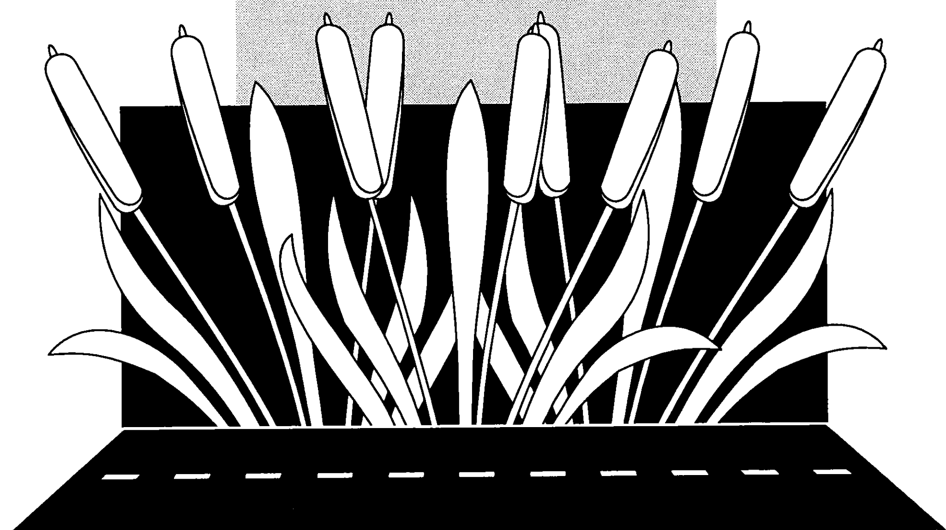
FINAL REPORT

THE CONTROL OF POLLUTION IN HIGHWAY RUNOFF THROUGH BIOFILTRATION

VOLUME II: TESTING OF ROADSIDE VEGETATION



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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/VTRC 95-R29		

4. Title and Subtitle The Control of Pollution in Highway Runoff through Biofiltration Volume II: Testing of Roadside Vegetation	5. Report Date September 1995
	6. Performing Organization Code
7. Author(s) Yu, S. L. and Kaighn, R. J.	8. Performing Organization Report No. VTRC 95-R29
9. Performing Organization Name and Address Virginia Transportation Research Council 530 Edgemont Road Charlottesville, Virginia 23219	10. Work Unit No. (TRAIS)
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address Virginia Department of Transportation 1401 E. Broad Street Richmond, Virginia 23219	13. Type of Report and Period Covered Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

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

16. Abstract

A field monitoring program was begun in 1991, testing the pollutant removal efficiency of selected best management practices (BMPs) to obtain detailed information for design guidelines for stormwater BMPs included in the Virginia Department of Transportation's *Stormwater Management Manual*. This report summarizes Phase III of this project. Data from a grassed highway median swale monitored in an earlier study was compared to data from the swale monitored in this phase. The swale in this study had no checkdam and differed from the earlier swale in slope, traffic volume, and vegetation height, all of which affected pollutant removal. Manual and automatic sampling techniques were used to monitor highway runoff flowing into and out of the grassed swale. Pollutant removal efficiencies were calculated on a mass balance method. Also, the pollutant removal ability of a short buffer strip receiving highway runoff was examined. Pollutants monitored included total suspended solids, chemical oxygen demand, total phosphorus, and zinc. The results of the field monitoring program suggest that properly designed short buffer strips and swales with check dams can remove pollutants from highway runoff.

17. Key Words	18. Distribution Statement
vegetation, biofiltration, pollution control, highway runoff	No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	40	

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(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

September 1995

VTRC 95-R29

Environmental Research Advisory Committee

ABSTRACT

A field monitoring program was begun in 1991, testing the pollutant removal efficiency of selected best management practices (BMPs) to obtain detailed information for design guidelines for stormwater BMPs included in the Virginia Department of Transportation's *Stormwater Management Manual*. This report summarizes Phase III of this project. Data from a grassed highway median swale monitored in an earlier study was compared to data from the swale monitored in this phase. The swale in this study had no checkdam and differed from the earlier swale in slope, traffic volume, and vegetation height, all of which affected pollutant removal. Manual and automatic sampling techniques were used to monitor highway runoff flowing into and out of the grassed swale. Pollutant removal efficiencies were calculated on a mass balance method. Also, the pollutant removal ability of a short buffer strip receiving highway runoff was examined. Pollutants monitored included total suspended solids, chemical oxygen demand, total phosphorus, and zinc. The results of the field monitoring program suggest that properly designed short buffer strips and swales with check dams can remove pollutants from highway runoff.

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FINAL REPORT

THE CONTROL OF POLLUTION IN HIGHWAY RUNOFF THROUGH BIOFILTRATION

VOLUME II:

TESTING OF ROADSIDE VEGETATION: PHASE III

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INTRODUCTION

This report is the culmination of three years of research in the use of best management practices (BMPs) for controlling highway runoff. In the early 1990s, regulations were passed requiring the Virginia Department of Transportation (VDOT) to control the quality as well as the quantity of runoff from highway projects. These regulations included the National Pollutant Discharge Elimination System (NPDES), the Chesapeake Bay Preservation Act, the Virginia Stormwater Management Act, and the Virginia Erosion and Sediment Regulations.

A previous project created a manual of practices by which VDOT could fulfill these regulations.[1] Several research projects were undertaken to test these practices and develop design guidelines. This is a report on the use of biofiltration in grassed swales and roadside vegetation to remove pollutants from highway runoff. Biofiltration is the filtering of polluted water through vegetation, taking advantage of the vegetation's ability to remove pollutants, and in some cases allowing the water to infiltrate into the soil.

Previous research examined a grassed swale on U.S. Route 29 north of Charlottesville, Virginia.[2,3] This study examined a swale on U.S. Route 29 south of Charlottesville, with characteristics different from the previous site. Also, the side slope vegetation on the grassed swale, acting as a buffer strip, was examined for its ability to remove highway pollutants.

This report summarizes three years of study into the use of biofiltration through roadside vegetation to remove highway pollutants, including pertinent information from literature, illustrating the ability of roadside vegetation to remove highway pollutants.

PURPOSE AND SCOPE

The objectives of the study were to:

1. Perform field tests on the use of biofiltration through roadside vegetation as a BMP for controlling highway runoff.
2. Develop design guidelines to be incorporated in VDOT's *Stormwater Management Manual*, and update the manual with respect to new information on BMP design, recommendations from VDOT, and comments from other agencies such as the Federal Highway Administration (FHWA) and other state departments of transportation.

MATERIALS AND METHODS

Site Description and Preparation

A grassed swale on U.S. Route 29 south of Charlottesville, Virginia, was monitored for its ability to remove highway pollutants (Figure 1). This site was chosen because its characteristics contrasted with the swale on U.S. Route 29 north of Charlottesville monitored in previous studies.[2,3] Table 1 summarizes the characteristics of the two swales.

Table 1
SWALE CHARACTERISTICS

Characteristic	29 N Site	29 S Site
Location (see Figure 1)	U.S. Route 29, North of Charlottesville, Va.	U.S. Route 29, South of Charlottesville, Va.
Length	30 m	30 m
Slope	5%	2.5%
Drainage Area	0.202 ha	0.326 ha
Percent Impervious	62%	57%
ADT	50,000	30,000
Mowing	every 2 weeks during the growing season	4 times per year
Average Grass Height	5-15 cm	15-45 cm
Checkdam	Yes	No

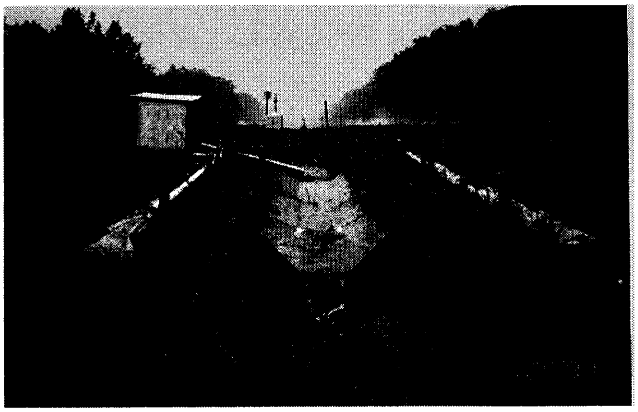

Figure 1. 29S swale monitoring site.

The 29N swale had a slope of around 5%, whereas the 29S swale had a slope closer to 2%. The ADT of the 29N site was approximately 50,000, and the 29S site had an ADT of approximately 30,000. Mowing was much more frequent at the 29N swale, occurring about once every two weeks during the growing season, while the 29S swale was mowed only four times during the same period. These differences should have led to higher removal efficiencies for the 29S swale, according to the literature.

The 29S swale site was arranged similarly to the 29N site. Both were 30 m in length, had lateral inflow barriers so that a mass balance could be done between the two sampling points, used tipping bucket rain gauges to measure rainfall depth and intensity, and used automatic sampling equipment to collect runoff at each end of the swale. Weirs were used to measure the flow entering and leaving the swale.

One can see the effect of the downstream weir on the swale flow characteristics at the 29N site shown in Figure 2. A significant amount of stormwater is ponded behind the weir, creating a small detention pond, where pollutants are allowed to settle, and runoff is allowed to infiltrate. This functions similarly to a berm, or checkdam, which is recommended to help pollutant removal. However, VDOT did not want to use checkdams in their roadside swales because of potential maintenance problems, particularly with the mowing of the grassed swale. Therefore, the 29S site was modified to eliminate the check dam at the downstream end.

As shown in Figure 1, the weir was in a concrete channel downstream from the sampling point, sampling the runoff before it ponded behind the weir. Sampling was done just before the flow entered the concrete channel, using half of a PVC pipe to collect runoff to sample. This configuration is shown in Figures 3 and 4. Since the weir was placed in a concrete channel, ponded stormwater could not infiltrate.

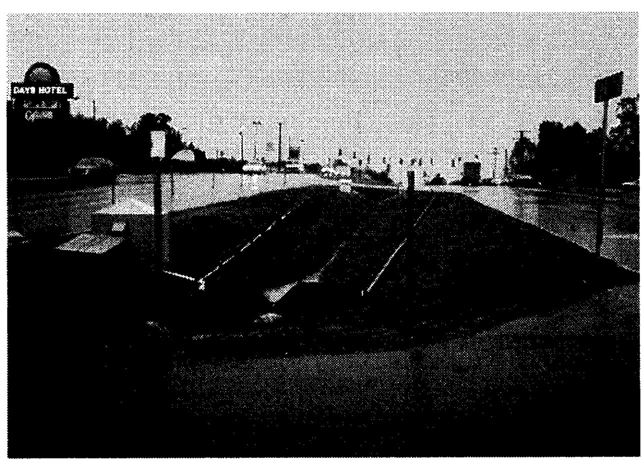

Figure 2. 29N swale monitoring site.

After eight storm events were sampled, the focus was switched from the grassed swale to the strip of vegetation (buffer strip) that storm-water had to flow through before reaching the swale channel. Runoff was sampled at the end of the curb and gutter on one side of U.S. Route 29, and after the runoff had flowed through the vegetation in the median, before flowing into the concrete channel. This second site (Figure 5) is slightly south of the 29S swale site.

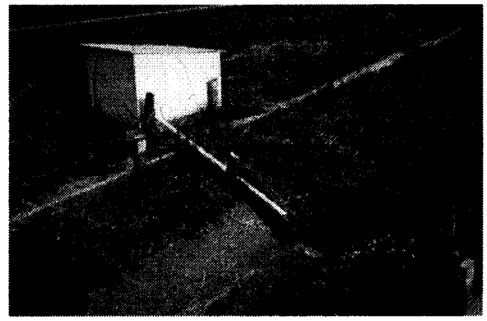

Figure 3. 29S swale outflow sampling point.

Flow at the end of the curb and gutter (representing the edge of pavement) was collect-ed from the outside southbound lane of U.S. Route 29. Runoff was sampled using half of a PVC pipe and an automatic sampler (Figure 5).

Figure 4. Close-up of 29S swale outflow sampling point.

Runoff which had flowed through the 3 m buffer strip was collected again using half of a PVC pipe. This pipe was laid along the edge of the concrete channel for a length of approximately 10 m to collect a significant volume of the overland flow. The median site configuration is shown in Figure 6. The positioning of the sites relative to each other is also visible in Figure 5.

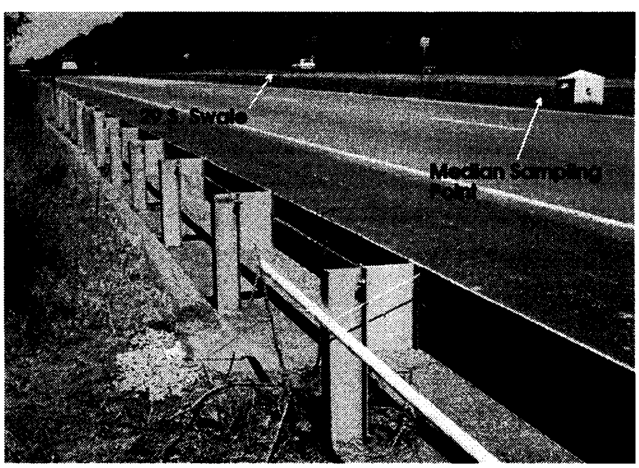

Figure 5. 29S edge of pavement sampling point.

Sample Analysis

Runoff samples were collected using automatic samplers at the analysis points. Collected samples were then taken to the Stormwater Laboratory at the University of Virginia, where they were analyzed for Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Total Phosphorus (TP), and Total Zinc (Zn). Some Particle Size Distributions (PSD) were also done on a few samples. The laboratory analyses for the study were performed with a quality assurance/quality control program as specified by the EPA.

Removal efficiencies were calculated using the change in mass of pollutant flowing in and the mass of pollutants flowing out, shown in the following equation:

$$Removal\ Efficiency\ (\%) = \frac{(Mass\ in\ -\ Mass\ out)}{(Mass\ in)} \times 100 \quad (1)$$

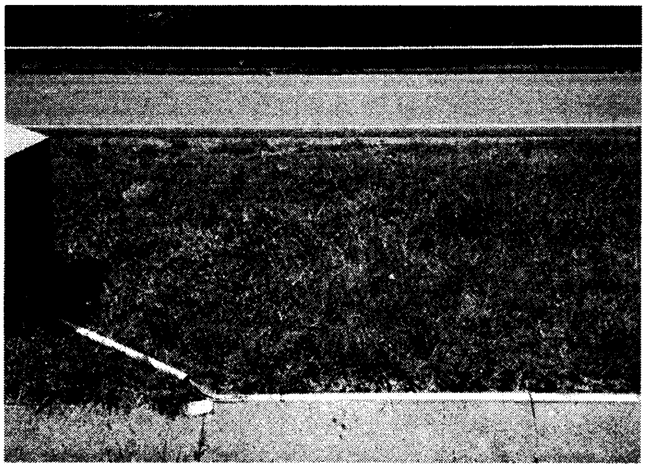

Figure 6. Closeup of 29S buffer strip site.

The mass of pollutants was determined by multiplying the flow by the concentration over the duration of the storm to get a pollutograph. The area under the pollutograph was computed, yielding a mass of pollutant. This mass was calculated for the swale inflow and outflow and used in the above equation.

Flow through the vegetated buffer strip was not measured. Removal percentages are derived from the change in concentration only.

RESULTS

Precipitation

Precipitation for the 11 storms monitored in this study is summarized in Tables 2 and 3. The first 8 storms are from the 29S swale monitoring, and are in Table 2. The precipitation for the 3 buffer strip storms is shown in Table 3. To get runoff into the 29S swale required approximately 7 mm (0.25 in) of rainfall. This is slightly higher than the 5 mm (0.20 in) needed at the 29N site, which reflects the slightly lower imperviousness of the 29S site. As little as 1 mm would generate runoff at the edge of pavement monitoring site, illustrating its impervious drainage area.

Table 2
SWALE PRECIPITATION DATA

Storm No.	Date (mm-dd-yr)	Depth (mm)	Duration (hr)	Average Intensity (mm/hr)	Dry Days	Days Since Runoff
1	10-31-94	23.6	13.0	1.8	4	19
2	11-17-93	17.8	1.5	11.9	1	17
3	12-04-93	55.1	25.0	2.2	7	7
4	03-27-94	23.4	7.0	3.3	3	6
5	04-13-94	11.7	7.0	1.7	2	16
6	06-26-94	15.2	2.0	7.6	5	10
7	07-17-94	19.3	1.5	12.9	1	3
8	07-23-94	36.3	0.5	72.6	1	6

Table 3
BUFFER STRIP PRECIPITATION DATA

Storm No.	Date (mm-dd-yr)	Depth (mm)
9	09-25-94	15.5
10	10-09-94	8.9
11	10-23-94	11.9

Monitored Parameters

A sample of the data collected for the swale monitoring is shown in Figures 7 and 8 for Storm 8. Figure 7 shows observed inflow and outflow of the 29 S swale, along with the observed precipitation. Figure 8 shows the concentrations of the four pollutants monitored in this study. Data for the other observed storm events is included in Appendixes A and B.

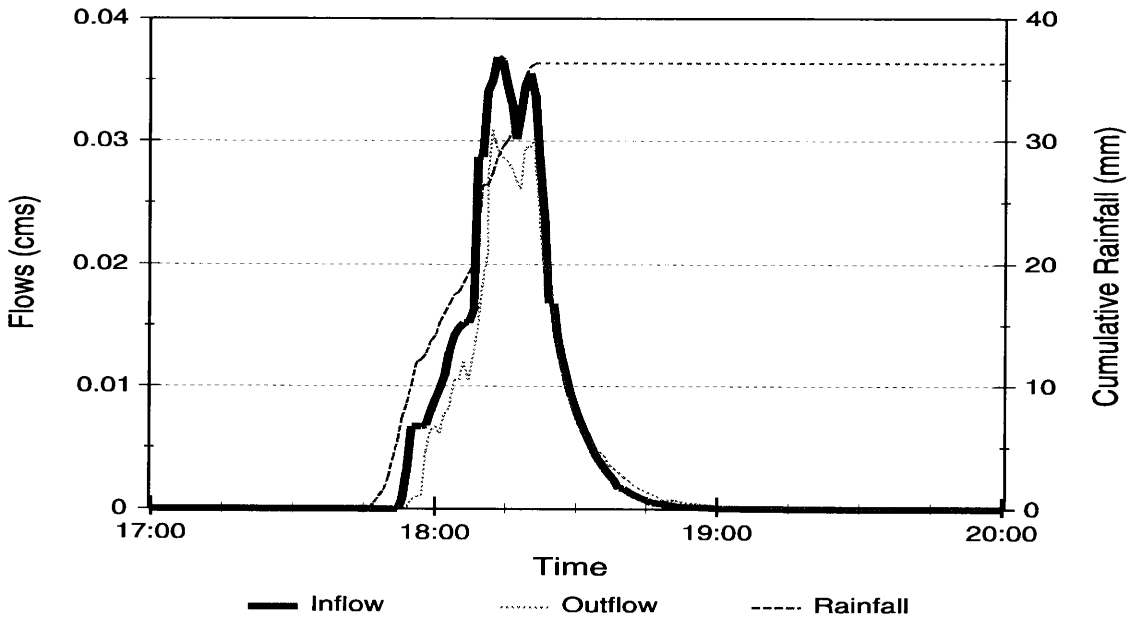

Figure 7. Flow and precipitation data, 07-23-94 storm.

Swale Pollutant Removal

Pollutant removal efficiencies for the swale were calculated using equation 1 and are shown in Table 4. Also shown are removal percentages for both flows and pollutant concentrations. For storms 4 and 6, part of the flow data was not collected due to equipment problems. For a few of the storms, the measured outflow increased significantly while flowing through the swale; the table also shows the mass removal percentages when these storms are omitted.

To better characterize the pollutants, one sample from storm 2 was analyzed to see how much of the pollutants were in a dissolved form. For COD, 55% of the pollutant was in the dissolved form; 58% of the TP was dissolved, and 90% of the ZN was in a dissolved form (by definition, none of the TSS is in a dissolved form).

Also, a particle size distribution (PSD) was done for an event on 08-03-94, an intense storm with 32 mm of rainfall. One manual grab sample was taken at each of the following locations: the edge of the pavement, the inlet of the swale, the midpoint

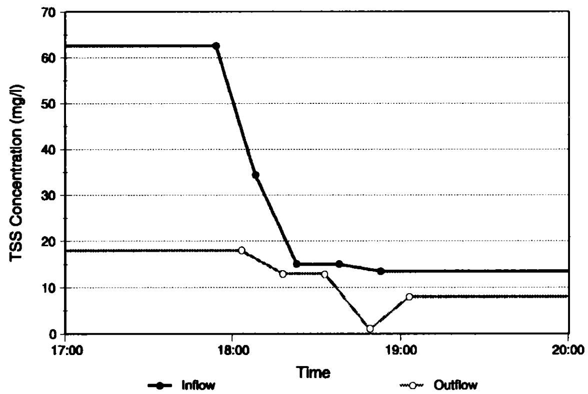

Figure 8A. Swale pollutant concentrations for TSS.

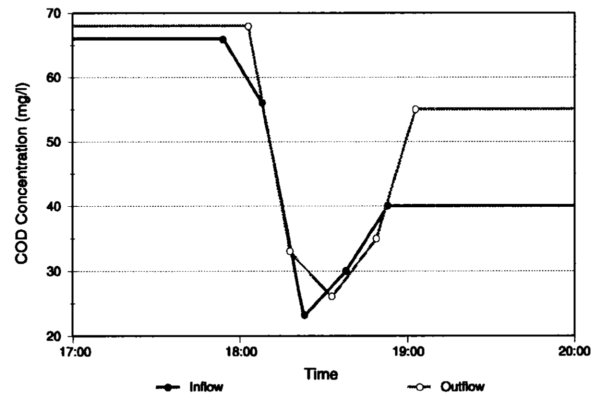

Figure 8B. Swale pollutant concentrations for COD.

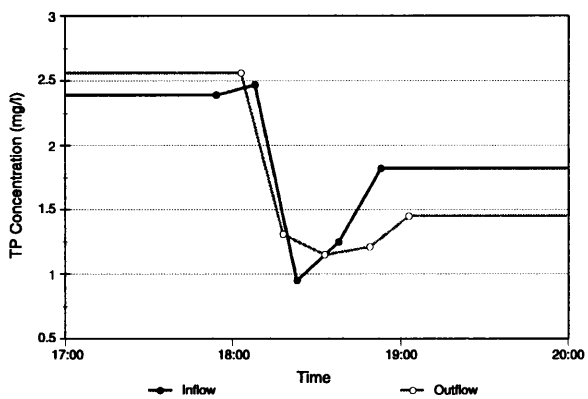

Figure 8C. Swale pollutant concentrations for TP.

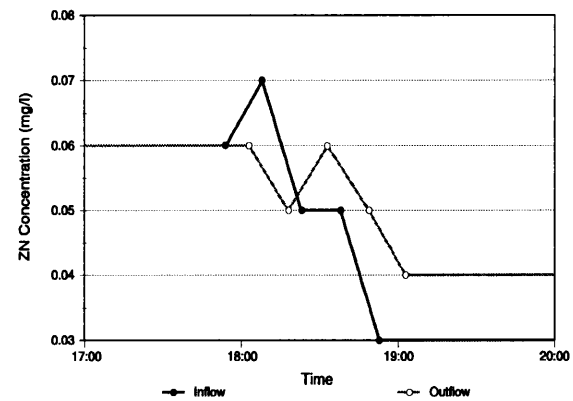

Figure 8D. Swale pollutant concentrations for Zn (Figs. A - D, 07-23-94 storm).

of the swale, and the outlet of the swale. Table 5 shows observed concentrations and PSD for this storm at the four sampling points.

Buffer Strip Pollutant Removal

Observed pollutant concentrations are included in Appendix B. Table 6 shows the removal percentages on a concentration basis (flow was not observed) between the edge of pavement and after the runoff had flowed through the buffer strip. Also, the overall average removal for each pollutant is shown.

Table 4
REMOVAL PERCENTAGES FOR 29 S SWALE

Storm No.	Percent Change in Mass[1]					Percent Change in Concentration			
	TSS	COD	TP	Zn	Flow	TSS	COD	TP	Zn
1	-4.1	-27.8	-14.9	12.3	6.5	-5.9	-39.2	-25.2	9.4
2	-37.8	-102.5	6.2	-159.2	-96.3	31.3	8.0	34.6	-4.3
3	57.4	54.9	55.6	35.4	63.7	3.7	11.9	-20.8	14.6
4[2]						16.7	10.6	-14.7	-10.5
5	-43.5	-186.0	-106.3	-0.5	-127.1	35.8	-16.7	5.9	48.4
6[2]						61	1.7	12.3	-2
7	7.9	-1.5	5.9	5.1	4.6	13.5	-7.4	-3.6	-4.3
8	57.9	18.5	24.8	25.0	18.3	62.3	-0.9	13.5	0
Avg.	6.3	-40.7	-4.8	-13.6	-21.7	29.7	-5.6	-0.4	11.1
Only Positive Flow Loss	23.3	29.8	11.0	17.8	19.5	--	--	--	--

[1] Negative values represent an increase of constituent in the swale.
[2] Flow data for these storms was not obtained.

Table 5
OBSERVATIONS FROM 08-03-94 SWALE STORM

	Edge of Pavement	Swale Inlet	Swale Midpoint	Swale Outlet
Particle Size				
>25μm	53.6%	44.6%	60.5%	39.3%
>8μm	67.9%	55.3%	74.5%	68.8%
>3μm	92.9%	96.4%	81.5%	87.6%
Concentration				
TSS (mg/l)	28	56	48	15
COD (mg/l)	88	92	86	70
TP (mg/l)	3.86	4.27	3.69	3.67
Zn (mg/l)	0.29	0.11	0.11	0.14

Table 6
REMOVAL PERCENTAGES FOR 29 S BUFFER STRIP

Storm	Pollutant			
No.	TSS	COD	TP	Zn
9	57.0	88.8	43.5	88.2
10	80.6	74.3	-25.8	85.9
11	4	45	-404.7	89.6
Avg.	63.9	59.3	-21.2	87.6

DISCUSSION

29 S Swale Results

As previously mentioned, the characteristics of the 29S site suggested that its removal efficiencies should have been higher than at the 29N site. They were not. The average mass removal percentages for COD, TP, and Zn are negative for the 29S site. This is mainly because of the increase in measured flow in storms 2 and 5.

The increased flow may have been due to the lateral barriers not working properly. They had been in the field for several months before monitoring was started, and had even been hit by a vehicle that ran off the road. If they had worked properly, the flow should not have doubled between the inflow and outflow points of the swale. The main advantage of not allowing lateral flow is for the mass balance approach to pollutant removal. Analysis based exclusively on concentration is unaffected by the flow.

If storms 2 and 5, where the flow increased, are omitted, the pollutant removal percentages are all less than 30 percent (23.3%, 29.8%, 11.0%, and 17% for TSS, COD, TP, and Zn, respectively), which is significantly less than the 80-90 percent removal observed at the 29N site. The only advantage the 29N site had over the 29S site was the downstream weir acting as a check dam. The 29N site had significant decreases in flow, which lead to significant pollutant reductions. We can only assume that this flow loss was a direct consequence of the downstream weir acting as a check dam.

Moreover, if flow is ignored, and only pollutant concentration is examined, the 29 N swale still performed better. Percent decrease in concentrations of the four pollutants at the 29 N site were: 49%, 3%, 33%, and 13% for TSS, COD, TP, and Zn, respectively. As shown in Table 4, the percent decrease in concentrations at the 29 S site were: 29%, -6%, -0.4%, and 11% for TSS, COD, TP, and Zn, respectively. Obviously, the check dam significantly increased pollutant removal by allowing pollutants to settle.

Many studies have been done elsewhere on the effectiveness of swales at removing pollutants. A study by Lorant (1992),[4] done in Canada, compared the pollutant concentrations of highway runoff collected in grassed channels and paved channels. It was shown that, on average, water quality parameters were 63% lower in the grassed channel than the paved channel.

Several other projects have been done in Florida by Yousef and Wanielista. They developed design guidelines to take advantage of infiltration in swales, and using checkdams when necessary.[5] Infiltration of all the runoff is shown as one way to get 100% removal of pollutants. Several of the smaller storms (less than 7 mm in depth) would fall into this category at the 29S swale site.

The use of grassed swales instead of paved channels is promoted by many to improve highway runoff quality. Finley and Young (1993)[6] point out the water quality benefits, aesthetic benefits, and reduced costs of swales compared to paved channels. To develop a relationship between swale length and pollutant removal, a literature search was done. Eight different swales were found which monitored Zn for various lengths. The data was regressed and Figure 9 shows the data points from various studies,[3, 5, 7-9] along with the regressed curve, for which the equation is

$$R_{ZN} = 8.302\, D^{0.50} \tag{1}$$

where:

D = Length(m); and
R_{ZN} = Zinc Removal (percent).

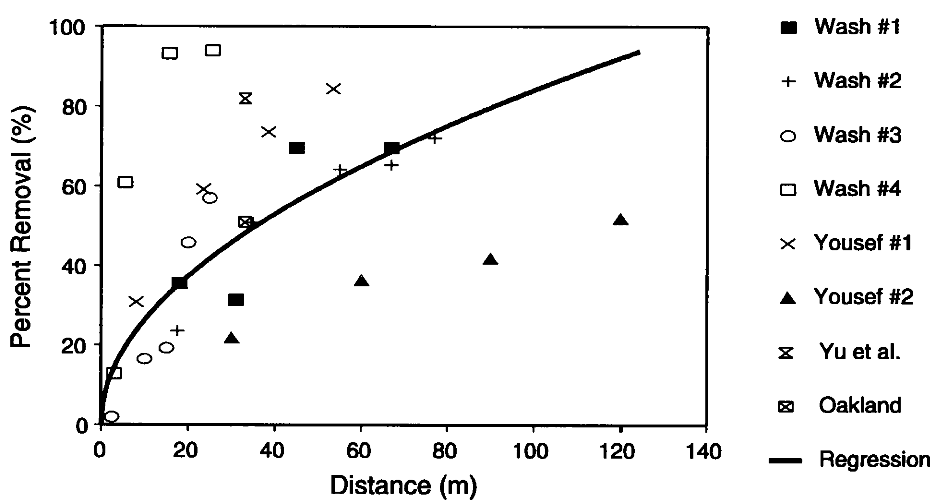

Figure 9. Relationship between swale length and pollutant removal as reflected in the literature.

The scatter of data points illustrates the inconsistent results between studies. Obviously swale length is not the only important parameter. Swale shape, slope, flow rate, type of vegetation, and infiltration rates are just some of the variables that could affect pollutant removal.

29 S Buffer Strip Results

The motivation for examining the buffer strip the runoff flows through before reaching the swale came from an examination of the pollutants entering the 29S swale. In Phase II of this study,[3] pollutant concentrations leaving the 29N swale were approximately 80% lower than those observed in an edge of pavement study done adjacent to the 29N site.[2] This edge of pavement study found similar results to a study done by FHWA.[10] Table 7 compares observed pollutant concentrations from the edge of pavement studies and the 29N and 29S swales, showing that both the average concentrations and the range of the concentrations from the edge of pavement studies were generally higher (sometimes significantly higher) than in the swales.

From these observations, it was thought that significant pollutant removal was occurring before the stormwater reached the swale. One of the samples from this year's study was analyzed to see how much of the pollutants were dissolved. As reported in the previous section, COD and TP were found to 50-60 % dissolved, and Zn was found to be 90% dissolved. This does not correspond to what is reported in the literature. It is generally thought that the majority of pollutants in highway runoff is in a suspended form and not a dissolved form.[10] This is illustrated in Table 8, which shows that the percentage of street pollutants which are associated with particles greater than 43 μm, and thus not dissolved, is generally greater than 75%.

This did not agree with our observations. The pollutant characteristics were being affected before reaching the swale; the larger, more settleable particles were being removed before the runoff reached the swale, and the remaining pollutants are more difficult to remove (being associated with smaller particles or in dissolved form), which is reflected in the results of the swale monitoring. Thus the project's focus was switched to examine the vegetated buffer strip which the runoff from the roadway must flow through before entering the swale.

Removal percentages for the buffer strip (Table 6) give good results for TSS, COD, and Zn, which are generally in suspended form, as illustrated in Table 8. TP showed inconsistent results; a smaller percentage of TP is associated with suspended particles. Thus, it would seem that pollutants associated with larger particles, are easily removed by the vegetated buffer strip.

Table 7
COMPARISON OF POLLUTANT CONCENTRATION FROM EDGE OF PAVEMENT AND SWALE STUDIES

Pollutant (mg/l)	FHWA[10]		29 N Edge of Pavement[2]	
	Average	Range	Average	Range
TSS	261	4 - 1656	112.9	21 - 410
COD	147	4 - 1058	295.4	86 - 458
TP	0.79	0.05 - 3.55	3.71	0.91 - 6.51
Zn	0.41	0.01 - 3.4	0.65	0.25 - 1.60
Pollutant (mg/l)	**29 N Swale Inflow [3]**		**29 S Swale Inflow**	
	Average	Range	Average	Range
TSS	38.7	12 - 332	32.8	13.5 - 110.5
COD	61.1	16 - 143	64.9	20 - 105
TP	1.08	0 - 3.77	1.86	0.28 - 3.6
Zn	0.15	0 - 0.44	0.10	0 - 0.27

Table 8
PERCENTAGE OF HIGHWAY POLLUTANTS ASSOCIATED WITH LARGER PARTICLES

Pollutant	Percent Associated with Particles Greater Than 45 μm
Total Solids	94.1
Volatile Solids	74.4
COD	77.3
BOD_5	75.7
TKN	81.3
Phosphates	43.8
All Toxic Metals	72.2

(Source: adapted from Bell, 1994 [11])

One other observation that may prove significant in future research was the observed color of the runoff samples. Samples taken at the edge of pavement were black in color, most likely from tire and asphalt wear on the roadway. Samples taken after the runoff had flowed through the buffer strip were red in color, from the underlying soil. It is possible that the site installation stirred up the sediment and increased the amount of solids in the samples. Or it is possible that the runoff is picking up smaller sediment particles, replacing the larger solids washed off the roadway.

Many research projects have been done on the ability of buffer strips to remove pollutants from agricultural runoff. They also observe significant removal of suspended solids and associated pollutants in short distances. Chaubey et al.[12] found significant removal of TSS in 3 m, with only slight removal thereafter. Dillaha et al.[13] found 84% and 70% removal of TSS for strip lengths of 9.1 and 4.6 m, respectively.

The sedimentation process depends upon flow characteristics and particle size. Gravity is the main sedimentation force, and larger particles will settle more easily. Large turbulent flows have the ability to carry larger particles, whereas shallow laminar flow, which would characterize an overland buffer strip, cannot carry the larger particles, and they settle. Modeling of sedimentation in vegetated filters has been done by Tollner et al.[14] Promoting sedimentation can be done by designing buffer strips with small flows and flat slopes, slowing the runoff. This should also promote infiltration.

Overall, it would seem that highway runoff, which is characterized by larger, suspended particles, can easily be treated by flow through vegetation. Past research focused on the grassed swale, but the significant pollutant removal expected did not materialize. This may be because the easily settleable pollutants had already been removed before the runoff entered the monitored swale, and the pollutants remaining were not as easily removed, being very small suspended particles, or dissolved pollutants. However, these pollutants can still be removed through infiltration, which was not examined in the buffer strip monitoring, but was shown to be significant in the swale monitoring.

Another advantage of the buffer strip is the ratio of buffer strip area to pavement drained area. Drainage to the buffer strip from the pavement came from only one lane of the highway, yielding a pavement to buffer strip area ratio of about 1:1. This ratio is cited in many BMP handbooks as a very important parameter in judging the efficiency of different BMPs.

As far as the useful life of a buffer strip, the 29S site was opened to traffic in the early 1970s, and after more than twenty years of service, still demonstrated significant pollutant removal.

UPDATE OF VDOT'S *STORMWATER MANAGEMENT MANUAL*

The manual was updated to show the latest requirements set forth by the Department of Conservation and Recreation (DCR), including:

- New requirements for sediment basins which increased the storage volume from 67 cu. yds. per acre to 134 cu. yds., which includes 67 cu. yds. of wet storage and 67 cu. yds. of dry storage.
- Descriptions of three more erosion and sediment control practices were added: Storm Drain Inlet Protection, Turbidity Curtains, and Construction Entrances. The use of Straw Bales for erosion control is no longer promoted by the VDOT, and this section was removed.
- New requirements stating that Stormwater Management Regulations apply to linear development projects which affect 1 acre per local outfall or watershed. Also the regulations apply only to development projects where there is an increase in flow as a result of the project.

CONCLUSIONS

1. The grassed swale monitored in this study removed less than 30 percent of the pollutants monitored. This swale did not have a checkdam at the outlet, whereas the 29N swale previously monitored did, and higher removal percentages were observed in the swale with the checkdam. Checkdams can increase pollutant removal by ponding stormwater, allowing pollutants to settle and the ponded water to infiltrate. Also, stormwater from smaller storms (less than 7 mm at the 29S site) can be completely absorbed by the roadside vegetation.

2. Highway runoff is characterized by pollutants in suspended form which are easily settleable.

RECOMMENDATIONS

1. Roadside vegetation has been shown to remove suspended pollutants from highway runoff. The use of a buffer strip and a grassed swale with a check dam should be used where possible to reduce the amount of pollutants washing from a roadway. In general this should not be a burden, since vegetated channels are usually cheaper than paved channels. Checkdams could be placed near inlets to reduce maintenance problems.

2. Further research may be needed to allow this management strategy to be used instead of other practices recognized by regulatory agencies, especially in terms of the buffer strip, where only three storm events were monitored.

3. Infiltration has been shown to be a significant factor in pollutant removal. More study needs to be done to get accurate infiltration rates for design purposes. In filtration was not examined in the buffer strip monitoring, and should lead to even higher pollutant removal percentages.

4. The fate of highway pollutants should be examined once removed from highway runoff to determine if they are tightly bound to the surrounding soil, or if they are able to be resuspended into surface flows or migrate downward to groundwater.

5. The continued research in different types of BMPs is needed to give designers options when faced with difficult decisions. Detention ponds, which are the most popular BMP, are not always the best or most practical way to control highway runoff.

ACKNOWLEDGEMENTS

This research was conducted under the general supervision of Dr. Gary R. Allen, Director of the Virginia Transportation Research Council. Special thanks go to Michael M. Sprinkel, Research Manager of the Materials and Environmental Group, for his assistance. The project was financed with HPR funds administered by the Federal Highway Administration. Charles A. McIver, State Hydraulics Engineer, VDOT, and his colleague Roy T. Mills are gratefully acknowledged for their assistance. Richard Ziller, Christienne O'Flaherty, and David Wyant, Jr., are recognized for their help, which included field sampling and site preparation. Daniel Liao, who did most of the laboratory work, is also thanked. Michael Fitch, Daniel McGeehan and Michael Sprinkel of VTRC, Charles McIver of VDOT, and Edward Sundra of FHWA peer reviewed the draft report. Linda Evans, Gary Mawyer, Margaret Edwards, Randy Combs, Ed Deasy, Arlene Fewell, and Jerry Garrison assisted in the production of the report.

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APPENDIX A: DATA FROM 29 S SWALE MONITORING

TABLE A1
OBSERVED POLLUTANT CONCENTRATIONS FROM MONITORED STORMS

TSS Concentrations (mg/l)

29ss01		10-31-93		29ss02		11-17-93	
Inflow		Outflow		Inflow		Outflow	
Time	TSS	Time	TSS	Time	TSS	Time	TSS
8:23	21	9:34	14.5	18:25	110.5	19:30	40.5
9:32	31	10:34	26.5	19:25	44.5	20:30	49.5
11:32	23	11:34	27	20:25	41.5		
12:32	16.5	13:34	21				
14:32	28	15:34	37.5				
Avg:	23.9		25.3	Avg:	65.5		45
% Change:			-5.86	% Change:			31.30

29ss03		12-4-93		29ss04		3-27-94	
Inflow		Outflow		Inflow		Outflow	
Time	TSS	Time	TSS	Time	TSS	Time	TSS
17:45	42	17:50	23.5	5:02	28.5	5:35	26
20:02	18	20:02	28	6:02	28	7:05	22.5
22:02	22	22:02	23	7:02	31.5	8:35	28.5
00:02	22.5	00:02	22	9:02	28.5	10:05	19.5
02:02	18	02:02	21.5	11:02	27.5	11:35	23.5
Avg:	24.5		23.6	Avg:	28.8		24
% Change:			3.67	% Change:			16.67

29ss05		4-13-94		29ss06		6-26-94	
Inflow		Outflow		Inflow		Outflow	
Time	TSS	Time	TSS	Time	TSS	Time	TSS
10:47	44	11:15	25	10:57	65	11:20	13
11:46	36	11:45	27	11:11	20		
12:46	20	12:15	19	11:26	15		
		12:45	18				
		13:15	18				
Avg:	33.33		21.4	Avg:	33.33		13
% Change:			35.8	% Change:			61

TABLE A1 (cont'd)
OBSERVED POLLUTANT CONCENTRATIONS FROM MONITORED STORMS

29ss07		7-17-94		29ss08			7-23-94
Inflow		Outflow		Inflow		Outflow	
Time	TSS	Time	TSS	Time	TSS	Time	TSS
8:15	58	8:23	34	5:54	62.5	6:03	18
8:29	15	8:38	17	6:08	34.5	6:18	13
8:44	17	8:53	21	6:23	15	6:33	13
8:59	17	9:08	20	6:38	15	6:49	1
9:29	19	9:38	17	6:53	13.5	7:03	8
Avg:	25.2		21.8	Avg:	28.1		10.6
% Change:			13.49	% Change:			62.28

	Avg.	Max.	Min.
Inflow:	11.18	110.5	16.5
Outflow:	8.79	49.5	0
% Change:	21.36		

COD Concentrations (mg/l)

29ss01		10-31-93		29ss02			11-17-93
Inflow		Outflow		Inflow		Outflow	
Time	COD	Time	COD	Time	COD	Time	COD
8:23	69	9:34	92	18:25	92	19:30	62
9:32	74	10:34	94	19:25	51	20:30	65
11:32	57	11:34	84	20:25	64		
12:32	61	13:34	80				
14:32	71	15:34	112				
Avg:	66.4		92.4	Avg:	69		63.5
% Change:			-39.16	% Change:			7.97

29ss03		12-4-93		29ss04			3-27-94
Inflow		Outflow		Inflow		Outflow	
Time	COD	Time	COD	Time	COD	Time	COD
17:45	72	17:50	77	5:02	64	5:35	55
20:02	50	20:02	40	6:02	59	7:05	49
22:02	27	22:02	24	7:02	53	8:35	40
00:02	24	00:02	12	9:02	46	10:05	47
02:02	20	02:02	17	11:02	62	11:35	63
Avg:	38.6		34	Avg:	56.8		50.8
% Change:			11.92	% Change:			10.56

TABLE A1 (cont'd)
OBSERVED POLLUTANT CONCENTRATIONS FROM MONITORED STORMS

29ss05		4-13-94		29ss06			6-26-94
Inflow		Outflow		Inflow		Outflow	
Time	COD	Time	COD	Time	COD	Time	COD
10:47	105	11:15	101	10:57	93	11:20	77
11:46	72	11:45	98	11:11	67		
12:46	80	12:15	87	11:26	75		
		12:45	102				
		13:15	112				
Avg:	85.67		100	Avg:	78.33		77
% Change:			-16.73	% Change:			1.70

29ss07		7-17-94		29ss08			7-23-94
Inflow		Outflow		Inflow		Outflow	
Time	COD	Time	COD	Time	COD	Time	COD
8:15	71	8:23	73	5:54	66	6:03	68
8:29	73	8:38	73	6:08	56	6:18	33
8:44	79	8:53	98	6:23	23	6:33	26
8:59	87	9:08	89	6:38	30	6:49	35
9:29	98	9:38	105	6:53	40	7:03	55
Avg:	81.6		87.6	Avg:	43		43.4
% Change:			-7.35	% Change:			-0.93

	Avg.	Max.	Min.
Inflow:	64.93	105	20
Outflow:	68.59	112	12
% Change:	-5.64		

TP Concentrations (mg/l)

29ss01		10-31-93		29ss02			11-17-93
Inflow		Outflow		Inflow		Outflow	
Time	TP	Time	TP	Time	TP	Time	TP
8:23	2.7	9:34	3.8	18:25	1.77	19:30	0.65
9:32	3.2	10:34	4	19:25	1.26	20:30	1.26
11:32	3	11:34	3	20:25	1.35		
12:32	3	13:34	4.4				
14:32	3.2	15:34	3.7				
Avg:	3.02		3.78	Avg:	1.46		0.955
% Change:			-25.17	% Change:			34.59

TABLE A1 (cont'd)
OBSERVED POLLUTANT CONCENTRATIONS FROM MONITORED STORMS

29ss03		12-4-93		29ss04		3-27-94	
Inflow		Outflow		Inflow		Outflow	
Time	TP	Time	TP	Time	TP	Time	TP
17:45	1.9	17:50	2.66	5:02	0.86	5:35	0.68
20:02	1.23	20:02	1.97	6:02	0.47	7:05	0.79
22:02	1.32	22:02	1.41	7:02	0.64	8:35	0.53
00:02	1.48	00:02	1.36	9:02	0.34	10:05	0.5
02:02	1.34	02:02	1.38	11:02	0.28	11:35	0.47
Avg:	1.454		1.756	Avg:	0.518		0.594
% Change:			-20.77	% Change:			-14.67

29ss05		4-13-94		29ss06		6-26-94	
Inflow		Outflow		Inflow		Outflow	
Time	TP	Time	TP	Time	TP	Time	TP
10:47	3	11:15	2.6	10:57	2.51	11:20	1.62
11:46	3.6	11:45	2.7	11:11	1.51		
12:46	2.2	12:15	3.8	11:26	1.52		
		12:45	2.6				
		13:15	2.1				
Avg:	2.93		2.76	Avg:	1.85		1.62
% Change:			5.91	% Change:			12.27

29ss07		7-17-94		29ss08		7-23-94	
Inflow		Outflow		Inflow		Outflow	
Time	TP	Time	TP	Time	TP	Time	TP
8:15	1.66	8:23	1.84	5:54	2.39	6:03	2.56
8:29	1.63	8:38	1.07	6:08	2.47	6:18	1.31
8:44	1.88	8:53	2.41	6:23	0.95	6:33	1.15
8:59	2.19	9:08	1.94	6:38	1.25	6:49	1.21
9:29	2.14	9:38	2.58	6:53	1.82	7:03	1.45
Avg:	1.9		1.968	Avg:	1.776		1.536
% Change:			-3.58	% Change:			13.51

	Avg.	Max.	Min.
Inflow:	1.86	3.6	0.28
Outflow:	1.87	4.4	0.47
% Change:	-0.41		

TABLE A1 (cont'd)
OBSERVED POLLUTANT CONCENTRATIONS FROM MONITORED STORMS

ZN Concentrations (mg/l)

29ss01		10-31-93			29ss02		11-17-93
Inflow		Outflow		Inflow		Outflow	
Time	ZN	Time	ZN	Time	ZN	Time	ZN
8:23	0.16	9:34	0.11	18:25	0.1	19:30	0.1
9:32	0.13	10:34	0.1	19:25	0.07	20:30	0.06
11:32	0.12	11:34	0.1	20:25	0.06		
12:32	0.1	13:34	0.09				
14:32	0.13	15:34	0.18				
Avg:	0.128		0.116	Avg:	0.077		0.08
% Change:			9.38	% Change:			-4.35
29ss03		12-4-93			29ss04		3-27-94
Inflow		Outflow		Inflow		Outflow	
Time	ZN	Time	ZN	Time	ZN	Time	ZN
17:45	0.09	17:50	0.06	5:02	0.07	5:35	0.09
20:02	0.11	20:02	0.06	6:02	0.09	7:05	0.08
22:02	0.06	22:02	0.07	7:02	0.1	8:35	0.07
00:02	0.04	00:02	0.1	9:02	0.07	10:05	0.08
02:02	0.11	02:02	0.06	11:02	0.05	11:35	0.1
Avg:	0.082		0.07	Avg:	0.076		0.084
% Change:			14.63	% Change:			-10.53
29ss05		4-13-94			29ss06		6-26-94
Inflow		Outflow		Inflow		Outflow	
Time	ZN	Time	ZN	Time	ZN	Time	ZN
10:47	0.15	11:15	0.08	10:57	0.27	11:20	0.17
11:46	0.22	11:45	0.09	11:11	0.23		
12:46	0.13	12:15	0.08	11:26	0		
		12:45	0.09				
		13:15	0.09				
Avg:	0.167		0.086	Avg:	0.167		0.17
% Change:			48.4	% Change:			-2

TABLE A1 (cont'd)
OBSERVED POLLUTANT CONCENTRATIONS FROM MONITORED STORMS

29ss07		7-17-94		29ss08		7-23-94	
Inflow		Outflow		Inflow		Outflow	
Time	ZN	Time	ZN	Time	ZN	Time	ZN
8:15	0.06	8:23	0.04	5:54	0.06	6:03	0.06
8:29	0.03	8:38	0.03	6:08	0.07	6:18	0.05
8:44	0.04	8:53	0.05	6:23	0.05	6:33	0.06
8:59	0.03	9:08	0.05	6:38	0.05	6:49	0.05
9:29	0.07	9:38	0.07	6:53	0.03	7:03	0.04
Avg:	0.046		0.048	Avg:	0.052		0.052
% Change:			-4.35	% Change:			0

	Avg.	Max.	Min.
Inflow:	0.10	0.27	0
Outflow:	0.09	0.18	0.03
% Change:	11.08		

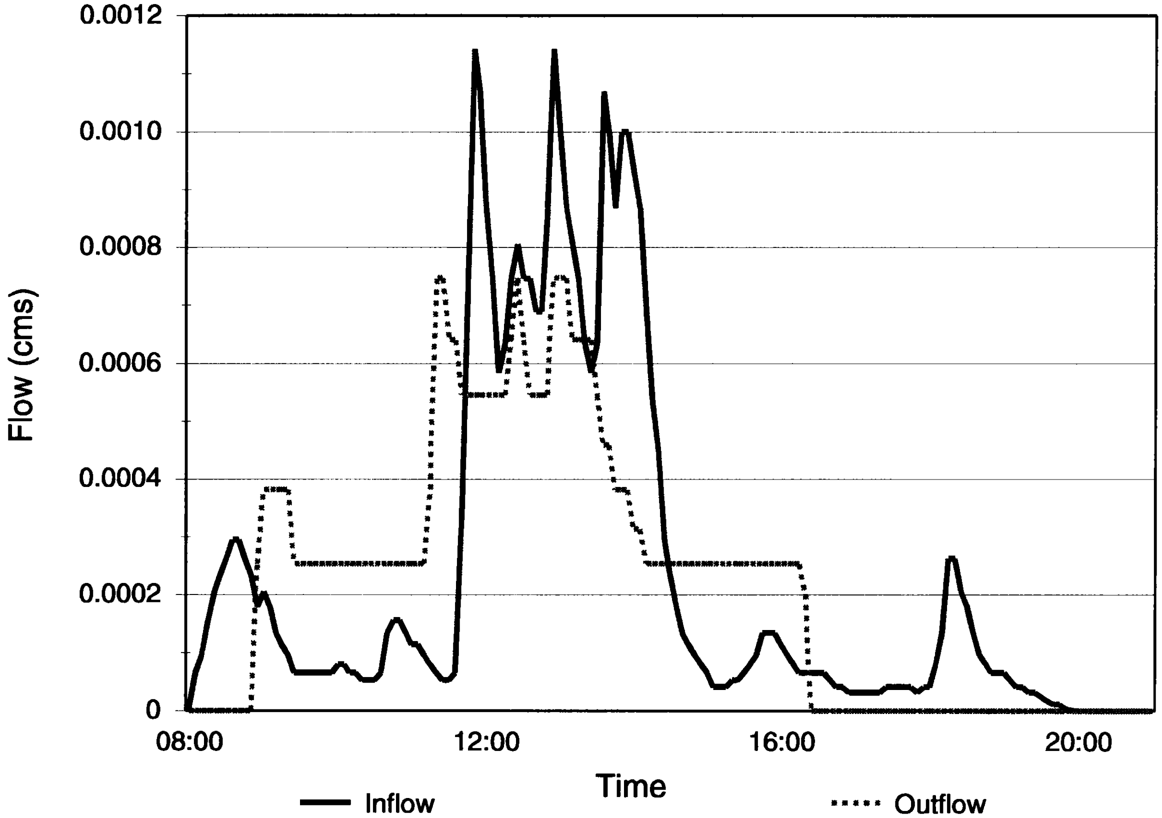

Figure A1. Flow data, 10-31-93 storm.

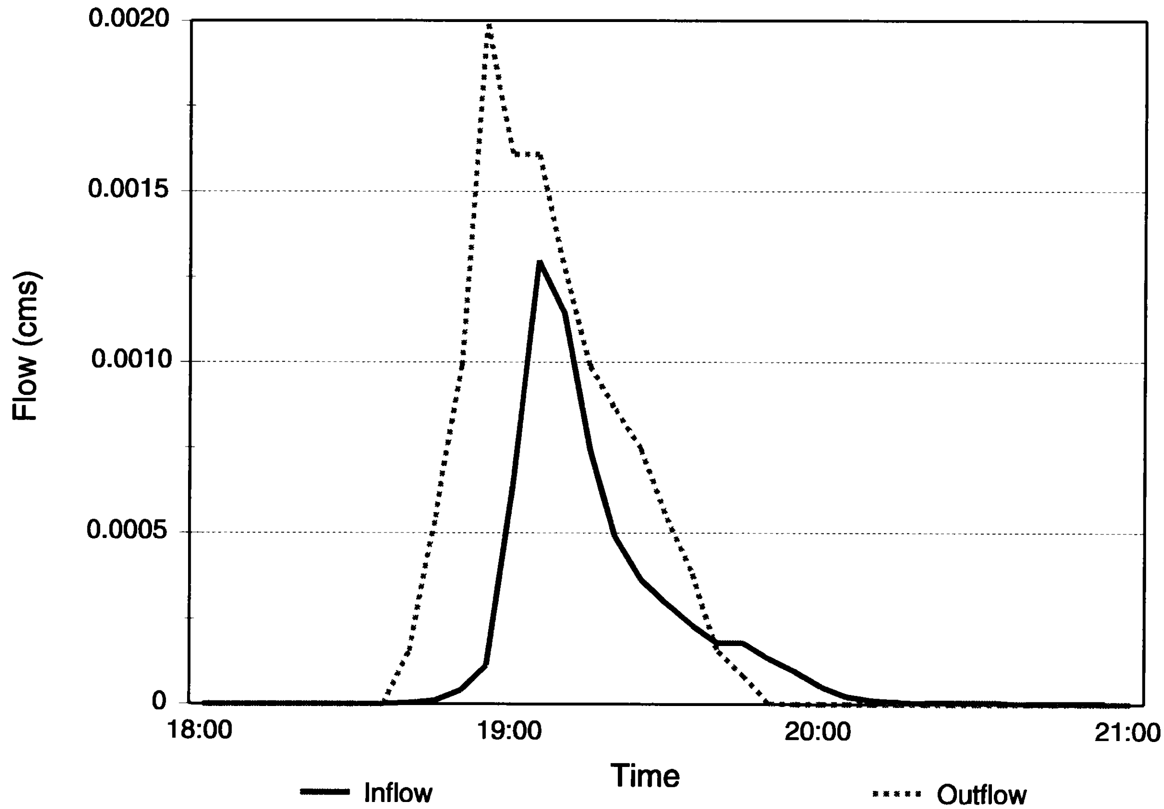

Figure A2. Flow data, 11-17-93 storm.

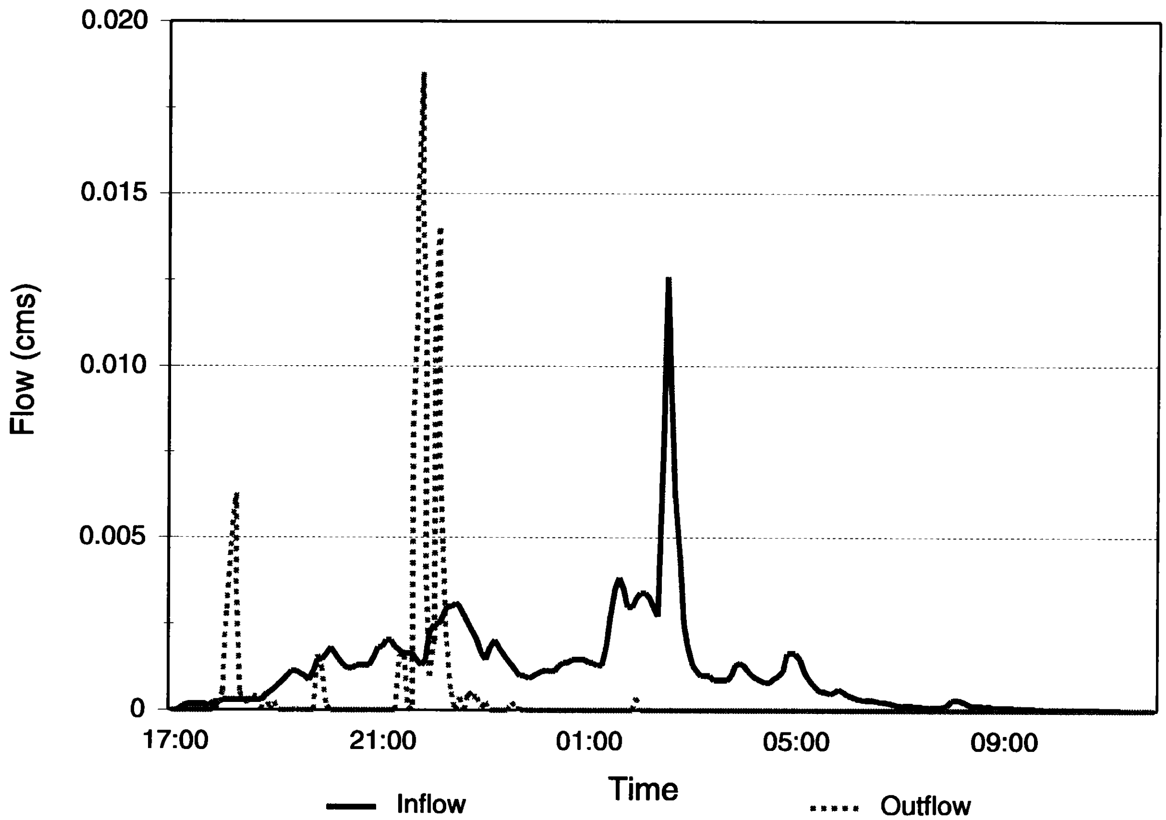

Figure A3. Flow data, 12-4-93 storm.

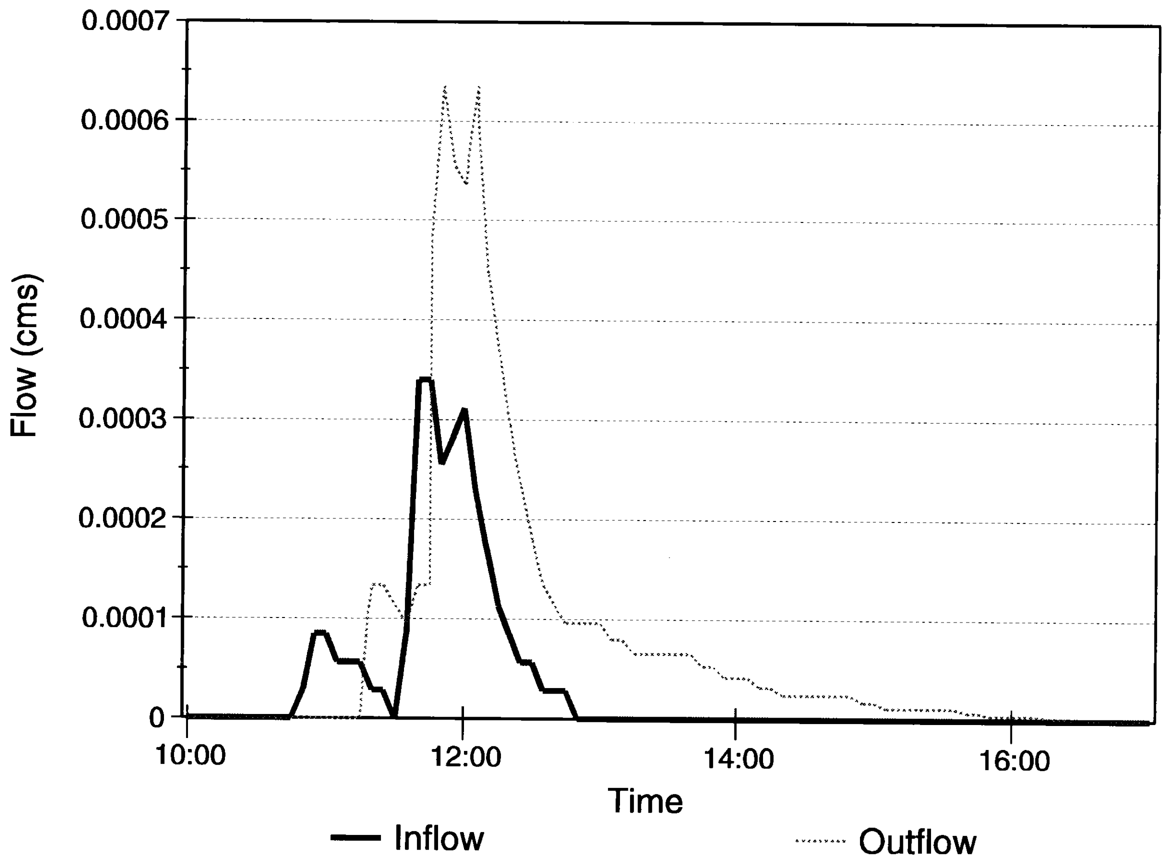

Figure A4. Flow data, 04-13-94 storm.

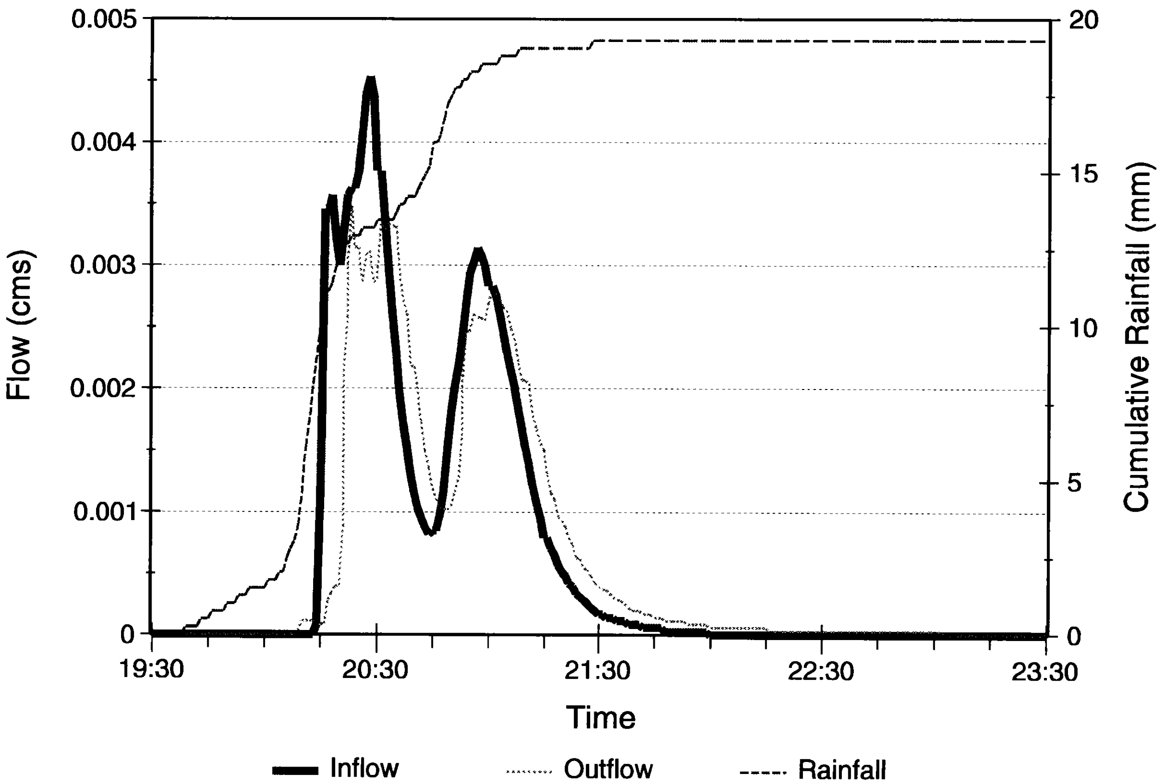

Figure A5. Flow and precipitation data, 07-17-94 storm.

APPENDIX B: DATA FROM BUFFER STRIP MONITORING

TABLE B1
OBSERVED POLLUTANT CONCENTRATIONS FROM MONITORED STORMS

TSS Concentrations (mg/l)

09-25-94				10-09-94				10-23-94			
EOP		Median		EOP		Median		EOP		Median	
Time	TSS	Time	TSS	Time	TSS	Time	TSS	Time	TSS	Time	TSS
16:40	65			17:09	220	17:15	35	04:56	40	05:45	35
20:09	205	20:22	41	17:38	180	17:44	21	05:40	18	06:29	25
		03:51	75	18:08	33			06:25	24	07:14	35
								07:10	20	07:59	19
								07:55	23	08:44	6
Avg:	135		58	Avg:	144.33		28	Avg:	25		24
% Change:			57.04	% Change:			80.60	% Change:			4

	Avg.	Max	Min
Inflow:	101.44	220	18
Outflow:	36.67	75	6
% Change:	63.86		

TABLE B1 (cont'd)

OBSERVED POLLUTANT CONCENTRATIONS FROM MONITORED STORMS

TP Concentrations (mg/l)

09-25-94			
EOP		Median	
Time	TP	Time	TP
16:40	1.5		
20:09	4.34	20:22	1.33
		03:51	1.99
Avg:	2.92		1.66
% Change:			43.15

10-09-94			
EOP		Median	
Time	TP	Time	TP
17:09	2.83	17:15	1.74
17:38	0.83	17:44	2.06
18:08	0.87		
Avg:	1.51		1.90
% Change:			-25.83

10-23-94			
EOP		Median	
Time	TP	Time	TP
04:56	1.2	05:45	4.2
05:40	0.85	06:29	1.79
06:25	0.24	07:14	1.52
07:10	0.07	07:59	1.94
07:55	0	08:44	2.46
Avg:	0.472		2.382
% Change:			-404.66

	Avg.	Max	Min
Inflow:	1.634	4.34	0
Outflow:	1.98	4.2	1.33
% Change:	-21.22		

TABLE B1 (cont'd)
OBSERVED POLLUTANT CONCENTRATIONS FROM MONITORED STORMS

ZN Concentrations (mg/l)

09-25-94				10-09-94				10-23-94			
EOP		Median		EOP		Median		EOP		Median	
Time	ZN	Time	ZN	Time	ZN	Time	ZN	Time	ZN	Time	ZN
16:40	0.75			17:09	1.01	17:15	0.11	04:56	0.52	05:45	0.04
20:09	0.77	20:22	0.06	17:38	0.28	17:44	0.06	05:40	0.32	06:29	0.03
		03:51	0.12	18:08	0.52			06:25	0.22	07:14	0.01
								07:10	0.13	07:59	0.02
								07:55	0.25	08:44	0.05
Avg:	0.76		0.09	Avg:	0.60		0.085	Avg:	0.288		0.03
% Change:			88.16	% Change:			85.91	% Change:			89.58

	Avg.	Max	Min
Inflow:	0.55	1.01	0.13
Outflow:	0.068	0.12	0.01
% Change:	87.59		