FINAL REPORT

CONTROLLING HIGHWAY RUNOFF POLLUTION IN DRINKING WATER SUPPLY RESERVOIR WATERSHEDS

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the
Virginia Department of Transportation and
the University of Virginia)

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

October 1999
VTRC 00-R7

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ACRONYMS

BMP	Best Management Practice
BOD	Biological Oxygen Demand
Cd	Cadmium
COD	Chemical Oxygen Demand
Cu	Copper
EMC	Event Mean Concentration
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
MCL	Maximum Contamination Level
N_{ox}	Nitrates/Nitrites
NURP	Nationwide Urban Runoff Program
P	Phosphorus
Pb	Lead
PRE	Pollutant Removal Efficiency
PWS	Public Water Supply
RSD	Relative Standard Deviation
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
VDOT	Virginia Department of Transportation
VTRC	Virginia Transportation Research Council
Zn	Zinc

ABSTRACT

This study evaluated the effectiveness of an innovative stormwater best management practice in treating highway runoff and protecting the integrity of the drinking water reservoir in Warrenton, Virginia. The research focused on the use of a biodetention pond, which combines the concepts of detention ponds and bioretention in an attempt to provide higher overall pollutant removal.

Storm event and background concentrations were all within or below the expected range for highway runoff pollutants and below Virginia's ambient maximum contamination levels for drinking water. The majority of the pollutant removal efficiencies were below values reported in the literature for well-designed wet/dry detention ponds and bioretention areas. Concentration comparisons for one storm event indicated serious problems with sediment re-suspension or short-circuiting in the biodetention facility.

Design recommendations are made to potentially improve pollutant removal in the biodetention facility, and design guidelines are offered for future biodetention pond construction. In spite of pond short-circuiting and re-suspension, the study concludes that the biodetention pond adequately protects the integrity of the Warrenton Reservoir and is an innovative alternative for treating stormwater runoff.

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INTRODUCTION

The Virginia Department of Transportation (VDOT) is required under the National Pollutant Discharge Elimination System created by the federal Clean Water Act, the Chesapeake Bay Preservation Act, the Virginia Stormwater Management Regulations, and the Virginia Erosion and Sediment Control Regulations to provide erosion and sediment controls and stormwater runoff controls before and after construction of highways. These controls, known as best management practices (BMPs), are designed to minimize the impact of pollutants in highway runoff on receiving water quality. Because the Virginia Ambient Water Quality Standards require higher standards for drinking water than for water used for other purposes, a higher degree of runoff control for the former may be necessary. Consequently, VDOT may need to implement stormwater BMPs with the highest pollutant removal efficiencies (PRE) when constructing roads or other facilities in watersheds that are the source for drinking water.

The 1996 Amendments to the Safe Drinking Water Act expanded the list of potential contamination sources under federal regulation. They also promoted source water protection, a community-based approach to protecting sources of drinking water from contamination. In the past few years, the U.S. Environmental Protection Agency (EPA) has been encouraging states and communities to undertake source water protection programs that would reduce the need, and therefore the cost, of water treatment. Through the efforts of the EPA and other environmental agencies and groups, public awareness of the importance of source water protection is increasing. Citizens and local water officials recently notified VDOT of their strong concerns over the possible effect of roadway runoff on drinking water sources, e.g., in the Warrenton and Charlottesville-Albemarle areas.

The Rte. 17 Bypass in Warrenton, Virginia, links the Rte. 29 Bypass and Rte. 17. The Rte. 17 Bypass, which opened in late 1997, is a dual-lane highway approximately 4.0 km (2.5 mi) long with 1.6 km (1 mi) located in the watershed of the Warrenton Reservoir. The Warrenton Reservoir is the primary source of drinking water for the town of Warrenton and its surrounding communities. Local citizens living near the reservoir expressed concern that stormwater runoff from the roadway during and after the construction of the bypass could “carry toxic substances such as asbestos, gasoline, benzene and cadmium directly into the reservoir”

(Loos, 1996). During these discussions, VDOT was asked to install costly pollution control devices such as sand filters and container/vault types of structures, many of which were not field tested and not required by regulatory agencies under federal and state stormwater management programs.

To respond to citizens' concerns, in 1995, VDOT initiated a 1-year study through the Virginia Transportation Research Council to examine the impact of stormwater runoff from the project on the reservoir during its construction phase (Loos, 1996). A field monitoring program was implemented to collect background samples during dry weather and runoff samples during storm events at selected locations adjacent to the Warrenton Reservoir. The samples were analyzed for several water quality constituents such as sediment, phosphorus, copper, mercury, iron, lead, cadmium, oil/grease, and the BTEX group (benzene, toluene, ethylbenzene, xylene, and MTBE, a gas additive). Results from the monitoring effort and subsequent modeling analyses indicated that stormwater runoff from the project site did not violate the safe drinking water quality standards for the Warrenton Reservoir. The sediment level was high, but the problem was temporary during the construction period and occurred only when there were large storm events. The phosphorus levels were also significant, but the residential areas and croplands around the reservoir were found to contribute more phosphorus loads to the reservoir than the runoff from the project site.

In the Charlottesville-Albemarle area, VDOT is planning to build a 10-km (6.25-mi), limited access bypass of Rte. 29. The proposed road is located west of Rte. 29, and 6.7 km (4.2 mi) lies within the watershed boundary of the South Fork Rivanna Reservoir. The reservoir serves as the main drinking water supply source for more than 60,000 people in the Charlottesville-Albemarle area. Although Virginia's Commonwealth Transportation Board approved the bypass project in April 1997, local citizen groups and the County of Albemarle continue to voice strong opposition to the project. The most frequent source of this opposition is the concern over the impact the bypass will have on the water quality of the reservoir. Those in opposition argue that the stormwater management facilities VDOT plans to implement for the project do not effectively treat certain types of pollutants that may be present in highway runoff and will not adequately protect the Charlottesville-Albemarle drinking water supply from potential hazardous spills.

It was against this background that this project was conceived. This project focused on a biodetention pond as an innovative practice for highway pollutant control. A biodetention pond is a facility that combines the concepts of detention ponds and bioretention in attempt to provide higher overall pollutant removal. Little is known about the overall efficiency of bioretention. Bioretention is a new urban BMP developed by Prince George's County, Maryland, and the Maryland Department of Environmental Resources. Typical bioretention facilities consist of a vegetated strip of land that allows stormwater percolation for biological and physical treatment. Bioretention is typically used in an area of 1 acre or less and consists of an excavated bed filled with sand and covered with a layer of permeable soil. Pollutant removal processes in bioretention areas include adsorption, volatilization, ion exchange, and decomposition. Terrestrial vegetation with a high moisture tolerance is suggested for planting in bioretention areas. Only one study has released data on the pollutant removal potential of bioretention. This study performed by the University of Maryland (1977) suggested the potential benefits of bioretention for use in urban areas. Bioretention is an aesthetically pleasing alternative to conventional stormwater BMPs.

Biodetention, the unique combination of a bioretention area in conjunction with a detention pond, appears to be a promising means of treating highway runoff. Thus, a biodetention pond located adjacent to the Rte. 17 Bypass was selected for this study.

PURPOSE AND SCOPE

The purpose of this study was to evaluate the use of biodetention ponds as stormwater BMPs. The objective was to document the water quality benefits of biodetention ponds as an innovative control device for treating stormwater runoff from highways.

The site studied was biodetention pond 10P-2 constructed by VDOT at the Rte. 17 Bypass site in Warrenton, located in Northern Virginia (see Figure 1). The pond is a 0.7-ha facility receiving runoff from 15.1 ha from several sources including the highway, the Highland School (field and roof), and grassed medians. The pond collects the runoff from approximately

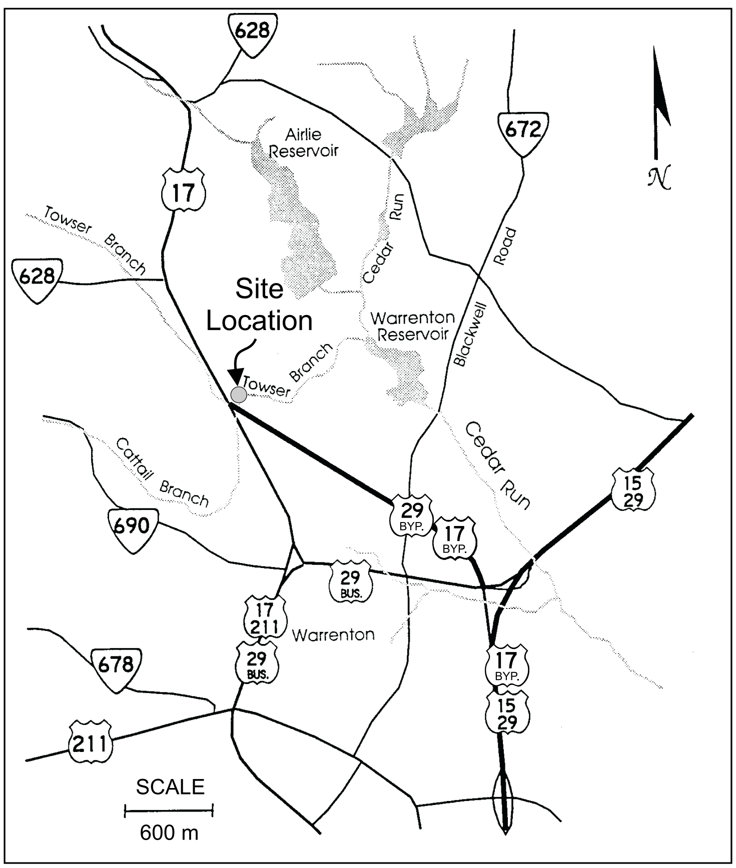

Figure 1. Location of Project Site in Warrenton

0.88 km of highway or approximately 40% of the 2.0 km of newly constructed highway area. The researchers sought to determine its pollutant removal efficiency to assess the potential post-construction impact of the Rte. 17 Bypass project on the water quality of the Warrenton Reservoir. The drinking water quality criteria required by federal and state regulations were used as a guide in the assessment. Monitoring of the site began in April 1998 and ended in May 1999.

LITERATURE REVIEW

A literature review was conducted to determine the national primary and secondary drinking water standards; to obtain an overview of the EPA's newly proposed concept of source water protection and the movement toward a watershed protection approach to protecting the drinking water supply; and to review state-of-the-art and commonly employed structural BMPs for control of highway runoff and stormwater pollution.

National Primary and Secondary Drinking Water Regulations

The National Primary Drinking Water Regulations are legally enforceable standards governed by the 1996 Amendments to the Safe Drinking Water Act (U.S. EPA, 1999). They are designed to protect the quality of drinking water by setting standards or maximum contamination levels (MCL) for public water supply (PWS) systems. These standards are specifically designed to target common water supply contaminants and limit the levels of these contaminants to avoid adverse public health effects (U.S. EPA, 1991a).

Also encouraged by the amendments was the establishment of National Secondary Drinking Water Regulations. These are aesthetically based standards recommended for characteristics that render water less desirable for use (Viesmann & Hammer, 1993) and include pollutants that can cause problems with odor, foaming, and color.

These primary and secondary national regulations, associated environmental and human health risks, and sources for contaminants analyzed in this study and other contaminants identified in the Nationwide Urban Runoff Program (NURP) are reviewed in Table 1. The NURP study was a 28-locality research project performed from 1978 to 1983 to characterize, identify, and provide solutions for runoff from urban areas (U.S. EPA, 1983; Novotny et al., 1994). As can be seen, many of the chemical constituents listed as common in the NURP studies are not regulated under the national primary and secondary regulations, but many of them still pose serious health and ecological threats to the environment. All NURP pollutants are common constituents in highway runoff and must be considered when highway operations are conducted in watersheds supplying drinking water reservoirs.

Table 1. National Primary and Secondary Drinking Water Standards

Contaminant	MCL (mg/L)	Potential Health or Ecosystem Threats	Sources of Contamination
Metals			
Copper	1.3	Gastrointestinal Distress, Liver or Kidney Damage	Plumbing, Cars, Wood Preservatives
Lead	0.015	Delay in Physical and Mental Development, Kidney Problems	Plumbing, Natural Deposits
Zinc*	5	Taste and Odor Problems	Tire Wear, Motor Oil, Grease Deposits
Cadmium	0.005	Kidney Damage	Galvanized Pipes, Batteries, Paints, Refineries, Natural Deposits
Nutrients			
Total Phosphorus	N/A	DO Variability, Eutrophication	Fertilizers, Septic Tanks, Sewage, Soil Erosion
Soluble Phosphorus	N/A	Same as above	Same as above
Total Nitrogen	N/A	Same as above	Same as above
Nitrates	10	Blue Baby Syndrome, Eutrophication	Same as above
Nitrites	1	Same as above	Same as above
Conventional Parameters			
pH*	6.5-8.5	Harmful to Aquatic Life, Harmful Chemical reactions	Acid Rain
Total Suspended Solids*	N/A	Light Reduction	Soil Erosion, Construction Practices
Total Dissolved Solids*	500	Light Reduction	Same as above
Biological Oxygen Demand*	N/A	DO Depletion	Wastewater, Debris
Chemical Oxygen Demand*	N/A	DO Depletion	Wastewater, Debris
Temperature*	N/A	Harmful to Aquatic Life	Thermal Discharges
Biological Parameters			
Fecal Coliforms	5%	Indicator of Presence of Harmful Organisms	Human and Animal Fecal Waste

*****Non-enforceable national secondary standards.
N/A = No data available or not regulated.
Source: U.S. EPA, 1999; Lijklema et al., 1992.

Source Water Protection

With the enactment of the 1996 Amendments to the Safe Drinking Water Act, national priority was given to protecting the nation's drinking water sources. This concept, termed *source water protection*, is slowly being endorsed as a primary measure for protecting drinking water supplies. *Source water* can be simply defined as any water (surface or groundwater) that is used as a drinking water source by a PWS system. Source water protection is a pollution prevention approach that includes the protection of rivers, lakes, streams, and groundwater that serve as a supply of public drinking water (U.S. EPA, 1996). Pollution prevention and the source water protection approaches rely on two key concepts: a clear state lead in the development of source water protection programs and a strong public involvement in the development process. Source water protection can be a cost-effective alternative to the conventional practice of treating water exclusively at a drinking water treatment facility.

All states were required under Section 1453 of the Amendments to the Safe Drinking Water Act to establish source water assessment programs by February 6, 1999. Along with the programs, states had to submit the delineation of water protection areas, an inventory of significant contaminants in these areas, and a determination of the susceptibility of each public water supply to potential contamination (U.S. EPA, 1997).

Drinking water standards for PWS systems are much more stringent than the current ambient water quality standards for surface water bodies. For source water protection to work, ambient water quality standards for watersheds that supply drinking water reservoirs will have to become more stringent. As the water quality standards for the streams become more rigid, the regulation of runoff from highways and other facilities within the watershed will too.

Watershed Protection Approach

The 1972 Clean Water Act and the 1974 Safe Drinking Water Act were paramount in the progress to attaining the EPA’s ultimate goal of “protecting and restoring the physical, chemical and biological integrity of our waters” (U.S. EPA, 1995b). Significant advances have been made in water pollution control with the management and monitoring of point sources of pollution required by the two acts. Now, more 20 years after the passage of the acts, over 40% of our nation’s rivers and streams still remain too polluted for fishing, swimming, and other recreational uses (U.S. EPA, 1991b). The primary causative agents are non-point sources of pollution such as silt, fertilizer, and stormwater runoff. Many studies have recognized other causes of impairment including sewage from combined sewer overflow, disease-causing bacteria, toxic metals, and oil and grease (U.S. EPA, 1995b). To address these pollutants, the EPA is promoting a new integrated program called the watershed protection approach.

The watershed protection approach is a comprehensive approach to water resource management that addresses multiple water quality problems, such as non-point source pollution, point source pollution, and habitat degradation. The EPA suggests that integrating point and non-point source pollution control and management on a watershed scale can best protect water quality resources. Watershed approaches are likely to result in significant restoration and maintenance of water quality because of their broad range and focus. Many states, including Washington, South Carolina, North Carolina, and Oklahoma, are already managing environmental problems on a watershed scale (U.S. EPA, 1995a). The watershed protection approach and water resource management can be integrated in a comprehensive environmental program (U.S. EPA, 1995a). States considering the implementation of a watershed protection plan should refer to these rudimentary programs already established. The watershed protection framework recommended by the EPA is in its juvenile stage, and modifications of the watershed protection plans are encouraged as necessary. Inclusion of watershed protection approaches into environmental legislation is also in progress, and its focus should be followed closely.

Best Management Practices

Much of the literature suggests that significant portions of total stormwater pollution loads are produced during the first stages of a storm event. This phenomenon is typically called the first flush phenomenon, which is usually considered to be the first half inch of runoff from a drainage area (Young et al., 1996). Stormwater treatment facilities typically focus on treating the first flush of pollutants.

BMPs are any measures used to control non-point sources of pollution. BMPs can be defined as any practice, structural or non-structural, designed to act as a practical means of minimizing the impact of non-point source pollution on water quality (Bell & Nguyen, 1994). Structural BMPs function by trapping runoff for an extended period of time while physical processes remove pollutants. Non-structural BMPs can be defined as any means or measures designed to reduce pollutant accumulation and initial pollutant concentrations in stormwater runoff (Dennison, 1996).

FHWA has performed extensive research on highway stormwater quality, control, and (Young et al., 1996). In fact, the majority of stormwater and BMP research has been presented in government documents with little representation in technical journals (Loos, 1996). The most comprehensive stormwater sources from the FHWA to date include *Constituents of Highway Runoff* (Gupta et al., 1981), *Effects of Highway Runoff Pollution on Receiving Water Bodies* (Dupuis et al., 1985), *Pollutant Loadings and Impacts From Highway Stormwater Runoff* (Driscoll et al., 1990), and *Evaluation and Management of Highway Runoff Water Quality* (FHWA, 1996).

Considerable research on stormwater control structures and BMPs has also been conducted at the state and local level. Many state departments of transportation have guidelines and manuals for the construction, selection, and evaluation of structural BMP stormwater controls. At the forefront of the research are the departments of transportation of Florida, Washington, California, Texas, and Virginia (Young et al., 1996).

Recently, a new trend in BMP development has occurred in the private sector with the development of new space-limited BMPs (FHWA, 1998). Prominent companies in BMP and stormwater management include GKY and Associates, Stormceptor, Stormwater Management, Vortechnics, StormTreat Systems, and Fox Environmental Systems (Zhang, 1998).

Detention/Retention Ponds

Wet and dry detention ponds are perhaps some of the most widely used structural BMPs for hydrologic and water quality control of stormwater runoff (Loos, 1996). The primary purpose of extended detention ponds and wet ponds is to remove particulates and reduce runoff peak flow and volume levels. Wet detention ponds, or retention ponds, are designed to retain a permanent pool of water in addition to detaining stormwater runoff temporarily (Osmond et al., 1995). Detention ponds are typically used on sites with large drainage areas, and a well-designed detention pond can function for approximately 20 years (Yousef et al., 1991). It is generally recognized that preliminary planning and design of detention ponds should be based on long-term assessment of pond performance (Yu & Field, 1992).

Wet Detention Ponds

When properly sized and maintained, wet retention/detention ponds can achieve a high removal efficiency for total suspended solids (TSS), biological oxygen demand (BOD), total nitrogen (TN), total phosphorus (TP), and heavy metals such as lead (Pb), zinc (Zn), copper (Cu), iron (Fe), nickel (Ni), chromium (Cr), and cadmium (Cd) (Yousef et al., 1991). Wet ponds, if well designed, have a greater potential for pollutant removal than extended dry ponds (Northern Virginia Planning District Commission, 1987). A large pond size and low soil infiltration rates are required. Maintenance requirements include inspection of the integrity of embankments, erosion control and periodic sediment removal, and algae control. Pond pollutant removal can be enhanced by maximizing the distance between pond inlets and outlets (Young et al., 1996).

Average PREs for wet detention ponds vary greatly depending upon maintenance and design. Average PREs for well-designed wet ponds for have been reported to be 74% for TSS, 49% for TP, 34% for TN, and 65% for metals (Young et al., 1996).

Dry Detention Ponds

Dry detention basins are ponds that dry out between storm events and do not maintain a permanent pool of water after storm events. Overall, they are comparatively less effective for pollutant removal than retention ponds, but they still are extremely effective at controlling downstream peak discharges. A designed control outlet regulates flows through detention ponds. Disadvantages of dry detention basins include aesthetic problems, sediment re-suspension, moderate area requirements, and the need for regular maintenance. Advantages include the lack of a need for maintenance of a permanent pool of water and smaller area requirements than wet detention pond systems (Dorman et al., 1988).

PREs of dry detention ponds vary greatly depending on design considerations and maintenance. Average PREs of 68% for TSS, 42% for TP, 40% to 60% for metals, and 42% for COD have been reported in the literature for a well-designed dry detention basin.

Bioretention Areas

Bioretention is a fairly new BMP developed by Prince George's County, Maryland, in 1987 that can be conceptualized as a modified infiltration trench that treats stormwater by adsorption, filtration, volatilization, ion exchange, and microbial decomposition (Young et al., 1996). Bioretention areas are typically designed to function like upland forest floors planted with indigenous shrubs, trees, and grasses known to have high pollutant removal capacities (Engineering Technology Associates [ETA], 1993). Bioretention can provide stormwater quantity and quality control. Bioretention areas typically consist of a surrounding grass buffer strip, sand bed infiltration area, ponding area, organic mulch layer, planting soil, and plants. In areas with high infiltration rates, the surrounding soil can be used for infiltration. In low percolation areas, runoff is collected through an underdrain system that leads to a conventional stormwater conveyance (ETA, 1993). Minimum design criteria for the construction and maintenance of bioretention areas can be found in the *Design Manual for Use of Bioretention in Stormwater,* which was recently updated in 1998, by the Prince George's County Maryland Department of Environmental Resources.

Potential benefits of bioretention include low-maintenance costs, water quality control potential, small size, and aesthetic enhancement. Potential problems with bioretention areas include groundwater contamination in high percolation areas and mosquitoes and pest breeding in areas were ponding levels are high (Coffman et al., 1997).

Although the conceptual benefits seem to be ascertainable, few studies have examined the PRE of this technology. Design considerations and maintenance for bioretention areas will certainly change as more monitoring data become available. Studies of bioretention areas are being performed at the University of Virginia (Yu et al., 1999) and have been performed by the University of Maryland (1997). Preliminary results from the University of Maryland study suggest potential high PREs for bioretention areas, but further studies are needed for a complete assessment. PREs for biodetention facilities have been reported as 80% for TSS, 72% for TP, 47% for TN, and 40% to 80% for metals (Yu et al., 1999).

METHODS

Overview

The primary focus of the field monitoring program was to assess the hydrology and water quality benefits of biodetention pond 10P-2. The sampling program was designed to test the long-term and storm event (short-term) PRE of the biodetention facility. To assess the benefits, appropriate inflows to and outflow from the biodetention facility were monitored for 1 year, beginning in the spring of 1998 and ending in the spring of 1999. As can be seen in Figure 2, there are nine inflows to and one outflow from the pond. The two primary inflows based on areas are located at inflows labeled I1 and I2. Because of limited resources, only these two primary drainage areas were monitored with automatic samplers. The outlet was also equipped with an automatic sampler. For the remaining inflows (I3 through I9), peak discharges were estimated using the rational method (Young et al., 1996) and pollutant loadings were approximated using the EPA's simple method (Young et al., 1996). To aid in estimating the pollutant loadings from these inflows, individual drainage areas were delineated with the use of a global positioning system (GPS).

Flow measurements were also made where possible. Depth sensors, compatible with the automatic samples, were the primary devices used. These sensors were calibrated at the University of Virginia Stormwater Laboratory in accordance with the American Sigma user's manual (American Sigma, 1996). Manning's equation (Young et al., 1996) was used to translate depth to flow for channels of regular geometry. Weirs were constructed, and the weir equation (Young et al., 1996) was applied to determine flows for irregular channels.

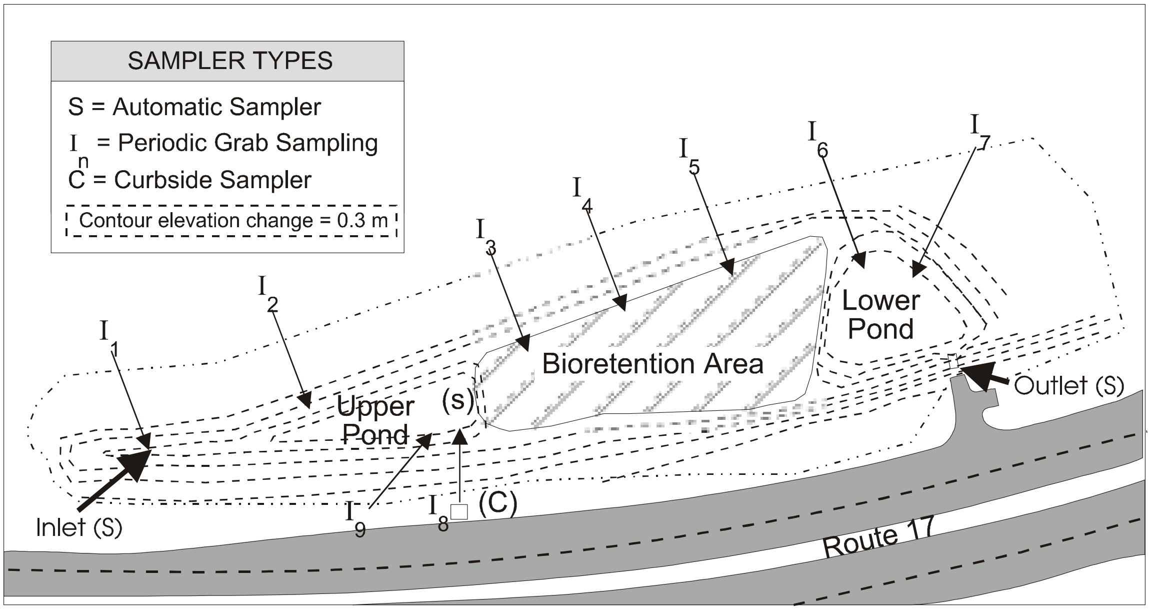

Figure 2. **Schematic of Biodetention Pond**

The sampling data were analyzed, and the results were used to calculate a final PRE for the biodetention pond.

Drainage Area Delineation

Individual drainage areas contributing to the biodetention pond were delineated by eye using a GPS. The GPS recorded points of the latitude and longitude that were directly converted to a coverage using the Arc/Info and Arcview software available from Environmental Systems Research Institute. Individual land uses were also recorded for each drainage area, and information was added to the final coverage. The graphical output and source information for the final coverage of drainage area delineation is presented in Figure 3.

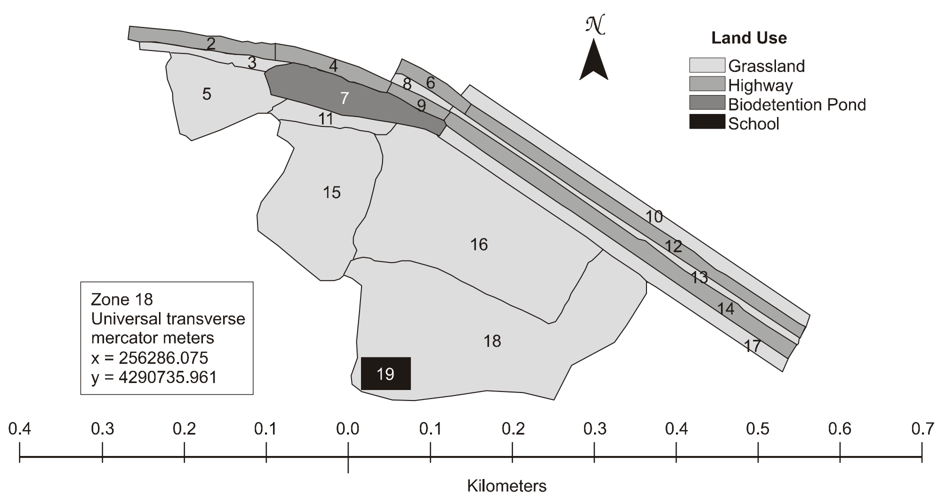

Figure 3. **Drainage Areas and Land Use for Pond 10P-2.** The numbers are polygon ID numbers.

Table 2 provides coverage attribute information for the individual drainage areas to each pond location. Table 2 was then used to determine drainage areas and land uses for estimating pollutant loadings using EPA's simple method (Young et al., 1996).

Table 2. **Drainage Area, Land Use, and Inlet No. for Pond 10P-2**

Inlet No. (s)	Land Uses	Area (m^2)	Area (acres)	% Impervious
1	H, G	36436	8.94	52
2	G, S	76135	18.7	12
3,4,5,6	G	18361	4.51	0
7	H, G	13398	3.3	36
8	H	2628	0.65	100
9	G	819	0.2	0
Sheet Flow	H, G	3821	0.94	34

H = Highway, G = Grass, S = School.

Sampling Procedures

Two types of samples were collected for analysis: background (or dry weather) samples and storm event (or wet weather) samples. The sampling locations are specified in Figure 2. Sample collection techniques included grab sampling and automated sampling.

Background Sampling

Procedures

Background samples were taken approximately every 2 weeks for approximately 4 months. The primary purpose of the background sampling was to assess dry weather pollutant loadings from the biodetention site to establish baseline contaminant concentrations for wet weather evaluation of the impacts of stormwater/non-point source pollution. Background concentrations in the upper pond were then compared to concentrations in the lower pond in an attempt to quantify the dry weather water quality benefits of the bioretention area.

Three initial grab samples were taken from each of the two ponds to assess concentration variations. If little variation was noted, one sampling point per pond would be selected for monitoring during the sampling period. If pollutant concentrations within the pond showed heterogeneities, then three samples would be collected before and after each event and mixed in equal proportions as a composite to obtain a representative concentration. Grab samples in the upper and lower ponds were collected at even time intervals, approximately every 2 weeks, to aid in modeling the long-term performance of the system. Samples were taken only if there was no precipitation prior to collection for at least 48 hours.

Grab sampling specifically involves filling a polyethylene sampling container directly from the water source. At the pond locations, this involved submerging the top of the bottle with the opening facing downstream of the flow. Sampling containers were collected one at a time from specific locations.

Sampling Locations

Grab samples were initially taken on the roadside, school side, and center of each pond for pollutant loading for the upper and lower pond. Figure 4 shows the pond sampling locations for the upper pond (P1U, P2U, P3U), and Figure 5 shows the initial grab sampling locations for the lower pond (P1L, P2L, P3L).

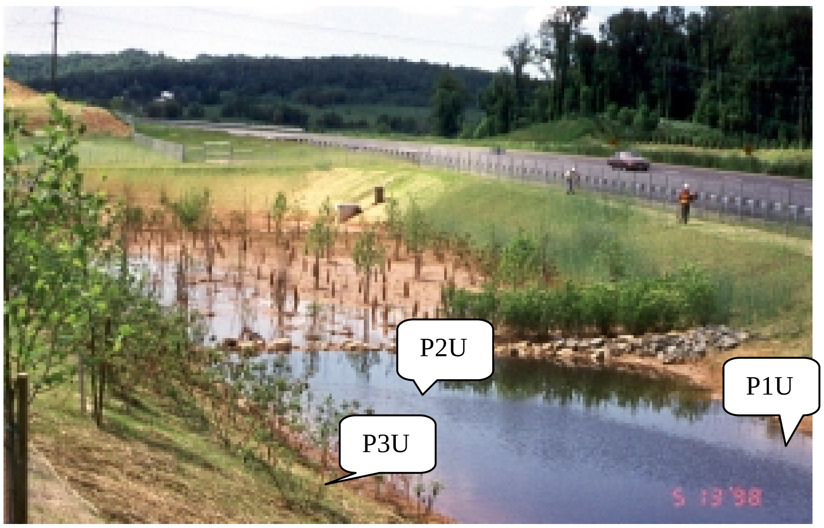

Figure 4. **Grab Sampling Locations for Upper Pond**

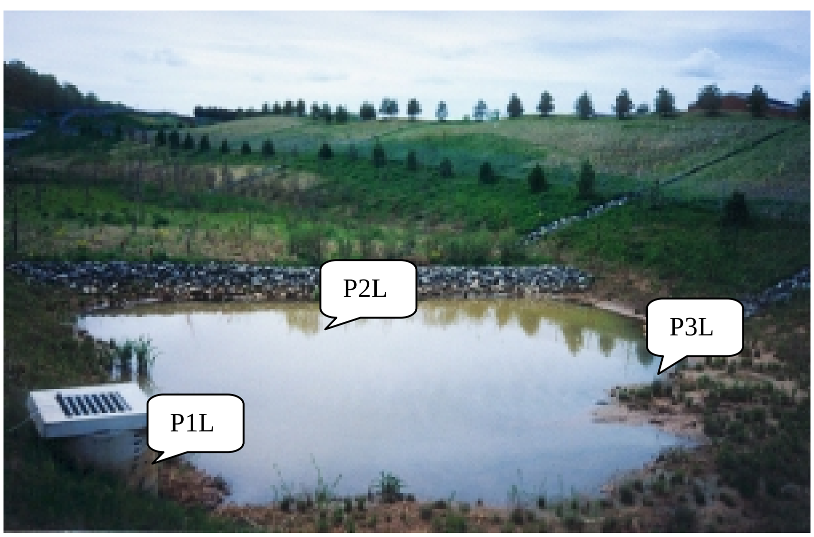

Figure 5. **Grab Sampling Locations for Lower Pond**

Storm Event Sampling

Procedures

Storm event sampling was the principal focus of this project. The primary objective of storm event monitoring was to assess PRE of the biodetention pond. Samples from storm events following the minimum EPA-recommended criterion of 72 hours of prior dry weather conditions were collected. Other criteria included a depth of rainfall over the entire basin of at least 2.54 mm and a total storm precipitation not exceeding 100% of the average rainfall (U.S. EPA, 1990). The average rainfall event for Warrenton is 15.24 mm per storm event; therefore, storms greater than 30.5 mm were not considered for this analysis. This criterion coincides with many states' BMP design criteria for the collection and treatment of the first 25.4 mm of rainfall or 12.7 mm of runoff from a drainage area (Young et al., 1996).

Storm event samples were collected using American Sigma 900 series automatic samples triggered by rainfall and/or a level rise. Rainfall and flow data were logged at 5-minute intervals by the automatic sampler. Rainfall data were logged by the Sigma sampler using a tipping bucket rain gage, and depth measurements for flow determination were logged by a pressure-sensitive transducer. Automatic samples were collected at 15-minute intervals as specified by the EPA (U.S. EPA, 1990).

Stormwater samples were primarily analyzed as flow-weighted or stage-weighted composite samples. Flow- or stage-weighted composites are single samples that are intended to be representative of the water quality for an entire storm event. Composite samples were selected to reduce the number of samples and total costs for the project. A composite sample is a mixed sample that is formed by combining a number of samples of specific volumes at specific time intervals (Dennison, 1996). Samples were weighted according to the flow or the stage height measured at a specific point in time. Composite sample analyses provide an event mean concentration (EMC) for a single storm event and provide an average concentration of pollutants over the storm event. One sample from each automatic sampler was taken for TSS analysis. Samples were collected and preserved, when necessary, in accordance with QA/QC protocols. Field samples were transported for TSS, COD, and TP analyses to the University of Virginia Stormwater Laboratory. Samples for metals and oil and grease analyses were sent to Aqua Air Laboratory in Charlottesville, Virginia.

Sampling Locations

Figure 2 shows the locations of the three American Sigma automatic samplers. The first location at I1 was equipped with an automatic sampler and a tipping bucket rain gage. A 120-degree V-notched weir was constructed at I1 for flow measurements (Figure 6). The total contributing drainage area to I1 is approximately 3.47 ha, or approximately 22% of the total drainage area of 15.1 ha.

Figure 6. **Location of Automatic Sampling Equipment at I1**

The second sampling location is in the upper pond (Figure 7). An automatic sampler equipped with a depth sensor was installed to measure stage heights within the upper detention pond. A stage-weighted composite was then mixed for average loading to the bioretention area. The total contributing drainage area to inlet I2 is approximately 7.56 ha, or approximately 50% of the total drainage area.

Figure 7. Sampling Point (*star*) in Upper Pond and Automatic Sampler

The final automatic sampling location was at the outlet riser pipe of the biodetention facility. Depth measurements and automatic samples were taken in an outlet pipe 42 in in diameter.   Manning's equation was used to calculate total outflows from the biodetention pond facility. Calculations were performed automatically by the Sigma automatic sampler. The outlet riser structure, automatic sampling equipment location, and sampling location are shown in Figure 8.

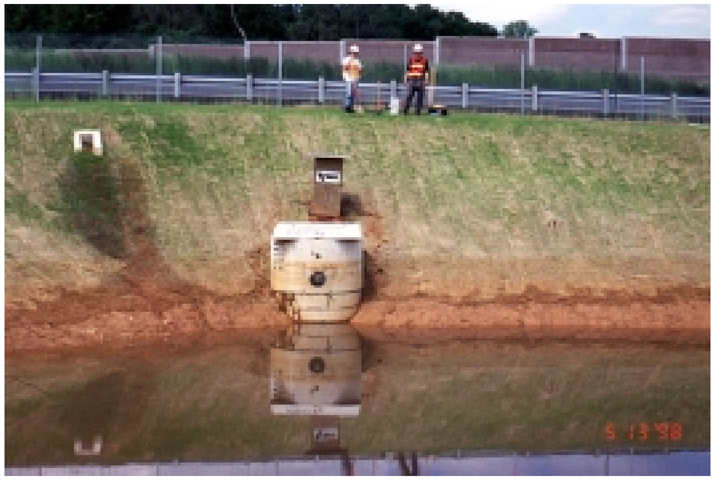

Figure 8. **Outlet Riser Structure, Automatic Sampling Equipment Location, and Sampling Location**

Laboratory Analysis

Analytical Parameters

Analytical parameters for this study were selected based on the objectives and resources of the project.   Table 3 lists analysis parameters recommended by NURP to characterize urban runoff. Limited project resources precluded analysis for all of these parameters. Parameters selected for this project were TSS, chemical oxygen demand (COD), TP, nitrates/nitrites (NO_x), Cu, Zn, Pb, and Cd. Cd is not listed as a NURP pollutant, but it was analyzed in accordance with Loos (1996).

Table 3. **Analytical Parameters Recommended by NURP to Characterize Urban Runoff**

Conventional Parameters	**Metals**
pH	Copper*
Total Suspended Solids*	Lead*
Biological Oxygen Demand	Zinc*
Chemical Oxygen Demand*	
Settleable Solids	
Temperature	
Nutrients	**Biological Parameters**
Total Phosphorus*	Fecal Coliform
Soluble Phosphorus	
Total Kjeldahl Nitrogen	
Nitrate/Nitrite Nitrogen*	

*Pollutants analyzed for this study.
Source: U.S. EPA, 1991a.

Sample Preservation

Sample containers and preservation techniques were selected based on the constituents to be analyzed. A volume of acid sufficient to lower the sample pH to less than 2 was placed in polyethylene bottles prior to sample collection. Three plastic bottles were used to split samples for different analyses: one with HNO_3 for metals; one with H_2SO_4 for TP, COD, and NO_3; and one with no preservative for TSS. Sampler bases were packed with ice at the time of collection, and then samples were transferred to the refrigerator in the University of Virginia Stormwater Laboratory. Table 4 lists samples preservation and handling guidelines for the constituents analyzed in this study.

Table 4. Sample Preservation and Handling Guidelines

Parameter	Container	Preservation	Maximum Holding Time
TSS	Polyethylene or glass	Cool, 4° C	7 d
TP	Polyethylene or glass	Cool, 4° C H_2SO_4 pH < 2	28 d
COD	Polyethylene or glass	Cool, 4° C H_2SO_4 pH < 2	28 d
Cu, Zn, Pb, Cd	Polyethylene or glass	HNO_3 to pH < 2	6 mo
NO_x and TN	Polyethylene or glass	Cool, 4° C H_2SO_4 pH < 2	28 d

Source: Earles, 1996.

Laboratory Procedures

All analyses were performed in accordance with EPA-approved laboratory procedures. Table 5lists the analytical parameters and procedures used for this study.

Table 5. Analytical Parameters and Procedures

Parameter	Type of Method	Procedure	MDL (mg/L)	Source
TP	Spectrophotometric	Hach Method 8190	0.10	*Hach DR/2000 Spectrophotometer Handbook* (Hach Company, 1991)
COD	Spectrophotometric	Hach Method 8000	5.0	*Hach DR/2000 Spectrophotometer Handbook*
TSS	Gravimetric	Standard Methods 2540D	2.5*	*Standard Methods for the Examination of Water and Wastewater* (Clesceri et al., 1989)
NO_x	Cadmium Reduction	Aqua Air SOP	0.097	Aqua Air Laboratory, Charlottesville, Va.
Zn	Atomic absorption	Aqua Air SOP	0.018	Aqua Air Laboratory
Pb	Graphite Furnace	Aqua Air SOP	0.0004	Aqua Air Laboratory
Cd	Atomic absorption	Aqua Air SOP	0.0026	Aqua Air Laboratory
Cu	Atomic absorption	Aqua Air SOP	0.015	Aqua Air Laboratory

*For 1-liter sample size.

RESULTS AND DISCUSSION

Background Sampling Results

Completely Mixed Reactor Evaluation

The first round of background sampling attempted to determine if the upper and lower detention ponds could be considered completely mixed during dry weather conditions. The results of the completely mixed reactor test are presented in Table 6.

Table 6 shows that each pond contained similar background concentrations for TP. Results for TSS were inconclusive because they were below the method detection limit of 2.5 mg/L. Statistical analysis using the relative standard deviation (RSD) demonstrated a 2.3% difference between TP concentrations at the sampling locations. The RSD provides an indication of differences between samples relative to each other. The lower the RSD, the closer a sample value is to other values in the sample group (Hogg & Ledolter, 1992). A 2.3% RSD is extremely low and was considered acceptable for this study. After the 07/03/98 test, one sample was taken at the berm (P2U) for the upper pond and near the outlet for the lower pond (P1L) sampling location.

Table 6. Background Concentrations for 07/03/98 CMR Test

Sample Location	Concentration			Sample Location	Concentration	
	TP (mg/L)	TSS (mg/L)			TP (mg/L)	TSS (mg/L)
Upper Pond				**Lower Pond**		
P1U	0.25	<2.5		P1L	0.24	<2.5
P2U	0.24	<2.5		P2L	0.25	<2.5
P3U	0.25	<2.5		P3L	0.25	<2.5
Statistics				**Statistics**		
Average	0.25	<2.5		Average	0.25	<2.5
Standard Dev.	0.006	0		Standard Dev.	0.006	0
RSD (%)	**2.3**	0		RSD (%)	**2.3**	0

Background Concentration Analysis

Background concentrations were logged for TP, COD, and TSS for approximately 4 months. Background Cu samples were taken for only 1 month, and Zn, Pb, NO_x and Cd samples were collected for only one sampling period. Table 7 lists the background sampling results for the upper and lower pond.

Table 7. Average Background Pollutant Concentrations and Standard Deviations

Pollutant	Sample No.	Average Concentration (mg/L)			
		Upper Pond	**Standard Dev.**	**Lower Pond**	**Standard Dev.**
TP	9	0.45	0.29	0.42	0.25
COD	7	12.1	5.6	16.1	9.1
TSS	8	5.3	3.0	6.9	4.5
NO_x	1	N/A	N/A	0.062	N/A
Cu	3	0.194	0.054	0.128	0.091
Zn	1	N/A	N/A	0.03	N/A
Pb	1	N/A	N/A	<MDL	N/A
Cd	1	N/A	N/A	<MDL	N/A

N/A = No samples taken or not applicable.

Average background sampling comparisons demonstrated little removal of pollutants between the upper and lower ponds during dry weather conditions. In fact, background concentrations of many pollutants were on average higher in the lower pond than in the upper pond, indicating potential negative removal by the center bioretention area. Since there was little variation between the upper and lower pond background concentrations, the lower pond was considered representative of the quality of the water exiting the biodetention pond.

Storm Event Sampling

Six storm events were captured for the period of May 1998 to May 1999. Four storms were considered complete (meaning both inflow and outflow samples taken), and two storms were considered incomplete (with only inflow samples). Table 8 presents precipitation data recorded for each storm date.

Table 8. Storm Event Precipitation Data

Storm	Date (mm/dd/yr)	Total Depth, mm (in)	Total Duration (h)	Average Intensity, mm/h (in/hr)
1	6/10/98	11.2 (0.44)	7	1.7(0.06)
2	7/23/98	24.9 (0.98)	1.5	16.6 (0.65)
3	9/9/98	18.0 (0.71)	4	4.5 (0.18)
4	9/18/98	64.8 (2.55)	1.5	43.2 (1.7)
5	10/9/98	54.6 (2.15)	13	4.2 (0.17)
6	5/8/99	20.8 (0.82)	6.5	3.2 (0.13)

Storm events were monitored for eight constituents including TP, COD, TSS, Zn, NO_x, Cu, Fe, and Cd. Complete storm events were monitored for TP, COD, TSS, and Cu, whereas only one event was monitored for NO_x, Zn, Pb, and Cd. Table 9 lists samples collected and analyses performed for each sampling date.

Table 9. Sample Collection and Analyses

Storm	Date (mm/dd/yr)	Samples Collected	Analyses
1	6/10/98	I1	TP, COD
2	7/23/98	I1, O	TP, COD, TSS
3	9/9/98	I1, O	TP, COD, TSS, Cu
4	9/18/98	I1	TP, COD
5	10/9/98	I1, O	TP, COD, TSS, Cu
6	5/8/99	I1, I2, O	TP, COD, TSS, NO_x and Metals

I1 = Inflow 1, I2 = Inflow 2, O = Outflow.

Concentration Comparisons

Total Phosphorus

TP is an indicator of all forms of phosphorus nutrient concentrations present in a water sample, including organic and inorganic forms. In nature, phosphorus is relatively scarce, but many human activities including animal waste application, fertilizer application, and urban land use practices can contribute significant additional loads of phosphorus to the natural environment (Chapra, 1997). The EMCs of TP expressed as PO_4^{-2} for the inflow and the outflow to the biodetention pond are presented in Figure 9. The average background concentration for the entire sampling period is also presented.

Figure 9 indicates a fairly high concentration of TP for several of the larger storm events, greater than 1 in of rain, with the exception of the storm on 07/23/98. The maximum

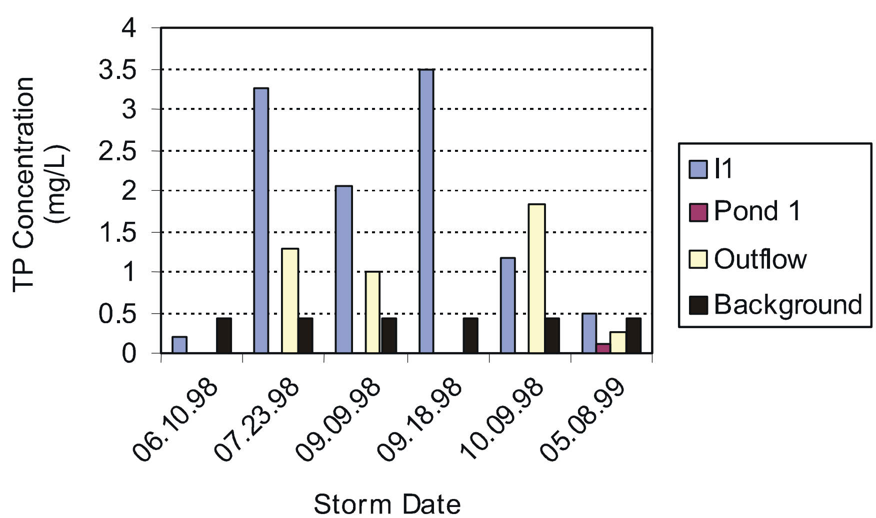

Figure 9. **Storm Event Total Phosphorus Event Mean Concentrations and Average Background Concentration**

storm event EMC was 3.48 mg/L, and the minimum was 0.11 mg/L. The average inflow and outflow concentrations were, respectively, 1.77 and 1.10 mg/L. As expected, storm event concentrations of TP were much higher than background concentrations. Higher TP concentrations for the 7/23/98 event were likely the result of increased sediment washoff attributable to ineffective bank stabilization at the time. In addition, higher intensity storm events had higher runoff concentrations than lower intensity storm events. For the 05/08/99 storm, storm event EMCs were much less than in the previous year, probably the result of further bank stabilization. Phosphorus can manifest in both bottom sediments as precipitated inorganic forms or as a part of organic compounds (Loos, 1996). Additional sources of TP are likely attributable to fertilizer application in grassed highway medians and the recreational fields adjacent to the Highland School. The 05/08/99 storm also showed an increase in TP concentration from the upper pond to the outflow, which may be attributable to short-circuiting of the lower pond. Short-circuiting takes place when an inflow is too close to the sample outflow, essentially resulting in a bypass of the treatment system.

Average values for TP in highway runoff typically range from 0.133 to 0.998 mg/L as PO_4^{-2} (Barrett et al., 1993). The total highway drainage area to the biodetention pond is approximately 2.4 ha, or 16% of the total drainage area. The remainder of the drainage area, with the exception of a 1 ha school roof, consists of grass. The elevated storm event concentrations as compared to typical highway concentrations are likely the result of fertilizer application from these additional land uses and increased erosion during the bank stabilization time. There are no water quality standards for TP for public drinking water supplies, but reservoir eutrophication from nutrients is always a significant concern.

Chemical Oxygen Demand

COD is a measure of the amount of organic or inorganic material susceptible to oxidation by a strong chemical oxidant (i.e., potassium permanganate). COD primarily provides a measure of the materials that are not readily degradable in the environment and require a high oxygen demand to be degraded. COD values can be correlated with ultimate biological oxygen demand values (BOD_u), which tend to be a measure of degradable organic material. One advantage of using the COD measure is the fact that the COD analysis can be performed in a short time whereas the BOD test typically takes at least 5 days. The COD test tends to have a higher dissolved fraction than typical BOD sources because it measures inorganic and organic fractions. Primary sources of COD include organic matter and solid waste. EMCs for COD and the average background concentrations during storm events at the biodetention pond site are listed in Figure 10.

Average concentrations of COD in the literature range from 14.7 to 272 mg/L (Barrett et al., 1993). As can be seen from Figure 10, almost all storm event EMCs fell within this range. The maximum COD EMC was 196 mg/L, and the minimum was below the MDL of 5 mg/L. The average inflow concentration over all storm events was 70.5 mg/L, and the average outflow concentration was 41.6 mg/L (no outflow was collected because of sampler malfunction for 06/10/98 or 09/18/98). Overall, the average inflow and outflow EMCs suggest removal of COD. In general, the average background sampling concentration for the 4-month sampling period was

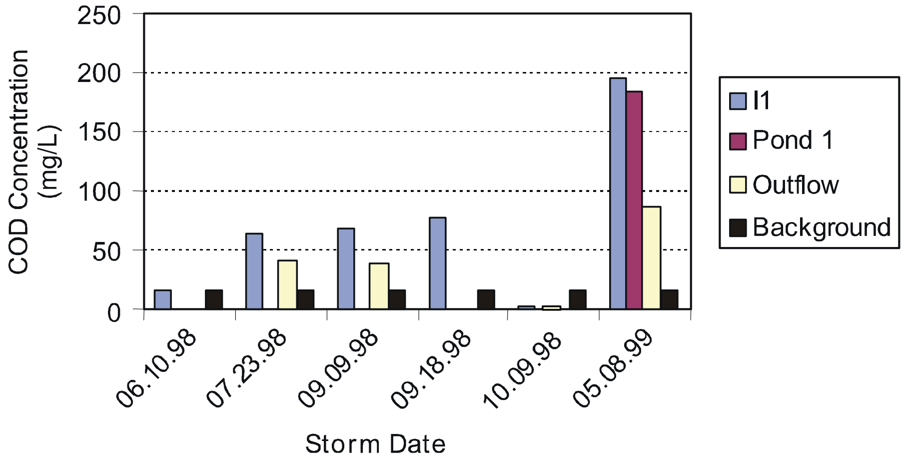

Figure 10. **Storm Event Chemical Oxygen Demand Event Mean Concentrations and Average Background Concentration**

less than storm event concentrations. A higher background concentration during the 10/09/98 storm event can be accounted for by the standard deviation from the average of ±9.12 mg/L. Decreases in COD EMCs were evident between all inflow and outflow points for all complete storm dates.

There is no ambient water quality standard limiting the allowable amount of COD that can be discharged to receiving waters, but the effluent standard for BOD for Virginia receiving waters is 30 mg/L. High COD levels can result in anoxic in-stream conditions if concentrations are extremely high (Dennison, 1996). COD levels have been reported in the literature to be 2 to 7 times higher than BOD measurements (Barrett et al., 1993). COD outflow EMCs were slightly higher than the BOD effluent standard, but it is likely that the BOD standard is still being met since COD tends to be 2 to 7 times higher than BOD values for stormwater. COD does not appear to be a major problem for the Warrenton biodetention site based on concentration variations.

Total Suspended Solids

TSS indicates the total concentration of suspended particulates with a diameter greater than 1 μm (Loos, 1996). The primary source of TSS is sediment erosion, and particulates can also result from washoff of accumulated dust/dirt and general impervious surface wear. TSS storm event and average background concentrations for the test period are presented in Figure 11.

The expected range of TSS concentrations in highway runoff is between 45 and 798 mg/L (Barrett et al., 1993). Storm event EMCs for TSS fell within the expected range, with a maximum concentration of 236 mg/L on 10/09/98 and a minimum concentration of 45 mg/L on 09/09/8. As expected, the maximum EMC occurred on the day with the maximum precipitation and the minimum occurred on the day with the least. The average inflow and outflow

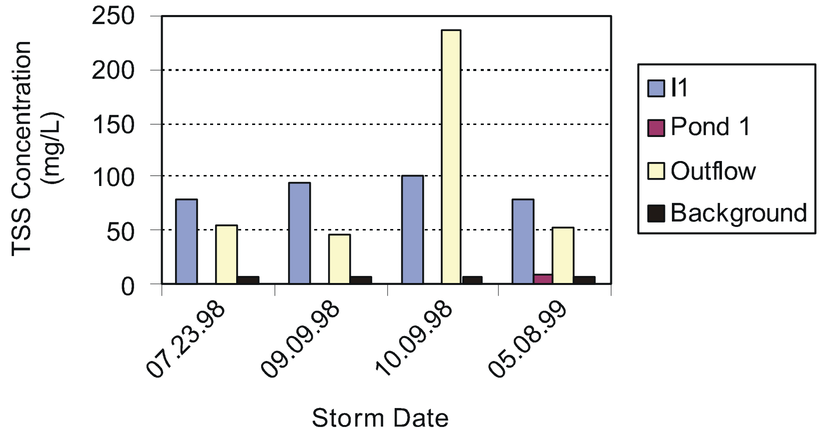

Figure 11. **Storm Event Total Suspended Solids Event Mean Concentrations and Average Background Concentration**

concentrations of TSS were 89 and 97 mg/L, respectively. These averages suggest potential negative removal of sediments by the biodetention site; however, for storms less than 25.4 mm, the average inflow and outflow EMCs were 85 and 51 mg/L, respectively. This comparison suggests a serious problem with re-suspension or short-circuiting in the lower pond of the biodetention facility. To further reinforce the re-suspension theory, a comparison of concentrations between the I1 and upper pond sampling points for the 05/08/99 event suggests a source of sediment below the upper pond berm.

The ambient water quality standard for TSS is that the monthly average should not exceed 5.0 mg/L with not more than 5% of samples exceeding 7.5 mg/L. This standard is applicable only to dry weather, background sampling conditions, not storm event samples. High TSS concentrations in streams can cause multiple adverse effects including increased turbidity, reduced light penetration, and adverse physiological animal affects (Dennison, 1996). The average TSS background concentration for the outflow of the biodetention facility was only 4.5 mg/L, which is below the ambient water quality standard.

Nitrates/Nitrites

The presence of NO_x is of major concern for water bodies and public drinking water supply systems. Nitrates contribute greatly to the common problem of lake and stream eutrophication. Excessive nitrates in drinking water supplies can result in serious adverse health effects including blue baby syndrome. The primary sources of nitrates in water bodies are fertilizer and animal waste. Nitrate EMCs and the background concentration for the 05/09/98 storm event are reported in Figure 12.

The typical concentrations of nitrates from highway stormwater runoff range from 0.15 to 1.636 mg/L (Barrett et al., 1993). The concentration for the inflow for the 05/08/99 storm event was 0.627, which falls within the expected range. As expected, storm event concentrations were much higher than the average background concentration of NO_x to the biodetention pond. The most likely source of nitrates for the biodetention facility is fertilizer application to highway medians and recreational fields.

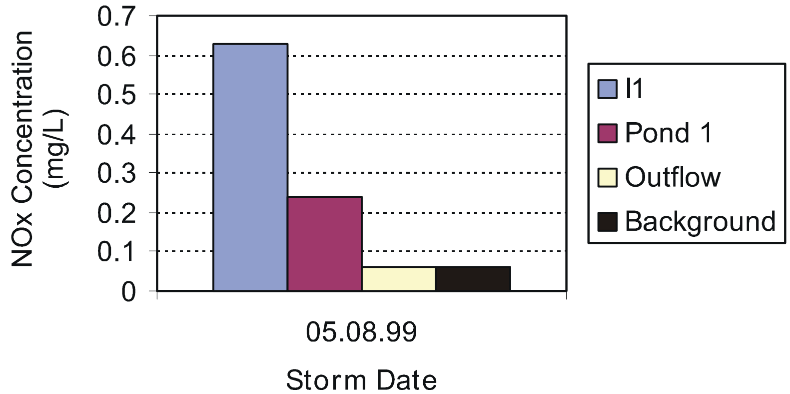

Figure 12. **Storm Event Nitrate/Nitrite Event Mean Concentrations and Background Concentration**

The current ambient drinking water standard for PWSs for nitrates is 10 mg/L. The NO_x concentration at the outflow for the 05/08/99 storm event was 0.063 mg/L, which is far below the specified drinking water standard. The background concentration for the lower pond was only 0.062 mg/L, well below the limit for drinking water.

Copper

The Cu test provides a measure of all forms of copper including free ions and organic and inorganic ligands. Cu in the environment is primarily sediment bound and is typically associated with TSS loads. Common sources of Cu for receiving water bodies are corrosion of plumbing, erosion of natural deposits, and leaching from wood preservatives (U.S. EPA, 1999). Storm event and the average background copper concentrations are compared in Figure 13.

Values for Cu in highway runoff in the literature range from 0.022 to 7.033 mg/L. Cu concentrations for the two storm events were well within this range. Storm event concentrations were higher than the background concentrations for most storm events.

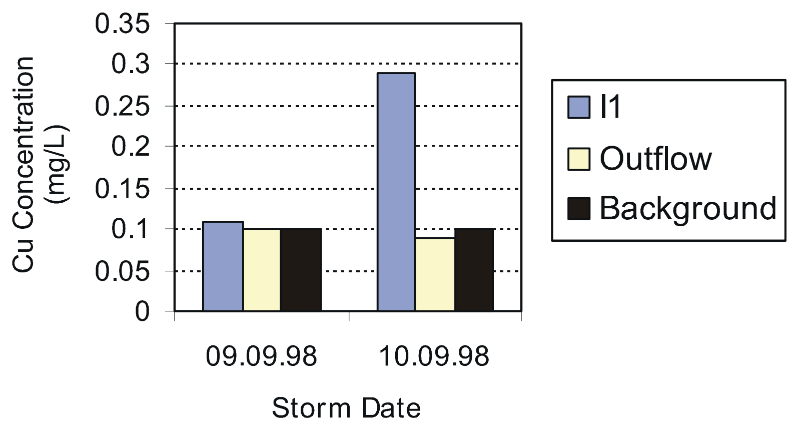

Figure 13. **Storm Event Copper Event Mean Concentrations and Average Background Concentration**

The current ambient drinking water quality standard for Cu is 1.3 mg/L. Short-term exposure and long-term health effects from copper exposure include gastrointestinal distress and liver or kidney damage (U.S. EPA, 1999). Storm event and background sample concentrations were well below the maximum drinking water standard. Cu runoff exiting the biodetention facility appears to pose little threat to the Warrenton Reservoir.

Zinc

Primary increases in Zn concentrations have been attributed to mining operations, agricultural use of sewage sludge, and fertilizer application (Loos, 1996). Common highway sources of Zn are from tire wear, motor oil, and grease deposits. Zn concentrations for the 05/08/99 storm event are provided in Figure 14.

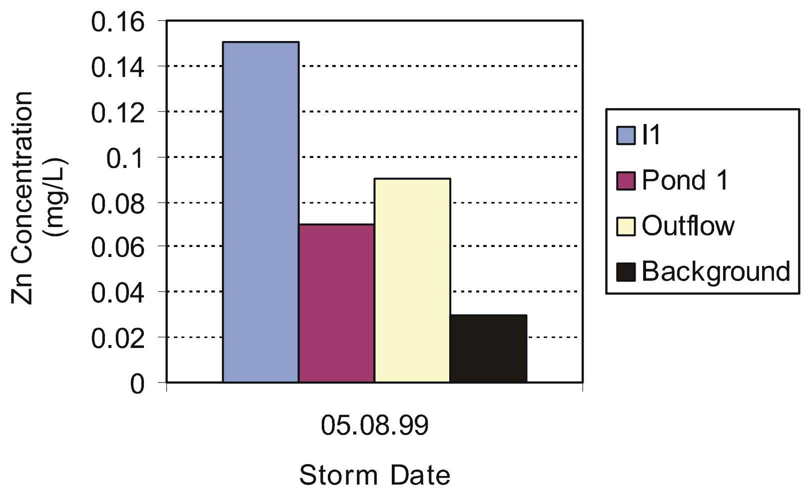

Figure 14. **Storm Event Zinc Event Mean Concentrations and Background Concentration**

Zn concentrations in highway runoff typically range from 0.056 to 0.929 mg/L (Barrett et al., 1993). Concentrations in storm event samples were within or below this expected range. The background concentration was below the EMC for the storm event samples, indicating additional loading from storm events.

The current nationally recommended maximum concentration for Zn is 5 mg/L. The primary concerns related to Zn are taste, odor, and aesthetic problems. Concentrations in samples analyzed for Zn were in compliance with this maximum standard.

Cadmium

The primary sources of Cd in the environment are corrosion of galvanized pipes, erosion of natural deposits, discharge from metals refineries, tire wear, and insecticide application. In the natural environment, Cd is typically found in suspended particles and bottom sediments.

Only the 05/08/99 storm event was tested for Cd concentrations. Cd concentrations for the I1, upper pond, outflow, and background sampling locations for the 05/08/99 storm event were below the MDL of 0.003 mg/L.

The typical concentrations of Cd from highway stormwater runoff range from 0.0 to 0.04 mg/L (Barrett et al., 1993). Concentrations in samples analyzed for this study fell within this range.

The standard for Cd in drinking water for PWS systems is a stringent 0.005 mg/L and for all other surface waters is approximately 0.42 mg/L. The primary health concern with Cd is its ability to cause kidney damage. Concentrations in samples collected from the biodetention site were below the MDL of 0.003 mg/L for the atomic absorption analysis. Cd concentrations in runoff leaving the biodetention facility were, therefore, below the MCL for drinking water and should pose little threat to the Warrenton drinking water supply.

Lead

The most common sources of Pb are corrosion of plumbing, leaded fuel, and erosion of natural deposits (U.S. EPA, 1999). Possible sources of Pb from highway runoff are leaded gasoline (exhaust), tire wear, lubricating oil, and bearing wear (Loos, 1996). Storm event and background Pb samples were collected only for the 05/08/99 event. Pb concentrations in the I1, upper pond, outflow, and background samples for the 05/08/99 storm event were below the MDL of 0.005 mg/L.

Average concentrations of Pb in the literature range from 0.073 to 1.78 mg/L (Barrett et al., 1993). Concentrations in samples collected for this study were below this range.

The MCL for Pb for drinking water in PWS systems is 0.015 mg/L. Pb can cause severe health effects in children and adults including delayed physical and mental development and kidney damage. Concentrations in samples analyzed for this study were less than 0.005 mg/L.

Storm Event Pollutant Removal Efficiencies

Individual storm event PREs were determined for the biodetention pond for the four complete storm dates. PREs were obtained to assess the facility's ability to remove TP, COD, TSS, NO_x, Cu, Pb, Zn, and Cd from the runoff entering the pond prior to discharge into the receiving water. Pollutant loadings for I1 and the outflow point were estimated using the storm event EMCs from flow-weighted composite analysis. The total mass loading for I1 and the outflow was derived from storm EMCs, multiplied by the total area under the curve of each hydrograph. Because of a lack of resources and the extensive number of inflows to the biodetention pond, it was necessary to estimate the pollutant loadings from inflows 2 through 9 empirically.

The EPA's simple method (Young et al., 1996) was used to estimate inflow pollutant mass loadings for constituents for the inflows I2 through I9 that were not monitored during storm event sampling. This method is applicable for areas less than 2.5 km^2 and is typically used for analysis of smaller watersheds or site planning (Young et al., 1996). The drainage area to the biodetention pond is approximately 1.5 km^2, which falls within the recommended area range for the method. The method provides estimates of total pollutant loads for a specified time interval and is:

$$L_p = \frac{(H_r P_j R_v)(C)(A)}{98.6}$$

where

L_p	=	pollutant load during interval (kg)
H_r	=	rainfall amount over time interval (mm)
P_j	=	percentage of runoff producing rainfall during interval
R_v	=	runoff coefficient
C	=	flow weighted EMC of pollutant in urban runoff (mg/L)
A	=	drainage area of the site (ha)
98.6	=	unit conversion factor.

All parameters in the equation were entered on a time scale based on the storm events. Rainfall and drainage area were entered from on-site field data. Runoff coefficients were approximated using a weighted value based on land use and area and were obtained from the GPS coverage. The P_j term is set equal to 1 when the method is applied for a single storm event. The C value is typically estimated using values obtained from the 1991 NURP study (U.S. EPA, 1983). In attempt to provide more site-specific results, inflow EMCs for inflow I1 were used as the C value for each drainage area contributing to the biodetention site.

After loadings to the biodetention facility were calculated for each storm event, a summation was performed to determine the total mass load into the pond. Once inflow and outflow mass loadings were calculated, they were used to calculate overall PREs for each parameter using the following equation:

$$PRE = \frac{MassIn - MassOut}{MassIn} \times 100\, percent$$

PREs for individual parameters were calculated for each parameter monitored at the site. Table 10 lists PREs and averages for the storm events monitored for this study.

PREs were positive with the exception of those for the 10/09/98 storm event. The total precipitation for this storm event was 54.6 mm, nearly double that for all other storms considered in the PRE analysis, and was above the 30.5-mm range acceptable for this study. PREs included in Table 11 had extremely high standard deviations, indicating highly variable or unpredictable PRE performance for the biodetention facility. The negative PREs and the high standard deviations were likely the result of short-circuiting or re-suspension in the lower detention pond.

Table 10. Pollutant Removal Efficiencies for Monitored Storm Events

Pollutant	Pollutant Removal Efficiency (%)				Average PRE	Standard Deviation
	7/23/98	9/9/98	10/9/98	5/8/99		
TP	56	39	-38	24	20	41
TSS	21	51	-107	9	-7	69
COD	25	30	-	28	28	3
No_x	-	-	-	86	86	-
Cu	-	73	9	N/A	41	45
Zn	-	-	-	16	16	-
Cd	-	-	-	N/A	-	-
Pb	-	-	-	N/A	-	-

N/A = Concentrations analyzed were below the MDL.
- = No data available.

Table 11 shows the calculated average PREs for storms with less than 30.5 mm of precipitation. Except for the 10/09/98 storm event, overall PREs were positive. Standard deviations also decreased, indicating a more consistent PRE for the biodetention pond for the 1-year sampling period.

Table 11. Average PRE for Storms < 30.5 mm

Pollutant	No. Storm Events	PRE	Standard Dev.
TP	3	40	16
TSS	3	27	22
COD	3	28	3
No_x	1	86	N/A
Cu	1	73	N/A
Zn	1	16	N/A

Almost all average PREs were below the expected PREs for well-designed wet/dry detention ponds and bioretention areas. The only exception was the PRE for NO_x, which was slightly higher. It is important to note that NO_x, Cd, and Pb PRE results were based on only one event, which makes it impossible to draw strong conclusions on overall pond PRE performance for these parameters. Lower PREs in the biodetention facility were likely the result of the short-circuiting of the lower section of the pond.

Pond Sediment Depths

Sediment levels in the upper and lower ponds were recorded to assess maintenance or dredging requirements for the biodetention facility. Upper pond sediment depth was recorded at a location before the berm for the upper pond of the biodetention facility as a conservative estimate of overall pond sediment depth. Also, the berm sampling location was initially the lowest point in the upper pond area. Pond sediment depth was recorded on 05/24/99 and was approximately 15.24 cm before the berm in upper pond. The original pond depth was 76.2 cm; therefore, approximately 20% of the original pond volume was lost.

Lower pond sediment depth was recorded in reference to the lower pond outflow orifice. This depth was approximately 21.34 cm, and the approximate original dry pond depth in reference to the height of the bioretention area was 140.2 cm. Based on the bioretention area reference point, approximately 15% of the volume of the lower pond was lost because of sediment backfill.

The most likely cause of sediment loads to the upper and lower ponds of the biodetention facility was erosion immediately following pond construction. Figure 15 shows the severe erosion problems encountered after the biodetention pond was constructed. It is highly likely that the majority of the upper and lower pond sediment backfill occurred before the detention sides were stabilized. Based on visual observation on 05/10/99, almost 2 years later, the pond banks have finally become more stabilized and pond siltation should decrease or stop completely. Figure 16 shows the current condition of the banks at the biodetention facility.

Figure 15. **Biodetention Pond 10P-2 as of 10/97**

Figure 16. **Biodetention Pond 10P-2 as of 05/08/99**

CONCLUSIONS

- *The Rte. 17/29 Bypass is posing no clear threat to the Warrenton Reservoir.* All outflow and most inflow pollutant concentrations were less than the MCL for drinking water for Virginia. The biodetention pond appears to be protecting the integrity of the water quality of the Warrenton Reservoir.

- *Pollutant concentrations in the upper and lower pond of the biodetention area are not significantly different.* Visual observation in the field revealed a small channel running through the bioretention segment that could result in poor infiltration and a bypass of the bioretention area. The channel is potentially the cause of the poor percolation into the bioretention facility. Because of a lack of resources and time, percolation rates for the bioretention area were not determined.

- *Pollutant concentrations increase during storm events.* The results clearly indicated a general increase in the levels of pollutants entering the biodetention facility during storm events. This result was expected, because storm events provide the mechanisms for pollutant washoff from surfaces. The only results that did not follow this trend were the TP, COD, and Cu results for 1 day each. Exceptions can be accounted for by the standard deviations calculated for the 4-month averaging period. All other parameters revealed a clearly positive trend with storm event activity.

- *Pollutant concentrations are within or below the range expected in highway stormwater runoff.* An increase in storm intensity and total rainfall resulted in an increase in total pollutant loads. Overall concentrations decreased between the inflow and outflow sampling points, suggesting possible pollutant removal by the biodetention pond area.

- *Short-circuiting or re-suspension is a significant problem in the lower detention pond.* For the majority of pollutants analyzed, pollutant concentrations increased between the upper pond and the outflow sampling locations. These results indicate serious problems with short-circuiting or sediment re-suspension in the lower pond. Short-circuiting is likely occurring between the I6, I7, and outflow locations because of their close proximity.

- *Pollutant removal efficiencies for the biodetention area vary significantly based on storm events.* PREs were positive for all storm events except the 10/09/98 event. Negative PREs can be accounted for by the large size of this event. In spite of the negative PREs on 10/09/98, the average PREs for all pollutants except TSS were positive. If the 10/09/98 storm event PREs are discounted, the average PREs were positive for all pollutants analyzed in the study. Overall, the biodetention facility did not demonstrate a higher potential PRE than well-designed wet/dry detention ponds or bioretention areas. Poor pond performance was likely the results of re-suspension and short-circuiting in the lower section of the biodetention facility.

- *Banks adjacent to the biodetention facility are stable.* Initially, erosion and bank destabilization appeared to be severe problems at the biodetention facility. Nearly 2 years after construction, the upper and lower ponds appear to have lost 15% to 20% of the their total volume because of sediment backfill. However, the banks appear to have stabilized and reached an equilibrium.

RECOMMENDATIONS

Design Modifications for Warrenton Biodetention Pond

1. *Add a baffle or wall parallel with I6 and I7 of the biodetention facility.* This will increase the flow path and detention time in the lower pond and provide additional removal of pollutants.

2. *Construct a check dam or micro-pool before the entrance of I7 into the lower pond.* Micro-pools can significantly increase the performance of dry detention basins by pretreating incoming runoff, preventing re-suspension, and reducing clogging (Schueler, 1998).

3. *Construct a second berm after the bioretention area of the biodetention facility.* This would result in a permanent pool of water in the bioretention area, increasing overall detention time and contact time with the vegetation.

4. *Divert I6 and I7 to the bioretention area.* Diversion of I7 could be accomplished by piping the flow from this area to the bioretention area, resulting in further treatment of runoff.

Design Considerations for Future Biodetention Ponds

1. *Eliminate the lower extended dry basin.* Dry detention basins have seldom been shown to remove sediment and have demonstrated virtually no capacity to remove nutrients (Schueler, 1998). The elimination of the lower pond for biodetention facilities would increase tree contact time and potentially reduce re-suspension.

2. *Limit the number of inflows to 1 or 2 per facility.* More inflows to a facility increase the difficulty of accurately assessing and monitoring a site's hydrology and water quality. Multiple inflows also increase the likelihood of short-circuiting, resulting from placing an inflow too close to the outflow.

3. *Use a more pervious planting soil.* A more pervious planting soil could increase filtration and water movement through the bioretention area. Highly pervious planting soils or sand is typically recommended for bioretention areas. A more pervious planting soil would also decrease the potential for channel formation and shortcutting of the bioretention area.

4. *Maintain a permanent pool of water in the bioretention area approximately 0.3 m (1 ft) below the surface of the bioretention area.* This would ensure adequate contact time to improve vegetative pollutant removal and maintain a permanent water supply for vegetation. The outflow riser could be modified for maintaining this permanent pool.

SUGGESTIONS FOR FURTHER STUDIES

This study demonstrated the potential benefits of using biodetention ponds for treating stormwater runoff. Currently, little data exist on field monitoring of biodetention and bioretention sites. VDOT should consider further study of existing or constructed sites to assess the potential of these new technologies and improve the facilities' performance and design. Continued monitoring of the Warrenton biodetention pond site is also recommended. This additional monitoring would allow VDOT to assess the pond's removal potential as vegetation matures and side slopes completely stabilize.

In attempt to alleviate potential adverse environmental impacts on the water quality of the Warrenton Reservoir, VDOT installed 10 BMPs to treat the highway runoff. Further monitoring of these sites is recommended for the assessment of overall pollutant removal on a small watershed scale. Recommendations from such watershed scale studies could then be directly applied to similar scenarios (e.g., The Rte. 29 Bypass in Charlottesville).

It is also recommended that a future study or review be performed to determine the total costs for the construction and maintenance of innovative BMPs. A BMP cost analysis was beyond the scope this project.

Additional studies of other highway construction projects conducted near or within watersheds supplying drinking water reservoirs are also recommended. This would allow VDOT and other government agencies to assess the adequacy of their stormwater management control strategies on a watershed scale.

ACKNOWLEDGMENTS

The authors thank many people for their assistance throughout this research study. Many people generously offered their assistance in conducting and shaping the frame of this research.

Specifically, the authors thank Mike Perfater and the VTRC for introducing this opportunity. Without the guidance and assistance of T. Andrew Earles and Elizabeth Fassman, this project would never have been completed. We also thank the entire Virginia Stormwater Research Group for their aid in the field sampling program and the performance of laboratory analyses on stormwater samples. Finally, we thank the wonderful staff at the VTRC for their aid and assistance in the completion of this final repoRte.

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