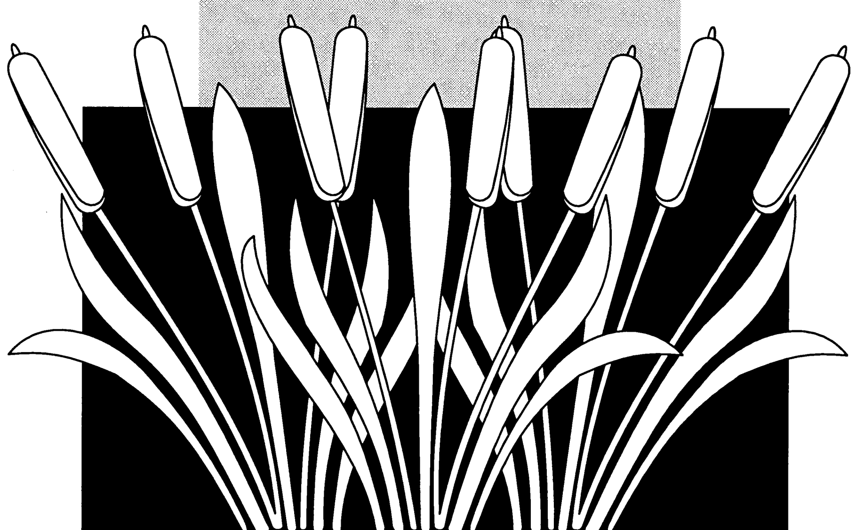
FINAL REPORT

THE CONTROL OF POLLUTION IN HIGHWAY RUNOFF THROUGH BIOFILTRATION

VOLUME I: EXECUTIVE SUMMARY



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16. Abstract

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ABSTRACT

Biofiltration is the process of filtering polluted water through vegetation to remove pollutants. Pollutants may be removed through settling, infiltration, and adsorption to sediment and vegetation. This report summarizes the findings of three parallel studies into the use of biofiltration to remove pollutants from highway runoff. A grassed swale and buffer strip were examined for their ability to remove pollutants including total suspended solids (TSS), chemical oxygen demand (COD), total phosphorus (TP), and zinc (Zn). Secondly, laboratory tests of some wetland species determined their ability to remove these pollutants from highway runoff. Finally, rainfall-runoff data collected at the grassed swale and other sources were used to examine the applicablity of several hydrologic methods to very small watersheds. The results of these parallel studies contribute to an understanding of biofiltration and stormwater runoff management.

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THE CONTROL OF POLLUTION IN HIGHWAY RUNOFF THROUGH BIO-FILTRATION

VOLUME I: EXECUTIVE SUMMARY

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INTRODUCTION

In the early 1990s, regulations were passed requiring the Virginia Department of Transportation (VDOT) to control the quality of runoff from highway projects, as well as the quantity. A project entitled "Stormwater Management and the VDOT" followed, and a stormwater management manual was created.[1] Research projects were undertaken to test these practices and develop design guidelines.

Grass and marsh plants slow down the velocity of runoff and enhance the settling of sediment-bound pollutants. Vegetation also removes dissolved pollutants as nutrients through plant uptake. The technique of using natural vegetation to treat runoff is called biofiltration. Since grassed swales and roadside ditches are part of highway drainage systems, it would be most cost-effective to consider using biofiltration as a stormwater best management practice (BMP).

As reported in Volume II of this study, summarized below, Yu and Kaighn[2] selected a grassed swale on U.S. Route 29 south of Charlottesville. The side slope vegetation on the swale, acting as a buffer strip, was examined for its ability to remove highway pollutants. A grassed swale on U.S. Route 29 north of Charlottesville, Virginia, was studied previously.[3,4]

In Volume III of this report, also summarized below, Yu and Liao reported the results of an experimental study of marsh plants.[5] Laboratory "bucket" wetland systems were constructed and planted with three different wetland plant species: bulrush, cattail, and reed. Wetlands are sinks for many pollutants, especially nitrogen and phosphorus. For decades, constructed wetland systems have been used to treat municipal and industrial wastewater and are considered to be more cost-effective than advanced wastewater treatment systems. However, using natural or constructed wetlands for controlling stormwater pollution has only recently been considered. Wetlands constructed within the right-of way, in median strips, in cloverleafs, etc., can be designed to provide a specific residence time and control highway runoff.[6] A second part of the wetland study documented existing mitigation wetland sites constructed by Virginia Department of Transportation (VDOT). Information on the sites was analyzed and certain sites were visited to prepare a list of potential sites for a full-scale field monitoring study, to be initiated in 1995.

Due to an increase in the number of designs for hydrologic structures for small watersheds, the Virginia Department of Transportation needs to determine methods for analyzing flow and time of concentration on very small watersheds. Because data was collected from small watersheds for the swale research, different hydrologic methods were tested using data collected in this and previous VTRC studies, along with data from other sources.

Three of the most important variables in hydrologic design are peak flow, volume of runoff, and time of concentration. Accurate methods for determining peak flow ensure that a structure can handle the runoff resulting from a storm. The volume of runoff is essential in designing detention facilities. McCuen et al. (1984)[7] state that as much as 75 percent of the error in estimating peak flow results from errors in computing the time of concentration. The Rational method, arguably the most widely used hydrologic design tool, is highly dependent on accurate estimates of the time of concentration for accurate estimates of peak flow.

The research in small watershed hydrology[8] summarized below was intended to provide designers with an overview of several available methods for calculating time of concentration, peak flow and the corresponding volume of runoff for small watersheds less than 81 hectares (200 acres) in size. Various methods were compared. Finally, the Virginia Time of Concentration Program (VIRTOC) was developed to allow the user to calculate time of concentration and peak flow for small watersheds in Virginia.

PURPOSE AND SCOPE

The objectives of the studies summarized here[2,5,8] were to:

1. Field test biofiltration by roadside vegetation as a BMP for controlling highway runoff;

2. Use bucket wetlands to study nutrient dynamics for given detention times and pollutant loadings, compare the relative pollutant removal efficiency of cattails, reeds, and bulrushes, and develop a plan for the full-scale field monitoring of a VDOT mitigation wetland site in Virginia;

3. Determine the applicability of various methods for calculating time of concentration and peak flow for very small watersheds in Virginia, and develop a stand-alone computer program to calculate the peak flow for a design storm using the Rational method which

gives the user several options for the determination of the Rational method variables;

4. Develop design guidelines to be incorporated in VDOT's *Stormwater Management Manual*, and continue to update the manual with new information on BMP design, VDOT recommendations, and information from other agencies such as the Federal Highway Administration (FHWA), other state departments of transportation, etc.

MATERIALS AND METHODS

Roadside Vegetation Site Description and Preparation

A grassed swale on U.S. Route 29 south of Charlottesville, Virginia, (29S swale) was monitored for its ability to remove highway pollutants.[2] This site was chosen for several reasons. Aside from its proximity to Charlottesville, the characteristics of the 29S swale contrasted those of the swale monitored in our previous monitoring at the swale on U.S. Route 29 north of Charlottesville (29N swale).[3,4]

The 29N swale had a slope of around 5%, whereas the 29S swale had a slope closer to 2%. The Average Daily Traffic (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 lead to higher removal efficiencies for the 29S swale, according to the available 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.

The downstream weir at the 29N site ponded a significant amount of stormwater, creating a small detention pond where pollutants were allowed to settle and runoff was allowed to infiltrate. This functioned like 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, so the 29S site was modified to eliminate the check dam at the downstream end.

After eight storm events were sampled, the focus was switched from the grassed swale to the strip of vegetation (buffer strip) that stormwater 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 3 m of vegetation in the median, before flowing into the concrete channel. This second site is slightly south of the 29S swale site. Flow was not measured.

The water quality parameters monitored were: total suspended solids (TSS); chemical oxygen demand (COD); total phosphorus (TP); and Zinc (Zn). Removal rates were calculated based on a mass flux basis, and also on a concentration basis.

Bucket Wetland Experimental Design

Four experimental buckets, batch-type, wetland systems were installed in the University of Virginia Environmental Engineering Laboratory. Each system consists of a 10-liter plastic bucket filled with 12 kg of washed gravel (3-7 mm dia.) as substratum. The surface area and the water depth of the bucket were 0.0434 m^2 and 0.2 m respectively. Cattails, reeds and bulrushes were planted directly into the substratum. One bucket system was not planted and was used as the control.

The water quality parameters monitored were: total suspended solids (TSS); chemical oxygen demand (COD); total phosphorus (TP); orthophosphate (OP); and Zinc (Zn). These water quality parameters were chosen because they are commonly found in highway storm runoff, and are likely to be present in high concentrations.

Stormwater runoff and primary and secondary wastewater samples spiked with stock Zn solution (1000 mg/l as Zn before dilution) were fed to the bucket wetlands. The stormwater runoff samples were taken from the 29S highway median swale site described above. The primary and secondary wastewater samples were from the Rivanna Wastewater Treatment Plant. Detention times of 1, 5, 7, 14, and 21 days were used to assess COD, TP, OP, and Zn dynamics and removal.

Parameters such as conductivity, redox potential, and pH were monitored constantly. The water depths were kept constant and recorded. Water quality parameters, including TSS, COD, OP, and TP in the water column, were monitored on days 1, 5, 7, 14, and 21 of the experiments. Samples were regularly collected at the inlet and outlet locations of the bucket wetlands. Pollutant removal rates were calculated from the difference in concentrations of pollutants between the initial values and values obtained after a given time interval.

The pollutant storage in the system was divided into three components: water column, substrate, and plant. The component analysis was based on a simplified nutrient system described by Kadlec.[9]

Laboratory Analysis of Water Samples

All water samples were analyzed according to the EPA-approved standard methodology or Hach's modified testing procedures.[10, 11] TSS was detected by filtration and drying to constant weight at 103-105° C. COD was analyzed by reactor digestion followed by colorimetric determination. TP was analyzed by the acid persulfate digestion method and followed by molybdate colorimetric determination.

Small Watershed Hydrology Methods

The methods available for calculating the time of concentration, T_c, for a watershed can be divided into three categories: overland, channel and mixed methods. Overland flow methods calculate the time of travel for overland flow and channel flow methods are used for calculating the time of travel through channels. Mixed methods can handle overland flow, channel flow and sometimes pipe flow. For mixed methods the time of travel for each type of flow is found separately and then combined to determine the time of concentration.

The analysis summarized here[8] compared the time of concentrations calculated by different methods for the 2, 10 and 25 year storms. The overland flow methods compared were the Kinematic Wave, Papadakis-Kazan, SCS Curve Number, sum of sheet and shallow concentrated flow for the TR-55 method, SCS Average Velocity and Seelye methods. For channel flow, the methods compared were the Kirpich, Manning and SCS Grassy Waterway methods. Finally, combinations of the overland flow and channel flow method results were compared to the SCS TR-55 procedure. Table 1 gives an overview of the information required to use each of the methods in this analysis for calculating time of concentration.

This analysis focused on comparing four methods of calculating peak flow and the runoff hydrograph. The methods included the Rational method, Snyder unit hydrograph, SCS dimensionless unit hydrograph and the TR-55 procedure. Table 2 shows the methods for calculating peak flow and the variables required for each method.

The comparative analysis used watershed data from seven watersheds in Maryland and Virginia ranging in size from 0.2 hectares to 46 hectares (0.5 acres to 114 acres). A detailed description of time of concentration equations, peak flow methods, watershed locations, and data collection can be found in O'Flaherty.[8]

Table 1: METHODS FOR ESTIMATING TIME OF CONCENTRATION

Time of Concentration Method	Kinematic Wave	Papadakis-Kazan	SCS Curve Number	SCS Average Velocity	Seelye	Kirpich	Manning	SCS Grassy Waterway	SCS TR-55
Type	O	O	O	O	O	C	C	C	M
Variables Required									
Length (L)	X	X	X	X	X	X	X	X	X
Manning's n	X	X					X		X
Intensity (i)	X	X							
Slope (%)	X	X	X		X	X	X	X	X
Curve Number (CN)			X						
Velocity (V)				X					X
Hydraulic Radius (R)							X		X
2-Year Rainfall									X
Rational C					X				

O - Overland Method; C - Channel Method; M - Mixed Method

Table 2: METHODS FOR ESTIMATED PEAK FLOW

Peak Flow Method	Rational	SCS Dimensionless	Snyder	TR-55
Variables Required				
Area	X	X	X	X
Rainfall Duration		X	X	24 hrs
Watershed Length		X	X	
Intensity	X			
Runoff Adjustment (C, CN, Ct...)	X		X	X
Time Variable			X	X

RESULTS

Roadside Vegetation

Eight storm events were monitored at the 29S swale site, with rainfall depths ranging from 11.7 to 36.3 mm and intensities ranging from 1.7 to 72.6 mm/hr. 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, and 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. Data for all the observed storm events are found in Volume II.[2]

For two storms, flow doubled between the inlet and outlet of the swale, which should have been impossible. If those storms are not included, average removal efficiencies calculated on a mass flux basis were: 23.3% for TSS, 29.8% for COD, 11.0% for TP, and 19.5% for Zn. Removal percentages calculated only on a concentration basis were: 29.7% for TSS, -5.6% for COD, -0.4% for TP, and 11.1% for Zn.

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 was in a dissolved form).

Three storm events were observed for the buffer strip monitoring. Average removal percentages calculated on a concentration basis were: 63.9% for TSS, 59.3% for COD, -21.2 for TP, and 87.6 for Zn.

Bucket Wetlands

Data was collected for the bucket wetlands fed with both stormwater runoff and wastewater. Table 3 compares the ranges and averages of pollutant concentrations of stormwater runoff and wastewater. Zn concentration was originally low (0.07-0.25 mg/l) in wastewater. To examine the dose response of the vegetation to potentially toxic Zn concentrations (5.9 mg/l), wastewater spiked with stock Zn solution (1000 mg/l as Zn before dilution) was fed to the wetlands.

The stormwater runoff samples were considered to be low in COD, TP, OP, and Zn, with average concentrations of 37, 3.6, 2.8, and 1.8 mg/l, respectively, and the wastewater was considered to be high in COD, TP, OP, and Zn (after spiking), with average concentrations of 96, 15.7, 13.2, and 4.1 mg/l, respectively. Figure 1 shows mean pollutant removal rates versus time for the control, bulrush, and reed buckets.

Table 3: COMPARISON OF THE RANGES AND AVERAGES OF POLLUTANT CONCENTRATIONS OF STORMWATER RUNOFF AND WASTEWATER (Units: mg/l)

Types of Samples	TSS		COD		TP		OP		Zn	
	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range
Stormwater Runoff	55	45-65	37	23-50	3.6	2.8-5.3	2.8	1.2-5.1	1.8	0.07-5.1
Primary Influent	300		210		27.3		21.6		5.9*	
Primary Effluent	160		113		15.0		13.6		4.8*	
Secondary Influ-ent	100		38		13.6		10.8		2.8*	
Secondary Effluent	50		23		7.0		6.9		2.8*	

* Spiked.

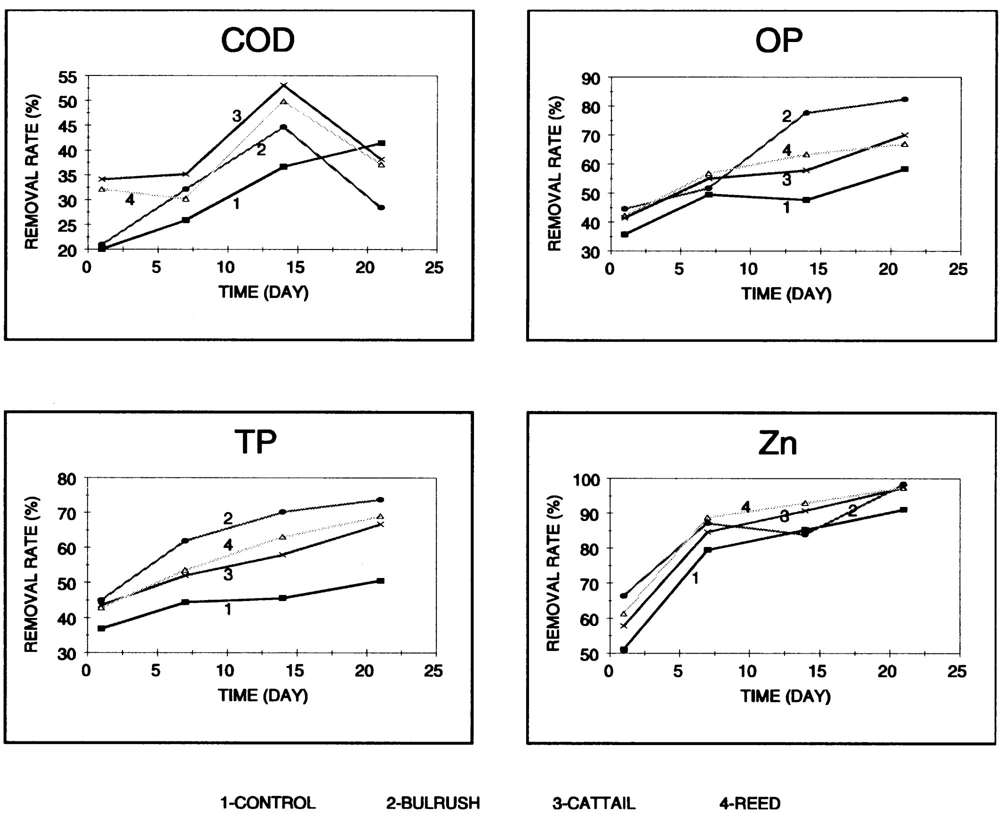

Figure 1. Mean pollutant removal rates versus time.

Small Watershed Hydrology

Complete results of the small watershed hydrology study are reported elsewhere.[8] Table 4 presents the results for the overland flow time of concentration method comparison. The results for the channel flow time of concentration methods appear in Table 5. Table 6 is a comparison of the time of concentration mixed method analysis.

Figure 2 shows the unit hydrographs developed for the Rt. 29N swale as an example of the unit hydrographs generated for each watershed. Figure 3 shows the results for the Rt. 29N watershed for the 10 year-1 hour storm as a typical example of the generated results.

The VIRTOC program was designed as a user-friendly tool for quickly and accurately calculating the peak flow for a given watershed. VIRTOC collects input and presents output in English or SI units. The user chooses the variables used in the Rational formula. The user may enter all of the required variables or choose to calculate the Rational runoff coefficient, time of concentration or intensity. The user may also calculate flow velocities corresponding to overland and channel flow. Finally, the user can print the results to an output file. VIRTOC's menu-driven format also allows the user to make changes in previous input values and recalculate the peak flow without leaving the program. VIRTOC is constrained by the assumptions of the Rational method, and should not be used for watersheds over 81 hectares (200 acres) in size. The program is valid only for storm durations between 5 minutes and 2 hours.[8]

Table 4: OVERLAND FLOW TIME OF CONCENTRATION RESULTS

Watershed	Ground Cover	Percent Imperv. (%)	Kinematic Wave 2 yr. (min)	Papadakis-Kazan 2 yr. (min)	SCS Curve Number (min)	TR-55 Sum Overland (min)	Seelye nomo (min)	SCS Average Velocity (min)
Baltimore, MD	grassed	52	34.01	11.56	16.19	13.06	15.50	5.06
Four Seasons 1	grassed	30	90.40	22.08	17.97	27.53	19.50	6.11
Four Seasons 2	grassed	30	39.14	11.04	6.21	21.11	11.20	1.97
I-95	paved	40	17.35	6.61	9.23	12.78	10.80	2.87
Massie Road	paved	77	3.71	1.90	4.89	2.52	7.90	1.75
Rt. 29 N Swale	paved	62	1.64	0.99	2.04	1.04	5.4*	0.47
Rt. 29 S Swale	paved	57	0.82	0.57	0.89	0.41	3.5*	0.15

* Extrapolated values.

Table 5: CHANNEL FLOW TIME OF CONCENTRATION RESULTS

Watershed	Ground Cover	Percent Imperv. (%)	Kirpich(min)	Manning (min)	SCS Grassy Waterway (min)
Baltimore, MD	paved	52	2.39	2.04	11.80
Four Seasons 1	grassed	30	5.47	10.88	4.24
Four Seasons 2	grassed	30	6.37	13.80	5.16
I-95	paved	40	0.16	0.10	0.36
Massie Road	paved	77	0.48	0.40	1.46
Rt. 29 N Swale	grassed	62	2.52	11.21	1.55
Rt. 29 S Swale	grassed	57	3.21	13.17	2.12

Table 6: MIXED METHOD TIME OF CONCENTRATION RESULTS

Watershed	Percent Imperv. (%)	SCS TR-55 2 yr (min)	SCS Avg. Vel. Manning (min)	Kin-Wave Kirpich (min)	Seelye Kirpich (min)	P-K Kirpich (min)	SCS CN Manning (min)
Baltimore, MD	52	15.10	7.09	36.41	17.86	13.96	18.22
Four Seasons 1	30	38.43	35.90	95.87	24.97	27.55	28.85
Four Seasons 2	30	34.95	38.92	45.51	17.57	17.42	20.00
I-95	40	14.14	2.97	17.51	10.96	6.77	9.33
Massie Road	77	2.92	2.16	4.20	8.38	2.38	5.30
Rt. 29 N Swale	62	12.26	11.67	4.16	2.52	3.51	13.25
Rt. 29 S Swale	57	13.61	13.31	4.02	3.21	3.78	14.06

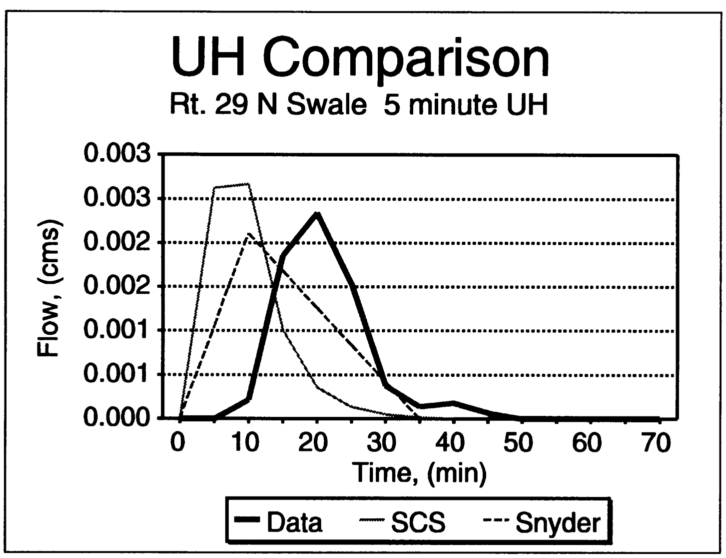

Figure 2. Rt. 29N unit hydrograph comparison.

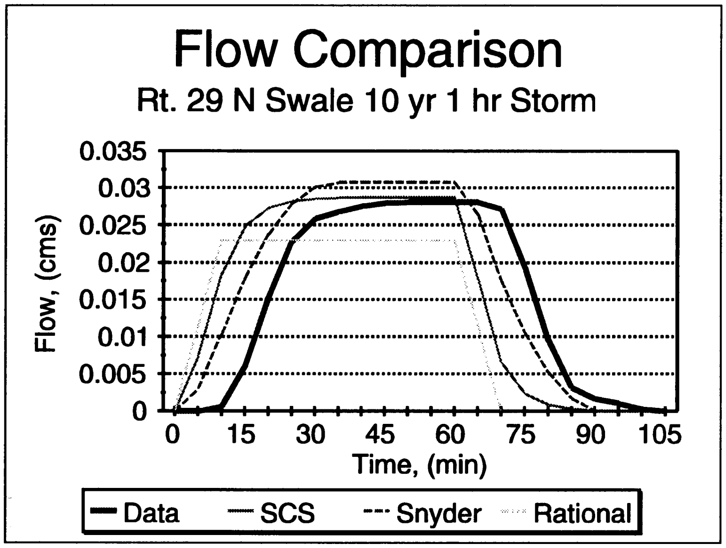

Figure 3. Rt. 29 N 10 yr.-1 hr. storm comparison.

DISCUSSION

Roadside Vegetation

Judging from the characteristics of the 29S site, its removal efficiencies should have been higher than the 29N site, but they were not. If the storms where the flow increased are omitted, the pollutant removal percentages at the 29S site are all less than 30 percent (23.3%, 29.8%, 11.0%, and 17% for TSS, COD, TP, and Zn, respectively), significantly less than the 80-90% 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 led to significant pollutant reductions. We can only assume that this flow loss was a direct consequence of the downstream weir. Moreover, if flow is ignored, and only pollutant concentration is examined, the 29N swale still performed better. Percent decrease in concentrations of the four pollutants at the 29N site were: 49%, 3%, 33%, and 13% for TSS, COD, TP, and Zn, respectively. The percent decrease in concentrations at the 29S 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.

The motive for examining the buffer strip through which the runoff flows before reaching the swale came from an examination of the pollutants entering the 29S swale. In Phase II of this study,[2] 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.[3] This edge-of-pavement study had results similar to an FHWA study.[12]

These observations implied that significant pollutant removal was occurring before the stormwater reached the swale. One of the samples from this study was analyzed to see how much of the pollutants was dissolved. COD and TP were 50-60% dissolved, and Zn was 90% dissolved. This does not correspond to reports in the literature. It is generally thought that highway runoff is in a suspended form, not a dissolved form. The percentage of street pollutants associated with particles greater than 43 μm, and thus not dissolved, is generally greater than 75%.[13]

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

Removal percentages for the buffer strip give good results for TSS, COD, and Zn, which are generally in suspended form. TP showed inconsistent results; a smaller percentage of TP is associated with suspended particles. Seemingly, pollutants associated with larger particles are easily removed by the vegetated buffer strip.

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 significant pollutant removal 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. 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.

Bucket Wetlands

The pollutant reductions observed in bucket wetlands are attributed to three main mechanisms: adsorption to the wash-gravel bed, plant uptake, and sedimentation. Since the pH of the synthesis storms remained neutral and redox potential was also stable, chemical precipitation was not a significant factor in this study.

Pollutant removal rates for the control, bulrush, cattail, and reed experiments were compared with values reported in the literature. Table 7 summarizes average removal rates for the four studied buckets and the values found in the literature, demonstrating comparable values. Retention times in this study ranged from 1 to 21 days. TSS removal is not a function of plant species, but is related to discrete particle settling following Stoke's law. For TP and OP, initial concentrations were 3.60 and 2.80 mg/l, respectively. After 14 days, average concentrations for both were reduced to about 1.00 mg/l and uptake of TP and OP was slowed. Ninety percent of TP is OP. The removal rate of TP is approximately ninety percent of OP. The main removal mechanism of phosphorus is in the OP forms, which is similar to Hanson and Westfalls' results.[14] For Zn, after seven days, the only removal mechanism in the control bucket is adsorption. The Zn removal rates in the bucket with vegetation were higher at seventh day and fourteenth day, but by twenty-first day the removal rate in the control was similar to the vegetated buckets.

It is also interesting to compare the removal rates between stormwater samples and wastewater samples. A comparison of average pollutant removal rates between stormwater runoff samples and wastewater samples for study buckets is shown in Table 8. Of the two samples, the results show lower COD removal rates and higher Zn removal rates in stormwater samples for all three types of vegetation. These results may be due to limited COD uptake at low concentration (14 mg/l). Similar results can be found in Green's study.[15] The three vegetated buckets tolerated a potentially toxic Zn concentration of 5.9 mg/l. However, lower Zn uptake at higher concentration (4.8 to 5.9 mg/l) in wastewater samples was observed.[5] McNaughton found similar results for cattails.[16]

Table 7: COMPARISON OF POLLUTANT REMOVAL RATES IN STORMWATER WETLANDS (%)

Sources	TSS	COD	TN	TP	OP	Cu	Pb	Zn
Literature	43-90	0-40	21-54	17-65	N/A	0-80	0-80	0-80
Day 7								
Control	95	12	N/A	43	59	N/A	N/A	48
Bulrush	95	9	N/A	69	82	N/A	N/A	56
Cattail	95	5	N/A	63	74	N/A	N/A	66
Reed	95	2	N/A	63	74	N/A	N/A	70
Day 14								
Control	97	9	N/A	44	52	N/A	N/A	56
Bulrush	97	16	N/A	67	82	N/A	N/A	75
Cattail	97	9	N/A	70	77	N/A	N/A	81
Reed	97	21	N/A	75	80	N/A	N/A	82
Day 21								
Control	99	31	N/A	51	56	N/A	N/A	95
Bulrush	99	9	N/A	68	77	N/A	N/A	99
Cattail	99	39	N/A	73	78	N/A	N/A	99
Reed	99	37	N/A	70	76	N/A	N/A	98

Table 8: COMPARISON OF AVERAGE POLLUTANT REMOVAL RATES BETWEEN STORMWATER RUNOFF SAMPLES AND WASTEWATER SAMPLES (%)

Stormwater Samples	Control	Bulrush	Cattail	Reed
TP	41	66	62	63
OP	57	79	72	73
Zn	90	87	95	97
COD	21	10	17	23
Wastewater Samples				
TP	44	62	52	55
OP	47	68	51	55
Zn	70	83	77	81
COD	35	39	48	43

One-Way ANOVA Analysis

One-Way ANOVA analyses tested the significance of pollutant removal rates with respect to time and type of vegetation. For TP and OP removal, One-Way ANOVA showed that the presence of all three vegetation types was significant ($p < 0.05$) for day 21 and day 14, but only bulrush was significant for day 7. For Zn removal, One-Way ANOVA showed that the presence of both bulrush and cattail was significant ($p < 0.05$) for day 21, and both cattail and reed were significant for day 14. For COD removal, the presence of vegetation was insignificant for all the data.

The results suggest that bulrush is the most effective of these three plant species for TP and OP removal. However, cattail and reed were very effective for Zn and COD removal, respectively. For design consideration, the combination of bulrushes, cattails, and reeds is encouraged for the removal of various pollutants.

Small Watershed Hydrology

In examining the time of concentration results presented in Tables 4, 5, and 6, the Kinematic Wave equation generally gives the highest results. For more impervious watersheds, it seems to give results similar to the other methods. The SCS Average Velocity Method generally gives the lowest estimate of the time of concentration. For channel flow, Manning's Equation gave the highest estimates for grassed channels, and the lowest for paved, while the SCS Grassy Waterway Equation gave the highest for paved and the lowest for grassed. The Kirpich equation was generally between the other estimates.

The peak flow analysis demonstrated that the Rational Method gave estimates of peak flow within twenty percent error. For quick, preliminary designs, this may be acceptable, but if more accuracy is required, one of the other methods should be used.[6]

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. 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 settle easily.

3. Pollutant concentrations in highway runoff are reduced after flowing through a small buffer strip. Buffer strips of only a few meters can remove a significant amount of suspended pollutants.

4. In bucket wetland systems, the removal rate differential between vegetated buckets and control buckets is highest for OP and is lowest for COD.

5. TSS removal is not a function of plant species. The data shows a larger percentage (about 40%) of TP, OP, and COD associated with TSS than with Zn (20%). Sedimentation played a more important role for TP, OP, and COD than for Zn.

6. Detention time seemed important to pollutant removal. The average concentration versus time showed an increased removal of TP, OP, and Zn, but not COD as time increased. These results may be due to limited COD uptake at low concentration (14 mg/l).

7. In this study, the main removal mechanisms in the control bucket were sedimentation and adsorption, which is similar to a detention basin without vegetation. The results of these three vegetated buckets show better pollutant removal (except for COD at low concentration), which is a function of time and vegetation. The presence of wetland species should provide improved water quality and could allow the use of smaller basins.

8. The time of concentration analysis showed that the results of different methods for different watersheds may vary greatly. In general the Kinematic Wave equation gave the highest estimates and the SCS Average Velocity gave the lowest estimates for overland time of travel. The SCS Curve Number, Seelye, and Papadakis-Kazan methods gave similar estimates for more impervious watersheds. The Seelye nomograph did not accommodate highly impervious watersheds with very small flow lengths.

9. For channel flow, Manning's equation gave the highest estimates for grassed channels and the lowest estimates for paved channels. The results for the SCS Grassy Waterway were exactly the opposite of the Manning's results. The Kirpich equation was consistently the middle estimate, though on the low side of the range.

10. The mixed methods showed that the time of concentration can be highly variable depending on which methods are chosen as a combination.

11. Comparison to the lag time available from literature for the Baltimore, MD watershed showed that the Papadakis-Kazan/Kirpich combination and the SCS TR-55 procedure most closely estimated the time of concentration when compared to data, with the Seelye/Kirpich and SCS curve number/Manning's combinations giving slightly overestimated values. The Kinematic wave/Kirpich combination greatly overestimated the watershed time of concentration.

12. An analysis of the variation of time of concentration to design storm frequency showed that the time of concentration decreased as storm frequency increased. However, for small watersheds the decrease in time may not be significant.

13. The analysis also showed that for very small watersheds the estimate of time of concentration may be under five minutes. The IDF curves are not clearly defined in the literature for a time of concentration less than five minutes. The choice of method may not be

important for these watersheds because the time of concentration must be rounded up to five minutes to find a rainfall intensity.

14. The flow analysis showed that the SCS Dimensionless unit hydrograph consistently out-performed the Rational method, TR-55 and Snyder method in estimating peak flow and volume of runoff. The Rational method was consistently within about 20 percent of the values estimated by data. Finally, TR-55 consistently overestimated the peak flow.

15. The VIRTOC program gives the designer quick and easy access to a choice of time of concentration methods and an preliminary analysis of a watershed from the Rational method.

RECOMMENDATIONS

1. Roadside vegetation removes suspended pollutants from highway runoff. 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, vegetated channels also cost less than paved channels. Checkdams could be placed near inlets to reduce maintenance problems.

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

3. Infiltration is a significant factor in pollutant removal. More study is needed to get accurate infiltration rates for design purposes. Infiltration was not examined in the buffer strip monitoring, and should lead to even higher pollutant removal percentages.

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

5. Continued research into different 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.

6. Bulrush was the most effective species for TP and OP removal of the three plants studied in bucket wetland systems. Cattail and reed were very effective for Zn and COD removal, respectively. For design consideration, the combination of bulrushes, cattails, and reeds is recommended for removal of various pollutants.

7. Further investigations of other plant species are desirable. The types of vegetation in this study (bulrush, cattail, and reed) seemed to improve water quality (especially for phos-

phorus and zinc removal). These wetland species provide a reliable and cost-effective material for highway stormwater runoff treatment. However, the reed used in this study is a very invasive noxious species that provides little habitat or other ecological benefit. It should be used cautiously with proper design and maintenance. The authors recommend that VDOT plant bulrushes and cattails in its mitigation wetlands in future field practice.

8. This study started with the hypothesis that bucket wetlands could provide water quality improvements to stormwater runoff and wastewater. We demonstrated that bucket wetlands can remove nutrients. Similar results might be derived from a field study. The field study should be monitored on both an acute and a long-term basis.

9. Ten wetland sites were visited as potential study locations. However, most were designed as impoundments, and no well-defined outlet structure could be found. It is difficult to balance water budget without a well-defined inlet or outlet. Another possibility is to monitor a stormwater basin colonized by wetland plants. More site visits are needed.

10. Particular care is needed in selecting a method for calculating time of concentration. The method should place the proper emphasis on the dominant type of flow for the watershed (overland or channel) and include adjustments to account for factors affecting the time of flow, such as roughness coefficients.

11. There are several methods for calculating time of concentration for very small watersheds with times of concentration under five minutes. The method used to calculate the time of concentration will not always make a significant difference, as the time must be rounded up to five minutes to find a rainfall intensity from the IDF curves.

12. The Rational method consistently gave estimates for peak flow within 20 percent error. The Rational method is an acceptable estimate of peak flow for a preliminary design. If a more detailed analysis is required, one should choose the SCS or Snyder methods.

13. TR-55 consistently overestimated the peak flow, indicating that it may be useful for conservative design based on peak flow. However, TR-55 should not be used to design flow detention structures, as the method consistently underestimates the volume of runoff.

14. Further research should include a more thorough comparison of time of concentration methods to data from the literature or to measured data.

15. Further research should include watersheds in other physiographic regions of the state, to ensure the usefulness of the design methods throughout Virginia.

16. Future modifications of VIRTOC should include additions to the built-in IDF data base, specifying the coefficients corresponding to Equation 17 for all counties in Virginia. The

program could be modified to include a hydrograph calculation for the Modified Rational method. This would give estimates of the volume of runoff for a design storm.

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REFERENCES

1. Yu, S. L. and Kaighn, R. J., Jr. 1992. *VDOT manual of practices for planning stormwater management*. VTRC Report No. 92-R13. Charlottesville: Virginia Transportation Research Council.

2. Yu, S. L., and Kaighn, R. J., Jr. 1995. *The control of pollution in highway runoffthrough biofiltration. II. Testing of roadside vegetation, phase III.* VTRC Report No. 95-R29. Charlottesville: Virginia Transportation Research Council.

3. Yu, S. L., Barnes, S. L., and Gerde, V. W. 1993. *Test of best management practices for controlling highway runoff.* VTRC Report No. 93-R16. Charlottesville: Virginia Transportation Research Council.

4. Yu, S. L., Kaighn, R. J., and Liao, S. L. 1994. *Test of best management practices for controlling highway runoff; Phase II.* VTRC Report No. 94-R21. Charlottesville: Virginia Transportation Research Council.

5. Yu, S. L., and Liao, S-L.1995. *The control of pollution in highway runoffthrough biofiltration. III. Laboratory test of marsh vegetation.* VTRC Report No. 95-R30. Charlottesville: Virginia Transportation Research Council.

6. Yu, S. L. 1993. *Stormwater management for transportation facilities.* National Cooperative Highway Research Program Synthesis of Highway Practice 174. Transportation Research Board. Washington, D.C.: National Research Council.

7. McCuen, R. H., Wong, S. L., and Rawls, W. J. 1984. Estimating urban time of concentration. *Journal of Hydraulic Engineering*, 110(7), 887-904.

8. O'Flaherty, C. E. 1995. *Hydrologic analysis of very small watersheds.* Masters Thesis. Department of Civil Engineering and Applied Mechanics, University of Virginia, Charlottesville, VA.

9. Kadlec, J. A. 1987. *Nutrient dynamics in wetlands.* Aquatic Plants for Water Treatment and Resource Recovery, ed. Reddy, K. R. and Smith, W. H., pp. 393-419. Orlando, Florida: Magnolia Publishing Inc.

10. APHA. 1989. *Standard methods for the examination of water and wastewater.* 17th edition. Washington D.C.: American Public Health Association.

11. Hach Company. 1993-1994. *Hach manual for water and wastewater examination, 1992-1993.* Loveland, Colorado: Hach Company.

12. Federal Highway Administration. 1984. *Sources and migration of highway runoff pollutants. Vol. 1: Executive summary.* Report No. FHWA/RD-84/057. Washington, D.C.

13. Bell, W. 1994. *Intermittent sand filter BMPs for stormwater quality.* Presented at the Engineers and Surveyors Institute's Stormwater Management Symposium, September 8, 1994.

14. Hanson, R. L., and Westfall, D. G. 1985. Orthophosphate solubility transformations and availability from dual applied nitrogen and phosphorus. *Soil Science Society of America Journal,* 49, 1283-1289.

15. Green, B. 1994. Constructed wetland are big in small communities. *Water Environment & Technology,* 6, 51-5.

16. McNaughton, S. J., Folsom, T. C., Lee, T., Park, F., Price, C., Roeder, D., Schmitz, J., and Stockwell, C. 1974. Heavy metal tolerance in typha latifolia without the evolution of tolerant races. *Ecology*, 55, 1163-1165.