	128.3
	9.3	64.3	518.3	11.2	60.4	596.2
Step 2	16.8	-	1002.8	16.8	-	937.4
	19.0	246.5	1536.5	20.8	192.8	1706.3
	28.6	241.4	3876.5	24.4	229.2	2467.7
0	29.4	-	4077.7	29.4	-	3612.6
Step 3	40.0	-	6631.9	40.0	-	6038.5
	45.2	328.2	8328.8	46.6	325.5	8194.0
	60.4	334.2	13388.0	59.9	322.7	12504.1
	75.3	332.8	18325.0	74.7	318.7	17248.4
Step 4	97.0	-	25562.9	97.0	-	24350.7
	108.9	266.9	28730.2	108.5	261.3	27364.0
	117.9	240.8	31141.2	115.9	233.3	29288.6
	130.1	240.9	34083.5	126.4	231.4	31724.5
	152.0	241.8	39353.6	151.6	231.7	37552.4
Step 5	181.9	-	46600.7	181.9	-	44588.5
	185.7	142.9	47134.0	185.9	145.3	45162.4
3	199.0	-	49050.6	199.0	-	47007.5
	209.2	143.9	50515.6	209.8	135.3	48520.5
	226.4	149.4	52979.0	224.4	151.7	50489.9
	254.0	152.6	57151.8	254.2	153.0	55032.9
Step 6	274.9	-	60344.0	274.9	-	58205.1
	279.5	61.1	60622.9	279.1	60.9	58457.9
	302.5	60.0	62014.8	298.9	59.3	59650.4
	328.8	58.8	63581.0	325.2	58.4	61198.4
	329.7	88.1	63631.0	328.8	-	61422.0
	336.0	65.0	64193.2	334.0	65.2	61727.5
	359.6	63.5	65708.3	359.1	64.0	63344.8
6	366.2	-	66126.6	366.2	-	63800.2

Table C-12. Effluent flow measurements of both vegetated columns for run 6. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Flow is the measured flowrate at a given time. Cum. V is the cumulative volume of effluent that the column produced. †: Volume of effluent collected between column runs.

Experimental Column				Control Column			
Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)	Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)
	39.0	193.4	3770.5		37.0	249.4	4613.5
0	45.8	-	5319.8	0	41.8	-	5958.9
	51.6	264.6	6655.3		48.0	315.3	7720.1
0.25	57.3	283.6	8223.3	0.25	53.0	313.3	9284.3
	68.8	328.8	11737.1		65.9	328.2	13424.0
0.5	73.3	346.6	13257.3	0.5	69.7	324.9	14664.1
	82.1	345.4	16290.8		79.1	319.5	17703.3
0.75	88.4	330.9	18432.6	0.75	85.5	307.2	19693.1
1	107.1	128.4	22716.2	1	103.4	235.0	24550.6
1.3	123.3	264.8	25914.3	1.3	122.9	231.3	29105.0
	132.4	251.4	28249.9		129.2	233.6	30561.6
	156.8	241.2	34258.6		152.5	235.6	36030.8
2	167.1	249.1	36795.5	2	164.3	232.7	38789.9
	179.6	235.3	39810.7		176.5	226.4	41594.6
	195.3	125.0	42648.0		191.9	120.3	44264.2
2.7	207.2	142.8	44234.4	2.7	203.9	122.6	45723.5
	234.6	147.9	48221.6		231.4	135.5	49263.8
3.3	245.7	150.8	49882.2	3.3	241.1	150.6	50651.4
	262.5	155.3	52451.3		259.2	146.3	53351.1
	284.6	115.0	55438.0		280.9	114.4	56173.1
4	294.6	147.6	56750.8	4	297.0	131.5	58158.3
	325.5	56.4	59904.2		319.0	57.0	60224.4
5	349.0	65.6	61336.8	5	351.1	55.7	62037.3
	364.1	60.9	62291.7		360.5	59.7	62578.7
6	382.6	69.1	63494.7	6	382.5	0	63892.1
	385.8	51.1	63683.1		386.3	0	63892.1
		† ~ 2.6 L	66233.1		390.0	13.3	63916.5
						† ~ 1.7 L	65581.5

Table C-13. Influent flow measurements of both vegetated columns for run 7. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Exp. Flow and Ctrl. Flow are the measured flowrates at a given time for the experimental and control column, respectively. V_e In and V_c In are the cumulative volume of influent applied to the experimental and control columns, respectively.

Experimental Column				**Control Column**			
Sample ID	Runtime (min)	Exp. Flow (mL/min)	V_e In (mL)	Sample ID	Runtime (min)	Ctrl. Flow (mL/min)	V_c In (mL)
	3.03	178.4	539.9		4.92	182.4	898.3
0	15.24	-	2696.4		6.01	179.4	1095.6
	27.64	174.8	4886.3	0	15.24	-	2733.9
	66.45	177.0	11712.4		25.05	175.6	4476.4
	97.48	176.3	17194.2		69.57	169.0	12146.0
	103.65	177.9	18286.2		95.42	166.9	16487.4
	132.03	175.7	23303.3		101.38	178.8	17483.1
	139.98	177.4	24706.9		129.25	170.4	22349.5
	170.33	174.5	30047.1		138.25	177.9	23883.4
	174.27	175.2	30734.7		168.40	169.0	29112.5
3	183.13	-	32288.0		172.10	177.8	29737.8
	197.52	191.2	34807.7	3	183.13	-	31733.6
	250.48	190.6	44919.9		199.43	184.0	34682.0
	280.57	192.4	50680.8		236.32	178.0	41358.1
	313.43	191.5	56990.3		252.92	195.1	44313.1
6	346.08	-	63254.6		278.58	192.1	49282.4
	352.48	192.2	64482.5		311.65	190.1	55601.0
				6	346.08	-	62089.2
					350.85	186.8	62987.4
					352.48	-	63292.4

Table C-14. Effluent flow measurements of both vegetated columns for run 7. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Flow is the measured flowrate at a given time. Cum. V is the cumulative volume of effluent that the column produced. †: Volume of effluent collected between column runs.

Experimental Column				**Control Column**			
Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)	Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)
	18.4	4.0	36.6		22.4	86.6	970.6
0	29.6	111.9	687.3	0	34.1	192.6	2606.7
0.25	47.7	178.4	3307.8	0.25	42.6	181.1	4191.9
0.5	63.8	179.8	6191.4	0.5	60.4	175.6	7358.0
0.75	77.4	178.5	8621.6	0.75	72.3	169.7	9413.0
1	91.9	176.0	11206.3	1	88.7	164.5	12165.0
1.3	113.1	177.8	14950.5	1.3	108.0	177.8	15468.2

	127.1	177.5	17437.2		125.7	155.7	18408.5
2	158.2	190.3	23158.9	2	157.1	199.5	23997.9
	177.5	174.7	26671.7		176.1	175.5	27551.3
2.7	192.7	177.6	29345.8	2.7	188.3	175.0	29692.4
	202.1	189.9	31081.9		201.0	175.5	31912.3
	224.8	190.7	35401.0		223.4	188.4	35987.7
3.3	234.0	190.7	37151.8	3.3	232.9	177.6	37726.2
	256.6	191.3	41461.2		255.4	190.5	41873.4
4	276.8	200.6	45435.4	4	275.4	231.0	46085.0
	294.9	195.1	49003.5		293.5	196.9	49965.1
5	333.5	197.9	56595.2	5	332.4	197.7	57633.7
	357.3	168.1	60944.5		356.0	173.0	62016.7
	364.4	84.0	61841.7		362.6	55.5	62764.8
	370.8	53.0	62277.8		369.0	29.6	63036.4
	378.4	36.0	62616.0		375.6	18.7	63195.8
6	432.6	31.0	64434.9	6	439.5	4.3	63931.3
	451.5	7.2	64794.9			† ~ 1.1 L	64981.3
		† ~ 1.2 L	65949.9				

Table C-15. Influent flow measurements of both vegetated columns for run 8. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Exp. Flow and Ctrl. Flow are the measured flowrates at a given time for the experimental and control column, respectively. V_e In and V_c In are the cumulative volume of influent applied to the experimental and control columns, respectively.

	Experimental Column			**Control Column**		
Sample ID	Runtime (min)	Exp. Flow (mL/min)	V_e In (mL)	Runtime (min)	Ctrl. Flow (mL/min)	V_c In (mL)
	1.981	179.6	355.8	4.368	179.0	782.0
0	9.18616667	-	1677.0	9.18617	-	1647.3
	61.1	187.1	11196.3	63.05	180.2	11321.4
	93.8666667	187.4	17332.4	92.2167	164.6	16349.2
	108.316667	188.6	20049.2	99.8	186.6	17597.4
	128.233333	187.1	23790.9	126.583	176.1	22453.9
	139.266667	188.1	25861.2	136.967	185.0	24281.9
	161.066667	185.5	29933.9	159.117	171.0	28224.1
	167.283333	187.1	31092.1	164.55	185.2	29153.0
3	194.983333	-	36270.5	194.983	-	34713.9

	200.933333	186.8	37382.8	198.55	180.2	35365.6
	234.4	187.9	43653.0	232.65	174.6	41415.5
	240.25	191.4	44752.5	238.217	200.2	42387.5
	287.55	190.7	53790.7	295.95	192.7	53729.6
	331.55	190.6	62179.6	329.667	191.9	60213.1
6	342.466667	-	64260.0	342.467	-	62669.5

Table C-16. Effluent flow measurements of both vegetated columns for run 8. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Flow is the measured flowrate at a given time. Cum. V is the cumulative volume of effluent that the column produced. †: Volume of effluent collected between column runs.

Experimental Column				**Control Column**			
Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)	Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)
	14.9	11.7	86.8		18.7	9.5	103.2
	19.4	37.4	198.1		22.9	113.1	358.9
0	47.6	205.8	3619.5	0	37.9	184.4	2590.7
0.25	59.3	199.8	5992.0	0.25	48.6	180.5	4552.0
	64.4	200.9	7017.1	0.5	58.4	176.5	6292.0
0.5	74.1	209.4	9000.1		65.6	171.1	7549.1
	82.4	203.8	10718.5	0.75	71.2	168.7	8509.3
0.75	89.5	210.3	12185.1		81.4	166.2	10214.6
1	109.7	217.7	16511.6	1	88.5	160.4	11365.9
	114.4	214.1	17540.6	1.3	110.8	182.0	15180.4
1.3	122.8	197.1	19253.8		115.6	179.6	16063.3
	142.2	198.0	23095.8		141.1	175.2	20586.6
2	176.9	-	29427.5	2	156.3	168.1	23181.3
	188.0	166.8	31439.7		171.6	190.2	25937.6
2.7	204.0	173.9	34176.8	2.7	189.3	180.7	29204.7
	226.4	172.8	38057.2		211.6	174.1	33162.9
3.3	242.9	180.1	40971.9	3.3	227.8	181.7	36047.2
	254.4	173.2	43000.4		253.3	200.7	40924.9
	268.3	183.4	45472.3	4	266.8	188.4	43545.0
4	286.0	170.4	48599.9		303.7	195.3	50625.2
	304.8	186.2	51954.7	5	327.3	190.1	55169.3
5	347.1	187.1	59847.1		353.1	97.4	58877.7
	354.2	165.9	61103.3		357.2	46.4	59172.5
	358.2	183.7	61805.5		359.7	35.9	59276.0

	367.8	58.6	62970.6		364.6	23.6	59422.9
	372.0	48.3	63196.0	6	439.8	3.9	60459.7
	375.2	40.8	63337.1			† ~ 1.0 L	61409.7
6	425.3	20.7	64878.6				
		† ~1.4 L	66268.6				

Table C-17. Influent flow measurements of both vegetated columns for run 9. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Exp. Flow and Ctrl. Flow are the measured flowrates at a given time for the experimental and control column, respectively. V_e In and V_c In are the cumulative volume of influent applied to the experimental and control columns, respectively.

Experimental Column				**Control Column**			
Sample ID	Runtime (min)	Exp. Flow (mL/min)	V_e In (mL)	Sample ID	Runtime (min)	Ctrl. Flow (mL/min)	V_c In (mL)
	0	11.9			2.5	63.5	157.2
	7.4	61.3	87.3		16.4	55.0	984.5
	11.6	71.9	344.4	Step 1 End	20.6	-	1212.3
	15.0	70.5	589.8	Step 2 Begin	22.1	-	-
	16.9	18.4	724.9		25.8	239.8	2114.2
Step 1 End	20.6	-	792.3		41.2	241.5	5803.5
Step 2 Begin	22.1	-	-	Step 2 End	43.8	-	6447.5
	27.4	232.0	2032.2	Step 3 Begin	44.9	-	-
	43.4	231.6	5741.2		49.8	344.1	8116.5
Step 2 End	43.8	-	5837.7		67.0	338.3	14014.0
Step 3 Begin	44.9	-	-		88.7	346.9	21443.1
	51.3	343.7	8026.1	Step 3 End	100.2	-	25432.7
	68.3	347.4	13906.8	Step 4 Begin	102.3	-	-
	87.5	349.0	20610.3		105.7	305.0	26454.3
Step 3 End	100.2	-	25037.3		107.9	278.3	27135.4
Step 4 Begin	102.3	-	-		141.5	283.4	36562.8
	104.3	293.1	25608.8		171.8	280.5	45115.7
	107.9	266.1	26673.8	Step 4 End	174.6	-	45905.8
	143.1	271.4	36128.4	Step 5 Begin	176.0	-	-
	169.9	269.8	43394.2		178.1	162.6	46241.8
Step 4 End	174.6	-	44658.0		183.7	151.4	47165.7
Step 5 Begin	176.0	-	-		213.0	148.6	51557.0
	180.1	171.6	45364.3		258.3	149.5	58298.7

	183.7	152.4	45987.7	Step 5 End	262.7	-	58966.6
	215.5	148.4	50760.7	Step 6 Begin	263.1	-	-
	256.1	149.0	56801.5		269.5	68.8	59410.4
Step 5 End	262.7	-	57790.0		314.6	66.8	62462.7
Step 6 Begin	263.1	-	-		348.7	-	64746.1
	268.2	68.5	58141.5				
	315.9	66.8	61366.8				
	348.7	-	63557.5				

Table C-18. Effluent flow measurements of both vegetated columns for run 9. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Flow is the measured flowrate at a given time. Cum. V is the cumulative volume of effluent that the column produced. †: Volume of effluent collected between column runs.

Experimental Column				**Control Column**			
Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)	Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)
	30.1	79.2	1190.0		35.5	135.2	2399.1
	36.6	5.4	1465.6		37.8	188.6	2779.7
	46.1	220.5	2544.4	0	48.1	200.2	4775.6
0	53.0	231.3	4091.9	0.25	57.1	351.1	7256.4
	56.0	230.0	4776.1		65.0	345.2	10001.0
0.25	63.8	241.4	6614.6	0.5	71.7	-	12323.8
	69.9	275.5	8212.8		76.8	346.4	14099.0
0.5	78.9	305.8	10804.4	0.75	85.5	364.3	17184.7
	83.0	307.1	12086.3		98.0	317.5	21423.0
0.75	92.7	329.9	15170.1	1	100.2	314.8	22139.5
	98.8	328.8	17156.9		115.4	279.1	26652.9
1	107.0	321.2	19832.6	1.3	120.6	291.7	28117.8
	114.6	332.0	22314.9		143.9	289.6	34899.2
1.3	127.5	316.3	26512.8	2	164.4	309.1	41035.8
	144.8	302.9	31848.0		189.4	182.3	47187.0
2	170.7	-	39411.3	2.7	201.1	145.7	49105.7
	172.6	281.2	39975.9		233.2	141.1	53710.3
	190.8	131.8	43726.8	3.3	241.6	151.8	54940.3
2.7	208.3	146.5	46168.6		274.1	59.7	58371.3
	234.6	160.1	50190.3	4	290.4	-	59448.0
3.3	252.3	166.3	53081.5		297.6	72.3	59919.8
	276.0	96.8	56205.4		319.7	63.1	61421.2

4	295.8	-	57871.2	5	327.9	-	61926.9
	300.1	71.7	58237.8		336.0	61.0	62428.5
	324.7	69.4	59967.2		350.0	58.0	63263.9
5	332.9	-	60508.0		357.8	48.4	63677.2
	337.5	62.5	60815.8		365.1	30.4	63964.0
	351.3	60.5	61666.0	6	464.7	-	65563.9
	359.5	58.2	62150.8		519.0	1.7	66435.7
	367.1	45.1	62542.2			† ~ 1.0 L	67385.7
6	422.5	-	64315.2				
	427.4	18.9	64470.3				
		† ~ 1.5 L	66005.3				

Table C-19. Influent flow measurements of both vegetated columns for run 10. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Exp. Flow and Ctrl. Flow are the measured flowrates at a given time for the experimental and control column, respectively. V_e In and V_c In are the cumulative volume of influent applied to the experimental and control columns, respectively.

	Experimental Column			**Control Column**		
Sample ID	Runtime (min)	Exp. Flow (mL/min)	V_e In (mL)	Runtime (min)	Ctrl. Flow (mL/min)	V_c In (mL)
	2.9	179.9	530.0	4.9	184.6	908.6
0	19.2	-	3476.6	19.2	-	3573.1
	33.6	181.7	6063.5	35.3	187.5	6554.5
	67.5	185.1	12284.4	70.0	186.3	13048.9
	93.3	184.5	17049.9	94.9	188.6	17716.0
	126.8	186.0	23261.8	128.7	189.6	24108.0
	168.3	186.1	30982.8	166.0	189.2	31176.1
3	191.1	-	35194.0	191.1	-	35892.1
	207.7	183.5	38268.4	205.9	187.6	38683.3
	246.3	184.4	45364.5	248.0	187.5	46575.8
	292.6	184.5	53909.3	294.5	186.6	55276.7
6	335.6	-	61841.0	335.6	-	62942.6
	343.7	-	63348.0	343.7	-	64466.5

Table C-20. Effluent flow measurements of both vegetated columns for run 10. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Flow is the measured flowrate at a given time. Cum. V is the cumulative volume of effluent that the column produced. †: Volume of effluent collected between column runs.

Experimental Column				**Control Column**			
Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)	Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)
	10.7	62.8	335.9		20.5	120.7	1238.3
	27.6	130.2	1966.8		22.5	161.9	1519.6
0	34.7	-	3049.3	0	30.5	202.0	2964.0
	41.0	177.3	4023.0		39.9	177.5	4763.0
0.25	53.5	189.0	6312.2	0.25	46.7	188.2	6003.2
	59.9	183.4	7510.0		54.7	179.9	7466.5
0.5	71.9	174.7	9661.5	0.5	63.0	196.9	9030.3
	79.0	175.7	10890.9		74.1	187.7	11174.4
0.75	83.5	175.3	11680.7	0.75	77.1	183.5	11722.0
	91.3	173.3	13052.1		85.6	185.9	13292.0
1	98.2	180.1	14268.3	1	89.1	191.0	13954.7
	112.1	174.4	16722.8		103.6	194.0	16739.6
1.3	120.8	183.8	18289.6	1.3	110.7	195.5	18132.0
	132.9	178.8	20483.1		131.3	179.3	21992.7
2	163.8	208.3	26469.4	2	157.1	241.3	27411.1
	170.4	198.2	27793.6		161.9	203.7	28478.9
	189.2	197.4	31514.8		190.4	187.3	34057.0
2.7	198.8	196.3	33414.1	2.7	193.7	191.8	34673.1
	211.6	195.3	35913.7		210.2	181.7	37757.3
	221.2	192.0	37769.6		220.1	186.6	39592.3
3.3	240.4	186.6	41413.8	3.3	230.9	190.5	41612.6
	259.3	172.1	44794.5		258.2	191.6	46834.8
4	282.4	185.6	48935.0	4	273.0	193.7	49686.5
	311.9	187.1	54424.4		313.1	185.7	57294.2
5	338.9	184.6	59440.1	5	331.0	188.6	60653.7
	348.5	161.8	61114.3		347.3	164.5	63517.1
	379.2	26.7	64003.3		379.2	7.0	66254.0
6	439.9	-	65124.4	6	490.0	-	66722.9
	444.0	10.2	65200.3		526.8	1.5	66878.6
		† ~1.2 L	66405.3			† ~ 1.0 L	67693.6

Table C-21. Influent flow measurements of both vegetated columns for run 11. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Exp. Flow and Ctrl. Flow are the measured flowrates at a given time for the experimental and control column, respectively. V_e In and V_c In are the cumulative volume of influent applied to the experimental and control columns, respectively.

	Experimental Column			Control Column		
Sample ID	Runtime (min)	Exp. Flow (mL/min)	V_e In (mL)	Runtime (min)	Ctrl. Flow (mL/min)	V_c In (mL)
	2.6	172.0	441.2	5.9	172.7	1022.7
	6.6	183.5	1137.5	6.6	185.2	1141.6
0	9.0	-	1578.2	9.0	-	1587.2
	41.2	185.6	7524.3	39.4	188.1	7267.8
	79.5	185.9	14631.6	77.7	188.8	14473.2
	122.7	185.4	22651.4	119.4	188.7	22349.8
	152.5	185.0	28180.5	150.8	188.8	28273.6
3	170.9	-	31572.9	170.9	-	32065.3
	172.8	-	31930.7	172.8	-	32430.3

Table C-22. Effluent flow measurements of both vegetated columns for run 11. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Flow is the measured flowrate at a given time. Cum. V is the cumulative volume of effluent that the column produced. †: Volume of effluent collected between column runs.

Experimental Column				Control Column			
Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)	Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)
	27.5	158.7	2180.7		18.8	63.5	595.3
	30.3	188.1	2669.0		21.1	175.5	875.5
0	37.3	200.8	4033.3	0	26.5	-	1872.4
	45.2	171.2	5506.0		29.3	191.8	2374.3
0.25	53.6	168.4	6926.8		34.4	190.1	3361.4
	58.1	174.9	7690.6	0.25	43.8	181.6	5108.2
0.5	69.5	177.0	9707.9		54.8	191.6	7151.6
	74.3	177.3	10552.3	0.5	62.9	189.7	8705.5
0.75	81.9	175.0	11894.1		66.9	185.2	9449.0
	94.2	183.0	14090.3	0.75	73.3	190.5	10654.2
1	97.1	183.2	14630.5		83.1	183.0	12481.4
	113.2	187.5	17611.6	1	93.1	175.5	14271.0
1.3	117.1	186.7	18335.1		101.5	185.5	15793.1
	147.1	188.3	23972.7	1.3	111.6	180.5	17637.9
2	158.1	192.0	26061.0		133.8	187.0	21716.3

	177.1	151.2	29321.5	2	148.9	189.0	24551.6
	182.6	119.9	30067.1		156.6	182.5	25985.1
	198.2	38.1	31301.0		181.2	73.5	29139.1
3	249.9	-	32591.2		191.9	22.2	29649.5
	253.5	11.9	32680.8	3	334.4	-	31294.1
		~1.3 L	34000.8		383.4	0.9	31859.1
						~ 0.6 L	32496.1

Table C-23. Influent flow measurements of both vegetated columns for run 12. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Exp. Flow and Ctrl. Flow are the measured flowrates at a given time for the experimental and control column, respectively. V_e In and V_c In are the cumulative volume of influent applied to the experimental and control columns, respectively.

	Experimental Column			**Control Column**		
Sample ID	Runtime (min)	Exp. Flow (mL/min)	V_e In (mL)	Runtime (min)	Ctrl. Flow (mL/min)	V_c In (mL)
	3.6	181.1	645.2	1.9	183.1	355.4
0	11.4	-	2087.8	11.4	-	2124.2
	45.1	186.6	8276.9	43.3	190.4	8076.3
	74.5	186.0	13754.3	69.8	190.6	13123.9
	120.1	184.5	22197.3	118.0	188.0	22249.8
	144.9	185.3	26786.6	143.1	190.5	26999.3
3	167.1	-	30906.2	164.8	186.0	31074.2
	169.8	184.7	31393.5	167.1	-	31517.4
	171.7	-	31750.5	171.7	-	32366.6

Table C-24. Effluent flow measurements of both vegetated columns for run 12. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Flow is the measured flowrate at a given time. Cum. V is the cumulative volume of effluent that the column produced. †: Volume of effluent collected between column runs.

Experimental Column				**Control Column**			
Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)	Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)
	9.7	11.0	53.6		17.8	115.6	1026.7
	27.1	16.7	293.1		19.0	171.6	1200.6
	28.3	192.6	423.8	0	24.5	203.8	2232.1

0	34.6	-	1670.5		29.6	187.5	3226.6
	36.5	205.5	2045.3		33.6	189.7	3996.3
	41.7	193.4	3082.3	0.25	40.7	186.0	5314.5
0.25	51.9	171.4	4954.9	0.5	57.6	189.2	8497.5
	58.9	174.4	6153.7		64.1	193.4	9740.7
0.5	67.5	173.9	7660.0	0.75	72.0	180.5	11204.8
0.75	81.2	182.0	10097.9		83.0	189.9	13247.7
	86.7	176.8	11078.6	1	85.6	185.9	13745.6
1	96.2	182.7	12795.4		97.3	184.3	15911.0
	108.4	182.0	15023.1	1.3	106.2	189.8	17569.2
1.3	115.9	183.2	16386.2		122.8	181.1	20653.5
	123.9	183.9	17857.4		138.4	198.3	23610.0
	139.4	197.6	20816.8	2	149.0	189.0	25662.8
2	155.6	-	24113.7		162.0	201.4	28190.6
	157.4	210.3	24480.8		175.8	155.6	30662.9
	161.0	193.8	25198.1		182.1	58.1	31337.7
	174.8	182.9	27800.2		188.4	29.1	31612.2
	179.9	134.3	28614.4	3	290.7	-	33170.7
	199.0	34.9	30228.0		364.7	1.4	34299.2
3	256.8	-	31981.7			† ~ 0.8 L	35082.2
	276.8	25.7	32586.2				
		† ~1.1 L	33731.2				

Table C-25. Influent flow measurements of both vegetated columns for run 13. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Exp. Flow and Ctrl. Flow are the measured flowrates at a given time for the experimental and control column, respectively. V_e In and V_c In are the cumulative volume of influent applied to the experimental and control columns, respectively.

	Experimental Column			**Control Column**		
Sample ID	Runtime (min)	Exp. Flow (mL/min)	V_e In (mL)	Runtime (min)	Ctrl. Flow (mL/min)	V_c In (mL)
	3.2	196.6	619.4	1.6	198.6	310.6
	4.0	183.9	784.8	4.0	179.0	768.9
0	22.6	-	4209.3	22.6	-	4182.8
	45.1	183.5	8333.3	41.4	187.2	7622.6
	78.7	180.5	14441.4	77.0	184.7	14236.9
	102.8	181.5	18808.8	101.0	185.5	18682.4
	136.0	185.2	24896.5	134.2	189.6	24900.2

	174.4	182.4	31955.7	172.6	185.6	32110.7
3	185.7	-	34010.1	185.7	-	34532.4
	204.4	181.7	37420.8	202.6	184.6	37660.6
	241.0	180.5	44046.8	239.2	184.4	44415.9
	274.2	181.9	50060.6	272.4	185.2	50553.0
	304.2	179.2	55474.3	302.3	182.7	56058.2
	332.5	178.4	60543.6	330.8	183.0	61259.3
6	347.6	-	63239.5	347.6	-	64308.3
	349.2	179.0	63528.4	347.2	180.0	64241.7
	350.5	-	63764.1	350.5	-	64835.8

Table C-26. Effluent flow measurements of both vegetated columns for run 13. Sample ID is provided if a sample was taken concurrently with measured flow. Runtime is the time of the measurement taken relative to the commencement of inflow. Flow is the measured flowrate at a given time. Cum. V is the cumulative volume of effluent that the column produced. †: Volume of effluent collected between column runs.

Experimental Column				**Control Column**			
Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)	Sample ID	Runtime (min)	Flow (mL/min)	Cum. V (mL)
	10.2	66.0	337.4		16.4	11.0	90.4
	26.5	6.7	928.1		17.7	81.1	149.9
	28.2	177.5	1084.3		19.9	151.5	411.2
	30.5	190.4	1506.6		21.0	187.1	591.4
0	35.5	-	2442.3	0	26.5	-	1612.3
	39.5	178.9	3184.1		29.4	186.0	2157.9
	49.3	155.2	4818.7		34.4	181.3	3073.3
0.25	51.6	-	5179.3	0.25	43.1	-	4690.4
	53.8	165.4	5532.0		48.0	191.2	5615.4
	59.1	171.6	6422.1		52.7	191.6	6505.5
0.5	67.4	-	7835.1	0.5	58.2	-	7550.5
	69.7	166.2	8212.3		60.1	189.5	7928.4
	74.2	174.7	8987.9		66.9	178.7	9174.3
0.75	81.3	-	10239.3	0.75	73.2	-	10301.0
	83.3	177.8	10585.9		75.3	181.8	10688.6
	89.1	183.0	11635.3	1	87.4	-	12908.2
1	96.1	-	12912.2		90.1	184.0	13399.1
	98.8	180.1	13390.3		97.3	182.3	14721.1
	111.3	179.7	15641.9	1.3	110.3	189.8	17133.3
1.3	118.4	179.1	16915.6		130.5	179.6	20867.3
	138.1	175.5	20411.3	2	153.1	186.2	24989.3

2	160.8	-	24512.8		161.8	188.4	26628.2
	163.0	185.9	24904.3		183.1	188.4	30643.9
	170.9	174.4	26330.2	2.7	189.3	-	31799.0
	184.4	174.9	28684.7		191.3	187.3	32171.5
2.7	200.3	179.6	31514.9		207.3	181.7	35126.0
	212.5	178.9	33702.3		219.0	186.0	37286.2
	221.8	178.5	35352.4	3.3	229.5	186.2	39243.7
3.3	237.5	178.8	38171.7		250.2	180.6	43031.2
	251.2	173.0	40578.2	4	268.3	-	46316.2
4	278.5	177.9	45365.0		270.4	182.7	46703.8
	288.2	174.2	47064.1		280.7	182.3	48577.6
	299.7	178.8	49096.8		298.6	181.5	51836.6
	310.5	174.6	51010.8		309.5	171.0	53757.6
	323.4	176.0	53277.9		322.4	177.8	56013.0
5	337.6	171.9	55744.9	5	327.8	-	56975.6
	345.6	173.0	57118.7		334.0	183.2	58103.7
	356.0	139.4	58743.4		344.6	179.1	60026.9
	365.4	64.9	59705.6		354.9	158.5	61754.5
	371.1	44.9	60019.7		363.3	36.2	62574.0
	384.5	18.4	60444.4		369.4	22.9	62753.9
6	485.4	-	61647.0		373.2	18.0	62831.6
	499.0	5.4	61808.3	6	530.1	-	64340.9
		† ~1.2 L	62998.3		570.3	1.3	64727.4
						† ~ 0.8 L	65527.4

Appendix D: Vegetated Column Contaminant Data

Table D-1. Influent characteristics for vegetated column run 1. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	6.42	0.2	-	115.3	-	0.74	< 2	0.93	n.d.
3	6.22	0.4	-	119.9	-	0.74	< 2	0.93	n.d.
5.5	6.24	0.5	-	116.0	-	-	< 2	1.07	-

Table D-2. Effluent characteristics for experimental vegetated column run 1.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	7.37	0.2	-	70.0	20.4	2.00	> 25	1.68	> 25
0.3	6.14	6.3	-	66.8	11.3	-	-	-	-
0.7	7.26	0.2	-	58.0	< 10.0	-	-	-	-
1	-	-	-	-	-	0.76	9.2	-	> 25
1.3	7.19	1.0	-	17.6	< 10.0	-	-	-	-
2	7.27	1.2	-	16.9	< 10.0	0.82	10.7	-	> 25
2.7	7.21	1.0	-	14.8	-	-	-	-	-
3.3	7.17	0.9	-	16.2	-	-	-	-	-
4	7.19	0.7	-	15.5	9.8	0.78	14.6	0.47	> 25
5	7.15	0.8	-	15.5	-	-	-	-	-
6	7.22	0.7	-	13.4	< 10.0	-	21.5	0.33	-

Table D-3. Effluent characteristics for control vegetated column run 1.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	6.53	155	-	593.0	336.4	0.53	> 25	2.15	16.1
0.3	6.31	20.8	-	251.7	204.5	-	-	-	-
0.7	6.36	8.1	-	185.4	153.7	-	-	-	-
1	-	-	-	-	-	0.79	23.1	-	30.5
1.3	6.28	3.2	-	147.0	129.2	-	-	-	
2	6.36	2.6	-	127.9	103.4	0.74	23.1	0.65	12.8
2.7	6.36	2.5	-	121.2	-	-	-	-	-
3.3	6.17	3.1	-	117.9	-	-	-	-	-
4	6.18	4.8	-	116.6	92.1	0.73	25.4	-	3.1

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
5	6.24	8.7	-	118.6	92.1	-	-	-	-
6	6.24	2.6	-	131.8	111.3	-	> 25	0.65	-

Table D-4. Influent characteristics for vegetated column run 2. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	5.68	0.3	-	113.1	-	0.69	< 2	1.03	n.d.
3	6.1	1.2	-	111.2	-	0.60	< 2	0.98	n.d.
5.5	6.03	0.3	-	109.8	-	0.82	< 2	1.21	n.d.

Table D-5. Effluent characteristics for experimental vegetated column run 2.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	7.02	1.2	-	37.5	15.1	0.22	2.0	0.79	> 25
0.25	7.09	1.9	-	59.2	-	-	-	-	-
0.5	7.16	1.4	-	45.4	20.3	0.45	2.4	-	> 25
0.75	7.05	1.4	-	30.9	-	-	-	-	-
1	-	-	-	-	0.7	3.28	-	-	> 25
1.3	7.04	0.8	-	28.9	-	-	-	-	-
2	7.09	1.3	-	16.4	< 10.0	0.58	5.8	0.42	> 25
2.7	7.01	0.7	-	11.1	-	-	-	-	-
3.3	7.04	0.7	-	10.5	-	-	-	-	-
4	7.05	0.6	-	15.7	< 10.0	1.01	8.0	-	> 25
5	6.98	0.7	-	8.5	-	-	-	-	-
6	7.1	0.4	-	10.5	< 10.0	0.71	10.1	0.33	> 25
7	7.29	1.2	-	< 10.0	-	-	-	-	-

Table D-6. Effluent characteristics for control vegetated column run 2.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	6.29	12.5	-	222.9	166.0	0.29	4.6	1.49	2.7

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0.25	6.16	18.0	-	232.6	155.6	-	-	-	-
0.5	6.1	21.5	-	216.4	134.2	0.46	4.6	-	4.0
0.75	6.1	23.0	-	193.8	111.6	-	-	-	-
1	-	-	-	-	-	0.55	5.0	-	1.8
1.3	6.13	22.2	-	157.5	88.3	-	-	-	-
2	6.11	35.3	-	186.0	91.5	0.72	4.6	0.84	0.9
2.7	6.17	24.8	-	140.1	74.1	-	-	-	-
3.3	6.12	25.9	-	131.7	74.1	-	-	-	-
4	6.17	25.7	-	129.7	76.0	0.68	4.6	-	0.5
5	6.12	28.5	-	122.6	75.4	-	-	-	-
6	6.33	23.8	-	120.7	76.6	0.67	5.8	0.56	0.5
7	6.46	8.5	-	87.6	74.1	-	-	-	-

Table D-7. Influent characteristics for vegetated column run 3. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	6.28	0.5	-	119.0	-	0.92	< 2	1.03	n.d.
3	4.32	0.4	-	123.5	-	0.72	< 2	1.12	n.d.
5.5	6.14	0.5	-	117.7	-	0.76	< 2	1.03	n.d.

Table D-8. Effluent characteristics for experimental vegetated column run 3.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	6.83	1.2	-	37.8	14.4	0.30	< 2	0.09	> 25
0.25	6.83	1.4	-	44.3	-	-	-	-	-
0.5	6.89	1.0	-	41.7	11.1	0.48	2.3	-	> 25
0.75	6.92	1.0	-	28.0	-	-	-	-	-
1	-	-	-	-	-	0.58	3.6	-	> 25
1.3	6.91	0.9	-	19.6	-	-	-	-	-
2	6.9	0.7	-	22.2	< 10.0	0.54	6.5	0.51	24.1
2.7	6.88	0.8	-	12.4	-	-	-	-	-
3.3	6.9	0.7	-	12.4	-	-	-	-	-
4	6.88	0.6	-	12.4	< 10.0	0.59	6.5	-	13.2

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
5	6.86	1.5	-	11.1	-	-	-	-	-
6	7.19	1.1	-	14.4	< 10.0	0.61	5.2	0.28	12.9

Table D-9. Effluent characteristics for control vegetated column run 3. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	6.06	38.8	-	269.1	164.1	0.37	10.2	1.45	0.6
0.25	6.08	32.0	-	245.4	154.0	-	-	-	-
0.5	6.11	33.6	-	230.0	130.0	0.48	7.3	-	1.0
0.75	6.06	26.1	-	196.4	118.4	-	-	-	-
1	-	-	-	-	-	0.53	7.3	-	0.5
1.3	6.12	25.7	-	160.1	91.5	-	-	-	-
2	6.16	25.3	-	159.4	85.5	0.50	6.5	1.21	n.d.
2.7	6.12	22.5	-	140.6	77.4	-	-	-	-
3.3	6.06	24.9	-	139.2	83.5	-	-	-	-
4	6.08	23.9	-	139.9	85.5	0.55	5.2	-	n.d.
5	6.2	31.9	-	132.5	83.5	-	-	-	-
6	6.51	25.6	-	138.6	88.9	0.49	4.0	0.61	n.d.

Table D-10. Influent characteristics for vegetated column run 4. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	6.26	0.5	-	114.9	-	0.79	< 2	1.12	n.d.
3	3.88	0.5	-	111.0	-	0.73	< 2	1.07	n.d.
6	6.17	1.3	-	114.9	-	0.71	< 2	-	n.d.

Table D-11. Effluent characteristics for experimental vegetated column run 4.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	6.68	0.8	-	24.5	< 10.0	0.12	< 2	0.28	25.1

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0.25	6.68	1.1	-	27.7	-	-	-	-	-
0.5	6.66	1.0	1.69	27.5	< 10.0	0.39	2.1	-	27.3
0.75	6.65	0.8	-	19.3	-	-	-	-	-
1	-	-	-	-	-	0.48	3.7	-	21.7
1.3	6.63	0.8	1.52	15.4	-	-	-	-	-
2	6.78	1.0	1.46	11.5	< 10.0	0.48	6.6	0.47	15.0
2.7	6.73	0.7	-	10.2	-	-	-	-	-
3.3	6.79	1.0	1.43	8.2	-	-	-	-	-
4	6.79	0.5	1.42	< 10.0	< 10.0	0.54	5.4	-	9.8
5	6.70	0.8	1.40	7.6	-	-	-	-	-
6	6.79	1.0	1.37	10.5	< 10.0	0.61	5.0	0.37	7.5
7	7.01	1.7	1.41	< 10.0	-	-	-	-	-

Table D-12. Effluent characteristics for control vegetated column run 4.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	6.1	47.5	-	313.1	206.3	0.36	17.5	1.45	1.1
0.25	6.03	35.2	-	262.4	173.5	-	-	-	-
0.5	5.98	37.1	1.45	248.0	159.1	0.60	14.2	-	0.6
0.75	5.98	32.4	-	214.5	135.1	-	-	-	-
1	-	-	-	-	-	0.53	11.7	-	0.6
1.3	6	31.0	1.32	179.3	113.6	-	-	-	-
2	6.12	34.8	1.26	196.2	104.9	0.52	10.4	1.03	0.4
2.7	6.07	32.2	-	168.3	104.5	-	-	-	-
3.3	6.14	31.2	1.29	161.8	101.9	-	-	-	-
4	6.12	38.2	1.3	208.3	105.9	0.54	11.2	-	0.4
5	6.04	31.7	1.31	161.1	103.9	-	-	-	-
6	6.18	36.3	1.28	197.2	106.9	0.59	8.3	0.70	0.4
7	6.72	33.7	1.31	180.2	-	-	-	-	-

Table D-13. Influent characteristics for vegetated column run 5. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	6.29	0.3	1.32	120.9	-	0.77	< 2	0.70	n.d.
3	6.06	0.3	1.31	115.7	-	0.73	< 2	1.17	n.d.
6	6.01	0.8	1.31	121.5	-	0.73	< 2	1.21	n.d.

Table D-14. Effluent characteristics for experimental vegetated column run 5.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	6.64	1.1	1.53	16.3	9.7	0.09	< 2	0.47	15.8
0.25	6.64	1.2	1.56	21.6	-	-	-	-	-
0.5	6.66	0.7	1.55	20.9	< 10.0	0.40	2.1	-	15.4
0.75	6.59	0.9	1.53	14.9	-	-	-	-	-
1	-	-	-	-	-	0.47	3.8	-	12.7
1.3	6.63	1.1	1.48	10.3	-	-	-	-	-
2	6.62	0.6	1.41	9.7	< 10.0	0.50	6.2	0.37	8.9
2.7	6.68	0.5	1.38	< 10.0	-	-	-	-	-
3.3	6.65	0.6	1.38	< 10.0	-	-	-	-	-
4	6.68	0.7	1.37	9.0	< 10.0	0.52	6.2	-	5.9
5	6.64	0.5	1.34	< 10.0		-	-	-	-
6	6.74	0.6	1.36	10.3	< 10.0	0.55	6.2	0.33	5.1

Table D-15. Effluent characteristics for control vegetated column run 5. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	6.11	57.6	1.58	378.1	191.0	1.01	34.3	2.29	0.7
0.25	6.09	50.0	1.47	294.7	166.6	-	-	-	-
0.5	6.13	38.2	1.41	247.3	152.0	0.92	18.8	-	0.5
0.75	6.05	33.3	1.39	211.9	124.8	-	-	-	-
1	-	-	-	-	-	0.73	20.8	-	0.4
1.3	6.03	30.4	1.33	174.6	104.6	-	-	-	-
2	6.1	31.7	1.31	168.5	103.7	0.59	11.9	0.89	0.4
2.7	6.07	28.8	1.28	155.0	96.0	-	-	-	-

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
3.3	6.02	29.7	1.29	155.6	93.4	-	-	-	-
4	6.08	25.9	1.28	155.3	132.8	0.57	39.1	-	n.d.
5	6.2	26.9	1.31	143.8	98.0	-	-	-	-
6	6.41	31.1	1.28	163.9	102.4	0.59	9.0	0.83	n.d.

Table D-16. Influent characteristics for vegetated column run 6. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
Step 1	-	-	-	174.5	-	-	-	-	-
Step 2	5.14	0.4	1.34	152.5	-	1.01	< 2	1.35	n.d.
Step 3	-	-	-	130.9	-	-	-	-	-
Step 4	-	-	-	109.1	-	-	-	-	-
Step 5	6.08	0.7	1.36	88.5	-	0.56	< 2	0.93	n.d.
Step 6	5.99	0.5	1.36	68.5	-	0.43	< 2	0.67	n.d.

Table D-17. Effluent characteristics for experimental vegetated column run 6.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	6.53	1.7	1.66	21.8	9.1	0.21	< 2	0.51	11.8
0.25	6.5	1.5	1.62	29.6	-	-	-	-	-
0.5	6.56	1.1	1.55	21.1	< 10.0	0.77	2.9	-	9.3
0.75	6.52	0.8	1.51	14.3	-	-	-	-	-
1	-	-	-	-	-	0.75	3.4	-	7.1
1.3	6.57	1.0	1.49	13.0	-	-	-	-	-
2	6.59	0.6	1.42	< 10.0	< 10.0	0.59	6.2	0.65	5.3
2.7	6.59	0.8	1.40	< 10.0	-	-	-	-	-
3.3	6.65	0.8	1.42	10.4	-	-	-	-	-
4	6.5	1.1	1.34	9.8	< 10.0	0.42	7.0	-	4.4
5	6.56	0.8	1.35	10.4	-	-	-	-	-
6	6.7	1.4	1.45	9.8	< 10.0	0.23	2.9	0.37	4.8

Table D-18. Effluent characteristics for control vegetated column run 6. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	6.1	61.7	1.64	509.3	247.7	1.15	23.6	2.01	0.4
0.25	6.06	43.0	1.52	313.7	150.2	-	-	-	-
0.5	6	28.0	1.44	235.3	127.9	0.92	12.3	-	n.d.
0.75	5.96	22.9	1.37	196.6	105.2	-	-	-	-
1	-	-	-	-	-	0.80	10.6	-	n.d.
1.3	6.06	31.1	1.38	179.4	85.3	-	-	-	-
2	5.94	24.5	1.34	152.5	81.2	0.62	10.6	0.84	n.d.
2.7	6.19	29.3	1.34	150.9	76.0	-	-	-	-
3.3	6.24	33.1	1.32	153.5	88.6	-	-	-	-
4	6.01	28.1	1.29	150.5	88.5	0.44	8.2	-	n.d.
5	6.19	34.6	1.3	146.9	84.6	-	-	-	-
6	6.35	35.3	1.31	157.2	94.5	0.33	8.6	0.75	n.d.

Table D-19. Influent characteristics for vegetated column run 7. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	6.08	0.4	1.29	277.0	-	2.18	< 2	2.38	n.d.
3	5.86	0.4	1.31	315.1	-	2.14	< 2	2.52	n.d.
6	4.14	0.3	1.36	346.8	-	2.31	< 2	2.90	n.d.

Table D-20. Effluent characteristics for experimental vegetated column run 7.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	6.43	0.9	1.49	13.8	< 10.0	0.18	< 2	0.37	8.9
0.25	6.48	1.6	1.61	28.5	-	-	-	-	-
0.5	6.43	0.9	1.53	29.8	< 10.0	1.94	2.5	-	8.6
0.75	6.39	1.3	1.52	22.8	-	-	-	-	-
1	-	-	-	-	-	1.91	3.8	-	7.7
1.3	6.42	1.0	1.46	17.0	-	-	-	-	-
2	6.54	0.6	1.40	15.7	< 10.0	1.87	6.6	0.65	5.7
2.7	6.38	0.6	1.36	15.1	-	-	-	-	-

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
3.3	6.45	0.9	1.36	10.0	-	-	-	-	-
4	6.37	0.5	1.34	10.6	< 10.0	1.99	7.8	-	3.8
5	6.62	0.5	1.35	10.6	-	-	-	-	-
6	6.95	1.3	1.32	15.1	< 10.0	2.17	10.2	0.98	3.2

Table D-21. Effluent characteristics for control vegetated column run 7. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	6.17	71.7	1.66	864.3	527.8	1.57	25.2	2.52	n.d.
0.25	6.11	57.0	1.53	608.1	358.4	-	-	-	-
0.5	6.08	37.7	1.45	505.5	289.7	1.94	21.2	-	n.d.
0.75	6.11	32.3	1.41	446.9	257.3	-	-	-	-
1	-	-	-	-	-	1.89	20.4	-	n.d.
1.3	6.02	26.6	1.35	358.4	218.1	-	-	-	-
2	5.92	26.4	1.32	245.2	151.9	1.95	20.0	1.40	n.d.
2.7	6.07	24.7	1.31	200.2	110.5	-	-	-	-
3.3	6.18	19.3	1.29	151.5	95.8	-	-	-	-
4	6.05	17.2	1.29	152.6	99.9	2.00	15.5	-	n.d.
5	6	16.9	1.29	132.3	117.6	-	-	-	-
6	6.41	21.1	1.32	133.5	83.4	2.49	17.5	1.37	n.d.

Table D-22. Influent characteristics for vegetated column run 8. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	5.76	0.4	1.27	111.5	-	0.69	< 2	1.31	n.d.
3	5.69	0.6	1.27	123.1	-	0.68	< 2	1.40	n.d.
6	5.72	0.4	1.28	118.6	-	0.73	< 2	1.04	n.d.

Table D-23. Effluent characteristics for experimental vegetated column run 8.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	6.28	0.9	1.46	13.8	9.9	0.44	2.1	0.75	5.8
0.25	6.38	1.5	1.57	30.4	-	-	-	-	-
0.5	6.45	1.5	1.52	25.9	9.1	3.00	2.5	-	6.3
0.75	6.43	1.3	1.46	18.1	-	-	-	-	-
1	-	-	-	-	-	1.15	2.1	-	5.3
1.3	6.36	1.5	1.36	14.9	-	-	-	-	-
2	6.45	1.1	1.35	15.7	< 10.0	0.63	4.2	0.84	3.8
2.7	6.39	0.9	1.33	16.8	-	-	-	-	-
3.3	6.4	0.9	1.33	10.4	-	-	-	-	-
4	6.41	1.7	1.48	< 10.0	-	0.67	5.0	-	2.7
5	6.46	0.9	1.32	9.1	-	-	-	-	-
6	-	-	-	13.8	< 10.0	0.65	5.4	0.47	2.3

Table D-24. Effluent characteristics for control vegetated column run 8. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	6.13	66.6	1.58	708.8	373.6	2.68	15.9	2.80	n.d.
0.25	6.04	47.2	1.5	492.4	243.7	-	-	-	-
0.5	6.15	35.2	1.44	413.8	225.6	2.09	14.3	-	n.d.
0.75	6.07	29.0	1.35	339.1	199.2	-	-	-	-
1	-	-	-	-	-	1.16	12.7	-	n.d.
1.3	5.99	25.5	1.29	199.2	84.5	-	-	-	-
2	6.06	21.7	1.28	126.4	41.9	0.77	9.8	1.07	n.d.
2.7	5.97	18.1	1.29	81.3	32.9	-	-	-	-
3.3	6.14	15.7	1.26	78.0	42.0	-	-	-	-
4	6.18	16.1	1.28	84.5	49.7	0.69	7.4	-	n.d.
5	6.13	13.1	1.27	87.7	63.2	-	-	-	-
6	-	-	-	93.1	65.6	0.69	8.2	1.10	n.d.

Table D-25. Influent characteristics for vegetated column run 9. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
Step 1	5.92	-	-	476.3	-	3.44	-	-	n.d.
Step 2	6.06	0.5	1.35	436.8	-	3.20	< 2	3.03	n.d.
Step 3	6.05	-	-	373.4	-	2.66	-	-	n.d.
Step 4	4.55	-	-	329.3	-	2.48	-	-	n.d.
Step 5	6.28	0.9	1.35	249.9	-	1.81	< 2	2.24	n.d.
Step 6	6.23	1.1	1.36	200.5	-	1.46	< 2	1.73	n.d.

Table D-26. Effluent characteristics for experimental vegetated column run 9.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	6.12	1.5	1.62	39.3	10.4	0.54	< 2	0.56	6.8
0.25	6.29	1.8	1.65	48.2	-	-	-	-	-
0.5	6.39	1.8	1.59	39.6	11.7	3.14	1.7	-	6.0
0.75	6.26	1.2	1.49	25.1	-	-	-	-	-
1	-	-	-	-	-	2.56	2.9	-	4.6
1.3	6.25	1.1	1.41	14.9	-	-	-	-	-
2	6.42	1.1	1.35	23.0	< 10.0	2.29	5.6	1.21	3.2
2.7	6.37	1.4	1.37	15.5	-	-	-	-	-
3.3	6.41	1.2	1.36	15.5	-	-	-	-	-
4	6.52	1.1	1.35	23.0	< 10.0	1.80	8.3	-	2.8
5	6.58	1.4	1.45	18.7	-	-	-	-	-
6	6.67	1.4	1.39	17.0	< 10.0	1.76	9.5	0.47	3.4

Table D-27. Effluent characteristics for control vegetated column run 9. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	6.07	72.8	1.69	894.2	466.9	2.50	19.2	2.61	n.d.
0.25	5.93	58.6	1.56	544.8	284.5	-	-	-	-
0.5	5.96	30.3	1.42	325.0	302.4	2.65	13.4	-	n.d.
0.75	5.94	25.7	1.38	253.8	137.3	-	-	-	-
1	-	-	-	-	-	2.56	14.9	-	n.d.
1.3	6.03	33.2	1.37	150.6	77.0	-	-	-	-

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
2	6.01	24.0	1.31	113.2	40.3	2.25	16.1	1.49	n.d.
2.7	6.17	26.2	1.32	89.1	28.3	-	-	-	-
3.3	6.11	27.6	1.31	82.7	27.7	-	-	-	-
4	6.23	24.0	1.36	83.3	29.9	1.80	24.7	-	n.d.
5	6.06	26.7	1.34	82.1	33.5	-	-	-	-
6	6.22	25.4	1.33	98.7	41.5	1.50	36.4	0.84	n.d.

Table D-28. Influent characteristics for vegetated column run 10. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	6.04	0.8	1.23	70.6	-	0.51	< 2	0.75	n.d.
3	5.96	-	1.23	66.6	-	0.51	< 2	0.84	n.d.
6	5.92	0.6	1.28	68.0	-	0.54	< 2	0.84	n.d.

Table D-29. Effluent characteristics for experimental vegetated column run 10.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)	SRP (µg P/L)
0	6.31	2.0	1.41	14.7	< 10.0	0.32	< 2	0.37	4.5	< 10.0
0.25	6.28	1.6	1.40	33.2	-	-	-	-	-	-
0.5	6.4	0.9	1.38	29.8	< 10.0	1.93	< 2	-	4.1	< 10.0
0.75	6.29	1.6	1.35	28.7	-	-	-	-	-	-
1	-	-	-	-	-	1.22	< 2	-	3.6	-
1.3	6.34	-	1.31	20.3	-	-	-	-	-	-
2	6.32	0.7	1.31	16.0	< 10.0	0.60	< 2	0.37	2.9	< 10.0
2.7	6.35	0.8	1.29	14.5	-	-	-	-	-	-
3.3	6.27	0.9	1.27	11.9	-	-	-	-	-	-
4	6.3	0.6	1.29	12.0	< 10.0	0.45	< 2	-	2.0	< 10.0
5	6.31	1.5	1.28	9.4	-	-	-	-	-	-
6	6.49	0.8	1.32	13.3	< 10.0	0.40	< 2	0.37	1.9	< 10.0

Table D-30. Effluent characteristics for control vegetated column run 10. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)	SRP (µg P/L)
0	6.05	63.1	1.53	1228.1	790.3	3.65	17.1	2.43	n.d.	782.1
0.25	6.02	50.0	1.38	680.9	338.8	-	-	-	-	-
0.5	6.03	39.9	1.33	589.8	306.6	1.92	17.5	-	n.d.	307.9
0.75	6.12	30.4	1.3	400.9	280.1	-	-	-	-	-
1	-	-	-	-	-	1.47	18.4	-	n.d.	-
1.3	6.03	-	1.27	326.0	212.8	-	-	-	-	-
2	6.06	21.3	1.23	234.4	146.5	0.65	15.1	0.65	n.d.	141.1
2.7	5.93	20.6	1.23	161.9	100.1	-	-	-	-	-
3.3	6.05	18.0	1.23	127.2	74.4	-	-	-	-	-
4	5.9	15.6	1.27	104.8	56.4	0.49	9.4	-	n.d.	52.0
5	5.97	17.7	1.28	83.4	51.9	-	-	-	-	-
6	5.83	14.4	1.29	89.0	33.8	0.43	13.5	0.56	n.d.	29.5

Table D-31. Influent characteristics for vegetated column run 11. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	5.21	0.3	1.28	113.1	-	1.90	< 2	1.03	n.d.
3	6.15	0.4	1.28	114.5	-	0.92	< 2	1.03	n.d.

Table D-32. Effluent characteristics for experimental vegetated column run 11.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	6.15	1.4	1.49	23.7	< 10.0	0.24	< 2	0.33	4.0
0.25	6.14	1.0	1.48	24.3	-	-	-	-	-
0.5	6.27	1.2	1.45	25.0	< 10.0	1.06	< 2	-	3.5
0.75	-	-	-	-	-	1.01	< 2	-	3.4
1	6.11	0.8	1.38	14.9	-	-	-	-	-
1.3	6.21	0.6	1.36	12.9	-	-	-	-	-
2	6.3	0.9	1.34	13.6	< 10.0	0.86	< 2	-	2.5
3	6.37	1.4	1.35	12.2	< 10.0	0.72	< 2	0.33	2.4

Table D-33. Effluent characteristics for control vegetated column run 11. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	6.01	89.3	1.55	2108.4	890.1	0.91	21.2	2.05	n.d.
0.25	5.89	65.1	1.44	843.4	453.7	-	-	-	-
0.5	5.9	49.6	1.38	665.7	475.5	0.84	18.4	-	n.d.
0.75	-	-	-	-	-	0.76	18.4	-	n.d.
1	5.9	38.6	1.32	491.1	310.3	-	-	-	-
1.3	5.83	32.0	1.3	416.3	238.6	-	-	-	-
2	5.91	23.8	1.3	307.2	257.3	0.90	17.5	-	n.d.
3	6.27	24.7	1.28	238.6	294.7	0.67	35.7	0.75	n.d.

Table D-34. Influent characteristics for vegetated column run 12. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	5.42	0.6	1.28	122.8	-	0.74	< 2	1.12	n.d.
3	6.18	0.4	1.33	120.8	-	0.92	< 2		n.d.

Table D-35. Effluent characteristics for experimental vegetated column run 12.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	6.09	1.4	1.38	14.7	< 10.0	0.10	< 2	0.37	3.3
0.25	6.06	0.8	1.42	18.0	-	-	-	-	-
0.5	6.13	0.7	1.39	16.0	< 10.0	0.99	< 2	-	2.7
0.75	6.14	0.9	1.39	12.7	-	-	-	-	-
1	-	-	-	-	-	0.80	< 2	-	2.6
1.3	6.11	0.4	1.36	< 10.0	-	-	-	-	-
2	6.14	0.6	1.35	< 10.0	< 10.0	0.65	< 2	-	2.2
3	6.39	0.5	1.36	< 10.0	< 10.0	0.60	< 2	0.28	2.0

Table D-36. Effluent characteristics for control vegetated column run 12. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	5.94	96.3	1.44	1130.5	591.0	1.02	14.3	1.68	n.d.
0.25	6.04	65.0	1.45	683.6	387.4	-	-	-	-
0.5	6.18	51.2	1.39	560.2	347.3	1.05	18.8	-	n.d.
0.75	6.18	40.4	1.34	470.7	313.4	-	-	-	-
1	-	-	-	-	-	0.75	18.8	-	2.8
1.3	6.16	29.4	1.31	313.4	214.9	-	-	-	-
2	6.13	24.8	1.3	216.3	144.0	0.69	16.7	-	0.2
3	6.24	23.0	1.34	149.3	83.0	0.55	28.6	0.84	n.d.

Table D-37. Influent characteristics for vegetated column run 13. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	6.36	0.3	1.31	123.8	-	0.69	< 2	1.03	n.d.
3	6.14	0.4	1.30	121.8	-	0.69	< 2	0.98	n.d.
6	6.12	0.5	1.33	120.4	-	0.73	< 2	1.12	n.d.

Table D-35. Effluent characteristics for experimental vegetated column run 12.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO_3^- (mg N/L)	NO_2^- (µg N/L)	TKN (mg N/L)	SO_4^{2-} (mg SO_4^{2-}/L)
0	6.14	1.4	1.49	22.7	-	0.18	< 2	0.56	3.4
0.25	6.17	1.0	1.44	25.3	-	-	-	-	-
0.5	6.21	1.0	1.45	20.7	-	1.13	< 2	-	2.9
0.75	6.15	0.7	1.43	17.9	-	-	-	-	-
1	-	-	-	-	-	0.79	< 2	-	2.7
1.3	6.14	0.6	1.38	11.8	-	-	-	-	-
2	6.19	0.5	1.35	14.0	< 10.0	0.71	< 2	0.19	2.2
2.7	6.14	0.5	1.34	< 10.0	-	-	-	-	-
3.3	6.09	0.4	1.35	< 10.0	-	-	-	-	-
4	6.15	0.5	1.35	< 10.0	< 10.0	0.72	< 2	-	1.5
5	6.26	0.6	1.35	< 10.0	-	-	-	-	-
6	6.37	0.7	1.37	< 10.0	< 10.0	0.69	< 2	0.23	1.5

Table D-39. Effluent characteristics for control vegetated column run 13. N.D.: Not detected.

Sample ID	pH	Turbidity (NTU)	Conductance (mmhos)	TP (µg P/L)	TDP (µg P/L)	NO$_3^-$ (mg N/L)	NO$_2^-$ (µg N/L)	TKN (mg N/L)	SO$_4^{2-}$ (mg SO$_4^{2-}$/L)
0	5.97	97.0	1.57	1169.4	685.9	0.98	20.0	2.15	0.2
0.25	5.92	60.4	1.49	809.8	391.5	-	-	-	-
0.5	5.9	50.2	1.42	645.7	374.8	0.74	21.9	-	0.5
0.75	5.92	41.8	1.39	572.5	278.1	-	-	-	-
1	-	-	-	-	-	0.75	23.1	-	0.2
1.3	5.96	31.6	1.35	409.5	197.4	-	-	-	-
2	5.91	29.8	1.32	294.4	133.2	0.64	20.4	0.65	0.4
2.7	5.99	25.4	1.32	218.3	101.3	-	-	-	-
3.3	5.96	20.7	1.31	169.2	74.4	-	-	-	-
4	5.83	21.0	1.32	139.9	53.5	0.73	14.6		n.d.
5	5.75	19.1	1.33	100.6	39.4	-	-	-	-
6	6.26	15.7	1.37	76.9	29.4	0.77	20.8	0.51	0.3

Appendix E: Media Oxalate Extraction Data

Table E-1. Oxalate extractions for batch media and media components. Mass is sample mass adjusted for water content.

Id	Mass (g)	Volume (mL)	P Concentration (mg/L)	P_{ox} (mg/kg)	P_{ox} (mmol/kg)	Fe Concentration (mg/L)	Fe_{ox} (mg/kg)	Fe_{ox} (mmol/kg)	Al Concentration (mg/L)	Al_{ox} (mg/kg)	Al_{ox} (mmol/kg)	PSI (%)	Oxalate Ratio
OX-BSM1	1.000	40	0.152	118.8	3.83	20.9	830.2	14.9	6.60	264.1	9.79	15.6	6.43
OX-BSM2	1.000	40	0.110	84.7	2.74	21.1	836.8	15.0	6.97	278.8	10.3	10.8	9.25
OX-BSM3	0.996	40	0.218	171.8	5.55	23.7	945.8	16.9	7.84	314.8	11.7	19.4	5.16
OX-WTR1	0.232	40	0.575	1970.7	63.6	22.1	3784.7	67.8	853.9	147,264.5	5458.3	1.15	86.8
OX-WTR2	0.231	40	0.534	1836.9	59.3	21.9	3765.4	67.4	891.8	154,566.0	5728.9	1.02	97.7
OX-WTR3	0.231	40	0.470	1613.7	52.1	20.2	3463.8	62.0	827.2	143,013.8	5300.7	0.97	102.9
WTR1	0.394	40	1.421	2880.8	93.0	27.2	2747.1	49.2	1596.0	161,969.0	6003.3	1.54	65.1
WTR2	0.395	40	1.380	2795.4	90.3	26.5	2678.9	48.0	1606.0	162,845.8	6035.8	1.48	67.4
WTR3	0.394	40	1.264	2564.6	82.8	23.2	2343.9	42.0	1585.5	161,081.6	5970.4	1.38	72.6
WTR4	0.396	40	1.305	2635.2	85.1	23.8	2396.0	42.9	1571.0	158,854.6	5887.9	1.43	69.7
WTR5	0.395	40	1.305	2642.4	85.3	22.2	2242.9	40.2	1585.5	160,756.1	5958.3	1.42	70.3
WTR6	0.395	40	1.247	2521.6	81.4	23.4	2359.3	42.2	1477.5	149,639.5	5546.3	1.46	68.6
WTR7	0.395	40	1.264	2554.2	82.5	22.1	2225.7	39.9	1428.0	144,501.0	5355.9	1.53	65.4
WTR8	0.394	40	1.443	2926.9	94.5	23.9	2419.3	43.3	1566.5	159,105.1	5897.1	1.59	62.9
HBM1-1	1.000	40	0.161	125.0	4.03	93.3	3730.0	66.8	10.0	399.8	14.8	4.94	20.2
HBM1-2	1.003	40	0.154	119.4	3.86	91.8	3661.0	65.6	10.0	398.8	14.8	4.80	20.8
HBM1-3	0.956	40	0.134	108.2	3.50	87.8	3671.5	65.7	9.07	379.6	14.1	4.38	22.8
HBM2-1	0.836	40	0.106	101.1	3.27	67.2	3213.0	57.5	7.56	361.9	13.4	4.60	21.7
HBM3-1	0.998	40	0.155	120.5	3.89	59.6	2386.8	42.7	7.63	305.8	11.3	7.19	13.9
HBM3-2	1.004	40	0.159	122.8	3.97	58.8	2342.6	41.9	7.00	279.0	10.3	7.58	13.2
HBM3-3	1.005	40	0.149	114.5	3.70	57.1	2270.6	40.7	6.91	275.0	10.2	7.27	13.8

Id	Mass (g)	Volume (mL)	P Concentration (mg/L)	P_{ox} (mg/kg)	P_{ox} (mmol/kg)	Fe Concentration (mg/L)	Fe_{ox} (mg/kg)	Fe_{ox} (mmol/kg)	Al Concentration (mg/L)	Al_{ox} (mg/kg)	Al_{ox} (mmol/kg)	PSI (%)	Oxalate Ratio
LC-1	0.995	40	0.588	469.0	15.1	58.9	2365.8	42.4	9.14	367.5	13.6	27.0	3.70
LC-2	1.005	40	0.616	486.5	15.7	50.8	2019.9	36.2	8.99	357.7	13.3	31.8	3.15
LC-3	0.977	40	0.639	519.8	16.8	54.3	2221.1	39.8	9.35	382.6	14.2	31.1	3.21
2% BSM	0.990	40	0.201	159.5	5.15	21.1	846.6	15.2	32.4	1306.6	48.4	8.10	12.3
4% BSM	0.975	40	0.242	195.1	6.30	23.6	961.6	17.2	61.1	2506.5	92.9	5.72	17.5
10% BSM	0.954	40	0.276	228.7	7.39	29.6	1233.3	22.1	254.7	10682.2	395.9	1.77	56.6
LFBSM	1.003	40	0.069	53.8	1.74	12.5	494.6	8.86	3.80	151.5	5.62	12.0	8.33
3% LFBSM	0.992	40	0.099	79.0	2.55	16.0	643.6	11.5	44.7	1799.8	66.7	3.26	30.7
6% LFBSM	0.972	40	0.126	102.9	3.32	15.2	622.8	11.2	126.5	5207.4	193.0	1.63	61.4
10% LFBSM	0.957	40	0.172	142.4	4.60	20.1	839.6	15.0	218.0	9115.2	337.9	1.30	76.7
BSM+HBM	0.983	40	0.147	119.3	3.85	23.9	970.7	17.4	6.20	252.2	9.35	14.4	6.94
2% HBM	1.003	40	0.268	213.1	6.88	32.0	1275.4	22.8	37.1	1477.6	54.8	8.87	11.3
4% HBM	0.972	40	0.198	159.8	5.16	21.1	859.4	15.4	77.3	3178.1	117.8	3.87	25.8
BSM+LC	1.003	40	0.215	170.9	5.52	26.0	1035.1	18.5	7.96	317.5	11.8	18.2	5.49
4% LC	1.003	40	0.218	173.2	5.59	13.6	538.6	9.64	42.3	1687.7	62.6	7.74	12.9
4% LC [OM+]	1.003	40	0.343	272.3	8.79	31.3	1244.0	22.3	36.1	1439.7	53.4	11.6	8.60
4% AH	0.990	40	0.253	203.2	6.56	27.9	1123.7	20.1	66.2	2676.2	99.2	5.50	18.2

Table E-2. Oxalate extractions for fresh minicolumn media. Mass is sample mass adjusted for water content.

Id	Mass (g)	Vol. (mL)	Concentration (mg/L)	P_{ox} (mg/kg)	P_{ox} (mmol/kg)	Fe Concentration (mg/L)	Fe_{ox} (mg/kg)	Fe_{ox} (mmol/kg)	Al Concentration (mg/L)	Al_{ox} (mg/kg)	Al_{ox} (mmol/kg)	PSI (%)	Oxalate Ratio
Set I													
BSM-1	0.995	40	0.123	96.1	3.10	18.4	732.1	13.1	7.14	287.0	10.6	13.1	7.65
BSM-2	1.002	40	0.175	137.3	4.43	18.7	740.7	13.3	8.80	351.3	13.0	16.9	5.93

Id	Mass (g)	Vol. (mL)	Concentration (mg/L)	P_{ox} (mg/kg)	P_{ox} (mmol/kg)	Fe Concentration (mg/L)	Fe_{ox} (mg/kg)	Fe_{ox} (mmol/kg)	Al Concentration (mg/L)	Al_{ox} (mg/kg)	Al_{ox} (mmol/kg)	PSI (%)	Oxalate Ratio
BSM-3	0.998	40	0.178	140.3	4.53	22.1	880.2	15.8	8.97	359.2	13.3	15.6	6.42
2% WTR-1	1.003	40	0.247	195.5	6.31	23.4	933.2	16.7	60.1	2398.0	88.9	5.98	16.7
2% WTR-2	1.001	40	0.220	174.4	5.63	22.6	902.0	16.2	71.5	2858.9	106.0	4.61	21.7
2% WTR-3	1.005	40	0.259	204.7	6.61	28.4	1130.8	20.2	54.4	2163.7	80.2	6.58	15.2
4% WTR-1	0.998	40	0.248	197.1	6.36	23.0	919.9	16.5	124.1	4971.0	184.2	3.17	31.5
4% WTR-2	1.000	40	0.225	178.3	5.76	23.0	917.6	16.4	125.0	4998.6	185.3	2.85	35.0
4% WTR-3	1.006	40	0.269	212.6	6.87	24.0	955.0	17.1	118.7	4716.2	174.8	3.58	28.0
2% HBM-1	1.004	40	0.230	182.0	5.88	21.4	850.8	15.2	71.7	2856.5	105.9	4.85	20.6
2% HBM-2	1.004	40	0.181	142.3	4.59	25.2	1005.2	18.0	96.3	3835.5	142.2	2.87	34.9
2% HBM-3	1.004	40	0.183	144.0	4.65	20.3	807.9	14.5	73.1	2913.0	108.0	3.80	26.3
4% HBM-1	1.008	40	0.237	185.6	5.99	27.4	1079.1	19.3	150.4	5967.3	221.2	2.49	40.1
4% HBM-2	1.004	40	0.274	216.1	6.98	28.6	1132.1	20.3	148.3	5912.6	219.1	2.91	34.3
4% HBM-3	1.004	40	0.193	151.6	4.89	26.1	1034.4	18.5	142.7	5686.7	210.8	2.13	46.9
4% LFBSM-1	1.000	40	0.176	139.4	4.50	15.9	635.8	11.4	89.6	3584.5	132.9	3.12	32.0
4% LFBSM-2	1.002	40	0.196	155.0	5.00	15.8	630.8	11.3	105.6	4215.3	156.2	2.99	33.5
4% LFBSM-3	1.003	40	0.199	157.4	5.08	15.3	608.3	10.9	130.9	5219.3	193.5	2.49	40.2
Set II													
BSM-1	0.998	40	0.178	141.5	4.57	14.4	573.3	10.3	9.62	385.4	14.3	18.6	5.37
BSM-2	0.998	40	0.151	119.7	3.87	10.9	432.1	7.74	8.76	351.2	13.0	18.6	5.37
BSM-3	1.004	40	0.155	122.8	3.96	7.9	310.0	5.55	8.58	341.8	12.7	21.8	4.60
4% WTR-1	1.000	40	0.385	303.3	9.79	31.2	1242.9	22.3	120.9	2321.7	86.1	9.04	11.1
4% WTR-2	1.002	40	0.276	215.9	6.97	26.7	1063.1	19.0	153.7	2946.9	109.2	5.44	18.4
4% WTR-3	1.002	40	0.258	201.3	6.50	25.2	1003.1	18.0	151.3	2900.6	107.5	5.18	19.3
4% Sand-1	1.009	40	0.092	68.5	2.21	2.7	104.9	1.88	141.2	5595.1	207.4	1.06	94.6
4% Sand-2	0.990	40	0.136	104.8	3.38	4.0	158.5	2.84	194.0	7834.1	290.4	1.15	86.7
4% Sand-3	0.998	40	0.062	45.1	1.46	2.4	91.5	1.64	112.7	4514.9	167.3	0.863	116

Id	Mass (g)	Vol. (mL)	Concentration (mg/L)	P_{ox} (mg/kg)	P_{ox} (mmol/kg)	Fe Concentration (mg/L)	Fe_{ox} (mg/kg)	Fe_{ox} (mmol/kg)	Al Concentration (mg/L)	Al_{ox} (mg/kg)	Al_{ox} (mmol/kg)	PSI (%)	Oxalate Ratio
4% HBM-1 (Int.)	1.007	40	0.228	177.3	5.73	18.5	725.9	13.0	113.6	4511.4	167.2	3.18	31.5
4% HBM-2 (Int.)	1.009	40	0.270	210.5	6.80	19.0	743.1	13.3	143.9	5704.6	211.4	3.02	33.1
4% HBM-3 (Int.)	1.010	40	0.205	158.7	5.12	17.1	667.4	12.0	116.1	4598.3	170.4	2.81	35.6
4% WTR-1 (Int.)	1.007	40	0.272	211.2	6.82	22.0	870.6	15.6	143.1	5681.1	210.6	3.02	33.2
4% WTR-2 (Int.)	1.015	40	0.481	374.3	12.1	32.8	1287.8	23.1	178.8	7043.7	261.1	4.25	23.5
4% WTR-3 (Int.)	1.012	40	0.351	272.7	8.81	26.3	1033.7	18.5	145.4	5744.3	212.9	3.81	26.3
4% LFBSM-1 (Int.)	1.007	40	0.154	118.0	3.81	15.2	599.1	10.7	141.3	5615.1	208.1	1.74	57.4
4% LFBSM-2 (Int.)	0.996	40	0.207	161.4	5.21	15.7	627.7	11.2	147.5	5922.7	219.5	2.26	44.3
4% LFBSM-3 (Int.)	1.006	40	0.269	209.5	6.76	21.1	836.3	15.0	153.9	6119.2	226.8	2.80	35.7

Table E-3. Oxalate extractions for minicolumn media post adsorption experiments. Mass is sample mass adjusted for water content.

Id	Mass (g)	Vol. (mL)	Concentration (mg/L)	P_{ox} (mg/kg)	P_{ox} (mmol/kg)	Fe Concentration (mg/L)	Fe_{ox} (mg/kg)	Fe_{ox} (mmol/kg)	Al Concentration (mg/L)	Al_{ox} (mg/kg)	Al_{ox} (mmol/kg)	PSI (%)	Oxalate Ratio
Set I													
BSM-1	1.085	40	0.163	116.9	3.77	23.4	859.2	15.4	7.36	271.2	10.1	14.8	6.74
BSM-2	1.008	40	0.174	134.5	4.34	21.1	834.4	14.9	7.27	288.4	10.7	16.9	5.90
BSM-3	1.010	40	0.192	148.5	4.80	20.7	819.0	14.7	7.30	289.4	10.7	18.9	5.29
2% WTR-1	1.027	40	0.229	177.4	5.73	18.7	726.3	13.0	47.3	1842.1	68.3	7.05	14.2
2% WTR-2	1.002	40	0.197	156.2	5.04	17.3	689.6	12.3	47.1	1880.2	69.7	6.15	16.3
2% WTR-3	0.990	40	0.222	178.2	5.75	17.9	723.5	13.0	49.7	2005.6	74.3	6.59	15.2
4% WTR-1	0.995	40	0.242	193.0	6.23	16.2	650.7	11.7	77.6	3117.8	115.6	4.90	20.4
4% WTR-2	1.005	40	0.282	223.4	7.21	19.4	771.0	13.8	84.9	3379.4	125.3	5.19	19.3
4% WTR-3	1.002	40	0.268	212.8	6.87	18.4	735.1	13.2	90.8	3622.5	134.3	4.66	21.5
2% HBM-1	1.004	40	0.265	208.1	6.72	19.3	767.8	13.7	74.9	2983.8	110.6	5.40	18.5

Id	Mass (g)	Vol. (mL)	Concentration (mg/L)	P_{ox} (mg/kg)	P_{ox} (mmol/kg)	Fe Concentration (mg/L)	Fe_{ox} (mg/kg)	Fe_{ox} (mmol/kg)	Al Concentration (mg/L)	Al_{ox} (mg/kg)	Al_{ox} (mmol/kg)	PSI (%)	Oxalate Ratio
2% HBM-2	1.005	40	0.320	250.9	8.10	25.0	991.2	17.7	68.1	2709.7	100.4	6.85	14.6
2% HBM-3	1.001	40	0.236	185.1	5.98	20.7	826.1	14.8	58.6	2343.7	86.9	5.88	17.0
4% HBM-1	1.029	40	0.338	260.0	8.40	24.6	951.1	17.0	117.2	4554.6	168.8	4.52	22.1
4% HBM-2	1.027	40	0.217	166.5	5.37	23.8	918.4	16.4	139.8	5444.1	201.8	2.46	40.6
4% HBM-3	1.022	40	0.230	177.7	5.74	26.3	1020.9	18.3	149.4	5849.9	216.8	2.44	41.0
4% LFBSM-1	1.019	40	0.429	335.6	10.8	22.1	867.4	15.5	135.4	5315.5	197.0	5.10	19.6
4% LFBSM-2	1.005	40	0.389	308.6	9.96	21.2	844.6	15.1	108.4	4315.5	160.0	5.69	17.6
4% LFBSM-3	0.997	40	0.394	314.9	10.2	18.1	726.3	13.0	147.1	5898.3	218.6	4.39	22.8
Set II													
BSM-1	1.005	40	0.148	114.3	3.69	16.5	649.3	11.6	6.43	255.9	9.49	17.5	5.72
BSM-2	1.005	40	0.153	118.0	3.81	16.1	632.2	11.3	7.32	291.3	10.8	17.2	5.80
BSM-3	0.997	40	0.127	98.5	3.18	14.3	563.2	10.1	4.14	166.2	6.16	19.6	5.11
4% WTR-1	0.998	40	0.297	234.6	7.58	18.5	732.7	13.1	111.2	4455.9	165.2	4.25	23.5
4% WTR-2	1.008	40	0.374	293.4	9.48	19.2	751.2	13.5	104.9	4160.9	154.2	5.65	17.7
4% WTR-3	1.003	40	0.343	269.8	8.71	17.3	682.6	12.2	116.0	4625.6	171.4	4.74	21.1
4% Sand-1	1.000	40	0.223	174.9	5.65	1.6	56.0	1.0	102.5	4099.7	152.0	3.69	27.1
4% Sand-2	1.005	40	0.211	164.0	5.30	1.7	59.2	1.1	96.5	3843.1	142.4	3.69	27.1
4% Sand-3	0.996	40	0.201	158.0	5.10	1.7	58.3	1.0	100.9	4052.0	150.2	3.37	29.6
4% HBM-1 (Int.)	1.001	40	0.410	322.9	10.4	26.1	1037.2	18.6	142.5	5695.1	211.1	4.54	22.0
4% HBM-2 (Int.)	0.999	40	0.351	276.2	8.92	25.5	1017.2	18.2	110.6	4428.1	164.1	4.89	20.4
4% HBM-3 (Int.)	1.005	40	0.276	215.0	6.94	22.6	897.7	16.1	109.4	4352.9	161.3	3.91	25.6
4% WTR-1 (Int.)	1.003	40	0.283	223.8	7.23	18.4	729.2	13.1	153.4	6116.2	226.7	3.01	33.2
4% WTR-2 (Int.)	0.996	40	0.249	197.7	6.38	19.0	758.0	13.6	123.5	4963.4	184.0	3.23	30.9
4% WTR-3 (Int.)	0.996	40	0.254	202.0	6.52	19.1	762.5	13.7	130.5	5239.1	194.2	3.14	31.9
4% LFBSM-1 (Int.)	0.994	40	0.301	237.6	7.67	18.4	737.3	13.2	122.5	4928.6	182.7	3.92	25.5
4% LFBSM-2 (Int.)	0.992	40	0.304	240.2	7.75	16.6	666.5	11.9	129.2	5209.6	193.1	3.78	26.4

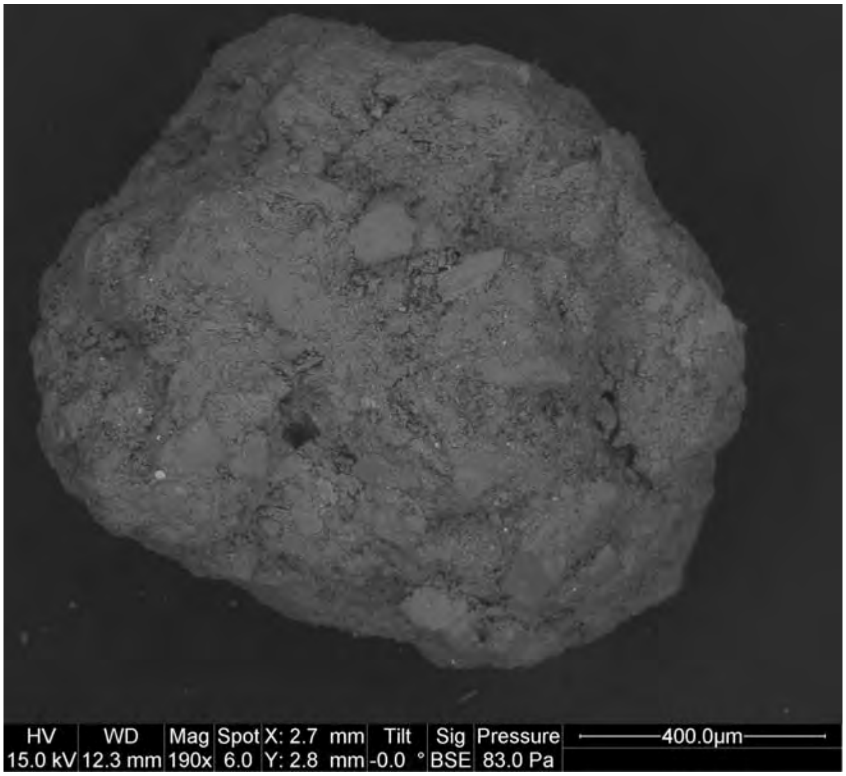
Id	Mass (g)	Vol. (mL)	Concentration (mg/L)	P_{ox} (mg/kg)	P_{ox} (mmol/kg)	Fe Concentration (mg/L)	Fe_{ox} (mg/kg)	Fe_{ox} (mmol/kg)	Al Concentration (mg/L)	Al_{ox} (mg/kg)	Al_{ox} (mmol/kg)	PSI (%)	Oxalate Ratio
4% LFBSM-3 (Int.)	0.999	40	0.263	205.7	6.64	16.4	651.2	11.7	115.2	4611.6	170.9	3.64	27.5

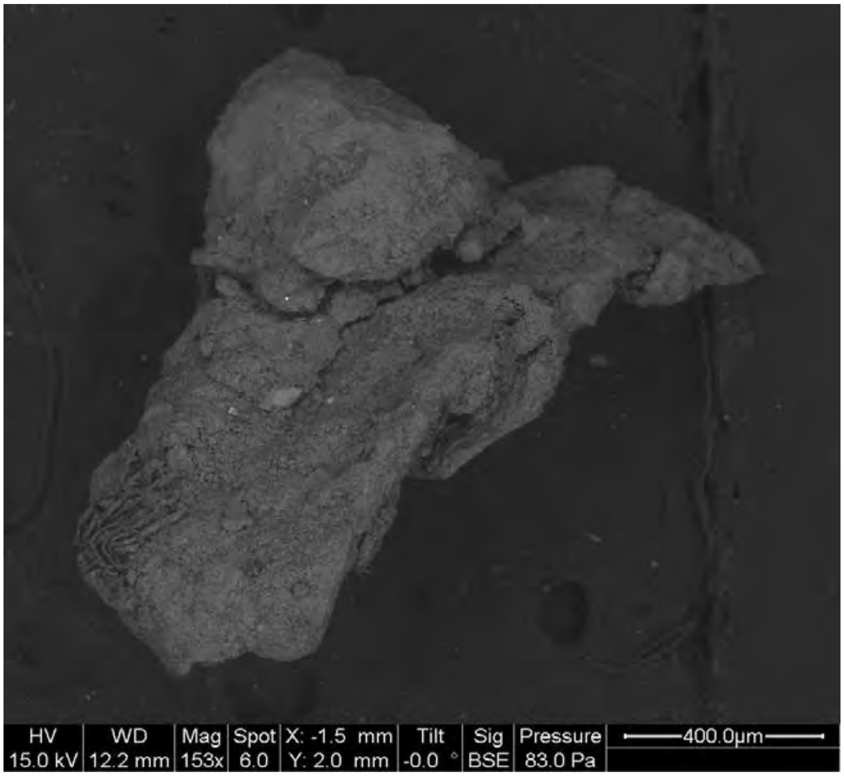
Table E-4. Oxalate extractions for vegetated column media both unused and post-adsorption at various depths. Mass is sample mass adjusted for water content.

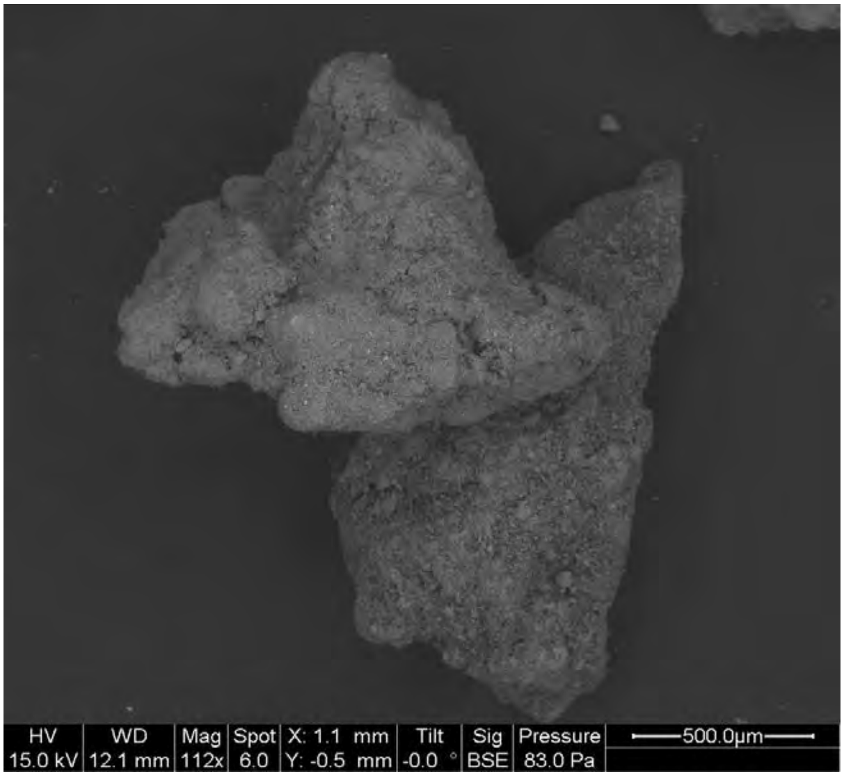
	Id	Mass (g)	Vol. (mL)	Concentration (mg/L)	P_{ox} (mg/kg)	P_{ox} (mmol/kg)	Fe Concentration (mg/L)	Fe_{ox} (mg/kg)	Fe_{ox} (mmol/kg)	Al Concentration (mg/L)	Al_{ox} (mg/kg)	Al_{ox} (mmol/kg)	PSI (%)	Oxalate Ratio
Control Column	(0-2 cm)-1	0.997	40	84.0	67.2	2.71	1.03	41.5	0.743	5.22	209.2	7.75	31.9	3.13
	(0-2 cm)-2	1.001	40	94.9	75.7	3.07	1.26	50.1	0.898	3.74	149.4	5.54	47.6	2.10
	(0-2 cm)-3	1.001	40	91.0	72.6	2.94	1.46	58.5	1.05	6.08	243.2	9.01	29.2	3.42
	(11-12 cm)-1	0.997	40	113.3	90.7	3.66	1.51	60.4	1.08	5.42	217.3	8.06	40.0	2.50
	(11-12 cm)-2	0.998	40	186.5	149.4	6.02	2.10	84.0	1.50	7.56	303.2	11.2	47.3	2.12
	(11-12 cm)-3	1.004	40	159.6	127.0	5.15	1.88	75.1	1.34	7.61	303.0	11.2	41.0	2.44
	(21-22 cm)-1	1.002	40	200.9	160.2	6.49	2.42	96.8	1.73	8.46	337.6	12.5	45.5	2.20
	(21-22 cm)-2	1.008	40	145.0	114.9	4.68	1.90	75.2	1.35	7.18	285.0	10.6	39.3	2.54
	(21-22 cm)-3	0.997	40	184.1	147.5	5.94	2.34	93.8	1.68	8.16	327.3	12.1	43.0	2.32
	(43-44 cm)-1	1.004	40	145.6	115.8	4.70	1.81	72.0	1.29	7.68	305.8	11.3	37.3	2.68
	(43-44 cm)-2	1.001	40	122.5	97.7	3.95	1.71	68.4	1.23	7.20	287.7	10.7	33.3	3.01
	(43-44 cm)-3	1.013	40	147.4	116.2	4.76	1.89	74.4	1.33	7.49	295.8	11.0	38.7	2.58
	Unused-1	1.011	40	163.3	129.0	5.27	2.02	79.8	1.43	7.01	277.2	10.3	45.1	2.22
	Unused-2	1.003	40	109.8	87.4	3.55	1.48	59.0	1.06	6.19	246.9	9.15	34.7	2.88
	Unused-3	1.002	40	116.8	93.1	3.77	1.80	71.9	1.29	6.61	264.1	9.79	34.0	2.94
enta 1	(0-2 cm)-1	1.002	40	449.2	358.3	14.5	2.27	90.5	1.62	137.3	5478.0	203.0	7.09	14.1

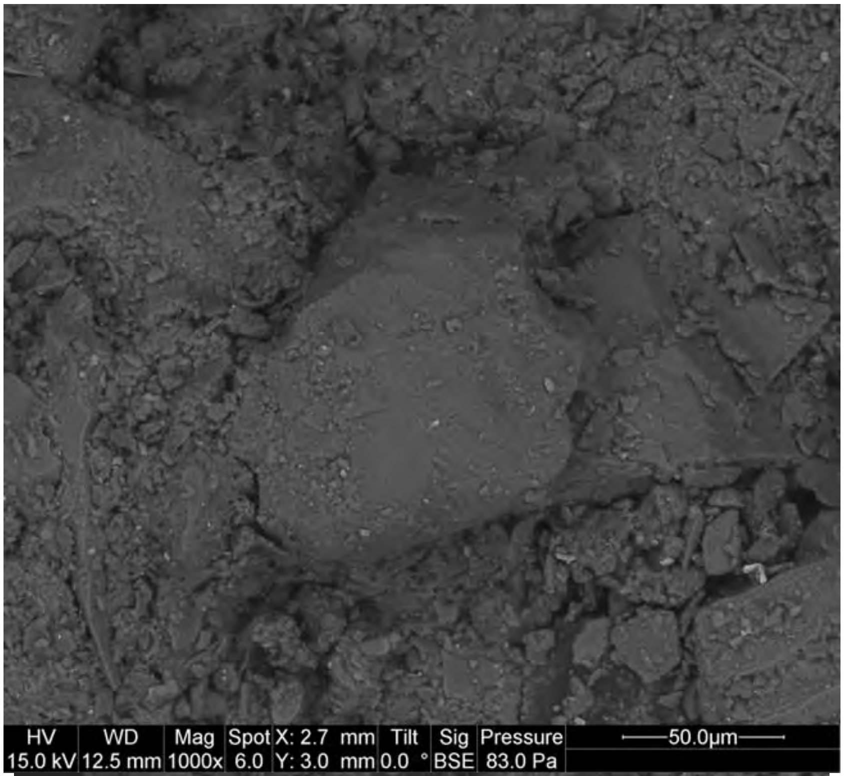
Id	Mass (g)	Vol. (mL)	Concentration (mg/L)	P_{ox} (mg/kg)	P_{ox} (mmol/kg)	Fe Concentration (mg/L)	Fe_{ox} (mg/kg)	Fe_{ox} (mmol/kg)	Al Concentration (mg/L)	Al_{ox} (mg/kg)	Al_{ox} (mmol/kg)	PSI (%)	Oxalate Ratio
(0-2 cm)-2	1.001	40	373.4	298.3	12.1	2.08	83.0	1.49	127.0	5074.2	188.1	6.36	15.7
(0-2 cm)-3	0.997	40	425.2	340.9	13.7	2.13	85.6	1.53	126.5	5074.9	188.1	7.24	13.8
(11-12 cm)-1	1.000	40	259.2	207.2	8.37	1.98	79.1	1.42	132.3	5291.5	196.1	4.24	23.6
(11-12 cm)-2	1.001	40	287.1	229.3	9.27	2.24	89.4	1.60	140.0	5593.1	207.3	4.44	22.5
(11-12 cm)-3	1.023	40	381.5	298.0	12.3	2.50	97.7	1.75	118.0	4611.7	170.9	7.13	14.0
(21-22 cm)-1	0.994	40	256.6	206.3	8.28	1.79	72.0	1.29	104.8	4216.5	156.3	5.26	19.0
(21-22 cm)-2	1.009	40	268.8	212.9	8.68	2.03	80.5	1.44	104.9	4158.6	154.1	5.58	17.9
(21-22 cm)-3	0.999	40	235.6	188.4	7.61	2.20	88.1	1.58	118.1	4728.2	175.2	4.30	23.2
(43-44 cm)-1	1.006	40	239.1	190.0	7.72	2.09	83.2	1.49	122.2	4859.3	180.1	4.25	23.5
(43-44 cm)-2	0.997	40	263.1	210.9	8.50	1.89	75.7	1.36	111.7	4482.8	166.2	5.07	19.7
(43-44 cm)-3	1.001	40	240.0	191.6	7.75	1.93	77.1	1.38	133.0	5311.7	196.9	3.91	25.6
Unused-1	1.006	40	282.8	224.7	9.13	1.99	79.2	1.42	131.7	5236.3	194.1	4.67	21.4
Unused-2	1.006	40	235.6	187.2	7.61	1.75	69.6	1.25	120.8	4804.0	178.1	4.24	23.6
Unused-3	1.010	40	213.8	169.2	6.90	1.75	69.1	1.24	115.0	4557.4	168.9	4.06	24.7

Appendix F: Electron Microscope Media Images




HV
15.0 kV
WD
12.2 mm
Mag
153x
Spot
6.0
X: -1.5 mm
Y: 2.0 mm
Tilt
-0.0 °
Sig
BSE
Pressure
83.0 Pa
400.0μm


HV
15.0 kV
WD
12.1 mm
Mag
112x
Spot
6.0
X: 1.1 mm
Y: -0.5 mm
Tilt
-0.0 °
Sig
BSE
Pressure
83.0 Pa
500.0μm


HV 15.0 kV
WD 12.5 mm
Mag 1000x
Spot 6.0
X: 2.7 mm
Y: 3.0 mm
Tilt 0.0 °
Sig BSE
Pressure 83.0 Pa
50.0µm


HV 15.0 kV
WD 12.2 mm
Mag 1000x
Spot 6.0
X: -2.1 mm
Y: 1.6 mm
Tilt 0.0 °
Sig BSE
Pressure 83.0 Pa
50.0µm

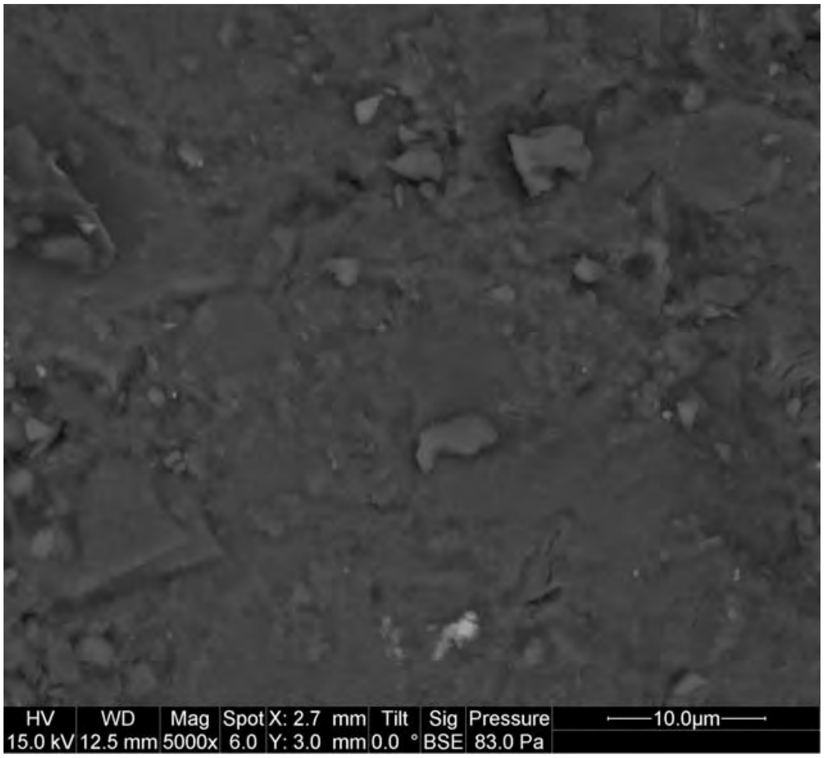
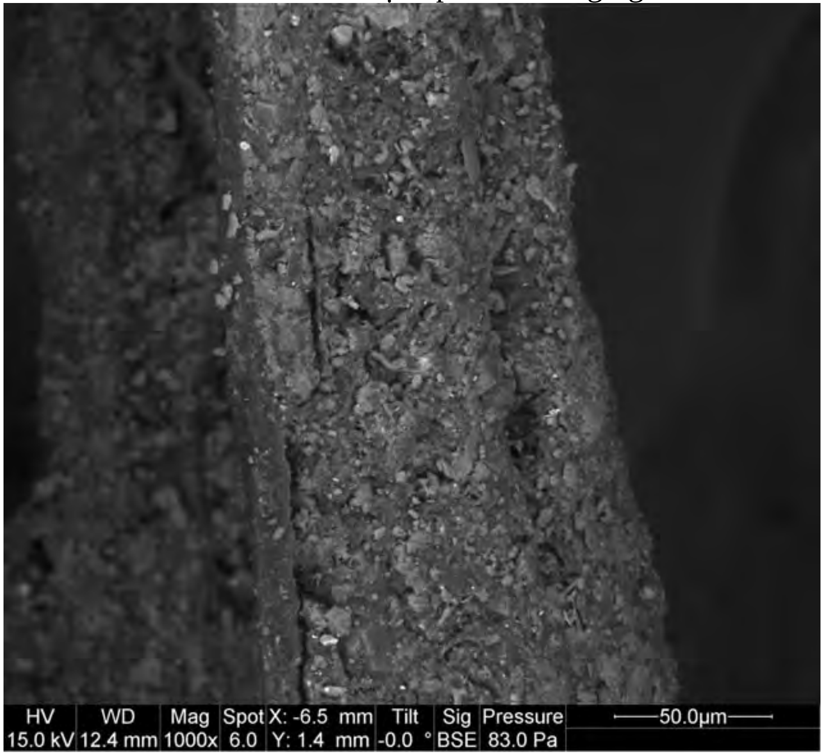


Figure F-1. Electron microscope images (6 frames) of BSM grains from an unused, “fresh” BSM + 4% WTR + HBM mixture. Media was dried at 103°C for 2 hours and sieved to between 300 and 590 µm prior to imaging.



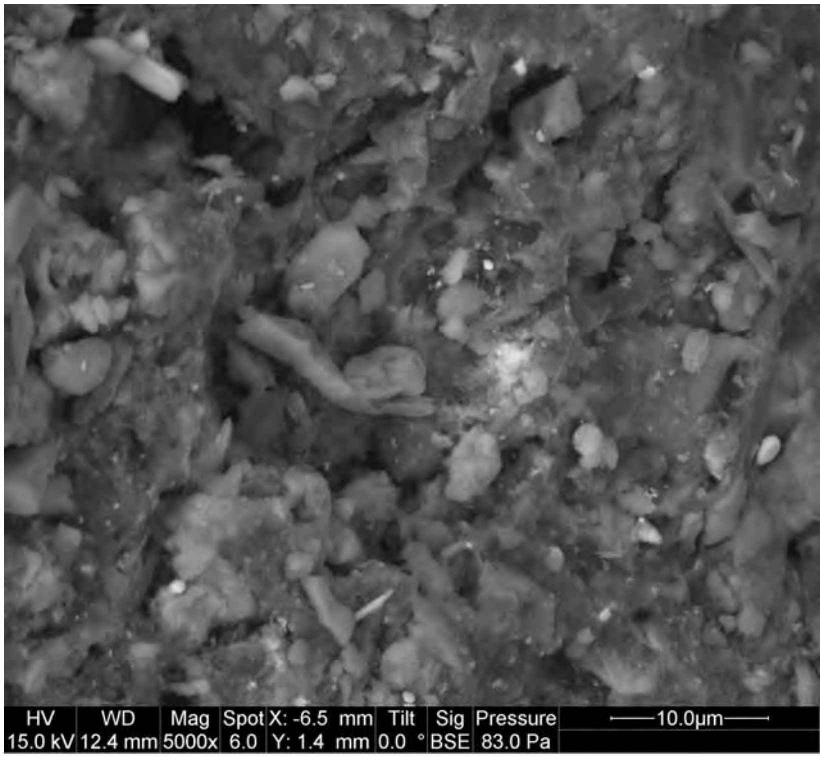
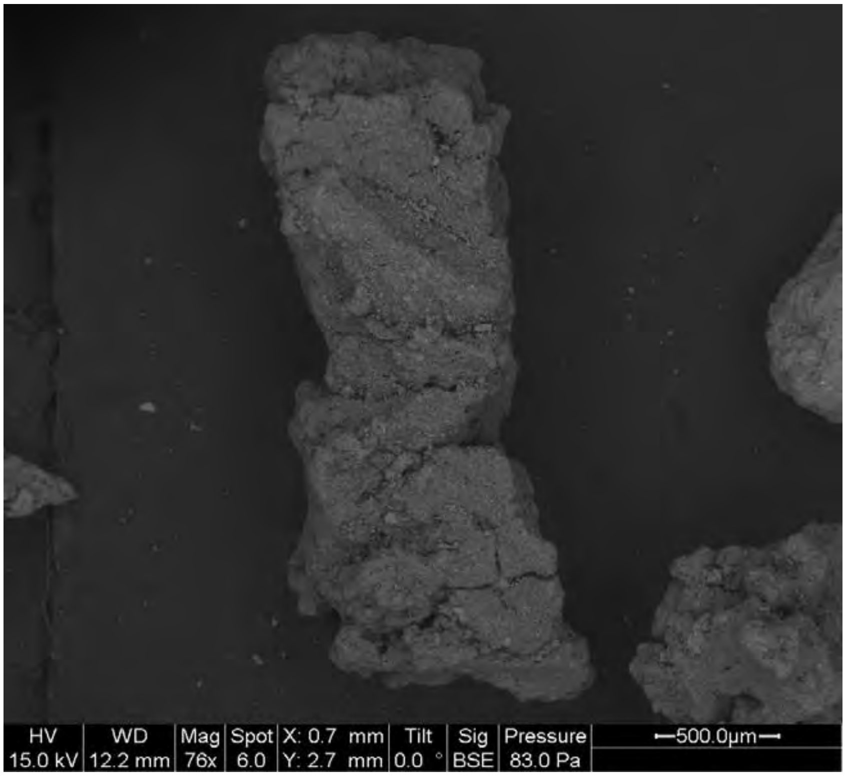
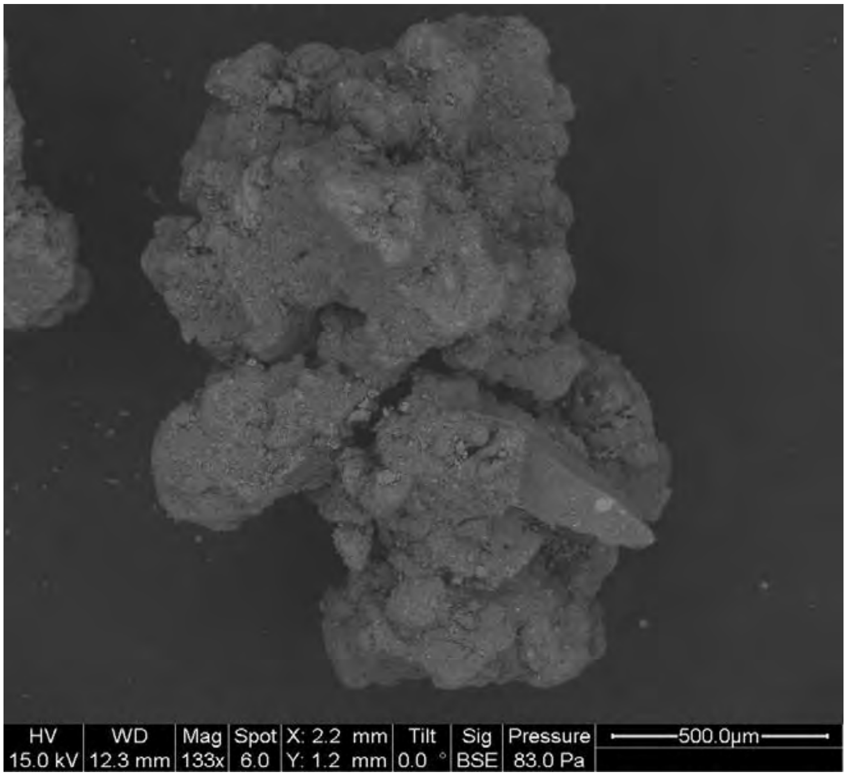
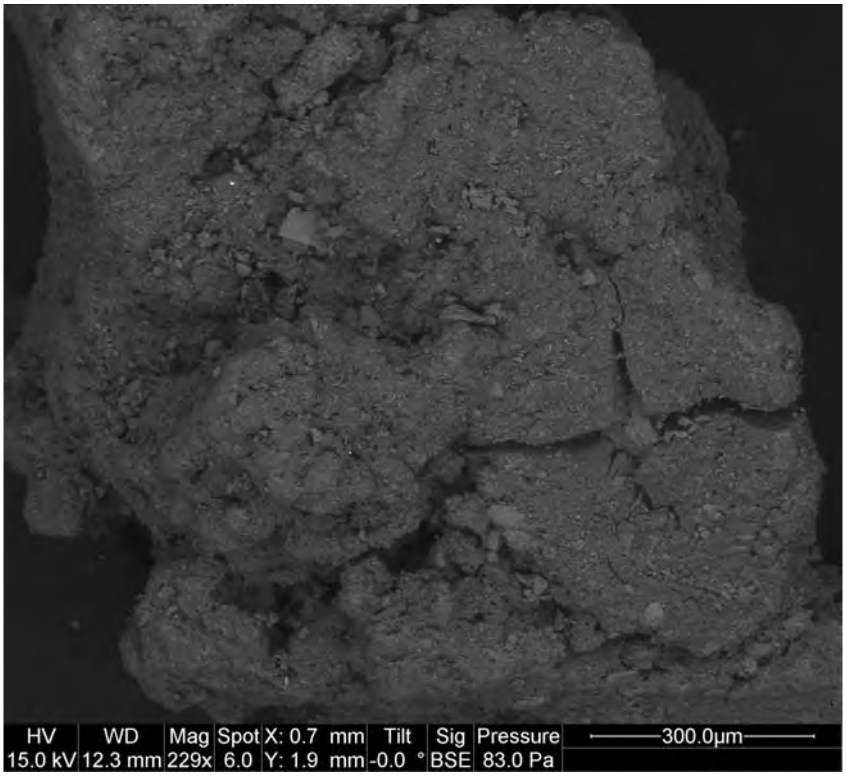
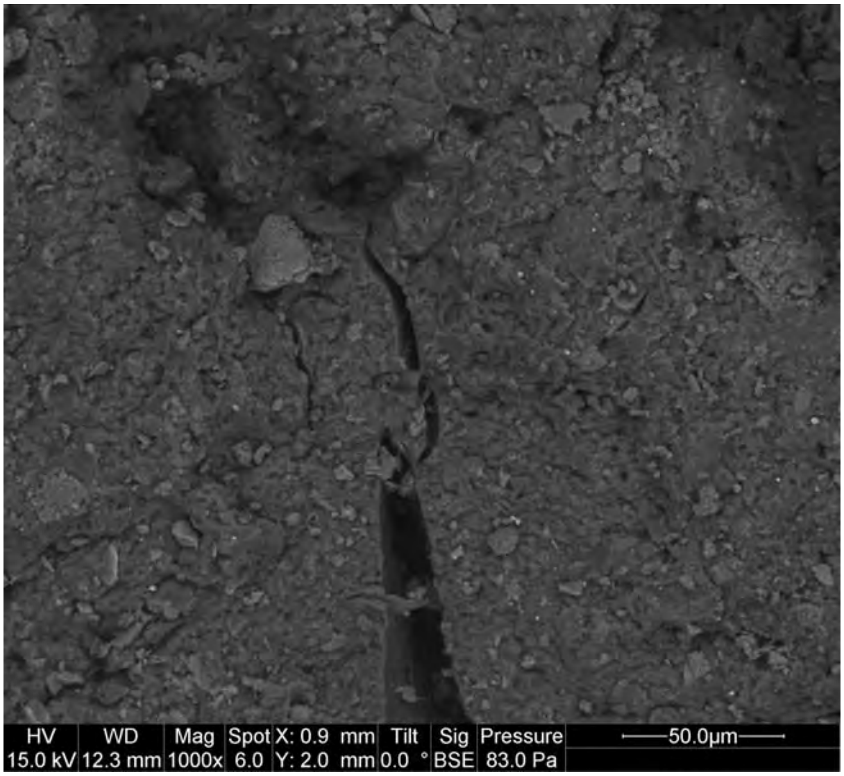


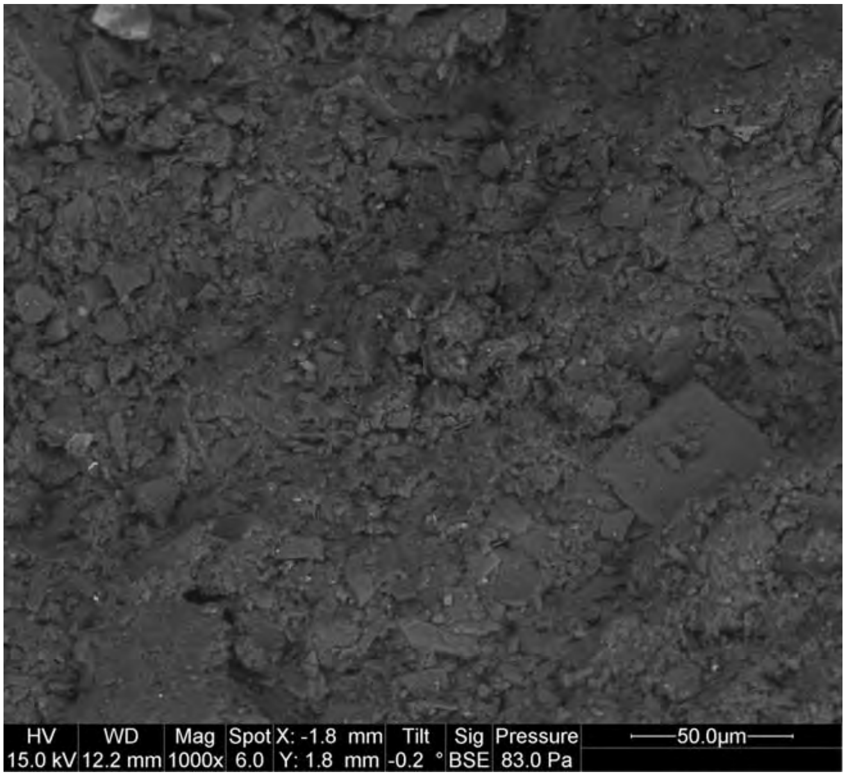
Figure F-2. Electron microscope images (2 frames) of HBM particles from an unused, “fresh” BSM + 4% WTR + HBM mixture. Media was dried at 103°C for 2 hours and sieved to between 300 and 590 µm prior to imaging.

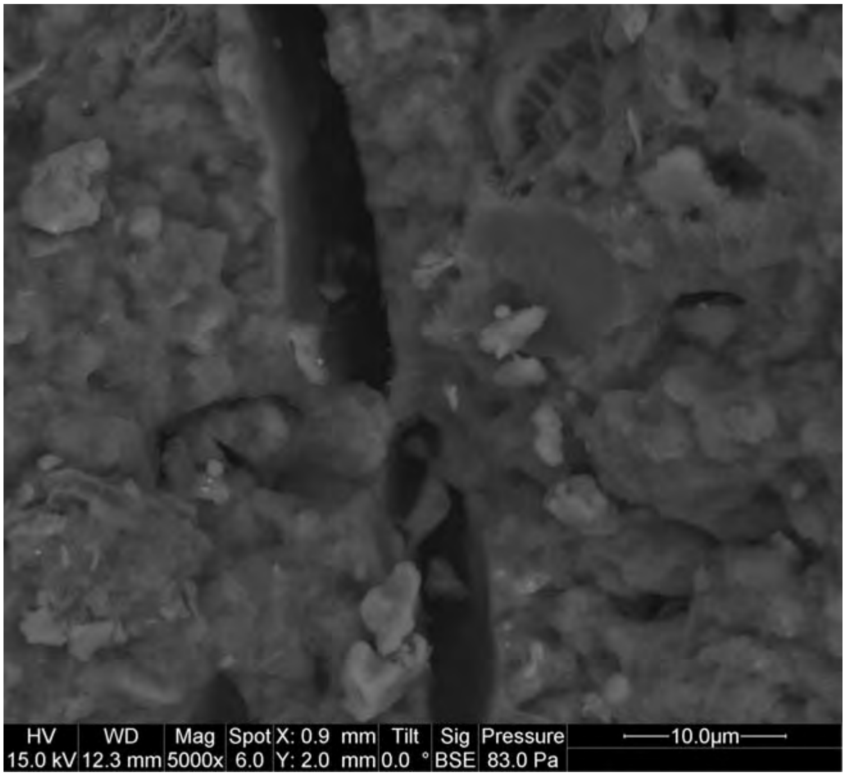

HV
15.0 kV
WD
12.2 mm
Mag
76x
Spot
6.0
X: 0.7 mm
Y: 2.7 mm
Tilt
0.0 °
Sig
BSE
Pressure
83.0 Pa
500.0μm


HV
15.0 kV
WD
12.3 mm
Mag
133x
Spot
6.0
X: 2.2 mm
Y: 1.2 mm
Tilt
0.0 °
Sig
BSE
Pressure
83.0 Pa
500.0μm


HV 15.0 kV
WD 12.3 mm
Mag 229x
Spot 6.0
X: 0.7 mm
Y: 1.9 mm
Tilt -0.0 °
Sig BSE
Pressure 83.0 Pa
300.0µm


HV 15.0 kV
WD 12.3 mm
Mag 1000x
Spot 6.0
X: 0.9 mm
Y: 2.0 mm
Tilt 0.0 °
Sig BSE
Pressure 83.0 Pa
50.0µm


HV 15.0 kV
WD 12.2 mm
Mag 1000x
Spot 6.0
X: -1.8 mm Y: 1.8 mm
Tilt -0.2 °
Sig BSE
Pressure 83.0 Pa
50.0µm


HV 15.0 kV
WD 12.3 mm
Mag 5000x
Spot 6.0
X: 0.9 mm Y: 2.0 mm
Tilt 0.0 °
Sig BSE
Pressure 83.0 Pa
10.0µm

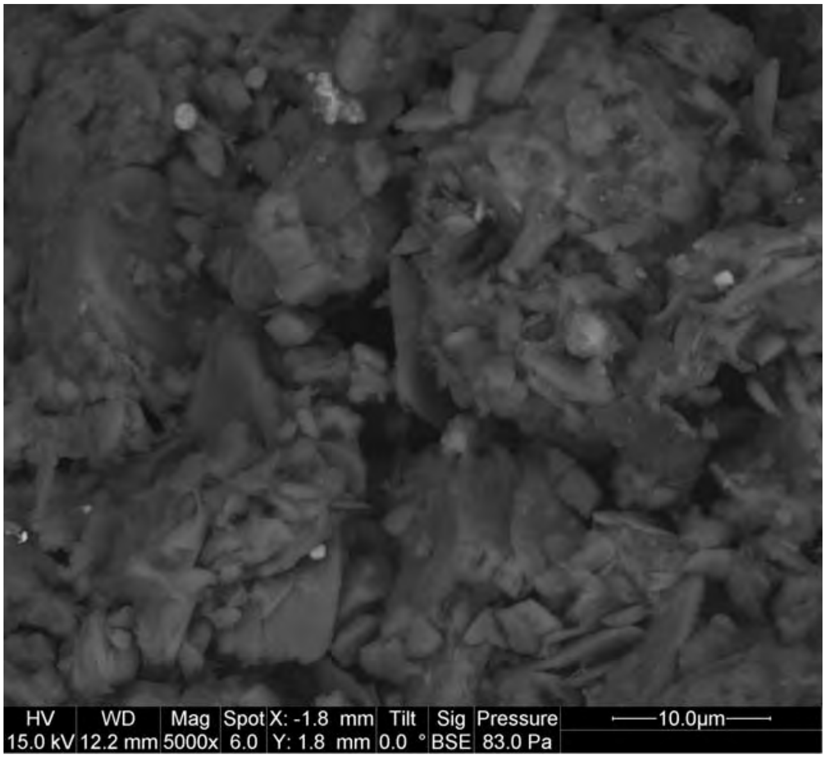
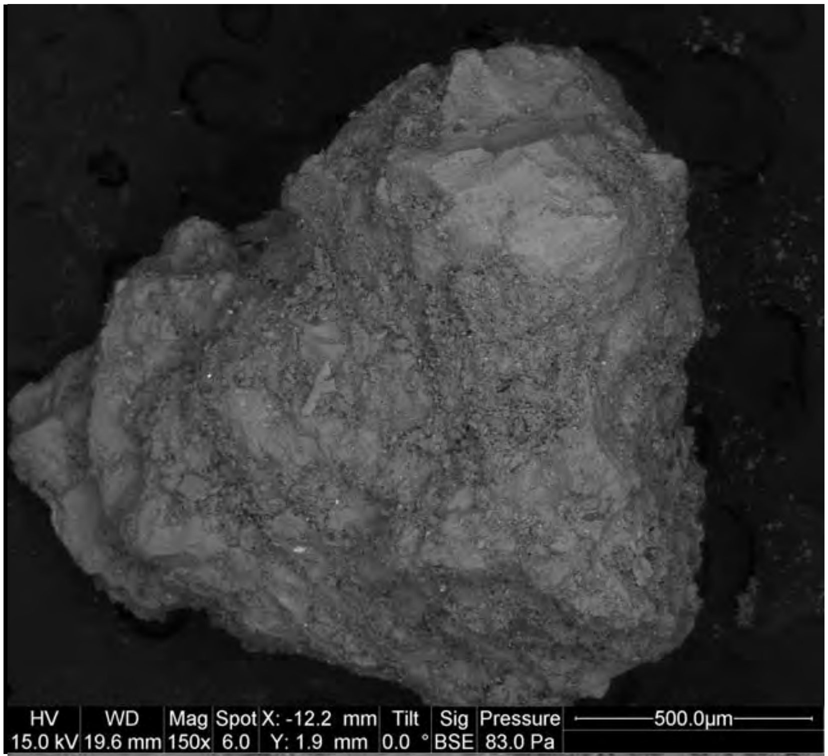
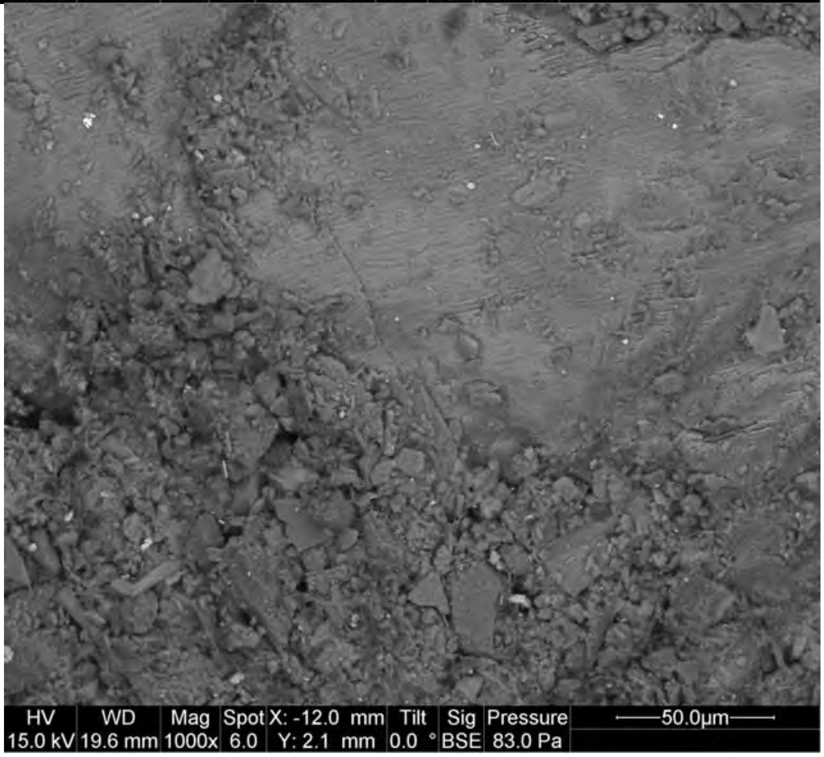


Figure F-3. Electron microscope images (7 frames) of WTR particles from an unused, “fresh” BSM + 4% WTR + HBM mixture. Media was dried at 103°C for 2 hours and sieved to between 300 and 590 µm prior to imaging.


HV 15.0 kV
WD 19.6 mm
Mag 150x
Spot 6.0
X: -12.2 mm Y: 1.9 mm
Tilt 0.0 °
Sig BSE
Pressure 83.0 Pa
500.0µm


HV 15.0 kV
WD 19.6 mm
Mag 1000x
Spot 6.0
X: -12.0 mm Y: 2.1 mm
Tilt 0.0 °
Sig BSE
Pressure 83.0 Pa
50.0µm

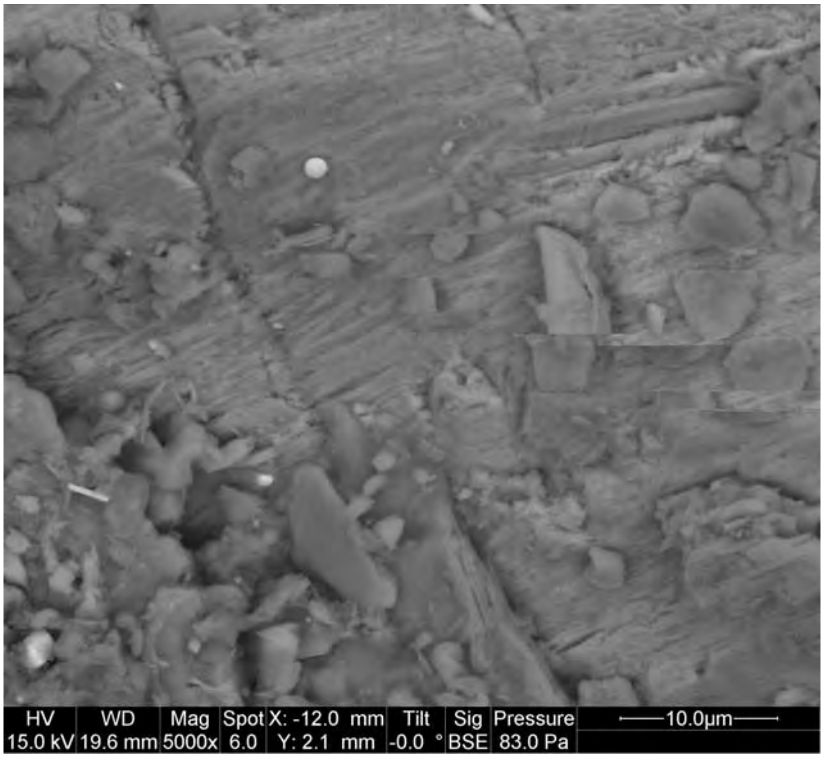
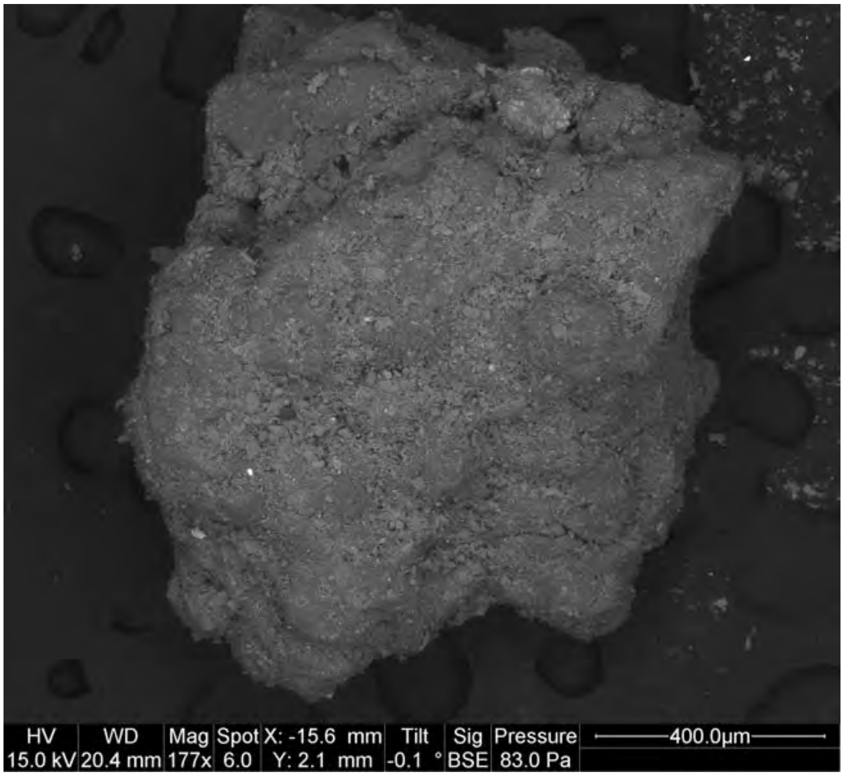
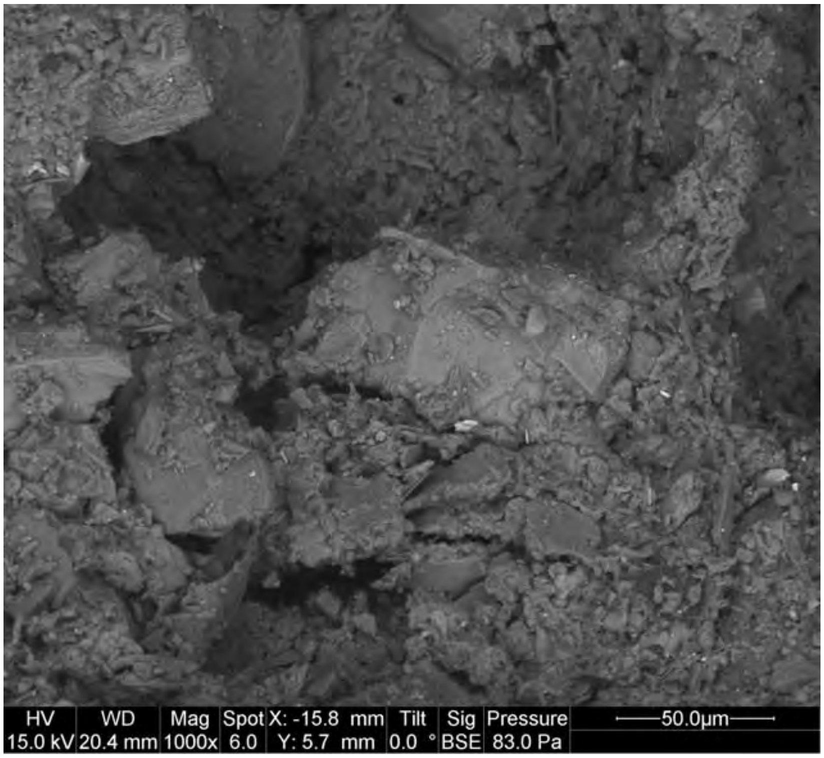


Figure F-4. Electron microscope images (3 frames) of BSM grains post-adsorption from a BSM + 4% WTR + HBM mixture subject to continuous flow. Media was dried at 103°C for 2 hours and sieved to between 300 and 590 µm prior to imaging.


HV
15.0 kV
WD
20.4 mm
Mag
97x
Spot
6.0
X: -16.2 mm
Y: 5.3 mm
Tilt
0.0 °
Sig
BSE
Pressure
83.0 Pa
500.0μm


HV
15.0 kV
WD
20.4 mm
Mag
177x
Spot
6.0
X: -15.6 mm
Y: 2.1 mm
Tilt
-0.1 °
Sig
BSE
Pressure
83.0 Pa
400.0μm


HV 15.0 kV
WD 20.4 mm
Mag 1000x
Spot 6.0
X: -15.8 mm
Y: 5.7 mm
Tilt 0.0 °
Sig BSE
Pressure 83.0 Pa
50.0µm

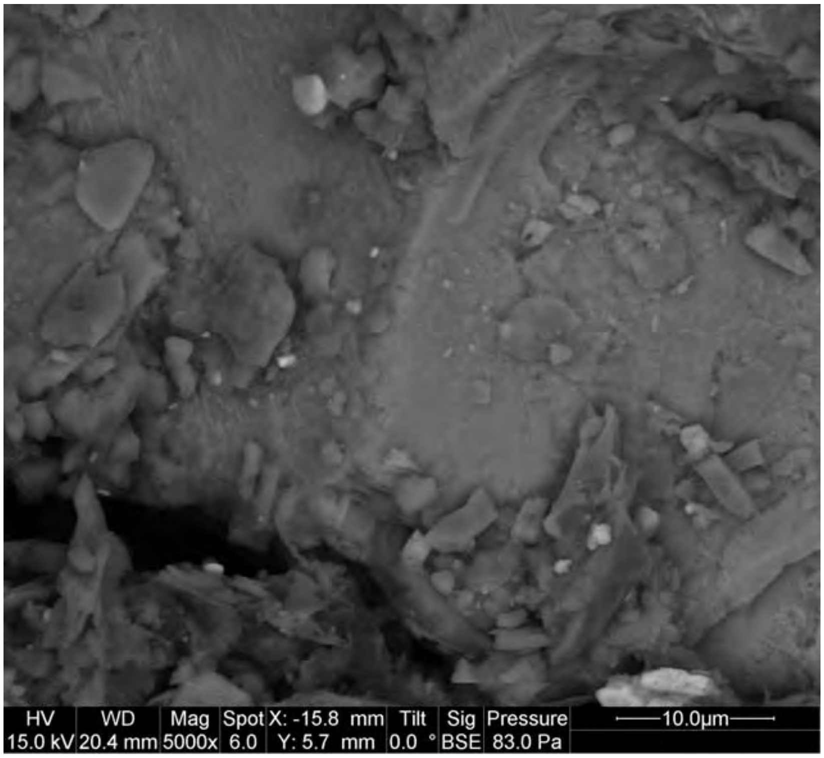
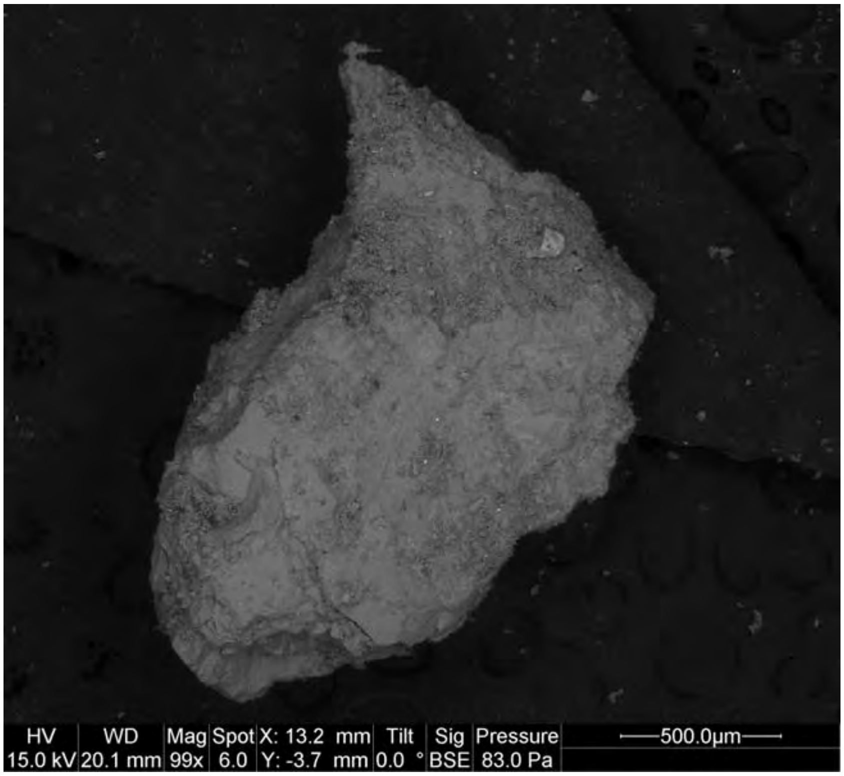
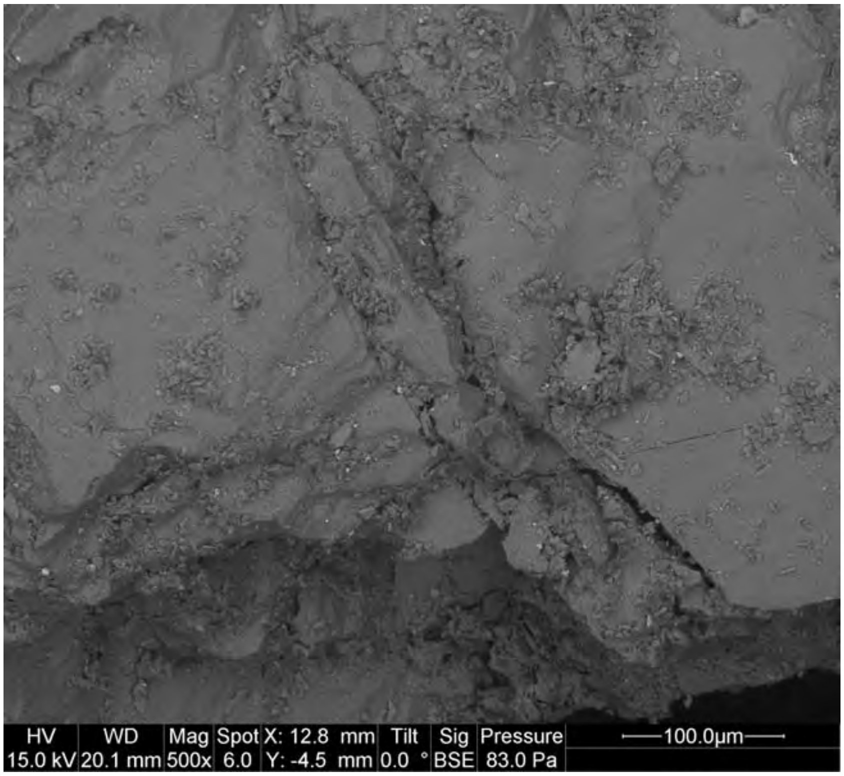
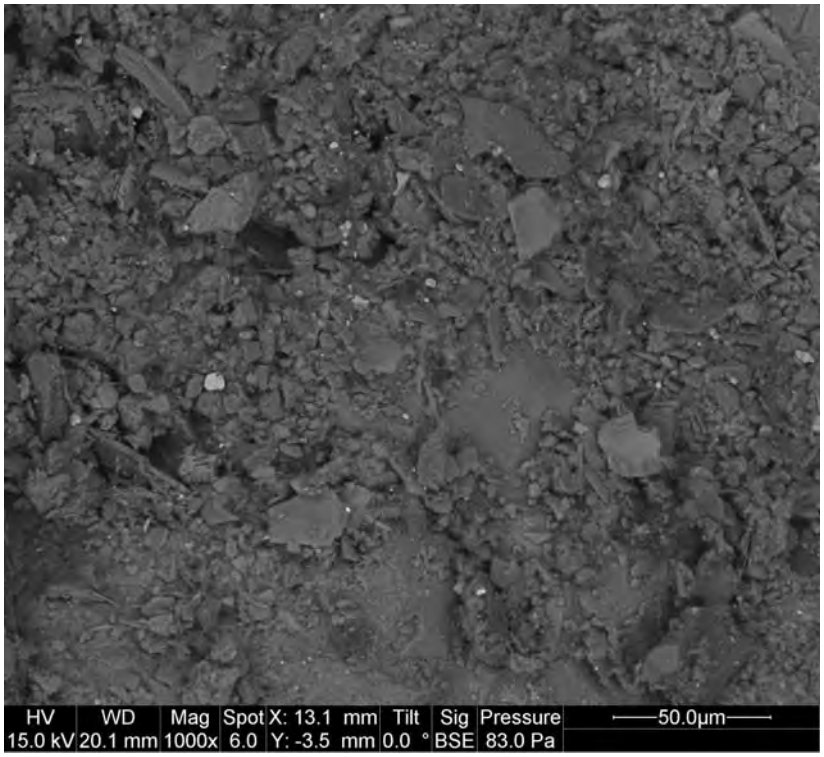

HV 15.0 kV
WD 20.4 mm
Mag 5000x
Spot 6.0
X: -15.8 mm
Y: 5.7 mm
Tilt 0.0 °
Sig BSE
Pressure 83.0 Pa
10.0µm

Figure F-5. Electron microscope images (4 frames) of WTR particles post-adsorption from a BSM + 4% WTR + HBM mixture subject to continuous flow. Media was dried at 103°C for 2 hours and sieved to between 300 and 590 µm prior to imaging.




HV 15.0 kV
WD 20.1 mm
Mag 500x
Spot 6.0
X: 12.8 mm
Y: -4.5 mm
Tilt 0.0 °
Sig BSE
Pressure 83.0 Pa
100.0µm


HV 15.0 kV
WD 20.1 mm
Mag 1000x
Spot 6.0
X: 13.1 mm
Y: -3.5 mm
Tilt 0.0 °
Sig BSE
Pressure 83.0 Pa
50.0µm

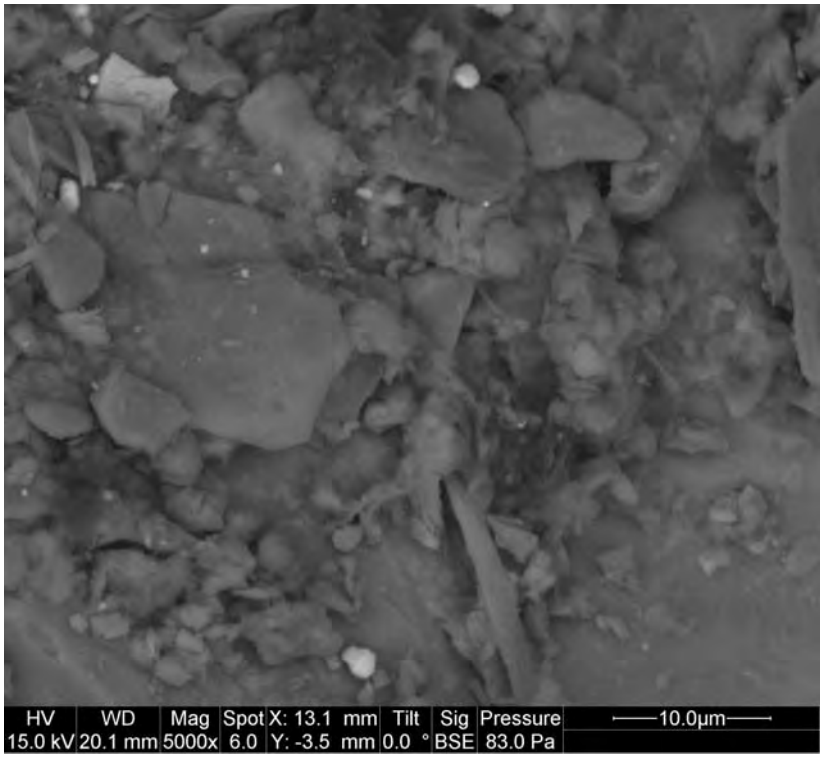
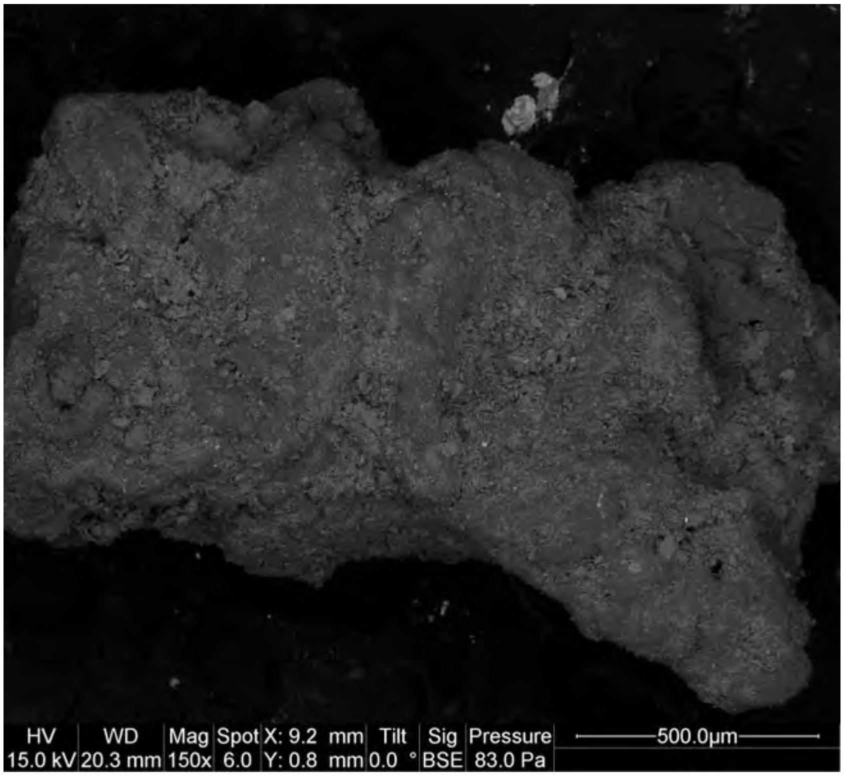
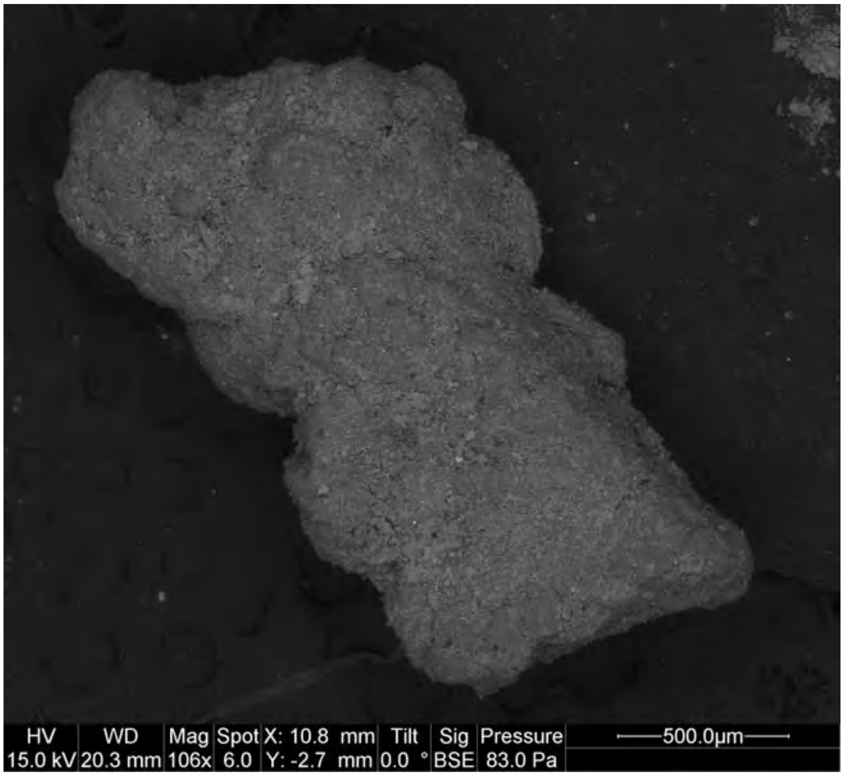


Figure F-6. Electron microscope images (4 frames) of BSM grains post-adsorption from a BSM + 4% WTR + HBM mixture subject to intermittent flow. Media was dried at 103°C for 2 hours and sieved to between 300 and 590 µm prior to imaging.


HV 15.0 kV
WD 20.3 mm
Mag 150x
Spot 6.0
X: 9.2 mm
Y: 0.8 mm
Tilt 0.0 °
Sig BSE
Pressure 83.0 Pa
500.0µm


HV 15.0 kV
WD 20.3 mm
Mag 106x
Spot 6.0
X: 10.8 mm
Y: -2.7 mm
Tilt 0.0 °
Sig BSE
Pressure 83.0 Pa
500.0µm

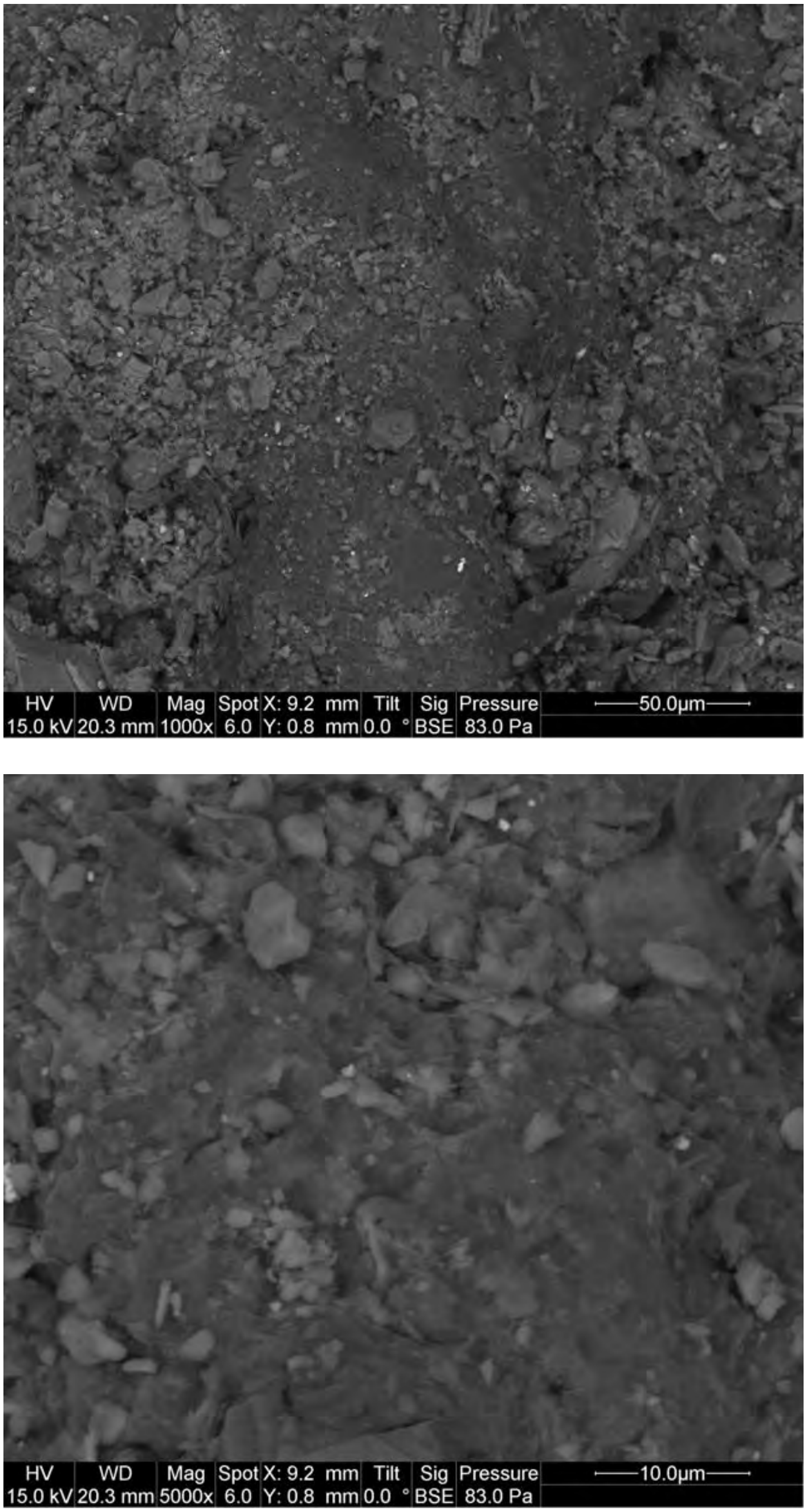


Figure F-7. Electron microscope images (4 frames) of WTR particles post-adsorption from a BSM + 4% WTR + HBM mixture subject to intermittent flow. Media was dried at 103°C for 2 hours and sieved to between 300 and 590 µm prior to imaging.

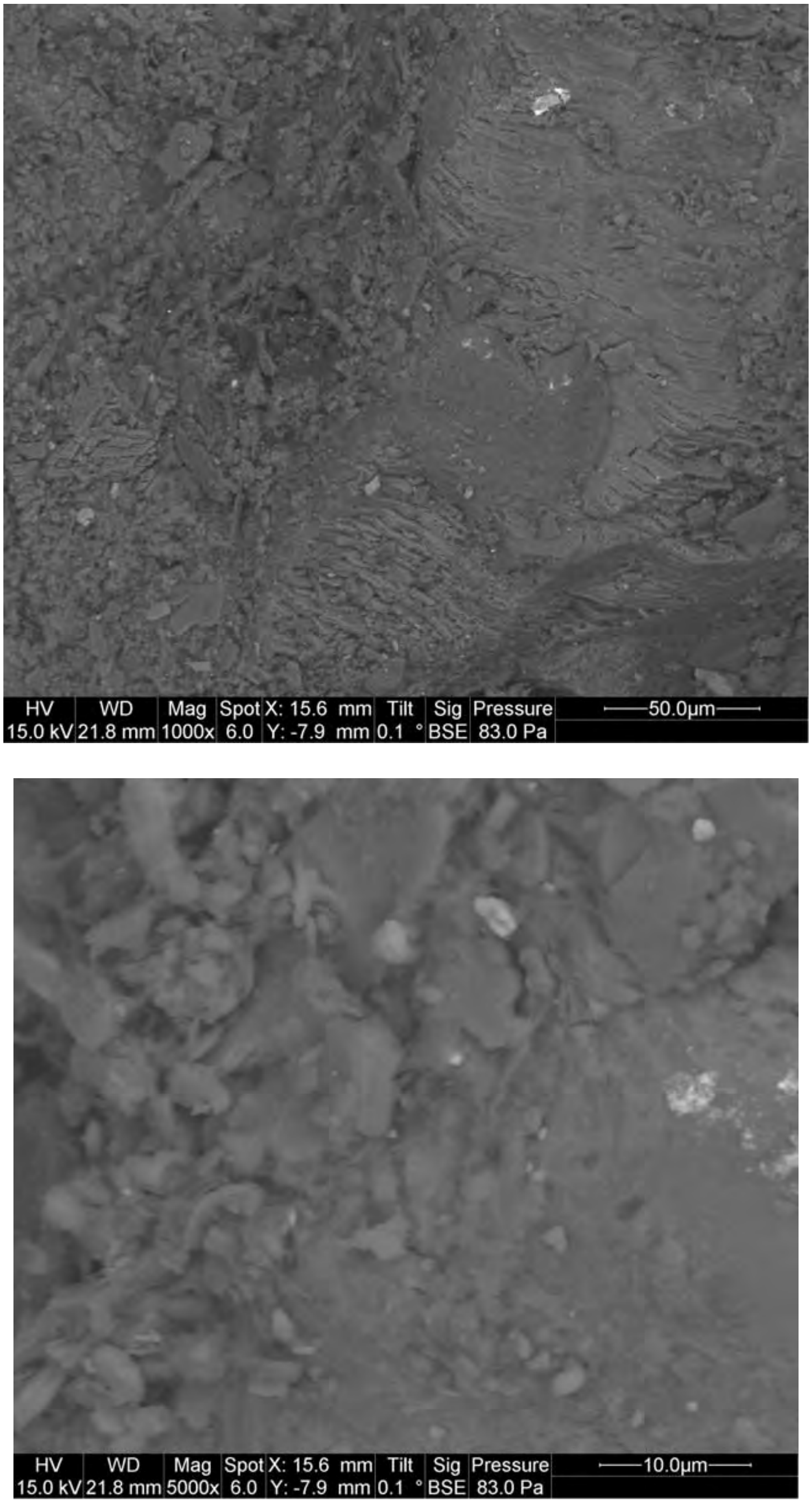
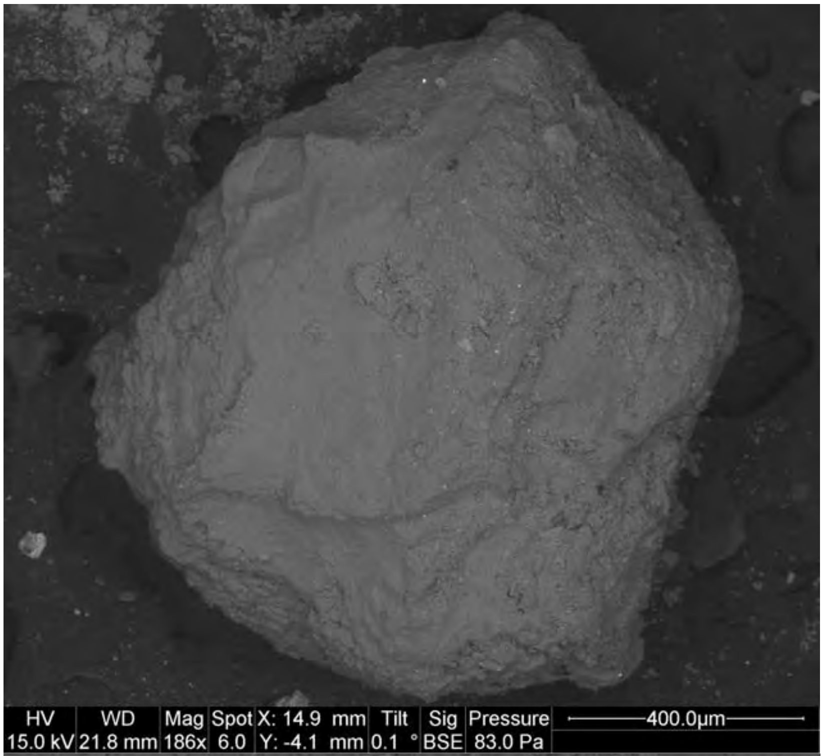
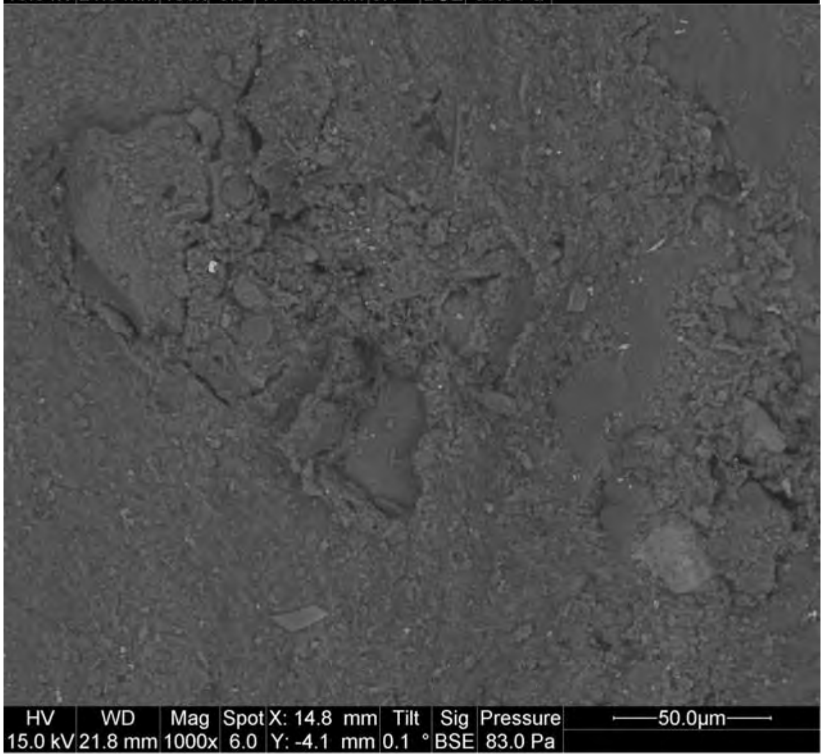


Figure F-8. Electron microscope images (3 frames) of soil grains (i.e., BSM grains) post-adsorption from a LFBSM + 4% WTR mixture subject to intermittent flow.

Media was dried at 103°C for 2 hours and sieved to between 300 and 590 µm prior to imaging.





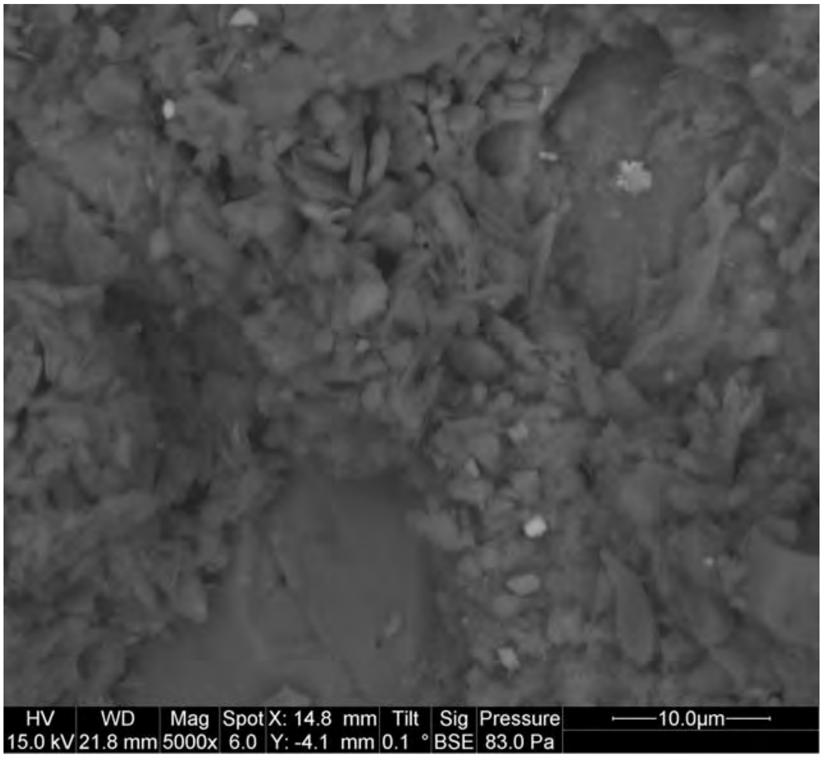
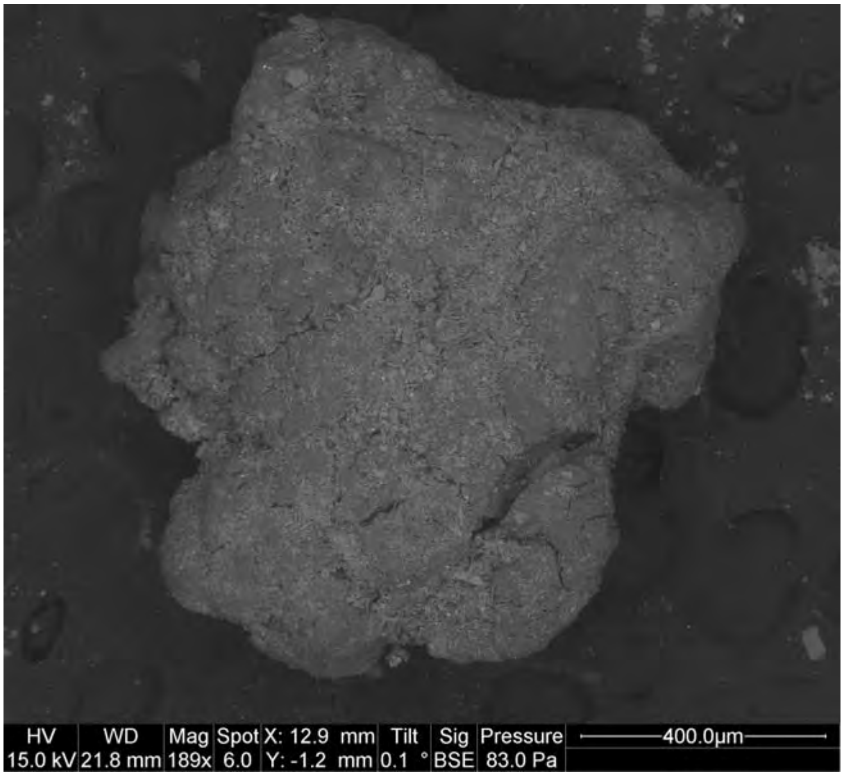
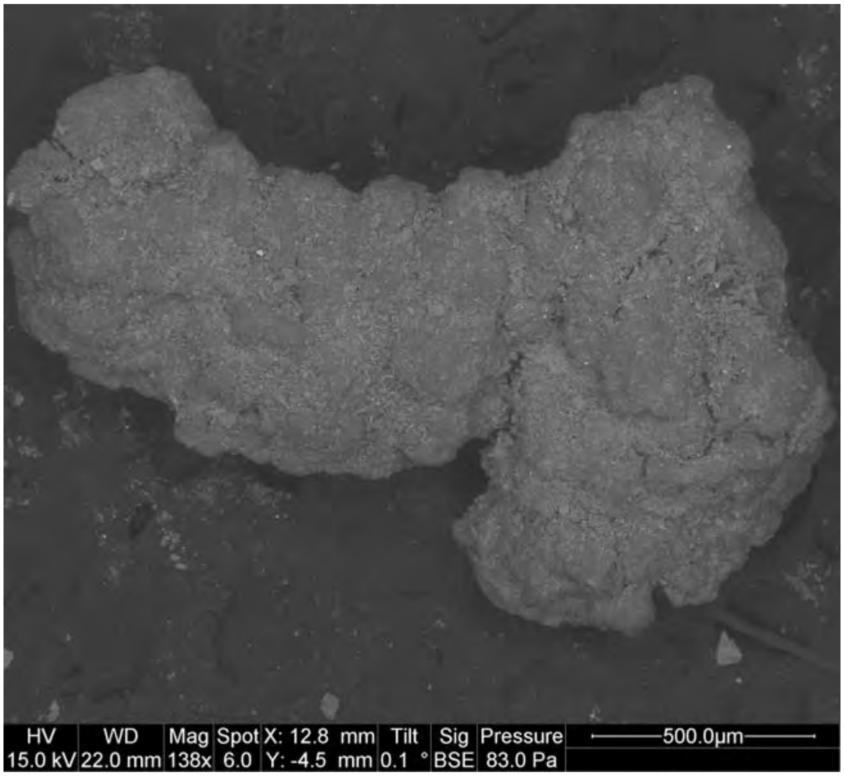


Figure F-9. Electron microscope images (3 frames) of quartz sand grains post-adsorption from a LFBSM + 4% WTR mixture subject to intermittent flow. Media was dried at 103°C for 2 hours and sieved to between 300 and 590 µm prior to imaging.


HV 15.0 kV
WD 21.8 mm
Mag 189x
Spot 6.0
X: 12.9 mm
Y: -1.2 mm
Tilt 0.1 °
Sig BSE
Pressure 83.0 Pa
400.0µm


HV 15.0 kV
WD 22.0 mm
Mag 138x
Spot 6.0
X: 12.8 mm
Y: -4.5 mm
Tilt 0.1 °
Sig BSE
Pressure 83.0 Pa
500.0µm

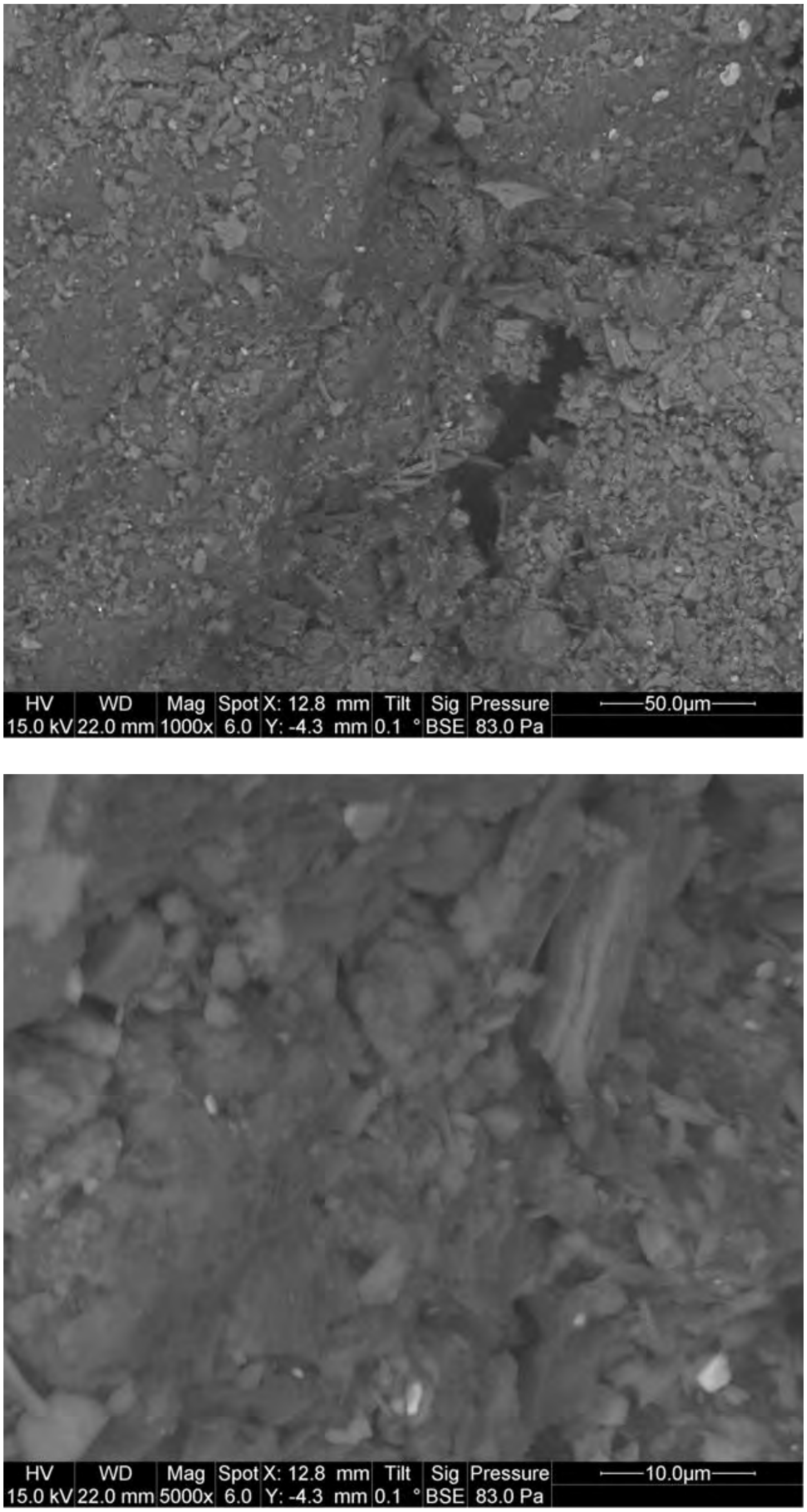


Figure F-10. Electron microscope images (4 frames) of WTR particles post-adsorption from a LFBSM + 4% WTR mixture subject to intermittent flow. Media was dried at 103°C for 2 hours and sieved to between 300 and 590 μm prior to imaging.

Citations

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APPENDIX E

Assessment of SHA Stream Restoration Projects in Maryland: 1998-2010

December 2010

ASSESSMENT OF SHA STREAM RESTORATION PROJECTS IN MARYLAND: 1998-2010

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Prepared for:
Maryland Department of Transportation
State Highway Administration
Highway Hydraulics Division
707 North Calvert Street
Baltimore, MD 21202

Principal Investigator
R. P. Morgan II

Contributing Staff
D. M. Gates
M. J. Kline
M. R. Lutmerding
M. R. Sell

University System of Maryland
Center for Environmental Science
Appalachian Laboratory
301 Braddock Road
Frostburg, MD 21532-2307

December 2010

ASSESSMENT OF SHA STREAM RESTORATION PROJECTS IN MARYLAND: 1998-2010

I. Introduction

A. Stream Restoration

Stream restoration is of critical importance to Maryland. The overall quality of life, now and in the future, is highly dependent on aquatic ecosystem integrity (reviewed by Simon 1999). The integrity of surface water resources is driven by chemical variables, flow regimes, biotic factors, energy sources, and habitat structure (Karr et al. 1986). Over the last quarter century, fish communities have been extensively employed to assess 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, habitat quality (and often quantity) is important to consider when examining fish communities, especially for all derived IBIs (Yoder and Smith 1999).

Stream restoration strongly focuses on physical habitat revitalization. However, indices of habitat quality to assess post-restoration processes have lagged behind fish and benthic IBI development. In part, this is because of difficulty in developing accurate, precise and complete methodologies to assess quantitatively and qualitatively habitat characteristics (Platts 1976, Platts et al. 1983). Impetus for including stream habitat as an important measure came initially from the west (reviewed in Platts et al. 1983). For example, Binns (1979) developed a Habitat Quality Index for trout streams, soon followed by Habitat Evaluation Procedures models (HEP) and Habitat Suitability Index models (HSI) for use with the 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 restoration attempts. Recolonization of a disturbed or restored area is a function of many factors, depending on stream size. Implicit in restoration is that long-term stream stability eventually recovers. However, benthic macroinvertebrates respond to many disturbances, and restoration processes directed towards the physical habitat may not take into account other problems. The importance of nearby refugia, as a source for recolonization is also critical (Wallace 1990).

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) – there is now 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, there are now powerful tools available to assess stream integrity in Maryland (Southerland et al. 2005, 2007). These indices are robust, and allow inferences on stream integrity and stability, either regionally, statewide, or at site-specific levels. In addition, these indices are constantly being refined with more MBSS rounds completed, especially with the development of coldwater 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 has often been 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).

B. Project History

The Maryland Department of Transportation, State Highway Administration (SHA) received federal funding for assessment of stream restoration projects in Maryland for a number of years. For these projects, the principal SHA goal was to restore stream physical structure in order to repair unstable physical habitat, with mitigation as a key component of their efforts.

SHA required 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 adminstration. Information collected from these studies, undertaken by the Appalachian Laboratory of the University of Maryland Center for Environmental Science, provided a framework and historical database for recommendations for future SHA restoration projects, and for assessment and potential revitalization of existing SHA restoration projects throughout Maryland.

The first set of SHA assessment projects was completed during 1998-1999 with studies on seven sites throughout Maryland, primarily in the Piedmont and Coastal Plain (Morgan et al. 1999). These first stream restoration assessments set the stage for future work. The second report on SHA assessment projects (1999-2000) focused on six sites, many of which were studied in 1998-1999, and included one site (Porter Run) in Allegany County that borders the Ridge and Valley/Allegheny Plateau physiographic provinces of Maryland (Morgan et al. 2000).

The third report covered seven sites that were studied in 2000-2001 (Morgan et al. 2001). Piney Creek, located in Baltimore County, was added to the list of sites for study. One other new site, located on Hammond Branch, was sampled for benthic macroinvertebrates in spring 2001. These seven sites spanned the western shore of Maryland from the coastal plain to the Ridge and Valley/Allegheny Plateau, and represented a variety of stream habitats present in Maryland. The fourth report covered eight sites studied in 2001-2002 (Morgan et al. 2002). Hammond Branch, a pre-restoration site, located in Howard County, was added to the list of sites for study. These sites continued to span the western shore of Maryland from the coastal plain to the Ridge and Valley/Allegheny Plateau.

The fifth report covered seven sites throughout Maryland assessed during 2002-2003 (Morgan et al. 2003). One site, Muddy Branch, previously assessed in 1998-1999 as a pre-restoration site, was now a post-restoration site. These sites continued to span the western shore of Maryland from the coastal plain to the Ridge and Valley/Allegheny Plateau. (Note: Another site located near Bowie, MD was added to the 2002-2003 sampling; since only spring sampling was performed, this site was discussed in the 2003-2004 report). In addition to reporting on the sites, we made monitoring recommendations on Little Paint Branch and Piney Creek: two sites that are no longer being assessed but have been placed on a long-term schedule to examine stream restoration effectiveness. The sixth report, in the SHA stream restoration assessment series, covered seven sites throughout Maryland assessed during 2003-2004 (Morgan et al. 2004). Two sites, Muddy Branch and Forty Foot Branch, previously were assessed in 1998-1999 as pre-restoration sites, and are now post-restoration sites. These sites spanned the western shore of Maryland from the coastal plain to the Ridge and Valley/Allegheny Plateau.

The seventh report, in the SHA stream restoration assessment series, covered nine sites throughout Maryland assessed during 2004-2005 (Morgan et al. 2005). Two sites, Muddy Branch and Forty Foot Branch, were assessed in 1998-1999 as pre-restoration sites – now post-restoration sites. These sites spanned the western shore of Maryland from the coastal plain to the Ridge and Valley/Allegheny Plateau. The eighth report, in the stream restoration assessment series, covers eight sites throughout Maryland assessed during 2005-2006 (Morgan et al. 2006). These SHA stream restoration sites spanned the western shore of Maryland from the Coastal Plain to the Ridge and Valley/Allegheny Plateau.

The ninth report, in the stream restoration assessment series, covers eight sites throughout Maryland assessed during 2006-2007 (Morgan et al. 2007). These SHA stream restoration sites spanned the western shore of Maryland from the Coastal Plain to the Piedmont. In addition, there is a special restoration project located on Route 220, near Cumberland, MD included in this report as a separate project. This site is surveyed annually for physical habitat only. The tenth report, in the SHA stream restoration assessment series, covers eight sites throughout Maryland assessed during 2007 – 2008 (Morgan et al. 2008). These SHA stream restoration sites spanned the western shore of Maryland from the Coastal Plain to the Piedmont. The first revisit of a restored site was done at Tributary Nine – five years after the last assessment. In addition, the special restoration project located on Route 220, near Cumberland, MD was included.

The eleventh report, in the SHA stream restoration assessment series, covered seven sites throughout Maryland assessed during 2008 – 2009 (Morgan and Lutmerding 2009). These SHA stream post-restoration sites spanned the western shore of Maryland from the Coastal Plain to the Piedmont. In addition, the special restoration project located on Route 220, near Cumberland, MD was included. During a spring storm, the effect of high flows on the restoration structure was assessed for the first time. Additional data was collected from 2009 -2010 at five sites, with this information folded into the analyses for this report.

C. Project Objective

For all SHA site projects, the overall objective was to assess and monitor completed (and proposed) SHA stream restoration efforts and to make recommendations for future restoration projects, as well as potential improvement and revitalization of current restoration projects. To complete the project objective, a number of field and laboratory tasks were undertaken in agreement with SHA. This current report focuses on a detailed analysis of fourteen sites, with the purpose of synthesizing data collected since 1998 to the present (Morgan and Lutmerding 2009, Morgan et al. 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, and 2008). Data collected in 2009-2010 were incorporated into the current report since these same sites were sampled in the 2008-2009 work. In addition, we developed a monitoring schedule for examining all fourteen completed stream restoration projects in the long-term (5, 10, and 25 years) based on observed results for each site.

II. Methods

A. Site Locations

From 1998 through 2010, fourteen stream restoration projects completed by SHA were assessed and monitored for benthic macroinvertebrates, fishes and physical habitat (Table 1). All restoration projects were in the Washington-Baltimore urban area (Piedmont and Coastal Plain) with the exception of Porter Run (Ridge and Valley), located in Allegany County near Frostburg, MD. In addition to those SHA projects where both pre-restoration and post-restoration assessments were completed over a number of years, seven other projects, including Long Draught Branch, an unnamed tributary to Tuscarora Creek, an unnamed tributary to Gunpowder Falls, an unnamed tributary to Fourth Mine Branch, Sullivan Branch, an unnamed tributary to Rocky Gorge Reservoir, and an unnamed tributary to Jennings Run, were surveyed as pre-restoration sites - no post-restoration assessment work has been done at these sites to date, with the potential that restoration construction may be cancelled for some sites..

All projects had a restoration site and a control site component with the exception of an unnamed tributary to Patuxent Run (Patuxent Run) and an unnamed tributary to Herbert Run (Herbert Run) in the stream restoration assessment program (Table 1). Often, control sites are very difficult to select in agricultural or highly developed watersheds, or in small watersheds. We 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 major habitat changes in control sites during the study. To compensate for this problem, we employed data from the Maryland Biological Stream Survey (MBSS) from 1995-1997 (Round One), 2000-2004 (Round Two), and 2007-2009 (Round Three) 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 held constant (Green 1979). This approach determines an effect, or effects, at a site relative to a valid control. However, there is so much anthropogenic activity in the landscape of the Coastal Plain (especially the western shore segment) and Piedmont, as well as other physiographic provinces of Maryland, that watersheds are being strongly altered through time and space (Lookingbill et al. 2009). It may be necessary at some sites to move downstream into lower reaches of the watershed and then determine current conditions to assess the upstream site. However, this is not a desirable approach, especially since the MBSS data is available for comparisons.

B. Benthic Macroinvertebrates

Assessment of benthic macroinvertebrates at each control and restoration site basically followed benthic macroinvertebrate protocols for MBSS sampling (Kazyak 1996, Stranko et al. 2010). One sample was collected near the lower (downstream boundary) of the project site. The upper sample was collected approximately one-third to one-half of the distance from the upper (upstream boundary) of the project (benthic sampling sites were modified dependent on site characteristics). An additional sample, serving as a control, was collected upstream of the stream restoration project, assuming that the upstream area acted as a suitable control area. For the pre-construction sites, two D-net samples were taken within the proposed project boundaries, along with a control from an upstream area.

C. Benthic Field Sampling Protocols

Benthic macroinvertebrate sampling was conducted in order to be able to qualitatively describe the community composition and relative abundance in favorable habitat at each sampling station. All survey collection methods for benthic macroinvertebrates followed MBSS protocols (Kazyak 1996, Stranko et al. 2010). D-net samples (a total of ~ 1.9 m^2 or ~ 20 ft^2) were taken at each sampling location (Kazyak 1996, Stranko et al. 2010). All benthic samples, as often as possible, were collected from riffle areas of the stream 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.

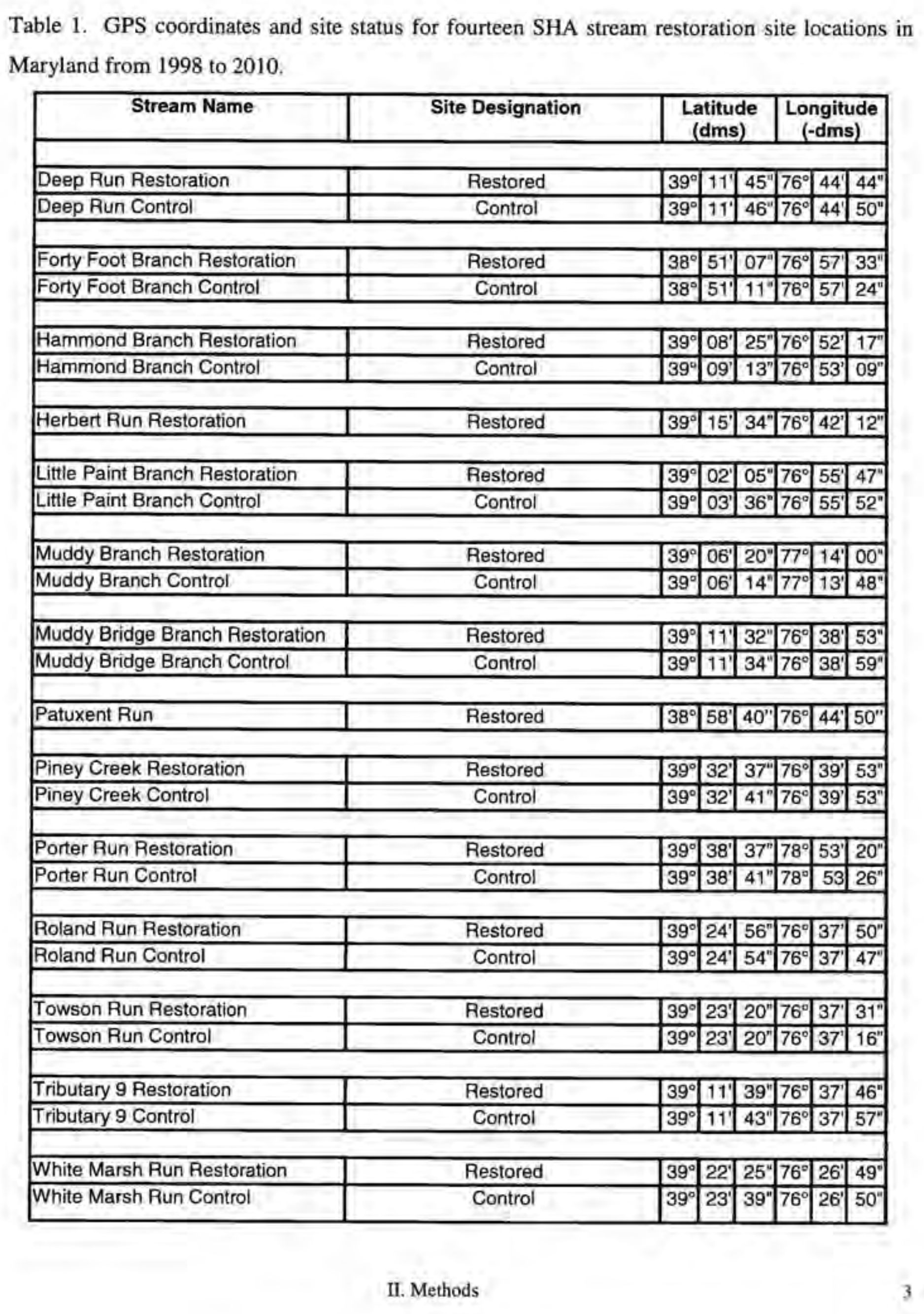

Table 1. GPS coordinates and site status for fourteen SHA stream restoration site locations in Maryland from 1998 to 2010.

Stream Name	**Site Designation**	**Latitude (dms)**			**Longitude (-dms)**		
Deep Run Restoration	Restored	39°	11'	45"	76°	44'	44"
Deep Run Control	Control	39°	11'	46"	76°	44'	50"
Forty Foot Branch Restoration	Restored	38°	51'	07"	76°	57'	33"
Forty Foot Branch Control	Control	38°	51'	11"	76°	57'	24"
Hammond Branch Restoration	Restored	39°	08'	25"	76°	52'	17"
Hammond Branch Control	Control	39°	09'	13"	76°	53'	09"
Herbert Run Restoration	Restored	39°	15'	34"	76°	42'	12"
Little Paint Branch Restoration	Restored	39°	02'	05"	76°	55'	47"
Little Paint Branch Control	Control	39°	03'	36"	76°	55'	52"
Muddy Branch Restoration	Restored	39°	06'	20"	77°	14'	00"
Muddy Branch Control	Control	39°	06'	14"	77°	13'	48"
Muddy Bridge Branch Restoration	Restored	39°	11'	32"	76°	38'	53"
Muddy Bridge Branch Control	Control	39°	11'	34"	76°	38'	59"
Patuxent Run	Restored	38°	58'	40"	76°	44'	50"
Piney Creek Restoration	Restored	39°	32'	37"	76°	39'	53"
Piney Creek Control	Control	39°	32'	41"	76°	39'	53"
Porter Run Restoration	Restored	39°	38'	37"	78°	53'	20"
Porter Run Control	Control	39°	38'	41"	78°	53	26"
Roland Run Restoration	Restored	39°	24'	56"	76°	37'	50"
Roland Run Control	Control	39°	24'	54"	76°	37'	47"
Towson Run Restoration	Restored	39°	23'	20"	76°	37'	31"
Towson Run Control	Control	39°	23'	20"	76°	37'	16"
Tributary 9 Restoration	Restored	39°	11'	39"	76°	37'	46"
Tributary 9 Control	Control	39°	11'	43"	76°	37'	57"
White Marsh Run Restoration	Restored	39°	22'	25"	76°	26'	49"
White Marsh Run Control	Control	39°	23'	39"	76°	26'	50"

In addition to D-net samples, a Coarse Particulate Organic Matter (CPOM) sample, containing several handfuls of litter, was also collected at each site, if available (Minshall et al. 1985). Samples were then transferred to polyethylene bottles and preserved in 5% neutral buffered formalin or denatured ethanol. Samples were collected during the MBSS spring index period and during the MBSS fall index period (Kazyak 1996, Stranko et al. 2010).

D. Benthic Laboratory Protocols

In the laboratory, samples were washed, picked, and stored in 70% isopropyl alcohol. Debris was removed from each, and the first 200 organisms (to the nearest grid) were picked for identification to the lowest taxon possible (Plafkin et al. 1989). If a sample contained less than 200 organisms, the sample was picked completely. All invertebrates in the CPOM samples were identified and enumerated into appropriate shredder, collector, scraper, and predator functional groups (Plafkin et al. 1989). For many years, we have also employed EPA protocols, or a modification of these protocols, for rapid assessment of stream benthic macroinvertebrates, using the Rapid Bioassessment Protocol III (RBP III) - Benthic Invertebrates (Plafkin et al. 1989)..

E. Benthic Macroinvertebrate Statistical Protocols

Seven basic metrics are usually calculated for the riffle/run and CPOM samples, using the RBP III (Plafkin et al. 1989, Klemm et al. 1990). These metrics are: taxa richness (or species richness), a modified Family Biotic Index (FBI) or modified Hilsenhoff Biotic Index (Hilsenhoff 1987, Resh 1995 and DeShon 1995), the ratio of scrapers to filtering collectors, the ratio of the number of shredders to the total number of individuals collected, the ratio of the total number of Ephemeroptera, Plecoptera, and Trichoptera to the total number of Chironomidae collected, the EPT index (total number of distinct taxa within the orders Ephemeroptera, Plecoptera, and Trichoptera), and the percent contribution of the dominant taxon in the riffle community (Plafkin et al. 1989). In addition to the seven metrics, we also calculate the number of Ephemeroptera taxa and % Ephemeroptera, dipteran taxa, % Tanytarsini, intolerant taxa and tolerant taxa.

F. Benthic Index of Biotic Integrity (BIBI)

A benthic index of biotic integrity (BIBI) for Maryland was used in this project (Stribling et al. 1998, Southerland et al. 2005, 2007). 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 good, 3.0 - 3.9 is fair, 2.0 - 2.9 is poor, and 1.0 - 1.9 is very poor (Table 2).

Table 2. Narrative descriptions of stream biological integrity associated with each of the IBI categories (both fish and benthic IBI scores).

Good	IBI score 4.0 - 5.0	Comparable to reference streams considered to be minimally impacted. Fall within the upper 50% of reference site conditions.
Fair	IBI 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	IBI 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	IBI 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.

G. Fishes

To sample fishes, protocols from the MBSS were also employed (Kazyak 1996). Quantitative double-pass electrofishing of 75-m stream segments were used to describe fish abundance and community composition. Collection was made using a Smith-Root backpack electrofishing unit (or more, depending on site size) with at least two field personnel. Fishes were sampled during the summer/fall index period (August to October). All fish from each pass were sorted and enumerated to species and recorded on the data sheet. Any individuals not clearly identifiable to species were retained for laboratory analysis. Fish were released after processing.

H. Fish Index of Biotic Integrity

Fish Indices of Biotic Integrity (FIBI) were developed for the MBSS (Roth et al. 1998, Southerland et al. 2005, 2007). The revised FIBI is broken down into Coastal Plain, Eastern

Piedmont, Warmwater Highlands, and Coldwater Highlands metrics (Southerland et al. 2005, 2007). Scoring for the FIBI follows the BIBI scoring (Table 2).

I. Habitat Assessment

Stream physical habitat data is an essential component of any assessment program. Habitat data normally is used to assess trends in water quality and to investigate the influence of land use practices that may affect water quality. Habitat assessments were performed at all sites in order to determine biological integrity and fishability. Habitat assessments were based on MBSS protocols (Kazyak 1996, Stranko et al. 2010). Physical habitat categories were defined as good being > 72 (> 50th centile), fair 42-72 (30th to 50th centile), poor 12-42 (10th to 30th centile) and very poor < 12 (10th centile).

J. Statistical Analyses

Statistica (Version 7.1, StatSoft, Tulsa, OK) and Stata (StataCorp LP, College Station TX) were used for parametric and non-parametric analyses, with statistical significance set at $\rho \leq 0.05$ (Elliott 1973). Prior to statistical analyses, appropriate transformations were employed and homogeneity was tested (Sokal and Rohlf 1995). Generally, we focused on analyses of the number of benthic taxa, number of EPT, number of Ephemeroptera, % Ephemeroptera, % Tanytarsini (non-biting midges), BIBI, FIBI and MPHI for each restoration site.

III. Results

Each SHA restoration project is reviewed based on analysis of fourteen SHA sites, with the purpose of synthesizing detailed site data collected since 1998 to the present (Morgan and Lutmerding 2009, Morgan et al. 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007 and 2008). Supporting information for each restoration site is contained within the yearly reports and not included in this report.

A. Deep Run

Deep Run, a post-restoration site in the Coastal Plain, is a second order stream, eventually becoming a third order stream before entering the Patapsco River. Sampling started for this site in October 1998 with sampling completed in March 2005 (Morgan et al. 2005).

Four benthic parameters (repeated measures ANOVA) did not show any significant difference of control versus restoration sites, but showed strong seasonal differences (Table 2). For example, the number of EPT taxa over all three sampling stations was 5.1 in the fall and 1.9 in the spring. This pattern held for three of the four benthic parameters analyzed except for % Tanytarsini. The reason for this difference may lie with the fall sampling being done at lower flows, where organisms may be more concentrated. However, there is also a possibility that the benthic assemblage responds to altered, higher flows in the spring especially if there is a significant amount of altered habitat in the upstream catchment. In addition, the non-significance value of the control site versus the two restoration sites is important since it indicates that the restoration sites are roughly equivalent to the upstream control after the construction activities are complete (Table 2). Basically, the restoration efforts have done no harm to the system, and now reflect the upstream characteristics.

Although BIBI values were low among sites (2.2-2.5), average FIBI for the restored site was 4.0 – a significant improvement since construction (Table 2). The mean MPHI for the control was 52 and for the restored site 75, indicating an overall improvement in stream habitat. The Kolmogorov-Smirnov (K-S) test was non-significant, but the t-test was significant ($\rho \leq 0.05$). We observed some variation over all sample years in MPHI related to the observed flow regime.

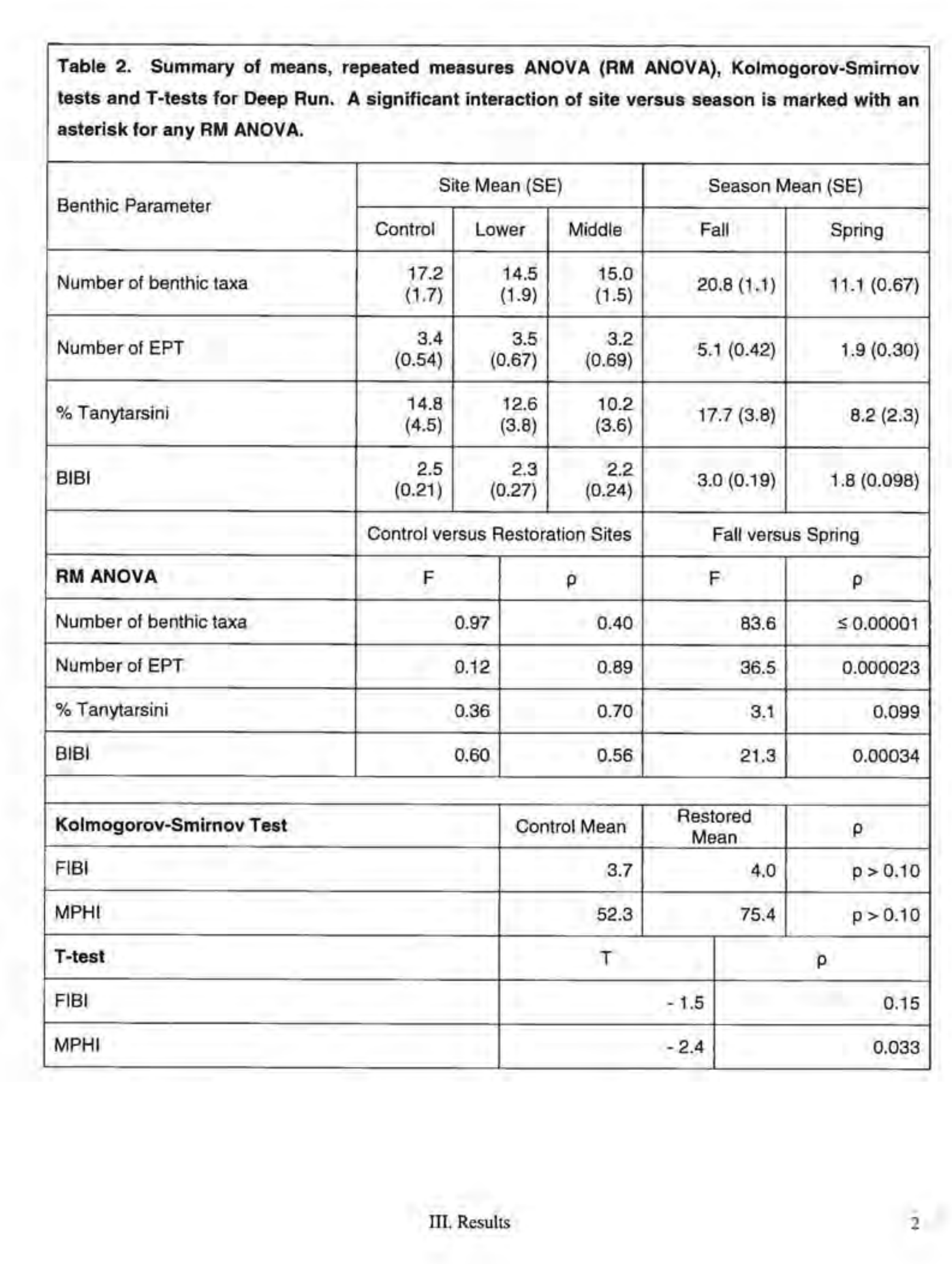

Table 2. Summary of means, repeated measures ANOVA (RM ANOVA), Kolmogorov-Smirnov tests and T-tests for Deep Run. A significant interaction of site versus season is marked with an asterisk for any RM ANOVA.

Benthic Parameter	Site Mean (SE)			Season Mean (SE)	
	Control	Lower	Middle	Fall	Spring
Number of benthic taxa	17.2 (1.7)	14.5 (1.9)	15.0 (1.5)	20.8 (1.1)	11.1 (0.67)
Number of EPT	3.4 (0.54)	3.5 (0.67)	3.2 (0.69)	5.1 (0.42)	1.9 (0.30)
% Tanytarsini	14.8 (4.5)	12.6 (3.8)	10.2 (3.6)	17.7 (3.8)	8.2 (2.3)
BIBI	2.5 (0.21)	2.3 (0.27)	2.2 (0.24)	3.0 (0.19)	1.8 (0.098)

	Control versus Restoration Sites		Fall versus Spring	
RM ANOVA	F	p	F	p
Number of benthic taxa	0.97	0.40	83.6	≤ 0.00001
Number of EPT	0.12	0.89	36.5	0.000023
% Tanytarsini	0.36	0.70	3.1	0.099
BIBI	0.60	0.56	21.3	0.00034

Kolmogorov-Smirnov Test	Control Mean	Restored Mean	p
FIBI	3.7	4.0	$p > 0.10$
MPHI	52.3	75.4	$p > 0.10$

T-test	T	p
FIBI	- 1.5	0.15
MPHI	- 2.4	0.033

B. Forty Foot Branch

Forty Foot Branch, located in Prince George's County, is a small first order stream flowing into Oxon Run, a tributary to the Potomac River. The stream is located within the Coastal Plain physiographic region and the Potomac-Washington Metro Basin, extending from Piscataway Creek in Prince George's County to the Little Monocacy River in Montgomery County. Sampling started for this site in October 1998 with sampling completed in April 2010 (Morgan and Lutmerding 2009, with additional information added from sample year 2009-2010).

For Forty Foot Branch, the four benthic parameters (repeated measures ANOVA) did not show any significant difference of control versus the two restoration sites, but showed strong seasonal differences for the number of EPT and the BIBI (Table 3). The benthic metric % Tanytarsini was higher in the fall than the spring, but the range was very variable from 0-21% (fall) versus 0-9.4% (spring). Over the three sites, the BIBI was consistent, ranging from 2.0-2.1, the poor range for this metric. As with Deep Run, the reason for this difference may lie with the fall sampling being done at lower flows or effects from higher spring flows. The non-significance value of the control site versus the two restoration sites for Forty Foot branch is important since it indicates that the two restoration sites are roughly equivalent to the upstream control after completed construction activities (Table 3).

The average FIBI for the control (1.3) and restored site (1.5) was in the very poor range. However, three fish species were collected at the restoration site versus one species at the control site – a pattern consistent since 2007, and perhaps expected due to the small stream size. The mean MPHI for the control was 35 and for the restored site 84, indicating an overall significant improvement in stream habitat at Forty-Foot Branch (K-S and t-test, Table 3).

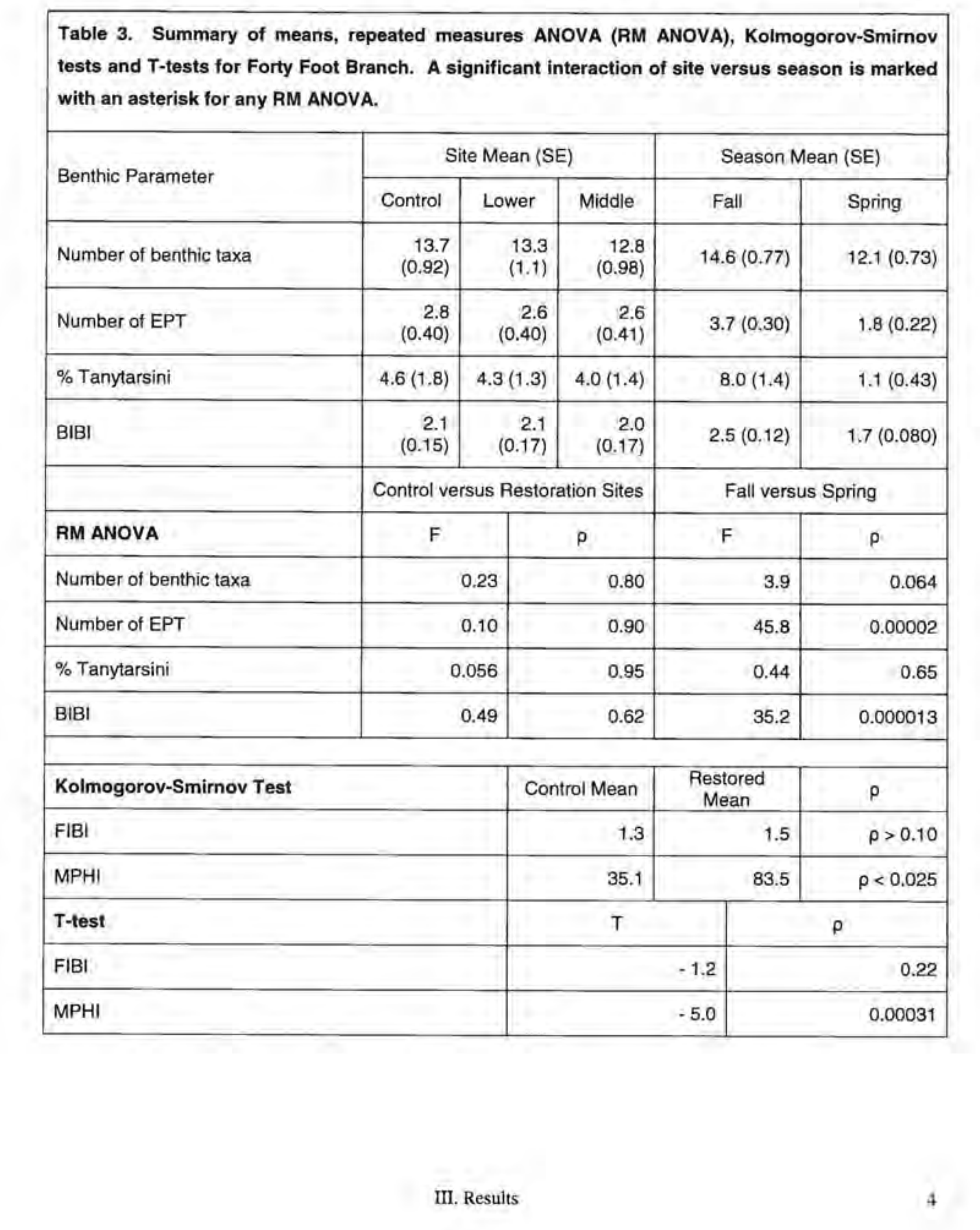

Table 3. Summary of means, repeated measures ANOVA (RM ANOVA), Kolmogorov-Smirnov tests and T-tests for Forty Foot Branch. A significant interaction of site versus season is marked with an asterisk for any RM ANOVA.

Benthic Parameter	Site Mean (SE)			Season Mean (SE)	
	Control	Lower	Middle	Fall	Spring
Number of benthic taxa	13.7 (0.92)	13.3 (1.1)	12.8 (0.98)	14.6 (0.77)	12.1 (0.73)
Number of EPT	2.8 (0.40)	2.6 (0.40)	2.6 (0.41)	3.7 (0.30)	1.8 (0.22)
% Tanytarsini	4.6 (1.8)	4.3 (1.3)	4.0 (1.4)	8.0 (1.4)	1.1 (0.43)
BIBI	2.1 (0.15)	2.1 (0.17)	2.0 (0.17)	2.5 (0.12)	1.7 (0.080)

	Control versus Restoration Sites		Fall versus Spring	
RM ANOVA	F	p	F	p
Number of benthic taxa	0.23	0.80	3.9	0.064
Number of EPT	0.10	0.90	45.8	0.00002
% Tanytarsini	0.056	0.95	0.44	0.65
BIBI	0.49	0.62	35.2	0.000013

Kolmogorov-Smirnov Test	Control Mean	Restored Mean	p
FIBI	1.3	1.5	$p > 0.10$
MPHI	35.1	83.5	$p < 0.025$

T-test	T	p
FIBI	- 1.2	0.22
MPHI	- 5.0	0.00031

III. Results 4

C. Hammond Branch

Hammond Branch is a 2nd order stream and is a tributary to the Little Patuxent River, which flows into the Patuxent River and then into the Chesapeake Bay, and borders the Piedmont and Coastal Plain Physiographic Provinces. The restoration and control sites on this stream were located in the Coastal Plain Physiographic Province, creating some problems in that there is the potential for a mixture of fish fauna from the two provinces. Sampling started for this site in May 2001 with sampling completed in April 2009 (Morgan and Lutmerding 2009).

For Hammond Branch, the four benthic parameters (repeated measures ANOVA) did not show any significant difference of control versus the two restoration sites (Table 4). All values for the control versus the two restoration sites are very similar, and reflect the basic fact that the restoration effort worked, with these sites slowly coming into equilibrium with the control site over time. The only significant seasonal differences (fall versus spring) observed were for the number of benthic taxa (23.0 versus 19.4) and the BIBI (3.2 versus 2.8). Over the three sites, the BIBI was consistent, ranging from 2.9 to 3.1 – bordering on poor to fair for the BIBI (Table 4).

The average FIBI for the control (3.6) and restored site (3.8) were in the fair range. However, eighteen fish species of fish were collected at the Hammond Branch restoration site in 2008, with thirteen species at the control site. Tessellated darters and redbreast sunfish dominated the fish community at the restoration site, while tessellated darters and rosyside dace were dominant at the control site. Also, the fish species complex is starting to include some intolerant species – a reflection of improved habitat at the restoration site. The mean MPHI for the control was 87 and for the restored site 71, indicating that the restoration site habitat is similar to the control site, but significantly lower based on the t-test (Table 4). Habitat at the upstream control for Hammond Branch was excellent, but the restoration area continued to improve over all sample years.

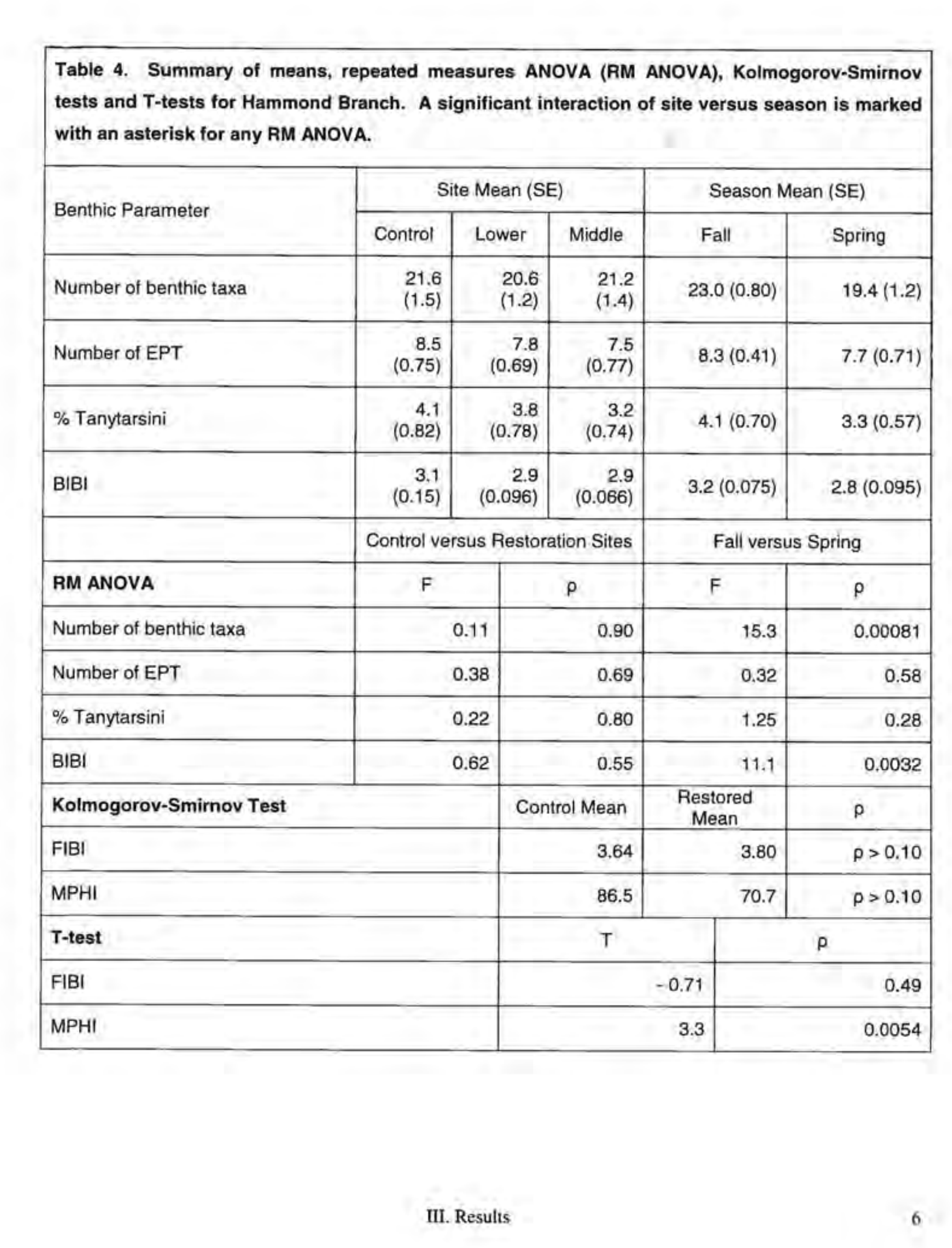

Table 4. Summary of means, repeated measures ANOVA (RM ANOVA), Kolmogorov-Smirnov tests and T-tests for Hammond Branch. A significant interaction of site versus season is marked with an asterisk for any RM ANOVA.

Benthic Parameter	Site Mean (SE)			Season Mean (SE)	
	Control	Lower	Middle	Fall	Spring
Number of benthic taxa	21.6 (1.5)	20.6 (1.2)	21.2 (1.4)	23.0 (0.80)	19.4 (1.2)
Number of EPT	8.5 (0.75)	7.8 (0.69)	7.5 (0.77)	8.3 (0.41)	7.7 (0.71)
% Tanytarsini	4.1 (0.82)	3.8 (0.78)	3.2 (0.74)	4.1 (0.70)	3.3 (0.57)
BIBI	3.1 (0.15)	2.9 (0.096)	2.9 (0.066)	3.2 (0.075)	2.8 (0.095)

	Control versus Restoration Sites		Fall versus Spring	
RM ANOVA	F	p	F	p
Number of benthic taxa	0.11	0.90	15.3	0.00081
Number of EPT	0.38	0.69	0.32	0.58
% Tanytarsini	0.22	0.80	1.25	0.28
BIBI	0.62	0.55	11.1	0.0032

Kolmogorov-Smirnov Test	Control Mean	Restored Mean	p
FIBI	3.64	3.80	p > 0.10
MPHI	86.5	70.7	p > 0.10

T-test	T	p
FIBI	- 0.71	0.49
MPHI	3.3	0.0054

III. Results 6

D. Herbert Run

Herbert Run (actually an unnamed tributary to Herbert Run) is a small 1st order stream tributary near Catonsville, MD draining into the Patapsco River (Coastal Plain Physiographic Region). In 2005-2010, fish and macroinvertebrate sampling was conducted at the Herbert Run site after restoration work had been completed, with no pre-restoration efforts. This restoration site was located between I-695 and Regina Drive. Upstream of the restoration site, Herbert Run is completely channelized under I-695, and no perennial stream could be found north of I-695. Additionally, Herbert Run is also channelized downstream of Regina Drive, thus potentially isolating the restoration site from biotic refugia. Because no appropriate section of stream was found to be used as a control, no control site was sampled on Herbert Run. Data from MBSS sites in the area were used to estimate reference conditions. Sampling started for this site in October 2005 with sampling completed in April 2010 (Morgan and Lutmerding 2009, with additional information added from sample year 2009-2010).

For Herbert Run, values for all four benthic parameters were higher for site means than the first-order coastal plain sites in the Patapsco River basin (site means - Table 5). Although not compared to a control site, the two restoration sites are very similar to each other, and reflect the basic fact that the overall restoration effort is successful. The mean values for each benthic parameter, as compared to the MBSS 95% CI, indicated that the number of benthic taxa and number of EPT were significantly higher than the MBSS, while % Tanytarsini and the BIBI were not statistically different. The only significant seasonal differences for fall versus spring samples were for the number of benthic taxa (21.8 versus 14.3) and the number of EPT (4.0 versus 1.9). For all site means and season means, the BIBI was in the poor category, ranging from 2.0 to 2.4.

The average FIBI for the MBSS sites was 1.7 (very poor) and 1.2 (very poor) for the restored site. The Herbert Run fish population is lacking, and will never be very good due to both upstream and downstream conditions, as well as being a small first-order stream. The mean MPHI for the MBSS was 62 and for the restored site 66 indicating that the restoration site habitat is similar, and reflects the restoration work completed (Table 5).

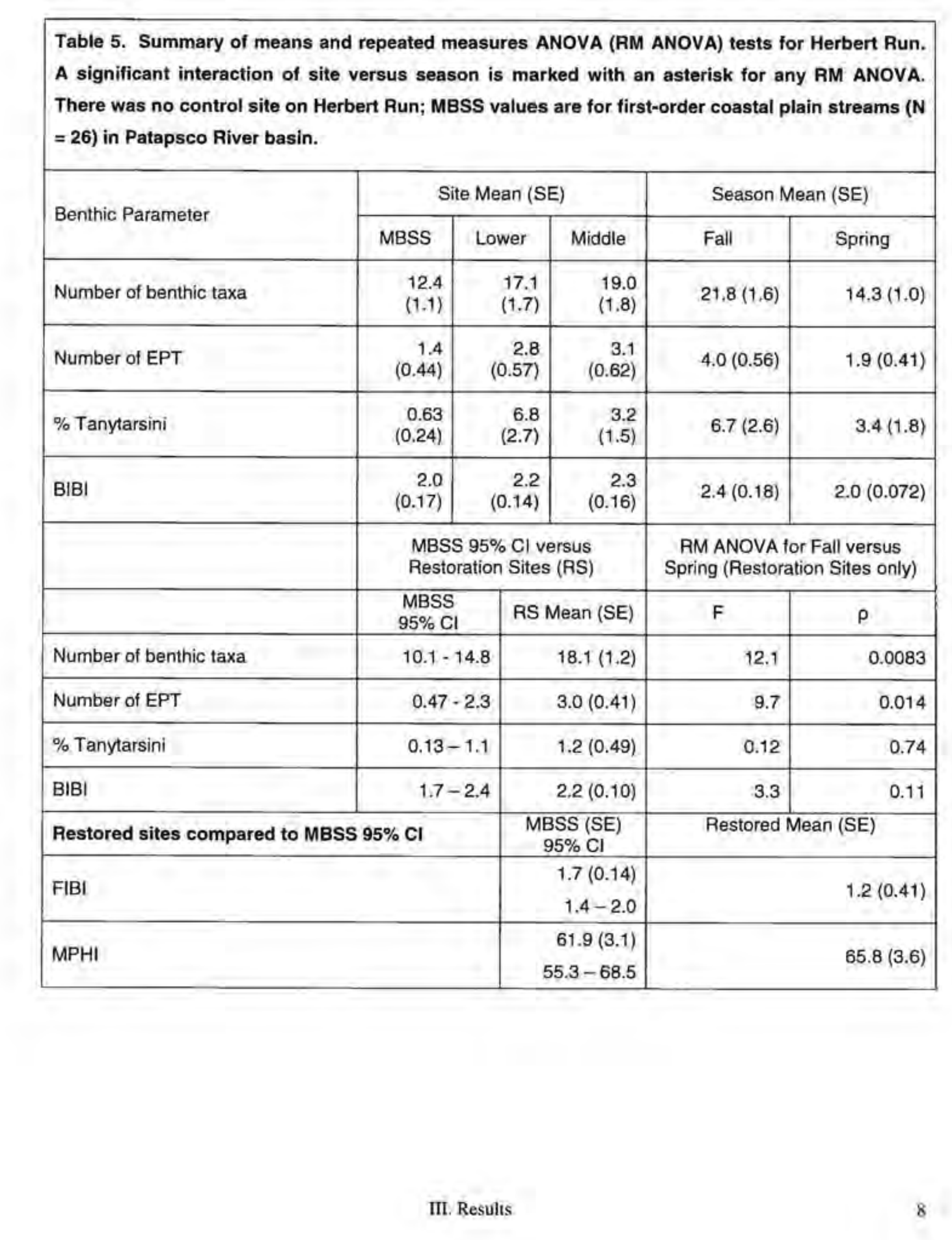

Table 5. Summary of means and repeated measures ANOVA (RM ANOVA) tests for Herbert Run. A significant interaction of site versus season is marked with an asterisk for any RM ANOVA. There was no control site on Herbert Run; MBSS values are for first-order coastal plain streams (N = 26) in Patapsco River basin.

Benthic Parameter	Site Mean (SE)			Season Mean (SE)	
	MBSS	Lower	Middle	Fall	Spring
Number of benthic taxa	12.4 (1.1)	17.1 (1.7)	19.0 (1.8)	21.8 (1.6)	14.3 (1.0)
Number of EPT	1.4 (0.44)	2.8 (0.57)	3.1 (0.62)	4.0 (0.56)	1.9 (0.41)
% Tanytarsini	0.63 (0.24)	6.8 (2.7)	3.2 (1.5)	6.7 (2.6)	3.4 (1.8)
BIBI	2.0 (0.17)	2.2 (0.14)	2.3 (0.16)	2.4 (0.18)	2.0 (0.072)

	MBSS 95% CI versus Restoration Sites (RS)		RM ANOVA for Fall versus Spring (Restoration Sites only)	
	MBSS 95% CI	RS Mean (SE)	F	p
Number of benthic taxa	10.1 - 14.8	18.1 (1.2)	12.1	0.0083
Number of EPT	0.47 - 2.3	3.0 (0.41)	9.7	0.014
% Tanytarsini	0.13 – 1.1	1.2 (0.49)	0.12	0.74
BIBI	1.7 – 2.4	2.2 (0.10)	3.3	0.11

Restored sites compared to MBSS 95% CI	MBSS (SE) 95% CI	Restored Mean (SE)
FIBI	1.7 (0.14) 1.4 – 2.0	1.2 (0.41)
MPHI	61.9 (3.1) 55.3 – 68.5	65.8 (3.6)

E. Little Paint Branch

Little Paint Branch is a third-order tributary to Paint Branch, and is located within the Potomac-Washington Metro Basin that extends from Piscataway Creek in Prince George's County to the Little Monocacy River in Montgomery County. Restoration assessment on this Coastal Plain site started in October 1998 and completed in May 2003 (Morgan et al. 2003).

For Little Paint Branch, the four benthic parameters (repeated measures ANOVA) did not show any significant difference of control versus the two restoration sites (Table 6). All benthic values for the control versus the two restoration sites were very similar, and reflect the basic fact that the restoration effort worked, with these sites slowly coming into equilibrium with the control site over time, similar to the situation observed at Hammond Branch. Again, significant seasonal differences (fall versus spring) observed were for the number of benthic taxa, number of EPT, and BIBI. Over the three sites, the BIBI was consistent, ranging from 2.5 to 2.7 – the poor category (Table 6). However, eight of the 20 restoration BIBI values were over 3.0 – the cutoff for the fair BIBI category.

The average FIBI for the control (4.2) and restored site (4.1) were in the good range. Nineteen and twenty fish species were collected at the restoration and control sites in 2002 - the highest number of species collected over the five years of sampling. In 2002, a total of 3265 fish were collected from the restoration site and 1306 fish were collected from the control site, an increase of nearly 300% from 2001. The mean MPHI for the control was 79 and for the restored site 78, indicating that the restoration site habitat is similar to the control site (Table 6). This site now represents stable habitat.

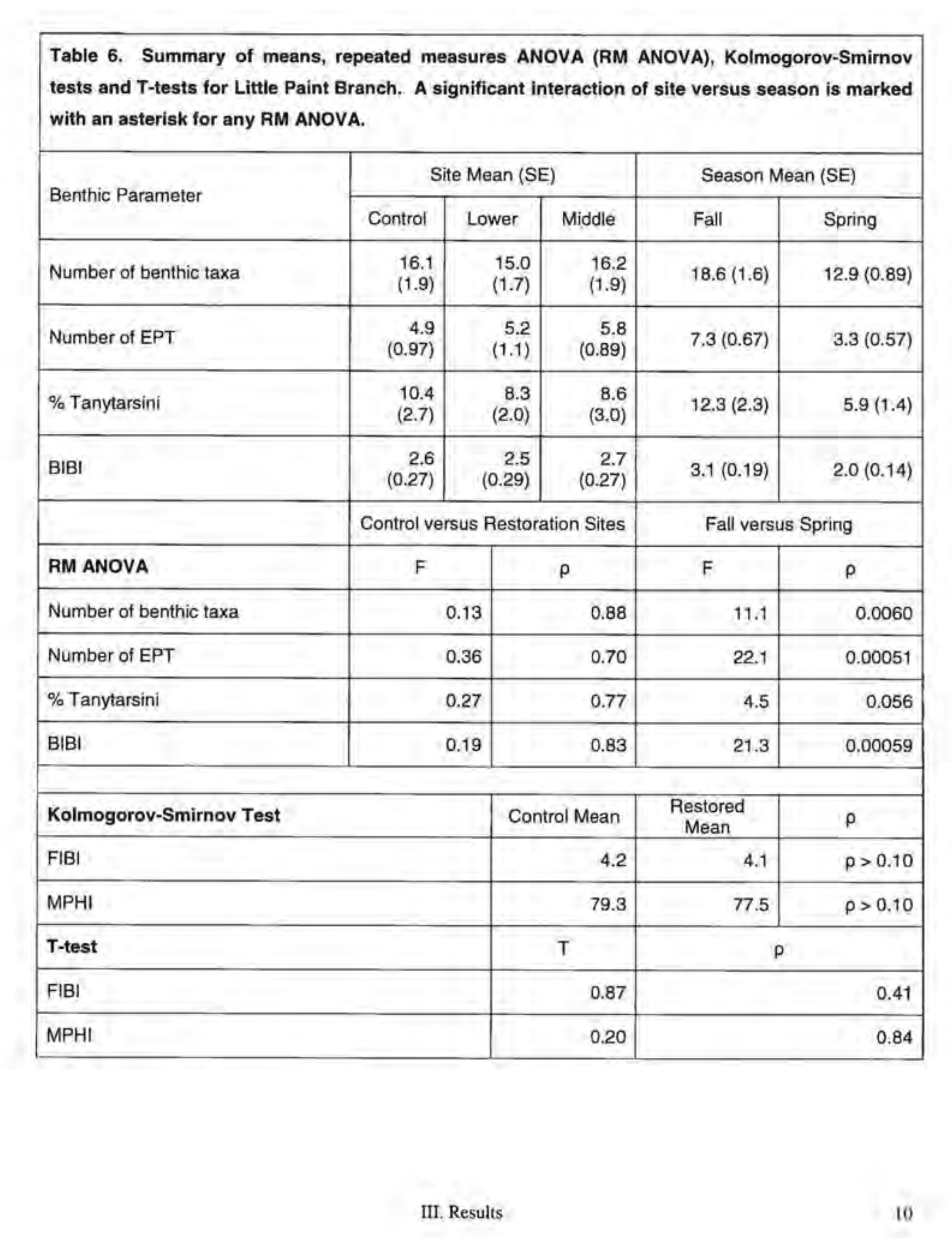

Table 6. Summary of means, repeated measures ANOVA (RM ANOVA), Kolmogorov-Smirnov tests and T-tests for Little Paint Branch. A significant interaction of site versus season is marked with an asterisk for any RM ANOVA.

Benthic Parameter	Site Mean (SE)			Season Mean (SE)	
	Control	Lower	Middle	Fall	Spring
Number of benthic taxa	16.1 (1.9)	15.0 (1.7)	16.2 (1.9)	18.6 (1.6)	12.9 (0.89)
Number of EPT	4.9 (0.97)	5.2 (1.1)	5.8 (0.89)	7.3 (0.67)	3.3 (0.57)
% Tanytarsini	10.4 (2.7)	8.3 (2.0)	8.6 (3.0)	12.3 (2.3)	5.9 (1.4)
BIBI	2.6 (0.27)	2.5 (0.29)	2.7 (0.27)	3.1 (0.19)	2.0 (0.14)

	Control versus Restoration Sites		Fall versus Spring	
RM ANOVA	F	p	F	p
Number of benthic taxa	0.13	0.88	11.1	0.0060
Number of EPT	0.36	0.70	22.1	0.00051
% Tanytarsini	0.27	0.77	4.5	0.056
BIBI	0.19	0.83	21.3	0.00059

Kolmogorov-Smirnov Test	Control Mean	Restored Mean	p
FIBI	4.2	4.1	p > 0.10
MPHI	79.3	77.5	p > 0.10

T-test	T	p
FIBI	0.87	0.41
MPHI	0.20	0.84

F. Muddy Branch

Muddy Branch sampling stations are located on a first order tributary to Muddy Branch proper - a tributary flowing into the Potomac River at Watkins Island. This stream is located within the Piedmont Physiographic Region and is part of the Potomac-Washington Metro Basin. Restoration assessment on this site started in October 1998 and completed in April 2009 (Morgan and Lutmerding 2009).

For Muddy Branch, the four benthic parameters (repeated measures ANOVA) did not show any significant difference of control versus the two restoration sites (Table 7). All values for the upstream control versus the two restoration sites (lower and middle) are very similar, and reflect the basic fact that the restoration effort worked, with these sites coming into equilibrium with the upstream control site over time. Over the three sites, the BIBI was uniform (2.3 – poor category), but there were three sample events out of a possible 30 events for the restoration sites where the BIBI was 3.0 (fair). This was an important improvement over the control since no fair BIBI scores were calculated at the control - this potentially indicates some upstream movement of benthic macroinvertebrates into the restoration site. Again, there were significant seasonal differences (fall versus spring) observed for the number of benthic taxa (21 versus 14), the number of EPT (5.0 versus 2.5) and the BIBI (2.6 versus 2.0), but not for % Tanytarsini (Table 7). This is another example of the strong seasonal differences seen in the benthic parameters at the different restoration sites.

The average FIBI for the control (2.8 - poor) and restored site (3.4 - fair) were not significantly different from each other, although the restored site was better than the control (Table 7). At the control site, the number of fish species ranged from 5-10, with the restored site having 8–17 species. The mean MPHI for the control was 53 and for the restored site 52, indicating that the restoration site habitat is essentially identical to the control site (Table 7).

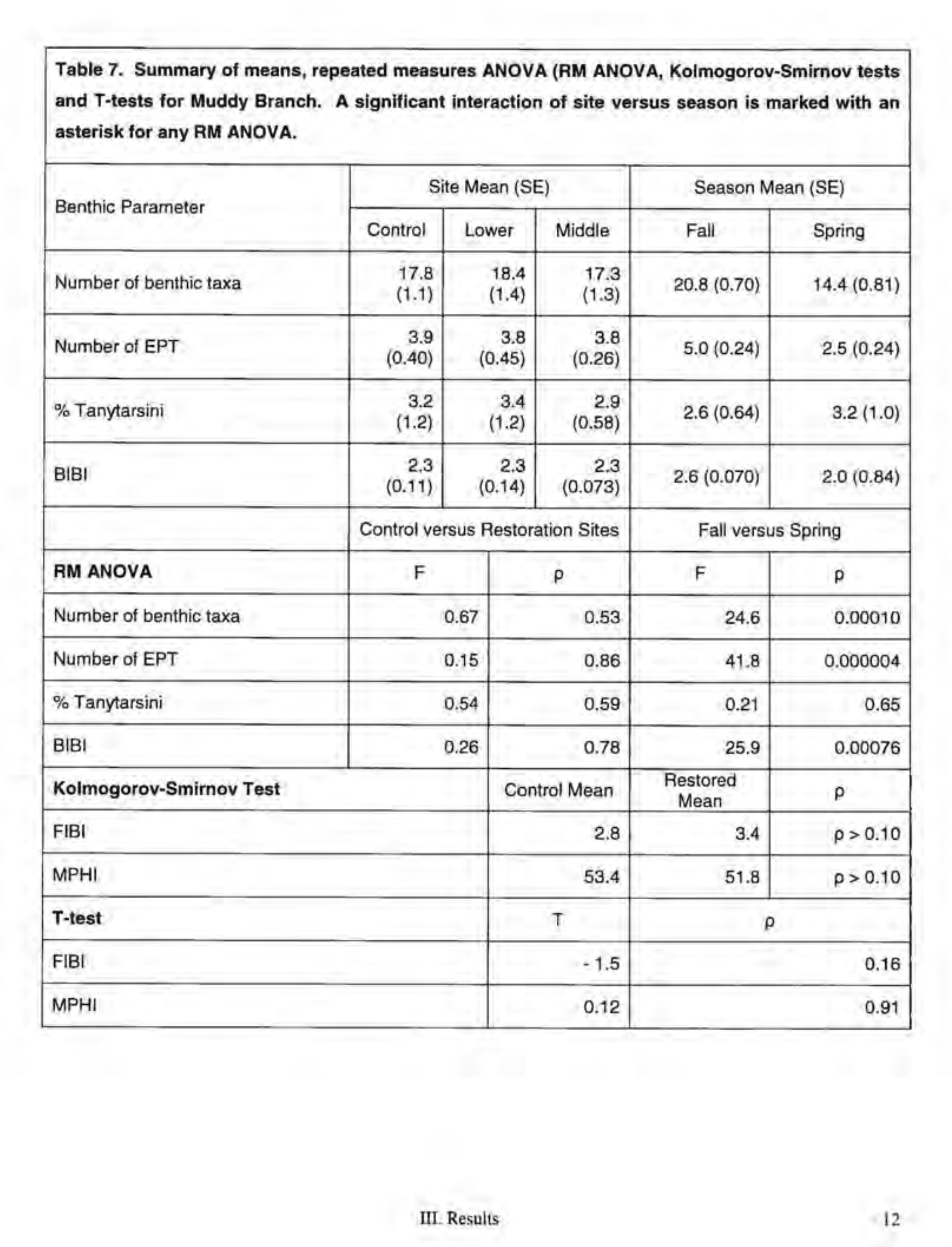

Table 7. Summary of means, repeated measures ANOVA (RM ANOVA, Kolmogorov-Smirnov tests and T-tests for Muddy Branch. A significant interaction of site versus season is marked with an asterisk for any RM ANOVA.

Benthic Parameter	Site Mean (SE)			Season Mean (SE)	
	Control	Lower	Middle	Fall	Spring
Number of benthic taxa	17.8 (1.1)	18.4 (1.4)	17.3 (1.3)	20.8 (0.70)	14.4 (0.81)
Number of EPT	3.9 (0.40)	3.8 (0.45)	3.8 (0.26)	5.0 (0.24)	2.5 (0.24)
% Tanytarsini	3.2 (1.2)	3.4 (1.2)	2.9 (0.58)	2.6 (0.64)	3.2 (1.0)
BIBI	2.3 (0.11)	2.3 (0.14)	2.3 (0.073)	2.6 (0.070)	2.0 (0.84)

	Control versus Restoration Sites		Fall versus Spring	
RM ANOVA	F	p	F	p
Number of benthic taxa	0.67	0.53	24.6	0.00010
Number of EPT	0.15	0.86	41.8	0.000004
% Tanytarsini	0.54	0.59	0.21	0.65
BIBI	0.26	0.78	25.9	0.00076

Kolmogorov-Smirnov Test	Control Mean	Restored Mean	p
FIBI	2.8	3.4	p > 0.10
MPHI	53.4	51.8	p > 0.10

T-test	T	p
FIBI	- 1.5	0.16
MPHI	0.12	0.91

G. Muddy Bridge Branch

Muddy Bridge Branch is a small first-order stream flowing into Sawmill Creek, and is a post-restoration site near Baltimore Washington International airport. Stream banks in the restored area were in fair to good condition, although approximately 25 m of streamside forested buffer was removed during the restoration process. An orange flocculent material was often present in the stream. For this site, restoration assessment started in October 1998 and completed in April 2002 (Morgan et al. 2002).

For Muddy Bridge Branch, three benthic parameters (repeated measures ANOVA) did not show any significant difference of control versus the two restoration sites, except for the number of EPT taxa (Table 8). The number of EPT at the middle site (3.3) was significantly greater than at the control (1.1) or lower site (1.6). The other three benthic parameters were similar among all three sites, except that % Tanytarsini was relatively high at all sites. As with other restoration sites, there were significant seasonal differences (fall versus spring) observed for all four benthic parameters - another example of the strong differences in the sampling period.

The average FIBI for the control (2.9) and restored site (2.8) were not significantly different from each other (Table 8). The mean MPHI for the control was 70 and for the restored site 74, indicating that the restoration site habitat is essentially identical to the control site (Table 8).

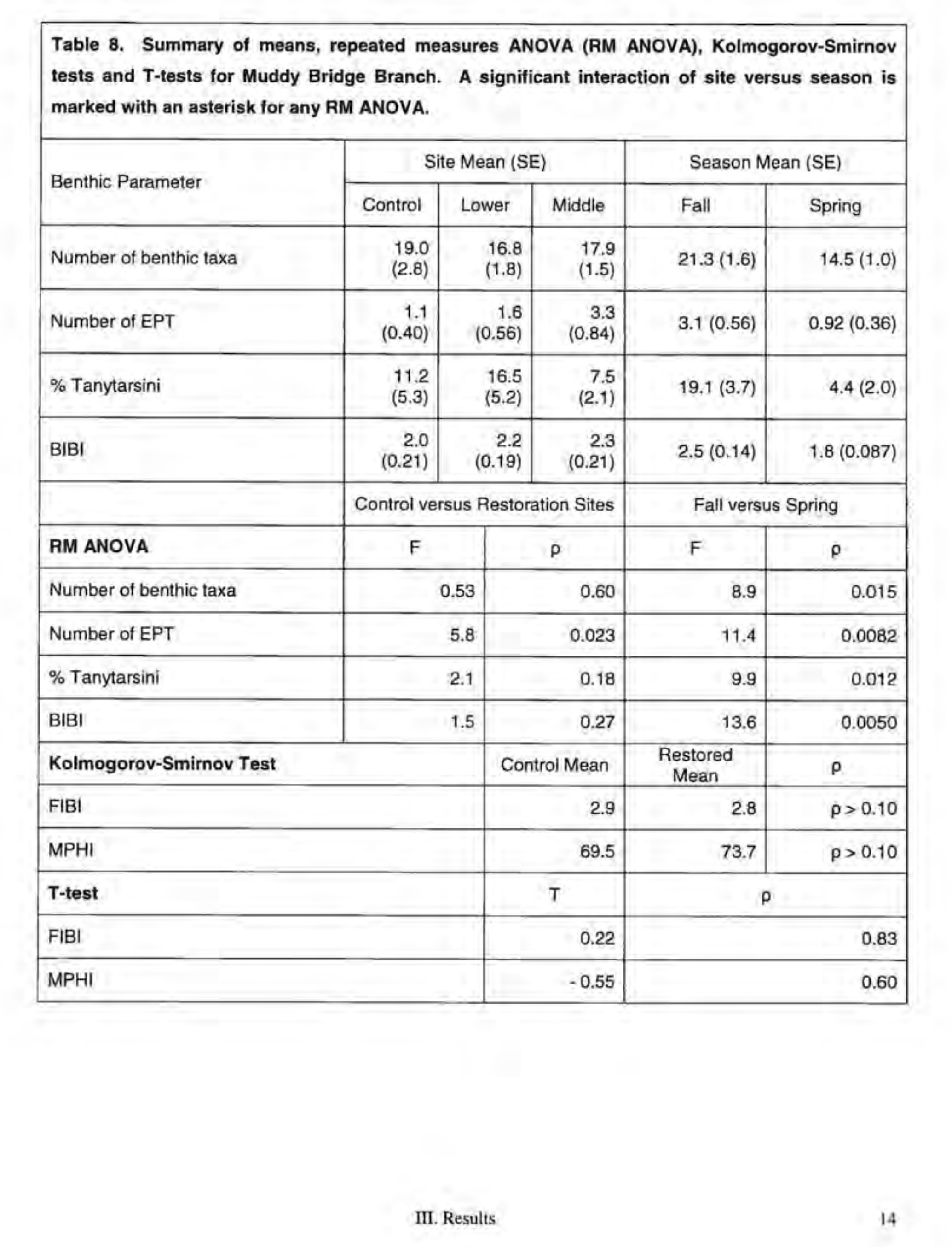

Table 8. Summary of means, repeated measures ANOVA (RM ANOVA), Kolmogorov-Smirnov tests and T-tests for Muddy Bridge Branch. A significant interaction of site versus season is marked with an asterisk for any RM ANOVA.

Benthic Parameter	Site Mean (SE)			Season Mean (SE)	
	Control	Lower	Middle	Fall	Spring
Number of benthic taxa	19.0 (2.8)	16.8 (1.8)	17.9 (1.5)	21.3 (1.6)	14.5 (1.0)
Number of EPT	1.1 (0.40)	1.6 (0.56)	3.3 (0.84)	3.1 (0.56)	0.92 (0.36)
% Tanytarsini	11.2 (5.3)	16.5 (5.2)	7.5 (2.1)	19.1 (3.7)	4.4 (2.0)
BIBI	2.0 (0.21)	2.2 (0.19)	2.3 (0.21)	2.5 (0.14)	1.8 (0.087)

	Control versus Restoration Sites		Fall versus Spring	
RM ANOVA	F	p	F	p
Number of benthic taxa	0.53	0.60	8.9	0.015
Number of EPT	5.8	0.023	11.4	0.0082
% Tanytarsini	2.1	0.18	9.9	0.012
BIBI	1.5	0.27	13.6	0.0050
Kolmogorov-Smirnov Test		Control Mean	Restored Mean	p
FIBI		2.9	2.8	$p > 0.10$
MPHI		69.5	73.7	$p > 0.10$
T-test		T	p	
FIBI		0.22	0.83	
MPHI		- 0.55	0.60	

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H. Patuxent Run

This unnamed tributary to the Patuxent River (designated as Patuxent Run for reporting purposes) is a small first order tributary, located within the Coastal Plain physiographic region. A control site was not sampled on this stream because the stream is entirely underground (channelized) upstream of the restoration work. In addition, there are severe upstream water quality problems at this site, potentially affecting downstream biotic assemblages. Data from first order MBSS sites (Patuxent River, Coastal Plain) in the area were used to estimate reference conditions. For this site, restoration assessment started in May 2003 and completed in April 2010 (Morgan and Lutmerding 2009, with additional information added from sample year 2009-2010).

For Patuxent Run, the values for all four benthic parameters were lower for restoration site means than the first-order coastal plain sites in the Patuxent River basin (site means - Table 9). Basically, although the restoration work stabilized the stream channel, the benthic assemblage is very poor. Not only is taxa richness low at both sites (11.8 and 12.3), but the number of EPT present is exceptionally low (0.73 and 0.33), and reflected in the very poor BIBI scores. The restoration site means fall well below the MBSS 95% CI for the number of benthic taxa and BIBI. In part, this is a reflection of poor upstream water quality, either episodic or chronic in this watershed. There were no differences in fall versus spring collections at this site (Table 9).

Over seven years of fish assessment, no fish were collected at the Patuxent Run sites. The mean MPHI for the MBSS was 70 and for the restored site 32 (Table 9). However, the MPHI score ranged from 6.8 – 15.7 from 2003 to 2006, but ranged from 53 - 62 from 2007 to 2009. This indicates that the restoration sites have attained some level of stability – a factor that needs to be assessed in the future.

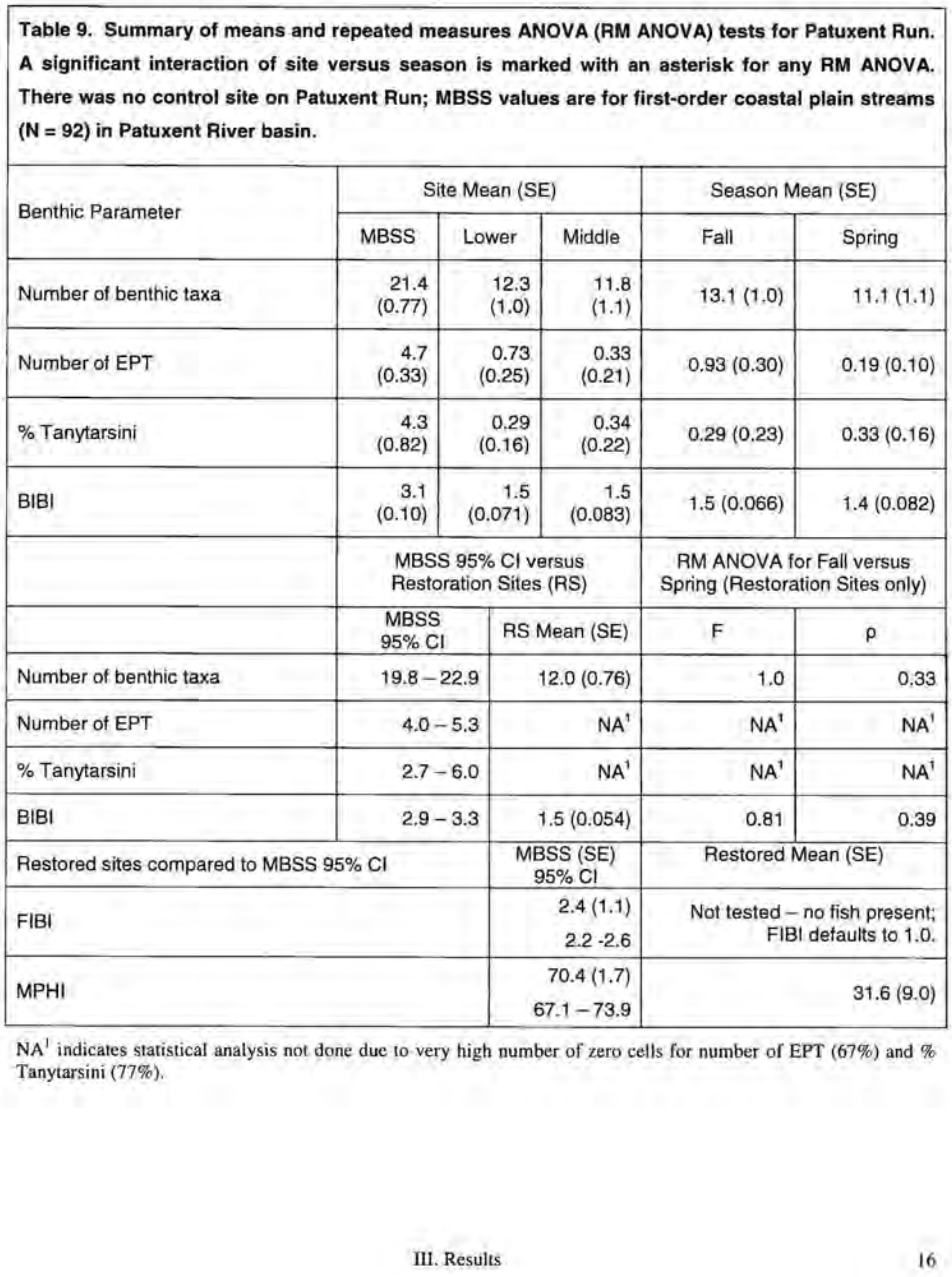

Table 9. Summary of means and repeated measures ANOVA (RM ANOVA) tests for Patuxent Run. A significant interaction of site versus season is marked with an asterisk for any RM ANOVA. There was no control site on Patuxent Run; MBSS values are for first-order coastal plain streams (N = 92) in Patuxent River basin.

Benthic Parameter	Site Mean (SE)			Season Mean (SE)	
	MBSS	Lower	Middle	Fall	Spring
Number of benthic taxa	21.4 (0.77)	12.3 (1.0)	11.8 (1.1)	13.1 (1.0)	11.1 (1.1)
Number of EPT	4.7 (0.33)	0.73 (0.25)	0.33 (0.21)	0.93 (0.30)	0.19 (0.10)
% Tanytarsini	4.3 (0.82)	0.29 (0.16)	0.34 (0.22)	0.29 (0.23)	0.33 (0.16)
BIBI	3.1 (0.10)	1.5 (0.071)	1.5 (0.083)	1.5 (0.066)	1.4 (0.082)

	MBSS 95% CI versus Restoration Sites (RS)		RM ANOVA for Fall versus Spring (Restoration Sites only)	
	MBSS 95% CI	RS Mean (SE)	F	p
Number of benthic taxa	19.8 – 22.9	12.0 (0.76)	1.0	0.33
Number of EPT	4.0 – 5.3	NA[1]	NA[1]	NA[1]
% Tanytarsini	2.7 – 6.0	NA[1]	NA[1]	NA[1]
BIBI	2.9 – 3.3	1.5 (0.054)	0.81	0.39

Restored sites compared to MBSS 95% CI	MBSS (SE) 95% CI	Restored Mean (SE)
FIBI	2.4 (1.1) 2.2 -2.6	Not tested – no fish present; FIBI defaults to 1.0.
MPHI	70.4 (1.7) 67.1 – 73.9	31.6 (9.0)

NA[1] indicates statistical analysis not done due to very high number of zero cells for number of EPT (67%) and % Tanytarsini (77%).

I. Piney Creek

Piney Creek is a second order stream at all locations sampled, and is a tributary to the Gunpowder River, flowing into Loch Raven Reservoir and then into Chesapeake Bay. Piney Creek is located within the Piedmont and Coastal Plain Physiographic Provinces, with one restoration and one control site on this stream in the Piedmont Physiographic Province. This site is adjacent to I-83, north of Baltimore. For this site, restoration assessment started in October 2000 and completed in October 2002 (Morgan et al. 2003), with a limited number of study years.

Piney Creek is somewhat of a restoration enigma since it flows in very close proximity to I-83, but supports a very good benthic and fish assemblage (Table 10). For Piney Creek, the four benthic parameters (repeated measures ANOVA) did not show any significant differences of either control versus the restoration site or fall versus spring collections (Table 10). Indeed, the values for all benthic parameters are similar, reflecting a high quality stream. These arrays of benthic values should be a goal of every restoration project (especially for any control site), but variable watershed characteristics (land use) in the Piedmont prevent this from occurring.

The FIBI for the control (2.9 - poor) and restored site (2.9 - poor) were not significantly different from each other (Table 10). Both sites are just under the MBSS cutoff point for poor to fair, with a standard error overlap of the MBSS 3.0 criterion for fair. The number of fish species ranged from 10-12 at both sites, with brown trout (exotic salmonid) and rosyside dace present – indicator species for good water quality. Fish numbers and biomass were very good at both sites over all years. The mean MPHI for the control was 73 and for the restored site 74, indicating that the restoration site habitat is essentially identical to the control site (Table 10) and reflecting stream restoration efforts.

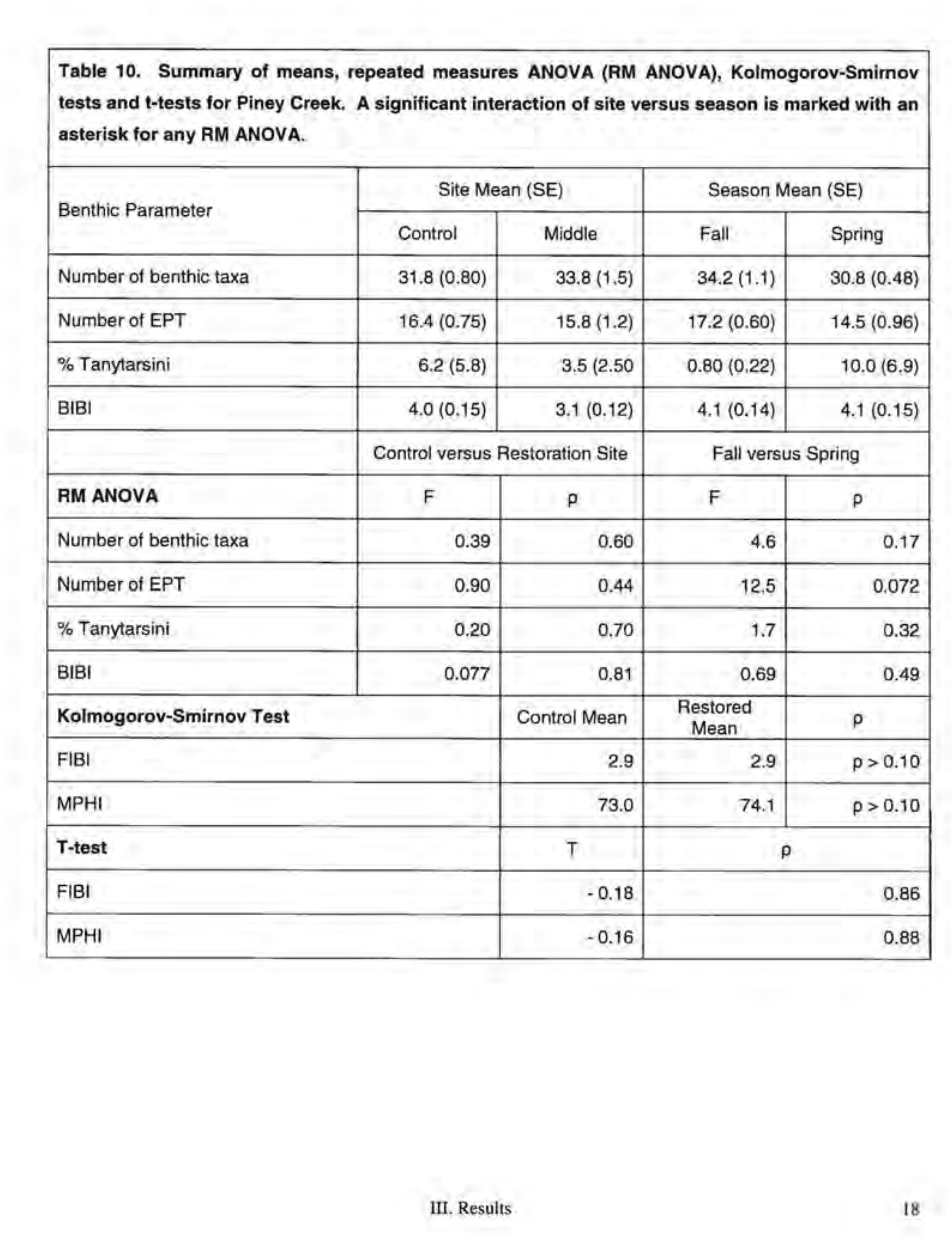

Table 10. Summary of means, repeated measures ANOVA (RM ANOVA), Kolmogorov-Smirnov tests and t-tests for Piney Creek. A significant interaction of site versus season is marked with an asterisk for any RM ANOVA.

Benthic Parameter	Site Mean (SE)		Season Mean (SE)	
	Control	Middle	Fall	Spring
Number of benthic taxa	31.8 (0.80)	33.8 (1.5)	34.2 (1.1)	30.8 (0.48)
Number of EPT	16.4 (0.75)	15.8 (1.2)	17.2 (0.60)	14.5 (0.96)
% Tanytarsini	6.2 (5.8)	3.5 (2.50	0.80 (0.22)	10.0 (6.9)
BIBI	4.0 (0.15)	3.1 (0.12)	4.1 (0.14)	4.1 (0.15)
	Control versus Restoration Site		Fall versus Spring	
RM ANOVA	F	p	F	p
Number of benthic taxa	0.39	0.60	4.6	0.17
Number of EPT	0.90	0.44	12.5	0.072
% Tanytarsini	0.20	0.70	1.7	0.32
BIBI	0.077	0.81	0.69	0.49
Kolmogorov-Smirnov Test		Control Mean	Restored Mean	p
FIBI		2.9	2.9	p > 0.10
MPHI		73.0	74.1	p > 0.10
T-test		T	p	
FIBI		- 0.18	0.86	
MPHI		- 0.16	0.88	

J. Porter Run

Porter Run is a small 1st order stream, and a tributary to Braddock Run (AMD impacted), which flows into Wills Creek and then to the North Branch of the Potomac River. This stream is located within the Appalachian Plateau Physiographic Province and is part of the upper North Branch of the Potomac River Basin. The restoration site was restored between 1999 and 2000, with restoration and control sites located adjacent of Route 40 in Clarysville, west of La Vale and east of Frostburg, Maryland. For this site, restoration assessment started in October 1999 and completed in October 2005 (Morgan et al. 2006). Recently (2010), a new sewer line was installed on the north side of Porter Run, near the control site and above the restored site.

Porter Run is also somewhat of a restoration enigma since it flows in very close proximity to Route 40, yet supports a fair benthic assemblage and brook trout (Table 11). The primary goal of this restoration work was to stabilize the poor bank condition (slumping) along the roadside. For Porter Run, the four benthic parameters (repeated measures ANOVA) did not show any significant differences of control versus the restoration sites (Table 11). For a small first order stream, the number of benthic taxa ranged from 21.8 to 22.8 with many EPT present (7.3 – 9.2). The BIBI at the control site was in the fair range, but the two restoration sites were in the upper part of the poor range, and there was statistical overlap among all three sites as seen in the standard errors for each BIBI (Table 11). As with other restoration sites, there were significant seasonal differences (fall versus spring) observed for both number of benthic taxa and number of EPT, but not for % Tanytarsini and the BIBI.

The CWIBI for the control (1.6 – very poor) and restored site (1.9 – very poor) were not significantly different from each other (Table 11). Although brook trout were present, the fish community was dominated by tolerant fish species (3), as well as a lack of sculpins and intolerant fish species. The mean MPHI for the control was 34 and for the restored site 42, indicating that the restoration site habitat is essentially identical to the control site. However, the site often scored poorly for flow parameters due to its small size.

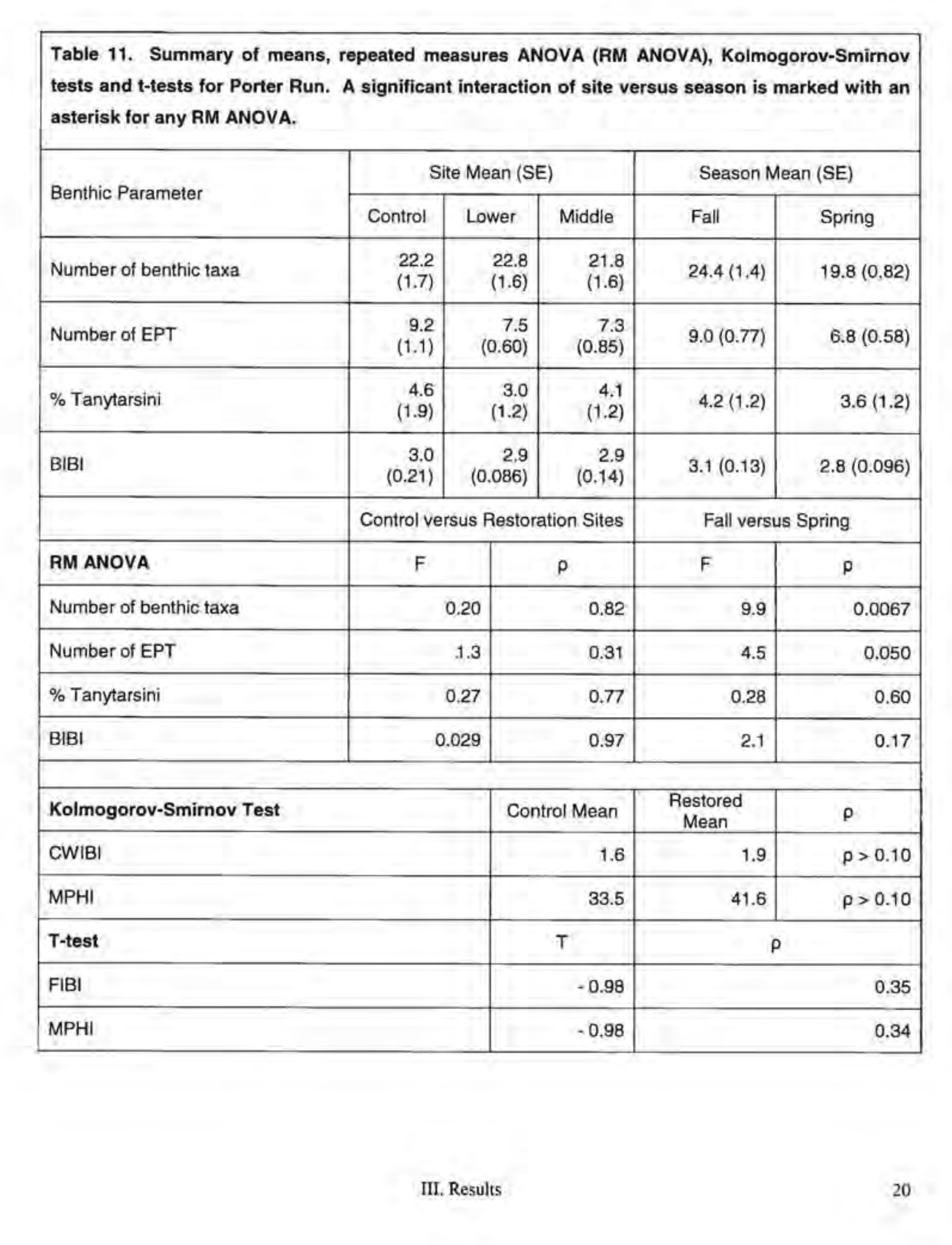

Table 11. Summary of means, repeated measures ANOVA (RM ANOVA), Kolmogorov-Smirnov tests and t-tests for Porter Run. A significant interaction of site versus season is marked with an asterisk for any RM ANOVA.

Benthic Parameter	Site Mean (SE)			Season Mean (SE)	
	Control	Lower	Middle	Fall	Spring
Number of benthic taxa	22.2 (1.7)	22.8 (1.6)	21.8 (1.6)	24.4 (1.4)	19.8 (0.82)
Number of EPT	9.2 (1.1)	7.5 (0.60)	7.3 (0.85)	9.0 (0.77)	6.8 (0.58)
% Tanytarsini	4.6 (1.9)	3.0 (1.2)	4.1 (1.2)	4.2 (1.2)	3.6 (1.2)
BIBI	3.0 (0.21)	2.9 (0.086)	2.9 (0.14)	3.1 (0.13)	2.8 (0.096)

	Control versus Restoration Sites		Fall versus Spring	
RM ANOVA	F	p	F	p
Number of benthic taxa	0.20	0.82	9.9	0.0067
Number of EPT	1.3	0.31	4.5	0.050
% Tanytarsini	0.27	0.77	0.28	0.60
BIBI	0.029	0.97	2.1	0.17

Kolmogorov-Smirnov Test	Control Mean	Restored Mean	p
CWIBI	1.6	1.9	p > 0.10
MPHI	33.5	41.6	p > 0.10
T-test	T	p	
FIBI	- 0.98	0.35	
MPHI	- 0.98	0.34	

K. Roland Run

This stream (designated as Roland Run for reporting purposes) is a small, unnamed 1st order tributary to Roland Run, located near Towson, MD. Roland Run flows into Jones Falls, which then empties into Baltimore Harbor. This stream is located within the Coastal Plain Physiographic Region and is part of the Patapsco River Basin. The stream restoration site was located immediately downstream of MD Route 139 and the control site was located immediately upstream of the culvert under MD Route 139. For this site, restoration assessment started in October 2005 and completed in April 2010 (Morgan and Lutmerding 2009, with additional information added from sample year 2009-2010).

For Roland Run, three benthic parameters (repeated measures ANOVA) did not show any significant difference of control versus the two restoration sites, except for the number of EPT taxa (Table 12). EPT numbers at the lower (3.7) and middle site (2.9) were significantly greater than the control (1.6) or lower site (1.6). The other three benthic parameters were similar among all three sites, except that the numbers of benthic taxa were higher at the lower and middle sites than the control. As with other restoration sites, there were significant seasonal differences (fall versus spring) observed for three benthic parameters - another example of the strong differences in the sampling period (Table 12). Average BIBI values fell into the poor range.

The average FIBI for the control (1.2) and restored site (1.5) were not significantly different from each other (Table 12), with both values in the very poor range. The fish community was dominated by four species, but one brown trout was collected in 2009 at the restored site. The mean MPHI for the control was 80 and for the restored site 51, indicating that the restoration site habitat is poorer than the control site (Table 12) – this was non-significant with the K-S test, but significant with the t-test.

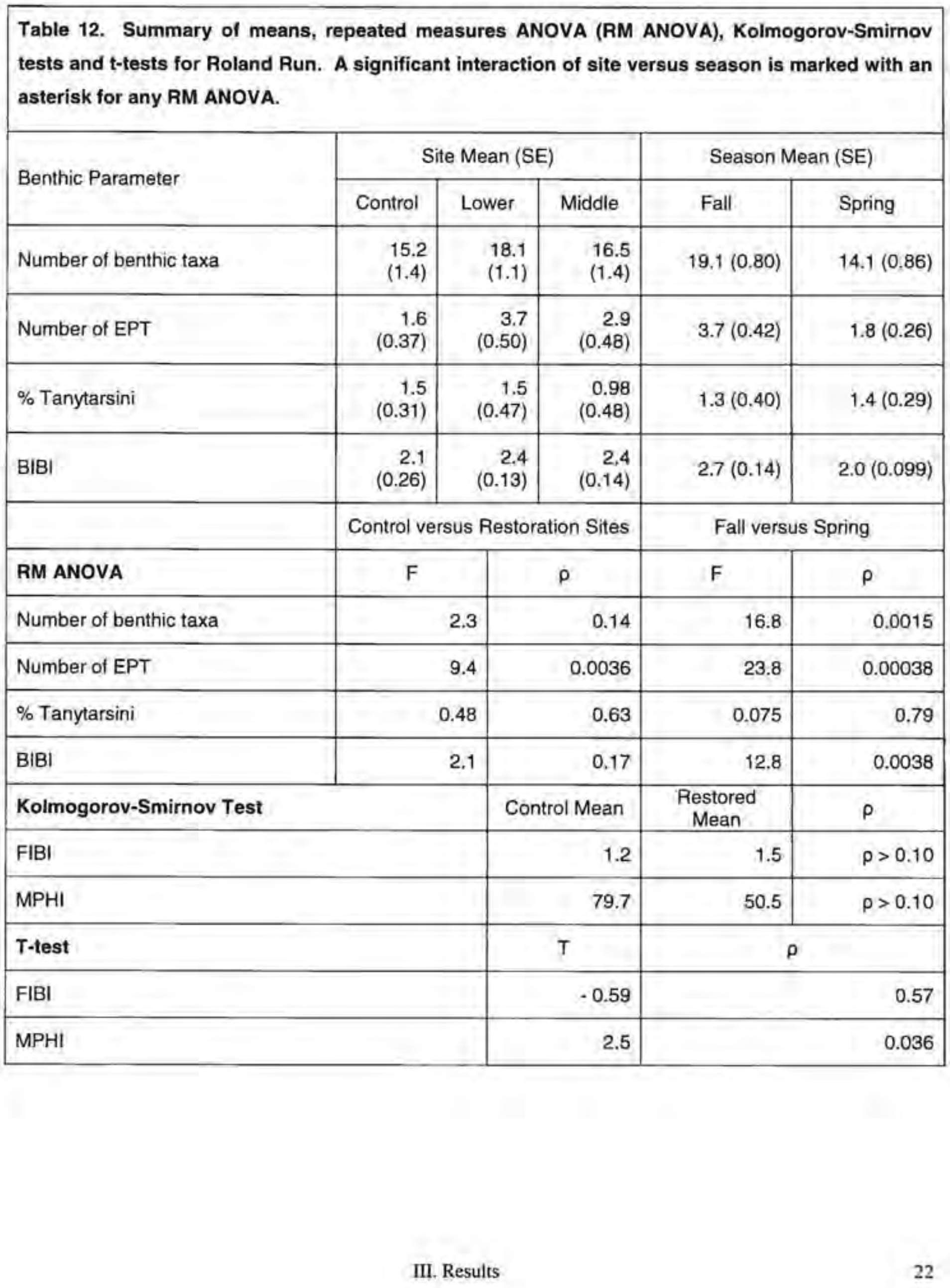

Table 12. Summary of means, repeated measures ANOVA (RM ANOVA), Kolmogorov-Smirnov tests and t-tests for Roland Run. A significant interaction of site versus season is marked with an asterisk for any RM ANOVA.

Benthic Parameter	Site Mean (SE)			Season Mean (SE)	
	Control	Lower	Middle	Fall	Spring
Number of benthic taxa	15.2 (1.4)	18.1 (1.1)	16.5 (1.4)	19.1 (0.80)	14.1 (0.86)
Number of EPT	1.6 (0.37)	3.7 (0.50)	2.9 (0.48)	3.7 (0.42)	1.8 (0.26)
% Tanytarsini	1.5 (0.31)	1.5 (0.47)	0.98 (0.48)	1.3 (0.40)	1.4 (0.29)
BIBI	2.1 (0.26)	2.4 (0.13)	2.4 (0.14)	2.7 (0.14)	2.0 (0.099)

	Control versus Restoration Sites		Fall versus Spring	
RM ANOVA	F	ρ	F	ρ
Number of benthic taxa	2.3	0.14	16.8	0.0015
Number of EPT	9.4	0.0036	23.8	0.00038
% Tanytarsini	0.48	0.63	0.075	0.79
BIBI	2.1	0.17	12.8	0.0038

Kolmogorov-Smirnov Test	Control Mean	Restored Mean	ρ
FIBI	1.2	1.5	ρ > 0.10
MPHI	79.7	50.5	ρ > 0.10

T-test	T	ρ
FIBI	- 0.59	0.57
MPHI	2.5	0.036

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L. Towson Run

This unnamed tributary to Towson Run (designated as Towson Run for reporting purposes) is a small first order stream. Towson Run, located within the Coastal Plain physiographic region, is a tributary to Jones Falls within the Gunpowder River basin. For this site, restoration assessment started in October 2004 and completed in April 2010 (Morgan and Lutmerding 2009, with additional information added from sample year 2009-2010).

For Towson Run, the four benthic parameters (repeated measures ANOVA) did not show any significant difference of control versus the two restoration sites (Table 13). These benthic parameters had similar values among all three sites; however, the % Tanytarsini was higher in the two restoration sites than at the control. As with other restoration sites, there were significant seasonal differences (fall versus spring) observed again for three benthic parameters - another example of the strong differences between sampling periods (Table 13). Average BIBI values fell into the poor range, although the lower site was slightly higher (2.6) than the control and middle site.

The average FIBI for the control (1.0) and restored site (1.1) were not significantly different from each other (Table 13), with both values in the very poor range. Only creek chubs were collected at the control and restoration site. The mean MPHI for the control was 37 and for the restored site 71, indicating that the restoration site habitat is better than the control site (Table 13) – these values were not significantly different with the K-S test, but were significantly different with the t-test (Table 13).

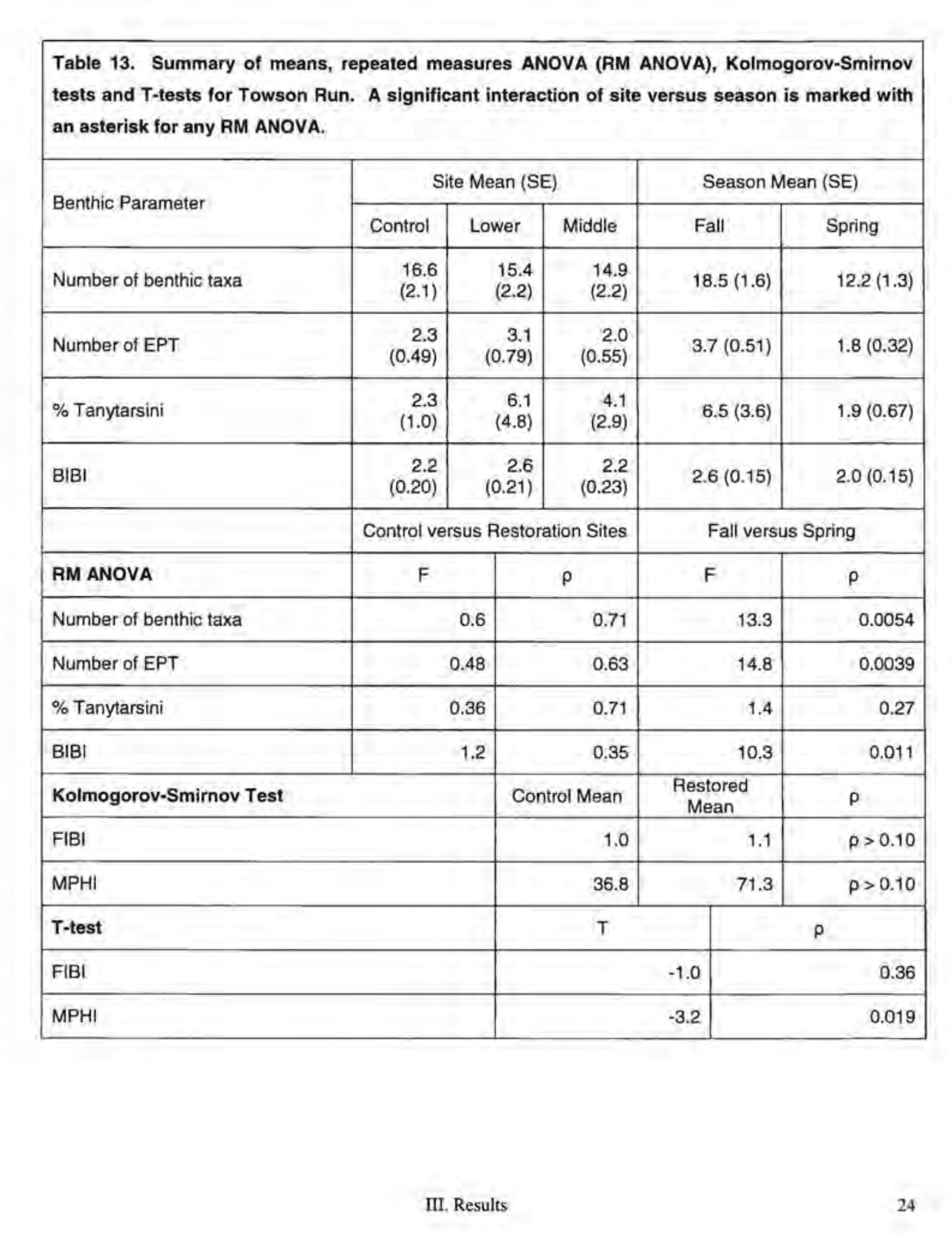

Table 13. Summary of means, repeated measures ANOVA (RM ANOVA), Kolmogorov-Smirnov tests and T-tests for Towson Run. A significant interaction of site versus season is marked with an asterisk for any RM ANOVA.

Benthic Parameter	Site Mean (SE)			Season Mean (SE)	
	Control	Lower	Middle	Fall	Spring
Number of benthic taxa	16.6 (2.1)	15.4 (2.2)	14.9 (2.2)	18.5 (1.6)	12.2 (1.3)
Number of EPT	2.3 (0.49)	3.1 (0.79)	2.0 (0.55)	3.7 (0.51)	1.8 (0.32)
% Tanytarsini	2.3 (1.0)	6.1 (4.8)	4.1 (2.9)	6.5 (3.6)	1.9 (0.67)
BIBI	2.2 (0.20)	2.6 (0.21)	2.2 (0.23)	2.6 (0.15)	2.0 (0.15)

	Control versus Restoration Sites		Fall versus Spring	
RM ANOVA	F	p	F	p
Number of benthic taxa	0.6	0.71	13.3	0.0054
Number of EPT	0.48	0.63	14.8	0.0039
% Tanytarsini	0.36	0.71	1.4	0.27
BIBI	1.2	0.35	10.3	0.011

Kolmogorov-Smirnov Test	Control Mean	Restored Mean	p
FIBI	1.0	1.1	p > 0.10
MPHI	36.8	71.3	p > 0.10

T-test	T	p
FIBI	-1.0	0.36
MPHI	-3.2	0.019

M. Tributary Nine

Tributary Nine is a small first-order stream that enters Sawmill Creek, near the Baltimore Washington International airport in the coastal plain. There is a strong potential that Tributary Nine may be affected by water quality problems stemming from flight operations at Baltimore Washington International airport. We did not investigate water quality at Tributary Nine, but Sawmill Creek was studied historically by MDNR. In addition, it may be important to monitor land use changes in this watershed since the site is located in an area of heavy development. The work done in 2007 - 2008 on Tributary Nine was a five year revisit (Morgan et al. 2008). The initial sampling period for this site was from October 1998 to April 2002 (Morgan et al 2002).

Tributary Nine reflected restoration efforts. Three of the four benthic parameters (repeated measures ANOVA) were significantly different for control versus the two restoration sites (Table 14). These benthic parameters had similar values among all three sites; however, the % Tanytarsini was higher in the lower restoration sites than the control. As with other restoration sites, there was a significant seasonal difference (fall versus spring) observed again for one benthic parameter – the number of benthic taxa (Table 14). Average BIBI values fell into the very poor range, although the restoration sites were slightly higher (1.9) than the control site.

The average FIBI for the control (1.0) and restored site (2.3) were significantly different from each other (Table 14). One to four fish species were collected at the restoration site, with no fish collected at the control site. The mean MPHI for the control was 24 and for the restored site 78, indicating that the restoration site habitat is better than the control site – these values were significantly different with both the K-S test and t-test (Table 14).

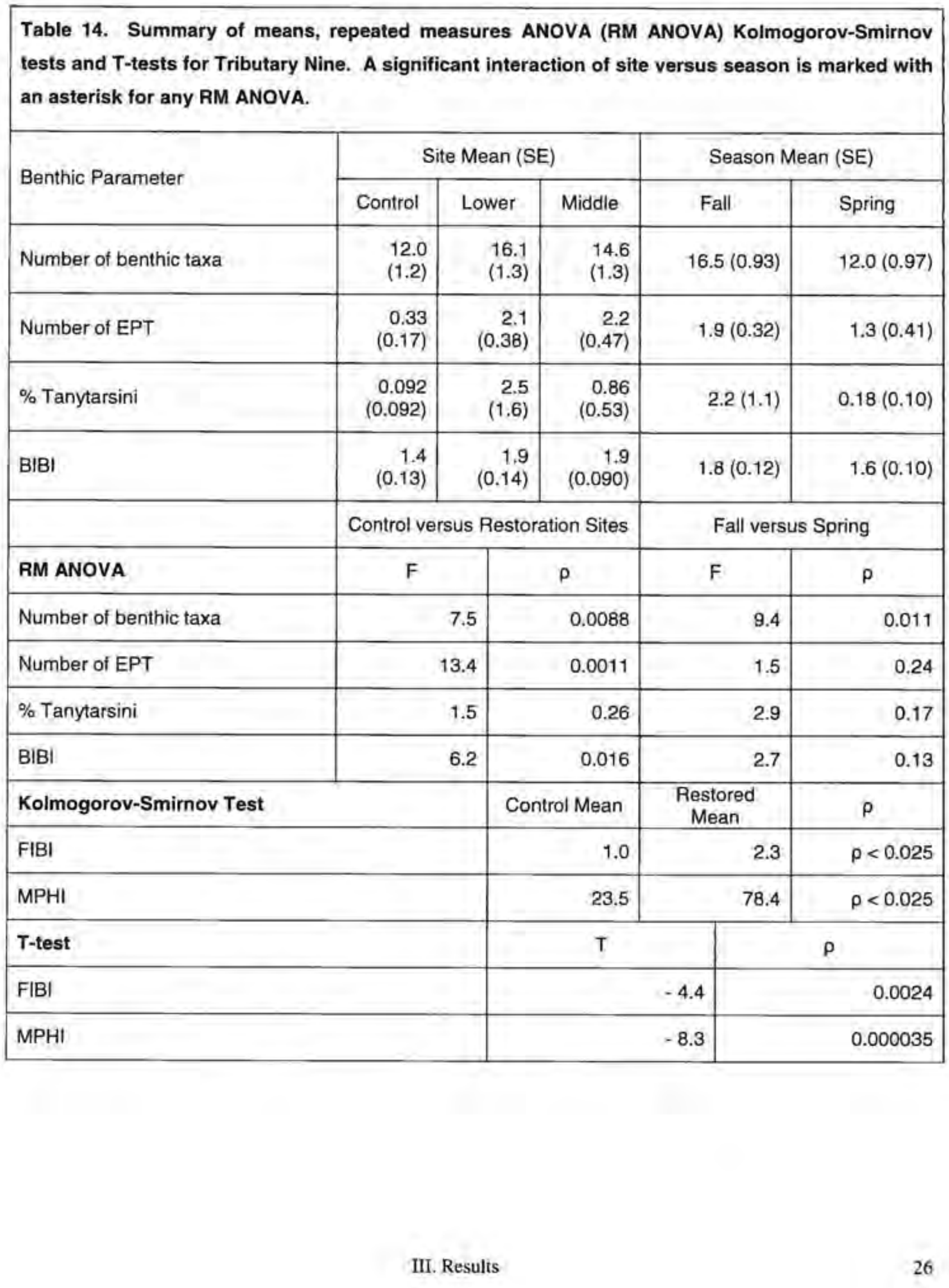

Table 14. Summary of means, repeated measures ANOVA (RM ANOVA) Kolmogorov-Smirnov tests and T-tests for Tributary Nine. A significant interaction of site versus season is marked with an asterisk for any RM ANOVA.

Benthic Parameter	Site Mean (SE)			Season Mean (SE)	
	Control	Lower	Middle	Fall	Spring
Number of benthic taxa	12.0 (1.2)	16.1 (1.3)	14.6 (1.3)	16.5 (0.93)	12.0 (0.97)
Number of EPT	0.33 (0.17)	2.1 (0.38)	2.2 (0.47)	1.9 (0.32)	1.3 (0.41)
% Tanytarsini	0.092 (0.092)	2.5 (1.6)	0.86 (0.53)	2.2 (1.1)	0.18 (0.10)
BIBI	1.4 (0.13)	1.9 (0.14)	1.9 (0.090)	1.8 (0.12)	1.6 (0.10)

	Control versus Restoration Sites		Fall versus Spring	
RM ANOVA	F	p	F	p
Number of benthic taxa	7.5	0.0088	9.4	0.011
Number of EPT	13.4	0.0011	1.5	0.24
% Tanytarsini	1.5	0.26	2.9	0.17
BIBI	6.2	0.016	2.7	0.13

Kolmogorov-Smirnov Test	Control Mean	Restored Mean	p
FIBI	1.0	2.3	$p < 0.025$
MPHI	23.5	78.4	$p < 0.025$

T-test	T	p
FIBI	- 4.4	0.0024
MPHI	- 8.3	0.000035

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N. White Marsh Run

White Marsh Run is a second order stream, located within the coastal plain that flows directly into the Chesapeake Bay. The initial 75 m control site was located upstream, adjacent to a shopping mall. Another restoration project, by Baltimore County, was under construction at the control site sampled in 1998 and 1999. A new control site was selected immediately upstream from the stream section that was under construction (there is a series of large culverts, draining the shopping complex, that discharge into the upper end of the Baltimore County restoration site). The work done in April 2004 and March 2005 was a revisit (Morgan et al. 2005). The initial sampling period for this site was from October 1998 to May 2003 (Morgan et al 2003).

White Marsh Run was a unique stream restoration project, situated in the middle of a heavily developed watershed in the coastal plain. None of the four benthic parameters (repeated measures ANOVA) were significantly different for control versus the two restoration sites (Table 15). These benthic parameters had similar values among all three sites. As with many other restoration sites, there were significant seasonal differences (fall versus spring) observed for all four benthic parameters (Table 15). Average BIBI values (2.0 – 2.4) fell into the poor range for all sites.

The average FIBI for the control (3.0) and restored site (3.1) were not significantly different from each other (Table 15). However, these values were in the fair range. Nine to ten fish species were present at both the control and restoration sites. The mean MPHI for the control was 62 and for the restored site 48 (one very low MPHI value may have skewed the mean) – these values were not significantly different with both the K-S test and t-test (Table 14).

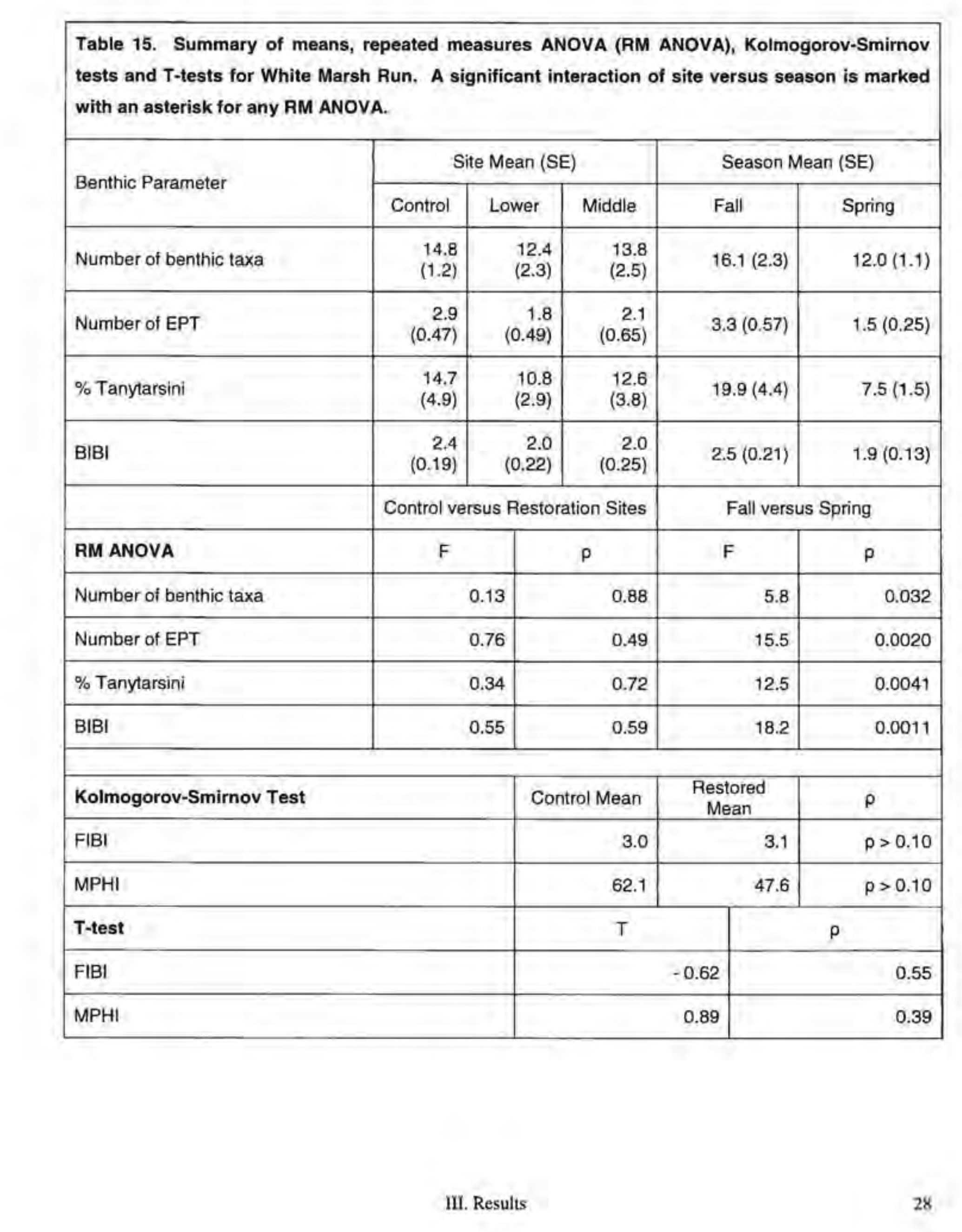


Table 15. Summary of means, repeated measures ANOVA (RM ANOVA), Kolmogorov-Smirnov tests and T-tests for White Marsh Run. A significant interaction of site versus season is marked with an asterisk for any RM ANOVA.

Benthic Parameter	Site Mean (SE)			Season Mean (SE)	
	Control	Lower	Middle	Fall	Spring
Number of benthic taxa	14.8 (1.2)	12.4 (2.3)	13.8 (2.5)	16.1 (2.3)	12.0 (1.1)
Number of EPT	2.9 (0.47)	1.8 (0.49)	2.1 (0.65)	3.3 (0.57)	1.5 (0.25)
% Tanytarsini	14.7 (4.9)	10.8 (2.9)	12.6 (3.8)	19.9 (4.4)	7.5 (1.5)
BIBI	2.4 (0.19)	2.0 (0.22)	2.0 (0.25)	2.5 (0.21)	1.9 (0.13)

	Control versus Restoration Sites		Fall versus Spring	
RM ANOVA	F	p	F	p
Number of benthic taxa	0.13	0.88	5.8	0.032
Number of EPT	0.76	0.49	15.5	0.0020
% Tanytarsini	0.34	0.72	12.5	0.0041
BIBI	0.55	0.59	18.2	0.0011

Kolmogorov-Smirnov Test	Control Mean	Restored Mean	p
FIBI	3.0	3.1	p > 0.10
MPHI	62.1	47.6	p > 0.10

T-test	T	p
FIBI	- 0.62	0.55
MPHI	0.89	0.39

O. Overview of SHA Restoration Sites

From 1998 to 2010, fourteen key SHA restoration sites were evaluated as to their success in stream restoration. The primary SHA goal was to establish stable streambanks at the restoration site, and to this end, stream restoration was generally successful (Tables 2-15). Water quality may be a continuing problem at two sites – Patuxent Run and Tributary Nine (near BWI). In addition, two sites (Herbert Run and Patuxent Run) did not have adequate upstream controls so it was difficult to assess restoration efforts (Green 1979).

It is perhaps counterintuitive that many of the statistical tests for the four benthic parameters among the control, the lower site, and the middle site were statistically non-significant. In most experimental design and statistical testing, one is generally testing for a significant experimental effect (rejection of the null hypothesis - H_o and acceptance of alternate hypotheses – $H_{(1-n)}$). The non-significance value (at $\rho \geq 0.05$) of the control site versus the two restoration sites is critical. This indicated that the restoration sites are roughly equivalent to the upstream control after restoration activities are complete. Basically, the restoration efforts have done no harm to the system, and biotic recovery occurred. The stream system recovered, and now reflects upstream characteristics for most sites after attaining equilibrium. The major exception to this general statement was Tributary Nine, where restoration sites were better than the control. In part, this was a function of the poorer stream quality in the control reach.

One other major factor relating to restoration assessment was the difference between the spring and fall benthic samples. For many sites (Tables 2-15), the fall samples were distinct from the spring samples for the four basic benthic parameters tested. This difference may lie with the fall sampling being done at lower flows, where organisms may be more concentrated in the stream. However, there is also a possibility that the benthic assemblage responds to higher flow regimes in the spring, especially if there is a significant amount of altered landuse in the upstream catchment.

P. Restoration Site Landuse

A major factor that drives stream restoration success, at any site, is the watershed landscape above a restoration site. Consequently, it is essential to determine altered land use (agriculture, urban, etc.) in the catchment area above a restoration site prior to project construction in order to predict potential fish and benthic assemblages. For example, Weijters et al. (2009), in a comprehensive review paper, determined that there was a 6% (± 0.83 SD) loss of fish and macroinvertebrates species for every 10% loss of natural landuse cover in a catchment. Other models dealing with urbanization (i.e., impervious surface) note that urban levels around 10% may be a threshold for biotic effects (Paul and Meyer 2001, Morgan and Cushman 2005, Walsh et al. 2005), although other literature now suggests that the threshold may be lower 5% (Weijters et al. 2009). Consequently, a stream restoration project with a highly altered catchment may never attain a high degree of success, but may support limited, stable fish and benthic assemblages, especially in highly urbanized watersheds.

Almost all restoration sites had highly altered landscapes (non-natural, including agriculture, transportation and urbanization) ranging from 21-94%, with Porter Run being the lowest and Muddy Bridge Branch the highest (Table 16). More importantly, 10 of the 14 sites had impervious surfaces greater than 20%, with four other sites ranging from 0.91% (Piney Creek) to 15.1% (Deep Run). These levels of impervious surface obviously affect both fish and benthic assemblages, and may be the reason that many control sites do not have benthic or fish assemblages that corresponded to the best MBSS sites (> 4.0).

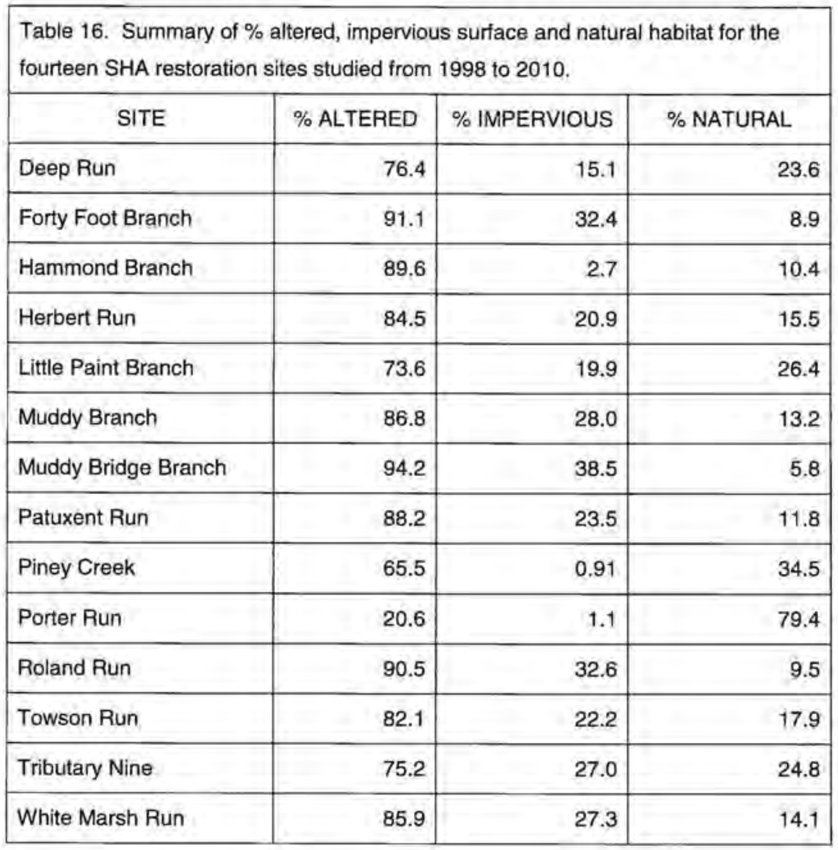
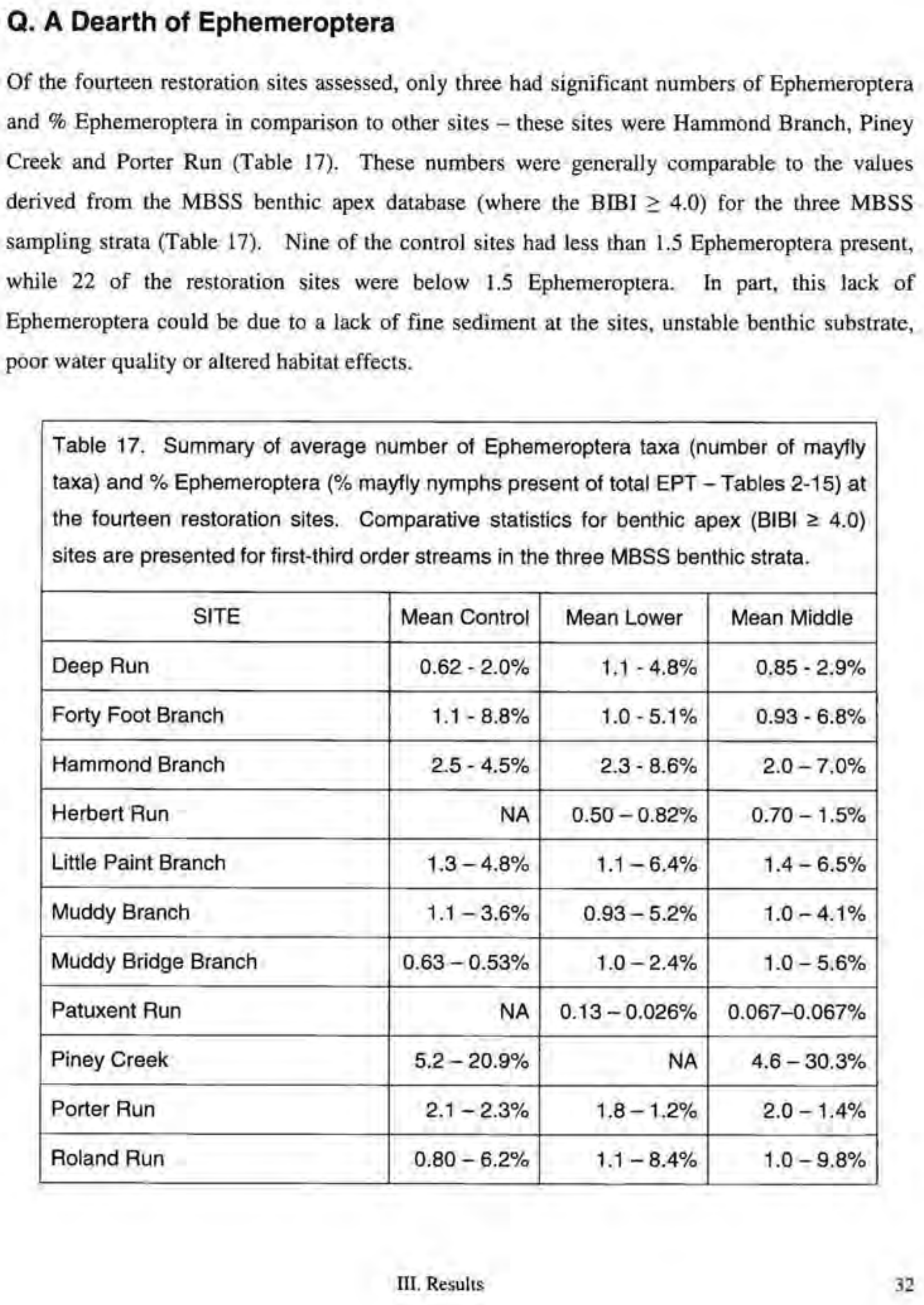


Table 16. Summary of % altered, impervious surface and natural habitat for the fourteen SHA restoration sites studied from 1998 to 2010.

SITE	% ALTERED	% IMPERVIOUS	% NATURAL
Deep Run	76.4	15.1	23.6
Forty Foot Branch	91.1	32.4	8.9
Hammond Branch	89.6	2.7	10.4
Herbert Run	84.5	20.9	15.5
Little Paint Branch	73.6	19.9	26.4
Muddy Branch	86.8	28.0	13.2
Muddy Bridge Branch	94.2	38.5	5.8
Patuxent Run	88.2	23.5	11.8
Piney Creek	65.5	0.91	34.5
Porter Run	20.6	1.1	79.4
Roland Run	90.5	32.6	9.5
Towson Run	82.1	22.2	17.9
Tributary Nine	75.2	27.0	24.8
White Marsh Run	85.9	27.3	14.1



Q. A Dearth of Ephemeroptera

Of the fourteen restoration sites assessed, only three had significant numbers of Ephemeroptera and % Ephemeroptera in comparison to other sites – these sites were Hammond Branch, Piney Creek and Porter Run (Table 17). These numbers were generally comparable to the values derived from the MBSS benthic apex database (where the BIBI ≥ 4.0) for the three MBSS sampling strata (Table 17). Nine of the control sites had less than 1.5 Ephemeroptera present, while 22 of the restoration sites were below 1.5 Ephemeroptera. In part, this lack of Ephemeroptera could be due to a lack of fine sediment at the sites, unstable benthic substrate, poor water quality or altered habitat effects.

Table 17. Summary of average number of Ephemeroptera taxa (number of mayfly taxa) and % Ephemeroptera (% mayfly nymphs present of total EPT – Tables 2-15) at the fourteen restoration sites. Comparative statistics for benthic apex (BIBI ≥ 4.0) sites are presented for first-third order streams in the three MBSS benthic strata.

SITE	Mean Control	Mean Lower	Mean Middle
Deep Run	0.62 - 2.0%	1.1 - 4.8%	0.85 - 2.9%
Forty Foot Branch	1.1 - 8.8%	1.0 - 5.1%	0.93 - 6.8%
Hammond Branch	2.5 - 4.5%	2.3 - 8.6%	2.0 – 7.0%
Herbert Run	NA	0.50 – 0.82%	0.70 – 1.5%
Little Paint Branch	1.3 – 4.8%	1.1 – 6.4%	1.4 – 6.5%
Muddy Branch	1.1 – 3.6%	0.93 – 5.2%	1.0 – 4.1%
Muddy Bridge Branch	0.63 – 0.53%	1.0 – 2.4%	1.0 – 5.6%
Patuxent Run	NA	0.13 – 0.026%	0.067–0.067%
Piney Creek	5.2 – 20.9%	NA	4.6 – 30.3%
Porter Run	2.1 – 2.3%	1.8 – 1.2%	2.0 – 1.4%
Roland Run	0.80 – 6.2%	1.1 – 8.4%	1.0 – 9.8%

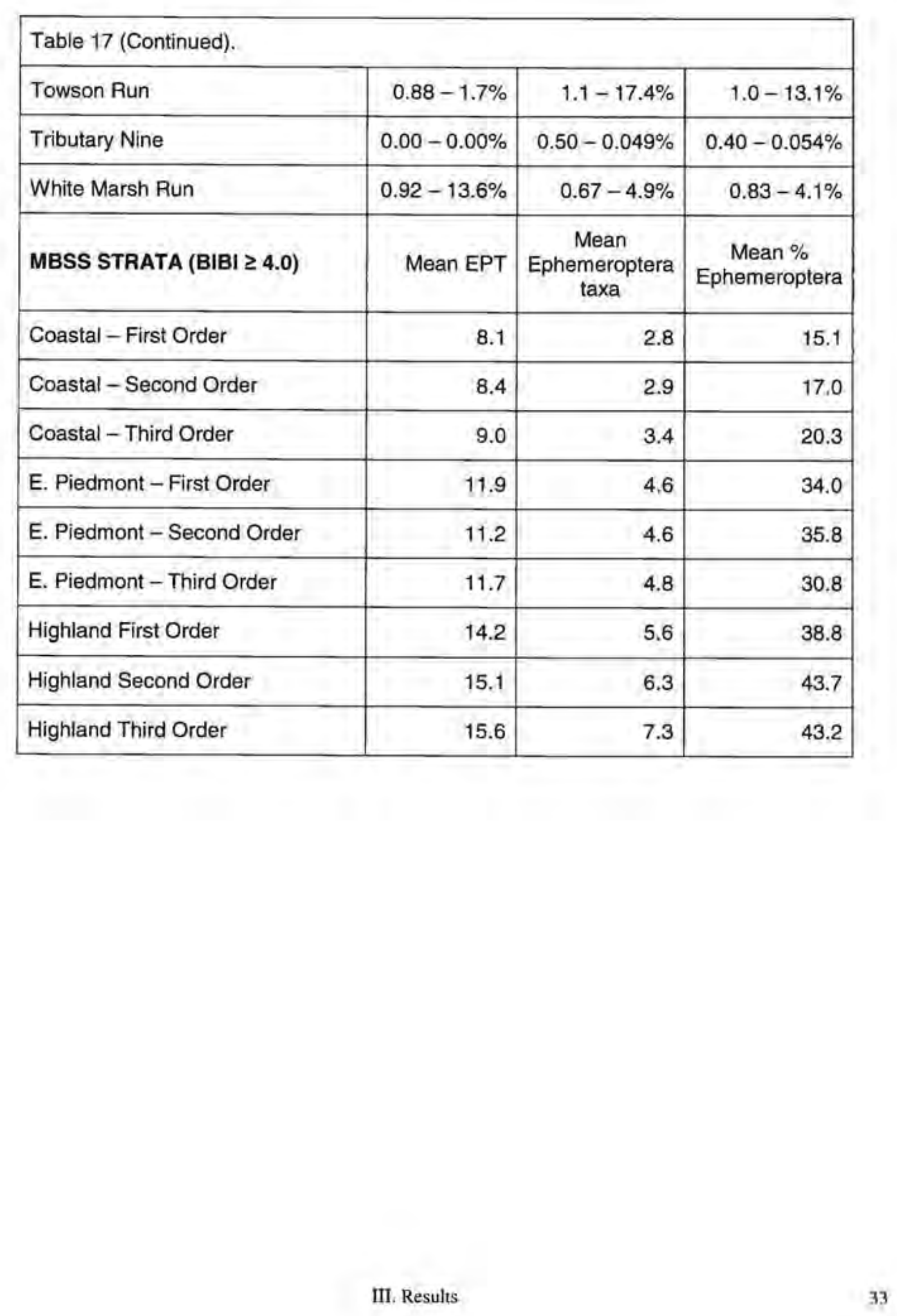


Table 17 (Continued).

Towson Run	0.88 – 1.7%	1.1 – 17.4%	1.0 – 13.1%
Tributary Nine	0.00 – 0.00%	0.50 – 0.049%	0.40 – 0.054%
White Marsh Run	0.92 – 13.6%	0.67 – 4.9%	0.83 – 4.1%
MBSS STRATA (BIBI ≥ 4.0)	Mean EPT	Mean Ephemeroptera taxa	Mean % Ephemeroptera
Coastal – First Order	8.1	2.8	15.1
Coastal – Second Order	8.4	2.9	17.0
Coastal – Third Order	9.0	3.4	20.3
E. Piedmont – First Order	11.9	4.6	34.0
E. Piedmont – Second Order	11.2	4.6	35.8
E. Piedmont – Third Order	11.7	4.8	30.8
Highland First Order	14.2	5.6	38.8
Highland Second Order	15.1	6.3	43.7
Highland Third Order	15.6	7.3	43.2

IV. Discussion

From 1998 to 2010, we assessed the status of stream restoration projects either constructed (pre- and post-assessment) or in planning and pre-construction (pre-assessment) by the SHA throughout Maryland. The majority of these SHA projects were in the western Coastal Plain and Eastern Piedmont, altered areas with potentially high urban or agricultural effects. Generally, each restoration site rapidly responded, reflecting the upstream dynamics of the catchment. The exception was Tributary Nine where the restoration site was significantly better than the control site. Two sites (small first-order catchments) were difficult to assess since no suitable upstream control areas were present. We also determined that there were significant differences between the fall and spring benthic samples for many of the benthic attributes analyzed, as well as noting a lack of Ephemeroptera in many streams.

Palmer et al. (2005) constructed a series of five criteria for consideration in stream restoration. For Palmer Criterion I (a guiding image exists), we did not define a dynamic ecological endpoint *a priori* for the SHA sites. However, we did initially hypothesize that the restoration sites would display some degree of ecological recovery and are at least in equilibrium after restoration - to a degree this occurred for most sites. We met Palmer Criterion II (ecosystems are improved) partially in that many restoration sites did show enhancement in the benthic assemblage, with some sites showing improvement in fish assemblages over time. However, we did not examine ecosystem functions such as nutrient processing, stream metabolism, etc. Palmer Criterion III (resilience is increased) was not measured nor tested since ecological resilience is not an easy criterion to test (Chapin et al. 2000), especially within cost and time constraints. However, there is a proposed framework (Table 18) for long-term assessment of the SHA projects, so resiliency within sites may be determined over a temporal scale. For Palmer Criterion IV (no lasting harm is done), most projects met this criterion. The only site where there was potential initial harm was Tributary Nine, with removal of significant amounts of riparian vegetation prior to restoration. We met, or will meet, Palmer Criterion V (ecological assessment completed, and there is some level of both pre- and post-project assessment with information available). Yearly reports were written and submitted to SHA, and this report will serve as a starting point for submission of a peer-reviewed paper(s) to be considered for publication.

The 'Field-of-Dreams' hypothesis relates to the re-establishment of the physical stream structure, with the assumption that if this ecological attribute is restored than organisms will re-establish (Palmer et al. 1997, Stier and Osenberg 2010). For freshwater systems, primary mechanisms for benthic re-establishment is drift from upstream refugia, individual movement and aerial flight ability, consisting of upstream and downstream movement with a minor contribution from lateral sources (Allen and Castillo 2007). With fishes, active upstream and downstream migration is important, especially with larval and juvenile fishes – the 'Propagule Redirection' hypothesis, strongly linked to altered habitat availability and suitability, connectivity, and temporal and spatial scales (reviewed in Stier and Osenberg 2010). In our studies on the fourteen SHA stream restoration sites, we observed benthic assemblage recolonization (from either upstream or downstream refugia), in equilibrium with the upstream control, as well as improvement in the fish community at several sites. Hammond Branch, Little Paint Branch and Piney Creek stand out as model examples of stream restoration.

V. Recommendations

Based on analyses of the fourteen stream restoration sites, we propose the following recommendations for SHA projects, and provide future monitoring recommendations for these sites (Table 18). This list (not in any logical order of priority) is not inclusive of all potential recommendations for assessment of stream restoration projects, but based on experience associated solely with SHA work from 1998 to 2010.

1. For any SHA stream restoration project in the future, there should be a minimum of two years of pre-construction sampling for biological condition and physical habitat if possible, including two sampling seasons each year – spring and fall for benthic macroinvertebrates and summer/fall for fishes and physical habitat. This approach would tend to smooth out any severe weather occurrences such as drought, hurricanes, etc., as well as providing for improved statistical testing for post-construction effects.

2. During construction, the control site should be sampled at least once with no sampling in the restoration area. In an ideal situation, there should be two control sites upstream and two restoration sites. This design provides for additional statistical power, although there is a potential to introduce pseudoreplication effects (Hurlbert 1984).

3. Detailed habitat mapping (Gordon et al. 1992) for each restoration site should be done both pre- and post-construction (two years after completion), followed by periodic site remapping (either 5 or 10 years post-project) to determine restoration physical stability and to identify potential problems with the restoration activity.

4. Correspondingly, for any SHA stream restoration project in the future, there should be a minimum refractory period of two years following the project completion before beginning biological and physical sampling. First, this recommendation centers on the recolonization potential of both benthic and fish assemblages, which may be highly dependent on refugia proximity to the restoration site (Wallace 1990), as well as time for the assemblages to colonize and develop into stable communities. Second, it takes time for the completed project to attain some level of post-construction physical equilibrium

with its catchment, especially with sediment dynamics. There may even be the potential that some restoration sites may need to be 'seeded' if adequate refugia are not present (Collier et al. 2009). In this case, it is important to seed the stream with the appropriate ecoregion assemblages, as well as assessing stream water quality to assure survival of any introduced, native species to the restoration site.

5. It is critical to conduct detailed GIS work for each project site prior to restoration construction. There are numerous reasons why this is critical to evaluating and determining project success. First, this effort would aid in identifying upper stream reaches that could serve as controls, often a difficult task in urban streams associated with the Piedmont or Coastal Plain. Second, it would serve to identify biological refugia, as well as stream blockages or other stream alterations that affect organismal movement into restoration sites, either from upstream or downstream of any restoration site. There is the potential to use the MBSS data set to estimate potential refugia in the vicinity of a restoration project.

6. It is also essential to determine the degree of altered land use (agriculture, urban, etc.) in the catchment area above a restoration site prior to project construction. Weijters et al. (2009), in a comprehensive review paper, determined that there was a 6% (± 0.83 SD) loss of fish and macroinvertebrates species for every 10% loss of natural land use cover. Consequently, a stream restoration project with a highly altered catchment may never attain a high degree of success, but may support a limited fish and benthic assemblage.

7. For watersheds having less than 125 ha (~ 309 acres) above a restoration site, fish assemblages should not be sampled since this area estimate is a key breakpoint for fish presence at MBSS sites (Southerland, pers. comm.). Assessment of the benthic assemblage is preferred in these small watersheds, with sampling of the amphibian community also a potential assessment tool.

8. Culverts are partial barriers to upstream insect migration (Blakely et al. 2006), and potentially to fishes depending on the physical structure. Consequently, all stream restoration projects in the future should examine the presence of culverts, or other barriers, downstream of the proposed site.

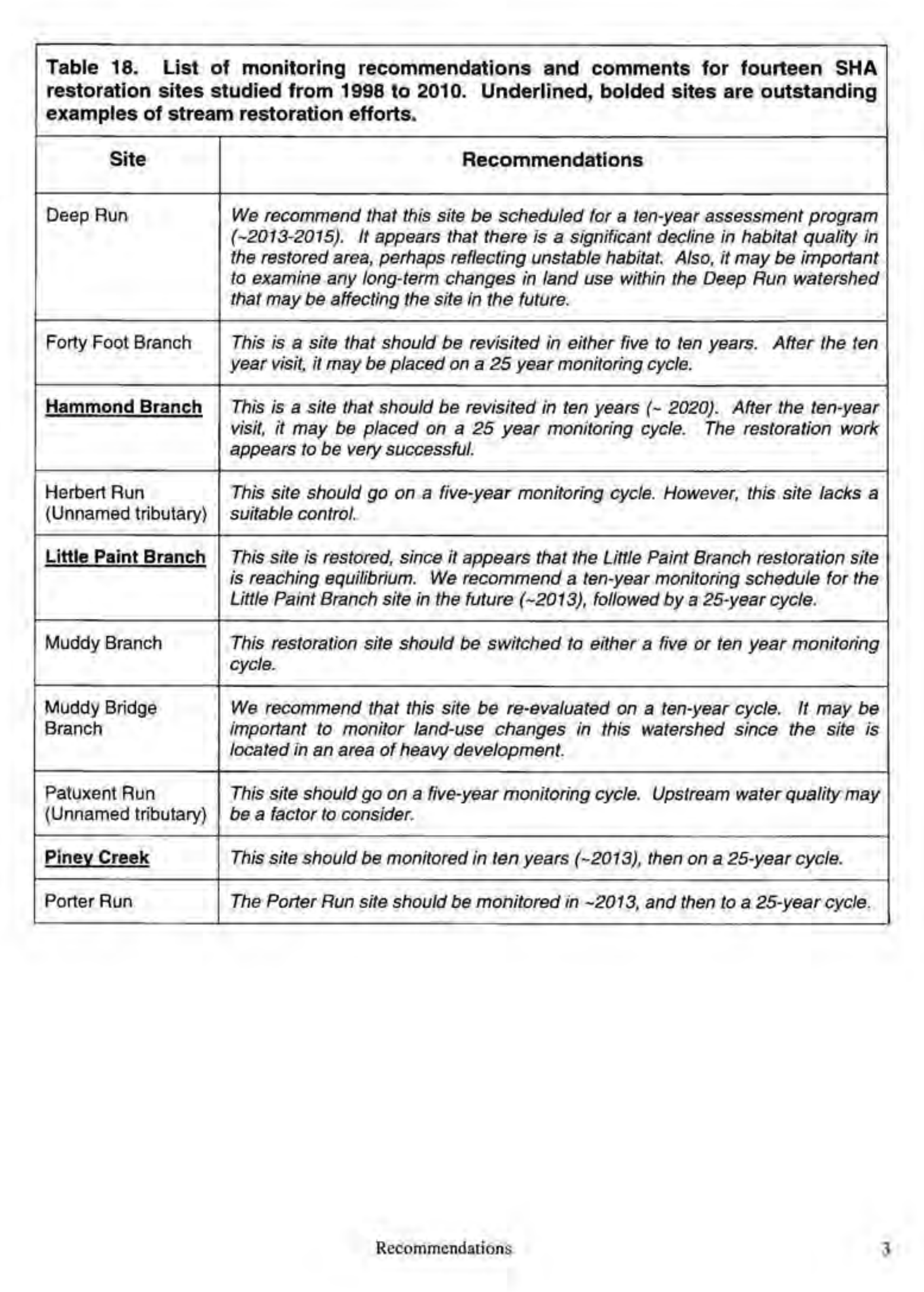


Table 18. List of monitoring recommendations and comments for fourteen SHA restoration sites studied from 1998 to 2010. Underlined, bolded sites are outstanding examples of stream restoration efforts.

Site	Recommendations
Deep Run	*We recommend that this site be scheduled for a ten-year assessment program (~2013-2015). It appears that there is a significant decline in habitat quality in the restored area, perhaps reflecting unstable habitat. Also, it may be important to examine any long-term changes in land use within the Deep Run watershed that may be affecting the site in the future.*
Forty Foot Branch	*This is a site that should be revisited in either five to ten years. After the ten year visit, it may be placed on a 25 year monitoring cycle.*
Hammond Branch	*This is a site that should be revisited in ten years (~ 2020). After the ten-year visit, it may be placed on a 25 year monitoring cycle. The restoration work appears to be very successful.*
Herbert Run (Unnamed tributary)	*This site should go on a five-year monitoring cycle. However, this site lacks a suitable control.*
Little Paint Branch	*This site is restored, since it appears that the Little Paint Branch restoration site is reaching equilibrium. We recommend a ten-year monitoring schedule for the Little Paint Branch site in the future (~2013), followed by a 25-year cycle.*
Muddy Branch	*This restoration site should be switched to either a five or ten year monitoring cycle.*
Muddy Bridge Branch	*We recommend that this site be re-evaluated 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.*
Patuxent Run (Unnamed tributary)	*This site should go on a five-year monitoring cycle. Upstream water quality may be a factor to consider.*
Piney Creek	*This site should be monitored in ten years (~2013), then on a 25-year cycle.*
Porter Run	*The Porter Run site should be monitored in ~2013, and then to a 25-year cycle.*

Table 18 (Continued). List of monitoring recommendations for all SHA restoration sites from 1998 to 2010.

Roland Run (Unnamed tributary)	*We recommend that this site be re-evaluated in five to ten years.*
Towson Run (Unnamed tributary)	*We recommend that this site be re-evaluated in five to ten years.*
Tributary Nine (9)	*Based on MPHI scores, we consider this site to be restored for physical habitat. However, FIBI and BIBI values are still poor, or very poor. We recommend that this site be re-evaluated in five to ten years.*
White Marsh Run	*We suggest that this site go to a ten-year assessment in ~2013, and then to a 25-year cycle. It may be important to monitor land-use changes in this watershed since the site is located in an area of heavy urban development.*

VI. Acknowledgments

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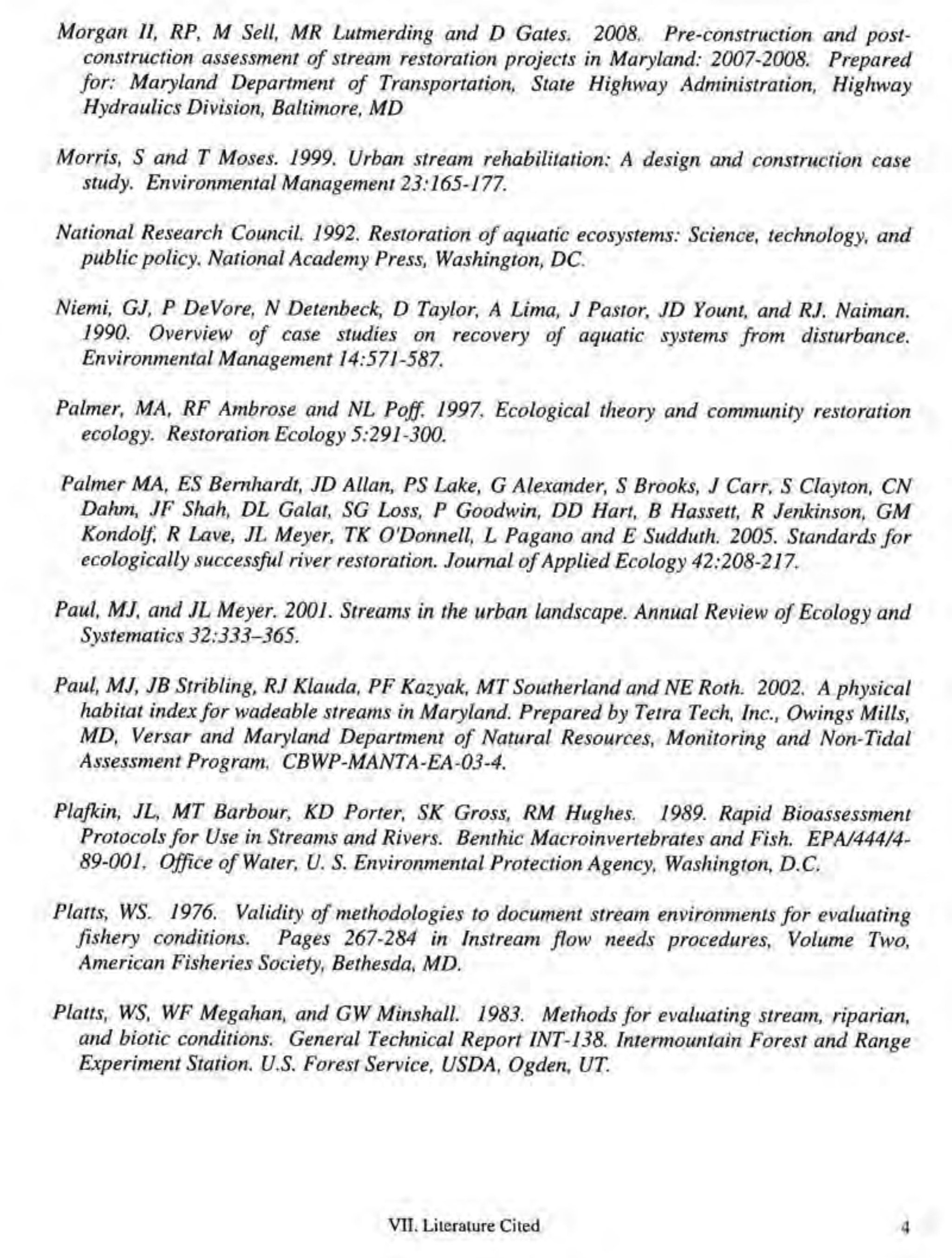

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