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16. Abstract

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FINAL REPORT

TESTING OF BEST MANAGEMENT PRACTICES FOR CONTROLLING HIGHWAY RUNOFF

Shaw L. Yu, Ph.D.
Faculty Research Scientist

Stewart L. Barnes, P.E.
Graduate Research Assistant

Virginia W. Gerde
Graduate Research Assistant

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

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In Cooperation with the U.S. Department of Transportation
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Charlottesville, Virginia

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ABSTRACT

In order to obtain the necessary detailed design guidelines for stormwater best management practices (BMPs) included in the Virginia Department of Transportation's stormwater manual, a field program was initiated in 1991 for testing the pollutant removal efficiency of selected practices. A dry detention pond with a small, highly impervious drainage area and a vegetated swale draining runoff from an urban highway were selected for the study. Manual as well as automatic sampling methods were used to monitor stormwater runoff into and out of the two facilities. Pollutant removal efficiencies were calculated by a mass balance method. Pollutants examined included total suspended solids, total phosphorus, and total zinc. Preliminary data showed that, if properly designed, these types of facilities can be an effective tool for removing stormwater pollution from highway runoff.

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INTRODUCTION

The U.S. Environmental Protection Agency (EPA) promulgated its stormwater regulations in November 1990. Permits in accordance with the regulations of the National Pollutant Discharge Elimination System (NPDES) are required for major municipal and industrial (including transportation) discharges. The impact of the NPDES requirements on transportation operations will be mainly in the following three areas:

1. highway storm sewers that convey runoff to a municipal system that is subject to permitting
2. construction projects disturbing an area greater than 2.03 ha (5 acres)
3. facilities such as maintenance shops, material handling facilities, and contractor batch plants.

It is expected that the NPDES Permit Program in Virginia will be administered by the State Water Control Board (SWCB). Currently, SWCB is working with EPA to develop a "general permit" program that will be applicable to the Virginia Department of Transportation (VDOT) to address areas 2 and 3.

In addition to the EPA regulations, VDOT must comply with the Virginia Stormwater Management Regulations, the Chesapeake Bay Preservation Act, and the Virginia Erosion and Sediment Control Regulations. In a previous project entitled "Stormwater Management Regulations and the VDOT," a manual of practice was developed that outlined specifications and practices that VDOT will follow in order to satisfy all the relevant state regulations.[1] The document is used as part of VDOT's annual submission to the Virginia Department of Conservation and Recreation for a "blanket" approval of VDOT construction and maintenance programs in lieu of submission of an application for a permit for each project. Currently, VDOT plans to work with SWCB so that such a document could also be used to satisfy the EPA NPDES requirements.

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PURPOSE AND SCOPE

In order to obtain the necessary detailed design guidelines for the stormwater best management practices (BMPs) included in the VDOT manual,[1] a field program was initiated in 1991 for testing the pollutant removal efficiency of selected practices.

The objectives of the study were as follows:

1. to perform field tests of selected stormwater management practices so that more detailed information on design guidelines could be obtained and then incorporated into the *VDOT Manual of Practice for Planning Stormwater Management*[1]
2. to determine the applicability of selected stormwater management practices in VDOT construction projects and maintenance programs.

Based on the literature review, a dry detention pond and a grassed swale were chosen for monitoring.

LITERATURE REVIEW

Detention Pond

The concept of using stormwater detention basins to reduce runoff pollution gained widespread attention as a result of studies authorized under Section 208 of the 1972 Clean Water Act established by the U.S. Congress. The "dual-purpose" detention pond design approach allows the pond (1) to reduce flood damages downstream, and (2) to reduce non–point source pollution from stormwater runoff.[2] The EPA nationwide urban runoff project[3] further demonstrated the water quality benefits of wet detention basins.

Dry ponds are depressed areas that store runoff during a storm. They are usually designed to reduce the peak flow resulting from a selected design storm (e.g., a 10-yr storm) to the predevelopment level to prevent downstream flooding. However, dry ponds are not very effective in removing pollutants; they are basically designed for controlling quantity, not quality. Because of the short detention times, many particulate pollutants do not have enough time to settle out of the runoff, and the ones that do settle to the bottom of the pond are easily resuspended by the next storm. The pollutant removal efficiency for dry ponds reported in the literature ranged from 0 to 20 percent for all pollutants as an average. Therefore, dry ponds, though efficient in controlling stormwater quantity, are not generally recommended if water quality control is needed.

To create an extended dry pond, the outlet structure of a dry pond can be modified in such a way that a "retention outlet" is provided that is sized for a slow release of the runoff from a designated "BMP storm." A BMP storm is a small and frequent storm, such as a 2-yr or more frequent type of storm, that is prescribed by regulations or ordinances as the BMP design storm.

The pollutant removal efficiency for extended dry ponds depends on how long and how much runoff is detained. In general, a moderate-to-high removal rate (40 to 70 percent) can be achieved for particulate pollutants such as suspended solids. For dissolved pollutants such as nutrients, the removal efficiency is fairly low.

Wet ponds, by maintaining a permanent pool, allow particulate pollutants to have time to settle out and dissolved pollutants to be removed by biological uptake or other decay processes. Consequently, the water quality benefits of wet detention ponds are well documented. For example, the long-term average removal rate estimates by Driscoll[4] ranged from around 50 percent to more than 90 percent for TSS, 40 to 60 percent for nutrients, and 40 to 45 percent for Zn. Several studies conducted in the Washington metropolitan area and summarized by Schueler[5] showed moderate efficiency for a wet pond. Moderate-to-high removal rates for wet ponds were also reported for studies in Florida,[6] North Carolina,[7] and Virginia.[8]

Pollutants are removed in a detention pond mainly through the following mechanisms:

- *Particle settling.* Particulate pollutants are removed by gravitational settling. Therefore, the removal rate for particulates should relate to the inflow particle size distribution of the pollutant and the detention time, which is affected mainly by the size of the pond and the design of the outlet structure.

- *Decay.* For nonconservative pollutants such as biochemical oxygen demand (BOD) and bacteria, biodegradation and die-off, respectively, will occur.

- *Biological uptake.* Dissolved nutrients are primarily removed by biological activities of the aquatic vegetation in the pond.

For most detention ponds, the dominant factors influencing the removal efficiency are the settling velocity (or size distribution) of the pollutants and the basin volume.

The settle ability of various pollutants differs. For example, Whipple and Hunter[9] performed column-settling tests and found that hydrocarbons and lead settle out similarly as TSS, but that phosphorus, zinc, copper, nickel, and BOD have quite different settling patterns.

Schueler[5] compiled results from a more complete laboratory column test and presented results relating removal rate to detention time for a number of pollutants, as shown in Figure 1.

The same trend was observed in field studies conducted by, for example, Wu et al.[7] and Yu et al.[8] Table 1 lists pollutant removal efficiencies for a number of BMPs. The table is based on information compiled through a review of relevant literature.

In general, the design of a detention pond based on particle settling should be made with the following understanding:

1. PSD in the inflow water is a very important design consideration, is very site specific, and may vary from storm to storm. It is, therefore, highly desirable to examine the typical PSD in urban runoff for various areas.

2. Suspended sediments, lead, and hydrocarbons may have similar settling characteristics, whereas phosphorus, nitrogen, and zinc may be grouped into one category.

3. Detention time is an important design parameter that is related to pond size and auxiliary devices such as baffles, etc.

Generally, the kinetic processes for decay and biological uptake by plants are both enhanced by longer detention time in a pond. Therefore, the detention time can be considered as the key design factor. A longer detention time (24 to 36 hr) may be preferred if biological uptake is desired.

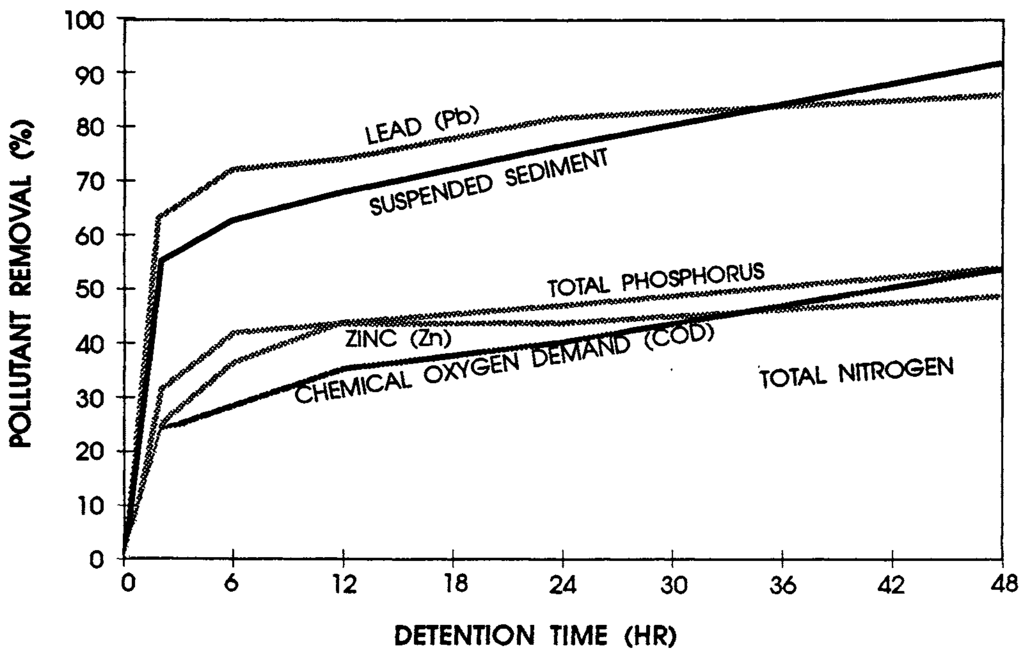

Figure 1. WET POND POLLUTANT REMOVAL VS. DETENTION TIME.
***Source*: Modified from Schueler.[4]**

Table 1
COMPARATIVE POLLUTANT EFFICIENCIES OF URBAN BMPs
(REMOVAL EFFICIENCIES IN %)

BMP	Total Suspended Solids	Total Phosphorus	Total Nitrogen	Total Lead	Total Zinc	Data Source (Ref. No.)
Detention Ponds						
Dry ponds	14	20	10	–5	–10	9
Ext. dry ponds						
4–6 hr detent.	29	40	25	29	25	9
6–12 hr detent.	70–74	13–56	24–60	24–61	40–57	9
Wet Ponds						7,11,12,17
a/A* < .01%	0–32	0–18				
0.1–1%	5–66	29–36				
1–2%	60–91	34–79		57	51	
2.85%	81	54				
7.51%	93	45				
Infiltration Trenches**	90+	30–70	30–70	15–80	15–80	2
Porous Pavements**	82–95	65	80–85	90+	90+	9
Vegetated Buffer Strip with Level Spreader	70	40		25	51	12
Grassed Swales with Check Dams**	20–40	20–40	20–40	0	0	9

*a/A = pond surface area/watershed area ratio.
**Estimates based on limited data.

Schueler[5] recommended some guidelines for designing BMPs. Highlights of the design considerations for extended dry ponds are:

- Volume should store the runoff quantity produced by a 25.4-mm (1-in) storm.
- For optimal pollutant removal, 24 hr of detention is desirable.
- Smaller storms (25 to 50 mm of runoff) should be detained for at least 6 hr.
- A two-stage design is recommended: an upper stage of the pond is to remain dry normally, and a "bottom" stage is to be regularly inundated, with its volume set to store about 15 mm of runoff.
- Marshes should be established at the bottom stage.
- The outlet control device should be designed to set water levels and should withstand partial clogging.
- A low flow channel is desirable.

By maintaining a permanent pool, wet ponds achieve particulate and dissolved pollutant removal through enhanced particle settling, decay processes, and biological uptake. In addition to the particle settling–based design approach, biological and other decay processes should be included in deriving design guidelines. In general, wet pond design methodology could include the following approaches:

- *Solids settling design.* Based on sedimentation theory, the method uses a PSD, and thus the settling velocity, as a key parameter. Pond size and configuration are designed so that particle settling is optimized.
- *Lake eutrophication model design method.* Hartigan[10] proposed that a wet pond can be considered as a small eutrophic lake that can be simulated by empirical models to evaluate lake eutrophication. Hartigan used the "input-output" phosphorus retention model developed by Walker[11] as a design tool. The Walker model relates phosphorus removal rate to such variables as the TP, second order decay rate, mean lake depth, and hydraulic residence time. By changing the wet pond volume and other geometrical characteristics, one can obtain the removal rate desired.
- *Detailed hydraulics / water quality modeling approach.* A wet pond can also be modeled in a more detailed fashion, as in the case of a lake. Flow patterns, pollutant transport, and transformation processes in a pond can be simulated under a variety of trial design conditions so that some guidelines can be obtained. For example, the geometry of the pond can be changed or a baffle installation can be tried and its effect on the removal rate examined by such a model.[12]

Vegetated Swale

As a BMP to improve water quality, grassed swales are reported to be fairly effective at reducing pollutant loads in stormwater runoff. When properly designed, swales may be well suited to control highway runoff quality. Grassed swales contribute to the removal of pollutants by increasing travel times, filtration, and infiltration, which allows them to settle out and be trapped before reaching the receiving waters. Dissolved pollutants and stormwater infiltrate the swale, and thus the pollutants discharged at the end of the swale are reduced or eliminated. A reduction in sediment and pollutant load at the source reduces the cost of other mitigation measures downstream. Vegetation provides stabilization for the soil surface and reduces overland velocities, thereby reducing erosion. Grassed swales can also reduce the peak runoff by slowing the flow velocity and increasing travel time.

In this report, the term *swales* refers to grassed or vegetated channels used to control the quantity and/or quality of highway runoff. Swales are usually located on the side or in the median of a roadway and may include check dams. Grassed swales are frequently used in roadway design for the conveyance and infiltration of stormwater runoff.

Swales are vegetated, or grassed, channels or ditches, which are usually part of a more extensive drainage system, and convey runoff to a receiving body of water. A covering of vegetation, such as grass, serves to inhibit erosion and enhance the settling of suspended solids. Swales have a medium-to-high level of applicability to interchanges and at-grade highways for both existing and future highways.

A reduction in the amount of suspended solids will result in the overall reduction of pollutants in stormwater runoff as the particulate pollutants settle out. A reduction in the flow volume due to infiltration will also cause a reduction in pollutants as the dissolved pollutants infiltrate. Therefore, the effectiveness of swales is related to storage capacity, pollutant loading, and swale shape and slope.

According to Maestri et al.,[13] swales have a high pollutant removal efficiency for particulates, heavy metals, and organics. In a study by Bell and Wanielista,[14] approximately 99 percent removal was achieved when the first 2.5 cm (1 in) of runoff was stored and treated (ultimately infiltrated into the soil of the ditch or swale).

Well-developed ground cover is important to provide effective filtering and prevent erosion. Although some swales or ditches may be left to develop wild vegetation, this is not as effective in pollutant removal as a grassed channel. Dillaha et al.[15] found that cover and vegetative conditions at ground level were too sparse for effective filtering or flow retardance.

Wanielista and Yousef[16] presented an equation that determines the length of swale required to infiltrate all the runoff from a given storm, which would mean 100 percent pollutant removal. This equation, which is presented later, is dependent on the infiltration rate, shape and roughness of the swale, and average flow through the swale.

If the length of swale necessary to infiltrate the entire storm is greater than the available distance, a check dam or other means to increase detention can be used. Kercher et al. reported the results of a swale study in Brevard County, Florida. The drainage area of the studied swale was 5.1 ha (12.7 acres), and seven parameters were analyzed, including BOD5, TSS, total Kjeldahl nitrogen, nitrate, TP, total iron, and total lead. Several conclusions were reached on the basis of their findings:[17, p. 54]

> The grassy swale system absorbed the runoff from 10 of the 13 storm events monitored, significantly reducing the amount of off-site stormwater runoff and down-stream flooding impacts.
>
> The residential grassy swale system removed 99 percent of the pollutants measured.

Schueler[5] estimated that the removal rate for a low-gradient swale with check dams is 20 to 40 percent for TSS and TP, and the removal rate for trace metals is 0 to 20 percent (see Table 1). The recommended drainage area for a swale system is up to 8 acres.

It is generally understood that pollutant concentrations peak and then decrease during a storm. The decrease is often extreme, such that the majority of the pollutants are washed off the land surface with the first few centimeters of runoff. This first flush of pollutants is a primary concern in the design of swale systems for water quality purposes, i.e., the swale system should be able to remove a significant amount of pollutants from the first flush.

According to the Virginia Stormwater Management Regulations,[18] a water quality volume (WQV) estimated at 1.3 cm (0.5 in) of runoff is assumed to contain a large portion of the total storm pollution and must be treated to improve water quality.

Settling and infiltration are the key removal mechanisms in grassed swales. Additional processes that may affect pollutant removal are sorption and filtration. Biological assimilation, which is the key transformation process that occurs between storms, reduces the concentration of pollutants in the soil. Photocatalytic decomposition, species differentiation, and volatilization also affect the concentration of pollutants in the swale between storms.

One of several conclusions by Bell and Wanielista[14, p. 20] was that "soil properties generally considered to be important in the retention of heavy metals are pH, cation exchange capacity, clay mineral content, and organic matter content."

Infiltration is the movement of surface water into the subsurface layer. The rate of infiltration can be affected by such factors as soil type and texture, land use and land cover, and the number of antecedent dry days. Infiltration through the soil reduces the amount of stormwater and dissolved constituents discharged at the end of the swale. Grassed swales increase the infiltration rates by reducing flow velocity and increasing storage capacity.

Although infiltration is important in the removal of pollutants, it is not the only mechanism involved. A study by Oakland[19] found significant pollutant removal from a swale even where there was no significant amount of infiltration.

A reduction in flow velocity also increases the effects of settling. Sedimentation rates are dependent on many factors, e.g., flow velocity, infiltration rate, and depth of flow. Reduction of the flow velocity by grassed swales enhances sedimentation. The solubility rates and association with particulate matter influence the sedimentation rate.

The effects of the following mechanisms vary in significance during dry and wet periods. Biological assimilation is negligible during storms due to the relatively short duration of storms. However, between storms, biological assimilation is an important mechanism for reducing pollutants in the soil. The uptake by plants of certain compounds will reduce the pollutant concentration in the soil, but the fate of the plants also affects the balance of these constituents; e.g., the grass may be eaten by passing animals who then leave the swale system; the grass may be cut and either leave the swale system or remain to decompose in the swale. Yousef et al.[20, p. 29] reported that "a fraction of heavy metals retained by flood-plain soil is available for biological uptake by plants and other forms of life."

The overall concentration of the compound in the soil matrix or the water may affect its adsorption rate or other reactions. Leaching of compounds from the soil matrix to the subsurface water also occurs. Leaching and adsorption do not work for all compounds of interest. Yousef et al.[20, p. 29] conducted a study on soils receiving runoff from bridges and reported that "the concentrations of several heavy metals extracted from soil samples at the bridge areas were significantly higher than concentrations of similar metals extracted from the control areas." Results from Bell and Wanielista[14, p. 16] indicated that heavy metals are retained by the soil and that "they are effectively immobilized and generally do not leach downward."

Bell and Wanielista[14] also concluded that (1) reactions between soils and heavy metals are site specific and (2) the organic portion of the soil is, in many cases, very important to its ability to retain heavy metals.

An empirical approach developed by Zimdahl and Skogerboe[21] predicts the capacity of the soil to adsorb lead:

$$N = 2.81 \times 10^{-6} CEC + 1.07 \times 10^{-5} pH - 4.93 \times 10^{-5} \qquad [1]$$

where

N = moles of lead per gram of soil at saturation

CEC = cation exchange capacity of the soil (meq/100 g)

pH = soil pH in units.

Bell and Wanielista[14] applied equation 1 to their data and obtained a regression coefficient of 0.971; the calculated value of N generally agreed within 10 to 20 percent with experimentally determined values.

Two of several conclusions reached by Bell and Wanielista[14, p. 20] were: (1) "the transport of heavy metals by overland flow results in large amounts of these metals coming into contact with the soil, where they are generally retained" and (2) "in laboratory studies, the capacity of the soil to retain lead can be reasonably predicted by pH and cation exchange capacity," although "many other variables may affect this capacity." Methods to estimate the volume of stormwater that should be treated and the pollutant removal efficiency are provided in Bell and Wanielista.

Volatilization of pollutants is not likely to occur during a storm. It is more likely to occur during the time the pollutants are on the road or swale surface between storms. Airborne pollutants may be reprecipitated during a storm.

The resuspension of solids from the soil matrix may occur during a high-intensity storm. Erosion may also occur during a long-duration storm. A related issue is termed the *mixing effect*. Settled pollutants are disturbed, rediluted, and discharged from the swale.

Bell and Wanielista[14, p. 16] observed that "other metals appeared to be somewhat more mobile in the soil so that some leaching could occur. At every sampling site, metal concentrations decreased with both depth into the soil and distance from the edge of the pavement." Yousef et al.[20] reported that heavy metals retained by soils can be released back to solution by lower pH values, anaerobic environments, organic complexing, and soil erosion.

Figure 2 shows an ideal swale designed to improve water quality. The side slope should be no more than 3:1 (6:1 ideal), and the longitudinal slope (down the channel) should be less than 5 percent.

Previous studies[8, 22] have shown that swales should be sufficiently long to reduce pollutant loading significantly. A majority of the removal may occur in the first 20 m of the swale due to the settling of large particles. A longer travel time allows for the settling of more and smaller particles.

According to several conclusions by Bell and Wanielista,[14, p. 21]

> . . . subsurface soil should be alkaline to promote removal of metals. Organic matter and clay minerals also aid in the removal of metals. Soils adjacent to pavements need to be replaced periodically because of metal saturation. Care should be exercised in the disposal of these soils.

Dorman et al.[23] offered several design considerations for swales:

- Side slopes should be as gradual as possible.
- Channel erosion should be minimized. (Well-developed vegetative cover will help to minimize erosion.)
- Swales should be at least 100 ft (30 m) in length.

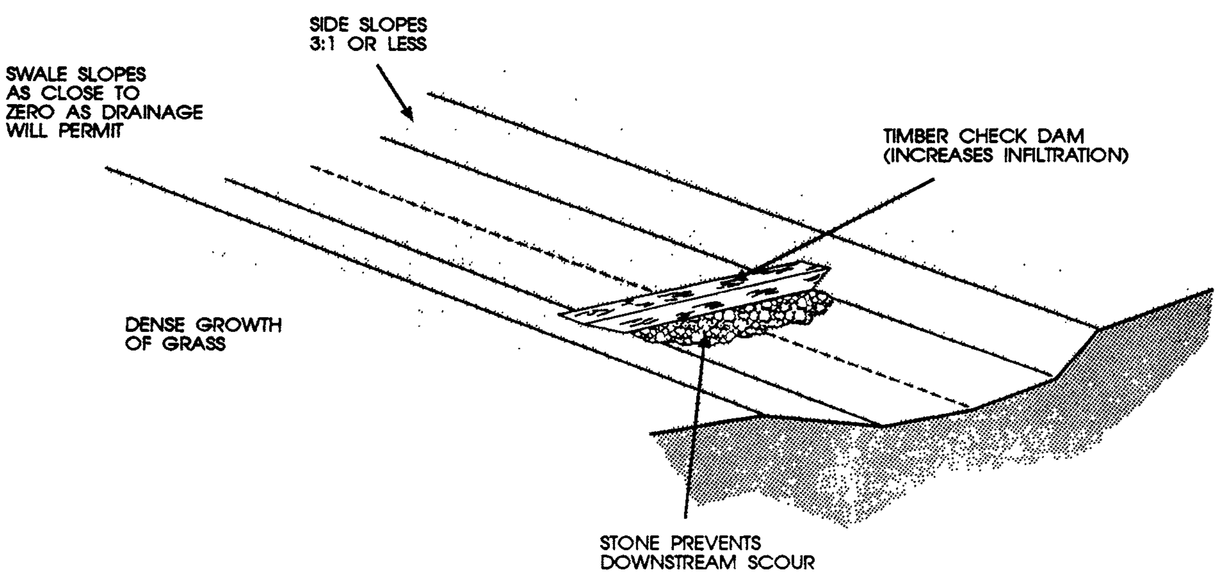

Figure 2. IDEAL SWALE TO IMPROVE WATER QUALITY.

As shown in Figure 2, check dams may be placed at specific locations along the swale to increase the detention storage capacity and increase the travel time. The check dams may provide enough storage capacity in the swale to infiltrate a required volume of runoff from the drainage area. These check dams may be more important along swales with a steep slope (>5 percent). The increased travel time and storage will improve overall sedimentation and infiltration of the runoff.

According to Bell and Wanielista,[14, p. 14] "soil is a significant 'sink' for heavy metals," and

> . . . it was postulated that overland flow of storm water from impervious surfaces to a ditch before discharge to lands or surface water bodies adjacent to the rights-of-way would be effective in reducing concentrations of metals. The overland flow of runoff would promote exposure of metals to the soil [through infiltration] and thus make maximum use of the ability of the soil to retain these metals.

According to Schueler,[5] the swale's infiltration rate should be at least 0.20 cm/hr (0.50 in/hr). Infiltration is possible but not as effective with a rate of 0.11 to 0.20 cm/hr (0.27 to 0.50 in/hr). Schueler reported that several factors influence the infiltration slope: depth to water table, land use, high sediment input, and underground barriers.

Wanielista and Yousef[16] gave the following equation to determine the length of a swale required to infiltrate completely the runoff from a design storm.

$$L = \frac{KQ^{5/8}S^{3/16}}{N^{3/8}f} \qquad [2]$$

where

L = length of swale required for total infiltration (m or ft)

K = constant that is a function of the swale's side slope

Q = average flow rate of runoff (m^3/s or ft^3/s)

S = longitudinal slope

N = Manning's roughness coefficient

f = infiltration rate (cm/hr or in/hr).

If the equation yields a length of swale that is greater than what is actually available, a check dam can be placed in the swale to retain the excess stormwater until it can be infiltrated. The storage volume required can be found by determining the volume that is infiltrated using the available length and equation 2 and subtracting that from the volume of runoff generated by the design storm.

The channel velocity is determined using the Manning equation for flow in open channels:

$$V = \frac{R^{2/3}S^{1/2}}{n} \qquad [3]$$

where

V = mean velocity (m/s)

R = hydraulic radius (m) = area/wetted perimeter

S = slope

n = Manning's roughness coefficient.

The travel time in the swale may be determined by dividing the length of the swale by the velocity of the flow through it. Wanielista and Yousef[16] found an average value of 0.056 for Manning's roughness coefficient in their study.

According to Maestri et al.,[13] swales have a low capital cost per hectare relative to other BMPs. They also noted that additional land requirements and routine/nonroutine operating and maintenance costs are low when compared with those of other BMPs.

The following conclusions were drawn by Kercher et al.[17, p. 54] based on studies of a swale system in Florida:

> The swale required less land area than the curb-and-gutter system.
>
> Based on drainage area, the swale was 40–50 percent less expensive to construct and maintain over a 25-yr period.
>
> Mosquito breeding in properly designed and maintained residential grassy swales will be minimal, since there will be no standing water.
>
> Swales require less maintenance than ponds because residents maintain the area up to the road, in urban areas.

METHODS

Overview

Major tasks of the study included:

1. selection and preparation of sites
2. development of sampling programs
3. field sampling
4. data analysis.

Selection and Preparation of Sites

Numerous sites were examined in the Charlottesville/Albemarle area (see Figure 3). After a careful review of all candidate sites and upon consultation with VDOT engineers, the following sites were selected for study:

1. a dry detention pond serving the Massie Road parking lot at the University of Virginia, Charlottesville
2. a grassed swale in the median strip of U.S. Highway 29 at the intersection with Hydraulic Road in Charlottesville.

Detention Pond

Detention facilities in the City of Charlottesville/Albemarle County area were surveyed in order to find a suitable site that most closely resembled a size and land use of interest to VDOT. Approximately 12 sites were investigated. All of the detention facilities were constructed to control the increased runoff generated by developments occurring in the watershed.

The study site selected was a dry detention pond located on the grounds of the University of Virginia near the intersection of Massie Road and Emmett Street (U.S. 29) (Figures 4 and 5). The basin is a parking facility for daily commuters and athletic event traffic at nearby University Hall Arena and Scott Stadium. The parking area also has university bus service, which travels through the basin at regular daily intervals.

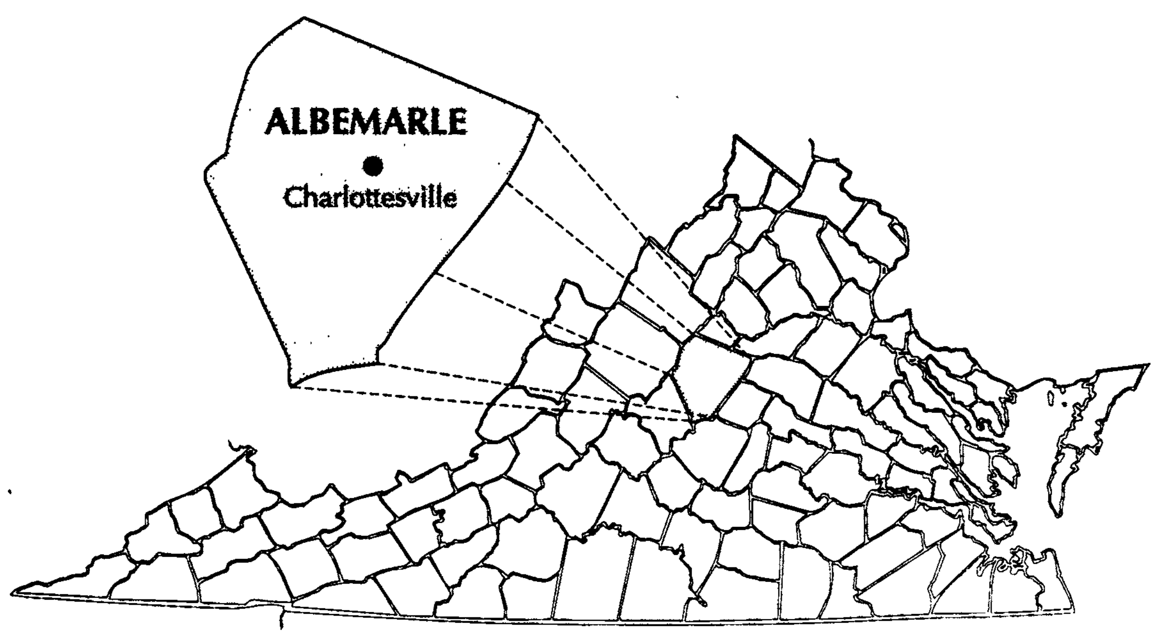

Figure 3. MAP OF VIRGINIA.

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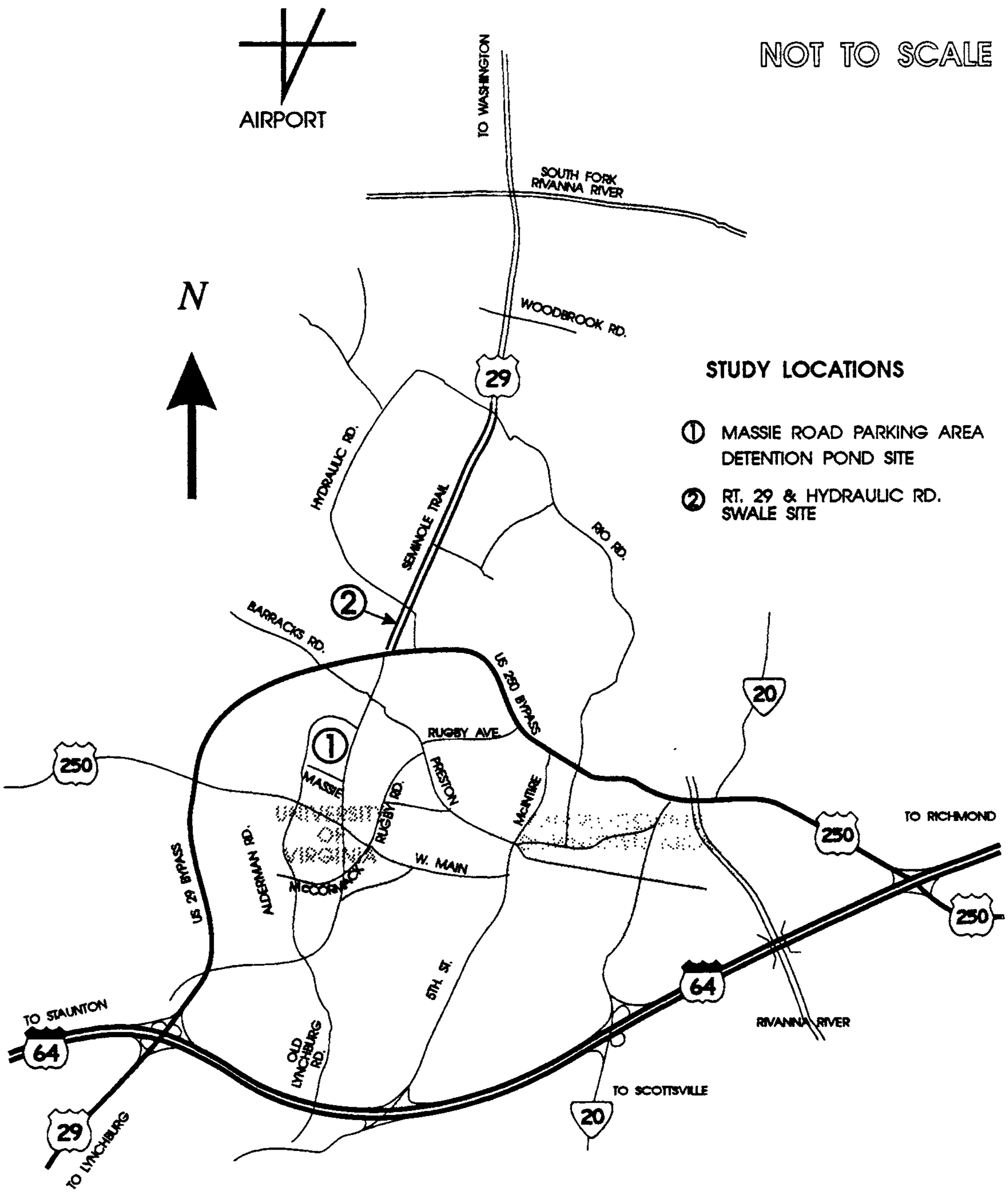

Figure 4. VICINITY MAP OF CHARLOTTESVILLE SHOWING STUDY SITES.

Figure 5. MASSIE ROAD DETENTION POND WITH RAIN GAGE IN FOREGROUND.

The watershed contributing to the detention pond is approximately 3.2 ha (7.9 acres) in size. The pond receives runoff from a riprap-lined channel that receives runoff from two sources: a 61-cm (24-in) concrete storm sewer draining 1.7 ha (4.2 acres) and a concrete trapezoidal ditch draining 0.6 ha (1.5 acres) (see Figures 6 and 7). The two inflows converge in the riprap ditch and proceed into the pond area. The balance of the drainage area is 0.9 ha (2.2 acres), which is the drainage area immediately surrounding the detention pond. The effluent from the detention pond discharges via a 30-cm (12-in) concrete pipe through a concrete structure into a small tributary to Meadow Creek, which flows to the north along Emmett Street. The detention pond size and other characteristics were obtained from construction plans and site visits (Tables 2 and 3). A photograph of the detention pond is shown in Figure 5.

This site was not ideal because the detention facility was not designed or constructed with any specific objective for water quality improvements. The pond was designed only to attenuate the postdevelopment peak runoff flow rate to the predevelopment flow rate for 2- and 10-yr storms. No provisions were made for the pond to retain a first flush of runoff and release it at a significantly slower rate to increase the detention time. In order for the pond to function in this capacity, a modification was made to the 30-cm (12-in) outfall pipe.

The modification consisted of casting a three-sided concrete structure around the inlet of the outfall pipe. The open side of the structure was grooved to facilitate inserting a plywood template with a 7.6-cm (3-in) circular orifice to close the fourth

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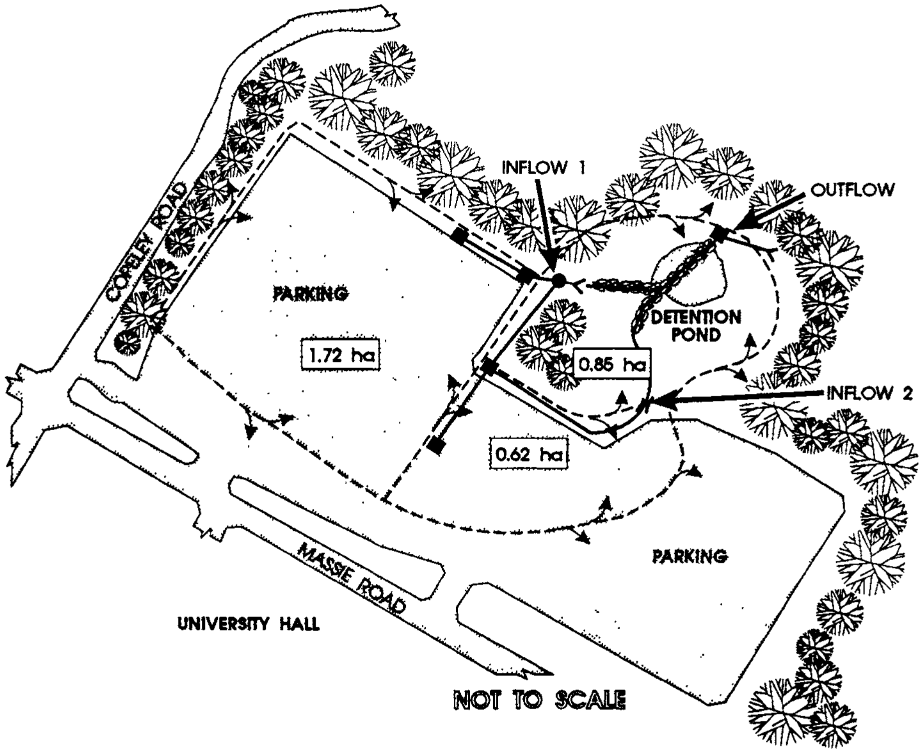

Figure 6. SKETCH OF MASSIE ROAD PARKING LOT AND DETENTION POND.

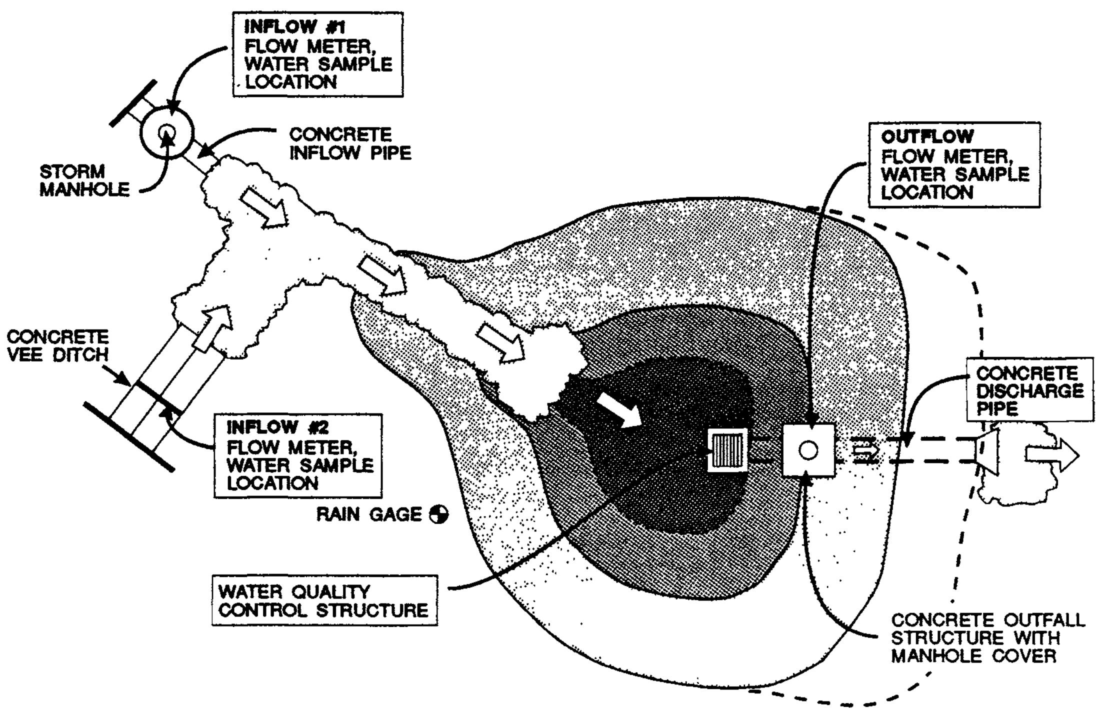

Figure 7. LAYOUT OF DETENTION POND.

Table 2
DRAINAGE BASIN CHARACTERISTICS

Watershed area	3.19 ha
Land use	60% paved parking 20% maintained grass 20% woods
Time of concentration	7 min
Drainage system	Concrete curb with concrete storm sewer and open channel ditches, concrete, and riprap

Table 3
DETENTION POND STAGE VS. STORAGE DATA

Elevation (m)	Surface Area (m^2)	Total Storage (m^3)
144.47	0.0	0.0
145.08	408.9	124.6
145.69	614.1	565.7
146.30	832.0	877.7

Source: Construction site plan entitled "Massie Road Parking Lot Improvements" prepared for the University of Virginia by Gloeckner and Osborne, Inc., Charlottesville, Va., 2 June 1992.

side. The use of this grooved open end will facilitate future study with different outlet shapes and sizes. Figure 8 shows a sketch of the outfall modifications, and Figure 9 shows the actual modification after construction. Figures 10 and 11 show the pond operating with the water quality structure in place.

Vegetated Swale

The swale under investigation is located in the median of U.S. Route 29 south of the intersection with Hydraulic Road (Figure 4) and is approximately 128 m (420 ft) in length. The swale receives runoff from approximately 0.6 ha (1.5 acres) of heavily traveled urban highway. The grass is mowed on a regular basis: approximately once every 2 weeks. No fertilizers are applied to the swale area.

The swale (Figure 12) was divided into four sections based on length and slope geometry, as shown in Table 4. Approximately a 28-m length of grassed area was upslope of the initial sampling location: "0 m."

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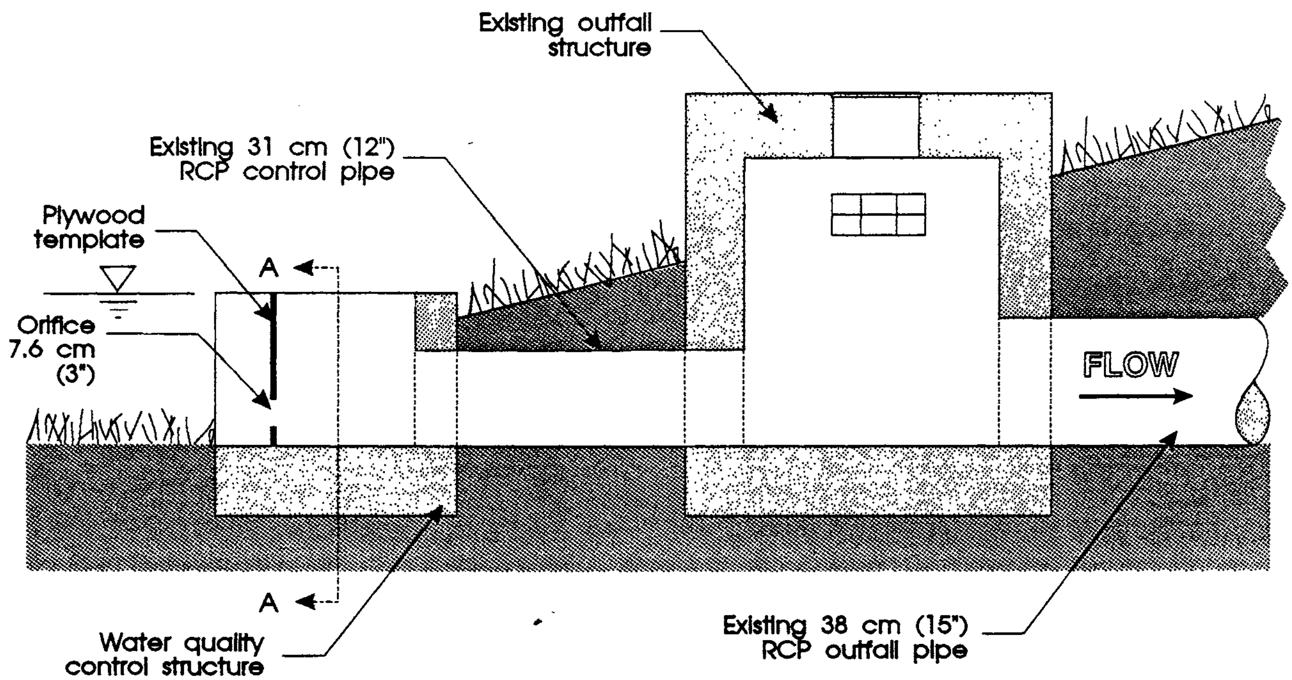
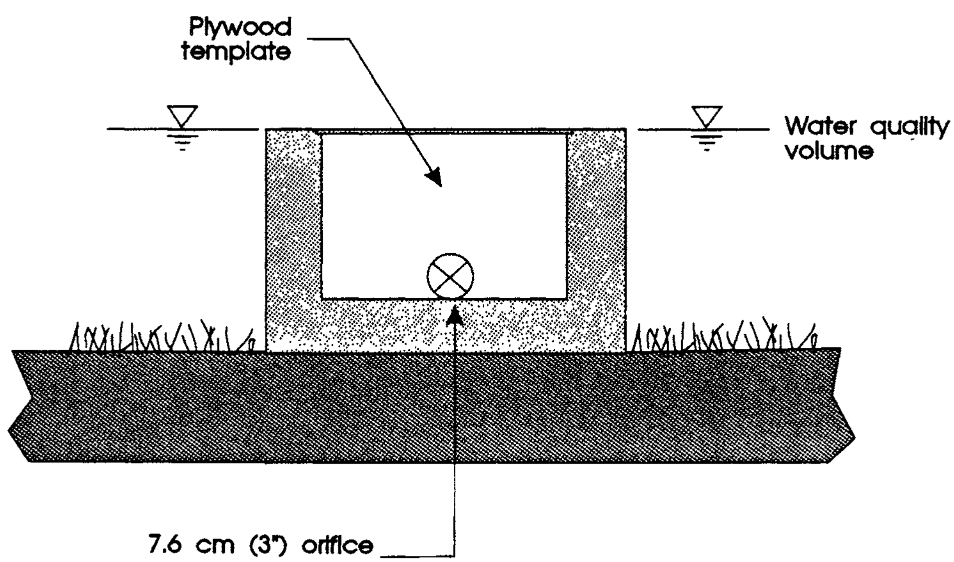


CROSS SECTION OF OUTFALL STRUCTURE
N. T. S.



SECTION A-A
N. T. S.

Figure 8. OUTFALL STRUCTURE DETAILS AT DETENTION POND.

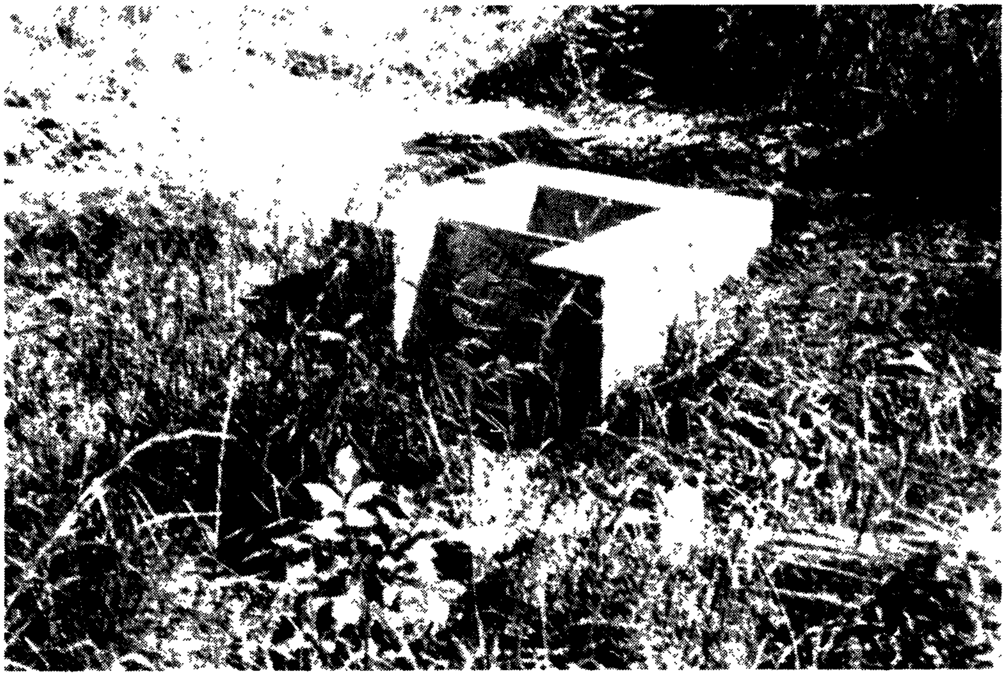


Figure 9. WATER QUALITY MODIFICATION TO DETENTION POND.

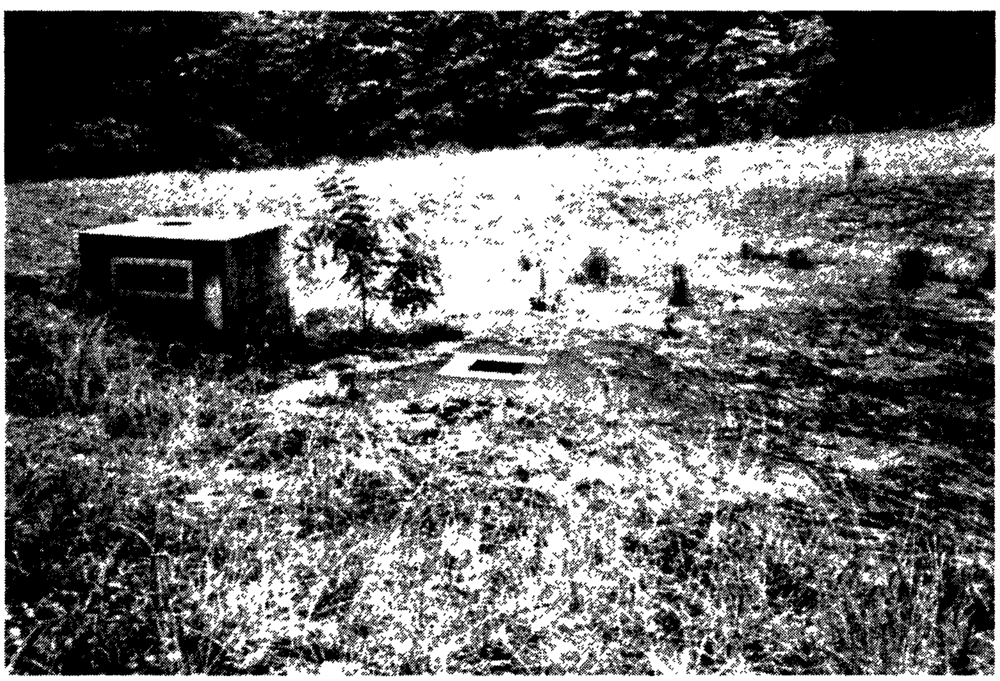


Figure 10. DETENTION POND DURING STORM.

Figure 11. WATER QUALITY STRUCTURE DURING STORM.

Table 4
SWALE SECTIONS AND SLOPE

Station	Drainage Area	Slope
0 m	0.05 ha	0 m to 33 m: 3.2%
33 m	0.11 ha	33 m to 68 m: 3.8%
68 m	0.19 ha	68 m to 100 m: 6.5%
100 m	0.25 ha	
Total	0.6 ha	

Sampling Plan

Most pollutants in the highway environment are generated by automobile exhaust, part wear, and fluid leaks. These pollutants are deposited on the road surface and on adjacent areas and are subsequently washed off during storms. Accumulation of pollutants is related to the number of dry days since the previous washoff and the amount of traffic on the roadway. Highway maintenance practices and wildlife can also contribute to the overall pollutant loads. Airborne particles can be transported by the wind and are deposited by precipitation during a storm.

Figure 12. SWALE SITE.

Sampling was conducted for four runoff parameters at discrete time intervals (usually 15 to 30 min) during each storm. The parameters monitored were:

1. total suspended solids (TSS)
2. total phosphorus (TP)
3. total zinc (Zn)
4. particle size distribution (PSD) (detention pond only).

TSS was sampled because particulate washoff and transport by stormwater runoff from watershed surfaces into receiving water bodies comprise one of the most significant sources of non–point source pollution. TSS is significant because it represents not only a suspended solid concentration in the water column but the particulate washoff is also a carrier for other pollutants that will adhere to the surfaces of the particles.

TP is important because in fresh water systems phosphorus is usually the rate-limiting constituent contributing to the eutrophication of receiving water bodies. Much of the thrust of the Chesapeake Bay Preservation Act is to reduce the amount of phosphorus loading to the bay. Therefore, the objective of many state and local stormwater laws and ordinances is to reduce phosphorus in runoff. Phosphorus is usually characterized in two phases: particulate and soluble. In this study, only the aggregate sum of the two phases, which is known as TP, was examined. Phosphorus can be deposited from the atmosphere and roadside fertilizers; particulates result from pavement wear, vehicles, the atmosphere, and maintenance.

Zn was chosen as a parameter for several reasons. First, we decided to examine a heavy metal. Highway runoff is characterized as being relatively high in heavy metal content such as zinc, cadmium, lead, nickel, and copper. Zinc was chosen because it is common in many automobile engine and mechanical parts as well as in automotive lubricants and fluids. According to Bell and Wanielista,[14, p. 13] zinc "results from tire wear and from the leakage of crankcase oil, in which high concentrations of zinc are used as a stabilizer."

A key design consideration for detention ponds is the distribution of particle sizes. For dry and extended dry ponds, and for wet ponds with a relatively short detention time, particle settling is the primary mechanism for pollutant removal. It is therefore important to examine particle sizes in storm runoff inflow to a detention pond so that the effect of PSD on the removal rates can be quantified. This information can then be used for deriving design guidelines that will optimize particle settling.

Laboratory Analysis

All of the chemical analyses for the study were performed with a quality assurance/quality control program as specified by EPA.

Total Suspended Solids (TSS)

TSS was analyzed using the procedures and quality assurance guidelines established by the standard methods for the examination of water and waste water.[24] The method used was 2540D, TSS dried at 103 to 105 degrees Celsius.

Total Phosphorus (TP)

TP was determined using method 8190, acid persulfate digestion, and method 8178, amino acid. The analytical guidelines and quality control procedures are established in the procedures manual for the laboratory equipment.[25]

Total Zinc (Zn)

Zn was determined by method 8009, the zincon method. The analytical and quality control procedures are established in the procedures manual for the laboratory equipment.[25]

Particle Size Distribution (PSD)

The Coulter principal is universally accepted as the reference method for particle sizing and counting. The counting principal is unaffected by changes in material composition, surface texture, refractive index, or light interaction effects that are inherent in the light blockage/scatter and diffusion system. The overall analysis range is 0.4 to 1,200 mm in diameter. Sixty-four to 256 selectable channels give high solution (up to 1 in 25,600). Number and mass distribution can also be displayed in the output.

Particle size analysis of soils was conducted using AASHTO T 88–90.[26] The test sample for particle size analysis is prepared in accordance with either AASHTO T 87 for dry preparation of disturbed samples for testing or AASHTO T 164 for wet preparation of disturbed soil samples for testing. The representative portions of the original air-dried samples selected are weighted. The weighted samples must be sufficient to yield quantities for particle size analysis as follows: The minimum amount required of material retained on the 4.75-mm sieve, the 2.00-mm sieve, or the 0.425-mm sieve depends on the maximum particle size but must not be less than the amount shown in Table 5.[26]

Table 5
PARTICLE SIZE ANALYSIS OF SOILS
(AASHTO T 88–90)

Nominal Size of Largest Particles	Nominal Size of Largest Particles	
Standard Sieve Designation (mm)	**Standard Sieve Designation (in)**	**Approximate Minimum Weight of Portion (kg)**
9.5	3/8	0.5
25	1	2
50	2	4
75	3	5

Detention Pond

Data were collected for seven storms. Of the seven, the first three were a characterization of the runoff, with only the pollutant concentration determined. The flow monitoring equipment was not yet in place for measuring the corresponding flows into and out of the pond. These storms were 6 March, 10 March, and 18 March. The other four storms were monitored with both flow and concentration to allow the determination of pollutant mass fluxes. Of these four storms, the 30 April and 5 May storms were a baseline study of the efficiency; no orifice was in place to increase the detention time of the first flush. The 29 May and 4 June storms occurred after the orifice was installed.

Rainfall was measured using a Plexiglas wedge gage at the site. Information was corroborated at a rainfall gaging station located at Birdwood Golf Course, which is continuously monitored by the State Climatology Office. The Birdwood gage is located approximately 2.5 km from the Massie Road parking area.

Flow was measured at all inflow and outfall points at the detention pond. Measurements were made using 90° V-notch weirs with a continuous bubble–type flow meter and a tube secured just below the crotch of the weir. Two types of weirs were used at the different flow points. The first type was a portable Plexiglas weir designed to fit into a circular pipe (Figure 13). These weirs were installed at inflow location 1 (see Figure 7) and the outflow, as shown in Figures 14 and 15. The second type of weir used was a plywood 90° V-notch weir. Flow was monitored in the

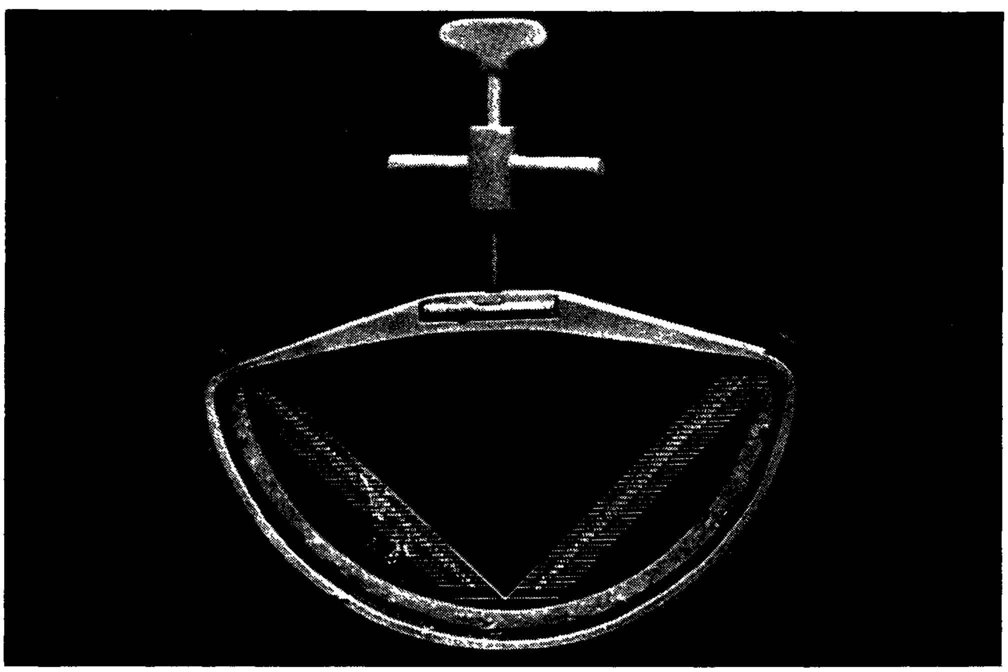


Figure 13. PORTABLE PLEXIGLAS WEIR.

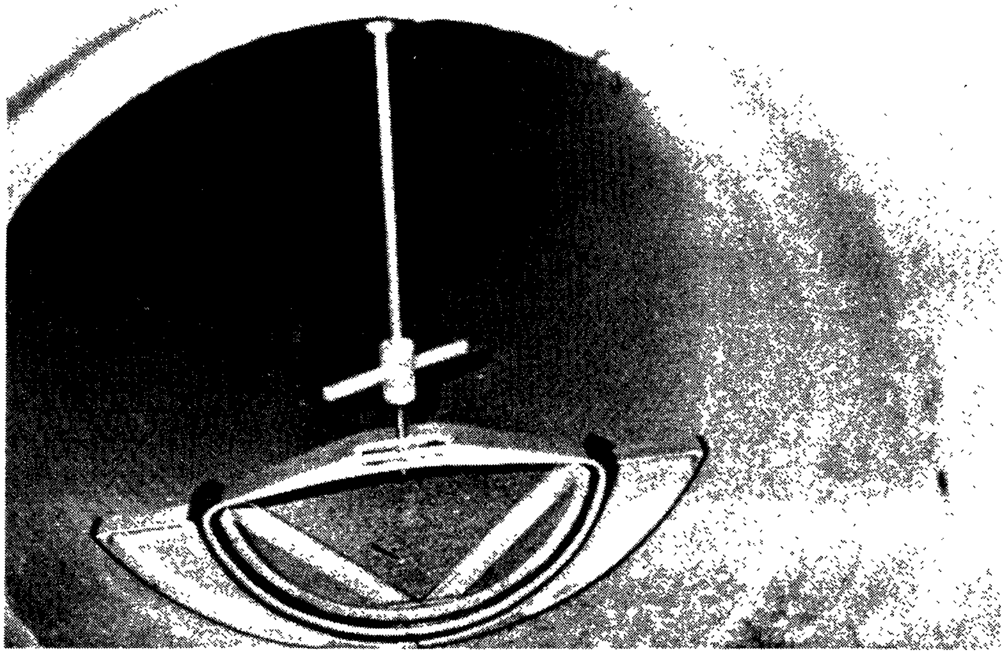


Figure 14. PORTABLE PLEXIGLAS WEIR IN PLACE AT END OF INFLOW PIPE IN MANHOLE AT INFLOW 1.

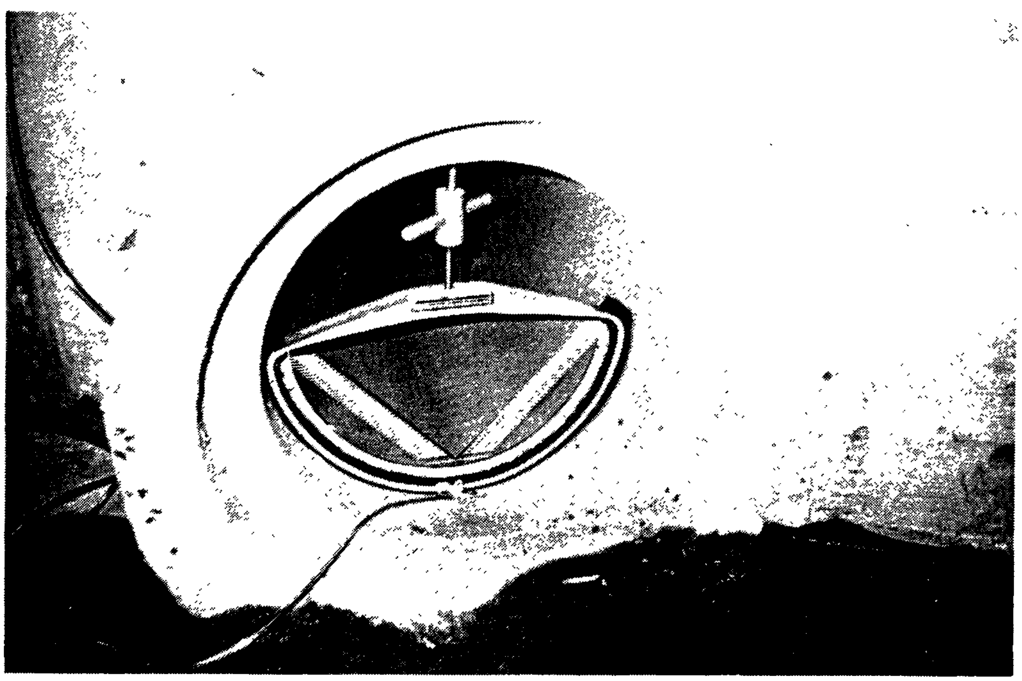


Figure 15. PORTABLE PLEXIGLAS WEIR PLACED AT INLET OF OUTFALL PIPE.

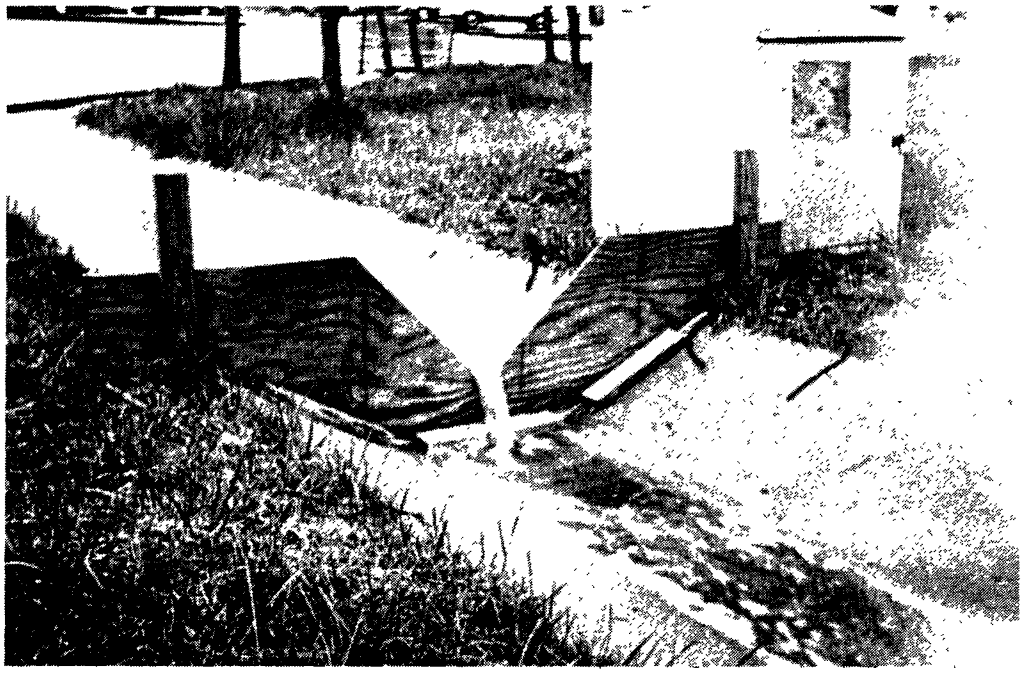


Figure 16. PLYWOOD V-NOTCH WEIR AT INFLOW 2.

concrete trapezoidal ditch in much the same manner as with the concrete pipes except that no manufactured weirs were available, so a plywood ditch block with a 90° weir was constructed as shown in Figure 16.

Manual grab samples were taken at the inflow and outflow locations at discrete times during runoff. At the two inflow sites, the samples were taken from the discharge flow at or immediately downstream from the weir. At the outflow, the samples were taken immediately downstream from the orifice immediately before discharging over the weir. Between three and seven samples were collected for each parameter during each storm at each location.

Vegetated Swale

Six storms were monitored from March 10 to June 4, 1992. Water quality samples were collected for all six of the storms, and flow was measured for the last four storms. The runoff from the eastern side of Route 29 directly across from the swale was sampled to establish a baseline of highway runoff quality.

Sampling stations were located at four lengths starting 25 m from the edge of the asphalt at the intersection: 0 m, 33 m, 68 m, and 100 m. Figure 17 shows swale cross sections at each of the four locations. Flow and water quality were measured

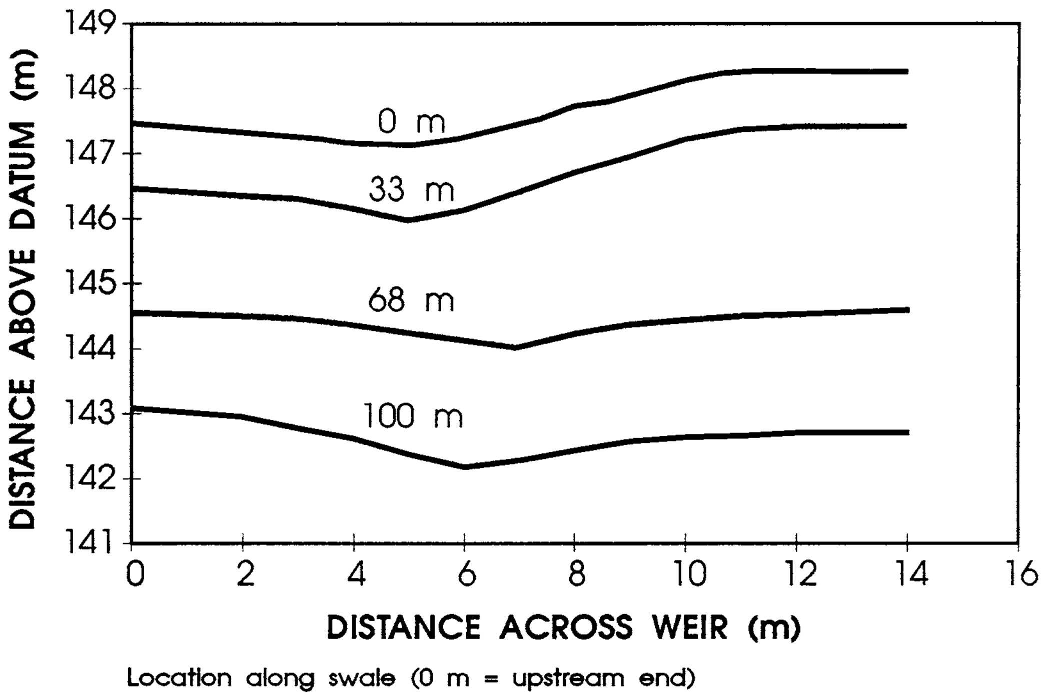


Figure 17. CROSS SECTION OF SWALE AT EACH OF FOUR WEIR LOCATIONS.

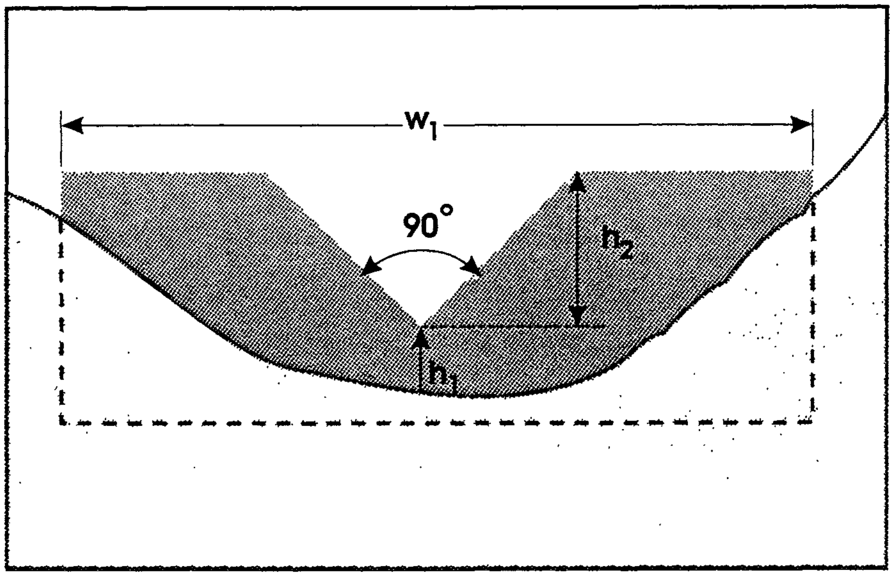
at each station to determine a mass flux. The drainage area for each station was then used to determine a mass flux per unit drainage area. A normalization was needed due to the amount of untreated lateral inflow each section of the swale received.

Due to the low flow conditions, the use of automatic flow meters was not practical at the swale site. Flow was measured using 90° V-notch weirs. Depth was manually measured at each sampling time and converted to flow. The weir at the 33-m station provided some storage, as a check dam would. The notch started approximately 17 cm from the ground. Figure 18 shows a general weir in a swale cross section.

Manual grab samples were collected as the water flowed over the V-notch at each station. Three to six samples were collected at each station for each storm. TSS, TP, and Zn were evaluated. Only the 4 June storm was monitored for Zn; however, future storms can easily be monitored for Zn.

During storms, the observer measured the depth of flow across the weir. Flow was calculated using the following equation:[27]

$$Q = 2.48 \times H^{2.48} \qquad [4]$$



Weir constructed of 3/4" plywood.
w_1, h_1, and h_2 determined after physical survey of swale.

Figure 18. GENERAL WEIR IN SWALE CROSS SECTION.

where

Q = flow (ft^3/s)

H = head (ft).

Due to the time variable nature of storms, a continuous precipitation record was obtained from the University of Virginia Department of Environmental Sciences. The gage is located at Birdwood Golf Course, approximately 3 km from the swale site. As with the detention pond site, a mass precipitation gage was located at the site to record the total precipitation volume from each storm.

A study of the quality of stormwater runoff that immediately exits the highway was conducted at the intersection of U.S. 29 and Hydraulic Road, immediately adjacent to the swale study site. A total of 11 parameters were monitored during this phase of the study. The data were collected by taking 500-ml grab samples during the first 30 min for four storms. The samples were manually taken from the discharge flume of a VDOT standard curb inlet located at the edge of pavement. Care was taken to ensure that the water samples reflected only highway pavement runoff and that no other mixing occurred in the storm sewer system. Care was also taken to ensure that the runoff sampled did not come into contact with any part of the vegetated-lined channels.

RESULTS AND DISCUSSION

Detention Pond

Precipitation

The precipitation data for the seven events are presented in Table 6. The total depth (mm) and duration (hr) of the individual storms were used to calculate the average storm intensity (mm/hr). All of these storms are considered as relatively small storms (e.g., less than 50 mm in total depth).

The use of average intensity should be observed carefully, especially for longer storms (4 hr or greater). The precipitation in these storms is rarely uniform, and the resulting intensities are highly variable. The average intensity may not be an accurate enough picture for analyzing pollutant loading.

Pollutant Parameters

The detailed results for the seven storms monitored are presented in Appendix A. Table A-1 shows the relative pollutant concentration changes only with respect to time for the storms on 6, 10, and 18 March. For these storms, two pollutant parameters were measured: TSS and TP. For the 6 March storm, only inflow 1 was sampled because of physical limitations at inflow 2. For the 10 and 18 March storms, both inflow locations were monitored. No outflow structural modifications were made to the detention pond at this point in the study.

Table A-2 shows the relative pollutant concentration changes with respect to time for the storms on 30 April, 5 May, 29 May, and 4 June. For these storms, flow were measured at the inflow and outflow points to the pond. Flow information is provided in Table A-3 for the storms on 30 April and 5 May. These storms were monitored by manual measurements. The runoff hydrographs are presented for the two storms occurring 29 May and 4 June. This information was collected using an automatic flow measuring device (see Figures A-11 and A-14). Two pollutant

Table 6
STORM PRECIPITATION DATA, SPRING 1992

Storm	Date (mm/dd/yr)	Total Depth (mm)	Total Duration (hr)	Average Intensity (mm/hr)
1	03/06/92	28.0	15	1.90
2	03/10/92	9.1	2	4.60
3	03/18/92	10.4	7	1.50
4	04/30/92	3.6	2	1.80
5	05/05/92	2.0	1.5	1.30
6	05/29/92	26.7	41	0.70
7	06/04/92	50.8	27	1.90

parameters, TSS and TP, were measured for all storms, and Zn was measured only during the 4 June storm. No water quality modifications were made to the pond until the 29 May storm. The results from the particle size analysis for inflow samples are shown in Table A-4.

The results show a fairly wide range of values for all three parameters. An examination of the data yields several items of interest, which are noted here. They include the first flush phenomenon of pollutants into the pond and the variable ranges of pollutants into and out of the pond.

A first flush trend was observed for most storms. This is reflected by higher concentrations of pollutants at the early stages of the storm and a decreasing concentration as the storm continues. Figure 19 illustrates this point. This figure is a bar graph plot of TSS concentration at four times during the storm. This was a short storm. The TSS concentrations steadily decreased as the storm continued, with a single peak concentration observed shortly after the start of the storm. The rainfall intensities were fairly uniform for this storm.

However, for longer storms, the single peak does not necessarily hold true. Figure 20 shows the TSS concentrations at various times during the 4 June storm. Two peaks are evident; this is attributed to an intense burst of rainfall that occurred well past the midpoint of the storm. The concentration of solids increased with the increased rainfall intensity. However, it did not approach the initial first flush concentration levels.

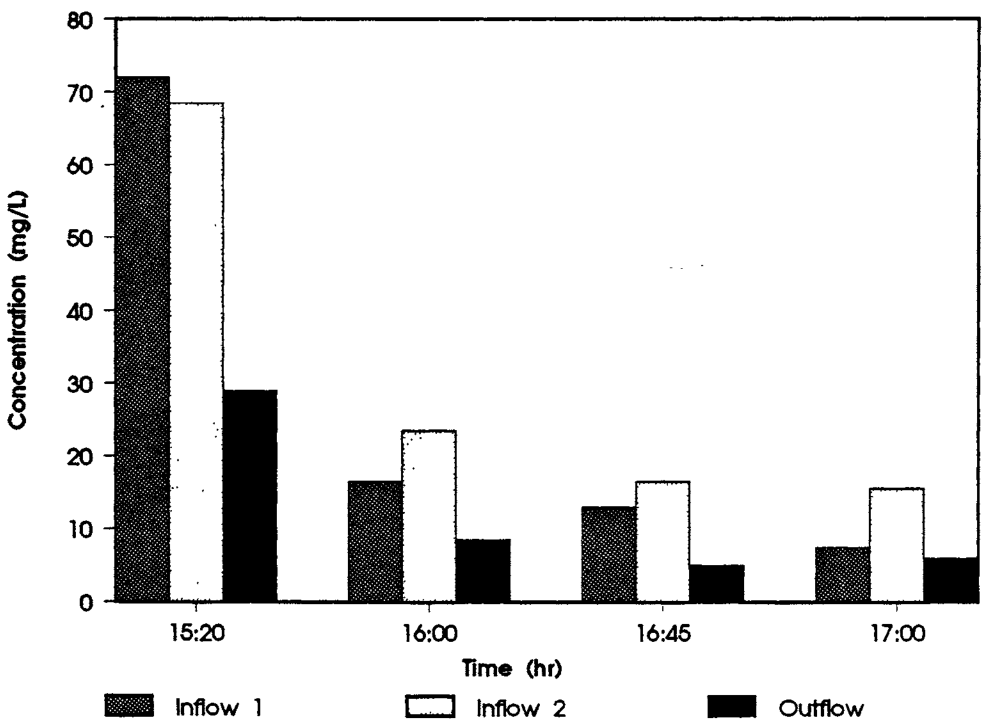


Figure 19. RELATIVE POLLUTANT CONCENTRATIONS OF TSS FOR 30 APRIL STORM.

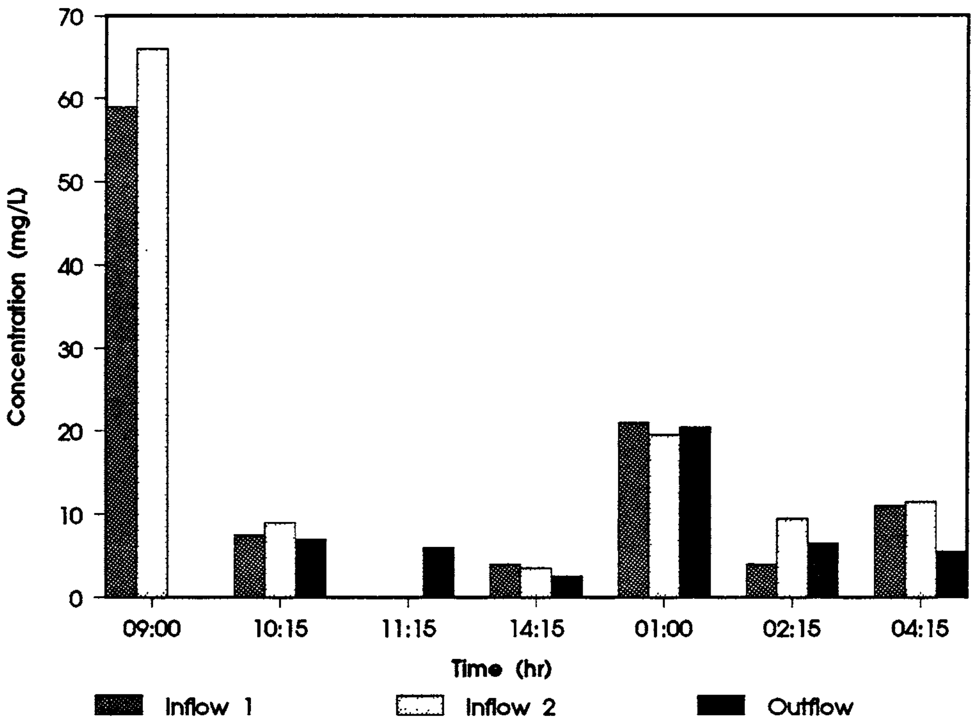


Figure 20. RELATIVE POLLUTANT CONCENTRATIONS OF TSS FOR 4 JUNE STORM.

Pollutant concentrations for the three parameters varied during a storm as well as from storm to storm. The ranges and average concentrations for all data were collected and analyzed. The summary results are shown in Table 7. The results show that the data for the pond site were fairly consistent. Table 8 presents the average pollutant concentrations with respect to the location into and out of the detention pond. A cursory review of the data suggests that concentrations into the pond are generally higher than concentrations out of the pond. The only deviation from this trend is for TP. This could be attributed to resuspension of particulate phosphorus. Since settling is the primary removal mechanism, dissolved phases of any pollutant constituents would not be readily removed.

Table 7
RANGES OF POLLUTANT CONCENTRATIONS

Parameter	Number Samples	High (mg/L)	Low (mg/L)	Average (mg/L)
TSS	84	121	N/D	19.7
TP	85	2.99	N/D	0.68
Zn	18	3.50	N/D	0.76

TSS = total suspended solids; TP = total phosphorus; Zn = total zinc; N/D = below detection.

Table 8
AVERAGE POLLUTANT CONCENTRATION BY LOCATION

Parameter	Inflow 1 (mg/l)	Inflow 2 (mg/l)	Outflow (mg/l)
TSS	23.8 (29)	23.0 (25)	13.0 (30)
TP	0.42 (30)	0.75 (25)	0.87 (30)
Zn	0.76 (6)	0.98 (6)	0.53 (6)

TSS = total suspended solids; TP = total phosphorus; Zn = total zinc; ( ) = number of samples at location.

Individual storm efficiencies were determined for the detention pond for four of the storms monitored. Efficiencies were obtained for the pond's relative ability to remove TSS, TP, and Zn from the runoff entering the pond prior to the discharge into the receiving water. The pollutant flux versus time (or pollutograph) was calculated, and the loading was approximated by the area beneath this curve. Once the constituent loading was determined for each parameter, the pond efficiency was determined by the following equation:[6]

$$\text{Pond efficiency (\%)} = \frac{(\text{Load in} - \text{Load out})}{\text{Load in}} \times 100 \qquad [5]$$

Because of the irregular shapes of many of the storm runoff hydrographs, especially the longer storms with irregular rainfall patterns, the detention time or residence time was approximated by the difference between the center of gravity of the inflow hydrograph and the center of gravity of the outflow hydrograph (Figure 21).

The 30 April and 29 May storms had limited flow data available. Discrete flows were observed as the samples were taken. The mass fluxes were computed in grams per day by multiplying concentrations with corresponding flow rates and were plotted versus time. The mass of pollutant discharged into and out of the detention pond was obtained by computing the areas beneath the pollutographs. Equation 5 was then applied to determine the pollutant removal efficiency for each of the constituents measured.

More detailed flow data were available for the 29 May and 4 June storms. For these storms, a storm mean concentration and an event mean flow rate were determined for each inflow and outflow hydrograph. The storm mean concentration was determined by dividing the mass volume of pollutant runoff (g) (area under pollutograph) by the volume of runoff (m^3) (area under hydrograph) to obtain a mean concentration in milligrams per liter. The mean flow was determined by dividing the volume of runoff (m^3) by the duration of the runoff. Table 9 is a summary of the pollutant mass fluxes and the corresponding removal efficiency. From the data collected to this point, it appears that a detention pond with a short detention time, 1 to 3 hr in this instance, could provide a fairly significant degree of pollutant removal. However, these were individual storm efficiencies that were obtained for

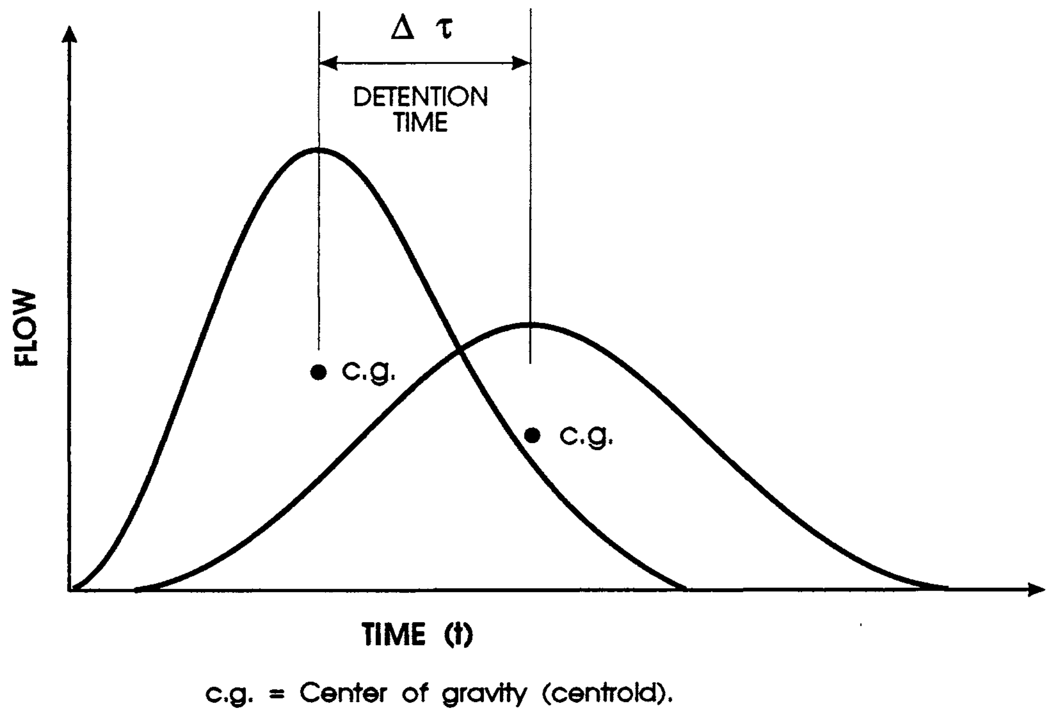


Figure 21. ESTIMATION OF DETENTION TIME.

Table 9
SUMMARY OF POLLUTANT LOADING AND EFFICIENCY

Storm Date	Detention Time (hr)	Pollutant	Pollutant Fluxes (g/d) In	Pollutant Fluxes (g/d) Out	Removal Efficiency (%)
4/30/92	1.5	TSS	757	195	74.2
		TP	27.2	1.7	93.8
		Zn	*	*	*
5/05/92	1.5	TSS	1,234	79	93.5
		TP	30.8	2.5	91.8
		Zn	*	*	*
5/29/92	3.1	TSS	5,140	1666	67.5
		TP	27.6	6.9	74.9
		Zn	*	*	*
6/04/92	3.2	TSS	38,657	9726	80.7
		TP	404	425	–18.6
		Zn	1,030	101	92.5

TSS = total suspended solids; TP = total phosphorus; Zn = total zinc; * = not measured.

four storms only and are in no way a reflection of long-term efficiencies. However, it is evident that the orifice did increase the detention time from approximately 1.5 to 3 hr (refer to Table 9). Indications from previous studies were that greater efficiencies would be gained from increased detention time.[5]

The two storms during which no orifice was in place and that had very short detention times had an unusually high degree of efficiency. These were very low-intensity and low-volume storms, with very low pollutant loadings to the pond. It is likely that the conveyance channel to the pond and the low flow channel through a pond provided enough of a mechanism to reduce the pollutant loads as they moved through the system. It is doubtful that a pond with no orifice in place would have been as efficient with a larger, more intense storm. As discussed, a following intense storm would possibly negate benefits by resuspending previously trapped sediments into the water column. Once the orifice was in place, the analysis appeared to show that the efficiencies decreased. Again, this was a function of the nature of the storm. The storms monitored after the orifice was in place were long, soaking rains with some short, intense bursts of rainfall. Larger volumes of runoff and pollution were generated during these storms. It is reasonable to assume that prior to installation of the orifice the detention pond could not remove the pollutant as efficiently given the same or similar storm.

Particle Size Distribution

PSD was analyzed for two of the storms (29 April and 5 May). From these storms, three samples were analyzed and the PSD in the samples was determined. The data were plotted against information on similar distributions organized by Pitt.[28] The plots (Figures 22 and 23) were shown as percent greater than the particle size versus particle size. The data for this study were plotted along with data developed in other studies to determine consistency. The data from both storms sampled suggested that the runoff contributing to the pond fell very close to the Nationwide Urban Runoff Project (NURP) particle size data.[28] These data are consistent with low solids concentration, which is the case with the pond data (Tables 7 and 8).

Possible Modifications to Detention Ponds

There are numerous modifications that should be considered when designing a dry detention pond that can be implemented to enhance the pollutant removal efficiency of the facility. Many of these modifications could also apply to existing facilities such as the one at Massie Road, which was not designed for water quality enhancement. These modifications include, for example, sediment forbays, baffles, outlet improvements, interactive design with other facilities, and increased maintenance and inspection.

The sediment forbay could be a very cost-effective and simple solution to increasing detention pond efficiencies, especially for dry ponds with very little function as a pollution control facility. These forbays, constructed near the inflow pipe,

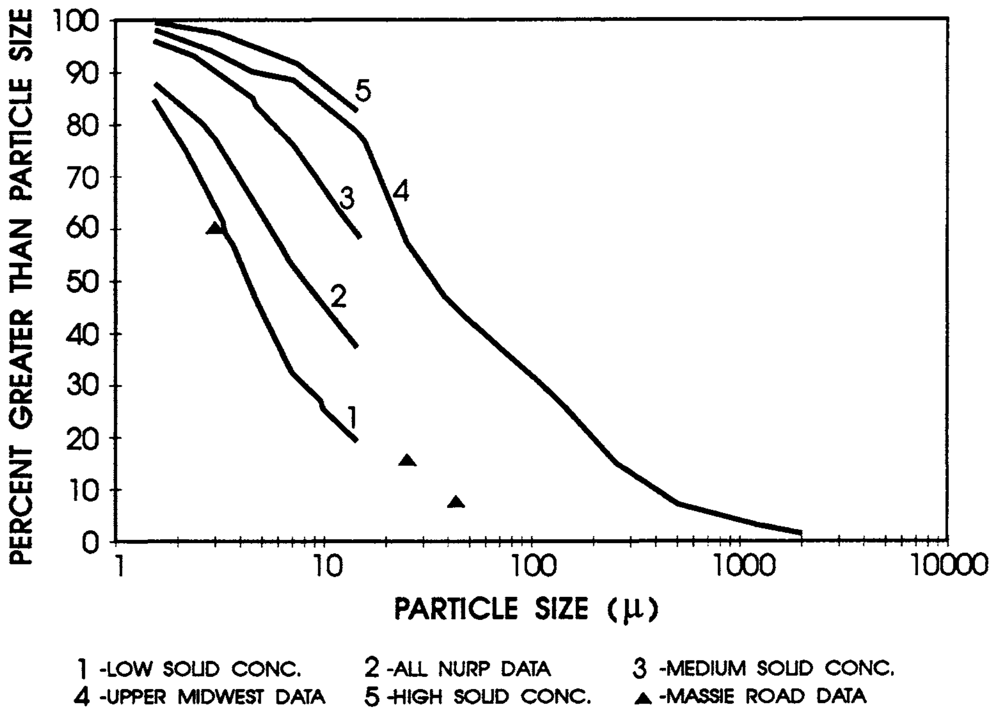


Figure 22. PARTICLE SIZE DISTRIBUTION FOR 30 APRIL STORM RUNOFF VS. REFERENCE DATA FROM OTHER STUDIES. ***Source*: Pitt.[28]**

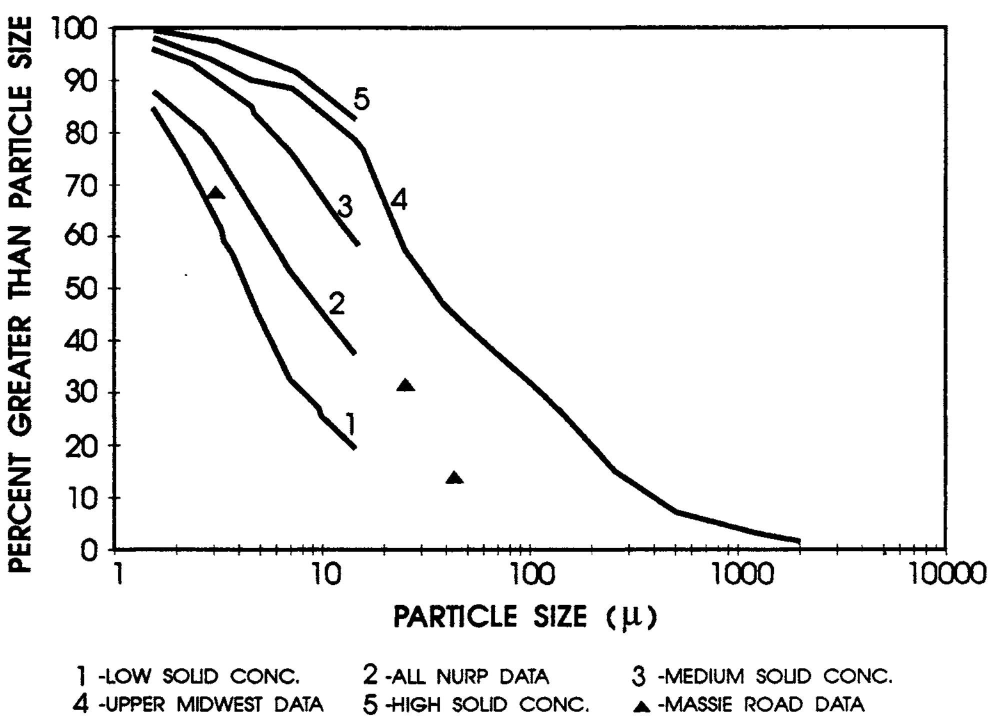


Figure 23. 5 MAY 1992 STORM RUNOFF PARTICLE SIZE DISTRIBUTION VS. REFERENCE DATA FROM OTHER STUDIES. ***Source*: Pitt.[28]**

would help to increase storage of the first flush of runoff and provide a setting basin in the pond to help reduce the particulate portion of the runoff. Inspection and maintenance of these are key to the performance. Without attention, these forbays could become a source of pollution in the pond, decreasing the efficiency.

Baffling could be employed to increase the removal efficiency of dry detention ponds. Baffles are structural modifications to the pond that impede or control the flow direction of the water in the pond. Baffles could be effectively employed to increase the circulation of the water in the pond. This would prevent short circuiting of water directly out of the pond prior to treatment. This technology has been used in water and wastewater treatment for years. This could prove to be very useful in existing ponds or new facilities where the shape is limited by physical features, right-of-way limitations, or any other problem encountered during the design process.

The outlet structure can be modified to improve efficiencies. Installation of skimmers on the outflow structure can reduce the amount of oil and grease and other floatable pollutants exiting the detention pond.

Innovative facility design such as combining two or more BMP facilities can also be employed to increase pollutant removal efficiencies. An example is using vegetative channels as much as possible to convey stormwater to a detention pond. This research as well as other studies has shown that grass-lined swales can be effective in removing pollutants from stormwater. Placing a swale upstream from a detention pond would certainly increase the overall efficiency. Other examples are placing a vegetative filter strip upstream from an infiltration trench and placing a detention pond before a wetland system, as described by Martin and Smoot.[6]

Maintenance is one of the most important aspects contributing to the performance of a dry pond, especially when the conditions are not ideal for pollutant removal. Because settling is the primary mechanism for pollutant removal in dry detention ponds, accumulation of pollutants at the detention pond bottom can lead to resuspension of pollutants and decreased efficiencies. A regular inspection and maintenance program should be developed to ensure that vegetation is properly maintained and in good condition. Sedimentation should be monitored to prevent decreased storage in the pond. Excavation of bottom material at regular intervals could add to increased efficiency of the detention pond.

Vegetated Swale

A summary of the type of data collected at the swale site is presented in Table 10. Table 11 summarizes the ranges of pollutant concentrations at the four sampling locations. Pollutant removal efficiencies of the full length of the swale for the four storms with complete data (storms 2 through 5) are presented in Table 12. All the raw data are presented in Appendix B.

Table 10
STORM SAMPLING SUMMARY

Number	Date	Flow	TSS Concentration	TP Concentration	Zn Concentration
1	March 10, 1992		•	•	
1A	April 20, 1992		•		
2	April 24, 1992	•	•	•	
3	May 8, 1992	•	•	•	
4	May 15, 1992	•	•	•	
5	June 4, 1992	•	•	•	•

Table 11
SUMMARY OF WATER QUALITY ANALYSES (RANGES OF CONCENTRATIONS)

Location	TSS (mg/1)	TP (mg/1)	Zn (mg/1)
0 m	1.50–36.50	0.11–2.77	0.00–0.60
33 m	1.00–33.50	0.22–3.53	0.00–0.38
68 m	1.00–37.00	0.22–2.79	0.00–0.64
100 m	1.00–27.00	0.42–2.31	0.00–0.18

Table 12
REMOVAL EFFICIENCY

Storm Number	Removal Efficiency (%)			Remarks
	TSS	TP	Zn	
2	72	70	—	High intensity, short duration, 2 cm (0.77 in), 40 min; samples collected after rain stopped
3	95	85	—	Low intensity, long duration, 1.6 cm (0.63 in), 4 hr
4	21	32	—	High intensity, short duration, 1.1 cm (0.4 in), 1 hr
5	82	52	74	Low intensity, long duration, 4 cm (1.6 in), 17 hours

TSS = total suspended solids; TP = total phosphorus; Zn = total zinc.

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Overall pollutant removal of the swale was computed by the mass balance method. The swale was effective for lower intensity storms. Several low-intensity storms did not produce significant runoff to be measured over the 100-m length of the swale. However, the swale is not as effective for high-intensity, short-duration storms, such as summer thunderstorms.

The check dam at the 33-m station increased travel time and enhanced infiltration of the initial runoff from the intersection, which improved efficiency. In addition, the less steep slopes from the 68-m station to the 100-m station increased efficiency by increasing travel time.

The effects of scour, species differentiation, biological assimilation, and photocatalysism were considered negligible for the storms studied.

The results from the edge-of-pavement study are presented in Table 13. These results are presented with information provided by the Federal Highway Administration (FHWA).[29] The values obtained were generally low compared with those of the FHWA with respect to TSS but high with respect to TP and Zn. All parameters were well within the FHWA ranges. As compared with the samples taken at the swale site, the average edge-of-pavement values for all parameters were in the high range.

Table 13
SUMMARY OF EDGE-OF-PAVEMENT HIGHWAY RUNOFF CHARACTERISTICS
U.S. 29 at Hydraulic Road, Charlottesville

	Pollutant Concentration from FHWA[28] (mg/l)		Pollutant Concentration from U.S. 29 (mg/l)	
	Average	Range	Average	Range
TSS	261	4–1656	112.9	21–410
TDS	—	—	55.0	20–110
COD	147	4–1058	295.4	86–458
TKN	2.99	0.1–14.0	7.08	3.1–12.6
NO_2+NO_3	1.14	0.01–8.4	1.13	0.5–1.8
TP	0.79	0.05–3.55	3.71	0.91–6.51
ORTHO–P	—	—	1.27	0.28–1.0
O and G	—	—	22.8	10.2–37.0
Cu	0.103	0.01–0.88	0.066	0.04–0.13
Pb	0.96	0.02–13.1	0.105	0.021–0.40
Zn	0.41	0.01–3.4	0.65	0.25–1.60

TSS = total suspended solids; TDS = total dissolved solids; COD = chemical oxygen demand; TKN = total Kjeldahl nitrogen; NO_2+NO_3 = nitrite and nitrate as nitrogen; TP = total phosphorus; ORTHO–P = orthophosphorus; O and G = oil and grease; Cu = total copper; Pb = total lead; Zn = total zinc.

CONCLUSIONS

1. The pollutant removal efficiencies for the dry detention pond and vegetated swale found in this study were consistent with those found in previous studies. Both were effective in reducing TSS, TP, and Zn.
2. From the data collected to this point, it appears that dry detention ponds, if properly designed, with relatively short detention times, could provide a fairly significant degree of pollutant removal. For low-intensity, low-volume storms, the detention time does not seem to play as important a role in removing the pollutants from the water column. However, this cannot be completely borne out by the data presented to this point. More data are needed to determine the long-term average removal efficiency.
3. The actual efficiency of the detention pond alone is likely being masked by the inflow channels that convey the runoff from the two inflow sampling locations to the actual detention pond location. The channel is rock lined, with some vegetation growing through the lining. Some areas are extremely steep (approximately 8 to 10 percent), and some very flat (approximately 1 percent). The channel could be contributing solids in the case of excessive velocities (steep areas) and reducing suspended solids in the case of low velocities (flat areas). The combination of these factors makes it difficult to determine the detention pond efficiency.
4. Design modifications could be employed that would enhance the pollution removal efficiency of a dry detention pond with a short detention time, even for facilities that were not designed or constructed to serve as water quality control structures. Examples are sediment forbays, baffles, and a reduced low flow orifice size.
5. PSD is an important parameter for determining the removal efficiency of a dry detention pond because settling is the main process by which pollutants are removed. Low efficiencies for this pond can be attributed to the distribution of very small particles in the water column, which is consistent with the low solids concentration runoff that is the case at the Massie Road pond.
6. Although efficiencies on the average were comparable to those reported in the literature, the vegetated swale pollutant removal efficiencies are higher if the storms where all the runoff was infiltrated are considered.

RECOMMENDATIONS AND FUTURE RESEARCH

1. *Continue monitoring storms over a more significant time period* for both the dry detention pond and vegetated swale. More storms need to be added to the data base. These storms should be distributed throughout the entire year. Multiple years would also be ideal to allow a closer estimation of the long-term performance of the facilities.

2. *Examine at least two sites simultaneously for each BMP facility,* more than two if the scope of the project would allow. The idea is to examine sites with contrasting design parameters, such as basin size, slopes, traffic data, maintenance, and any other variable of importance. Information at different sites is critical in developing design guidelines for ponds and swales.

3. *Increase the number of parameters sampled in the pond.* Parameters of particular interest would be soluble phosphorus and oil and grease.

4. *Use more accurate / intelligent ("smart samplers") flow monitoring equipment.* The current state of the art has significantly advanced since the last pieces of equipment were purchased. Digital storage and control of the equipment can allow for monitoring more remote sites at any time.

5. *Install "tipping bucket" rain gages at each study site.* Rain intensity is a parameter for estimating pollutant loading and the precipitation is quite variable, even within the city limits of Charlottesville, especially during short, intense, summer storms.

6. *Collect and analyze composite flow samples.* This would allow more storms to be analyzed for less money. The average mass balance could still be used.

7. *At the Massie Road site, add an inflow structure below the point of convergence from inflow 1 (61-cm concrete pipe) and inflow 2 (concrete channel).* This would serve several purposes. First it would reduce the number of monitoring sites from three to two and provide a more streamlined sampling strategy. Second, it would eliminate the variable processes occurring in the riprap-lined channel and allow for exact analysis of the pond efficiency. Third, it would allow for possible analysis of the role the riprap-lined channel may play in the loading of pollutants into the pond; it is possible that in certain storms the channel could significantly reduce loading into the pond and that in other storms the channel could significantly increase the loads to the pond.

8. *Incorporate several design features into the Massie Road pond to increase the relative efficiencies.* For this site, however, two aspects of design should be considered due to the physical limitations at the pond. The first is to increase the length-to-width ratio. This would be achieved by installing a barrier to direct the flow of the runoff through the pond and prevent short circuiting of water out of the pond without receiving the treatment level desired. The second is to increase the detention time by decreasing the orifice diameter. For practical proposes, it would not be desirable to use less than a 7.6-cm (3-in) diameter orifice. However, with the smaller orifices, the relative effects of the increased detention times could be analyzed. Because of size limitations and other physical constraints at the site, the installation of a sediment forbay is not feasible.

9. *Block the lateral inflow at the swale by using barriers so that a more accurate flow and mass balance can be obtained.* Evaluate the effects of check dams on removal efficiency. Figure 24 depicts the swale and the proposed barriers to lateral inflow.

10. *Design the height of the check dam to retain the first 1.27 cm (0.5 in) of runoff for the drainage area* if the soil can infiltrate that amount in less than 24 hr.

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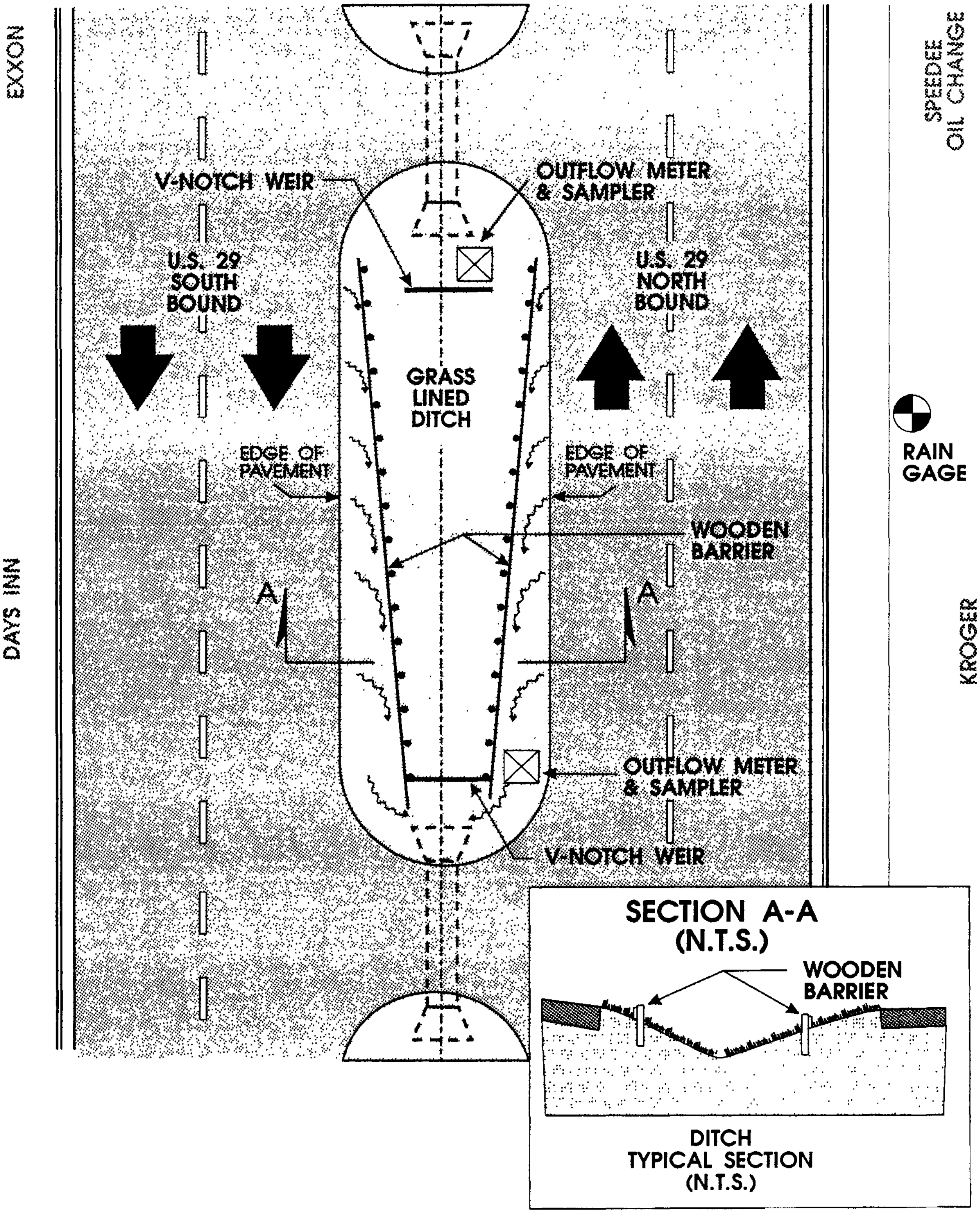

Figure 24. PROPOSED SWALE WITH BARRIER TO LATERAL INFLOW.

11. *Investigate a method for estimating the actual amount of infiltration.* Yousef et al.[23] in a Florida study reported differences between the theoretical and measured infiltration rates.

12. *Analyze dustfall, especially at the swale site.* Dustfall (air particulate fallout) measurements should be made at each site to assess the effects of the adjoining land use activity on the accumulation of pollutants. The mass contributed by air particulate could then be determined on a quantitative basis. A dustfall collection bucket can be placed in the middle of the swale 2 to 3 m above the ground (recommended ASTM method). The collected dust contents could be analyzed after each storm.

13. *Analyze underdrains for the swale.* An underdrain may increase the infiltration rate and thus increase the removal efficiency, especially for low-to-medium-intensity storms. Examination should include the cost and benefits of an underdrain as well.

14. *Evaluate the long-term effects of the accumulation of pollutants in each facility.* Do the facilities retain pollutants for a period of time and then discharge them during extreme runoff? This answer will be critical to any maintenance programs for BMP facilities, which will be the key to the long-term efficiency.

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Appendix A
DETENTION POND FIELD DATA

Table A-1
POLLUTANT CONCENTRATIONS
FOR 6, 10, AND 18 MARCH STORMS

	Inflow 1 Concentration (mg/l)		Inflow 2 Concentration (mg/l)		Outflow Concentration (mg/l)	
Time	**TSS**	**TP**	**TSS**	**TP**	**TSS**	**TP**
6 March 1992						
16:40	64.0	0.18	*	*	43.5	0.77
17:35	80.0	0.57	*	*	68.0	1.08
18:30	24.0	0.04	*	*	24.0	0.62
21:00	12.0	0.00	*	*	12.5	0.72
10 March 1992						
09:00	59.0	1.14	66.0	2.61	*	*
10:15	7.5	0.01	9.0	0.27	7.0	0.22
11:15	*	*	*	*	6.0	0.38
14:15	4.0	0.23	3.5	*	*	*
18 March 1992						
15:45	2.0	0.32	2.5	0.18	1.5	0.47
16:15	0.5	0.33	4.5	0.70	0.5	0.57
17:00	9.0	0.43	22.0	0.75	0.5	0.59
20:00	*	0.24	5.0	1.14	0.0	0.51

TSS = total suspended solids; TP = total phosphorus; * = not measured.

Table A-2
POLLUTANT CONCENTRATIONS
FOR 30 APRIL, 5 MAY, 29 MAY, AND 4 JUNE STORMS

	Inflow 1 Concentration (mg/l)			Inflow 2 Concentration (mg/l)			Outflow Concentration (mg/l)		
Time	**TSS**	**TP**	**Zn**	**TSS**	**TP**	**Zn**	**TSS**	**TP**	**Zn**
30 April 1992									
15:20	72.0	1.24	*	68.5	2.10	*	29.0	0.70	*
16:00	16.5	0.26	*	23.5	0.60	*	8.5	0.63	*
16:45	13.0	0.32	*	16.5	0.36	*	5.0	0.09	*
17:00	7.5	0.13	*	15.5	0.27	*	6.0	0.22	*
5 May 1992									
04:50	121	2.99	*	88.0	2.02	*	*	*	*
05:15	*	*	*	24.0	0.33	*	*	*	*
05:30	25.0	1.63	*	*	*	*	*	*	*
05:45	*	*	*	*	*	*	23.0	0.84	*
06:15	*	*	*	6.5	0.29	*	*	*	*
06:30	5.0	0.64	*	*	*	*	7.0	0.22	*
07:15	*	*	*	*	*	*	6.0	0.03	*
29 May 1992									
22:00	12.0	0.22	*	19.5	0.82	*	*	*	*
22:10	*	*	*	*	*	*	38.0	0.78	*
22:15	7.0	0.07	*	10.0	0.51	*	*	*	*
22:30	3.0	0.23	*	12.0	0.35	*	*	*	*
22:40	*	*	*	*	*	*	2.0	0.35	*
23:15	*	*	*	*	*	*	7.0	0.20	*
30 May 1992									
11:30	21.0	0.01	*	39.0	0.56	*	*	*	*
11:40	*	*	*	*	*	*	5.0	0.24	*
12:00	*	*	*	*	*	*	20.0	0.16	*
12:30	12.0	0.00	*	16.0	0.45	*	10.5	0.39	*
16:00	7.0	0.01	*	5.0	0.43	*	11.0	0.01	*
4 June 1992									
09:00	59.0	1.14	0.60	66.0	2.61	3.50	*	*	*
10:15	7.5	0.01	2.70	9.0	0.27	2.00	7.0	0.22	2.80
11:15	*	*	*	*	*	*	6.0	0.38	0.20
14:15	4.0	0.23	0.80	3.5	0.03	0.20	2.5	0.45	0.20
5 June 1992									
01:00	21.0	0.06	0.23	19.5	0.89	0.04	20.5	0.61	0.00
02:15	4.0	0.01	0.00	9.5	0.16	0.16	6.5	0.24	0.00
04:15	11.0	0.01	0.00	11.5	0.06	0.00	5.5	0.27	0.00

TSS = total suspended solids; TP = total phosphorus; Zn = total zinc; * = not measured.

Table A-3
FLOW DATA FOR 30 APRIL, 5 MAY STORMS

Time	Inflow 1 Flow ($x10^{-3}$ cm)	Inflow 2 Flow ($x10^{-3}$ cm)	Outflow Flow ($x10^{-3}$ cm)
30 April 1992			
15:20	1.9	0.8	0.2
16:00	1.5	0.1	1.2
16:45	2.0	0.8	6.0
17:00	1.5	0.1	2.9
5 May 1992			
04:50	3.5	0.5	0.0
05:15	*	0.4	0.0
05:30	0.1	*	0.0
05:45	*	*	1.4
06:15	*	0.01	*
06:30	0.1	*	0.5
07:15	*	*	0.2

Flow measurements taken manually.

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Table A-4
PARTICLE SIZE DISTRIBUTION DATA

	Inflow 1	Inflow 2	Outflow
Particle Size (μ)	Cumulative Fraction of Particles Less Than Indicated Size (%)	Cumulative Fraction of Particles Less Than Indicated Size (%)	Cumulative Fraction of Particles Less Than Indicated Size (%)
30 April 1992			
3	37	43	37
25	89	80	87
43	95	91	100
5 May 1992			
3	20	43	37
25	57	80	87
43	80	91	100

Sample Information

30 April 1992

Rain depth (at time of sample): 5.2 mm
Collected 20 min after storm began
Sample taken from inflows 1 and 2; results averaged

5 May 1992

Rain depth (at time of sample): 2.0 mm
Collected 25 min after storm began
Sample taken from inflows 1 and 2; results averaged

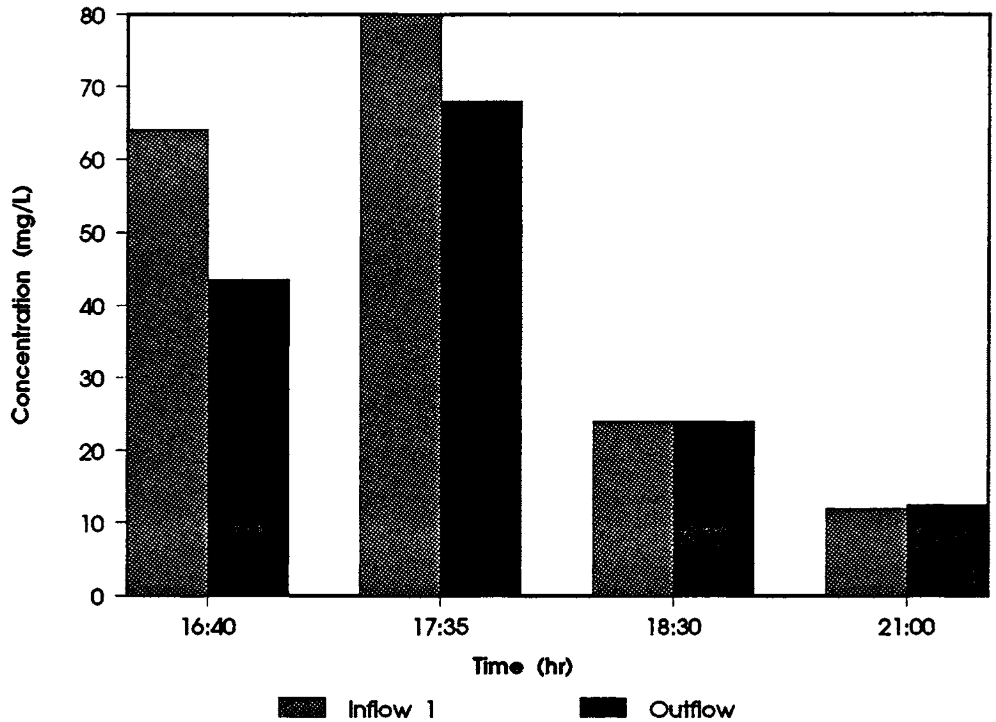

Figure A-1. TOTAL SUSPENDED SOLIDS, 3/06/92.

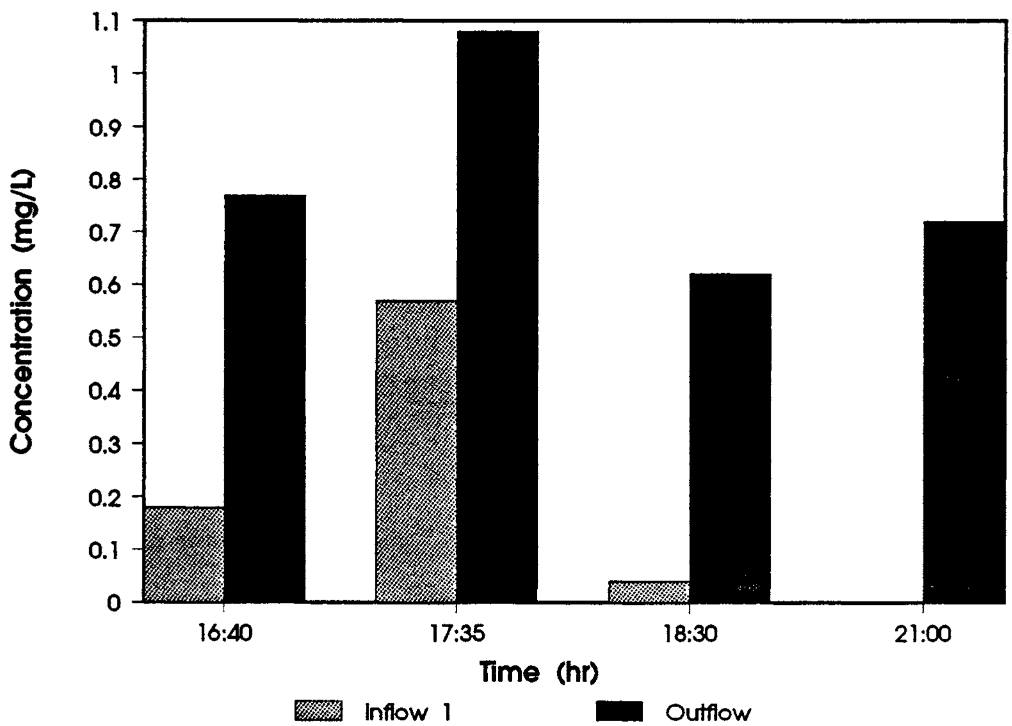

Figure A-2. TOTAL PHOSPHORUS, 3/06/92.

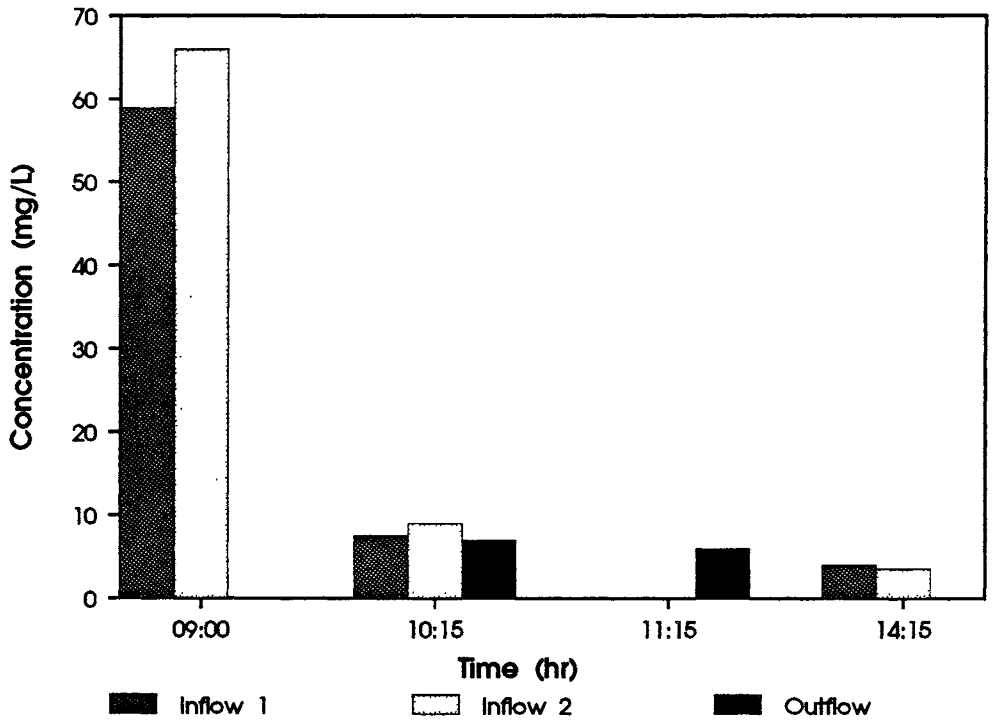

Figure A-3. TOTAL SUSPENDED SOLIDS, 3/10/92.

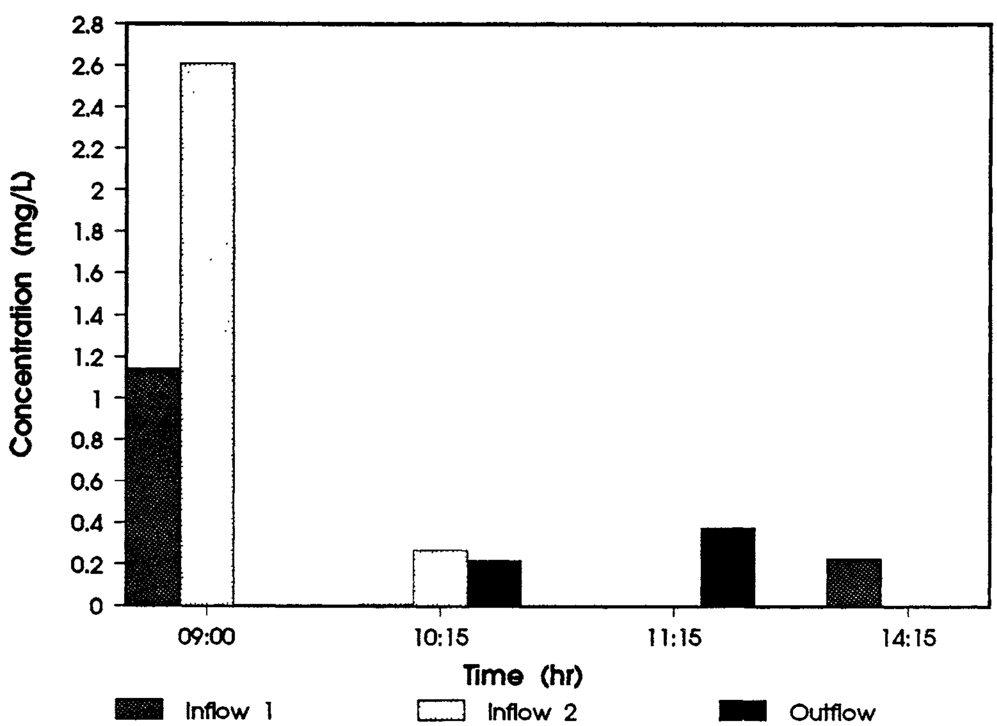

Figure A-4. TOTAL PHOSPHORUS, 3/10/92.

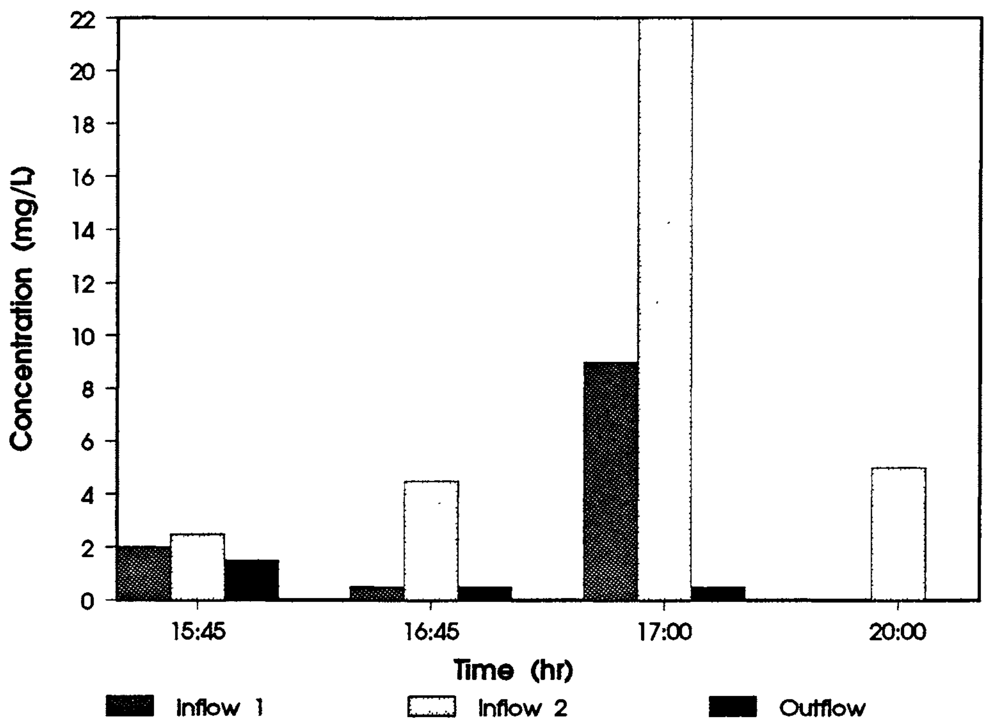

Figure A-5. TOTAL SUSPENDED SOLIDS, 3/18/92.

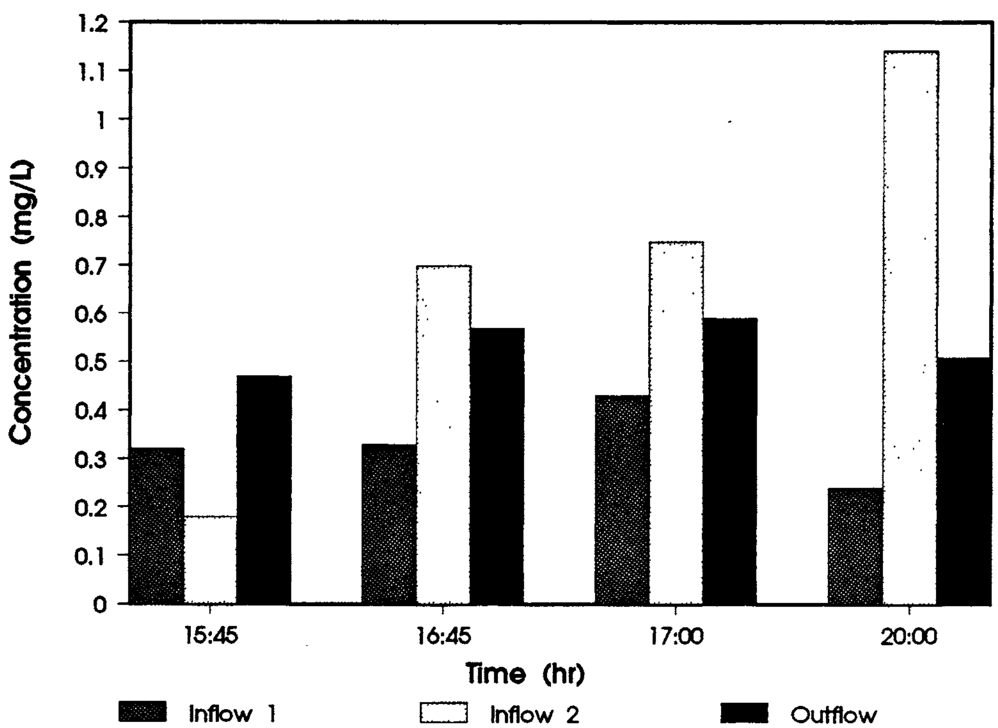

Figure A-6. TOTAL PHOSPHORUS, 3/18/92.

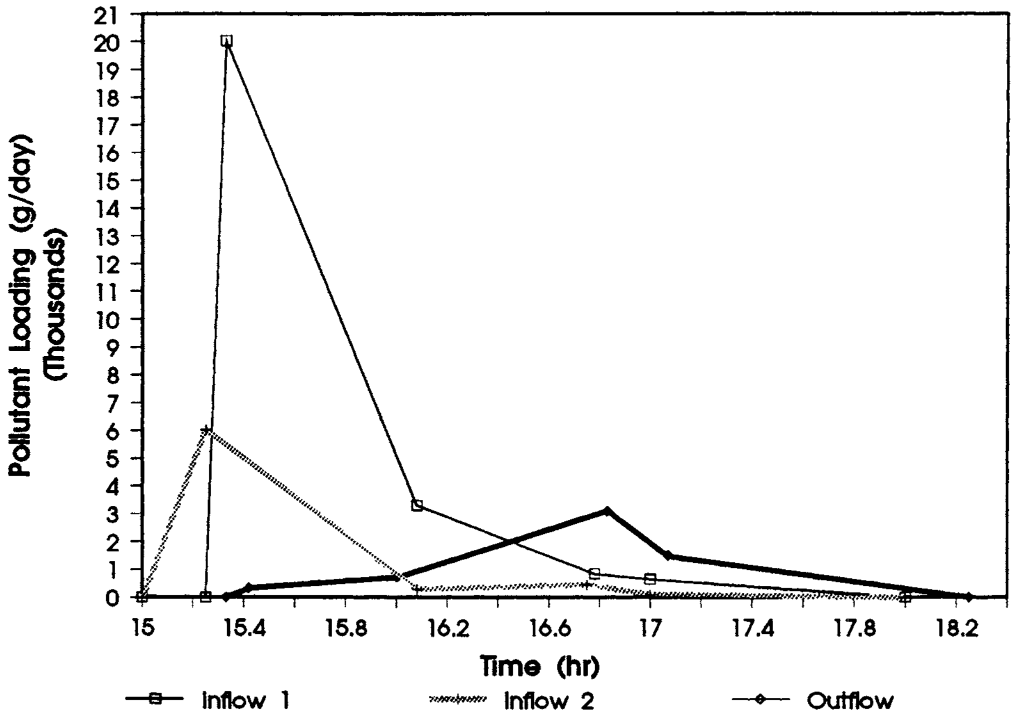

Figure A-7. TOTAL SUSPENDED SOLIDS LOADOGRAPH, 4/30/92.

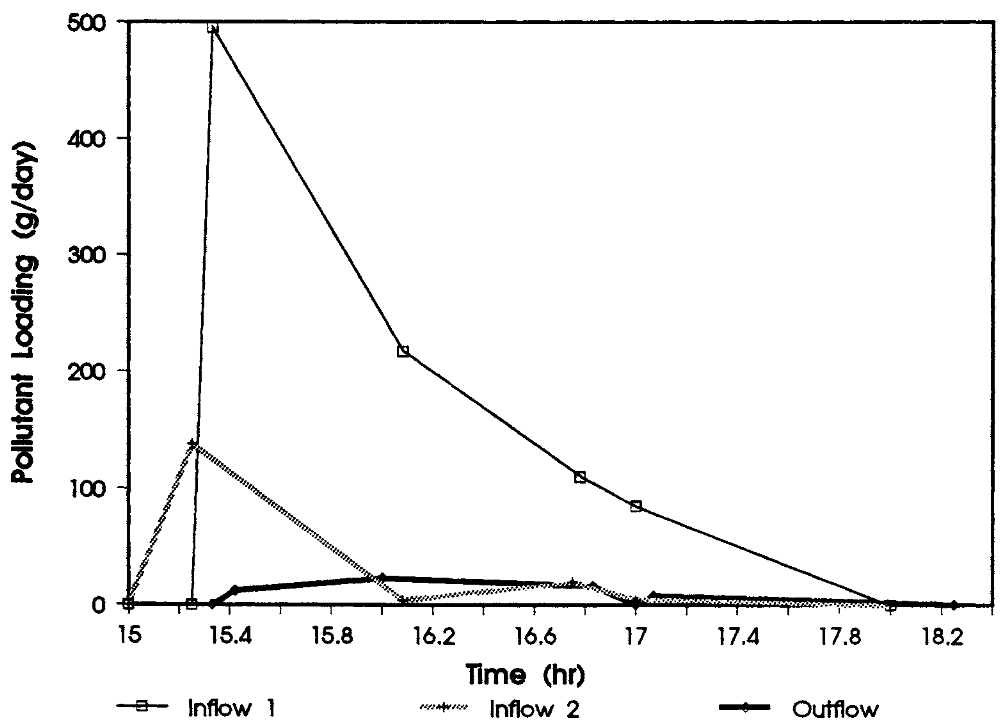

Figure A-8. TOTAL PHOSPHORUS LOADOGRAPH, 4/30/92.

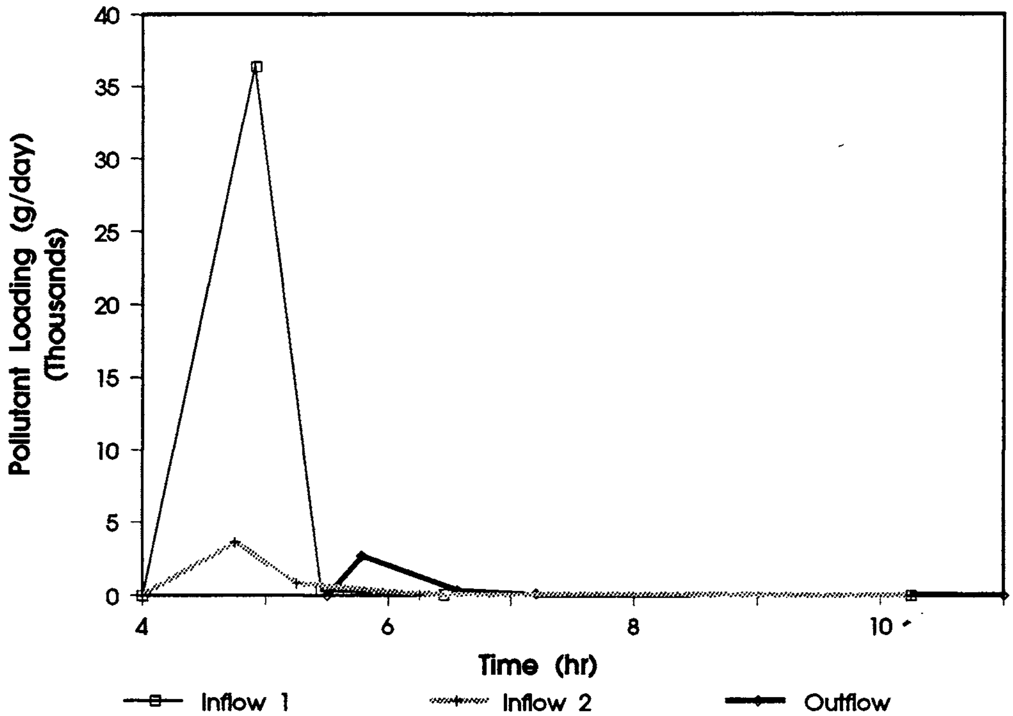

Figure A-9. TOTAL SUSPENDED SOLIDS LOADOGRAPH, 5/05/92.

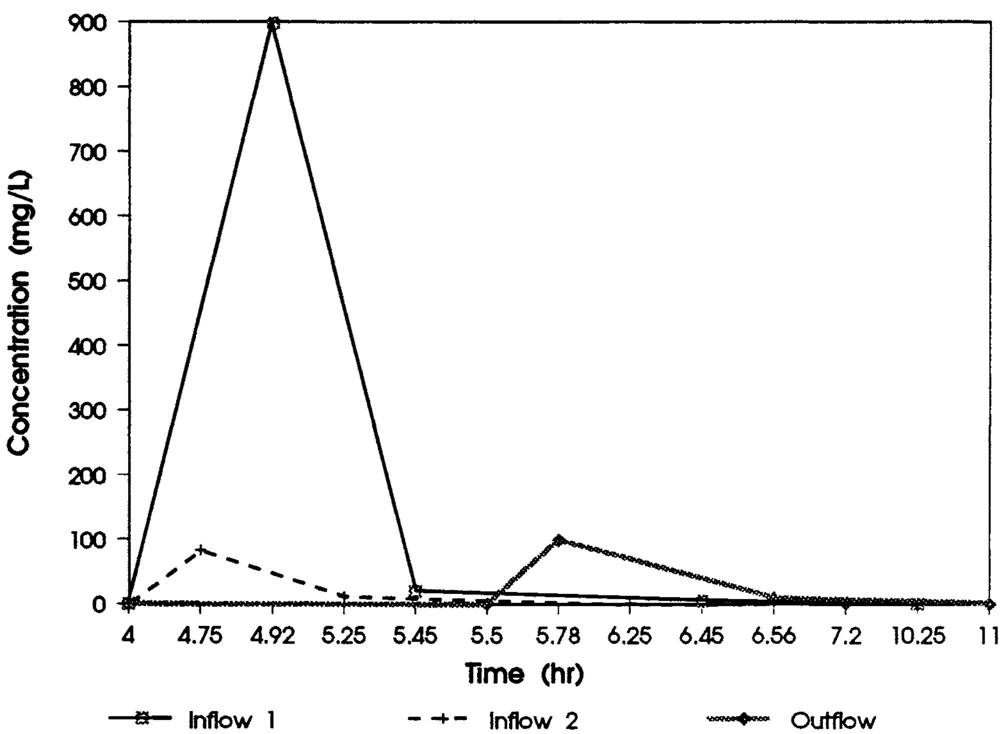

Figure A-10. TOTAL PHOSPHORUS LOADOGRAPH, 5/05/92.

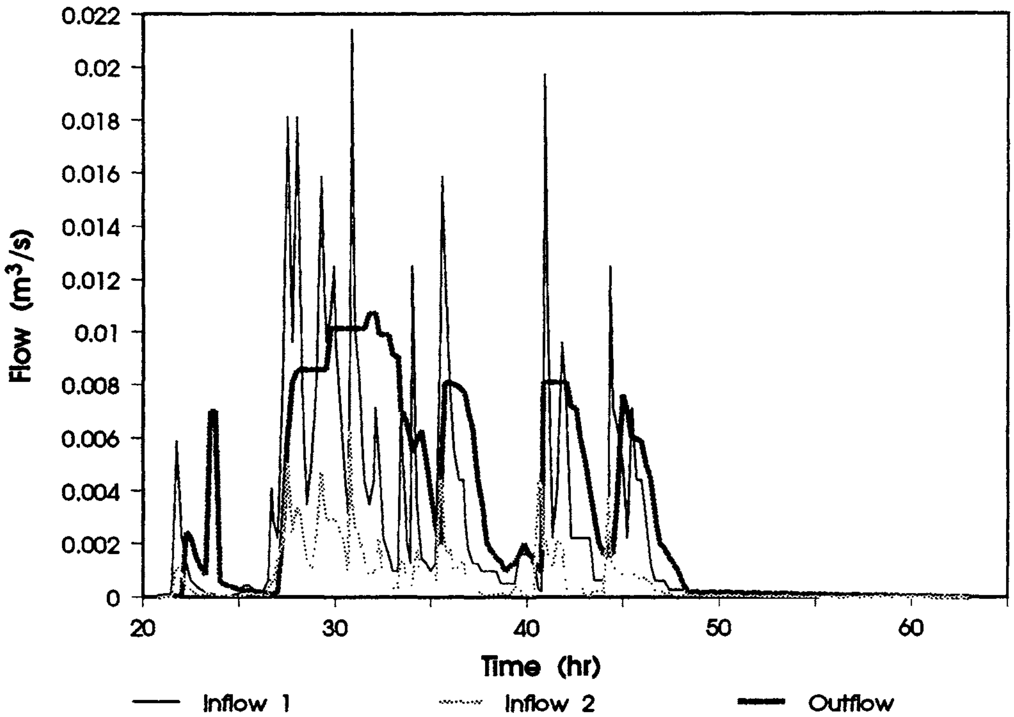

Figure A-11. RUNOFF HYDROGRAPH, 5/29/92.

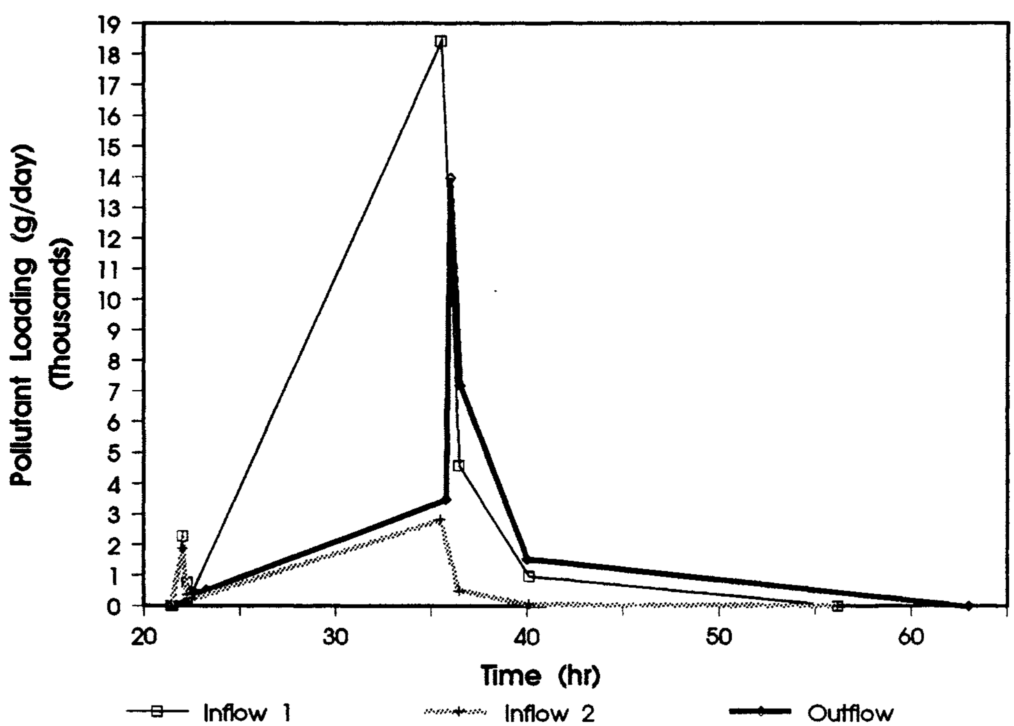

Figure A-12. TOTAL SUSPENDED SOLIDS LOADOGRAPH, 5/29/92.

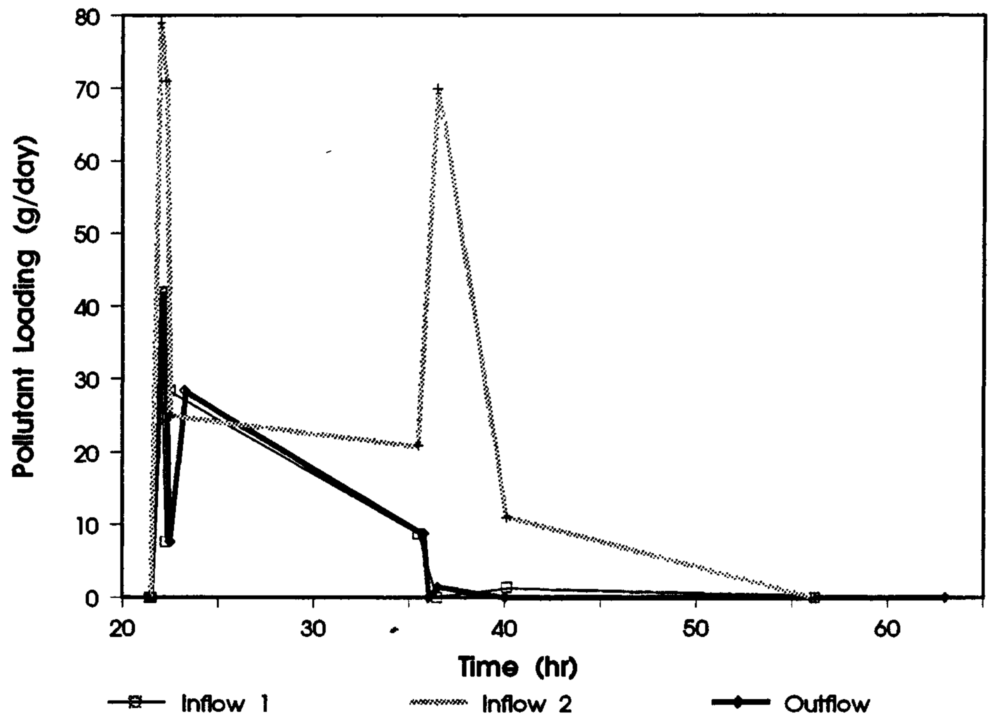

Figure A-13. TOTAL PHOSPHORUS LOADOGRAPH, 5/29/92.

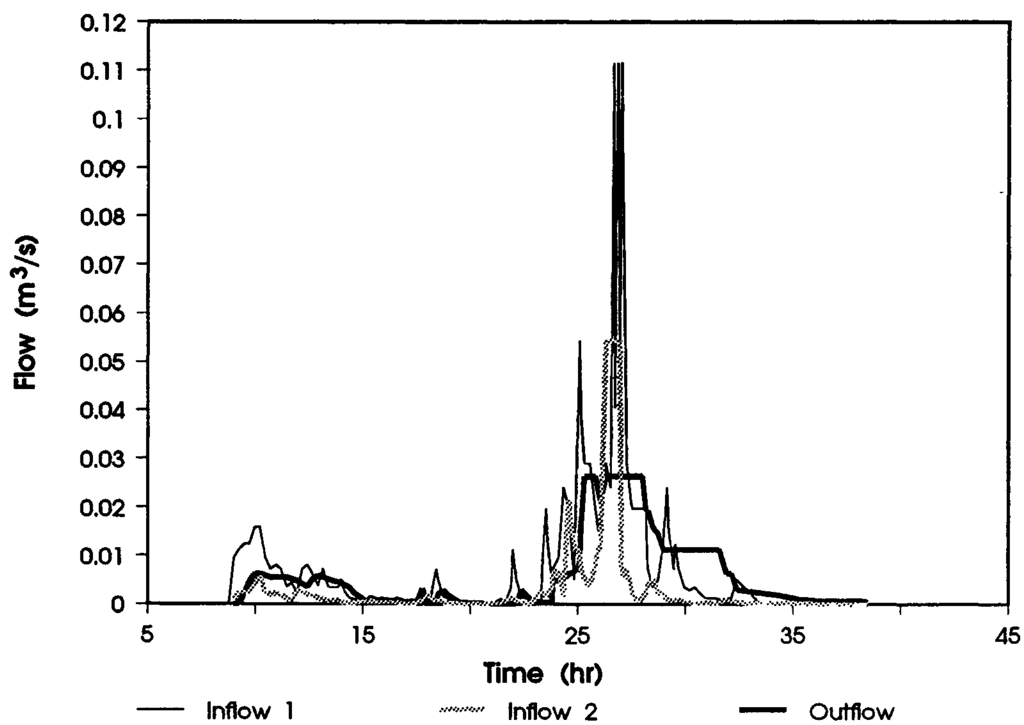

Figure A-14. RUNOFF HYDROGRAPH, 6/04/92.

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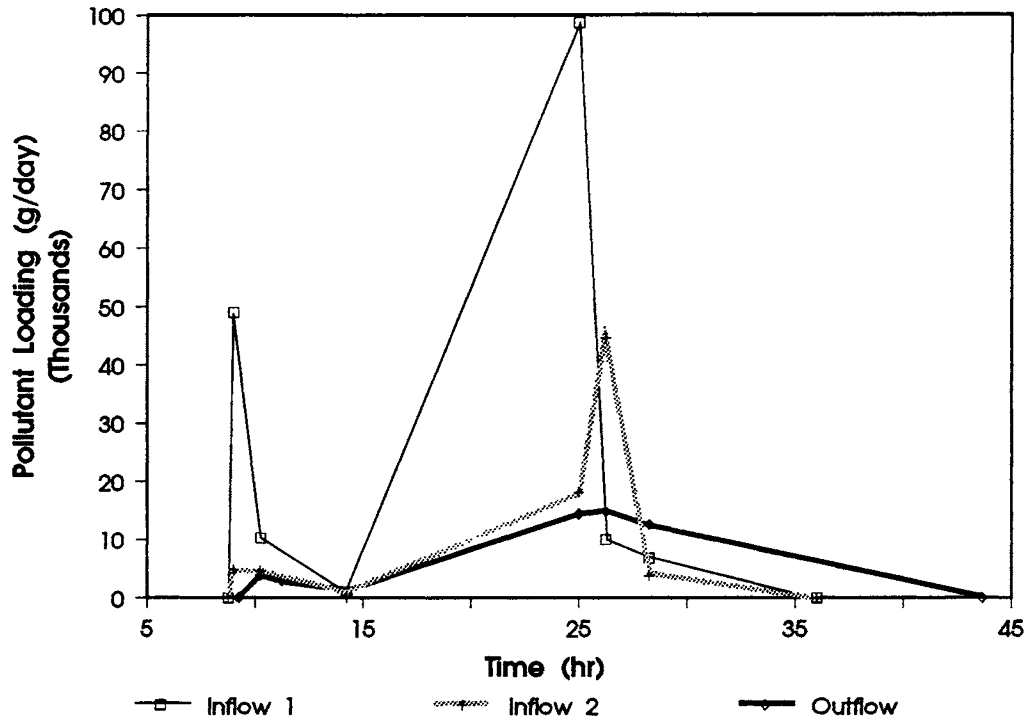

Figure A-15. TOTAL SUSPENDED SOLIDS LOADOGRAPH, 6/04/92.

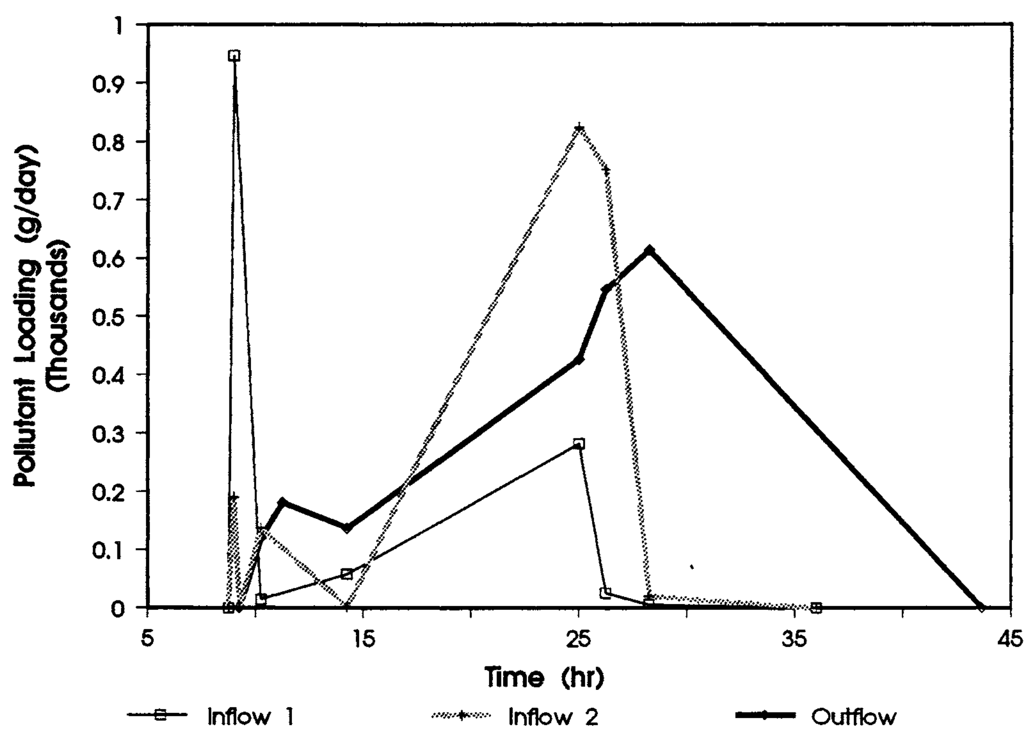

Figure A-16. TOTAL PHOSPHORUS LOADOGRAPH, 6/04/92.

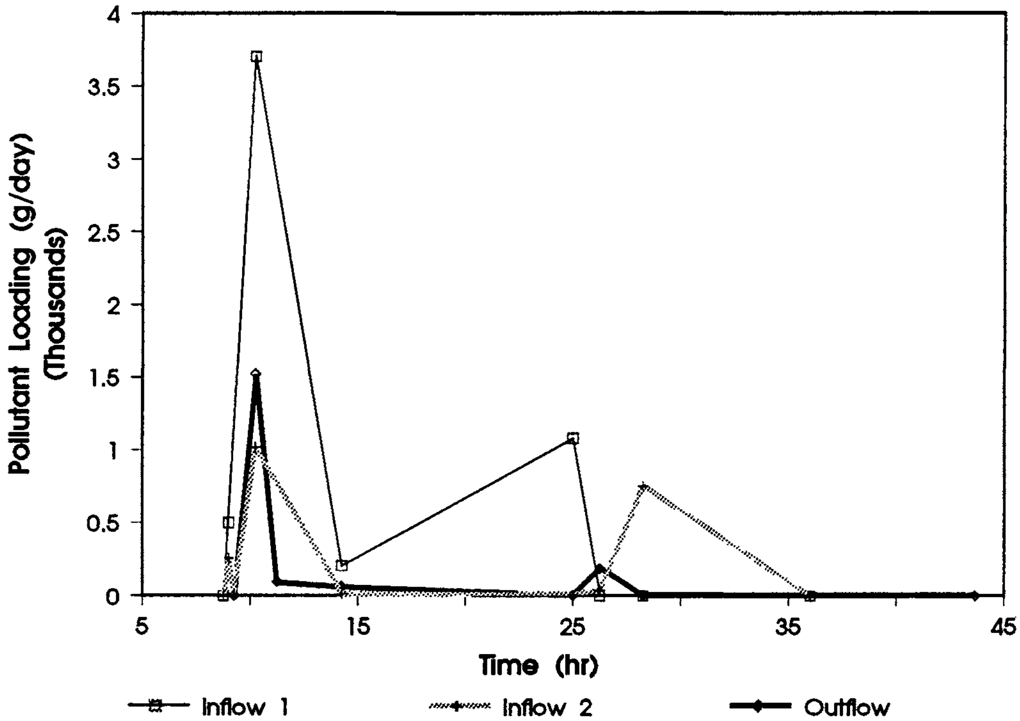

Figure A-17. TOTAL ZINC LOADOGRAPH, 6/04/92.

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Appendix B
VEGETATED SWALE FIELD DATA

Table B-1
INDIVIDUAL STORM DATA
(Concentration mg/l, flow cm)

Storm 1—March 10, 1992

	0 m		33 m		68 m		100 m	
Time	TSS	TP	TSS	TP	TSS	TP	TSS	TP
1500	8	1.12	21.5	0.59	25.5	1.30	26	1.33
1630	–	2.77	33.5	3.53	37	2.79	25.5	1.76

Storm 2—April 20, 1992

Time	0 m TSS	33 m TSS	68 m TSS	100 m TSS
1 –?	9.2	13.4	6.5	11
2 –?	–	9	12	11.5
3 –?	10.5	–	–	4.5

	0 m			33 m			68 m			100 m		
Time	TSS	TP	Flow	TSS	TP	Flow	TSS	TP	Flow	TSS	TP	Flow
Storm 2a—April 24, 1992												
1739	–	–	0	9	0.88	0.5749	6.5	0.84	0.6832	4	0.42	0.8028
1800	–	–	0	7.5	0.84	0.0251	10.5	0.8	0.0691	4	0.44	0.1016
Storm 3—May 8, 1992												
0642	12	0.63	0.3171	9.5	0.58	0.3171	10	0.74	1.2176	9	0.68	1.2176
0700	20	0.68	0.7702	6.5	0.7	0.5918	8	1.64	1.2176	8	0.93	1.4866
0730	7	0.82	0.0793	7.5	0.66	0.2152	7	0.68	0.6654	10	0.95	0.7702
0845	36.5	1.32	1.2176	10	0.75	0.1359	11	1.17	0.1359	16	1.36	0.1359
1030	20	0.54	0.0028	12	0.38	0.0028	12.5	0.89	0.0368	8	1.09	0.0368

continues

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Table B-1 (continued)

	0 m			33 m			68 m			100 m		
Time	TSS	TP	Flow	TSS	TP	Flow	TSS	TP	Flow	TSS	TP	Flow
Storm 4—May 15, 1992												
0325	1.5	0.2	1.2176	9	1.37	1.2176	18.5	1.78	1.7896	27	2.31	0.7702
0340	1.5	0.11	0.4417	4	0.61	0.5918	8.5	1	1.7896	10	1.35	2.2166
0355	6	0.28	0.0793	8.5	0.22	0.1359	7.5	0.22	0.7702	8.5	0.96	0.9798
0418	4.5	0.35	0.1359	9	0.39	0.0793	9	1.55	0.3171	7.5	1.2	0.2152

	0 m				33 m				68 m				100 m			
Time	TSS	TP	Zinc	Flow	TSS	TP	Zinc	Flow	TSS	TP	Zinc	Flow	TSS	TP	Zinc	Flow
Storm 5—June 4, 1992																
0945*	21	2.62	0.6	0.2152	5	1.88	0.02	0.1359	21	2.15	0.22	0.4417	7	1.65	0.12	0.4417
1100	15	1.46	0.24	0.1359	11	1.56	0.38	0.0142	15	1.89	0.64	0.3171	24	2.07	0.1	0.4417
1400	5	1.14	0.08	0.0793	1	0.8	0	0	1	1.31	0.02	0.1359	2	1.62	0.18	0.2152
2520	21	1.19	0.18	1.2176	15	0.98	0	1.2176	3	0.7	0	2.9081	1	0.6	0	2.9081
2600	4	0.17	0	0.4417	–	0.27	0.08	0.7702	12	0.76	0	1.2176	1.5	0.64	0.1	1.4866
2700	3	–	0	1.7896	12	–	0	3.3527	3	–	0.04	5.0970	1	–	0.02	5.5388

* 0 m sample taken at 945; other samples taken at 1030.