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RESEARCH REPORT

Grassed Swale Pollutant Removal Efficiency Studies

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16. Abstract

Grassed swales are a vegetated stormwater management technology that can remove surface runoff contamination through sedimentation, filtration by the grass blades, infiltration to the soil, and likely some biological processes. Three full-scale field monitoring studies were completed to evaluate pollutant removal effects of two grassed swales receiving highway runoff. Total suspended solids, nitrate, nitrite, lead, copper, and zinc event mean concentrations were decreased by 35-84% during the 3 sampling events studied. Export of phosphorus and chloride occurred during these sampling events. Pollutant concentrations evaluated with respect to time demonstrate the first flush phenomenon for water quality parameters in direct highway runoff. The grassed swales captured this initial flow by infiltration and thereby removed much of the highest pollutant concentrations.

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Table of Contents

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Executive Summary

Vegetated technologies have garnered support recently in roadway applications because of their emphasis on management of runoff through filtration and infiltration processes. One such vegetated technology that is commonly being employed in Maryland State Highway Administration (SHA) designs is grassed swales. Grass swales have been incorporated into highway medians and right-of-way as an aesthetically pleasing method for conveying highway runoff. Water quality benefits can also be realized through sedimentation, filtration by the grass blades, infiltration to the soil, and likely some biological processes. Nonetheless, good performance data and mechanistic understanding of swale design parameters are not available.

This project evaluates the performance of grass swales as a stormwater management technology using a field-scale monitoring study. The two major objectives of this study are to characterize the overall performance of grass swales and to evaluate the effect of the shallow sloped grass pre-treatment area adjacent to the swale in most designs.

The system is designed as an input/output comparison study to determine the removal of water quality parameters most important for roadways (total suspended solids, total phosphorus, nitrate, nitrite, total Kjeldahl nitrogen, cadmium, lead, copper, and zinc). Two grass swales were constructed in the median of Maryland Route 32 near Savage, Maryland to allow the determination of discharge water flow and quality parameters. One swale receives runoff directly from the highway (SHA swale), while the other has the shallow sloped filter strip pretreatment area between it and the highway (MDE swale). Because any direct monitoring of input parameters would be intrusive and affect output, an indirect method was used. A concrete channel, with similar dimensions and a roadway drainage area identical to those used for the grass swales, was constructed immediately adjacent to the roadway. The water flow and quality in this channel is assumed to be identical to the input for the swales. Flow data and water samples for all three channels were taken over 6-8 hour sampling periods at regular intervals during a rainfall event, resulting in 12 samples for each channel to be analyzed for the water quality parameters indicated above. Combining the flow and concentration data, a total pollutant mass and an event mean concentration (EMC), can be calculated. Comparing the inputs and outputs yields mass removals and EMC removals for each swale.

A large portion of the project was dedicated to site selection, swale construction, and purchase and setup of monitoring equipment. Three separate storm events with contrasting hydrologic characteristics were examined over the fall and winter of 2004/05. Flow data showed a rapid flow response to any rainfall in the direct runoff channel. Also, flow in this channel, which received runoff directly from the road, was strongly affected by any variations in rainfall. The two swales, however, showed a lag period of 1 to 4 hours behind the direct runoff flow. Presumably, this was due to initial abstraction caused by soil infiltration and also retarding of the flow by vegetation. The grassed swales also showed significant smoothing of the flow curves, which showed that the swales were not affected by variations in rainfall and tended to distribute this flow over a longer time than in the direct runoff channel.

In a similar manner to the flow data, the water quality data showed the importance of capturing the initial rainfall in the grassed swales. For water quality parameters such as Total Suspended

Solids (TSS), metals, and Total Kjeldahl Nitrogen (TKN), the direct runoff channel showed a distinct first flush effect, where initial concentrations are very high caused by the early rainfall washing off loosely bound pollutants that accumulate on the roadway during the antecedent dry period. The grassed swales generally managed this first flush through initial abstraction, thereby removing the initial high concentrations.

Both swales resulted in significant event mean concentration (EMC) removals of TSS (79%), nitrate (46%), nitrite (84%), copper (46%), lead (35%), and zinc (50%). These results were similar to values found in other similar studies conducted on grassed swales. There was, however, significant export of phosphorus (72% greater than input) and chloride (nearly 3 times the input). The export of phosphorus is common in grassed swales and is most likely due to organic material in the swale. The likely chloride source is the accumulation of highway deicing salts during winter months that are washed out during later rain events.

The grassed swales generally performed as expected, removing the initial runoff by infiltration and significantly reducing the concentrations of common roadway pollutants. However, the small sample population, caused by snow, technical problems, and destruction of one of the sampler boxes by an errant vehicle, did not allow any substantial confidence in statistical analyses of the data. With limited sampling, it appears the swales are effective in improving water quality. However, it was not possible to ascertain any significant difference between the grass swale with direct runoff (SHA swale) and the swale with pretreatment (MDE swale).

Stormwater management technologies are increasingly becoming focused on water quality issues. Because of this, it will become increasingly important for SHA to provide cost effective stormwater management to address transportation needs while still protecting surface waters and sensitive ecological environments from pollutant loadings caused by highway runoff. Grass swales appear to be a technology capable of addressing both runoff quantity and quality concerns.

Introduction

As part of a commitment to environmental protection, the Maryland State Highway Administration (SHA) is exploring the use of Low Impact Development (LID) technologies in roadway and transportation projects. LID technologies include emphasis on reducing rainfall runoff generation and management of runoff through filtration and infiltration practices. Performance information on LID practices in roadway application is necessary so that these practices can be integrated into SHA planning, design development, construction processes, and existing project retrofits.

One such LID technology that has been employed for the conveyance of stormwater runoff in SHA designs for many years is grassed swales. Water quality enhancements can be realized in these swales through sedimentation (due to the low velocity induced by the vegetation), filtering by the grass blades, infiltration, and likely some biological processes. Swales are commonly used on highway projects because they represent an aesthetically pleasing method for conveying runoff. While recent studies have revealed them as an effective LID technology, good performance data and mechanistic understanding of swale design parameters are not available.

As part of the Maryland SHA commitment to exploring the usefulness of LID and the great amount of uncertainty regarding the performance and pollutant removal mechanisms of grassed swales, a pilot project has been constructed on Maryland Route 32 near Savage, Maryland (see Figure 1). This swale system consists of two individual swales with different designs. The study system has been constructed to concurrently monitor representative inflow and outflow from the grassed swales, allowing the determination of pollutant removal efficiency. Performance information for grassed swales is critical to managing SHA roadway environmental impacts. Swale design flexibility will allow their use in a wider array of applications, allowing water quality benefits to be extended to a greater number of projects.

The goals for this project were to systematically quantify the effects of some operational parameters for water quality improvement using grassed swales. This project had two objectives. The first focused on the overall efficiency of a grassed swale on roadway runoff pollutant removal. The second examined the effect of the shallow sloped grass pre-treatment area adjacent to the grassed swale. Water quality parameters examined included those considered as being most problematic from roadway runoff. These include suspended solids, nutrients, and metals, which are among most common impairments in impaired Maryland waters under the Clean Water Act Section 303(d) Rules.

Flow rates were recorded to determine the effect of swales on stormwater quantity and so that total pollutant mass reduction could be calculated. The work was completed using two grassed swales with different designs and one concrete channel receiving runoff directly from the roadway, which is assumed to be equivalent in quantity and water quality to the inputs for the two swales. One grass swale received highway runoff directly from the road, while the other grass swale included a pre-treatment grassed area.

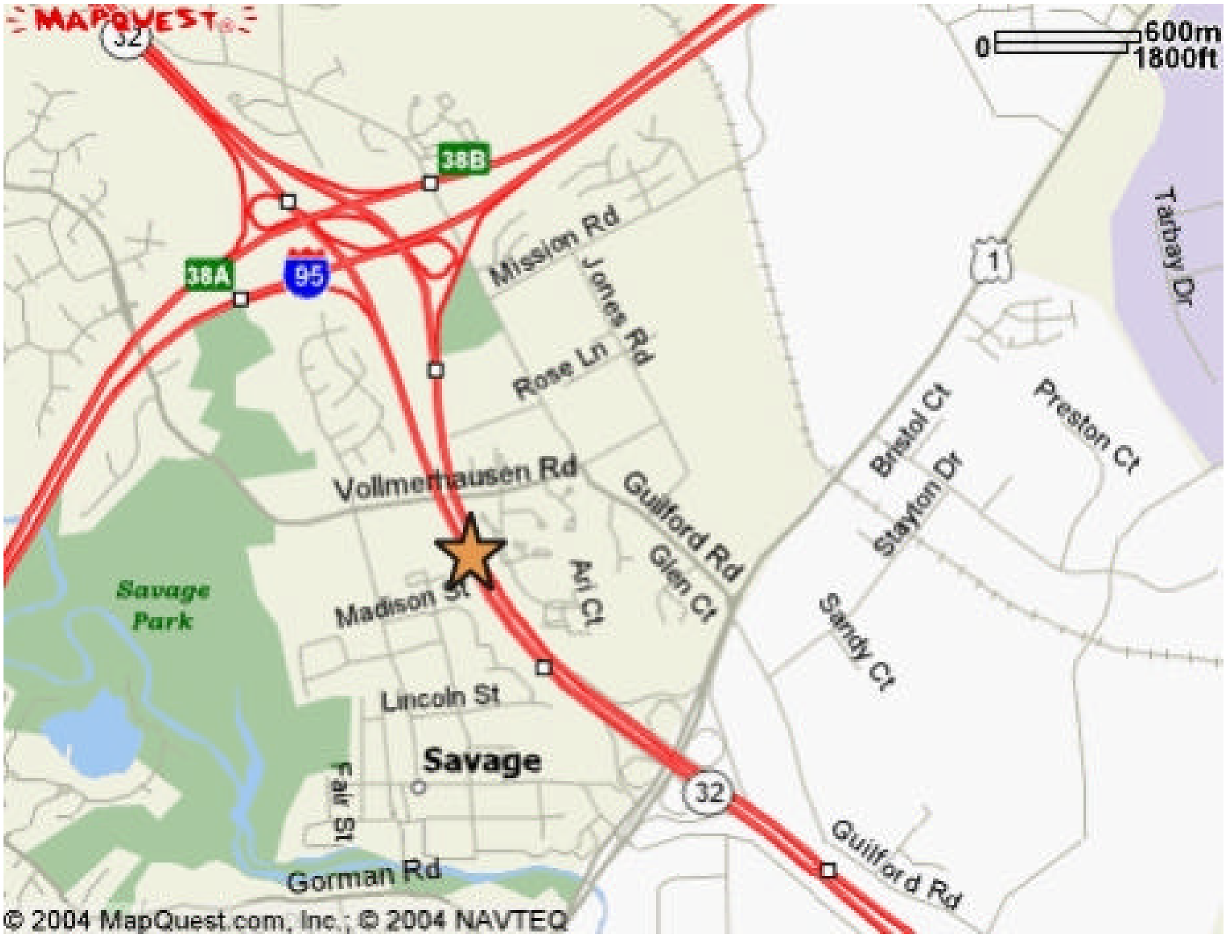

Fig. 1 Rt. 32 Swale monitoring site

Literature Review

Little consistent information on water quality improvements for swales is available, in large part because of the complexity of swale operation. Swales receive flow laterally through vegetated side slopes, which can greatly improve incoming water quality. Infiltration throughout the swale surface area can reduce flow volume and improve quality. Thus, swales have several points of water input and output, which can complicate simple performance analyses. This is supported by a summary report on swale performances from several states, which has shown sediment removals ranging from -85% (i.e., sediment increases) to 98% (Schueler 1994). These results indicate that many variables can contribute to the pollutant removal efficiency.

Barrett *et al*. (1998a) noted that flow from a moderate-use highway that passed through a grassy swale had better quality than runoff from two highways with curb and gutter systems. Further sampling of two grassed swales in Barrett *et al.* (1998b) showed significant EMC (event mean concentration) removals of total suspended solids (TSS, 86%), nitrate (37%), total Kjeldahl nitrogen (TKN, 39%), total phosphorus (39%), zinc (83%), lead (29%), and iron (77%). Additionally, removals of 67-93% of oil and grease and 65% of TSS and volatile suspended solids (VSS) were reported by Little *et al.* (1992).

The majority of grassed swale mechanistic studies have focused on the removal of suspended solids. Current studies (Backstrom 2002, Deletic 2001) have employed artificial grass swales in order to investigate the processes involved in suspended solid removal. Suspended particle concentrations tend to decrease exponentially with distance in the grassed swale until they reach a constant value. This baseline suspended solid concentration represents the solid fraction that is unable to be removed and is linked to particle size and thereby settling velocity through Stoke's Law (Backstrom 2002). Particles smaller than 6 μm in diameter are not retained by the grassed swales (Deletic 2001). There is also a possibility for resuspension of solids removed by the grass swale in the event of a storm event with relatively low suspended solid concentrations. In this case the swale will act as a pollutant source rather than a trap.

A very recent study comparing the performance of grassed swales to other stormwater best management practices on a much wider scale was performed by Barrett (2005). This study plotted influent mean concentrations against effluent mean concentrations for many paired samples. By plotting concentrations in this way, positive pollutant removal appeared as a trend with a slope lower than 1. It also enabled the author to fit a linear regression line for 42 events over 6 grassed swales so that effluent quality could be predicted from influent concentrations. Using these regression lines and a hypothetical storm influent event, grassed swale performance was compared to other stormwater best management practices. Across this large sample size, grassed swales removed metals (zinc 54%, copper 24%) and suspended solids (48%) successfully. However, significant export of nutrients (nitrate 28% greater than input, orthophosphorus 2.4 times input) was noted.

The effects of implementing grass swales in parking areas in Florida were investigated by Rushton (2001). Data clearly showed that use of the swales significantly reduced pollutant loadings from the paved parking lots. Major reductions in total load were found for ammonia, nitrate, suspended solids, copper, iron, lead, manganese, and zinc. Most of the load reduction occurred because runoff was held in the swales due to storage and infiltration; pollutant concentrations did not differ drastically between inlet and outlet conditions. The flow volume decrease was especially noticeable in small precipitation events.

Yu *et al.* (2001) compiled results from grassed swales from their work and that of others. Length was found to be the most important parameter in insuring good swale performance. A swale length of over 100 meters has proven to be successful in providing very good removal of suspended solids and other pollutants. The authors recommended using slopes less than 3%. Phosphorus removal was scattered, apparently because of phosphorus being contributed by the vegetation in the swale. The use of check dams was found to significantly improve treatment efficiency.

A large volume of work has been completed on pollutant removal through vegetated filter strips. Highway runoff quality data gathered by Wu *et al.* (1998) indicate that for small rain events, 50-

84% of the TSS is removed by the adjacent grassy filter strip. At higher rainfall events, the runoff became deeper and the removal decreased from 20 to 35%.

A study of the efficiency of vegetated filter strips for the treatment of highway runoff was completed by Yonge (2000). Three strips were installed along a roadway in western Washington. All were isolated, 6.1 m by 4.6 m, 0.6 m deep. One was filled with a biosolids compost, and the other two contained soil with slightly different characteristics. Untreated runoff was collected using a slot drain parallel to the roadway. Both overland flow and infiltrated flow were monitored. Total suspended solids removal for all three strips ranged from about 20 to 80%, with an average removal of 72% (average reduction of suspended solids from 41 to 6.7 mg/L). Total petroleum hydrocarbon removal was excellent, with most treated water having less than 1 mg/L TPH. Sampling and experimental problems precluded quantification of heavy metal removals. It was noted, however, that within captured suspended solids, the smallest size fraction studied (<0.074 mm), representing approximately 8% of the total solids, contained about 50% of the Cu, Pb, and Zn. No major differences in pollutant removals were noted among the three systems. No overland flow was developed in the biosolids mulch facility.

Several mechanistic studies on sediment removal via flow through vegetated strips have been published (Tollner *et al.* 1976; Hayes *et al.* 1984; Deletic 1999).

Pollutants Selected

Target pollutants for monitoring include total suspended solids (TSS), nitrate, nitrite, total Kjeldahl nitrogen (TKN), total phosphorus, chloride, cadmium, copper, lead and zinc. These pollutants are of the greatest concern in roadway runoff because of their toxicity, water quality concern, and/or concern for anticipated total maximum daily loads (TMDL) limits.

Total Suspended Solids (TSS)

Particulates in highway runoff are mainly from pavement wear, vehicles, atmospheric deposition, maintenance activities, and washoff from local soils. They can cause impacts that include increased water color and turbidity, decreased light penetration, clogging, and direct toxicity to aquatic organisms. Many pollutants are associated with the fine-size particles that do not settle easily. As a result, TSS themselves cause water quality problems, as do the many pollutant constituents that adsorb to TSS.

Nutrients

As impervious area increases, nutrients build up on surfaces, leading to high pollutant loads. Nutrients in urban runoff can accelerate eutrophication in receiving waters. Surface algal scums, water discoloration, taste and odors, depressed oxygen levels, and release of toxic compounds are possible impacts of high nutrient levels. The most important nutrients causing accelerated algal production are nitrogen compounds and phosphorus.

Nitrogen (Nitrate, Nitrite, TKN) - Nitrogen sources are derived from decomposing organic matter, animal and human wastes, fertilizers, and atmospheric deposition.

Phosphorus - Phosphorus is commonly bound to fine sediments. Phosphorus is derived from many of the same sources as nitrogen (Strecker, 1994); one source of phosphorus is tree leaves (Hodges, 1997).

Chloride
Chloride is found naturally, but is used in deicing agents on roadways.

Metals
Heavy metals in urban runoff have toxic effects on aquatic life and can contaminate drinking water supplies. Metals are present in the dissolved form and adsorbed to particulates. The bioavailability and mobility of dissolved metals are of the greater concern to aquatic life.

Copper - Sources of copper in roadway and urban runoff are brake pad materials, motor oil, and flashing used in buildings.

Lead - Tire wear, motor oil, and batteries are common sources of lead in roadway runoff.

Zinc – Sources of zinc in roadway and urban runoff are tire wear, brake pads, motor oil and grease, and zinc-coated building materials.

Cadmium – Cadmium is generally found with zinc and the sources are the same as for zinc.

Methodology

Monitoring Location

A large portion of this project was dedicated to site selection, swale construction, and purchase and setup of monitoring equipment. The monitoring location for this project was MD Route 32 near Savage, Maryland. This is a four-lane (two in each direction) limited access highway. The sampling areas are just south of the Vollmerhausen Road overpass (Figure 1). The area adjacent to the sampling area is wooded with nearby residential; however, the roadway is raised so that runoff is only created by the roadway. Two swales were constructed in the highway median to receive runoff laterally from the southbound roadway lanes (Figure 2). The first is a swale constructed based on Maryland Department of the Environment (MDE) guidelines, with a sloped grass pretreatment area between the roadway and the swale channel (Figure 3). The second swale, to the north, was identically constructed, but without the pretreatment area (known as SHA swale, Figure 4). Both swales run to an inlet where water flow and quality measurements are made. Since swale input flow is distributed along its length, a third sampling area was designed and constructed to sample runoff directly from the highway (known as Direct, Figure 5), south of the swales. Sampling areas were designed so that all three drainage areas are similar and therefore comparable (Direct 60,800 ft^2, SHA swale 42,464 ft^2, and MDE swale 65,910 ft^2). Sampling occurs at a V-notch weir located at the end of each swale.

Sampling Goals and Purpose

The system is designed as an input/output study. The runoff flow and pollutant load determined in the flow directly off the highway is considered as equal to the total input flow to each swale.

This value is compared to flow and water quality measured at the outlet of each swale. Efficiencies are directly calculated for each storm event. Additionally, the efficiencies for each swale can be directly compared. A goal of sampling one storm event per month was established.

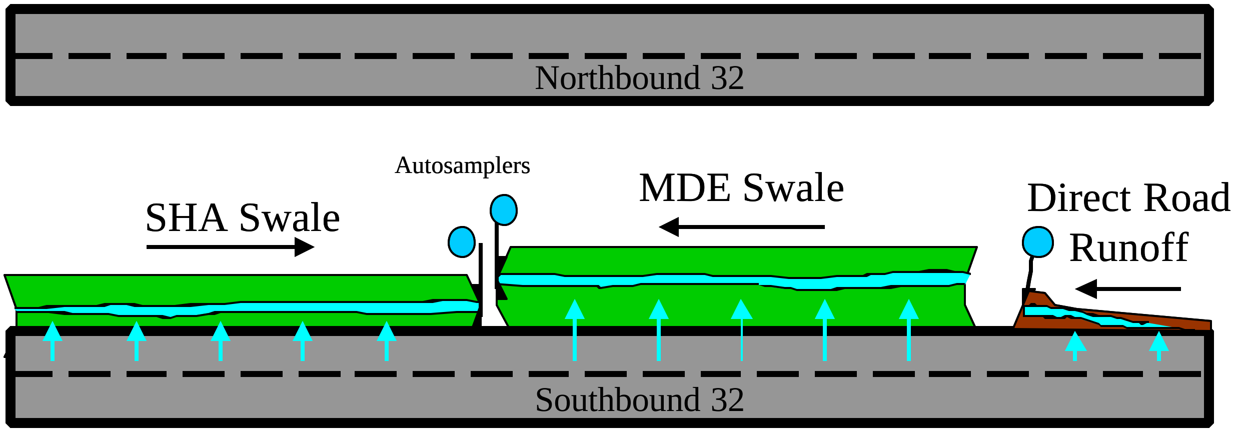

Fig. 2 Diagram of swale study area

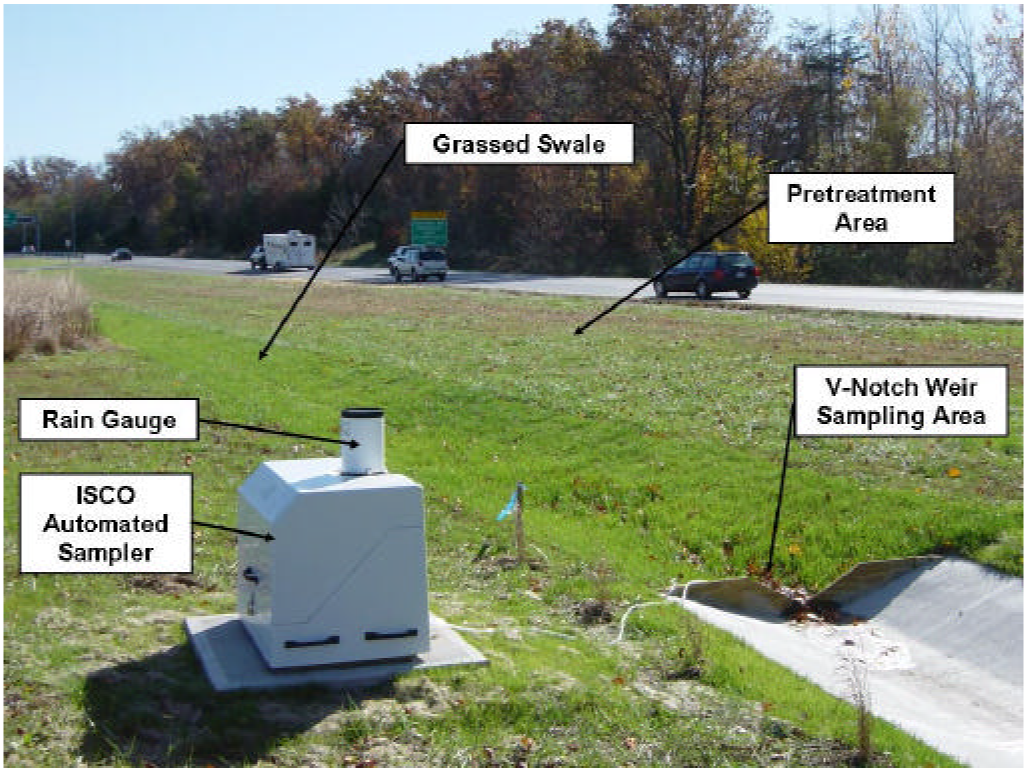

Fig. 3 MDE swale at Rt. 32

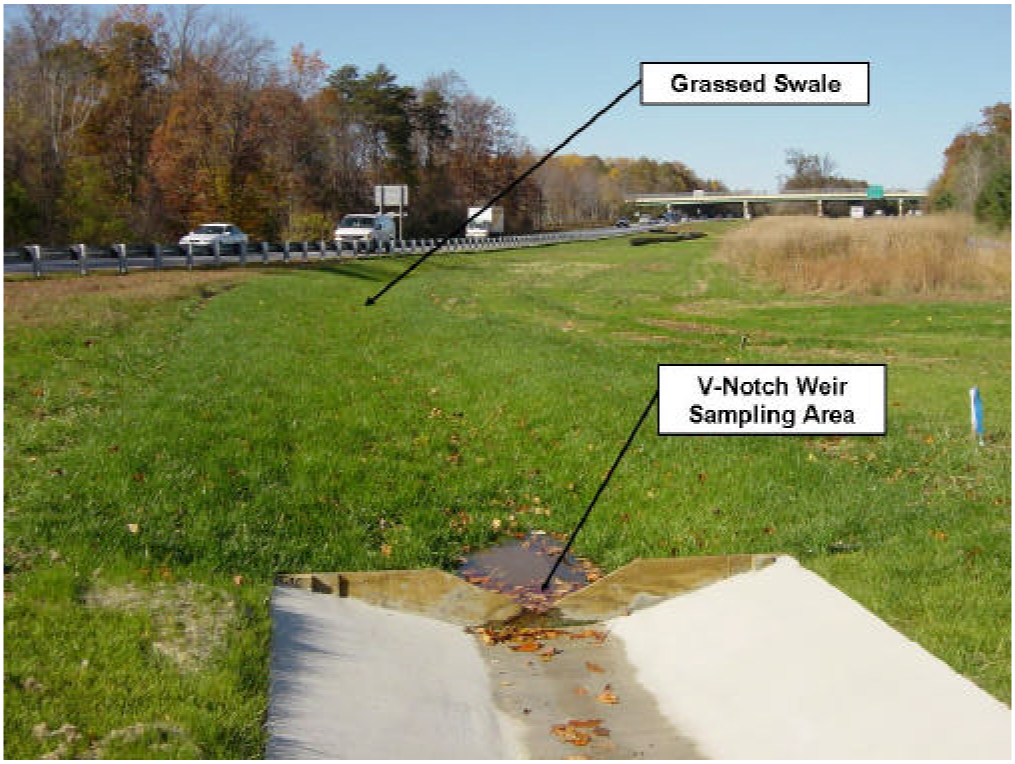

Fig. 4 SHA swale at Rt. 32

Fig. 5 Direct roadway runoff monitoring at Rt. 32

Table 1. Sampling Times for Automated Collection During Storm Events at Rt. 32

	Time	
Sample Number	Direct Runoff	Two Swales
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	2 hours	1 hour, 40 min
7	2 hr, 40 min	2 hours
8	3 hr, 20 min	2 hr, 20 min
9	4 hr, 20 min	2 hr, 40 min
10	5 hr, 20 min	3 hr, 40 min
11	6 hr, 20 min	4 hr, 40 min
12	8 hr	6 hr

Monitoring Equipment and Protocol

Construction of the grassed swales was completed in late October 2004. After allotting several weeks for the swales to stabilize, the sampling program was initiated.

In order to monitor flows and sample water quality, a 125-degree V-notch wooden weir was constructed at the end of each 500-ft swale. An ISCO Model 6712 Portable Sampler was installed in a secured vault adjacent to each swale. Each sampler has a bubble flow meter calibrated with the corresponding weir to monitor flow rates through the weir. The bubble tube was attached to the weir level with the V-notch. A stainless steel strainer was placed just upstream of the weir.

Each sampler contains twenty-four 300-mL glass bottles that are cleaned and acid washed before placement in the sampler. The sampling program is set to collect 12 samples per event (filling 2 bottles per sample to ensure adequate volume for all the water quality testing). The sample timing is presented in Table 1, with an emphasis on obtaining more samples in the early part of the precipitation event. The sampler for direct stormwater runoff has an adjusted sampling schedule in order to cover the time period of the two swales. Preliminary sampling has shown that the grassed swales trigger a few hours later, presumably due to initial infiltration, so the direct stormwater sampling times were lengthened accordingly.

A sampling event is triggered when the head behind the weir reaches 0.1 ft, which corresponds to a flow of about .0152 cfs. This flow rate corresponds to a rainfall intensity of .0241 in/hr, based on the direct sampler with a drainage area of 0.698 acres and a rational method c of 0.9. Samples were picked up within 24 hours and transported to the Environmental Engineering Laboratory, College Park, MD. At the lab, samples were immediately analyzed for total phosphorus, nitrate, nitrite, and TSS. After these initial analyses, remaining samples were preserved and refrigerated. One bottle for each sample, containing approximately 100 mL of sample, was preserved for metal analyses using six drops of concentrated trace level HNO_3. The second bottle for each sample was preserved by adding 2 mL of concentrated H_2SO_4 to 200 mL of sample for TKN analysis. TKN and metal digestion was completed within two weeks. Metal analyses were carried out within 6 months.

One ISCO 674 Tipping Bucket Rain Gauge with 0.01-inch sensitivity was installed on top of a sampler vault and connected to one of the portable samplers. This tipping bucket logs rainfall depth in 2-minute increments

Analytical Methodology

Analytical methodologies for pollutant measurements are described in detail below and are summarized in Table 2.

TSS Analysis

This test follows Section 2540D of Standard Methods (APHA *et al.*1995). A well-mixed sample is filtered through a weighed standard glass-fiber filter and the residue retained on the filter is dried to a constant weight at 103 to 105°C for 1 hour. The detection limit is 1 mg/L.

Table 2. Analytical Methods for Determination of Pollutant Concentrations in Rt. 32 Swale Storm Events.

Pollutant	Standard Method (APHA *et al*. 1995)	Detection Limit (mg/L)
Total Suspended Solids, TSS	2540D	1
Total Phosphorus	4500-P	0.24
Total Kjeldahl Nitrogen, TKN	4500-N_{org}	0.14
Copper	3030 E	0.002
Lead	3030 E	0.002
Zinc	3030 E	0.025
Cadmium	3030 E	0.002
Nitrite	4500-NO_2^- B	0.01 as N
Nitrate	Dionex DX-100 ion chromatograph 4500-NO_3^- B	0.1 as N 0.5 as N
Chloride	Dionex DX-100 ion chromatograph	2

Phosphorus Analysis

Total phosphorus analysis is divided into two general procedural steps: (a) conversion of the various phosphorus forms to dissolved orthophosphate by persulfate digestion, and (b) colorimetric determination of dissolved orthophosphate. As phosphorus may occur in combination with organic matter, a persulfate digestion method is used to oxidize organic matter effectively to release phosphorus as orthophosphate.

This test follows Section 4500-P of Standard Methods (APHA *et al.* 1995). Fifty-mL samples are placed into Erlenmeyer flasks; 20 drops of H_2SO_4 solution are added, along with 0.5 g $K_2S_2O_8$ (J. T. Baker). The flasks are then boiled until about 10 mL of liquid remains. Later 20 mL of distilled water is added to each flask. The liquid in each flask is further diluted to 100 mL with deionized water. Four mL of ammonium molybdate reagent and 10 drops of stannous chloride reagent are added to each flask. The samples are allowed to sit for 10 minutes. Finally, the samples are placed into a spectrophotometer (Shimadzu model UV160U) to measure the color at 690 nm. A detection limit of 0.24 mg/L as P has been established.

Nitrate, Nitrite, and Chloride Analyses

Analyses of nitrate and chloride were routinely performed using a Dionex DX-100 ion chromatograph. The eluent is 1.3 mM sodium carbonate/1.5 mM sodium bicarbonate (J. T. Baker) solution. The flow rate is adjusted to 1.4 mL/min to clearly differentiate nitrate and chloride. The concentration of nitrate in the samples is determined against standards of 0.14, 0.7, 1.4 and 3.08 mg/L as N prepared with sodium nitrate (Fisher Scientific) in deionized water. The concentration of chloride in the samples is determined against standards of 1, 3, 5 and 8 mg/L prepared using 1000 mg/L chloride stock solution (Fisher Scientific) in deionized water. Standard concentrations above the instrument detection limits are employed for nitrate and chloride due to the wide spread of sample concentrations found over the course of a storm event. The scale and standard concentrations are set to a range appropriate for the majority of samples in an event.

In samples where chloride levels were very high (winter), overlap between chloride and nitrate peaks prevent the use of this method. In these samples, spectrophotometric measurement of nitrate was carried out using a UV-visible recording spectrophotometer (Shimadzu model UV160U). Procedure details are as outlined in Standard Method 4500-NO_3^- B (APHA *et al.* 1995). Two spectrophotometric measurements were performed in order to measure nitrate and dissolved organic matter, which interferes. The nitrate concentrations were determined against standards of 1, 4, 7, and 10 mg/L as N, prepared by diluting 1000 mg/L stock solution to required calibration concentrations (Fisher Scientific).

Spectrophotometric measurement of nitrite is carried out similarly, using Standard Method 4500-NO_2^- B (APHA *et al.* 1995). Standards of 0.02, 0.08, 0.12, 0.24 mg/L as N are prepared by diluting 1000 mg/L stock solution (Fisher Scientific).

TKN Analysis

TKN is measured via Standard Method 4500-N_{org}, Macro-Kjeldahl Method (APHA et al., 1995). TKN analysis is completed in three steps: (a) digestion of a 200-mL sample by evaporation after addition of 50 mL of digestion regent prepared as detailed in the Standard Method, (b) distillation of digested sample diluted to 300 mL and treatment with 50 mL of sodium hydroxide-sodium thiosulfate reagent, and (c) titration of distillate with standard 0.02 N sulfuric acid titrant. The detection limit is 0.14 mg/L for TKN.

Cadmium, Copper, Lead, and Zinc Analyses
Metal analyses are divided into two steps: (a) digestion of samples by evaporation of 75 to 100 mL of sample, after addition of 5 mL of concentrated trace metal-grade HNO_3 (Standard Method 3030 E), and (b) analysis of cadmium, copper and lead on the furnace module of a Perkin Elmer Model 5100ZC atomic absorption spectrophotometer, Standard Method 3110, and zinc on the flame module, Standard Method 3111 (APHA et al., 1995). Standards for cadmium, copper, lead and zinc are prepared using 1000 mg/L Fischer Chemicals stock solutions.

Data Evaluation and Loading Calculations

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

$$M = \int_0^{T_d} QCdt \qquad (1)$$

where, Q is the measured stormwater flow rate and C is the pollutant concentration for each sample during the event. T_d is the event duration. The interval between samples is dt.

In cases where the concentration of a pollutant is below the detection limit, two calculations are made. One calculation uses the concentration of the smallest standard in the case of nitrate and chloride, and the instrument detection limit for the remaining pollutants; the other EMC calculation uses zero for the respective measurement. The calculated EMC is presented as the range between these two values.

Additionally, the event mean concentration (EMC) is calculated similarly as:

$$EMC = \frac{\int_0^{T_d} CQdt}{\int_0^{T_d} Qdt} \qquad (2)$$

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

The annual pollutant loadings are calculated using the Simple Method defined by Schueler (1987) and are given by:

$$L = P\ P_j\ R_v\ (CF)\ C \qquad (3)$$

where, L is the normalized annual pollutant load (kg/ha/yr or lb/ac/yr), P is the annual precipitation (in/yr), P_j is the dimensionless correction factor that adjusts for storms without runoff, R_v is the dimensionless average runoff coefficient, CF is a conversion factor for matching appropriate units, and C is the flow weighted average concentration (mg/L). Equation 3 can also be modified to calculate pollutant load per road lane-mile and based on average traffic density.

With the assumption that the drainage stretches of highway for each swale are identical, the direct concrete channel is viewed as equivalent to the input for each swale. Total pollutant mass loads are calculated per event for the input and each swale. Based on these values, mass reduction due to each swale is calculated for each pollutant both as a percentage, and on an absolute basis (kg/ha/yr or lb/ac/yr). A simple comparison between the grassed swale with pretreatment and the swale without pretreatment shows the effect of including a vegetated pretreatment area and also the effectiveness of the grass swales alone for the improvement of water quality.

Research Findings and Discussion

Snow, technical problems, and destruction of one of the sampler boxes by an errant vehicle, reduced the number of monitoring events evaluated. Three storm events were sampled and analyzed at the University of Maryland laboratory: 11/12/04, 12/19/04, and 1/13/05. Data for the MDE swale for the 12/19/04 storm event are not available because water in the swale froze before the sampler was activated. Likewise, no data were collected for the SHA swale for the 1/13/05 storm event because of a problem with the bubbler unit on the sampler.

Flow Data

The purely hydrologic effects of the grassed swales can be determined by examining the flow rates for each of the 3 storm events. These data are shown in Figures 6-8. During the 11/12/04 storm, 2 relatively similar peaks in rainfall were noted, with slight rainfall during the time between. Flow in the direct channel almost identically mirrored the rainfall with little to no lag time. The two grassed swales, however, showed a lag time before any flow was detected. As stated in the Methodology section, samplers were triggered when the depth of flow reached 0.1 ft. The lag time between the triggering of the direct channel and the swales was 3 hr 51 min for the SHA swale and 4 hr 3 min for the MDE swale. Presumably, this was due to initial abstraction caused by soil infiltration and also retarding of the flow by vegetation. The swales had remarkably similar lag times, yet the MDE swale does have a slightly longer lag time. Far more

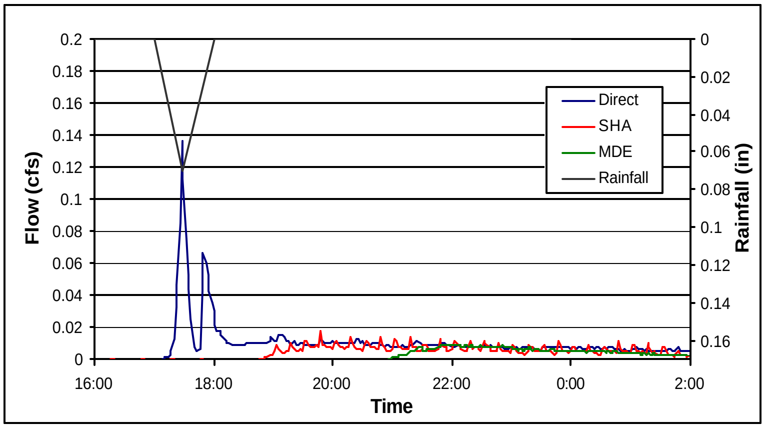

Fig. 6 Flow during 11/12/04 event

rainfall was required to produce substantial flow in the swales (0.31 inch SHA, 0.32 inch MDE) than in the direct channel (0.02 inch).

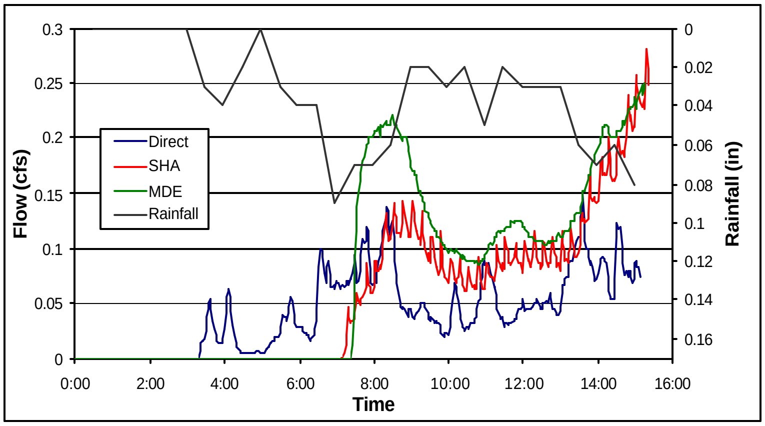

Fig. 7 Flow during 12/19/04 event

The plot of flows for the 11/12/04 storm event (Fig. 6) also showed that the MDE swale produced the highest flow peak. Both swales had similar curves that were significantly higher than the direct channel. The plot for the swales also shows significant smoothing. The flow rates for these swales were not affected by variations in rainfall, while the direct channel responded immediately to rainfall changes.

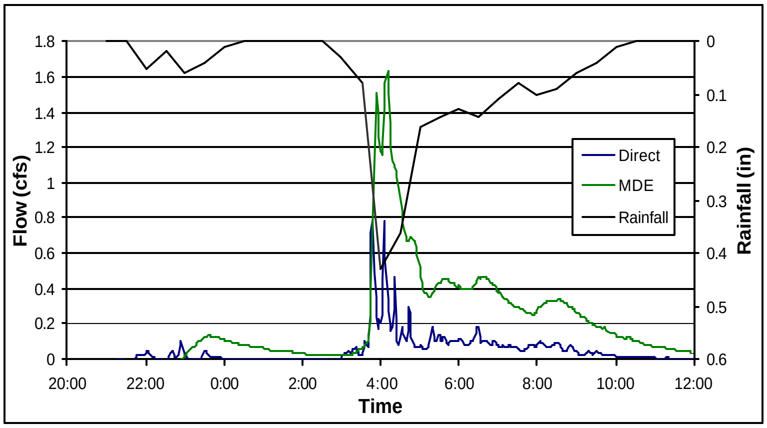

Fig. 8 Flow during 1/13/05 event

The 12/19/04 storm event occurred under a very different set of hydrologic conditions. This afforded the opportunity to compare the performance of the grassed swales across different situations. This storm event was caused by a spike of rain, roughly 0.07 inches, over 15 minutes. After this, no more rain fell until the temperature dropped and all water froze. Falling temperatures also caused the sampler bubbler lines to freeze and therefore, no accurate information was collected after 3:00-6:00 a.m. This condition showed the performance of the grassed swales in the case of a large slug of water. The direct channel reacted immediately to this sudden rainfall with two large peaks in flow. The time steps in rainfall data were too wide to differentiate these peaks in rainfall, however, it is assumed that rainfall followed a similar pattern to the direct channel flow.

The grassed swales performed especially well during this storm event in removing the initial peak flows. In fact, the SHA swale barely reached a flow rate high enough to trigger the sampler and the MDE swale did not trigger before the sampler froze. A 2 hr 4 minute lag time occurred before the SHA swale produced enough flow to trigger. After the initial flow surge, the direct channel flow rates dropped to values similar to the two grassed swales (0.008 cfs) and continued until the end of the sampling period. By removing these two initial peaks, the SHA swale reduced total flow (3,042 L) compared to the direct channel (7,006 L). Therefore, almost half of the highway runoff caused by this relatively small, but sudden slug of water was captured in the initial abstraction phase due to infiltration.

The storm event on 1/13/05 (Fig. 8) offered yet another contrasting condition. This storm event began with a small initial rainfall, followed by a period of inactivity, and then a much stronger wave of rainfall. Although water quality sampling ended at 5:46 a.m., flow data are available for the duration of the storm to determine the hydraulic effects of the swales. During this storm event, the SHA sampler was not functional, so only flows for the direct channel and the MDE swale were included. In a manner similar to the two previous storm events, the swale showed a pronounced lag time before the appearance of any recognizable flow. The direct channel produced flow immediately following the first rainfall. The lag time between the direct channel and the MDE swale was 1 hr 12 min. As in previous storms, the swale showed significant smoothing of the curve, while the direct channel showed large variations in flow corresponding to small changes in rainfall.

One of the more important features of this storm event was the 2-3 hour time period over which no rain fell. During this period, flow in the direct channel was negligible, while the MDE swale showed a steady decline. This showed that the swale slowed water flow and spread this flow out over a longer time. This is one of the positive effects attributed to grassed swales. The final interesting feature to note is that as the second wave of rainfall began, there was no lag time in the swale. This showed that the grass swale was now saturated and would not produce the characteristic initial abstraction effect. Both the direct channel and the grass swale responded immediately and almost identically to rainfall. This showed the importance of antecedent weather conditions in determining the performance of grassed swales in reducing flow. As in the other storm events, the MDE swale had significantly higher flows, possibly due to differences in drainage areas.

Total Suspended Solids (TSS)

Total suspended solids concentration is the most important water quality parameter studied because it is a good indicator of the swale effects for other water quality parameters. Also, the largest amount of grassed swale research has focused on TSS. Because of this, plots of TSS levels with respect to time for each storm event are included in Figures 9, 10, and 11.

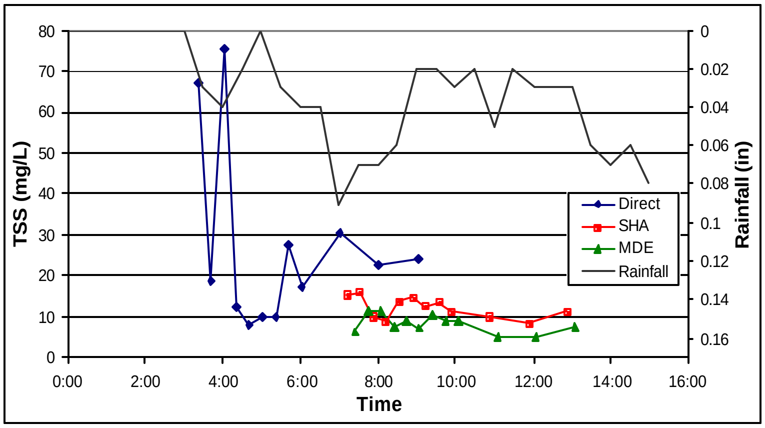

Fig. 9 TSS concentrations during 11/12/04 event

During the 11/12/04 storm (Fig. 9), the sampling schedule was not edited to compensate for the lag time in the swales. Because of this, no samples were available for the direct channel during the end of the storm to allow comparison. However, some trends and conclusions could be drawn from the data. A pronounced first flush effect is noted for the direct channel. TSS concentrations for the first few samples were nearly an order of magnitude higher than later samples. After this first flush effect concluded, TSS concentrations in the direct channel roughly mirrored the rainfall data. As rainfall increased, TSS concentrations increased; however, these concentrations never reached the levels of the first flush. Both grassed swales discharged much lower TSS concentrations when compared to the direct channel. While concentrations in the swales were similar, the MDE swale produced slightly lower TSS concentrations. In a manner similar to the direct channel, TSS concentrations from the swales mirrored the rainfall, increasing with increased rainfall. However, a significant difference was the absence of a substantially larger first flush TSS concentration in the two grassed swales. It appears that this first flush effect was captured by the grassed swales and that solids were being removed as the runoff was conveyed through the swales.

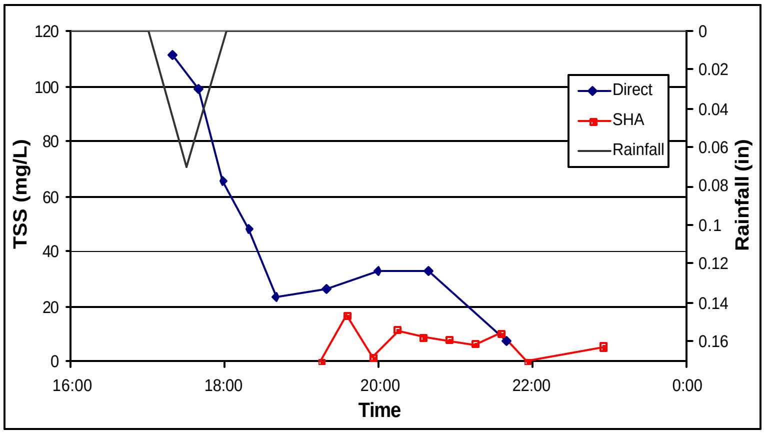

Fig. 10 TSS concentrations during 12/19/04 event

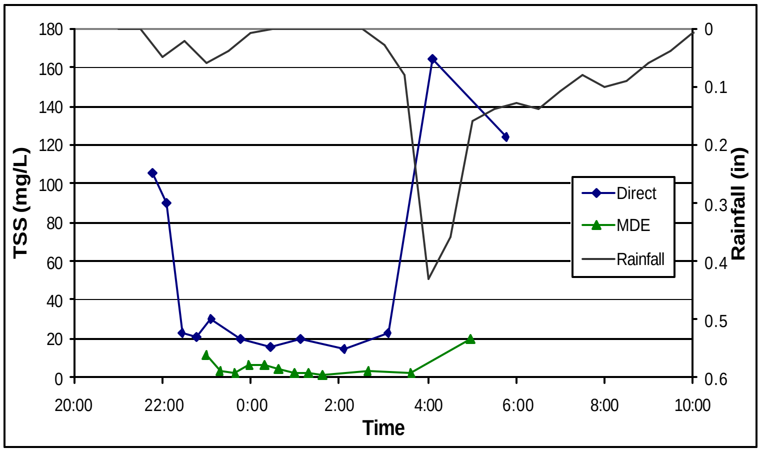

Fig. 11 TSS concentrations during 1/13/05 event

As stated above, the 12/19/05 storm (Fig. 10) showed the effects of a short burst of rainfall followed by a dry period. TSS concentrations in the direct channel once again showed a very large first flush, followed by a relatively steady decline. As in the previous storm event, the SHA swale had lower TSS concentrations than the direct runoff. TSS concentrations in this swale also gradually declined over time without any additional rainfall. This storm event allowed the opportunity to view the effect of the swale when receiving a slug of water. In this event, the swale performed similarly to the previous storm, managing the first flush of suspended solids and reducing the overall concentrations. For both the direct runoff and the SHA swale, TSS concentrations were negligible approximately 5 hours after the rainfall.

Finally, the 1/13/05 storm (Fig. 11) showed the effect of a second, more intense wave of rainfall after a smaller initial rainfall. The TSS concentrations for the direct channel follow a similar pattern as shown for the two prior storms. TSS concentrations began very high, with a first flush effect, and then dissipated rather dramatically. As there was no rainfall between the first wave of rain and the second, the TSS concentrations for the direct channel remain relatively constant. However, during the second, more intense rainfall, the TSS concentrations became higher than the initial concentrations. Because the rainfall during this event was far more intense, it is analogous to two first flush events. The second, more intense rain mobilized even more particulate matter from the roadway. As in previous storms, the TSS concentrations for the

MDE swale were significantly lower than the direct runoff, with the concentrations following the plot of rainfall. For both the first and second rainfall peaks, the first flush effect appears to be managed by the swale.

Metals

Lead concentrations during the 1/13/05 storm event (Fig. 12) and the 11/12/04 storm event (Fig. 13) are presented to contrast the effect of runoff infiltration on metal concentrations. During the 1/13/05 event, rainfall was intense enough to cause the MDE swale to capture less of the initial runoff, as shown by the shorter lag time and similar flow rate to the direct runoff (Fig. 8). Because of this, the first flush of pollutants from the road surface was not successfully captured. This is apparent in Fig. 12, which shows a large peak in lead concentration in the second sample for both the direct runoff and the MDE swale. This sample was taken 20 minutes after the samplers were triggered. The peak was approximately one order of magnitude larger than later concentrations throughout the storm event. In fact, lead concentrations for the remaining duration of the event stayed relatively low and constant. This demonstrated that lead is relatively mobile on roadway surfaces, is primarily affiliated with suspended solids, and is therefore primarily contained in the first flush. Very little residual lead remains on the roadway surface to be washed off by runoff after this first flush.

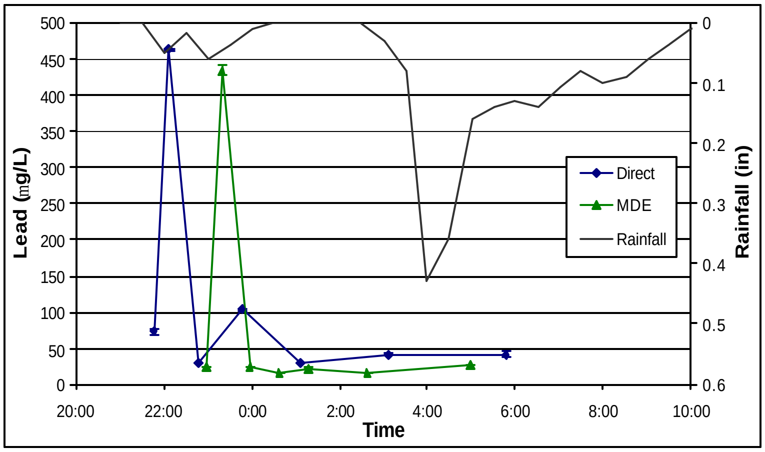

Fig. 12 Lead concentrations during 1/13/05 event

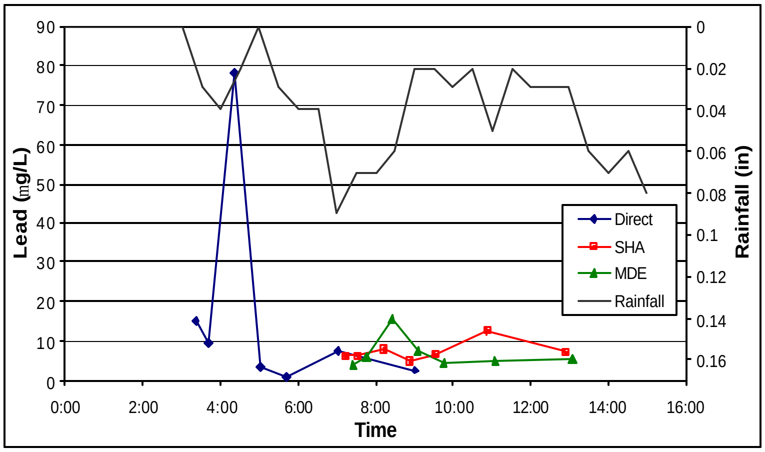

Fig. 13 Lead concentrations during 11/12/04 event

The 11/12/04 storm event (Fig. 13) further corroborated this theory. During this event, the initial flow was small enough that the first flush of pollutants was managed by both swales. The management of the initial flow was discussed above; however, it is apparent that this has important consequences for metal removal. As in the 1/13/05 storm event, the direct runoff produced an order of magnitude first flush peak in lead concentration within the first hour. However, for the 11/12/04 event, this first flush effect was managed by both swales, with no concentration peak noted. This was presumably because rainfall, and therefore flow, was low enough to allow infiltration, filtration, and settling along the length of the swales. Lead concentrations after the first flush were low (approximately 5-10 µg/L), similar to the 1/13/05 storm, and relatively constant. This further supports the claim that after the metal is flushed from the roadway during the beginning of the storm event, very little residual lead remains to be exported. This finding places extra importance on grassed swale performance during the initial phases of the storm. If the swale is capable of managing this first flush, metal concentrations will abate and return to near negligible values.

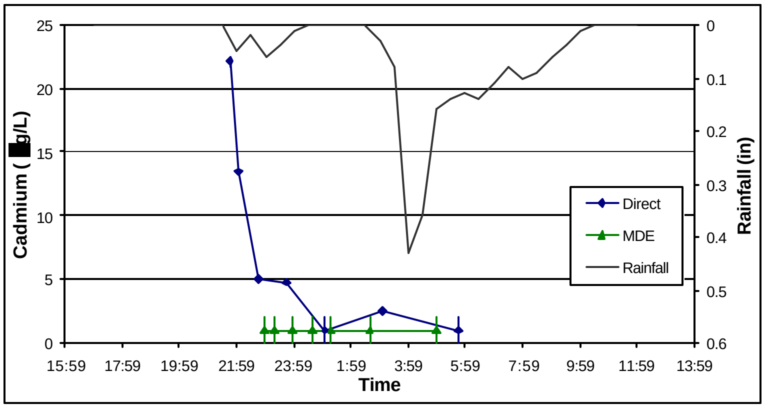

Fig. 14 Cadmium concentrations during 1/13/05 event

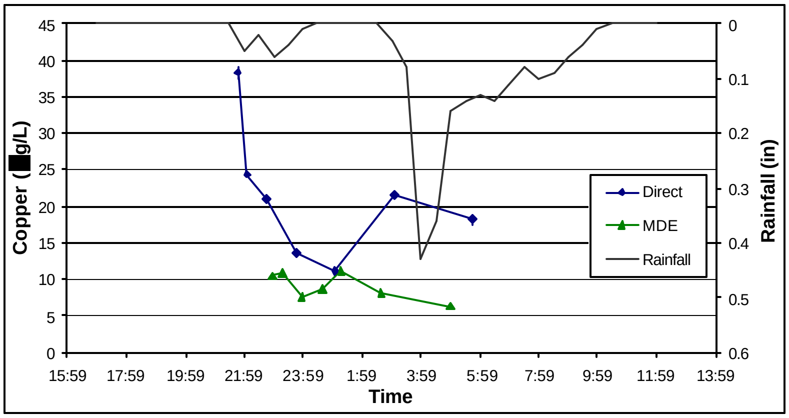

Fig. 15 Copper concentrations during 1/13/05 event

Plots for cadmium, copper, and zinc are presented in Figures 14-16. The direct runoff behavior is similar for all three metals. All show a similar first flush effect with an initial large peak and a smaller, but still substantial peak corresponding to the rainfall peak. Despite relatively high influent cadmium concentrations, effluent concentrations from the MDE swale were all below the detection limit for this metal (2 µg/L). The detection limit is shown by the large error bars on these later samples, showing the range of possible concentrations below this limit. For copper, the MDE swale kept the concentration at 12 µg/L or less, even though input concentrations ranged from 10 to 40 µg/L. With zinc, again, swale output concentrations were nearly an order of magnitude lower than the direct. Concentrations from the MDE swale were slightly less than those from the SHA swale during the initial few samples. Most of the swale zinc samples were below the 20 µg/L detection limit. Overall, metal concentrations were effectively managed by the swales.

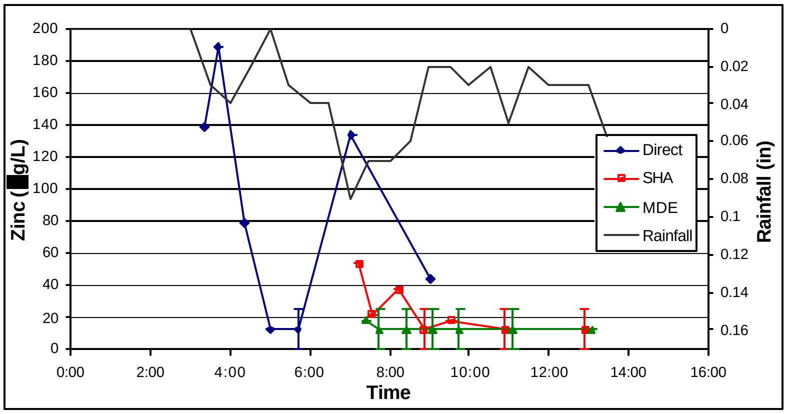

Fig. 16 Zincr concentrations during 11/12/04 event

Nitrate

Nitrate concentrations showed slightly more variation than suspended solids and metals with respect to time. Because of this, hypotheses may be drawn from the data, but more sampling events are required to test these theories. A typical plot of nitrate concentrations for the 1/13/05 storm event is presented in Figure 14. During this storm, the direct channel samples produced high nitrate concentrations during low flows, while producing low concentrations at high flows. The MDE swale showed relatively little change over the duration of the storm. This trend, counter to other pollutants shown above, must be analyzed to determine the cause.

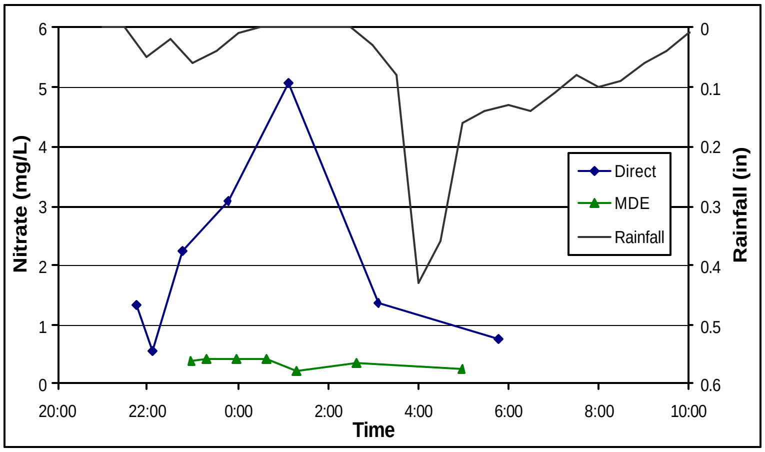

Fig. 17 Nitrate concentrations during 1/13/05 event

It appears that there is no first flush effect for nitrate in roadway runoff. One hypothesis is that nitrate is actually limited by its removal from the roadway surface and therefore did not exhibit the first flush characteristics. Comparing the mass export, rather than concentration, for this storm showed a much more consistent level of nitrate. This means that dilution effects were the main reason for low concentrations at high flows and high concentrations at low flows. More storm events will hopefully allow a more rigorous characterization of this process.

Total Kjeldahl Nitrogen (TKN)

Total Kjeldahl Nitrogen levels from the 1/13/05 storm event are presented in Figure 15. These results were typical of TKN levels for all three storms. TKN roughly followed suspended solids data. In both the direct runoff and the MDE swale, levels were high initially and slowly reduced over time. The initial peak was not as pronounced as in suspended solids or in metal concentrations. For this storm, the direct channel and swale had similar TKN concentrations initially, however, the swale appeared to remove the second peak as the second, and more intense, rain began. The direct channel concentrations were much more affected by this second storm wave. A similar trend was seen in the other storm events, with TKN concentrations steadily decreasing over time for the swales and concentrations following flow rate for the direct channel. Despite similar curve shapes, the first storm event produced higher concentrations in the swales than in

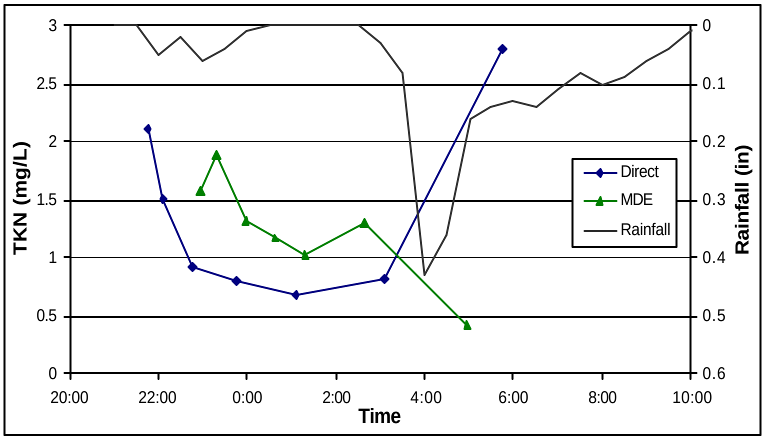

Fig. 18 TKN concentrations during 1/13/05 event

the direct channel. This is possibly due to fertilizer or grass seed applications caused by the construction of the swales. Export of TKN has not been seen since this first storm event and is possible evidence for the maturation of the swales. This effect is also shown and discussed below in the EMC section.

Phosphorus

Phosphorus results showed a very different trend than other nutrients because concentrations in the grassed swales are higher than the direct channel. These data and further EMC data shown below indicate that phosphorus was being exported from the grassed swales for almost all storm events. A typical storm event (11/12/04) is shown in Figure 16. This event showed no phosphorus first flush effect for the direct channel. In fact, phosphorus concentrations for the direct runoff are nearly independent of rainfall and are relatively low compared to the grassed swales. The grassed swales, however, showed phosphorus concentrations with respect to time that appear similar to other contaminants. Both swales have a high initial peak, expressed as the first flush of pollutants, followed by lower concentrations roughly increasing as rainfall increases. The appearance of this characteristic first flush in the swales, but not in the roadway runoff, substantiates the theory that the source of this excess phosphorus was some facet of the grassed swales themselves.

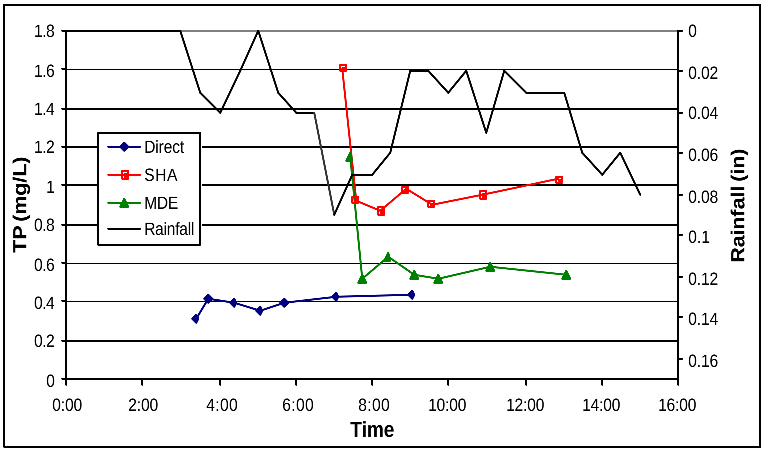

Fig. 19 Phosphorus concentrations during 11/12/04 event

Chloride

Chloride concentrations from the 11/12/04 storm event are presented in Figure 20. The results shown here are typical of chloride concentrations for all three storms. Chloride concentrations for the direct runoff are high immediately following the first rainfall and quickly fall to low values (10-20 mg/L). In the grassed swale effluents, however, chloride concentrations show a similar initial peak, followed by a gradual decrease in concentration. Overall, concentrations in the grassed swales were higher than in the direct channel (by several times) and show the same shape as the rainfall hydrograph. More rainfall resulted in higher concentrations of chloride.

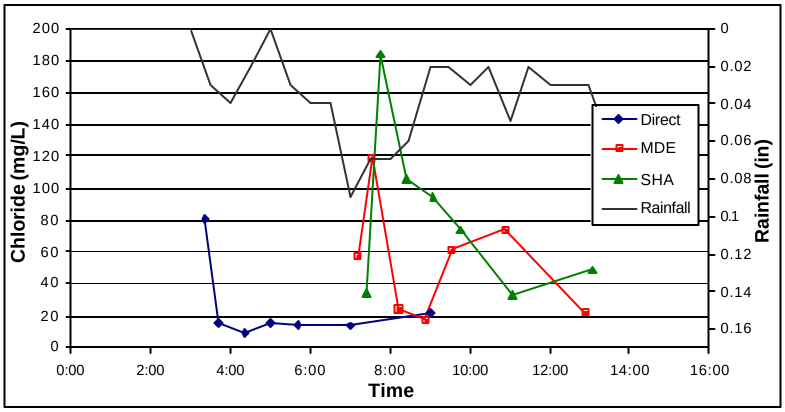

Fig. 20 Chloride concentrations during 11/12/04 event

Therefore, it appears the chloride is being exported from both grassed swales. It is likely that chloride, which is easily dissolved by water, is quickly and almost completely removed from the roadway during the first part of the storm, leaving little chloride to be washed from the roadway in later samples. However, there appears to be a source of chloride in the swales. Most likely, this is chloride trapped from road salting applications during the winter months. It appears that this source within the swale is contributing significant amounts of chloride and is releasing chloride at higher flows.

Event Mean Concentrations (EMC)

As described in the *Data Evaluation* section, EMCs and contaminant mass were calculated for each of the swales and from the direct runoff. EMC results are shown in Table 3. Comparing the EMC values of the two grassed swales to their assumed input from the direct runoff flow, a percent pollutant removal was calculated. These data are summarized in Table 4. Positive values represent pollutant removal, while negative values represent the export of pollutant from the swale. Also, in the case of readings below the detection limit, a range of values is presented representing the highest and lowest possible removal within this detection limit range.

The EMC data in Table 4 show mostly successful removal of nitrate, nitrite, TSS, and the metals copper, lead, and zinc for these three storm events. Along with these removals, there appears to be an export of phosphorous and chloride from the swales, based on the limited data set. It is difficult to draw any conclusions about the two swales currently because only one full data set is available for both swales (11/12/04).

EMC results show a good correlation with other available grassed swale studies. Data for suspended solids, which is the most common water quality parameter studied for grassed swales, have shown discharge TSS concentrations ranging from 10 to 50 mg/L with removals of 48% to 98%. As shown in Tables 3 and 4, the current results are very similar to these studies. EMC results were also similar to literature values for other contaminants (Barrett *et al.* 1998, Backstrom 2003, Barrett 2005). It is important to note that although the swales appear to exporting phosphorus, Barrett (2005) finds that export percentages close to 240% were not uncommon for the 42 storm events he compiled. No discussion of chloride removal by grass swales was noted in any available literature. Therefore, the relatively large export of chloride found in this study cannot be corroborated. However, these concentrations have been repeatedly checked.

Finally, it appears that the grass swales are maturing. As time passes, grass grows and the swales become acclimated to the environment. Some evidence suggests that swale performance characteristics have changed. One source of evidence is the hydrologic data gathered. In the first storm, flow in both swales was much higher than at the direct runoff sampler. However, later storms showed a decrease in flow for the grass swales to a level comparable to the direct runoff. As the swales mature, runoff is slowed and more of this water can infiltrate into the soil.

Table 3. Pollutant EMC for swales and direct runoff from Rt. 32 study.

Storm Event	Swale	TKN (mg/L)	Nitrate (mg-N/L)	Nitrite (mg-N/L)	Total P (mg/L)	TSS (mg/L)	Chloride (mg/L)	Cu (μg/L)	Pb (μg/L)	Zn (mg/L)
11/12/04	Direct	1.1	9.7	0.21	0.41	27	18	26	11	0.78-0.93
	MDE	1.3	5.4	0.02	0.59	8	76	18	7	0.059-0.077
	SHA	1.9	7.3	0.02	0.97	11	48	15	8	0.009-0.026
12/19/04	Direct	2.2	87	0.26	0.21	61	28	-	-	-
	SHA	1.4	-	0.02	0.46	6	69	-	-	-
1/13/05	Direct	1.6	1.3	0.06	0.34	104	17	20	48	0.099
	MDE	0.8	0.3	0.02	0.33	6	110	7	28	0.14

Table 4. Pollutant removal percent based on EMC for swales. The removals are calculated as compared to the direct runoff water quality from Rt. 32.

Storm Event	Swale	TKN	Nitrate	Nitrite	Total P	TSS	Chloride	Cu	Pb	Zn
11/12/04	MDE	(-20)	44	89	(-42)	71	(-325)	32	37	~92
	SHA	(-75)	19	89	(-133)	58	(-166)	42	27	~98
12/19/04	SHA	36	-	92	(-117)	91	(-147)	-	-	-
1/13/05	MDE	50	76	65	4.3	94	(-540)	64	42	(-41)
Mean (both swales)		(-2)	46	84	(-72)	79	(-295)	46	35	50
Standard deviation (both swales)		57	29	13	64	17	182	16	8	79

Just as the EMC normalized pollutant mass by the total flow, in order to compare hydrology data, flows must be normalized by the respective drainage areas for the swales. This allows comparison of flow data to determine if and how much flow is infiltrating into the soil. There appears to be a problem with this, however, because despite this normalization, the swales are producing higher flows than the concrete channel. Inspection of the topographic design of the swales and site inspections suggest that the drainage areas are different from those initially thought. Specifically, for the SHA swale, it appears that additional drainage from the north areas of the median is flowing to the weir area, increasing the measured flow rates. Similarly, the MDE swale drainage area appears to include a significant part of the median. Because of these problems with the flow balance, mass balance calculations yield variable and misleading results. The calculation of total pollutant mass should be normalized by the total drainage area of each swale to allow comparisons between the swales. This would allow the calculation of a total mass removal. However, without confirmed drainage area values, the mass removals are not included in these results.

EMC calculations are relatively unchanged by the uncertainty in drainage area, as these values are normalized with respect to flow, which inherently incorporates the actual drainage area. However, as stated above, if the flows are incorporating flow from drainage areas other than the grass swale, the roadway, and the area between the two, then the EMC could be integrating a dilution effect. This assumes that there is negligible pollutant concentration in the grass median areas outside the primary study area.

Conclusions and Recommendations for Implementation

Limited data for the grass swales show promise in their removal of pollutants from highway runoff. Most measured pollutants showed positive removal, with only phosphorus and chloride showing significant export. Higher concentrations of phosphorus in the grass swale effluent than the roadway runoff is not surprising because phosphorus is present in organic matter and in fertilizers. The amount of data is small and no statistical conclusions can be derived from them; overall, however, it does appear that the grass swales are reducing pollutant levels. It is recommended that SHA expand the use of grass swales for the conveyance of stormwater runoff to benefit from the water quality improvements and the reductions in flow velocity and volume.

This grassed swale study provides important information for the SHA to develop cost efficient stormwater management programs that not only meet transportation needs, but also protect surface and ground waters, special living resources, wetlands, streams and other sensitive habitats. Continued monitoring of these grassed swales will provide increasingly reliable data for the determination of the effect of swales on pollutant removal and flow attenuation.

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