Testing of Roadside Vegetation for Highway Runoff Pollutant Removal

ROBERT J. KAIGHN, JR., AND SHAW L. YU

A field monitoring program was begun in 1991 to test the ability of grassed swales to remove pollutants from highway runoff. The two swales monitored had different slopes, traffic volumes, and vegetation heights, all of which can affect pollutant removal. One had a check dam, which proved to significantly influence pollutant removal. Also, the pollutant-removal ability of a short buffer strip was examined. Pollutants monitored included total suspended solids, chemical oxygen demand, total phosphorus, and total zinc. Manual and automatic sampling techniques were used to monitor runoff. The results suggest that properly designed short buffer strips and swales with check dams can remove pollutants from highway runoff.

This paper is the culmination of three years of research into the use of roadside vegetation for controlling highway runoff. In the early 1990s, regulations were passed requiring the Virginia Department of Transportation (VDOT) to control not only the quantity of runoff from highway projects, but also the quality of runoff. These regulations include the National Pollutant Discharge Elimination System (NPDES), the Chesapeake Bay Preservation Act, the Virginia Stormwater Management Act, and the Virginia Erosion and Sediment Regulations.

Two grassed swales on US-29 near Charlottesville, Virginia have been studied. Two reports on the swale north of Charlottesville (US-29N swale) were published: in 1993 (Phase I) (*1*) and 1994 (Phase II) (*2*). A third study published in 1995 (*3*) focused on the second swale, which is south of Charlottesville (US-29S swale). The second swale had different characteristics from those of the first swale. Also, the side slope vegetation on the grassed swale, acting as a buffer strip, was examined for its ability to remove highway pollutants.

Many studies have attempted to show the water-quality benefits of grassed swales, with varying degrees of success. Wang et al. (*4*) examined the retention of heavy metals by swales in Washington state. In that study, a grassed swale of 20 m had 60 percent lead removal, whereas a 60-m swale had 90 percent lead removal. Total suspended solids (TSS), volatile suspended solids (VSS), and chemical oxygen demand (COD) were also shown to be removed by grassed swales.

Several studies have also been conducted in Florida. Yousef et al. (*5*) examined two swales for heavy metal, phosphorus, and nitrogen removal. They found that removal efficiencies were dependent upon contact time and infiltration rates and that removal rates could be very significant, especially where infiltration rates are high. However, Oakland (*6*) examined a swale where infiltration rates were very low and also observed removal of pollutants.

Not all the literature is positive. Schueler et al. (*7*) observed 10 swales and found that only half of them had high-to-moderate removal, while the rest had insignificant removal or were actual sources of pollution.

Whatever the water-quality benefits derived from grassed swales, they do have some obvious advantages over the traditional curb-and-gutter system. They generally cost less, are more aesthetic, and are easier to maintain (*8,9*). They also increase the perviousness of highway drainage, possibly decreasing runoff volume. Curb-and-gutter systems tend to concentrate and quickly transport pollutants from the highway (*10*). A study by Lorant (*11*), conducted in Canada, compared the pollutant concentrations of highway runoff collected in both grassed and paved channels. On average, water-quality parameters were 63 percent lower in the grassed channel than the paved channel.

Many variables affect the removal of pollutants by grassed swales. Swale length, shape, slope, flow rate, type of vegetation, and infiltration rates are just some of the variables that might explain the inconsistencies reflected in the literature.

Buffer strips have also been shown to be effective at removing pollutants. Research projects on the ability of buffer strips to remove pollutants from agricultural runoff have been conducted. They have observed 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 percent and 70 percent removal of TSS for strip lengths of 9.1 and 4.6 m, respectively. Meyer et al. (*14*) found that stiff-grass hedges could remove 90 percent of coarse sediment (larger than 125 μm) and 20 percent of the finer sediment (smaller than 32 μm). Buffer strips have also been shown to remove other pollutants, including phosphorus, nitrogen, and COD from agriculture effluent (*12,15*). Yu et al. (1987) observed a buffer strip that received runoff from a shopping center parking lot. Average removal after the 45.7 m buffer strip was 71 percent for TSS, 38 percent for TP and 51 percent for zinc. Concentrations seemed to level off after flowing through only 21.3 m of the buffer strip. The buffer strips examined generally had very small flows compared to a highway-median swale.

MATERIALS AND METHODS

Site Description and Preparation

Two grassed swales on US-29, one located south of Charlottesville, Virginia (US-29S swale), and one north (US-29N swale), were monitored for their ability to remove highway pollutants. Table 1 summarizes the characteristics of the two swales.

The US-29N swale had a slope of around 5 percent, whereas the US-29S swale had a slope closer to 2 percent. The average daily traffic (ADT) of the 29N site was approximately 50,000. The 29S site had an ADT of approximately 30,000. Mowing was much more

Virginia Transportation Research Council, 530 Edgemont Road, Charlottesville, Va. 22903.

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

frequent at the 29N swale, occurring about once every 2 weeks during the growing season, while the 29S swale was mowed only four times during the season. These differences should have led to higher removal efficiencies for the 29S swale, according to the literature.

The two swale sites were arranged similarly. Both were 30 m in length and had lateral inflow barriers, so a mass balance between the two sampling points could be performed. Tipping bucket rain gauges were used to measure rainfall depth and intensity, and automatic sampling equipment collected 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 in Figure 1. 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 as a berm, or check dam, which is recommended to help pollutant removal. However, VDOT did not want to use check dams in their roadside swales because of potential maintenance problems, particularly with mowing. Therefore, the 29S site (Figure 2) was modified to eliminate the check dam at the downstream end.

The weir was located 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 a polyvinyl chloride (PVC) pipe to collect runoff. Because the weir was placed in a concrete channel, ponded stormwater could not infiltrate.

After eight storms were sampled, the focus was switched from the grassed swale to the strip of vegetation (buffer strip) through which stormwater flowed before reaching the swale channel. Runoff was sampled at the end of the curb and gutter on one side of US-29, after the runoff had flowed through the vegetation in the median and before it flowed into the concrete channel. This buffer strip site is slightly south of the US-29S swale site.

Flow at the end of the curb and gutter (representing the edge of pavement) was collected from the outside southbound lane of U.S. Route 29. Runoff was sampled using half of a PVC pipe and an automatic sampler (Figure 3).

FIGURE 1 US-29N site.

FIGURE 2 US-29S site.

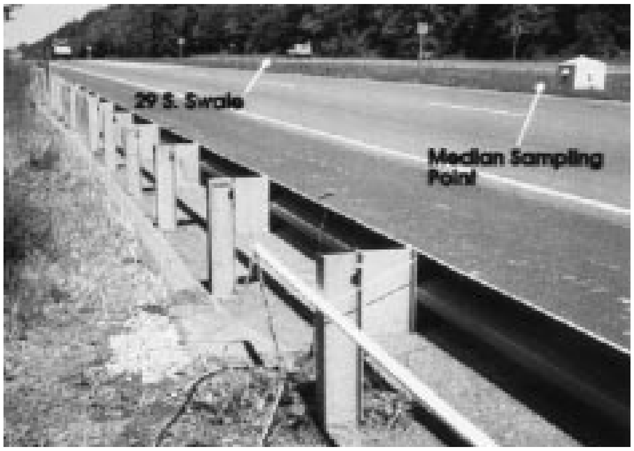

FIGURE 3 US-29S edge-of-pavement site.

Runoff that had flowed through the 3-m buffer strip was collected again, using half 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 site configuration is shown in Figure 4.

Sample Analysis

Runoff samples were collected using automatic samplers at the analysis points. The samples were taken to the Stormwater Laboratory at the University of Virginia, where they were analyzed for TSS, 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 the mass of pollutants flowing in and the mass of pollutants flowing out. 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. Flow through the vegetated buffer strip was not measured; removal percentages are derived from the change in concentration only.

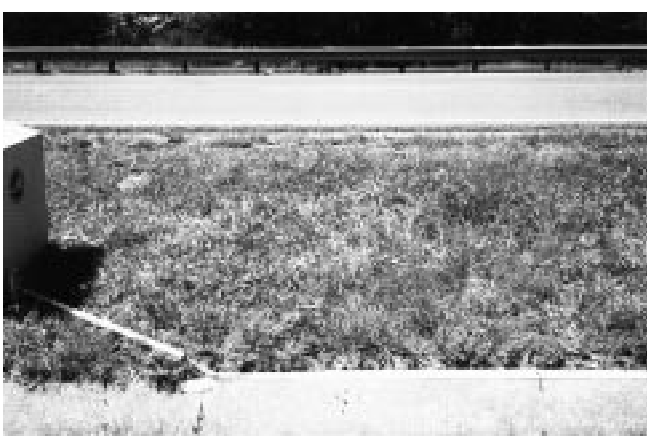

FIGURE 4 US-29S buffer strip collection point.

RESULTS

Precipitation

Surface runoff flow into the 29S swale required approximately 7 mm of rainfall. This is slightly higher than the 5 mm 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 the pavement monitoring site, illustrating its impervious drainage area.

Monitored Parameters

Examples of the data from the swale monitoring are shown in Figures 5 and 6. Observed inflow and outflow of the 29S swale, along with the observed precipitation for a storm, are shown in Figure 5. The concentrations of the four pollutants monitored in this study are shown in Figure 6.

Swale Pollutant Removal

Pollutant removal efficiencies for the swales are shown in Table 2. The eight storms shown were chosen because there was a positive flow loss through the swale. The surface flow doubled during several of the other observed storms, most likely because the lateral barriers were not working, and consequently a mass balance between the inflow and outflow points would not be valid. Removal efficiencies based on concentration only also were calculated:

		Removal Efficiencies Based on Concentration (%)			
Site	*Number of Storms*	*TSS*	*COD*	*TP*	*Zn*
US-29N	12	49	3	33	13
US-29S	8	29.7	–5.6	–0.4	11.1

To better characterize the pollutants, one sample from the 29S site was analyzed to see how much pollutant was in a dissolved form. For COD, 55 percent of the pollutant was dissolved; 58 percent of the TP was dissolved, and 90 percent of the Zn was dissolved (by definition, none of the TSS is in a dissolved form).

Buffer Strip Pollutant Removal

Table 3 shows the removal percentages on a concentration basis (flow was not observed) between the edge of the pavement and after the runoff had flowed through the buffer strip for three storms. Also, the overall average removal for each pollutant is shown.

DISCUSSION

29S Swale Results

As previously mentioned, the characteristics of the 29S site suggested that removal efficiencies should have been higher there than at the 29N site, which they were not. The pollutant removal percentages are all less than 30 percent (23.3 percent, 29.8 percent,

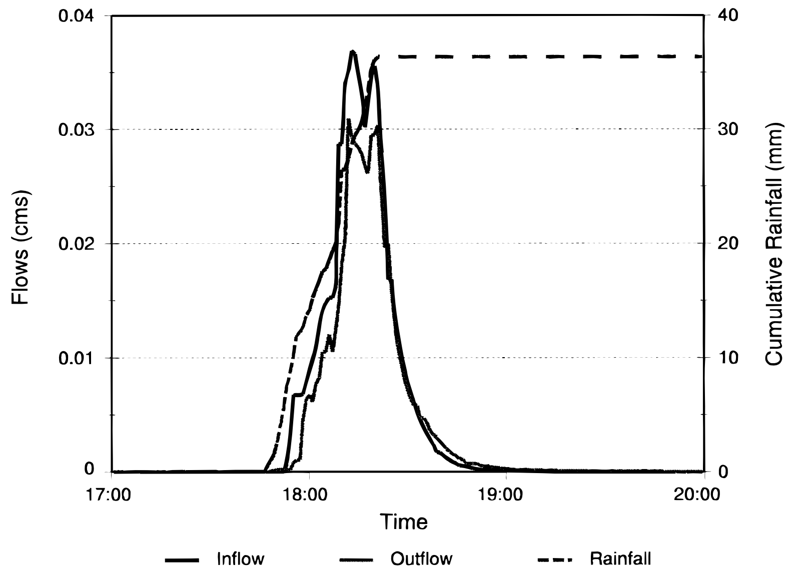

FIGURE 5 Observed inflow, outflow, and precipitation of US-29S site (7-23-94 storm).

11.0 percent, and 17.8 percent for TSS, COD, TP, and Zn, respectively) for the 29S swale, which is significantly less than the 80 to 90 percent removal observed at the 29N swale. 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 led to significant pollutant reductions. This flow loss was most likely a consequence of the downstream weir.

If flow is ignored and only pollutant concentration is examined, the 29N swale also performed better. The decreases in concentration of the four pollutants at the 29N site were: 49 percent, 3 percent, 33 percent, and 13 percent for TSS, COD, TP, and Zn, respectively. The decreases in concentration at the 29S site were: 29 percent, –6 percent, –0.4 percent, and 11 percent for TSS, COD, TP, and Zn, respectively. Obviously, the check dam significantly increased pollutant removal by allowing pollutants to settle.

Infiltration of all the runoff is one way to remove 100 percent of pollutants. Several of the smaller storms (less than 7 mm in depth) would fall into this category at the 29S swale site. The 29N swale required approximately 5 mm of rainfall to generate surface flow through the swale, because its drainage area was slightly more impervious.

Swale Length and Pollutant Removal

To develop a relationship between swale length and pollutant removal, a literature search was conducted. Eight different swales that monitored Zn for various lengths were found. The data were regressed. Figure 7 shows the data points from various studies, along with the regressed curve, for which the equation is

$$R_{ZN} = 8.302\ D^{0.50} \quad (1)$$

where D is the length (m), and R_{ZN} is the zinc removal (percent). The scatter of data points and the regression coefficient of 0.40 illustrate 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 the removal of pollutants.

29N Buffer Strip Results

The motivation for examining the buffer strip through which the runoff flows before reaching the swale came from an examination of the pollutants entering the swales. Pollutant concentrations entering the 29N swale were significantly lower than those observed in an edge-of-pavement study done adjacent to the 29N site (*1*). This edge-of-pavement study had results similar to those of a study reported by FHWA (*16*). Observed pollutant concentrations from the edge-of-pavement studies and the 29N and 29S swales are compared in Table 4. The table shows that both the average concentrations and the range of the concentrations from the edge-of-pavement studies generally are higher (and sometimes significantly higher) than what was observed in the swales.

These observations suggested that significant pollutant removal was occurring before the stormwater reached the swale. One of the samples from the 29S swale was analyzed to see how much pollutant was dissolved. COD and TP were found to be 50 to 60 percent dissolved, and Zn was found to be 90 percent dissolved. This does not correspond to published literature. Highway runoff is believed to be in a suspended form and not a dissolved form (*17*). The percentage of street pollutants associated with particles greater than 43 μm, and thus not dissolved, generally is reported as greater than 75 percent (Table 5). This did not agree with this study's observations. 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 were more difficult to remove (being associated with smaller particles or in dissolved form), which is reflected in the results of the swale monitoring. Therefore, the project's focus was modified to examine the vegetated buffer strip through which the runoff from the roadway must flow before entering the swale.

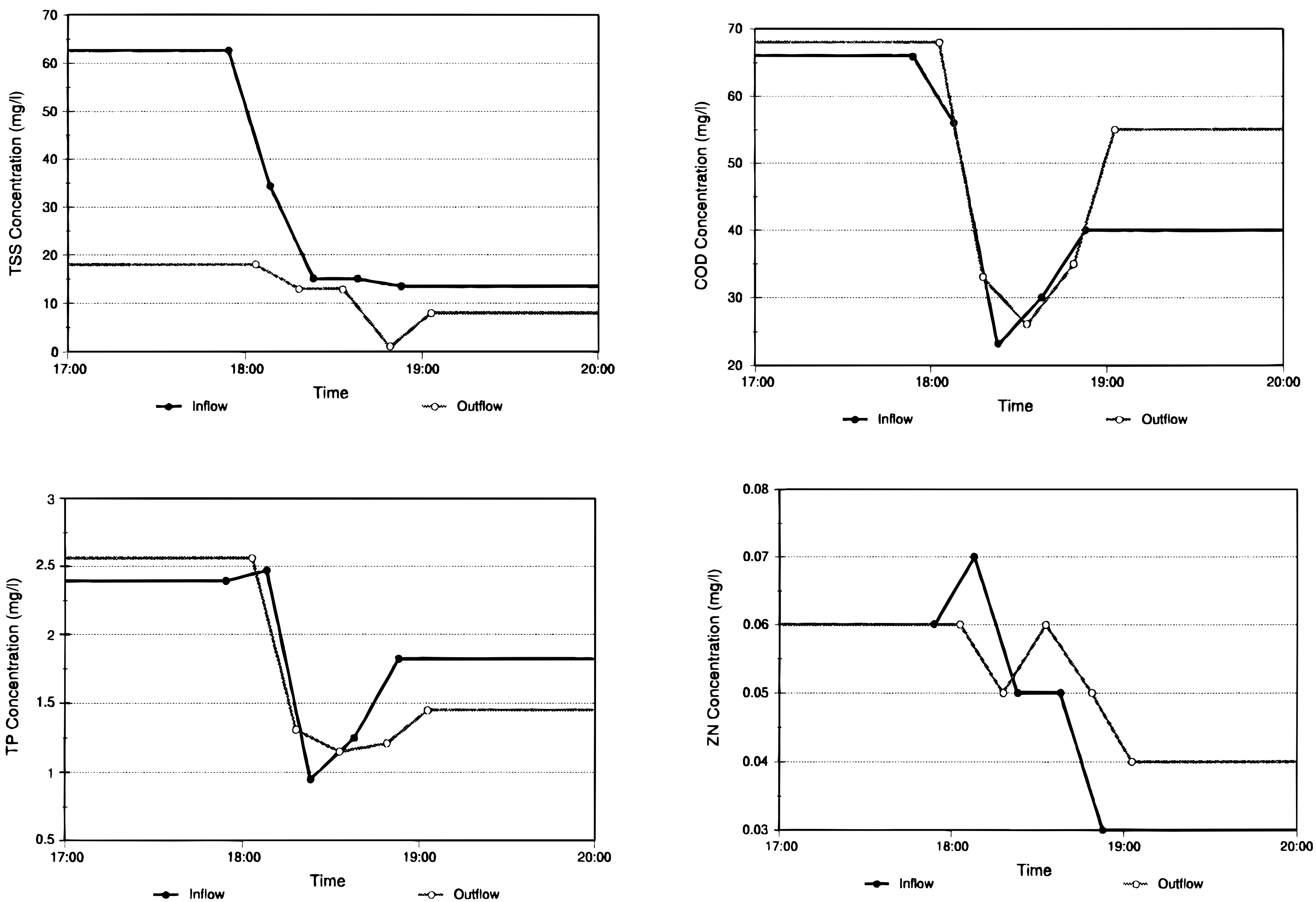

FIGURE 6 Concentrations of four pollutants at US-29S site (7-23-94 storm).

TABLE 2 Removal Percentages for Swales

	Percent Change in Mass[1]				
Location	TSS	COD	TP	ZN	Flow
29N	89	88	92	88	88
29N	100	100	100	100	100
29N	73	81	94	89	85
29N	86	67	80	58	83
Avg.	87	84	91.5	83.8	89
29S	-4.1	-27.8	-14.9	12.3	6.5
29S	57.4	54.9	55.6	35.4	63.7
29S	7.9	-1.5	5.9	5.1	4.6
29S	57.9	18.5	24.8	25.0	18.3
Avg.	23.3	29.8	11.0	17.8	19.5

[1] Negative values represent an increase of constituent in the swale.

TABLE 3 Removal Percentages for US-29S Buffer Strip

Storm	Pollutant			
No.	TSS	COD	TP	ZN
1	57.0	88.8	43.5	88.2
2	80.6	74.3	-25.8	85.9
3	4	45	-404.7	89.6
Avg.	63.9	59.3	-21.2	87.6

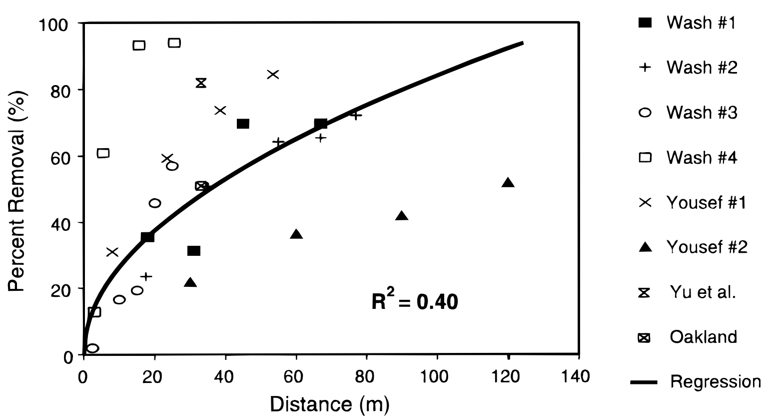

FIGURE 7 Regression curve showing relationship between swale length and zinc pollutant removal.

TABLE 4 Comparison of Pollutant Concentration from Edge-of-Pavement and Swale Studies

Pollutant	FHWA[16]		29 N Edge of Pavement[1]	
(mg/l)	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	29 N Swale Inflow[2]		29 S Swale Inflow [3]	
(mg/l)	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

Removal percentages for the buffer strip (Table 3) give good results for TSS, COD, and Zn, which generally are in suspended form. TP showed inconsistent results; a smaller percentage of TP is associated with suspended particles. Pollutants associated with larger particles appear to be easily removed by the vegetated buffer strip.

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

The sedimentation process depends on flow characteristics and particle size. Gravity is the main sedimentation force, and larger particles settle more easily. Large, turbulent flows can carry larger particles. The shallow, laminar, overland flow in a buffer strip cannot carry the larger particles, and they settle. Modeling of sedimentation in vegetated filters has been performed by Tollner et al. (*18*). Buffer strips designed with small flows and flat slopes, slowing the runoff, should promote sedimentation and infiltration.

Overall, 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 from it was not observed. 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, because they were 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 best management practices (BMP) handbooks as a very important parameter in judging the efficiency of different BMPs. It also leads to smaller flows through the buffer strip.

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

CONCLUSIONS AND RECOMMENDATIONS

Two swales were monitored for their ability to remove pollutants from highway runoff. Although several factors could have affected their ability to remove pollutants, the most important seems to be a check dam at the downstream end. The swale monitored with the check dam substantially outperformed the swale without, removing more than 80 percent of the monitored pollutants compared with less than 30 percent removal at the swale without the check dam. Use of a check dam improves pollutant

TABLE 5 Percentage of Highway Pollutants Associated with Larger Particles [Adapted from Bell (*17*)]

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

removal by allowing pollutants to settle and by increasing infiltration. Unfortunately, check dams can interfere with highway maintenance. If the check dam could be placed at a drop inlet in a swale, it would interfere less.

Swales have definite advantages over curb-and-gutter systems. They generally have lower construction and maintenance costs and are more aesthetically pleasing. Moreover, storm water from smaller storms can be completely absorbed by the swale. In this study, the 29S site absorbed 7 mm and the 29N site absorbed 5 mm, whereas 1 mm of rainfall would generate runoff at the edge of the pavement. This absorbing of runoff also leads to a reduction in the first-flush volume.

Highway runoff is characterized by pollutants in suspended form, which are easily settleable. A large percentage of these particles can be removed by a short buffer strip. A buffer strip of 3 m removed large percentages of TSS, COD, and Zn, which generally are in suspended form in highway runoff.

A well-designed buffer strip and swale-with-check-dam system should be able to remove significant amounts of pollutants and should be used instead of a curb-and-gutter-system. Pollutants can be removed through sedimentation and infiltration, which should be promoted in the design. Mild slopes, dense grass, small flows, and ponding of storm water should be used to improve the removal of pollutants.

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