U.S. Department
of Transportation
**Federal Highway
Administration**

Publication No. FHWA-RD-96-095
November 1996

Retention, Detention, and Overland Flow for Pollutant Removal from Highway Stormwater Runoff

Volume I: Research Report

Research and Development
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FOREWORD

The highway system may be a source of a wide variety of pollutants to nearby surface and groundwater. The effects of highways on water resources can have an important role in the planning, design, construction, and operation of a transportation system.The Federal Highway Administration and State highway agencies have approached the problem in a multi-phase research effort including studies to:

Phase 1 - Identify and quantify the constituents of highway runoff.
Phase 2 - Identify the sources and migration paths of these pollutants from the highways to the receiving waters.
Phase 3 - Analyze the effects of these pollutants in the receiving waters.
Phase 4 - Develop the necessary abatement/treatment methodology for objectionable constituents.

This investigation was part of the Phase 4 effort.Three management methods to remove or treat highway stormwater pollutants have been identified: vegetative controls utilizing overland flow of runoff, detention basins and wetlands, and retention basins.This study was designed to: (1) quantify, by laboratory bench-scale testing, the rates of pollutant removal from highway stormwater samples, (2) evaluate a variety of representative appropriate field installations, (3) assess the performances of these management methods, and (4) develop guidelines and specifications to assist in the implementation of the technology.

The final report of this investigation has two volumes: FHWA-RD-96-095 Volume I: Research Report and FHWA-RD-96-096 Volume II: Design Guidelines.

These publications will be of interest to highway engineers and environmental practitioners involved in planning and designing for the mitigation of highway runoff water quality impacts to surface and ground water. Copies of these publications are being distributed to the Federal Highway Administration regional and division offices and to each State highway agency. Additional copies may be obtained from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161.

Charles J. Nemmers, P.E.
Director, Office of Engineering R&D

NOTICE

Technical Report Documentation Page

1. Report No.
FHWA-RD-96-095

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
RETENTION, DETENTION, AND OVERLAND FLOW FOR POLLUTANT REMOVAL FROM HIGHWAY STORMWATER RUNOFF

Volume I: Research Report

5. Report Date
November 1996

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.

9. Performing Organization Name and Address

Versar, Inc.
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10. Work Unit No. (TRAIS)
3K7A

11. Contract or Grant No.
DTFH61-85-C-00117

12. Sponsoring Agency Name and Address
Federal Highway Administration
Office of Research, Development and Technology
6300 Georgetown Pike
McLean, VA 22101-2296

13. Type of Report and Period Covered
Final Report - Volume I
September 1985 - June 1989

14. Sponsoring Agency Code

15. Supplementary Notes
FHWA Contract Manager (COTR): Mr. Douglas Smith, HNR-20

16. Abstract

This volume is the second in a two-volume report entitled "Retention, Detention, and Overland Flow for Pollutant Removal From Highway Stormwater Runoff." The research developed design guidelines and specifications for measures to reduce or eliminate the impacts of highway runoff on surface waters. The titles of the volumes of this report are:

FHWA-RD-96-095	Vol. I.	Research Report
FHWA-RD-96-096	Vol. II.	Design Guidelines

This volume documents the research performed under this project. It presents the findings of literature reviews, laboratory bench-scale testing, and actual field monitoring of pollution control measures (grassed channels and wet detention basins).

"Retention, Detention, and Overland Flow for Pollutant Removal from Highway Stormwater Runoff. Interim Guidelines for Management Measures" (FHWA-RD-87-056) are available.

17. Key Words
Best management practices, Wetlands,
Pollutant mitigation, Detention,
Highway runoff, Retention,
Vegetative controls, Overland flow,
Grassed channels, Infiltration

18. Distribution Statement
No restriction. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
179

22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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1. INTRODUCTION

1. BACKGROUND OF FHWA INVESTIGATIONS

The Clean Water Act (PL 95-217), as amended, set forth national policy and national water quality programs to restore and maintain the chemical, physical, and biological integrity of water resources. To realize the objectives of the Act, the following were established as national goals:

- That the discharge of pollutants into the navigable waters be eliminated.
- That, wherever attainable, an interim goal of water quality, which provides for recreation in and on the water, be achieved.
- That a major research and demonstration effort be made to develop technology necessary to eliminate the discharge of pollutants into the water resources.
- The Federal agencies cooperate with State and local agencies in minimizing pollution.

The Federal Highway Administration (FHWA) has purview over protecting the environment from pollution by highway sources under the Clean Water Act and other Federal laws. The FHWA, in response, has initiated a cooperative Federal and State research program to identify and quantify the effects of highway runoff and to develop management practices for the protection of water resources. The FHWA has approached the problem in a four-phase contract research program, as follows:

1. Identify and quantify the constituents of highway runoff.
2. Identify the sources of these pollutants and migration paths from the highway to the receiving water.
3. Analyze the effects of these pollutants in receiving waters.
4. Develop the necessary analytical tools and abatement/treatment criteria and guidelines to minimize the effects of objectionable constituents.

Phases 1, 2, and 3 are now complete. Phase 4 has been addressed by three research projects. The first research project is complete and constitutes a literature review and state-of-the-art synthesis of stormwater best management practices (BMP) applicable to highway systems. (Burch, et al. 1985a; Burch, et al. 1985b; Maestri, et al. 1985a; and

Maestri, et al. 1985b) The second research project is the purpose of this report and is a continuation the first project in Phase 4. The objective of this project is the development of design guidelines and specifications through the evaluation of retention (infiltration), detention (basins and wetlands), and overland flow (including vegetated channels) measures for pollutant removal from highway stormwater runoff based on additional literature reviews and laboratory/fielding testing. These guidelines are presented under a separate cover.

The third research project is nearing completion and will improve upon the existing procedures for estimating pollutant loadings from highways.

2. PURPOSE AND SCOPE OF PROGRAM

The purpose of this research project is to complete the FHWA's investigations into controlling various pollutants contained in highway stormwater runoff. This project specifically investigated the effectiveness of retention, detention, and overland flow mitigation measures for pollutant removal efficiencies. Throughout the duration of the project, the following was performed: a review of current practices and knowledge of the effectiveness of these systems, preparation of interim guidelines, bench-scale (laboratory) testing to determine key design parameters, and field testing of identified sites via sampling and analysis of highway stormwater runoff that passes into and out of actual mitigation measures. The ultimate goal of this project was the development of implementable design criteria, guidelines, and specifications for each mitigative measure demonstrated to be cost effective for pollutant removal. These criteria and guidelines are to be used by State highway engineers and planners to control the runoff of pollutants from existing urban arterial highways and high-volume freeways and in new designs.

The approach taken for this research project consisted of 5 steps (10 tasks):

1. Preparation of Interim Guidelines

   Task A: State of the Technology Review
   Task B: Identification of Potential Pollutant Removal Systems

2. Design and Implementation of Laboratory Study

   Task C: Development of Laboratory Work Plan
   Task D: Laboratory Test and Evaluation

3. Design and Implementation of Field Study

   Task E: Field Test Plan
   Task F: Field Test and Evaluation

4. Prepare final reports (design guidelines, research report, and technical summary)

   Task G: Design Criteria, Guidelines, and Specifications
   Task I: Preparation of Final Research Report
   Task J: Preparation of Executive Summary

5. Attend technical seminars and present papers on project

   Task H: Meetings and Presentations

The discussion of each of the first four steps are presented in the following chapters:

Chapter 2	Interim Guidelines
Chapter 3	Laboratory Test and Evaluation
Chapter 4	Field Test and Evaluation
Chapter 5	Conclusions and Recommendations

Under Task H (step 5), two papers were presented at technical seminars. This first paper, "Guide for Mitigation of Highway Stormwater Runoff Pollution", was presented at the Second International Symposium on Highway Pollution during July 1986 in London, England. (Maestri and Lord, 1986) The second paper, "Managing Pollution from Highway Stormwater Runoff", was presented at the Annual Meeting of the Transportation Research Board during January 1988 in Washington, D.C. (Maestri, et al. 1988)

2. INTERIM GUIDELINES

The focus of Tasks A and B were to prepare interim design guidelines for retention, detention, and overland flow mitigation measures that could be utilized by State highway agencies (SHAs) while the final guidelines were being developed through bench- and full-scale testing and additional literature reviews. The interim guidelines were to reflect the current state-of-the-art technologies for removing pollutants from highway runoff for each of the selected management measures.

In order to provide SHAs with the information on the design of highway stormwater runoff pollutant removal systems in a timely fashion, the FHWA decided that the initial output from this research project, under Task B, would be an update of the FHWA report entitled "Management Practices for Mitigation of Highway Stormwater Runoff Pollution." (Burch, et al. 1985a) This revised report was to be updated by additional literature searches and new information from FHWA experts obtained under Task A, using a modified format to provide the user with step-by-step instructions on how to select and design vegetative controls (grassed channels and overland flow), wet detention basins, retention systems (basins, trenches, and wells), and wetlands for pollutant removal.

1. LITERATURE SEARCH ON THE STATE-OF-THE-TECHNOLOGY (TASK A)

The first step was to collect state-of-the-art information on the four types of mitigation measures to augment the existing reference base identified during Phases 1 and 2 of the FHWA research program, as well as the additional information compiled by project team for use in preparing the Management Practices Research Report. (Maestri, et al. 1985a) This initial literature search used computerized bibliographic databases.

The initial literature search utilized the Lockheed DIALOG Information Retrieval Service to perform an automated search of relevant bibliographic fields. This search was accomplished through five basic steps: (1) file section, (2) key word selection, (3) logic set-up, (4) search, and (5) technical review.

The file section was based on subjects to be investigated and keywords that would be used in the search. Descriptions of databases in each file, as well as experience in using files, were used to select applicable files. There are over 150 searchable files in the DIALOG system, of which 5 were particularly relevant to this specific literature search. The selection of these five files (NTIS, AQUALINE, COMPENDEX, 34-SCISEARCH, and 87-SCISEARCH) was based on previous experience in preforming the literature search for the precursor program. The Transportation Research Information Service (TRIS) data system was also accessed directly through the Department of Transportation using the same search strategy as that used for DIALOG.

Key words were identified by the technical staff based on topics relating to the research being preformed. The keywords were then arranged in a strategy which allowed for a logical search of information.

The output from the initial search was analyzed by the technical staff to determine whether the numbers of hits seemed to be reasonable. When an unreasonable number of hits were obtained, alternative search strategies were developed and employed. Once workable numbers of hits appeared, an author-title printout was requested. This was used to determine whether the search strategy was relevant and complete, and which titles appeared to be pertinent to the research effort.

Titles identified as pertinent were retrieved again in full format. In most files, this included additional information, such as abstracts, publishers, sponsoring agencies, keywords, descriptors, holding libraries, and ordering numbers. These abstracts were reviewed by the project technical staff, and publications of apparent relevance to the project were identified for hard copy acquisition.

Data evaluation focused on subjects dealing with mitigation of highway stormwater runoff and nonpoint pollution control effectiveness, as limited by the scope of work. This material was scanned to identify additional information on the design of the types of management measures being evaluated under this project and their effectiveness in removing pollutants from runoff. For each mitigation measure, information was assessed for the following key topic areas:

- Pollutant removal effectiveness.
- Design.
- Physical characteristics (e.g., highway and geological).
- Environmental characteristics.
- Other considerations (including cost and operational/maintenance requirements).

Emphasis was placed on identifying specific information that could be used to provide additional state-of-the-art information on retention, detention, and overland flow systems and to address current data gaps that existed in the Management Measures Report. (Burch, et al. 1985a) The major data gaps included: (1) particle size distributions for pollutants found in highway stormwater runoff; (2) design procedures for overland flow treatment systems (as opposed to grassed channel design); (3) simplified design procedures for the design of retention and detention measures; and (4) procedures for designing wetlands for stormwater treatment and the effects of treatment (primarily pollutant accumulation) on the wetland ecosystem.

2. PREPARATION OF INTERIM GUIDELINES (TASK B)

As stated in the previous section, the purpose of Tasks A and B were to develop an interim guidance manual that could be used by State highway agencies to select and design appropriate mitigation measures for controlling pollution from highway stormwater runoff. The basis for this manual was a previous FHWA report that presented findings from an extensive literature review and interviews with cognizant highway officials on measures to control highway runoff pollution. (Burch, et al. 1985a) The goal of Task B was to transform this report into a manual that would provide step-by-step instructions on how and when to design and implement the necessary BMPs, both nonstructual and structural. The preparation of this guidance manual would also aid in identifying specific data gaps that could be addressed in the later bench-scale and field studies of this research project.

Based on the direction of the FHWA project officer and the results of the Task A literature search, four major areas of revision/modification were necessary to update the previous work. These areas were: (1) revise and simplify the methodology for designing wet detention basins; (2) update the retention basin design procedures; (3) add a procedure for determining the effectiveness of overland flow BMPs; and (4) develop worksheets to aid the user in design computations and steps. Each of these areas are discussed below.

A. WET DETENTION BASIN DESIGN

The methodology for designing wet detention basins presented in the Management Measures Report was based on work performed by Driscoll (1983) on the effectiveness of wet basins in removing total suspended solids (TSS) from urban runoff. (Burch, et al. 1985a) This methodology factored in both quiescent (between storm events) and dynamic (during storm events) removal, based on the percent of solids within five settling velocity ranges. The settling velocity distribution, along with basin depth, drainage and basin areas, and mean values and coefficients of variation for rainfall volume, intensity, duration, and storm interval, were necessary to complete the design procedure for a particular basin using curves developed by Driscoll. In order to construct a curve that related basin/runoff area ratios to TSS removal efficiencies, the computations were intensive.

To aid in simplifying this process, two activities were performed. The first involved characterizing the settling velocity of suspended solids from highway runoff (as opposed to urban runoff) by using particle size distributions presented in Kobriger, et al. (1982) and converting them, through the use of Stoke's Law, into settling velocities. These settling velocities were then plotted, and a conservative distribution selected that "enveloped" a majority of the individual velocity curves (see figure 1). The results of this exercise are shown in table 1 below:

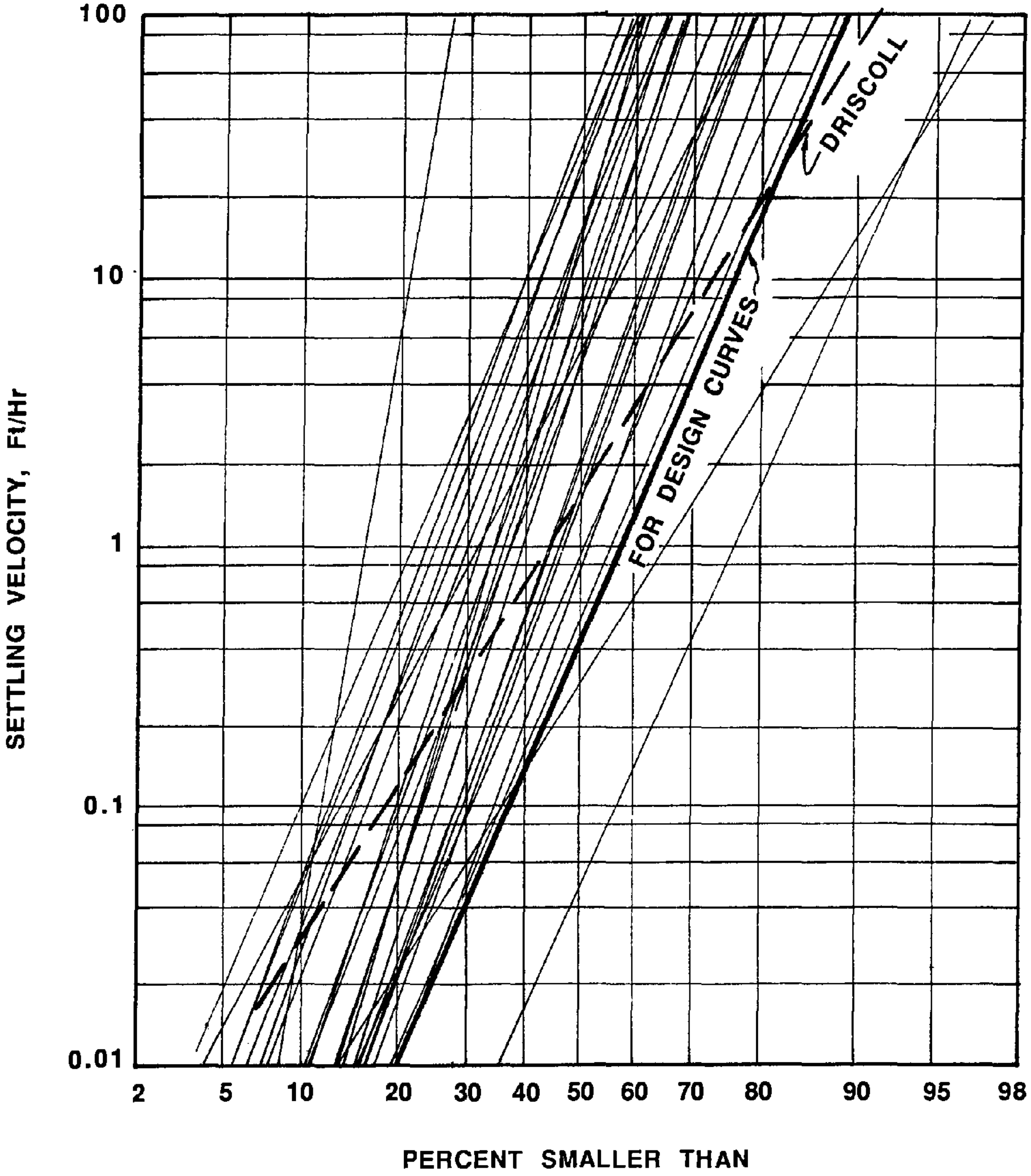


Figure 1. Settling velocity distributions.

Table 1. Interim guidelines settling velocity distributions.

Average Particle Size Velocity (ft/sec)	Driscoll's Urban Runoff Distribution (percent)	Revised Distribution for Interim Guidelines (percent)
0.03	20	36
0.3	20	17
1.5	20	13
7.0	20	13
65.0	20	21

The second activity in revising the wet detention basin design methodology was to develop design curves for regions of the United States that have similar rainfall characteristics and incorporating the revised settling velocity distribution, therefore, eliminating the need for the user having to develop his own curves. Driscoll (1983) had previously summarized the rainfall characteristics (table 2) for 9 regions in the contiguous 48 States (figure 2). In simplifying the design procedure, Regions 1, 2, 3, and 4 were combined, and Regions 5 and 9 were combined. Five sets of removal effectiveness curves were developed, relating the basin volume/runoff volume ratio to TSS removal efficiency for three basin depths at 2, 6, and 10 ft (0.6, 1.8, and 3.0 m).

These curves are based on long-term removal effectiveness and not particularly appropriate in estimating removal rates for individual storm events. In utilizing these curves, the user could determine the effectiveness of an existing wet detention basin or, for a given removal rate, determine the required basin volume to attain that specified rate.

For users that have the need to develop more site-specific design curves based on locally-derived rainfall characteristics and different settling velocity distributions, a step-by-step methodology for developing these curves was also presented.

B. RETENTION BASINS

The retention basin design procedure presented in the Management Measures Report was based on the storage indication method. (Burch, et al. 1985a) With this procedure, a design storm event is selected, and the resultant runoff hydrograph determined. The stormwater flow is then routed through a retention (infiltration) basin of preselected dimensions and a predetermined infiltration rate. The maximum volume of storage for the selected storm event is determined, along with the

Table 2. Summary of rainfall characteristics. (Driscoll, 1983)

Zone	Period	Rainfall Statistics							
		Volume (in)		Intensity (in/hr)		Duration (hr)		Interval (hr)	
		Mean	ν_v	Mean	ν_i	Mean	ν_D	Mean	ν_D
1	Annual	0.26	1.46	0.051	1.31	5.8	1.05	73	1.07
	Summer	0.32	1.38	0.082	1.29	4.4	1.14	76	1.06
2	Annual	0.36	1.45	0.066	1.32	5.9	1.05	77	1.05
	Summer	0.40	1.57	0.101	1.37	4.2	1.09	77	1.08
3	Annual	0.49	1.47	0.102	1.28	6.2	1.22	89	1.05
	Summer	0.48	1.52	0.133	1.34	4.9	1.33	68	1.01
4	Annual	0.58	1.46	0.097	1.35	7.3	1.17	99	1.00
	Summer	0.20	1.54	0.122	1.35	5.2	1.29	87	1.06
5	Annual	0.33	1.74	0.080	1.37	4.0	1.07	108	1.41
	Summer	0.38	1.71	0.110	1.39	3.2	1.08	112	1.49
6	Annual	0.17	1.51	0.045	1.04	3.6	1.02	277	1.48
	Summer	0.17	1.61	0.060	1.16	2.6	1.01	425	1.26
7	Annual	0.48	1.61	0.024	0.84	20.0	1.23	101	1.21
	Summer	0.26	1.35	0.027	1.11	11.4	1.20	188	1.15
8	Annual	0.14	1.42	0.032	0.91	4.5	0.92	94	1.39
	Summer	0.14	1.51	0.041	1.13	2.8	0.80	125	1.41
9	Annual	0.15	1.77	0.036	1.35	4.4	1.20	94	1.24
	Summer	0.18	1.74	0.059	1.44	3.1	1.14	78	1.31

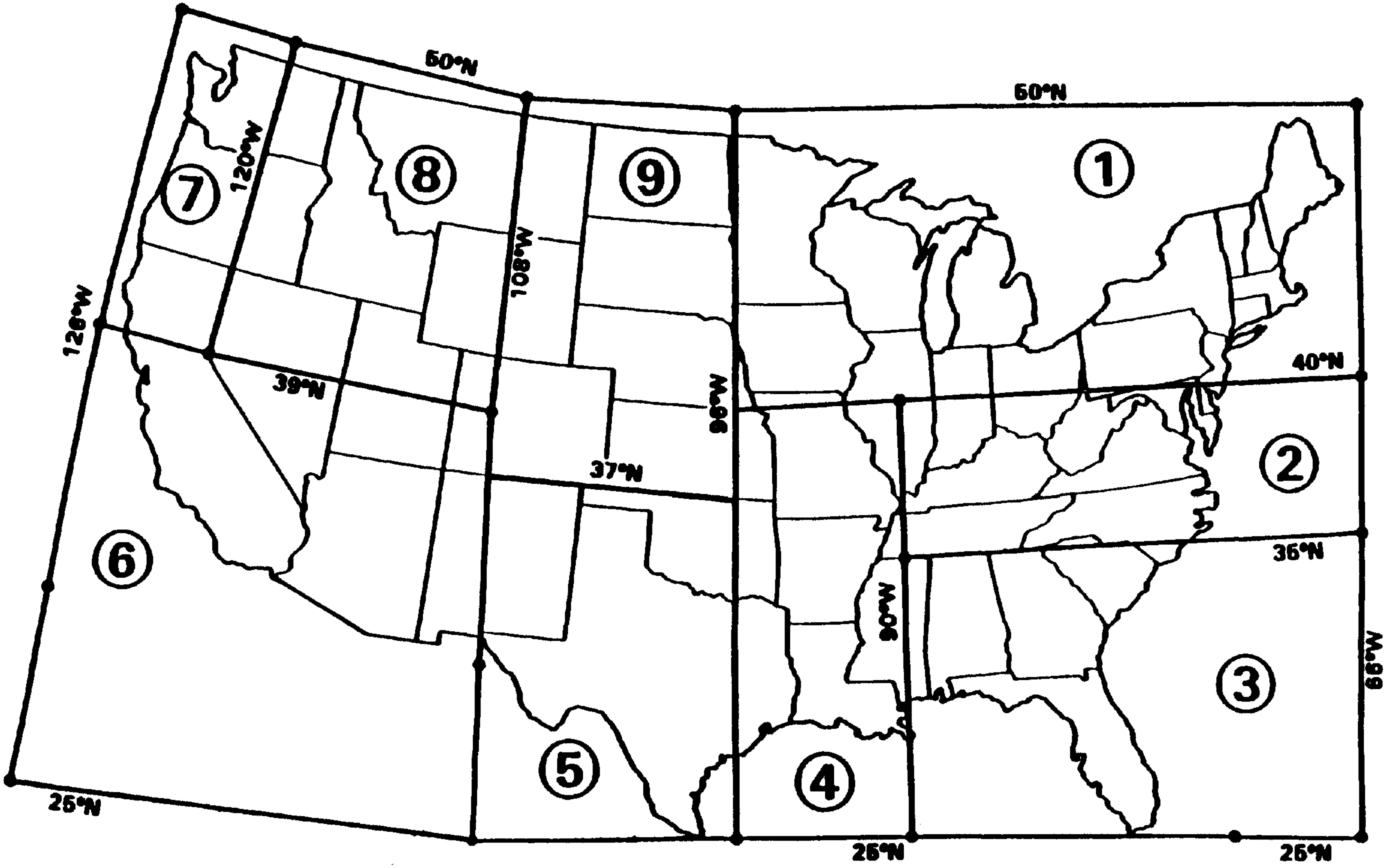


Figure 2. Rainfall zones. (Driscoll, 1983)

resultant height of water in the basin. This procedure would have to be reiterated if the selected basin size did not provide adequate storage volume for the design storm or the basin was grossly oversized.

The revised method of designing retention basins is based on the "first-flush" principle, where the basin is sized to capture a certain selected volume of the initial stormwater runoff (generally in inches of rainfall over the drainage area). Because the majority of the pollutant load is associated with the first-flush volume of runoff, this method can provide a high degree of pollutant removal by focusing on the capture of the initial runoff volume. This method is consistent with nonpoint source regulations in Florida and Maryland.

Other factors in determining the size of the retention basin are the infiltration rate and allowable dewatering time. With these two factors and the first flush volume, the basin can be sized with a minimum number of iterations and relatively simple calculations.

C. OVERLAND FLOW

Pollutant removal in overland flow systems (filter strips) has generally been assumed to occur; however, little information has been available to estimate the effectiveness of such systems, particularly for nonpoint pollution control. For this reason, no guidance was provided in the Management Measures Report on filter strips. Information on vegetative controls focused on grassed channel (swale) systems, where pollutant removal was based on channel stability and length.

The interim guidelines provided a method for estimating pollutant effectiveness for filter strips based on research performed on overland flow treatment of municipal wastewater. This method relates hydraulic loading rate to detention time, which can then be used to determine the percent of TSS removed. This method relates to filter strips that are 100 ft (30 m) to 150 ft (45 m) in length with slopes between 5 and 8 percent. As with the grassed channel system, slope stability (noneroding) is a key to designing filter strips.

D. DESIGN WORKSHEETS

The final major revision to the Management Measures Report was to provide worksheets for the user to aid in the steps and computations necessary to design the individual pollution control measures.

The remainder of revisions and modifications made to the Management Measures Report focused on providing: (1) behavior and fate information on the major pollutant groups found in highway runoff; (2) discussing receiving water impacts of highway stormwater runoff; (3) construction considerations; and (4) operation and maintenance information for each of the four general types of control measures.

The preparation of the "Interim Design Guidelines for Management Measures" allowed the project team to identify specific areas where additional information, necessary to refine and/or update design methodologies, should be gathered and analyzed through bench-scale and field monitoring studies. In addition to testing the methodologies presented in the interim guidelines, these studies, to be addressed under Tasks C through F, focused on the following existing data gaps:

1. Particle size distribution of pollutants in highway stormwater runoff.
2. Settling characteristics of highway runoff pollutants.
3. Design parameters for grassed channels other than channel length.
4. Effectiveness of BMPs (particularly wet detention basins) in treating highway runoff as opposed to urban runoff.
5. Pollutant accumulation in highway stormwater runoff control measures.
6. Groundwater impacts of highway runoff routed through infiltration measures.
7. Wetland design parameters.

The laboratory phase (Tasks C and D) focused on addressing the first two data gaps listed. Tasks E and F (field phase) attempted to address the remaining data gaps. These two phases of the project are discussed in chapters 3 and 4.

3. LABORATORY TEST AND EVALUATION

The laboratory test and evaluation consisted of two tasks: Task C, which involved the preparation and design of the actual bench-scale studies; and Task D, under which the sample collection and laboratory work was performed.

As originally proposed under the laboratory phase of this research project, the studies to be performed included settling column studies of pollutant removal in detention basins and analyses of pollutant accumulation with the bottom sediments of grass channels. Two additional studies were also recommended: analyses of pollutant transformation processes with the permanent pool of wet detention basins, and analyses of pollutant accumulation with the bottom sediments of detention basins.

The evaluation and examination of the pollutant transformation process within wet detention basins, as proposed, was to focus mainly on the removal mechanisms for nutrients and oxygen-demanding pollutants. After discussions with the FHWA project officer, this study was removed from further consideration since the major pollutants of concern in highway stormwater runoff are suspended solids and metals. At this time, it was also decided to postpone the sediment analyses until the field phase so that sediment samples could be collected at the same sites where runoff monitoring was to be performed. Therefore, the laboratory phase focused on performing settling column studies on highway stormwater runoff to: (1) determine particle size distributions and settling velocities necessary to refine the wet detention basin design methodology; and (2) evaluate the settling characteristics (discrete or flocculating) of suspended solids in highway runoff. Additional information that was to be obtained in the laboratory phase included: the relationships between detention time and pollutant removal for various constituents; relationships between initial TSS concentrations and pollutant removal rates; and typical levels of maximum pollutant removal for various constituents. Sections 1 and 2 of this chapter discuss the field/laboratory methods used to collect and analyze the runoff samples and the results of the settling column studies, respectively.

1. <u>FIELD/LABORATORY METHODS</u>

A. STUDY DESIGN

The collection runoff samples for the settling column studies was proposed at four different highway sites in the Washington, D.C. region during late spring and summer of 1986. Two storm events would be sampled at each site, providing runoff samples for eight settling column tests. The highway sites selected were to exhibit high traffic volumes (e.g., greater than 60,000 ADT) to ensure that the treatability study would be based on relatively high nonpoint pollution concentrations. The sites were also to exhibit a drainage area that was large enough to produce adequate flows from short-duration rainstorms and include no runoff from off-site land use and, ideally, only a limited amount of pervious area. To ensure that the runoff samples represented elevated concentrations that could be transported to a detention basin, most of the selected highway runoff sites were to be drained primarily by paved ditches rather than grass channels. Sites with grass channel systems exhibit pollutant removal along the channel length upstream of the sampling point, reducing the pollutant levels. However, at least one grass channel site was to be chosen if enough runoff flow occurred to allow sampling.

Due to drought conditions during the summer of 1986 and the holding time for TSS being exceeded for six of the seven runoff samples, six additional samples for the settling column study were collected during the summer of 1987.

For the 1986 sample collection and settling column tests, four sites were selected. Two additional sites were selected for sample collection in 1987, along with one of the sites used during 1986. The sample collection sites were selected based on a visual inspection of the major Interstate highways (I-95, I-395, I-495, and I-66) in the Northern Virginia area. These sites had to be accessible from the highway to allow for sample collection and provide a safe area near the collection site to await the rainfall event. The site characteristics and sample collection dates are provided in table 3. All runoff collection sites had ADTs of over 100,000 vehicles per day. Appendix A provides photographs of these sampling sites.

B. EQUIPMENT AND PROCEDURES

Grab sampling techniques were used to collect the required runoff samples at each site. To assess detention basin design performance under worst-case conditions, the grab sampling program was designed to isolate first-flush runoff from the highway site. Two to five 5.5-gallon (7.6 to 20.8 L) polyethylene carboys were filled at 5- to 10-minute intervals during the initial 20 to 25 minutes of runoff. By concentrating the sampling on the rising limb of the runoff hydrograph, the composite sample used in the settling column analysis would exhibit the elevated concentrations typical of first-flush conditions. The procedure for runoff sample collection was as follows:

1. Based upon local weather forecasts, one to two technicians would visit the sampling site prior to the onset of rainfall. All sampling containers were cleaned and prepared as necessary before leaving the laboratory.

Table 3. Characteristics of runoff collection sites for laboratory phase.

Site Designation	Site Description	Drainage Area (Acres)	Channel Type	Sample Dates	
				1986	1987
A	I-395 N at I-495	1.0	Concrete	06/12, 06/28	05/03, 05/12
B	I-395 S near Seminary Road	1.2	Concrete	07/16, 08/02	-
C	I-95 E near I-395	0.3	Concrete	08/06, 08/27	-
D	I-95 E near I-395	1.1	Grassed	08/06	-
E	I-495 E at Gallows Road	7.5	Concrete	-	05/03, 06/20
F	I-395 N between Edsall Road and Duke Street	1.8	Concrete	-	05/12, 06/20

1 ac = 0.405 ha

2. The first grab sample was collected about 5 minutes after runoff flows were detected in the channel, using a 1.5-gallon (5.7 L) polyethylene bucket. Additional grab samples were at 1- to 5-minute intervals, depending on storm intensity, runoff volume, and safety considerations. These samples were transferred to the 5.5-gallon (20.8 L) carboys. When sufficient samples were collected, the carboys were transported to the contractor's laboratory for bench-scale analysis.

Once the samples had been returned to the laboratory, the contents of the carboys were throughly mixed and composited into a single carboy and immediately poured into the settling column.

The settling columns used in this study were constructed of plexiglass with an outside diameter of 6 in (152.4 mm) and 0.25-in (6.4 mm) thick walls. The column height was 5 ft (1.53 m), which is representative of the typical range of permanent pool mean depths 3 to 9 ft (1 to 3 m). Since the settling column depth approximates the depth of the prototype pool, errors were not introduced by scale effects or extrapolation.

The columns were firmly embedded in a 12-in (305 mm) square platform and had four sampling ports, located at 1-ft (0.305 m) intervals from the bottom. The ports were designated by their distance from the bottom of the column (i.e., port 2 was 2 ft (0.61 m) from the bottom). A fifth port was installed at the bottom to permit draining after the settling tests. Two columns were used to permit concurrent analyses (under a slightly staggered schedule) of runoff samples collected at different highway sites.

As soon as the entire composite sample had been transferred into the column (i.e., time zero), a 670-ml sample was collected at the 2-ft depth to represent the initial concentrations in the well-mixed column. Thereafter, individual 370-ml samples were collected at the 3-, 2-, and 1-ft (0.915 m, 0.61 m, 0.305 m) depths at 2, 6, 12, and 24 hours after the test began. After 48 hours after test initiation, two 370-ml samples were taken at the 3- and 1-ft (0.915 m and 0.305 m) depths and a 670 ml sample taken from the 2-ft (0.61 m) depth. At each sampling interval, the samples were withdrawn from the 3-ft (0.915 m) port first, followed by the 2-ft port, and then the 1-ft port. The temperature of the collected samples from the 2-ft port were measured and recorded. The samples at each time interval were then preserved and analyzed separately for specified constituents (rather than composited) in order to evaluate removal with time and depth.

The samples were collected using graduated cylinders and stored in labeled, 250-ml polyethylene sample bottles. Sample preservation techniques and analytical procedures used in this study are summarized in table 4. The samples collected at each port and time were analyzed for the following constituents (the dissolved parameters, ortho-phosphorus,

Table 4. Reference methods, preservation, and holding times for parameters analyzed in laboratory phase. (U.S. EPA, 1982)

Parameter	Reference Method	Preservation	Holding Time
Total Metals (Pb, Zn, Cd, Cr, Cu)	200.7 or 200.0	pH <2, HNO_3	6 months
Dissolved Metals	200.7 or 200.0	Filter (0.45 μ), pH <2, HNO_3	6 months
Nitrate + Nitrite (Filtered, 0.45 μ)	353.2	pH <2, H_2SO_4; Cool to 4°C	28 days
Total Kjeldahl Nitrogen	351.2	pH <2, H_2SO_4; Cool to 4°C	28 days
Total Phosphorus	365.2	pH <2, H_2SO_4; Cool to 4°C	28 days
Ortho Phosphorus	365.2	Filter, 4°C	48 hours
Soluble Phosphorus	365.2	Filter, 4°C, H_2SO_4	28 days
Total Suspended Solids	160.2	Cool to 4°C	7 days
Total Dissolved Solids	160.1	Filter, cool to 4°C	7 days

and pH were only analyzed for the samples collected at the 2-ft (0.61 m) port and the 0- and 48-hour intervals):

Metals (total and dissolved)

- Lead.
- Copper.
- Zinc.
- Cadmium.
- Chromium.

Nutrients

- Nitrogen (TKN, nitrate + nitrite).
- Phosphorus (total, ortho, dissolved).

Suspended solids (total, dissolved)

pH

The selection of these parameters was based on reviews of previous studies that have analyzed constituents in highway runoff, focusing on those pollutants that occur as a direct result of highway operation. (Gupta, et al. 1981 and Kobriger, et al. 1982) The nutrients were included because of their overall impacts in nonpoint source pollution.

As noted previously, the 7-day sample holding time for TSS was exceeded for six of the samples taken in 1986. Therefore, six additional samples were collected and settling column analyses performed in 1987. In addition, a special study of the holding time for TSS was performed, analyzing the 1987 samples within the recommended 7-day period and after 28 and 56 days. This study showed that there was some variability for the individual samples, most likely due to microbial conversion of organic solids. However, overall, there was no significant difference between the TSS values for samples analyzed 1, 4, and 8 weeks after receipt.

2. LABORATORY RESULTS

A. NUMERICAL RESULTS

The settling column study covered 13 storms monitored at 6 highway sites in the Northern Virginia area. Seven storms were monitored in 1986, and six were monitored in 1987. The average pollutant concentrations found in the highway runoff and the ranges for both years are shown in table 5. The average concentrations, as well as the concentration ranges, differ from those reported in previous studies. (Gupta, et al. 1981) Cadmium, chromium, and lead levels were found

Table 5. Average runoff concentrations.

Parameter		Units	1986			1987			1986 + 1987			Interim Guidelines		
			Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum
Cadmium	(Total)	μg/l	<10	<10	11	7	<3	9	<10	<3	11	40	10	400
Chromium	(Total)	μg/l	15	<5	67	32	7	57	22	<5	67	40	10	400
Copper	(Total)	μg/l	66	11	213	171	72	218	114	11	218	103	10	880
Lead	(Total)	μg/l	257	<50	878	339	111	562	295	<50	878	960	20	13,100
Zinc	(Total)	μg/l	1,161	71	3,380*	1,488	360	2,670	1,312	71	3,380*	410	10	3,400
Suspended Solids	(Total)	mg/l	363	100	1,120	792	452	1,066	578	100	1,120	261	4	1,656
Nitrate + Nitrite	(Total)	mg/l	2.00	0.77	4/23	6.57	1.51	9.06	4.11	0.77	9.06	1.14	0.01	8.4
TKN	(Total)	mg/l	4.60	1.67	12.38	22.30	12.4	29.5	12.77	1.67	29.5	2.99	0.1	14.0
Phosphorus	(Total)	mg/l	0.98	0.08	.4	0.85	0.396	1.97	0.92	0.08	3.4	0.79	0.05	3.55
Cadmium	(Dissolved)	μg/l	<10	<10	<10	<3	<3	7	<3	<3	7	--	--	--
Chromium	(Dissolved)	μg/l	<5	<5	<20	<4	<4	5	<5	<4	5	--	--	--
Copper	(Dissolved)	μg/l	24	<5	50	58	10	123	40	<5	123	--	--	--
Lead	(Dissolved)	μg/l	<50	<50	<50	<40	<40	81	<40	<40	81	--	--	--
Zinc	(Dissolved)	μg/l	843	<20	3,420*	885	341	1,620	862	<20	3,420*	--	--	--
Suspended Solids	(Dissolved)	mg/l	169	42	352	--	--	--	169	42	352	--	--	--
Phosphorus	(Dissolved)	mg/l	0.14	0.03	0.37	0.77	0.18	1.85	0.43	0.03	1.85	--	--	--
Ortho-phosphorus	(Dissolved)	mg/l	0.13	<0.01	0.51	--	--	--	0.13	<0.01	0.51	--	--	--
Temperature			24.6	22.4	26	--	--	--	0.13	<0.01	0.51	--	--	--
				5.9	6.7	--	5.9	6.8	--	5.9	6.8	--	--	--

*Analytical precision questionable for these two values.

to be less than in previous studies, while zinc was much higher. Nutrients and TSS were also higher in this study. However, since the focus of sample collection was on first-flush runoff volumes, this explains these higher concentrations.

The laboratory analyses for the individual storms are summarized in appendix B. These summaries provide the concentrations at each sampling port for each time period. The concentrations at time zero are assumed to be the same at all ports since the samples were mixed prior to being transferred to the settling columns.

B. LABORATORY DESIGN EFFICIENCIES

The pollutant removal efficiency for each settling column sample is calculated by dividing the concentration at settling time "t" by the initial concentration (time zero) in the settling column, and then subtracting from 100 percent. The measured pollutant removal efficiency for each of the 13 storm events is summarized in appendix C. Separate entries are presented for settling times of 2, 6, 12, 24, and 48 hours. While appendix C summarizes removal efficiencies for each sampling port, mean efficiencies for the entire column at each settling time can also be calculated by pooling the observations from individual storms for each of the three sampling ports. Appendix D summarizes the mean efficiencies for the 1986 and 1987 datasets and table 6 summarizes the pooled dataset for both years.

The summary tables shown in appendix D indicate that the measured efficiencies occasionally declined with increasing settling times. These types of fluctuations tended to be more evident in the 1987 dataset. The fluctuations can probably be attributed to laboratory precision and experimental errors that are encountered in bench-scale studies. Rather than run the risk of biasing the database by making what may be arbitrary judgments about the accuracy of certain data points, the analyses are based on the entire database.

Table 7 summarizes mean removal efficiencies at 6-hour and 48-hour settling times for the laboratory settling column datasets. Mean efficiencies reported for settling column studies with runoff from commercial land use watersheds (MWCOG, 1983) and assumed by the recommended design method in the Interim Design Guidelines are also presented for comparison with the settling column results.

The pooled settling column results indicate that the majority of pollutant removal occurs within the initial 6 hours of quiescent settling, similar to the results of the Washington, D.C. National Urban Runoff Program (NURP) study. (MWCOG, 1983) The 48-hour removal rates for the settling column study, which are assumed to approximate maximum values, are lower than the other two studies in the case of total

Table 6. Summary of percent removal versus time (hrs) all storms (1986 + 1987).

Parameter	Port[1]	Percent Removal				
		Time (Hr)				
		2	6	12	24	48
Cd (μg/l)	3	56%	18%	11%	33%	47%
	2	40%	55%	50%	13%	25%
	1	25%	34%	41%	19%	43%
Cr (μg/l)	3	41%	60%	57%	64%	80%
	2	41%	44%	50%	60%	64%
	1	40%	46%	67%	70%	59%
Cu (μg/l)	3	33%	44%	46%	55%	58%
	2	28%	44%	39%	69%	56%
	1	29%	43%	48%	54%	53%
Pb (μg/l)	3	50%	65%	71%	78%	82%
	2	50%	60%	68%	73%	72%
	1	47%	64%	70%	75%	79%
Zn (μg/l)	3	28%	34%	37%	39%	42%
	2	26%	34%	39%	40%	40%
	1	26%	35%	37%	39%	42%
TSS (mg/l)	3	56%	78%	84%	89%	92%
	2	53%	70%	77%	84%	87%
	1	55%	73%	80%	86%	88%
NO2+NO3 (mg/l)	3	3%	9%	16%	30%	53%
	2	2%	9%	23%	31%	56%
	1	7%	10%	17%	33%	54%
TKN (mg/l)	3	15%	24%	22%	25%	31%
	2	12%	20%	23%	26%	24%
	1	12%	19%	20%	23%	30%
Phos. (mg/l)	3	34%	39%	36%	41%	46%
	2	30%	33%	43%	44%	44%
	1	26%	37%	33%	43%	43%

[1] Ports 1, 2, and 3 are located 1 ft, 2 ft, and 3 ft, respectively, from the bottom of the column.

Table 7. Comparison of pollutant removal efficiencies based on settling column study, Washington, D.C. NURP Study, and Interim Design Manual 6- and 48-hour settling times.

	Settling Column Study									
	1986 Monitored Storms		1987 Monitored Storms		1987 + 1987 Monitored Storms		Wash., D.C. NURP		Interim Design Manual	
	6-hour	48-hour	6-hour	48-hour	6-hour	48-hour	6-hour	48-hour	6-hour	48-hour[1]
TSS	71-77%	86-93%	71-79%	85-91%	70-78%	87-92%	62%	92%	--	100%
Total P	45-52%	71-72%	16-27%	11-5%	33-39%	43-46%	36%	54%	--	60%
Suspended P	58-67%	91-93%	100%	76-100%	58-68%	77-81%	67%	100%	--	100%
TKN	22-32%	31-40%	13-17%	18-21%	19-24%	24-31%	25%[2]	41%[2]	--	--
Total Copper	45-49%	49-59%	36-43%	56%	43-43%	53-58%	--	--	--	50%
Total Lead	62-67%	74-88%	59-65%	71-80%	60-65%	72-82%	72%	87%	--	90%
Total Zinc	31-33%	36-41%	36-37%	43-44%	34-35%	40-42%	42%	49%	--	50%

[1] Reported maximum removal rates are assumed to be comparable to 48-hour settling column tests.

[2] Total N removal efficiencies (TKN statistics were not reported).

phosphorus and somewhat lower in the cases of lead and zinc. In summary, the heavy metal removal rates for all three studies are generally comparable, while the nutrient removal rate for the 1987 data tend to be lower than reported in other studies. The 1986 data for total phosphorus compare well with the other studies.

An analysis of pollutant removal versus TSS removal was also performed to compare with the data developed by Driscoll (1983), as presented in the Interim Design Guidelines. Using the pooled 1986 and 1987 datasets, the TSS removal at each port and time was compared to the removals for the following pollutants: copper, lead, zinc, TKN, and total phosphorus. A regression analysis was performed on removal data for each pollutant (with r^2 ranging from 0.65 for phosphorus to 0.97 for lead). The results are graphically presented in figure 3. The maximum removals developed through the relationships from the settling column data are similar to Driscoll's (1983). A comparison of these relationships are shown in table 8 below:

Table 8. Comparison of maximum removal rates.

	Maximum Removal	
Pollutant	Settling Column Data	Urban Runoff (Driscoll)
Lead	87%	90%
Phosphorus	49%	60%
Copper	61%	50%
Zinc	47%	50%

These maximum removals, developed using the settling column data for highway stormwater runoff, indicate that the settling characteristics are similar to those reported for urban runoff. A further evaluation of the similarity between highway and urban runoff, based on settling velocity characteristics, is presented in the following section.

C. TREATABILITY/SIMULATION RESULTS

The main purpose of the laboratory phase of this project was to better define the settling characteristics of highway runoff. To do this, settling column studies were performed on a number of runoff samples. By collecting samples at various depths within the column at different times, settling velocity distributions were determined. When considered together, the depth of water above the sampling port and the

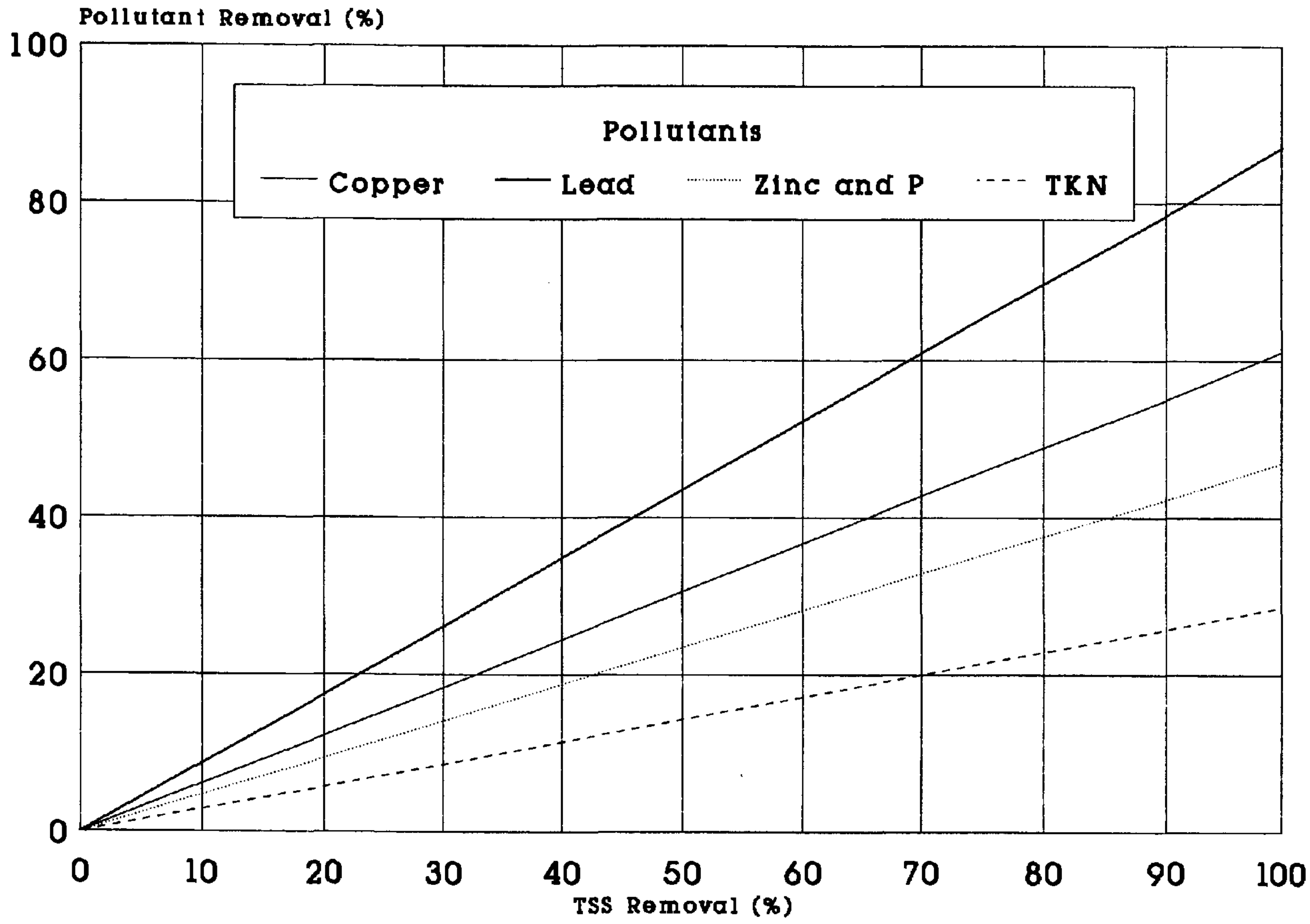


Figure 3. Pollutant removal versus TSS removal.

sampling time correspond to a settling velocity. For example, assuming that the depth of water in the settling column is 5 ft (1.52 m), the settling velocity associated with the 12-hour sample port 2 (i.e., 2 ft (0.61 m) from the bottom) is 0.25 ft/hr (i.e., [5 ft (1.52 m) - 2 ft (0.61 m)]/[12 hr]. For TSS, each settling column measurement (i.e., percent removal) represents the percent of the total mass that exhibits settling velocities equal to or greater than the settling velocity associated with the sampling port depth and sampling time. For example, if the TSS removal rate at sampling port 2 after 12 hours of settling is 80 percent, it may be assumed that 80 percent of the TSS load exhibits settling velocities equal to or greater than the port 2, 12-hr rate of 0.25 ft/hr (76.2 mm/hr) (or 20 percent of the load exhibits settling velocities less than 0.25 ft/hr) (76.2 mm/hr). Based on all observations during the 48-hr settling column test, a plot of settling velocity versus probability of occurrence or exceedance may be derived. The probability relationships were then used to check the particle size distributions assumed in the recommended design method for wet detention basins. (Dorman, et al. 1987)

Since the settling column studies produce a slight change in water depth following the withdrawal of each sample, the calculations of settling velocity for each "sampling port/sample time" combination should account for the approximate water depth at the time of each observation. The settling velocities shown in table 9 are based on the approximate depth of water at the start of each sampling run. The minimum settling velocities reported in this table were used to evaluate particle size distributions exhibited by the settling column tests.

The evaluation of the settling column data was based on computerized regression to determine the settling velocity distributions. A computer program was developed to translate the probability and log plots to a linear scale, from which regression equations could be used to accurately characterize the distributions. The results of this program for TSS data from 10 of the 13 settling column tests are shown in table 10, along with pooled data for 1986, 1987, and 1986/1987.

The pooled 1986/1987 results indicate a slightly different distribution than reported by Driscoll and the interim guidelines. The distribution shows a higher percentage (28 percent) of the TSS load with an average settling velocity of 65 ft/hr (19.8 m/hr). Table 11 compares the reported settling velocity distributions presented by Driscoll (1983) and Dorman, et al. (1987), with the distributions of the settling column data. The runoff samples collected for the settling column study focused on first-flush conditions, which should contain a higher level of larger particles and, thus, can be responsible for the larger percentage of particles with the higher settling velocity (65 ft/hr) (19.8 m/hr). For a total storm duration and runoff volume (not first-flush only), the settling velocity distribution should exhibit characteristics similar to those reported by Driscoll.

Table 9. Minimum settling velocities associated with various sampling depths and settling times: 5-ft settling column.

1 ft = 0.305 m

Settling Time (hrs)	Minimum Settling Velocity (ft/hr)		
	Port 1	Port 2	Port 3
2	1.91	1.41	0.91
6	0.58	0.41	0.25
12	0.26	0.18	0.10
24	0.12	0.08	0.03
48	0.05	0.03	0.01

NOTES:

1. Ports 1, 2, and 3 are located 1 ft, 2 ft, and 3 ft, respectively, from the bottom of the settling column.
2. Settling velocity accounts for changes in depth of water during settling column tests.

Table 10. Settling velocity distributions for individual storms and pooled data.

	Portion of Total TSS Load												
	1986 Storms					1987 Storms							
Average Settling Velocity (ft/hr)	#1	#2	#4	#5	#7	#1	#2	#4	#5	#6	Average 1986	Average 1987	1986 + 1987 Average
0.03	0.11	0.11	0.13	0.16	0.14	0.13	0.23	0.07	0.18	0.21	0.18	0.18	0.18
0.3	0.12	0.26	0.13	0.19	0.18	0.12	0.22	0.08	0.15	0.11	0.19	0.15	0.17
1.5	0.14	0.31	0.15	0.21	0.20	0.13	0.20	0.10	0.15	0.11	0.20	0.16	0.17
7.0	0.19	0.23	0.20	0.21	0.22	0.18	0.18	0.16	0.18	0.14	0.20	0.19	0.19
65.0	0.44	0.10	0.39	0.23	0.26	0.44	0.17	0.60	0.34	0.42	0.23	0.32	0.28

= Storm number

Table 11. Summary of reported settling velocity distributions.

	Percentage of Total TSS Load		
Average Settling Velocity (ft/hr)	Urban Runoff (Driscoll 1983)	Interim Design Guidelines (Dorman, et al. 1987)	Settling Column Study
0.03	20	36	18
0.3	20	17	17
1.5	20	13	17
7.0	20	13	19
65.0	20	20	28

D. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

There were several inconsistencies noted between the 1986 and 1987 storms monitored for the settling column study. Results from the 1986 data were very consistent with other settling column studies (e.g., NURP) and also with the design efficiencies predicted in the Interim Design Manual. The 1987 storm results show significantly lower removal efficiencies for total phosphorus and TKN. The 1987 storms were characterized by much higher initial concentrations and much lower fractions of suspended phosphorus. The only apparent difference was that larger, more intense rainfall events were emphasized during the 1987 monitoring (1986 was also a drought year for the Northern Virginia area, especially during the storm water collection period). Therefore, both sets of data were considered in this analysis, and these results may be considered representative of a wide range of hydrometeorological conditions. These results indicate the importance of pollutants in dissolved form that are not settleable.

The settling column test results confirm that the majority of pollutant removal occurs within the first 6 hours of quiescent settling. The 48-hour removal rates, which are assumed to approximate maximum values, are somewhat lower for total phosphorus and in the same range for heavy metals in comparison with the NURP study results and the predicted design efficiencies.

The settling column study showed that the particle size distribution assumed in the Interim Design Manual appears to be somewhat conservative. About 36 percent of the suspended solids mass was assumed to be grouped within the smallest particle size classification (i.e., settling velocity of 0.03 ft/hr) (9.1 mm/hr). Data from storms monitored for this phase of the project indicate that less than 20 percent of the suspended solids mass is within this category. The particle size distribution for the settling column data are similar to the distributions assumed for urban runoff, with the exception of particles in the highest settling velocity class 65 ft/hr (19.8 m/hr), which is most likely the result of concentrating sample collection on the first-flush volumes.

Two major conclusions were inferred from the results of the settling column study data. The first was that extended dry detention basins may be appropriate pollution control measures for highway stormwater runoff if the runoff volumes are detained for periods of 6 hours or more. The second major conclusion was that the design method for wet detention basins presented in the Interim Design Manual was conservative, and a further refinement was necessary for the final design specifications and guidelines.

4. FIELD TESTING AND EVALUATION

The field testing and evaluation phase of this research project was intended to collect new and/or additional effectiveness data on highway stormwater runoff control measures and evaluate the design assumptions presented in the Interim Design Guidelines.

The major design assumptions that were to be verified or refined during the field phase included:

- The pollutant removal effectiveness of stable grassed channels should be based on residence time within the channel (which takes into account both length and slope), rather than length alone.
- The design methodology for overland flow systems, adapted from municipal wastewater design techniques, needs to be based on different parameters (i.e., residence time) rather than hydraulic loading for use with highway systems.
- The methodology for evaluating the performance of wet detention basis in treating urban nonpoint source runoff can be adapted for use in designing wet basins for controlling highway stormwater runoff pollution.
- Dry, extended detention basins can achieve pollutant removal efficiencies approaching those observed for wet detention basins.
- The same methodology for designing wet detention basis can be used for wetlands.
- The methodology developed for designing retention measures, which is currently used in the State of Maryland, is applicable to other areas of the country.

The major tests that were expected to be performed in the field phase included: monitoring inflow and outflow from selected control measures; collection of flow proportional composite samples of both inflow and outflow for laboratory analysis; and the collection of bottom sediment samples. Information on State highway agency (SHA) operation and maintenance practices were also to be collected for further evaluation during the development of the final design criteria and specifications.

1. FIELD TEST METHODS

As proposed for the field phase of this project, nine highway stormwater runoff control measures in three areas of the country were to be monitored. Of these nine measures, three were to be detention basins (including wet, extended dry, or wetlands), three were to be vegetative controls (grassed channels or overland flow), and three were to be retention measures (infiltration basins, trenches, or wells). Ideally, each area would have one of each type of control measure; but at a minimum, at least two of the three types. The monitoring strategy for the sites was to include the collection of 12 runoff samples (both inflow and outflow) over a 6- to 12-month period. This period would preferably include the area's rainy season.

A. SITE SELECTION

In February 1986, the FWHA headquarters Office of Engineering and Highway Operations Research and Development contacted the FHWA Regional Administrators requesting that contact with each State within their respective regions be initiated concerning their willingness to cooperate in this research. Specifically, State involvement would include aiding in site selection and possible operation of the monitoring sites. Through the regional offices, 15 SHAs responded that they might be interested in the project. The site selection process began with subsequent contact of these 15 SHAs requesting that they determine if any sites within their jurisdiction met the general and control measure-specific criteria presented below.

General Site Selection Criteria

The general criteria that pertain to all control measure sites were as follows:

- Control measure sites should receive mostly highway stormwater runoff. The control measure can receive runoff from undeveloped open areas; but should not receive runoff from areas (such as industrial facilities, agricultural, construction, or eroding areas) that may contribute substantially different pollutants and/or loadings.

  The following information should be available, or obtainable, on the control measure and surrounding area:

  - Drainage area characteristics.
  - Average daily traffic volumes (ADTs must be greater than 30,000 vehicles per day). Higher ADTs are preferable, but not essential.
  - Construction or site plans of the site.
  - Date the control measure was installed or constructed along with dates of any site modifications.

- Maintenance records, detailing the type and frequency of any maintenance activities that are related to the control measure.

Both inflow and outflow from the control measure should be easily monitored (i.e., must be able to install a primary flow monitoring device). If monitoring inflow is not feasible, then monitoring of a "control" area with similar drainage characteristics and traffic volumes should be feasible. This is less desirable than actual inflow monitoring, but will be an important concern in monitoring overland flow areas.

Necessary modifications to the control measure should be able to be performed, so as to allow the measure to meet design assumptions.

Space should be available for the installation of small sheds, to house the monitoring equipment (a minimum of 30 ft (9.1 m) from the roadway) out of sight from traffic. This will help protect against vandalism and damage from vehicles. The site should also be located in a "safe" working area with limited access.

Assistance from SHAs, USGS, universities or the contractor's regional offices will be necessary to provide routine inspection and maintenance of equipment and to ensure responsive sample shipment.

Sites that have access to an electrical power source are preferable, since the use of batteries will require more frequent maintenance.

Control Measure-Specific Criteria

The criteria specific to the three general types of control measures were as follows:

Vegetative Controls - Two types of vegetative controls will be assessed: grassed channels and overland flow areas. Both types of controls will have slopes such that the measure is not subject to erosion (generally less than 8 percent). Grassed channels should have the majority of inflow entering the upstream portion of the channel. The channels will be at least 200 ft long (61 m) with a width of between 2 to 5 ft (.61 to 1.52 m). The minimum requirements for the overland flow areas are a length of 40 ft (12.2 m) (in the direction of flow) and a width of 40 ft (12.2 m). Overland flow areas will also require that an "unmanaged" area be monitored to determine the inflow characteristics, since inflow to the overland flow area will most likely be via sheet flow over a large area.

Detention Basins - Detention basins can include wet detention basins, dry basins that detain runoff for an extended period of time (greater than 6 hours), and wetlands. The basins should be sized so as not to create a flood hazard and should have one inlet and outlet to facilitate monitoring. The permanent pool depth should be between 2 and 10 ft (.61 to 3.1 m) (the lower value pertaining to wetlands). Wetlands should be preceded by a control measure to reduce solids and metals loadings. Basin configurations should not allow short-circuiting of inflow through the basin.

Retention Measures - Retention, or infiltration, measures that will be studied in the field phase include basins and trenches. Both retention systems should be preceded by a control measure to reduce large solids in the runoff from clogging the soil pores. Retention basins, sized to retain a design stormwater runoff event, should have one inlet with either a bypass or overflow structure to divert flows above the design flow. The soils beneath the basin should be relatively permeable (permeability of 0.3 in/hr (7.6 mm hr) or greater), and the groundwater table should be at least 2 ft (0.61 m) below the bottom of the basin. Monitoring wells around the perimeter of the basin to determine the local impacts on groundwater would be ideal, but not necessary. Infiltration trenches should be 3 to 10 ft (0.915 to 3.05 m) deep and backfilled with either sand or gravel. Depth to groundwater can be less than 2 ft (0.61 m) since the trenches will have runoff storage capacities much less than basins, and their impacts on groundwater levels should be minimal.

Eight of the 15 SHAs contacted felt that they had sites that met most of the site selection criteria. Each of the eight SHAs were then requested to provide detailed plans or specifications for each of their recommended control measure sites. Six of the SHAs responded to this request. Their responses concerning the types of sites to be found in their respective States were as follows:

- Virginia: Dry detention basins, wet detention basins, grassed swales, and wetlands.
- Maryland: Infiltration trenches.
- Connecticut: Wet detention basins.
- New York: Infiltration basins
- Florida: Wet detention basins, wetlands, infiltration basins, and grassed swales.
- Minnesota: Wet detention basins, retention pond (infiltration basin), and grassed channels.

The review of the information furnished by these six States revealed that one of the control measure types, retention measures, would be extremely difficult and costly to monitor in a way that would provide useful information on design specifications and removal effectiveness. All but one of the recommended retention measures had multiple inflow points and no provisions for emergency bypass or overflow (i.e., all were designed for extremely large storm events). Therefore, an evaluation of percent of runoff volume captured versus percent of total pollutant load captured could not be performed on these control measures. The only other recommended retention system was constructed with an inflow pipe that would surcharge under normal flow conditions and had a "sinkhole" near the edge of the basin that caused short-circuiting. Since no appropriate retention measures could be located, the focus was to find additional detention and vegetative control measures.

Another major problem encountered during the site selection effort was the lack of sites that represent ideal sites. One of the most common problems was the presence of more than one inlet or outlet at the control measures. This was the limiting factor at most of the detention basins visited during this effort. Many of the grass channels observed received lateral inflow along the side slopes of the channel rather than through one discrete inlet. At these sites, untreated highway runoff enters the control measure along the full length of the channel, making it virtually impossible to monitor inflow at only one point. It was also very difficult to locate sites that receive mostly highway runoff. Many of the recommended sites were observed to receive runoff from other areas, such as parking lots, housing developments, agricultural areas, etc. In addition, many of the sites that met all other criteria were not easily monitored without major modification of the control measure.

Based on a review of site plans and visits to a majority of the suggested sites, none of the vegetative controls recommended by the SHAs were "monitorable" for the purposes of this study. However, one grassed channel was found in Florida during a site visit to a nearby wet detection basin. Two additional channels, one in Virginia and one in Maryland, were found during inspections of potential sites in the Washington, D.C. metropolitan area. The three selected detention basins (Connecticut, Florida, and Minnesota) were all sites recommended by local SHA officials. Even these sites were less than ideal, with two receiving multiple inflows and the third having a permanent flow (groundwater) entering the pond. Because of the lack of additional sites, the six selected sites were to be monitored for additional storm events (more than the 12 originally proposed for the field phase).

B. SITE DESCRIPTIONS

Site-specific descriptions of the control measures monitored and evaluated during the field phase of this project are presented below. Photographs of these sites are included in appendix E.

Virginia

The Virginia grass channel site was located adjacent to the west bound lanes of I-66 in Northern Virginia, between the Cedar Lane overpass and the Nutley Road exit. The grass channel was located at the end of a 1,200-ft (366 m) concrete channel and ultimately drained into a small unnamed brook that flowed under the highway to the south. The average slope of the channel was 4.7 percent and had several areas where moderate erosion had occurred. Indirect flow entered the channel via overland flow along the length of the channel.

The drainage area contributing to this channel was appoximately 1.27 ac (0.51 ha) of which 0.85 ac (0.34 ha) was impervious (pavement), and 0.42 ac (0.17 ha) was pervious (grassed). The Virginia Department of Transportation reports that the 1986 average daily traffic volume (ADT) on the west bound lanes of I-66 was 67,460 vehicles per day (½ of the total ADT of 134,920 vehicles per day).

Maryland

The Maryland grass channel site was located adjacent to the south bound lanes of I-270 approximately 10 miles (16 km) miles south of Frederick, Maryland. The grass channel was located at the end of a concrete channel draining approximately 1 ac (.40 ha) of highway. The average slope of the channel was 3.2 percent. Indirect flow entered the channel as overland flow along the east side of the channel, and a small area of fallow pasture and agricultural land drained into the channel along the west side. The 1985 average daily traffic volume on the south bound lanes of I-270 was 42,000 vehicles per day.

Florida

Two sites were located in Florida, a grass channel and a wet detention basin. The Florida grass channel site was located between the east and west bound lanes of I-4, immediately to the west of South Orange Blossom Trail (SOBT) near the city of Orlando. The grass channel was situated in a grassy median between the I-4 west bound exit ramp to SOBT and SOBT itself. The channel received stormwater runoff from the exit ramp and a portion of I-4, entering the channel through two storm drains along the exit ramp. The runoff ultimately drained under the I-4 exit ramp into a wet detention basin ("West Pond") located on the west side of the exit ramp. The total drainage area was 0.56 ac (0.23 ha), of which 0.35 ac (0.14 ha) were impervious (pavement), and 0.21 ac (0.085 ha) were pervious (grass). The Florida Department of Transportation reported that the 1985 average daily traffic volume on the west bound lanes of I-4 was 41,545 vehicles per day.

The Florida wet detention basin was located on the west side of the I-4 exit ramp, directly across from the grass channel site between the east and west bound lanes of I-4. The basin received storm water runoff through a 36-in (0.91 m) concrete pipe under the I-4 exit ramp and a 15-in (0.38 m) pipe along the east bound lanes of I-4. The 36-in (0.91 m) concrete pipe received storm water runoff from the grass channel site, and a system of other grass and concrete channels along the I-4 exit ramp. The 15-in (0.38 m) pipe directed storm water runoff into the basin below the level of the permanent pool from the east bound lanes of I-4. Additional inputs to the basin included suspected groundwater discharge and overland flow from grassy areas adjacent to the pond. These grassy areas received highway runoff from several 15-in (0.38 m) draining the east bound lanes of I-4. These additional inputs, however, were not thought to be significant.

The basin was approximately 385 ft (117 m) in length and ranged from 70 to 146 ft (21.4 to 44.5 m) in width. The side slopes of the basin were relatively steep. Average depth was 4.4 ft (1.34 m), and the maximum depth was 5.5 ft (1.68 m). The volume of the permanent pool was estimated to be approximately 222,250 ft^3 (6220 m^3) (1,670,000 gallons (6,320,000 L).

The drainage area was comprised of a combination of highway pavement and grassy areas between sections of highway. Portions of both the east and west bound lanes of I-4, SOBT, and two exit ramps were included within the drainage area. The total drainage area was 26.25 ac (10.6 ha), of which 8.5 ac (3.44 ha) were impervious (pavement) and 17 ac (6.9 ha) pervious (grass).

The average 1985 daily traffic volumes for sections of the highway contributing runoff to this site were: 41,545 for the west bound lanes of I-4; 41,203 for the east bound lanes of I-4; and 35,437 for the South Orange Blossom Trail.

Connecticut

The Connecticut wet detention basin site was located adjacent to the east bound lanes of I-84 immediately to the west of Buckland Street in the town of Manchester, Connecticut. The basin was situated in an area between the exit ramp for Buckland Street and the east bound lanes of I-84. Portions of both the east and west bound lanes of I-84, Buckland Street, and two exit ramps were included within the drainage area. The total drainage area was approximately 20 ac (8.1 ha), of which 7 ac (2.8 ha) were impervious (pavement), and 13 ac (5.26 ha) were grassy areas. Storm water runoff within this drainage was conveyed to the wet detention basin through a series of closed conduits, open concrete channels, and over 8,000 ft (2440 m) of grass channels.

The basin was originally designed as an erosion control measure (sedimentation basin) for use during highway construction; however, it was functioning as a wet detention basin. The basin was fed by a 36-in (0.91 m) diameter pipe and a rip-rap lined channel. The outfall has been designed to be pervious and consists of a rip-rap embankment overlain by a layer of 3/8-in (10 mm) stone and sand. The outfall embankment was also equipped with an emergency spillway. Storm water discharged from this basin flowed through a rip-rap-lined channel that ultimately drained under an I-84 exit ramp and into a pond.

The basin had a surface area of approximately 5,900 ft^2 (550 m^2), with a length of roughly 131 ft (40 m) and a width of 45 ft (14 m). Basin depth ranges from 0.5 ft to 4.0 ft (0.15 to 4.0 m), with an average depth of approximately 2.0 ft (0.6 m). The volume of the permanent pool is estimated to be 72,700 gallons (275,000 L). During large storm events, the basin level rises approximately 1 ft (0.3 m), increasing the volume to greater than 114,950 gallons (435,000 L).

The Connecticut Department of Transportation reported that the 1986 average daily traffic volume on I-84 east of Buckland Street was 71,400 vehicles per day. The east bound lanes were responsible for 35,100 and the west for 36,300.

Minnesota

The Minnesota wet detention basin ("West Pond") was located adjacent to the Route 5 and I-494 interchange, approximately 500 ft (150 m) to the west of the Minnesota River in the city of Bloomington, Minnesota. This basin was situated immediately to the south of the I-494 Minnesota River Bridge on the west side of the river. A small portion of the basin was actually located directly beneath the bridge.

The inlet to the basin consisted of a 48-in (1.2 m) pipe terminating at a rip-rap-lined channel approximately 100 ft (30 m) long. The pipe conveyed highway runoff from all lanes of the Route 5/I-494 interchange. Additional highway runoff from a section of the I-494 bridge was conveyed to the pond through a series of bridge deck drains emptying into rip-rap-lined channels. The basin drained eastward through a 48-in (1.2 m) corrugated metal pipe into the Minnesota River. A groundwater seep was located approximately 150 ft (45 m) to the north of the basin; producing the majority of the flow exiting the basin during non-storm periods.

The surface area of the basin, based on the level of the permanent pool, was approximately 28,000 ft^2 (2600 m^2). Basin depth averages approximately 1.5 ft (0.46 m), with a maximum depth of 3.5 ft (1.05 m). The deepest portions of the basin are associated with beaver channels excavated in the bottom of the basin. The total volume of the permanent pool was estimated to be 42,300 ft^3 (1184 m^3), or 316,450 gallons (1,198,000 L).

The drainage area contributing to this basin was comprised of a combination of highway pavement and grassy median areas between sections of the highway. A very small portion of additional flow was contributed to the basin from overland flow and groundwater discharge. Portions of both the east and west bound lanes of I-494, a small section of the I-494 Minnesota River Bridge, a portion of Route 5, and four exit ramps were included within the drainage area. The total drainage area contributing to this basin was approximately 76 ac (31 ha), of which 25 percent was estimated to be impervious. The area of the I-494 bridge deck contributing direct highway runoff to the basin is approximately 2 ac (0.81 ha).

The Minnesota Department of Transportation reported that the 1987 average daily traffic volume on I-494 at the Minnesota River Bridge was 53,400 vehicles per day.

C. SAMPLING STRATEGY

The primary objective of the field phase of this project was to verify and/or refine the design assumptions presented in the Interim Design Guidelines. (Dorman, et al. 1987) The strategy employed to meet this objective involved monitoring and sampling the inflow and outflow from various control measures to determine the overall pollutant removal effectiveness for each type of control measure. Flow rates at the inlet and outlet of the control measures were monitored. This provided data regarding the quantity of runoff entering and leaving the control measure and allowed for the collection of flow proportioned samples, where discrete aliquots of sample were collected at equal, flow-proportioned intervals throughout the entire storm event. The samples were shipped to the contractor's laboratory and analyzed for the following pollutants:

- Total Suspended Solids (TSS)
- Heavy Metals (Cadmium, Chromium, Copper, Lead, and Zinc)
- Nitrogen (Total Kjeldahl Nitrogen and nitrate/nitrite)
- Total Phosphorous
- Total Organic Carbon

It was proposed that over the course of 6 months to 1 year at least 12 stormwater runoff events would be monitored and sampled at each site. Both frequent and infrequent rainfall periods would be monitored and sampled; the majority involving discrete stormwater runoff events following at least 2 days of dry weather. However, in an attempt to determine overall pollutant removal effectiveness, continuous rainfall periods of 7 to 14 days, including up to five storm events, would also be sampled.

D. EQUIPMENT

Sampling and monitoring stations were installed at the inlet and outlet of each control measure site evaluated during the field phase. Each sampling and monitoring station consisted of a primary flow control device installed in the inlet or outlet structure, automatic flow monitoring and sampling instrumentation, and a metal shed used to house the automatic instrumentation.

Primary Flow Control Devices

Primary flow control devices are hydraulic structures designed to produce a flow characterized by a known relationship between liquid level and flow rate in the stream. These devices include flumes and weirs. H-type flumes were the first choice as these structures operate over a wide range of flow conditions and are generally self-cleaning. V-notch weirs and compound weirs were also used at several of the sites when the use of flumes was not practical.

H-type flumes were used in all the grass channel sites and in the wet detention basins in Florida and Connecticut. The flumes were constructed of galvanized steel and were attached to an approach box with wing walls, directly in the inlet or outlet channels. The approach boxes and wing walls were constructed with marine-grade plywood supported by a 2- by 4- in (50 by 100 mm) frame and 4- in by 4- in (100 by 100 mm) posts. The wing walls were attacked to the upstream end of the approach box and funneled the flow into the flume. The function of the approach box was to reduce turbulence and stabilize the flow prior to entering the flume.

A 90-degree, V-notch weir was used in the outlet to the Florida wet detention basin. V-notch weirs are accurate flow measuring devices particularly suited for low flows and consists of an angular notch (90 degrees in this case) cut into a bulkhead in the flow channel. The apex of the notch is at the bottom, and the sides are set equally on either side of a vertical line from the apex. The weir used at the Florida wet detention basin was constructed of marine grade plywood and attached to a concrete bulkhead at the outlet of the basin.

Compound weirs were used at both the inlet and outlet at the Minnesota wet detention basin. The compound weirs consisted of a 1-ft (0.305 m), 90-degree, V-notch weir used in combination with an 8 ft-by-2 ft (2.44 m-by-0.61 m) rectangular weir. The V-notch was cut in the bottom center of the rectangular weir. During low-flow conditions, the stucture acts as a combination V-notch weir only. During high-flow conditions, it acts as a combination V-notch/rectangular weir. The average storm event at this site was expected to be accommodated by the V-notch weir. However, as the drainage area contributing to this site was very large, occasional very high flows were expected. This structure allowed for very accurate flow measurement during small, low-flow storm events and also accommodated high flows during intense storm events.

Sampling and Monitoring Instrumentation

Open channel flow meters, chart recorders, liquid-level actuators, and samplers were used in conjunction with the above-described primary devices to complete the sampling/monitoring stations.

The flow meters were used for three purposes: (1) to measure the liquid level in the primary device; (2) to convert the measured liquid level into flow rate using the known liquid level-flow rate relationship of the primary device; and (3) to send signals, at flow-proportioned intervals, to the automatic samplers. ISCO Model 1700, 1870, and 2870 flow meters were used. Flow rates were recorded on built-in (Model 1870 and 2870) or separate (Model 1700) chart recorders.

Two types of automatic samplers were used, ISCO Model 1680 discrete samplers or ISCO Model 2710 composite samplers. Both models pump uniform small sample increments into receptacles housed within the sampler. The Model 1680 operates as a discrete sampler, filling up to 28 individual bottles, which were later composited. The Model 2710 operated as a composite sampler, filling a single 4-gallon (15.1 L) container.

Liquid-level actuators (ISCO Model 1640) were used at those sites where the potential for constant flow into or out of the control measure existed. The actuator initiates the sampling program when runoff flow reached a predetermined height.

Marine deep-cycle, 12-volt batteries were used to power the instrumentation. All of the instrumentation was housed in 10- to 14-gauge, galvanized-steel sheds located within 25 ft (7.62 m) of the primary devices.

E. SAMPLING/MONITORING PROCEDURES

The initial step regarding the individual sampling/monitoring programs in each State involved the installation of primary flow control devices and associated instrumentation. The flow meters were activated immediately after installation; however, samples were not collected for a period of approximately 1 month after installation. The purpose of this waiting period was twofold: (1) it allowed the disturbed area adjacent to the recently installed primary structure to stabilize; and (2) an average flow rate was determined to obtain calibration data for the instruments. The instruments were then calibrated and activated, based on the previously determined average flow rates, to collect flow-proportioned samples across the entire storm hydrographs.

Throughout the course of the sampling/monitoring programs, the sample stations were visited by field technicians after every storm event and on a weekly or biweekly basis. The following tasks were completed at every weekly/biweekly visit to the sites:

- A visual check of the entire sample station was conducted to ensure that everything was in proper operating condition.
- A standardized log form was completed detailing all observations regarding site conditions and operating status of the instruments.
- Chart paper and batteries were removed and replaced.
- All instruments were recalibrated.

The sample stations were also visited within 24 hours of every storm event to collect samples. The tasks completed during every post-storm visit were similar to those presented above with two exceptions:
(1) batteries and chart paper were not replaced unless necessary; and
(2) samples were collected.

The field technicians were equipped with individual 4-gallon (15.1 L) composite containers for each site, 500-ml sample bottles, and coolers filled with ice. At the sites where Model 1680 samplers were used, the first task in sample collection involved compositing the samples from up to 28 individual bottles. Each individual bottle was removed from the sampler, capped, and mixed. The bottles were then emptied into the prewashed 4-gallon (15.1 L) composite container and mixed once again. Once thoroughly mixed, the composite sample was transferred into two 500-ml sample bottles. The Model 2710 samples use only one 4-gallon (15.1 L) sample bottle; therefore, the collected liquid was mixed and transferred directly into the 500-ml sample bottles. These bottles were labeled with the date, time, and site name and immediately placed in coolers with ice. The coolers were then shipped or directly transported to the laboratory facilities.

F. ANALYTICAL PROCEDURES

Upon receipt at the laboratory, the samples were removed from the coolers and preserved appropriately according to the parameters for which they were to be analyzed. The samples were then stored in a walk-in refrigerator (maintained at 4°C) until analysis. The laboratory methods and analytical procedures are described in table 12.

G. OTHER TESTS AND EVALUATIONS

In addition to the above-described tests and evaluations, sediment analyses were conducted at each control measure to determine the spatial

Table 12. Laboratory methods and analytical procedures used for field phase water samples. (U.S. EPA, 1982)

Parameter	Reference Method	Preservation	Holding Time
Nitrate + Nitrite	353.2	Filter; pH <2, H_2SO_4; Cool to 4°C	28 days
Total Nitrogen, Kjeldahl	351.2	pH <2, H_2SO_4; Cool to 4°C	28 days
Total Phosphorus	365.2	pH <2, HSO_4; Cool to 4°C	28 days
Dissolved Phosphorus	365.2	Filter; pH <2, H_2SO_4; Cool to 4°C	28 days
Total Suspended Solids	160.2	Cool to 4°C	7 days
Total Organic Carbon	415.1	pH <2, H_2SO_4; Cool to 4°C	28 days
Total Metals (Pb, Zn, Cd, Cr, Cu)	200.7	pH <2, HNO_3	6 months

distribution of pollutants deposited within the control measures. These analyses also provided data regarding long-term sediment accumulation rates. Accumulation rates for heavy metals is an important factor in determining the required frequency of sediment removal since high levels of metals can preclude the sediment from being disposed of in a conventional manner (e.g., sediment could be hazardous if metals reach levels established by EPA). With vegetative controls, the distribution of pollutants along the flow path provides an indication of pollution removal efficiencies along the length of the control measure. It also provides information regarding the process by which pollutants are broken down, adsorbed, or biodegraded by the vegetation and soil.

Sediment analysis of the wet detention basins was used to define the need and frequency of sediment removal (based on both accumulation rates and metals concentrations) and the potential impact the runoff may have on vegetation and aquatic life within the basin.

At each control measure site, samples of surface sediments (top 5 cm) were collected at the beginning of the field monitoring phase. Samples were collected both within the control measure site and at control points adjoining the site (for background). The locations and number of samples varied between sites and types of control measure, but the overall sampling strategies and numbers of samples for each type of control measure are discussed below:

Grassed Channels

Samples were collected at approximately the following intervals within the channel: 0 ft (0 m), 10 ft (3.0 m), 20 ft (6.1 m), 30 ft (9.15 m), 40 ft (12.2 m), 50 ft (15.25 m), 75 ft (22.9 m), 100 ft (30.5 m), 125 ft (38.1 m), 150 ft (45.8 m), 175 ft (53.4 m), and at the end of the channel. These intervals were modified slightly at each site as the length of each channel varied. Within a zone extending 0.5 ft (.15 m) on either side of each transect, 6 to 10 sediment samples (approximately 2.5 cm diameter by 5 cm deep) were collected from the bottom of the channel and composited. Control samples, used to determine the background levels of the constituents in the soil, were collected between 25 and 50 ft (7.6 and 15.25 m) from the grassed channel (in the direction away from the roadside) along a transect parallel to that established for the channel sediment sample location: 0 ft (0 m), 20 ft (6.1 m), 40 ft (12.2 m), 75 ft (22.9 m), 100 ft (30.5 m), 150 ft (45.8 m), and across from the end of the channel. The same collection procedures were used for control samples as the sediment samples. All the samples were collected using stainless-steel spoons. The sample sites were prepared by carefully removing grass and debris with clippers or a trowel.

Wet Detention Basins

Each basin was divided into a grid, and samples were taken along transects established by the grid. The exact number and spatial distribution of the sample collection points were dependent upon the shape and size of the basin. At each sampling location, several sediment samples were collected within a 2-m grab diameter circle and composited. The samples were collected using a Peterson sampler. Control samples were collected at 6 locations around the perimeter of the basin (locations were determined on a site-specific basis). Enough sediment sample was collected at each location to fill a 500-ml Nalgene plastic sample bottle.

All sediment samples were analyzed at the laboratory for the following constituents:

- Heavy Metals (cadmium, copper, chromium, lead, and zinc).
- Nitrogen (TKN, nitrate + nitrite, as N).
- Total Phosphorus (as P).
- The determination of solids content and pH was also performed.

Table 13 provides the analytical and preservation techniques used for the sediment samples.

2. FIELD TEST RESULTS

A. MONITORING DATA

The stormwater quality monitoring data for the grassed channels and wet detention basins included duration of flow, peak flow, total flow, and constituent concentrations for the inflow to and the outflow from the channels. The samples were analyzed for total suspended solids (TSS), total organic carbon (TOC), total Kjeldahl nitrogen (TKN), nitrate plus nitrite nitrogen, total phosphorous (TP), cadmium, chromium, copper, lead, and zinc. All water quality analyses were from flow-proportional composite samples. The raw data are presented in appendix F. Sediment core sample data (appendix G) for the grassed channels and wet detention basins include average, maximum, and minimum sediment concentrations of total phosphorous, total Kjeldahl nitrogen, nitrate plus nitrite nitrogen, chromium, copper, lead, and zinc. Summaries of the monitoring activities and problems encountered at each control measure are provided in the following paragraphs.

Virginia Grassed Channel

The monitoring stations at the Virginia grassed channel were constructed between June 1 and June 12, 1987. The stations were activated on June 13, 1987 and were operational until November 12, 1987, when freezing weather conditions prevailed. During this time period a total

Table 13. Laboratory methods and analytical procedures used for field phase sediment samples.

Parameter	Reference Method	Preservation	Holding Time
Total Phosphorus	U.S. DA, 1965 (Section 73)	Freeze	Unlimited
Total Nitrogen, Kjeldahl	U.S. DA, 1965 (Section 84)	Freeze	Unlimited
Nitrate + Nitrite	U.S. DA, 1965 (Section 84)	Freeze	Unlimited
Metals (Sediment)	U.S. EPA, 1981	4°C	Unlimited

of 25 storm events were recorded; samples were collected from 12. Of the 12 collected samples, 11 were from single storm events and one was from a series of four storm events over a period of 48 hours. It was originally planned to reactivate the stations in the spring of 1988; however, the site was destroyed by highway construction activities.

Sediment samples were collected on May 11, 1987. Eleven samples were collected within the channel and six were taken to represent background.

A number of storm events were recorded that resulted in higher flow volumes at the outflow station than at the inflow station. It was assumed that overland flow was occurring along the length of the channel and, therefore, not recorded at the inflow station. Other problems encountered with the data included outflow constituent concentrations that were higher than the inflow concentrations. In most cases, this could be attributed to erosion occurring along the bottom of the channel resulting in the resuspension of accumulated pollutants in the sediments. Two attempts were made to stabilize this channel. The channel was seeded and mulched in June; however, the seed was washed-out when municipal water supply maintenance crews discharged a water main directly into the channel. Later in June, in another attempt to stabilize this control measure, sod was laid along the length of the channel. This attempt was not very successful due to drought conditions experienced in the local area.

Maryland Grassed Channel

The Maryland grassed channel monitoring stations were constructed between June 14 and June 17, 1987. The stations were activated on June 18, 1987 and were operational until mid-September 1987. A total of five storm events were recorded; with samples were collected from four. All four were from single-event storms.

Sediment samples were collected on June 14, 1987. Twelve samples were collected in the channel, and six were collected to represent background.

The data collected from this site was limited due to a lack of rain in the local area during the monitoring period. Discrepancies between the inflow and outflow volumes, as well as between the inflow and outflow constituent concentrations, were also experienced at this site. Overland flow along the length of the channel is thought to be the primary cause for these discrepancies.

Florida Grassed Channel

The monitoring stations at the Florida grassed channel were constructed between January 11 and 20, 1988. The stations were partially activated on January 21, 1988, to collect rainfall/flow rate information necessary to calibrate the sampling equipment. The stations became fully operational on February 25, 1988, and were deactivated on October 31, 1988. A total of 13 storm events were collected during this time period.

Sediment samples were collected on January 22, 1988. Twelve samples were collected within the channel, and seven samples were taken 35 ft from the channel to represent background.

Equipment malfunctions hampered the collection of data at this site. Some of the instrumentation behaved erratically due to extreme high temperatures and high humidities. In July, an unidentified foul smelling soil-like substance was dumped immediately upstream from the inlet station. This material was removed by field technicians and was not thought to contribute any additional pollutant load to the samples collected from this site. Problems regarding inflow and outflow volumes and constituent concentrations were also experienced at the Florida grassed channel.

Florida Wet Detention Basin

The monitoring stations at the Florida wet detention basin were constructed, activated, and operated on the same schedule as the grassed channel stations. A total of 15 storm events were collected during the monitoring period.

Sediment samples were collected on January 22, 1988. Twelve samples were collected within the basin, and six samples were taken around the perimeter to represent background.

Discrepancies in inflow and outflow volume and constituent concentrations were also experienced at this site. There are two direct inlets to this basin, a 36-in (0.91 m), concrete pipe and a 15-in (0.38 m), corrugated metal pipe. The 36-in (0.91 m) pipe was the primary inlet to the basin and was the only one of the two inlets monitored. The 15-in (0.38 m) pipe entered the basin below the level of the permanent pool of the basin; therefore, monitoring was not feasible. Additional flow entered the basin via overland flow. Groundwater discharge and recharge may have also been a small component to the hydrologic system associated with this basin. These unmonitored flows to and from the basin are thought to be the cause for any discrepancies in flow volumes and constituent concentrations. Vandalism and accidents plagued the monitoring program at this site. Portions of the inlet flow monitoring structure were destroyed, due to vandalism, on several occasions. Minor repairs were made by the field technicians in all cases. In August, a tanker truck, transporting diesel fuel, ran off the road and spilled approximately 100 gallons (360 L) of its contents immediately upstream of the inlet station. The guard rail was destroyed, and an area of soil was exposed to erosion adjacent to the inlet station. This area was reseeded and stabilized as soon as possible after the accident.

Connecticut Wet Detention Basin

The Connecticut wet detention basin monitoring stations were constructed between May 18 and 27, 1987. The stations were activated on July 2, 1987, and were operational until November 30, 1987. A total of 12 storm events were recorded, and samples were collected from seven. Of the seven, five were collected from multiple storm events and two from single storm events.

Sediment samples were collected on July 7, 1987. Sixteen samples were collected within the basin. No control or background samples were taken because no undisturbed areas near the basin could be found (i.e., the areas around the basin were either fill or gravel).

The lack of sufficient rainfall during the monitoring period was a primary factor in limiting the quantity of data at this site. Only 12 storms were recorded during the 4-month period. An algal bloom at the outflow monitoring structure was an additional factor limiting the quantity of representative data. As with the other sites, inflow and outflow volume and constituent concentration discrepancies were noted at the Connecticut stations.

Minnesota Wet Detention Basin

The monitoring stations at the Minnesota wet detention basin were constructed between April 18 and 25, 1988. The flow meters were operated between April 25 and May 26 to obtain calibration data for the sampling equipment. The samplers were activated on May 26, 1988, and were operational until October 31, 1988. A total of 14 storms were recorded during this time period, and samples were collected from 13. Of the 13, 1 was from a multiple storm event, and the remainder were single-storm events.

Sediment samples were collected on April 24, 1988. Twelve samples were collected from the basin, and 6 samples were collected around the perimeter to represent background.

Problems encountered during the monitoring period included: off-site erosion contributing pollutants to the downstream station; erosion and leaking around the inlet flow monitoring structure; and active use of the basin by muskrats, beaver, and waterfowl. Approximately 2 ac (.81 ha) of a bridge deck drained directly into this basin via four bridge deck drains. Erosion channels were formed between these drains and the basin. Observations during storm events indicated that these channels were eroding badly and contributing an additional, unmonitored, sediment load into the basin. Personnel from the MNDOT repaired these channels by lining them with geotextile fabric and placing rip-rap along their length.

Erosion and leaks at the influent monitoring station were a regular problem during the first half of the study period. The soils in the vicinity of the influent channel were thought to be river bottom fill soils (muck) and were very fine and highly erodible. On several occasions, project personnel had to repair leaks under the weir caused by undercutting. Additional cement was poured and rip-rap was placed both upstream and downstream of the weir to prevent further erosion. An intense storm occurring in early August, washed out a large area under this weir. This was repaired by digging a trench on the upstream side of the weir, placing a 4-ml plastic liner from the weir to about 6 ft(1.8 m) upstream, and backfilling the trench with rip-rap and soil. No major leaks or erosion problems were noted after these repairs were made.

This basin was frequented by a variety of wildlife. Muskrat and beaver activity contributed debris (e.g., sticks and cuttings) that often partially clogged the effluent weir. The activity of these animals also increased the turbidity of the basin. The beavers also chewed the upright supports on the weirs; however, this did not lead to any damage requiring repairs. This basin was also frequented by a variety of waterfowl, including ducks, geese, and herons. The contribution of nutrients from the waste of these birds is unknown.

B. DATA ANALYSIS AND EVALUATION

The storm event runoff water quality data and sediment core sample data presented above was analyzed for three grassed channels and three wet detention basins. The purpose of the analyses of the water quality data was to determine pollutant removal efficiencies for both types of control measures, and to determine if there is a relationship between TSS removal and particle settling in the grassed channels.

The purpose of the analyses of the sediment core data was to determine whether significant pollutant accumulation has occurred in both control measures, and to estimate the service life of the grassed channels. Summaries of the analyses are provided below.

Pollutant Removal Efficiencies for Grassed Channels

Synoptic storm summary data was used to calculate pollutant removal efficiencies for total suspended solids (TSS), total organic carbon (TOC), total Kjeldahl nitrogen (TKN), nitrite plus nitrate nitrogen, total phosphorus (TP), cadmium, chromium, copper, lead and zinc. Three different analysis methods were used to estimate pollutant removal efficiencies for the grassed channels. The methods are as follows:

- Mean storm event efficiency.
- Event mean concentration (EMC) efficiency.
- Long-term efficiency.

In the mean storm event method, the removal efficiency was calculated for each synoptic storm, and the efficiency values were then averaged to determine the mean removal rate.

For the EMC method, the geometric means of the inflow EMC and the outflow EMC were used to calculate removal efficiency.

In the long-term method, inflow and outflow mass loads for each storm were added, and the sums of the loads were used to calculate removal efficiency.

Due to limitations in the monitoring program and resulting data, several assumptions were made in the analysis water of the quality data. These assumptions are presented in table 14. As shown in the table, all of the assumptions are associated with either flow volume or concentration.

The volume assumptions were required to reconcile inflow and outflow volumes in situations where the flows were unknown or inconsistent. In cases where the inflow volume was less than the outflow volume, it was assumed that the difference was due to material inflow entering the channel between the inflow and outflow monitoring points. In cases where either inflow or outflow was unknown due to mechanical malfunction or other reason, it was assumed that inflow was equal to outflow. At all three sites, the drainage area to the outflow monitoring point was typically not much greater than the drainage area to the inflow monitoring point, so that the assumption of inflow equaling outflow is reasonable.

The concentration assumptions were applied almost exclusively to the metals data. Of the three most common metals (copper, lead, and zinc), lead values were most frequently below the detection limit. In contrast, zinc values were consistently at or above the detection limit. To include values below the detection limit, it was assumed that the inflow concentration was equal to the detection limit, and that the outflow concentration was equal to either the detection limit or 10 percent of the detection limit. By assuming a high and a low estimate of the outflow concentration, a range of removal efficiencies was calculated for any constituent with outflow values below the detection limit.

After the database was adjusted according to the assumptions discussed above, the storm data were screened to eliminate storms with anomalous data. Initially, the storms were screened based on inflow/ outflow relationships and documented monitoring problems. Then, the storms were further screened to eliminate storms with other unusual data (e.g., outflow concentrations substantially larger than inflow concentrations).

The results presented for the Virginia and Florida channels are based on storm data after it had been screened: the Virginia results are based on nine storms (three storms excluded), and the Florida results are based

Table 14. Assumptions in calculating removal efficiencies.

Assumptions in Calculating Removal Efficiencies	
Inflow volume less than outflow volume	Inflow volume = outflow volume
Inflow volume unknown	Inflow volume = outflow volume
Outflow volume unknown	Inflow volume = outflow volume
Inflow concentration less than detection limit	Inflow concentration = detection limit
Outflow concentration less than detection limit	Set outflow concentration = either detection limit or 1/10 of detection limit (i.e., look at lower and upper range of range)

on eight storms (five storms excluded). Review of the results showed that the removal efficiencies before and after screening were typically similar, using the EMC method of calculation.

The results presented for the Maryland channel are based on the total database of four storms. This database may already be too small to provide meaningful removal efficiency estimates, and it was felt that reducing the size of the database further by screening was not appropriate. Because of the problems with the data and the limited number of storms, the Maryland results are not considered as reliable as the results for the Virginia and Florida channels.

The results of the pollutant removal estimation process are presented in table 15. For each of the three channels, the table lists the total number of storms and the number of storms that were included in the database after data screening, and lists removal efficiencies for 10 different constituents, estimating using the three methods discussed earlier. As mentioned previously, the results for Virginia and Florida are considered more reliable than the results for Maryland.

Regardless of the removal estimation method, the following observations can be made:

- TSS removal varied widely between the three sites. This is significant because all three channels are approximately the same length, and would therefore be expected to have the same removal efficiency according to the interim FHWA guidelines. The results suggest that length alone should not be used to estimate channel efficiencies.

- The Florida channel, which is most effective in removing TSS, is different from the Virginia and Maryland channel in several respects. First, the Florida channel has a lower slope than the other two channels. Second, the Florida channel is wider (i.e., has less steep side slopes) than the other channels. Third, the drainage area for the Florida channel is smaller than for the Virginia channel, such that the Florida channel should receive lower flows since the percent impervious is approximately the same for both sites.

- Because of the differences mentioned above, the Florida channel will tend to have shallower flow depths and a longer detention time than the other channels. Theoretically, these conditions should be more conducive to solids settling, and results tend to indicate that this is the case.

- Removal of metals in the channels appears to be directly related to the TSS removal. Similar to TSS, the removal of copper, lead, and zinc in the Florida channel is much better than in the

Table 15. Pollutant removal estimates for grassed channels.

Location	Number of Monitored Storms	Number of Analyzed Storms	Method of Analysis	Percent Removal Estimates									
				TSS	TOC	TKN	NO2+NO3	TP	CD	CR	CU	PB	ZN
Virginia	12	9	EMC	52	31	17	2	36	8-87	(-10)-34	12	17-78	27
			Mean Event	56	29	26	15	40	15-86	(-28)-(-8)	22	28-58	35
			Long Term	65	76	17	11	41	12-98	12-16	28	41-55	49
Maryland	4	4	EMC	(-65)-7	(-3)-42	3-46	(-113)-(-28)	(-19)-33	64-94	5-83	(-2)-43	8-98	18
			Mean Event	-63	22	23	-128	3	74-94	38-75	22	25-93	34
			Long Term	-85	23	9	-143	12	85-91	22-72	14	18-92	47
Florida	13	8	EMC	98	58	13	12	-47	(-29)-46	29-47	42-56	33-91	69
			Mean Event	87	66	51	52	26	31-47	56-65	65-78	59-87	81
			Long Term	98	64	48	45	18	29-45	51-61	62-67	67-94	81

Ranges of percent removal results from inflow or outflow concentrations that are below detection limit.

Virginia channel. In addition, the relationships between TSS and metals removal are typically consistent with the settling column relationships. Regressions performed on the settling column data indicated that 60 percent of copper, 90 percent of lead, and 50 percent of zinc was associated with suspended solids. Using these values and monitored TSS values to predict metals removal (e.g., measured 90 percent TSS removal results in predicted zinc removal of 90 percent x 50 percent = 45 percent, results show that the monitored lead and zinc removal values in the Virginia channel, and the monitored copper and lead removal values in the Florida channel, are in agreement with the predicted values. The predicted value for copper in the Virginia channel is higher than the monitoring value, and the predicted value for zinc in the Florida channel is lower than the monitoring value. This could mean that zinc in the Florida channel is being removed by mechanisms other than sedimentation (e.g., adsorption).

- Nutrient removal varies widely between channels, and does not appear to be related to TSS removal. Even though the Florida channel was effective in removing TSS and metals, the nutrient results indicate low removal of TKN and nitrate, and negative removal for TP based on the EMC method. In contrast, the otherwise less effective Virginia channel is comparable to the Florida channel in removal of TKN and nitrate, and had a relatively high rate of TP removal. These results suggest that nutrient removal cannot be related to TSS removal, and that relatively low nutrient removal values may be expected even in channels that are effective in removing other pollutants.

These observations support a change in the efficiency estimation method presented in the FHWA interim guidelines. The guidelines state that TSS and lead removal in grassed channels can be estimated from channel length only. The results presented herein suggest that characteristics, such as channel geometry, channel slope, and average flow rate, in addition to length, will determine the efficiency of the channel. Further, the results suggest that metals removal efficiency can be estimated based on TSS removal efficiency, although nutrient removal cannot.

Pollutant Removal Efficiencies for Wet Detention Basins

Synoptic storm summary data was used to calculate pollutant removal efficiencies for total suspended solids (TSS), total organic carbon (TOC), total Kjeldahl nitrogen (TKN), nitrite plus nitrate nitrogen, total phosphorus (TP), cadmium, chromium, copper, lead, and zinc. The analysis methods and assumptions presented for the grassed channel systems were also used to estimate the pollutant removal efficiencies for the wet detention basins.

After database adjustment according to the assumptions discussed for grassed channels, the storm data were screened to eliminate storms with anomalous data. Initially, the storms were screened based on inflow/outflow relationships and documented monitoring problems. Then, the storms were further screened to eliminate storms with other unusual data (e.g., outflow concentrations substantially larger than inflow concentrations).

The results presented for the Minnesota and Florida detention basins are based on storm data after it had been screened. The Minnesota results are based on eight storms (five storms excluded) and the Florida results are based on six storms (nine storms excluded). Review of the results showed that the removal efficiencies before and after screening were typically similar, using the EMC method of calculation.

The results presented for the Connecticut detention basin are based on the total database of seven storms. Considering that no inflow-outflow relationship could be established and that deleting three storms for high outflow concentrations would reduce the database to only four storms, it was felt that eliminating storms was not appropriate. Because of the problems with the data, the Connecticut results may not be as reliable as the results for the Minnesota and Florida basins.

The results of the pollutant removal estimation process are presented in table 16. For each of the three basins, the table lists the total number of storms and the number of storms that were included in the database after data screening, and lists removal efficiencies for 10 different constituents, estimated using the 3 methods discussed earlier. As mentioned previously, the results for Minnesota and Florida are considered more reliable than the results for Connecticut.

The following observations can be made from the values shown in table 16:

- Predicted removal efficiencies vary, depending on the estimation method. Differences between the three methods were smallest for the Minnesota detention basis, for which only TP and perhaps nitrate/nitrite show substantial differences. Considering the Florida site, the mean event and long-term methods tend to be similar, and both are larger than the EMC estimate. This was because the Florida basin outflow was typically less than the basin inflow, and the EMC method does not account for flow volumes. For the Connecticut basin, the long-term estimate was typically larger than the estimates using the other methods. The mean event and EMC estimates were lower in part because of two small storms that showed poor removal efficiencies. Unlike the long-term method in which the effect of each storm on the estimation process depends upon the mass of constituent entering and leaving the basin, the EMC and mean event methods weigh each

Table 16. Pollutant removal estimates for wet detention basins.

Location	Number of Monitored Storms	Number of Analyzed Storms	Method of Analysis	Percent Removal Estimates									
				TSS	TOC	TKN	NO2+NO3	TP	Cd	Cr	Cu	Pb	Zn
Connecticut	7	7	EMC	14	15	-4	-2	-8	(-116)-(-55)	1-73	38	8-86	22
			Mean Event	-34	25	10	17	-3	(-88)-(-67)	15-68	38	17-78	34
			Long-Term	61	33	24	22	45	(-27)-(-16)	21-47	38	18-59	51
Minnesota	13	8	EMC	61	18	26	79	11	8-91	38-85	36-85	8-88	67
			Mean Event	56	13	25	67	-4	6-91	36-78	33-48	7-83	66
			Long-Term	65	19	23	61	25	12-91	48-76	37-51	8-79	66
Florida	15	6	EMC	18	24	36	92-98	59	48-72	5-88	55-94	6-91	66
			Mean Event	49	49	58	92-93	68	41-47	37-77	67-89	41-94	73
			Long-Term	54	45	68	96-98	69	43-51	48-88	66-81	41-94	69

Note: Negative ranges shown in parentheses.

storm equally. Thus, the long-term efficiency estimates were not affected by the monitoring results for the small storms, but the EMC and mean event estimates were. In addition, the EMC method did not account for the fact that two storms had monitored outflow that was substantially less than the monitored inflow.

- The Florida basin was the most effective in removing nutrients. Table 16 shows that from 40 to 60 percent of the TKN, over 90 percent of the nitrate, and 60 to 70 percent of the TP was removed at the Florida site. In contrast, the Minnesota basin was removing 20 to 30 percent of the TKN, 60 to 80 percent of the nitrate/nitrite, and less than 25 percent of the TP.

- The Florida basin was also the most effective in removing metals, although the other two basins were also achieving a moderate level of removal. Results for cadmium, and particularly lead, were inconclusive because monitored values were often at or below the detection limit; therefore, copper and zinc provide the best indication of metals removal efficiencies. In the Florida basin, 60 to 90 percent of the copper and 65 to 75 percent of the zinc are removed. Minnesota also appeared to be quite effective, removing 35 to 65 percent of the copper and 65 to 70 percent of the zinc. Even the Connecticut pond showed removal efficiencies of 30 to 40 percent for copper and 20 to 50 percent for zinc.

- Processes other than sedimentation are important in wet detention basins. Given the low to moderate TSS removal estimates and the settling column results associating nutrients and metals with suspended solids, high removal rates for both nutrients and metals cannot be explained by sedimentation alone. For example, given a 60 percent TSS removal in the Minnesota basin and the settling columns regression associating approximately 50 percent of zinc with suspended solids, a 30 percent zinc removal value would be expected if sedimentation was the sole removal process. Monitoring results show zinc removal in the Minnesota basin to be 65 to 70 percent, much greater than the 30 percent estimate based on settling alone. Other processes that may be responsible for removal in wet detention basins include biological uptake and adsorption to bottom sediments.

Sediment Sample Analyses for Grassed Channels

The sediment core sample data was analyzed to determine whether significant pollutant accumulation has occurred in the channels, and to compare the accumulations at the three grassed channel sites.

A cursory examination of the data revealed several facts. One is that the channel sediment concentrations are not always higher than the background sediment concentrations, particularly for the nutrients. This may support the conclusion that the channels are not effective in removing these pollutants. Another observation is that sediment concentrations for the Virginia channel were often less than the sediment concentrations in the Maryland and Florida channels. Factors, such as the age of the channel, the annual pollutant load to the channel, and the removal efficiency of the channel, are all important in determining why accumulations vary from one site to another.

For each channel, statistical analyses were applied to compare core sample data for the channel with core sample data for the adjacent undisturbed area. The objective of this analysis was to determine whether channel sediment concentrations were significantly greater than background sediment concentrations. If so, one could conclude that the channel is removing pollutants that are accumulating in the channel sediments; if not, one could conclude that the channel is not effectively removing pollutants.

Nonparametric statistics were used in analyzing the channel and background data. By definition, a nonparametric statistic is one that assumes no underlying distribution for the populations being considered.

The two nonparametric tests that were used in the comparison of channel and background data are the Wilcoxon Rank Sum Test and the two-sided Kolmogorov-Smirnov (K-S) Test. The Wilcoxon Rank Sum Test is designed to test hypotheses regarding the difference between two medians. With respect to the sediment data, the Wilcoxon test was used to determine if the median pollutant concentration in the channel sediment is significantly different than the concentration in the background sediment. The two-sided K-S test is designed to test the hypothesis that two populations are identical. With respect to the sediment data, the two-sided K-S test was used to determine if the distribution of pollutant concentration in the channel sediment is significantly different than the distribution of concentration in the background sediment.

Statistical analyses were also applied to compare core sample data from each channel to core sample data from the other channels. The objective of the analyses was to determine whether there were significant differences between the data from the different sites. If so, it could demonstrate that one site is more effective than another in removing pollutants, though the difference may also depend upon the annual pollutant loading to the channels and the number of years that each channel has been in service. As with the comparison of channel and background data, the Wilcoxon Rank Sum Test and the two-sided K-S test were used in the site comparison analysis. The Wilcoxon test was used to determine if the median pollutant concentration at one site is significantly different than the median concentration at another site, and the two-sided K-S test was used to determine if the distribution of pollutant concentration differed from one site to another.

Table 17 presents the results of the Wilcoxon Rank Sum Test and the two-sided K-S test for the comparison between channel concentrations and background concentrations. For each of the three sites, the table indicates whether the channel sediment and the background sediment had significantly different distributions based on the two-sided K-S test; whether the channel sediment and the background sediment had significantly different median values based on the Wilcoxon Rank Sum Test; and in cases where the median was significantly different, whether the median value was higher in the channel or in the background sediment. For both the two-sided K-S test and the Wilcoxon Test, results are based on a level of significance of 0.05.

The results shown in table 17 support the conclusion that the Florida channel is the most effective of the three channels in removing pollutants. Table 17 shows that, for the Florida channel, the concentration of all seven analyzed pollutants was significantly higher in the channel than in the background sediments. In contrast, only four of the seven pollutants are significantly higher in the Maryland channel, and only three of the seven pollutants are significantly higher in the Virginia channel as compared to corresponding background concentrations.

The analysis also indicates that both nutrients and metals are removed in the grassed channels. Of the 12 Wilcoxon tests conducted for metals, nine revealed a significantly higher metal concentration in the channel sediment, and only one revealed a higher metal concentration in the background sediment. In comparison, of the nine Wilcoxon tests conducted for nutrients, five revealed a significantly higher nutrient concentration in the channel sediment, and two revealed a higher nutrient concentration in the background sediment. These results suggest that metals removal is more reliable in grassed channels than nutrient removal. The two-sided K-S test results are very similar to the Wilcoxon test results in that constituents with significantly different median values tended to also exhibit significantly different distributions.

Table 18 presents the results of the Wilcoxon Rank Sum Test and the two-sided K-S test for the comparison of channel sediment concentrations between sites. In the table, each site is compared to one of the other two monitored channels. Differences detected by the test may be explained by differences in annual pollutant loadings, removal efficiencies, and service lives of the channels.

The results in table 18 indicate that metals concentrations in the Maryland channel are generally significantly higher than concentrations in the Virginia and Florida channels. Because Maryland site data, such as drainage area and service life, were not available, it is difficult to

Table 17. Comparison of channel sediment and background sediment.

	VIRGINIA			MARYLAND			FLORIDA		
Constituent	2-Sided K-S Test: Signif. Different Distrib.	Wilcoxon Rank Sum Test: Signif. Different Mean or Median	Higher Mean/ Median Value	2-Sided K-S Test: Signif. Different Distrib.	Wilcoxon Rank Sum Test: Signif. Different Mean or Median	Higher Mean/ Median Value	2-Sided K-S Test: Signif. Different Distrib.	Wilcoxon Rank Sum Test: Signif. Different Mean or Median	Higher Mean/ Median Value
Total P	No	No		No	No		Yes	Yes	Channel
TKN	Yes	Yes	Channel	Yes	Yes	Backgr.	Yes	Yes	Channel
Nitrite + nitrate	Yes	Yes	Backgr.	Yes	Yes	Channel	Yes	Yes	Channel
Chromium	No	Yes	Channel	No	Yes	Backgr.	Yes	Yes	Channel
Copper	No	No		Yes	Yes	Channel	Yes	Yes	Channel
Lead	No	No		Yes	Yes	Channel	Yes	Yes	Channel
Zinc	Yes	Yes	Channel	Yes	Yes	Channel	Yes	Yes	Channel

Based on level of significance = 0.05

Table 18. Comparison of channel sediment at different sites.

	VIRGINIA VS MARYLAND			MARYLAND VS FLORIDA			FLORIDA VS VIRGINIA		
Constituent	2-Sided K-S Test: Signif. Different Distrib.	Wilcoxon Rank Sum Test: Signif. Different Mean or Median	Higher Mean/ Median Value	2-Sided K-S Test: Signif. Different Distrib.	Wilcoxon Rank Sum Test: Signif. Different Mean or Median	Higher Mean/ Median Value	2-Sided K-S Test: Signif. Different Distrib.	Wilcoxon Rank Sum Test: Signif. Different Mean or Median	Higher Mean/ Median Value
Total P	No	No		Yes	No		Yes	No	
TKN	Yes	Yes	Maryland	No	No		Yes	Yes	Florida
Nitrite + nitrate	Yes	Yes	Maryland	No	No		Yes	Yes	Florida
Chromium	Yes	Yes	Maryland	Yes	Yes	Maryland	Yes	Yes	Virginia
Copper	Yes	No		Yes	Yes	Maryland	Yes	Yes	Virginia
Lead	Yes	Yes	Maryland	Yes	Yes	Maryland	Yes	Yes	Florida
Zinc	Yes	Yes	Maryland	Yes	Yes	Maryland	No	Yes	Florida

Based on level of significance = 0.05

attribute the difference in concentrations to specific factors. If it is assumed that the Maryland channel is about the same age and has approximately the same drainage area (i.e., annual pollutant loads are similar) as the Virginia channel, then the difference in metals concentration between those two channels could be attributed to better removal efficiency in the Maryland channel, or loss of sediment metals due to observed erosion in the Virginia channel. Under the same assumptions, the difference between the Maryland and Florida sites could be attributed to the facility ages (the Florida channel has been in service only 4 to 6 years) or the larger annual loading.

The results also indicate that differences in nutrient accumulations are not as pronounced as differences in metals accumulation. In fact, for TP there is not a significantly different median between any of the three channels, although the TP distribution for the Florida site is significantly different than the distribution at the other two sites. For TKN and nitrate, the concentrations in the Florida and Maryland channels are significantly higher than the concentrations in the Virginia channel, which has probably been in service as long or longer than the other two channels. These observations may suggest that grassed channels are not effective in removing nutrients from stormwater runoff, or that some other mechanism (e.g., biological uptake) is removing nutrients. As in the comparison of channel and background sediment, the two-sided K-S test results are generally similar to the Wilcoxon test results.

In summary, the results of the statistical analysis of core samples in the three grassed channels suggest the following:

- Nutrients and metals are removed in grassed channels.
- Metals are removed more reliably than nutrients in grassed channels.
- The Florida channel is the most effective of the three channels in removing pollutants.

Sediment Sample Analyses for Wet Detention Basins

The sediment sample data was analyzed to determine whether significant pollutant accumulation has occurred in the basins, and to compare the accumulations at the three wet detention sites.

An examination of the data reveals several facts. One is that the basin sediment concentrations are typically higher than the background sediment concentrations. This may support the conclusion that the basins are effective in removing pollutants. Another observation is that sediment concentrations for the Connecticut basin are often less than the sediment concentrations in the Minnesota and Florida basins. Factors, such as the age of the basin, the annual pollutant load to the basin, and the removal efficiency of the basin, are all important in determining why accumulations vary from one site to another.

For each basin, statistical analyses similar to those described above for the grass channel sites, were applied to compare core sample data for the basin with core sample data for the adjacent undisturbed area. The objective of this analysis was to determine whether basis sediment concentrations were significantly greater than background sediment concentrations. If so, one could conclude that the basin is removing pollutants that are accumulating in the basin sediments; if not, one could conclude that the basin is not effectively removing pollutants.

Nonparametric statistics were also used in analyzing the basin and background data. The two nonparametric tests that were used in the comparison of basin and background data are the Wilcoxon Rank Sum Test and the two-sided Kolmogorov-Smirnov (K-S) Test.

Statistical analyses were also applied to compare core sample data from each basin to core sample data from the other basins. The objective of the analyses was to determine whether there were significant differences between the data from the different sites. If so, it could demonstrate that one site is more effective than another in removing pollutants, though the difference may also depend upon the annual pollutant loading to the basins and the number of years that each basin has been in service. As with the grassed channel analyses, nonparametric statistics (i.e., Wilcoxon Rank Sum Test and the two-sided K-S Test) were used for job site comparison analysis, and to determine if the distribution of pollutant concentrations in the basin is significantly different from the distribution in the background.

Table 19 presents the results of the Wilcoxon Rank Sum Test and the two-sided K-S test for the comparison between basin concentrations and background concentrations. For each of the three sites, the table indicates whether the basin sediment and the background sediment had significantly different distributions based on the two-sided K-S test; whether the basin sediment and the background sediment had significantly different median values based on the Wilcoxon Rank Sum Test; and in cases where the median was significantly different, whether the median value was higher in the basin or in the background sediment. For both the two-sided K-S test and the Wilcoxon Test, results are based on a level of significance of 0.05.

The results shown in table 19 support the conclusion that the Florida basin is more effective in removing pollutants than the Minnesota basin. Table 19 shows that, for the Florida basin, the median concentration of six of the seven analyzed pollutants was significantly higher in the basin than in the background sediments. In contrast, none of the seven

Table 19. Comparison of detention basin sediment and background sediment.

	CONNECTICUT			MINNESOTA			FLORIDA		
Constituent	2-Sided K-S Test: Signif. Different Distrib.	Wilcoxon Rank Sum Test: Signif. Different Mean or Median	Higher Mean/ Median Value	2-Sided K-S Test: Signif. Different Distrib.	Wilcoxon Rank Sum Test: Signif. Different Mean or Median	Higher Mean/ Median Value	2-Sided K-S Test: Signif. Different Distrib.	Wilcoxon Rank Sum Test: Signif. Different Mean or Median	Higher Mean/ Median Value
Total P	NA	NA		No	No		Yes	Yes	Basin
TKN	NA	NA		No	No		Yes	Yes	Basin
Nitrite + nitrate	NA	NA		Yes	Yes	Backgr.	No	No	
Chromium	NA	NA		No	No		Yes	Yes	Basin
Copper	NA	NA		No	No		Yes	Yes	Basin
Lead	NA	NA		No	No		Yes	Yes	Basin
Zinc	NA	NA		No	No		Yes	Yes	Basin

Based on level of significance = 0.05

Tests could not be conducted for Connecticut site because no background sediment concentrations were available.

pollutants are significantly higher in the Minnesota basin than in the background sediments. Considering that both basins have been in operation for approximately 5 years, and that the annual pollutant load to the Minnesota basin is probably higher than the annual load to the Florida basin by virtue of the Minnesota basin's substantially larger drainage area, the results indicate that removal efficiencies in the Florida basin are higher than in the Minnesota basin.

Table 20 presents the results of the Wilcoxon Rank Sum Test and the two-sided K-S test for the comparison of basin sediment concentrations between sites. In the table, each site is compared to one of the other two monitored basins. Differences detected by the test may be explained by differences in annual pollutant loadings, removal efficiencies, and service lives of the basins.

The results in table 20 indicate that metals concentrations in the Connecticut basin are generally significantly lower than concentrations in the Minnesota and Florida basins. Three of the four metals analyzed in the Florida basin sediments and all four of the metals in the Minnesota sediments had significantly higher median concentrations than in the Connecticut basin sediments. One possible explanation is that the Connecticut basin has been operating for only 3 years, whereas the other basins have been operating approximately 5 years. In addition, the Minnesota site drainage area is over three times as large as the drainage area of the Connecticut site, which suggests that metals loads to the Minnesota site will be much larger than metals loads to the Connecticut site. However, the surface area of the Minnesota basin (i.e., the area over which pollutants are expected to accumulate in the sediments) is over four times as high as the Connecticut basin's surface area, which tends to nullify the impact of the difference in drainage areas. Another explanation of the differences in sediment concentrations is that the Minnesota and Florida basins are simply more effective in removing pollutants. It is probably a combination of better efficiency and longer service life that account for the significantly higher sediment metals concentrations in the Minnesota and Florida basins.

The results presented in table 20 for nutrients show the same trend as the metals results. Both the Florida and Minnesota sites have significantly higher sediment concentrations of TP and TKN than the Connecticut site. Again, shorter service life and less efficient pollutant removal are probably the reasons for the difference.

In summary, the results of the statistical analysis of core samples in the wet detention basins suggest the following:

- The Florida detention basin is the most effective of the three basins in removing nutrients and metals.

Table 20. Comparison of detention basin sediment at different sites.

	CONNECTICUT VS MINNESOTA			MINNESOTA VS FLORIDA			FLORIDA VS CONNECTICUT		
Constituent	2-Sided K-S Test: Signif. Different Distrib.	Wilcoxon Rank Sum Test: Signif. Different Mean or Median	Higher Mean/ Median Value	2-Sided K-S Test: Signif. Different Distrib.	Wilcoxon Rank Sum Test: Signif. Different Mean or Median	Higher Mean/ Median Value	2-Sided K-S Test: Signif. Different Distrib.	Wilcoxon Rank Sum Test: Signif. Different Mean or Median	Higher Mean/ Median Value
Total P	No	Yes	Minn.	Yes	Yes	Florida	Yes	Yes	Florida
TKN	Yes	Yes	Minn.	Yes	No		Yes	Yes	Florida
Nitrite + nitrate	No	No		No	No		No	No	
Chromium	Yes	Yes	Minn.	No	No		Yes	Yes	Florida
Copper	No	Yes	Minn.	Yes	Yes	Minn.	No	Yes	Conn.
Lead	No	Yes	Minn.	Yes	Yes	Florida	Yes	Yes	Florida
Zinc	Yes	Yes	Minn.	No	NBO		Yes	Yes	Florida

Based on level of significance - 0.05

- Constituent concentrations in the Florida and Minnesota basin sediments are significantly higher than the concentrations in the Connecticut basin sediments because the Florida and Minnesota basins have been in service longer and are more effective in removing pollutants.

TSS Removal for Discrete Settling

The objective of this analysis was to determine if TSS removal in grassed channels could be accurately predicted based on the concept of discrete particle settling using particle-size distribution typical of highway runoff.

This analysis was limited to the Virginia channel due to data problems for the other channels. The Florida storm data did not include sampling duration data that were necessary to calculate average flow rates for each storm, and the Maryland data included a small number of storms with unusual TSS values (e.g., outflow TSS typically greater than inflow TSS, perhaps due to lateral inflow from an adjacent agricultural area).

For the Virginia channel, 7 of the 12 monitored storms were used in the analysis. Of the excluded five storms, three had been eliminated from the storm database after screening, and the other two did not have any flow duration data. Two of the seven storms that were used had only inflow duration data, and it was assumed for these cases that outflow duration was equal to inflow duration.

The first step in the analysis was to calculate the average channel flow for each storm event, using total flow volume and duration data supplied in the storm summaries. The equation used is:

$$Q = \frac{VOL}{(DUR)(449)} \qquad (1)$$

where:
Q = average channel flow (ft^3/s)
VOL = total volume of outflow (gal)
DUR = duration of outflow (min)
449 = conversion factor

Once the flow was established, the average depth and travel time for each storm was calculated.

Table 21 contains the individual storm calculations and the summary results for the Virginia storms. For each storm, the table lists the storm duration, average flow, inflow and outflow TSS concentration, and all values calculated in the process of determining the flow depth and travel time. The geometric values for inflow and outflow TSS concentration are presented and are used to estimate TSS removal efficiency.

Table 21. Flow depth, travel time, and TSS removal estimates for Virginia grassed channel.

Storm Number	Duration (min)	Avg. Q (cfs)	Inflow TSS Conc. (mg/l)	Outflow TSS Conc. (mg/l)	Maximum Depth (ft)	X-Sect Area (ft++2)	Hydr. Radius (ft)	Calc. Mannings n	VR	Chart Mannings n	Average Depth (ft)	Critical Settling Velocity (ft/hr)	Travel Time (min)
2	80	0.89	794	182	0.40	0.56	0.26	0.083	0.42	0.09	0.31	9.67	1.93
3	92	0.40	224	154	0.30	0.39	0.21	0.111	0.22	0.13	0.24	4.89	2.99
5	60	0.25	648	344	0.31	0.41	0.22	0.187	0.13	0.18	0.25	3.03	4.96
7	50	0.18	278	160	0.26	0.33	0.19	0.1195	0.10	0.20	0.22	2.28	5.67
8	125	0.44	183	127	0.35	0.47	0.24	0.133	0.22	0.13	0.28	5.04	3.31
9	135	0.05	92	44	0.20	0.24	0.15	0.408	0.03	0.38	0.17	0.786	13.59
11	259	0.48	59	29	0.35	0.47	0.24	0.123	0.24	0.12	0.28	5.45	3.06
Geometric Mean Value			228	114							0.25		4.18

Percent TSS Removal Based on EMC Values 50.0%

Percent TSS Removal Based on Depth and Travel Time 51.3%

The results in table 21 indicate that the estimation method based on travel time and flow depth accurately predicted the TSS removal efficiency that was measured through monitoring. Based on the EMC values for the seven storms, the monitored TSS removal efficiency was equal to 50 percent. In comparison, the channel calculations yielded a median flow depth of 0.25 ft and a median travel time of 4.2 minutes, which translated into a critical settling velocity of 3.59 ft/hr, and a predicted TSS removal efficiency of 51.3 percent.

Estimation of Long-Term TSS Removal for Grassed Channels

The same technique applied above to the Virginia channel can be used to estimate long-term TSS removal in any grassed channel, and presumably overland flow system as well. The key unknown in applying this method to long-term removal estimation is selection of the design flow. Unlike stability design, where it is appropriate to select an extreme event such as a 5-year or 10-year flow, long-term removal analysis should be based on a typical storm event.

One possibility for determining a design flow for TSS removal analysis is calculating the flow using the Rational method, along with rainfall intensity data supplied in table 2 (chapter 2). The average flow, Q_a, would be calculated as:

$$Q_a = (C)(i)(A) \tag{2}$$

where: C = runoff coefficient (inches of runoff/in of rainfall)
i = rainfall intensity (in/hr)
A = drainage area (ac)

Table 2 includes average hourly rainfall intensities for the 48 contiguous States. Thus, the average flow can be calculated by selecting the appropriate value from this table if the size and percent imperviousness of the drainage area are known.

In applying this average flow estimation method to the Virginia channel, a Q_a value of 0.054 ft^3/s was calculated. This result assumes a drainage area of 1.27 ac, a C value of 0.64, and the annual intensity for zone 2 (0.066 in/hr) from table 2. A comparison of this value to the monitored flow values shows that the calculated average flow is less than or equal to the monitored flow for all seven storms. Even if the more conservative value of 0.102 in/hr (summer mean intensity) is used, the Q_a value of 0.83 ft^3/s is less than or equal to five of the seven storms.

The relationship between the calculated average flow, and the monitored flows may simply indicate that the monitoring period was characterized by unusually intense storm events. In comparing the duration data in table 21 to the mean duration data in table 2 (5.9 hours annual and 4.2 hours summer for Zone 2), it is apparent that all of the monitored storms have durations that are typically less than 4 hours, and more than half are less than 2 hours. In addition, review of the storm data indicated that five of the seven analyzed storms also had a total rainfall that was greater than the mean volume values in table 2. These observations suggest the calculation of average flow may be reasonable, even though it is very different from the storms monitored in 1987.

Assuming an average flow of 0.054 ft^3/s, the Virginia channel is expected to achieve a TSS removal efficiency of approximately 70 percent, substantially better than the monitored data. This value reflects an average flow depth of 0.17 ft and a travel time of 13.6 minutes. If a more conservative value of 0.083 ft^3/s is assumed, an average flow depth of 0.19 ft and a travel time of 10.0 minutes are calculated, and the predicted TSS removal is 67 percent.

The long-term removal in grassed channels for metals and nutrients can be estimated as a function of the suspended solids removal. Based on settling column data, as well as other literature data, the following percentages of water columns are associated with suspended solids:

• Lead	90 percent.
• Copper	60 percent.
• Zinc	50 percent.

Therefore, if 80 percent suspended solids removal is predicted, the corresponding prediction of lead removal would be: 90 percent times 80 percent equals 72 percent. Similarly, the following percentages are suggested for nutrients:

• TKN	30 percent.
• TP	50 percent.

Unlike metals, however, the water quality monitoring results for the three grassed channels suggest that TKN and TP removal are not as effective as would be predicted by using these percentages.

Estimated Service Life of Grassed Channels

For each site, the core sample and water quality data were analyzed to estimate the age of each of the grassed channels. The estimated ages were then compared to the actual number of years that the channels have been in operation. The objective of this analysis was to determine whether or not the removal efficiencies based on the water quality data are reasonable.

The estimation of years of service for the grassed channels was a four-step process. First, hydrologic data (e.g., drainage area, percent imperviousness) and water quality data (median inflow EMC values) were used to estimate annual copper, lead, and zinc loads to each channel. Next, the mass of the solids in the sediments to which the metals absorb was estimated. Then, the annual accumulation rate in the sediments was calculated based on the annual load, the sediment mass, and the channel removal efficiency (based on the water quality monitoring data). Finally, the calculated accumulation rate and the measured metals concentrations in the channel sediments were used to estimate service life.

Table 22 presents the results for the service life estimation analysis. Note that actual service data were available only for the Virginia and Florida sites.

For the Virginia channel, the actual service life is much greater than that calculated using copper, lead, and zinc data. This suggests that either the removal efficiencies calculated from the monitoring data are as much as an order of magnitude too high, or that the metals removed during a given storm are eventually transported downstream rather than accumulating in the channel. Given that the metals removal efficiency estimates seem reasonable with respect to observed TSS removal, and that erosion was observed at the Virginia site during monitoring, resuspension of metals would appear to be the most plausible explanation.

In contrast, the actual and estimated service life for the Florida channel are in good agreement. The estimates based on copper and zinc data are both approximately 6 years, which is equal to the upper range of what is believed to be the actual years of service. Lead data, on the other hand, result in an estimated service life of about 17 years, well above the actual years of service. There are two potential explanations for this discrepancy. One is that the removal efficiency is based on the middle of the range of lead removal efficiencies calculated from the monitoring data. If it is assumed that lead removal is actually on the high end of the estimated efficiency range, the estimated years of service would be lower. Considering that the monitoring data estimated about 90 percent removal of TSS in the Florida channel, and the settling column studies indicated that about 90 percent of the lead in highway runoff is associated with suspended solids, it would be reasonable to expect lead removal in the Florida channel to be about 80 percent, somewhat higher than the 64 percent removal estimate used in the service life calculations. Alternatively, it may be that lead EMC values were much higher in the years before monitoring (i.e., when leaded gasoline was much more prevalent), such that lead accumulation was much more rapid in the early years of the channel. Both explanations are reasonable and it is probably a combination of the two that resulted in the high estimated years of service.

Table 22. Estimation of grassed channel service life.

Location	Metal	Sediment Median EMC Concen. (mg/l)	Annual Rainfall Depth (in)	C	Drainage Area (acres)	Annual Metal Load to Channel (mg/yr)	Mass of Sediment (kg)	Percent Removal Based on EMC Method	Annual Pollutant Load to Sediment (mg/kg/yr)	Average Metal Concen. in Sed. (mg/kg)	Estim. Service Life (years)	Actual Service Life (years)
Virginia	Copper	0.020	42.0	0.64	1.27	70234	2019	12	4.2	29.7	7.1	20+
	Lead	0.085				298495		43	63.6	75.7	1.2	
	Zinc	0.092				323076		27	43.2	80.9	1.9	
Maryland	Copper	0.012	42.0	0.64	1.27	42140	2388	21	3.7	24.0	6.5	Unknown
	Lead	0.049				172073		45	32.4	315.0	9.7	
	Zinc	0.043				151003		18	11.4	188.8	16.6	
Florida	Copper	0.012	42.0	0.60	0.56	17420	4624	49	1.8	11.4	6.2	4-6
	Lead	0.044				63874		63	8.6	143.1	16.7	
	Zinc	0.118				171299		69	25.6	144.2	5.6	

Because many of the site data (including actual years of service) are unknown for the Maryland site, it is difficult to make observations or draw conclusions regarding this site. One observation that can be offered is that the service life estimate based on zinc is substantially higher than for copper or lead, which again can be expected to be high in light of recent reductions of leaded gasoline use. This may suggest that the zinc removal efficiency estimate based on the monitoring data is too low.

In summary, the results of the service life estimation analysis suggest the following:

- Resuspension of metals (e.g., channel erosion) appears to be offsetting removal of metals in the Virginia channel.
- Copper, lead, and zinc are being removed from runoff and are accumulating in the Florida channel sediments. Removal estimates of copper and zinc, based on the water monitoring data, appear to be reasonable; the actual removal efficiency for lead is probably at the high end of the estimated removal efficiency range.
- The zinc removal efficiency estimate based on water monitoring data for the Maryland channel may be lower than the actual removal efficiency.

C. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Storm event runoff water quality data and sediment core data for three grassed channels and three wet detention basins were analyzed as part of this project to refine the FHWA interim guidelines for designing BMPs to control highway runoff. Results from these analyses, specific to the monitored sites, are presented above. This section presents generic conclusions and recommendations based on an evaluation of the overall results.

Grassed Channels

Storm event runoff water quality data for the three grassed channels was evaluated to determine pollutant removal efficiencies, to refine a concept relating TSS removal to discrete particle settling, and to estimate the long-term pollutant removal in grassed channels. Sediment core data was evaluated to determine if the removal efficiencies based on water quality data were reasonable and, if significant, pollutant and water quality data were used to estimate the service life of the channels. Based on an evaluation of the results presented above, the following generalizations can be made:

- Removal of metals in the channels appears to be directly related to TSS removal.

- Nutrient removal cannot be related to TSS removal. Relatively low nutrient removal may be experienced in channels that are effective in removing other pollutants.

- Channel characteristics such as channel geometry, channel slope, average flow rate, and length are the controlling factors in pollutant removal.

- Nutrients and metals are removed in grassed channels; however, metals removal is more reliable.

- TSS removal can be estimated using travel time and flow depth relationships in the grassed channel.

Wet Detention Basins

Storm event runoff water quality data for the three wet detention basins was evaluated to determine pollutant removal efficiencies and sediment core data was evaluated to determine if significant pollutant accumulation is occurring in the basins. The following generalizations can be made regarding wet detention basins:

- Pollutant removal efficiencies are variable between different wet detention basins. Controlling factors appear to be basin depth, basin storage volume to watershed area ratio, and maintenance.

- Pollutant removal efficiencies for TSS in basins are less than or equal to removals within general channels. The removal of metals in basins is similar to the removals found in grassed channel systems.

- Pollutant removal efficiencies as high as 40 to 70 percent for TKN, 90+ percent for nitrate/nitrite, and 60 to 70 percent for TP, were observed in the monitored wet detention basins.

5. CONCLUSIONS AND RECOMMENDATIONS

This section summarizes the design guidelines for the retention, detention, and overland flow systems for the control of highway runoff pollution. The procedures were developed based on the literature, state-of-the-art practices, and bench scale/field testing; they represent the best available technology for pollutant removal from highway runoff. This section presents general concepts, methods, and procedures for the design and use of the effective measures reflecting conditions applicable to all highway runoff situations. The operation and maintenance requirements for each measure are also summarized. A more complete description of the design procedures, along with step-by-step instructions and example designs, is provided in the Design Guidelines report. (Hartigan, et al., 1989)

1. MITIGATION SYSTEMS DESIGN AND POLLUTANT REMOVAL EFFICIENCIES

A. VEGETATIVE CONTROL SYSTEMS

Vegetative controls (grassed channels and overland flow areas) are the most common management measures for highway runoff pollution. They are adaptable to a variety of site conditions, are flexible in design and layout, and are a relatively inexpensive management measure. Vegetative controls can be used as sole management measures or in combination with secondary measures (e.g., detention basins, infiltration systems, and wetlands). Grass is the most common vegetation used and is more effective at pollutant removal than shrubs, tress, or other vegetation.

Sedimentation is the primary removal mechanism for stormwater pollutants in grassed channels and overland flow areas. Consequently, design considerations should focus on creating conditions that are conducive to sedimentation (i.e., shallow flow depths, sufficient detention time). Factors that affect flow depth and detention time in grassed channels include channel width, length, and slope and vegetative cover. By minimizing flow depth and maximizing detention time, a substantial percentage of solids and associated pollutants can be expected to be deposited in the channel.

In addition to sedimentation, there are several secondary removal mechanisms, including infiltration and adsorption. Unlike sedimentation, infiltration and adsorption processes result in the removal of soluble pollutants. Like sedimentation, these processes will be more effective when the flow depth is minimized and detention time is maximized. Longer detention times provide more opportunities for the stormwater to infiltrate into the soil and adsorb to the vegetation.

The effectiveness of vegetative controls in removing pollutants from highway runoff is dependent on flow depth and detention time. Because the measures will be designed to achieve a long-term removal efficiency, the runoff event used to consider pollution removal should be less than the runoff event considered in analyzing channel stability. The long-term mean runoff event will be appropriate for the removal efficiency analysis.

Because stability is such an overriding concern in vegetative control design, the controls should be designed for stability first and then adjusted, if necessary, for pollutant removal. Any changes that will be made to the control in order to increase removal efficiency will increase the stability of the control.

The stability of an open channel or overland flow area is dependent on the erodibility of the soils in which the channel or slope is constructed and the shear stress exerted on the soil interface by the flow. There are no reliable quantitative measures of the erodibility of soils and, generally, local experience is relied upon. A potentially unstable channel/flow area in bare soils can be made stable by lining it with high grass, rock rip-rap, concrete, or other materials, thereby changing its susceptibility to erosion. However, only a grass lining offers effective pollutant removal.

Factors, such as slope, flow width, flow length, and vegetative cover, affect the flow depth and detention time in vegetative measures. Detention time can be extended by increasing the flow width and length, decreasing the slope, or providing a more dense vegetative cover (i.e., a higher resistance factor).

However, decreasing the slope or providing denser cover will also increase the flow depth, offsetting the benefit of increasing the travel time to some extent. Increasing the flow width appears to be the best alternative, because it both reduces flow depth and increases travel time. Increasing the flow length increases travel time, but does not affect flow depth.

The design of a grassed channel or overland flow management measure involves use of the following steps:

1. Estimate runoff flow rates for design runoff event (i.e., from 5- and 10-year storms).

2. Establish grade of proposed channel or overland flow area.

3. Select a grass cover suitable for the site.

4. Determine maximum permissible flow depth for the grass cover and slope to be used.

5. Estimate channel or overland flow area dimensions.

6. Determine flow velocity.

7. Determine if design flow is less than maximum permissible flow (stable) or greater than maximum permissible flow (unstable).

8. If channel or overland flow area is unstable, reduce flow depth by increasing bottom width or using flatter side slopes or both. Also, maximum noneroding depth can be increased by decreasing the slope.

9. Determine if provisions for erosion protection are necessary during establishment of grass cover.

10. Determine removal efficiencies for channel or overland flow area. If removal is not sufficient, increase flow width or flow length.

Total suspended solids (TSS) removal thickness is related to average flow depth and detention time in grassed channels. Figure 4 presents the relationship between TSS removal and combinations of average flow depth and travel time, based on particle settling velocity distribution data for highway runoff. (Hartigan et al., 1989)

Removal efficiencies for lead, copper, and zinc can be estimated as follows:

- Copper 60 percent of TSS removal efficiency.
- Lead 90 percent of TSS removal efficiency.
- Zinc 50 percent of TSS removal efficiency.

(For example, 90 percent removal of TSS corresponds to a copper removal efficiency of 90 percent x 60 percent = 54 percent).

Removal efficiencies for nutrients vary widely and do not show a strong relationship with TSS removal efficiency.

B. WET DETENTION BASINS

Where vegetated roadside ditches are not practical, wet detention basins may be the most practical and effective stormwater runoff management measure for pollution abatement. Detention is a highly effective management measure for pollutant removal if sufficient detention time is provided for particulates to settle out in the stormwater runoff. Performance of basins that retain a pool of water has been found to range from poor to excellent, depending on the size of the basin relative to the size of the drainage area served and storm

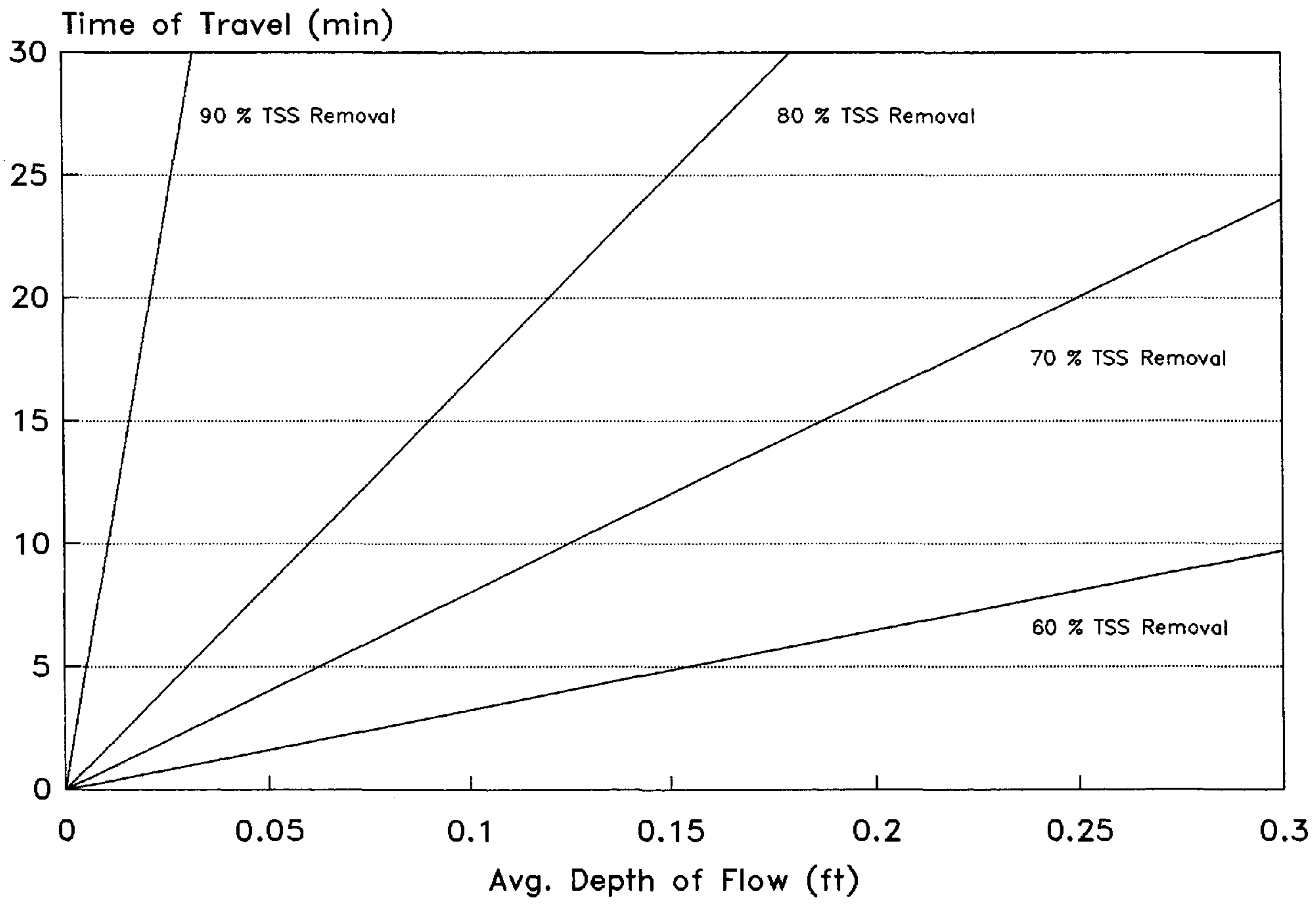


Figure 4. Long-term TSS removal for vegetative controls.

characteristics of the area. The principal mechanism for the removal of particulate forms of pollutants in wet basins is sedimentation, but some basins exhibit substantial reductions in soluble nutrients, such as soluble phosphorus, and nitrate and nitrite nitrogen. This may be attributable to biological processes in the pool.

Two different approaches are recommended to evaluate the performance and formulate the design procedures. One approach relies upon the solids settling theory and assumes that all pollutant removal within the basin is due to sedimentation. (Driscoll, 1983) The other approach views the wet detention basin as a lake achieving a controlled level of eutrophication in an attempt to account for biological and physical/chemical processes that have been documented as the principal nutrient removal mechanisms. (Hartigan, 1988; Walker, 1987) Both approaches suggest that pollutant removal efficiency should be positively related to hydraulic residence time, although the controlled level of eutrophication approach results in greater storage capacities and longer residence times.

Solids Settling Model

The first approach, based on the settling theory, should be used where only particulate pollutant control is required and where nutrient removal is not required for protection of the receiving water. Driscoll reported a procedure based on a probabilistic analysis methodology used to compute long-term average performance from the statistical properties of detention basin inflows. (1983) The analysis assumes that overall performance is due to the combined effects of removal under dynamic conditions as flows move through a basin and under quiescent conditions between storms. It may be used to estimate long-term efficiency of wet detention basins or to estimate the dimensions of proposed basins to achieve desired removal rates. The procedure is not applicable to dry basins, and it cannot be used to size basins for peak flow attenuation for flood flow management.

For particulate pollutant control, such as for TSS, lead, copper and zinc, wet detention basins rely on settling as the primary pollutant removal mechanism. Rainfall and runoff characteristics, settling velocities for suspended solids in the runoff, and the distribution of particulates and pollutants in each size range are needed to design wet detention basins to achieve pollutant removal objectives.

The following design procedure for wet detention basins was developed for rainfall zones delineated in figure 5, with rainfall characteristics summarized in table 1. It is recommended that the long-term mean and the coefficients of variation of rainfall event columns, durations, intensities, and intervals between the midpoints of successive events be developed for the area in which the management measure is to be constructed.

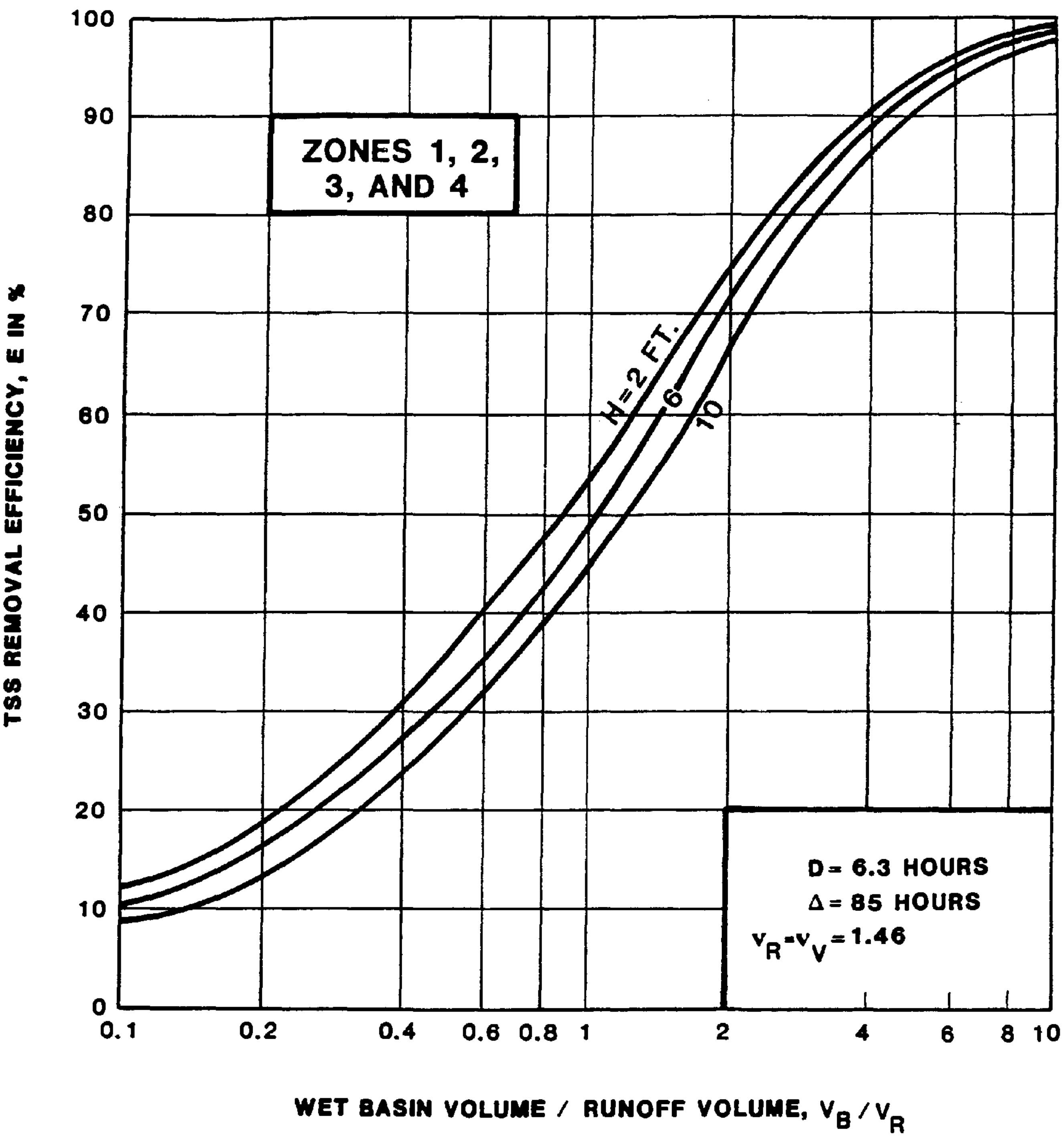


Figure 5. TSS removal versus VB/VR ratio for zones 1, 2, 3, and 4.

The following steps are required to use the design procedure for wet detention basins to control particulate pollution:

1. Determine rainfall characteristics for location in which basin will be constructed.
2. Determine the long-term mean rainfall volume (depth) for the appropriate locale. Summer rainfall statistics should be used when they will result in a more conservative design (i.e., where summer is a wet season).
3. Establish the runoff coefficient.
4. Compute the long-term mean event runoff volume.
5. Establish the dimensions of the area in which a wet detention basin could be constructed.
6. Compute approximate basin volumes for trial retained pool depths and the ratio, basin volume/runoff volume for each trial depth. Use the volume of the wet pool in computing the ratio, basin volume/runoff volume.
7. Enter appropriate basin volume/runoff volume versus TSS removal curve for particular rainfall zone (see figure 5 as example), and use the trial values computed in step 5 to select the design that will perform as desired. Alternately, enter the appropriate figure with the desired TSS removal efficiency and find the required depth of the retained pool in the basin and the basin volume/runoff volume ratio to achieve that efficiency.
8. Estimate pollutant removal efficiencies for pollutants of concern. Steps 7 and 8 may be used in reverse order if the objective is to achieve a specified removal efficiency for a particular pollutant.
9. Design the basin configuration to minimize the potential for short-circuiting. If this is not practicable, choose a more conservative design, i.e., choose a design that will yield higher removal efficiencies to compensate for possible adverse effects from short-circuiting.
10. Design all basin bank slopes at 3:1 or flatter and specify grass cover for areas not in the retained pool of water.

The efficiency of wet detention basins in removing suspended solids from stormwater influent is dependent on the distribution of particle sizes and other factors, such as time in residence, short-circuiting, and basin depth. The terminal velocity of fall of a suspended particle in quiescent water is dependent on the size, shape, and specific gravity of the particle and the viscosity of the water. Therefore, the distribution of sizes in the silt and clay fractions is determined by settling velocities that are analogous to physical size ranges.

Reported settling velocities of particles in urban runoff are presented in table 23. (Driscoll, 1983)

Table 23. Settling velocities for urban runoff.

Proportion, %	Average Settling Velocity (ft/hr)
20	0.03
20	0.3
20	1.5
20	7.0
20	65.0

Based on the settling column results for TSS, the approximate relationship for the pooled 1986 and 1987 datasets is shown in table 24.

Table 24. Settling velocities for highway runoff.

Proportion, %	Settling Velocity (ft/hr)
18	0.03
17	0.3
17	1.5
19	7.0
28	65.0

This distribution is based on first-flush conditions, which probably biases the distribution towards the higher settling velocities. Other evaluations of pollutant removal characteristics (previously mentioned in chapter 2) indicate that highway runoff behaves in a similar manner to urban runoff; therefore, the 20 percent proportion for each of the settling velocity categories is recommended as the design distribution.

Specific pollutant removal efficiencies were developed as a percentage of the TSS removal efficiencies. The percentages are based on regression analysis performed on removal efficiencies as part of the laboratory. The following percentages are recommended to be applied to the removal efficiency of TSS for the specific pollutants: lead, 90 percent; copper, 60 percent; and zinc, 45 percent.

For example, if for a given design, the TSS removal efficiency is 80 percent, then the removal efficiency for lead is approximately 72 percent. For TKN and BOD, the percentage of the TSS removal efficiency ranges from 20 percent to 30 percent, with the larger percentage corresponding to the larger basins. (EPA, 1983)

Lake Eutrophication Model

The second approach, based on a controlled level of eutrophication, is most appropriate for areas where the receiving water quality problem is caused by nutrient loadings. Since nutrients typically required extended hydraulic residence times that caused a serious receiving water quality problem, examples of situations where nutrient control is needed include watersheds of reservoirs, lakes, tidal embayments, and estuaries. This procedure is an application of a lake eutrophication design model developed by Walker. (1987)

Because the lake eutrophication model design method accounts for the biological uptake of dissolved nutrients, it produces a more conservative design that is more appropriate for nutrient control than the solids settling design method. The permanent pool storage resulting from a eutrophication model design is on the order of three times larger than a design based on the solids settling model.

This approach assumes that a wet detention basin is a small eutrophic lake that can be represented by empirical models used to evaluate lake eutrophication impacts. The intent of this approach is to use lake eutrophication models to account for the significant removal of dissolved nutrients observed in the field and attributable to biological processes, such as uptake by algae and rooted aquatic vegetation. Using this design method, a wet detention basin can be sized to achieve a controlled rate of eutrophication and an associated removal rate for nutrients.

The following design procedure is based on the phosphorus retention coefficient model developed by Walker. (1987) Like most input/output lake eutrophication models, the Walker model is an empirical approach that treats the permanent pool as a completely mixed system and assumes that it is not necessary to consider the temporal variability associated with individual storm events. The Walker model is based upon annual flows and loadings.

The following steps are required to use the design procedure for wet detention basins for controlling particulate and soluble pollution:

1. Identify the rainfall zone in which the basin will be located.
2. Determine the long-term mean rainfall volume (depth) for the appropriate zone.
3. Establish the runoff coefficient.
4. Compute the long-term mean event runoff volume.
5. Establish the dimensions of the area in which the wet detention basin could be constructed.
6. Select a 2-week average hydraulic residence time and compute basin volume.
7. Establish mean depth. Verify depth of basin appropriate for surface dimension and side slopes.
8. Establish inflow orthophosphorus/total phosphorus ratio and inflow total phosphorus.
9. Compute phosphorus removal efficiency.
10. Determine removal efficiency for particulate pollutants (using procedures presented for solids settling model).
11. Design the basin configuration to minimize the potential for short-circuiting. If this is not practicable, choose a more conservative design (i.e., choose a design that will yield higher removal efficiencies to compensate for possible adverse effects from short-circuiting).
12. Design all basin bank slopes at 3:1 or flatter and specify grass cover for areas not in the retained pool of water.

As an estimate of the total phosphorus from highway runoff, the following concentrations are recommended for use in the design procedure:

- Urban highways (ATD >30,000): Use 0.3 mg/l (300 μg/l) TP.
- Rural highways (ATD <30,000): Use 0.2 mg/l (200 μg/l) TP.

The lake eutrophication model also requires an inflow orthophosphorus to total phosphorus ratio. An ortho P/total P ratio, F, of 0.25 is recommended. This ratio is based on a review of the ratios compiled in the Guidebook for Screening Urban Nonpoint Pollution Management Strategies. (NVPDC, 1979)

The phosphorus retention coefficient model developed by Walker is applied in two parts: (1987)

$$K_2 = (0.056)(Q_s)(F)^{-1}\ (Q_s + 13.3) \qquad (3)$$

where: K_2 = second order decay rate (m^3/mg-yr)
Q_s = mean overflow rate (m/yr) = Z/T
F = inflow ortho P/total P ratio
Z = mean depth (m)
T = average hydraulic residence time (yr)

$$\text{and:}\quad R = 1 + (1 - (1 + 4N)^{0.5})/(2N) \qquad (4)$$

where: R = total P retention coefficient - removal efficiency
N = $(K_2)(P)(T)$
P = flow total P (μg/l)

As may be seen, the model relies upon a second order reaction rate, which means that the total P removal per unit volume is proportional to the concentration squared. The second order decay rate (K_2) is calculated from the mean overflow rate and the ortho P fraction of total P. The average total P removal rate (R) is then calculated from the decay rate, the inflow total P concentration, and the average hydraulic residence time. The model was developed from a database for 60 Corps of Engineers' reservoirs and verified for 20 other reservoirs.

C. DRY EXTENDED DETENTION BASINS

Dry extended detention basins can be used in place of wet detention basins where the major concern is for the removal of particulate forms of pollutants and not the additional removal of soluble pollutants. Dry extended detention basins capture storm runoff and release it over an extended period of time. During this period of time, sedimentation occurs, which is the primary removal mechanism for pollutants. Limited removal of soluble forms of pollutants will occur during the drawdown period.

The advantage of using a dry extended detention basin under circumstances where high levels of nutrient control are not required is that the basin volume is much less than the basin volume required for a wet detention basin. Therefore, the area of space required and the costs for extended detention basin are less than the area and cost for a wet detention basin.

The following design procedure for dry extended detention basins was developed to be consistent with the rainfall and runoff characteristics used for the wet detention basin design. The storage volume required for extended detention is the runoff volume from the long-term mean rainfall event. The pollutant removal efficiencies are based on settling column studies, and the slope and size of the extended detention basin are based on available space and a suggested minimum depth of 2 ft.

The following steps are required to use the design procedure for extended dry detention basins:

1. Identify the rainfall zone in which the basin will be located.
2. Determine the long-term mean rainfall volume (depth) for the appropriate zone. Summer rainfall statistics should be used when they will result in a more conservative design, i.e., where summer is a wet season.
3. Establish the runoff coefficient.
4. Compute the long-term mean event runoff volume to be stored with extended detention.
5. Establish the dimensions of the area in which a dry extended detention basin could be constructed.
6. Compute the extended detention depth, a minimum depth of 2 ft is recommended, and determine basin surface area required based on available area and depth.
7. Determine pollutant removal efficiencies (see following).
8. Design basin configuration for maximum length to width ratio specifying bank slopes at 3:1 or flatter, basin slope minimum of 2 percent, grass cover for basin area, and 24-hour draw down period to provide an average 12-hour detention period.

Dry extended detention basin performance can be characterized by the amount of runoff detained and by the removal efficiency associated with the extended period of time that the runoff volume is detained.

The storage volume subjected to extended detention for pollutant removal from highway stormwater runoff should be large enough to capture and "treat" a significant percentage of annual nonpoint pollution loadings. Criteria for the extended detention storage volume typically are based upon "first-flush" runoff. (NVPDC, 1979) Thus, capture and treatment (i.e., sedimentation) of a relatively small percentage of total annual runoff volume can achieve significant removal of suspended pollution loadings.

Pollutant removal efficiency is based on settling behavior of the particulate pollutants. Experimental settling column data and field monitoring data for dry extended detention basins have been used to evaluate pollutant removal performance. Settling column experiments have been performed to determine the percent removal of various pollutants over time. (Driscoll, 1986; Grizzard et al., 1986; and Occoquan Watershed Monitoring Laboratory, 1983) Settling column studies were also performed as part of this study for 13 storms monitored at 6 highway sites in the Virginia suburbs of Washington, D.C. Two field studies at extended dry detention basins in the Washington, D.C. area have also been performed, one during the NURP study in Montgomery County, Maryland; and one in Northern Virginia. (MWCOG, 1983; OWML, 1987)

The removal efficiencies of dry extended detention basins are similar to wet basins for particulate pollutants, such as TSS, lead, and zinc. However, removal efficiencies that also have soluble forms are not as great for dry extended detention basins as they are for wet basins due to the lack of biological activity. The pollutant removal efficiencies recommended for dry extended detention basins using a 12-hour detention time are given in table 25 below:

Table 25. Recommended efficiencies for dry detention basins.

Pollutant	Removal Efficiency (%)
TSS	80-90
Total Lead	70-80
Copper	50-60
Zinc	40-50
Total Phosphorus	20-30
Total Kjeldahl Nitrogen	20-30
BOD	20-30

D. RETENTION SYSTEMS

Retention facilities differ from detention facilities in that they do not discharge "treated" waters into the surface runoff conveyance system. Instead, these measures release captured stormwater into the soil profile beneath the retention measure, thereby achieving significant pollutant removal through natural processes within the soil profile underlying the facility.

Retention measures that may be suitable for highway applications include:

- Retention Basin: An open pit or impoundment with vegetated sides that releases stored runoff by infiltration through the bottom and sides of the basin and is generally suitable for drainage areas of 5 to 50 ac.

- Retention Trench: An excavated trench backfilled with stone suitable for use on small watersheds, general less than 5 ac.

- Retention Well: A vertical shaft extending to pervious strata that either may be backfilled with aggregate or may be lined with precast concrete or metal pipe.

Since it is easier to maintain than the retention trenches and wells, the retention basin is the preferable mitigation measure for highway runoff. Trenches and wells are susceptible to similar clogging problems due to sediment and, to a lesser extent, oil and grease in highway runoff. The trenches can be expected to clog primarily at the surface of the facility (i.e., upper layers of stone), while wells can exhibit clogging of the soil around the bottom and sides of the well. Due to the higher construction costs (e.g., excavation, casings) per cubic foot of runoff storage and the potential for clogging of deeper layers and less filtering prior to recharging groundwater, well systems may be less desirable measures than retention trenches for certain highway site conditions.

Unlike detention measures and vegetative controls, the feasibility of retention measures is very dependent upon site conditions. Typically, the site must satisfy the following feasibility tests in order to be suitable for a retention measure:

1. Saturated soil infiltration rate that permits adequate percolation of stored runoffs: It is recommended that retention measures be restricted to sites with minimum infiltration rates of about 0.3 in/hr within the underlying and surrounding soil profile.

2. Maximum allowable dewatering time should minimize the risk of carry-over runoff storage between rainstorms: If the retention facility requires an excessive amount of time to dewater, storage will not be available for runoff from subsequent rainstorms. Ideally, the dewatering time should be related to statistics on the interval between rainstorms in a particular rainfall zone.

3. Minimum distance between the bottom of the facility and the seasonally high water table, bedrock, limestone, ore, and other water-conducting stratas: Adequate travel time through unsaturated soil is required to ensure sufficient pollutant removal. In the eastern United States, a minimum separation distance of 2 to 4 ft is typically used in areas (e.g., Maryland and Florida) where water table depths are relatively shallow,

while 10 ft is typically used in some western states. If there are no standards required for a particular area, a minimum distance in the range of 3 to 10 ft should suffice, with the upper end of this range most suitable for areas where there is considerable concern about groundwater contamination potential.

4. Acceptable topographic features: Certain retention measures may not be suitable for areas with relatively steep slopes (e.g., greater than 7 percent). Likewise, the use of retention measures on fill material is not recommended due to the possibility of creating an unstable subgrade. Finally, a retention facility should exhibit a minimum horizontal separation of 100 ft from any water supply well adjoining the highway.

All three retention measures also require some type of upstream "pretreatment" facility to minimize the loadings of solids and debris that can cause clogging problems. The most appropriate upstream pretreatment devices are vegetative controls, such as grassed channels and grassed overland flow areas. Because the vegetative controls are intended primarily to remove settleable and floatable materials, shorter travel lengths than those recommended earlier should suffice for pretreatment purposes.

Retention measures are typically designed to capture and "treat" the first-flush flows in stormwater runoff. Two of the retention measures (trenches and wells) operate as offline storage devices that capture the initial stages of runoff and automatically bypass subsequent flows when the available storage capacity is filled. The other retention measure (basins) operates as an online storage device that will exhibit overflows of runoff when its storage capacity is exceeded. Therefore, an important design criterion is the volume of first-flush runoff that will be stored in retention facilities before bypasses or overflows occur. The larger the storage requirement, the higher the runoff capture efficiency and vice versa. It is typically assumed that natural mechanisms in the soil profile underlying retention facilities will achieve relatively high pollution removal rates for captured runoff waters, with removal rates of 90 percent or greater projected for heavy metals, BOD, and sediment; and about 50-65 percent for nutrients. (NVPDC, 1979)

Storage criteria for retention measures are typically based on analyses of the runoff capture statistics associated with different first-flush storage volumes. Two methods are available for developing "runoff capture-storage" relationships that account for the variability of runoff characteristics from storm to storm: (a) applications of continuous simulation models to route a long-term runoff record (e.g., 25 to 30 years) through the assumed offline storage volume; and (b) statistical methods that approximate capture-storage relationships based upon statistical properties of rainfall and runoff. (Goforth, et al., 1983) The statistical method, which is similar to the detention basin design method outlined in an earlier section, is much simpler and easier to apply than the continuous simulation method. Comparisons of the two methods indicate that the statistical method can provide an adequate approximation of continuous simulation results, with the statistical method typically producing a more conservative estimate (i.e., lower values) of runoff capture. (DiToro and Small, 1979; Goforth, et al., 1983) Because of the ease of application and the conservative results, the statistical method was selected for determining storage volume requirements for retention measures.

The statistical method has been used to analyze the expected long-term efficiencies of highway runoff capture and pollutant mass capture for typical retention storage requirements (0.5 in to 1.0 in) in effect around the United States. The results suggest that a 0.5-in storage requirement can achieve a minimum runoff capture efficiency of about 60 to 70 percent for most rainfall zones, and a minimum pollutant mass capture efficiency of about 70 to 80 percent after accounting for first-flush effects. Capture efficiencies for a 1.0-in storage requirement are about 10 to 20 percent higher than the values associated with a 0.5-in storage level. Given the estimated pollutant removal rates for the soil profile beneath retention facilities, these relatively high capture efficiencies indicate that retention measures for highway runoff control should be very competitive with other control measures in terms of expected pollutant removal rates.

The following steps can be used to determine the storage required for retention basins and retention trenches:

1. Identify the rainfall zone in which the basin will be located.
2. Determine the long-term mean rainfall volume (depth) for the appropriate zone.
3. Establish the runoff coefficient.
4. Compute the long-term mean event runoff volume (V_{ro}).
5. Compute storage release by dewatering (V_d).
6. Compute V_d/V_{ro} ratio.
7. Select ratio of retention basin volume to runoff volume (V_b/V_{ro}) and use CV=1.38 to given percent fraction captured (E) between 60 and 80 percent in figure 6. Select design basic volume.
8. The retention basin or trench dimensions can then be calculated by determining allowable depth and computing length, width, and side slopes.

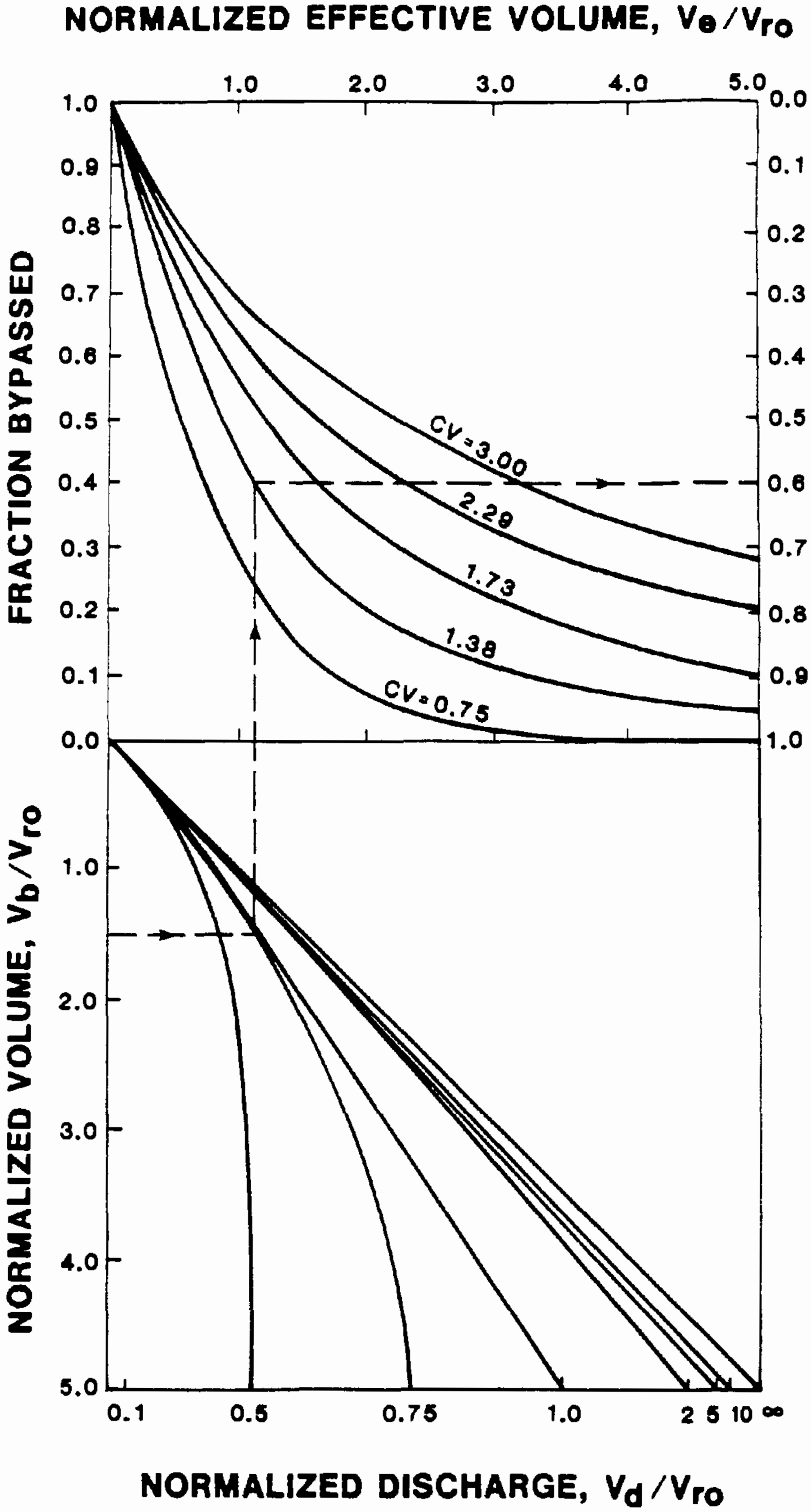


Figure 6. Statistical method for determining long-term runoff capture efficiency. (Goforth, et al. 1983)

The procedure for design retention trenches may also be used for shallow dry well designs. The major differences between the dry well and trench designs are that the surface area for the former will generally be much smaller and circular in shape (in comparison with a rectangular shape for the trench).

Due to the limited storage volumes in individual wells, deep wells will typically be used in groups. The design procedure involves determining the number of wells required to control the specified highway runoff volume and evaluating the need for a detention basin upstream of the well system to serve a flow equalization function. The capacity of individual deep wells can be determined using infiltration equations for the case of a constant suddenly applied over a semi-infinite porous medium. For deep wells packed in sand or gravel, calculations of storage capacity should account for storage in the void spaces of the packing area (e.g., void ratio of 0.25 or less for sand).

E. WETLAND SYSTEMS

Wetland systems can potentially provide significant water quality treatment to highway runoff. Most of the available research and literature on wetlands pertains to the use of these systems for providing final treatment of municipal wastewaters. There are, however, a growing number of field studies and applications that focus on the use of wetlands for the treatment of urban stormwater runoff. Florida has recently adopted new regulations that promote the use of some wetlands for stormwater runoff treatment. Also, Maryland recently developed guidelines for the construction of shallow wetlands in stormwater basins to reduce runoff pollution loadings. This chapter presents a summary of wetland planning and design experience to date that may be applied as guidelines for the use of wetland areas as mitigation measures for highway runoff pollution.

Wetlands provide hydraulic resistance to surface runoff resulting in decreased velocities and increased deposition of suspended sediments. Toxicants (e.g., heavy metals) sorbed to suspended sediments can be deposited and retained within the wetland. The large surface area provided by surface soils and vegetation contributes to higher levels of adsorption, absorption, filtration, microbial transformation, and biological utilization than might normally occur in more channelized water courses.

Pollutants may be removed from the water column by physical, chemical, and biological means. Physical processes include sedimentation, emulsification, adsorption, and filtration. Chemical processes include chelation, precipitation, decomposition, and chemical adsorption. Biological processes are primarily vegetative uptake and removal, with some biological transformation and degradation occurring. Many of the processes are interrelated and variable for different pollutants.

The selection of wetland design parameters will often require consideration of site-specific features or performance standards promulgated by regulatory agencies. Wetland designs for management of highway runoff pollution should consider the following general design parameters:

- Relatively long retention time of runoff inflow (generally 2 to 3 weeks).
- Shallow water with a low basin gradient resulting in slow-moving, well-spread sheet flow.
- Minimal direct open channels (where open channels exist, circuitous flow routes are preferred).
- Maximum contact between runoff inflows and wetland soils and vegetation.
- Irregular bottom morphology and bank edges.
- Constricted outlet or no surface outlet.
- Persistent emergent and/or floating aquatic vegetation forms.
- Sufficient storage volume for runoff.

For wetland areas that include a shallow open water basin, the design procedures for wet detention basins can be used. These methods use estimates of runoff from the mean annual storm event.

The effectiveness of wetlands for pollutant removal varies with wetland type and a number of site-specific parameters. The identification and quantification of the roles of individual mechanisms is difficult to assess. Field studies of wetland treatment of stormwater generally produce the following conclusions: (Kutash, 1985)

- A wide disparity in the nonpoint pollution removal capabilities of wetlands, particularly with regard to nutrients.
- The greatest consistency in pollutant reduction appears to be for BOD, suspended solids, and heavy metals.
- The nature of flow and seasonal factors are major influences on pollutant removal capabilities in certain wetlands.

In general, hydrology tends to be the primary determinant of pollutant removal in wetlands as a result if its influence on processes of sedimentation, aeration, biological transformation, and adsorption onto bottom sediments. Wetlands with gradual gradients and low flow velocities that allow sedimentation of sediment-adsorbed pollutants will generally be more effective for treatment of stormwater runoff.

2. OPERATIONAL AND MAINTENANCE REQUIREMENTS

A. VEGETATIVE CONTROL SYSTEMS

The basic objective in the maintenance of vegetative controls is to promote the healthy growth of the established vegetation. Procedures involved in this maintenance include routine mowing, removal of grass clippings and debris, and removal of accumulated sediment.

Maintenance must also include the prompt repair of channels or overland flow systems with erosion problems. Studies indicate that metals that are removed by grassed swales, and detention basins tend to accumulate in the upper 5 to 10 cm of the sediments. (Wigington et al., 1983; Yousef, Wanielista, and Harper, 1986; MWCOG, 1983) Consequently, erosion from a grassed channel or overland flow system could carry substantial loads of metals and other pollutants in addition to the solids load. As a result, repairs by seeding or sodding should be made swiftly to maintain the vegetative cover.

B. DETENTION BASINS (WET AND DRY EXTENDED)

Inspections should be performed at regular intervals to assure that the detention basin is operating as designed. Annual inspections should be considered at a minimum, with additional inspections following storm events. Some inspections can be arranged to coincide with scheduled maintenance visits in order to minimize site visits and to ascertain that maintenance activities are performed satisfactorily. The embankment, emergency spillway and side slopes of the basin should be checked to ensure that they do not show signs of erosion, settlement, slope failure, tree growth, wildlife damage, or vehicular damage.

Routine or preventive maintenance refers to procedures that are performed on a regular basis in order to keep the basin sightly and in proper working order. Routine maintenance should include grass mowing, debris removal, and nuisance controls of insects, weeds, odors, and algae, as required.

Nonroutine or corrective maintenance refers to a rehabilitative activity that is not performed on a regular basis.

Erosion and Structural Repair

Areas of erosion and slope failure should be filled and compacted, if necessary, and reseeded as soon as possible. Eroded areas near the inlet or outlet should be revegetated and, if necessary, filled, compacted, and reseeded or lined with rip-rap. Damaged side slopes and embankments should be repaired using fill dirt of adequate permeability. Major damage to inlet/outlet and riser structures should be repaired as soon as possible.

Access to detention basins is necessary for excavating equipment, trucks, mowers, and personnel for routine maintenance, erosion repair, and removal of sediment accumulation. Where access is particularly difficult or impractical, basins should be overdesigned to allow for sediment accumulation.

Sediment Removal and Disposal

Sediment removal is a very important maintenance activity because detention basins are designed to remove pollutants by sedimentation. Sediments collect at the bottom of the basin reducing storage volume, and accumulated sediment can reduce the pollutant removal efficiency of the basin.

Under existing EPA regulations (40 CFR 261), any material cleaned from a detention basin should be screened to determine whether it is a solid waste and whether it is a hazardous waste. Sediment accumulated in a wet detention basin qualifies as a solid waste and is subject to the Extraction Procedure (EP) toxicity test. This test should be carried out for accumulated sediment. If the sediment fails the test, it is subject to the Resource Conservation and Recovery Act (RCRA) regulations and must be disposed of in an approved manner at an RCRA-approved facility. If the EP toxicity test is negative, then States are free to impose their own solid waste regulations.

C. RETENTION SYSTEMS

For retention measures, an effective operations and maintenance (O&M) program depends upon the use of proper design and construction practices. Pretreatment facilities, such as grass channels and buffer strips, are necessary to minimize the sediment and debris discharges into the retention facility. In the absence of effective pretreatment measures, the costs for frequent major clean-out operations to relieve clogging conditions may be prohibitive, particularly for trenches and wells. Likewise, the use of filter fabric lining is essential for trench and well systems. Finally, it is important that the retention facility not be activated until the entire drainage area contributing stormwater runoff has been stabilized.

Facility Inspections

Retention facilities should be inspected following at least one storm per year and at the time any maintenance activities are performed. For the inspection following a major storm, the inspector should visit the site at the end of the specified dewatering period to ensure that the facility is draining properly. At the time of all site visits, the inspector should check accumulations of debris, sediment, and oil and grease (aggregate filled measures only) within the retention facility at inlets, outlets, and within major pretreatment areas.

For retention basins, the embankment (if applicable) and side slopes of the basin should be checked to ensure that they exhibit no visible signs of erosion, settlement, slope failure, wildlife damage, or vehicle damage.

For retention trenches and shallow dry wells, inspections to check for surface clogging should be made once or twice per year during nonfreezing conditions. Approximately every 2 to 5 years, a trench with an aggregate surface can be expected to exhibit clogging of the surface layers and the top roll of filter fabric. In the absence of periodic maintenance, the surface layers of the trench will eventually reach a fully clogged condition that approximates an impervious surface.

In addition to visual inspection, the existence of surface clogging at a trench or shallow dry well should be checked by pouring about one gallon of water onto a 1-ft by 1-ft section (i.e., 1.0 ft^2). Assuming that the water is applied fairly evenly to the 1.0 ft^{22} section over about a 15-second period, the water should percolate into the lower layers fairly rapidly so that there is no significant ponding and/or runoff. Several sections should be checked in this manner to ascertain if the clogging problem is widespread or localized. The top aggregate layer (approximately 1-ft deep) should be removed in a small area (by hand or with the aid of a trowel), and the condition of the filter fabric should be checked to confirm the existence of clogging conditions.

Routine Maintenance

Grass can be mowed occasionally, if desired. Grasses of the fescue family can be mowed twice per year, in June and September. In addition to grass maintenance, any other vegetation in the retention basin area or access area that has reached nuisance levels (e.g., bushes and weeds) should be trimmed or removed. Fertilization activities may not be necessary due to the nutrient concentrations in highway runoff.

For the retention basin, if the inspector determines the dewatering rate is too slow, the basin should be tilled. It is anticipated that tilling operations will be required about once a year. Before the basin can be tilled, however, all accumulated sediment must be removed. Sediment should be removed using light equipment only after the layer has dried, cracked, and separated from the natural floor of the basin. After the sediment accumulations have been carefully removed, tilling should be performed using the methods outlined above for construction practices.

For trenches and well systems, the elimination of clogging problems falls under the category of nonroutine maintenance activities.

Debris should be removed from the surface of the retention facility, the inlet/outlet, and major pretreatment areas whenever the site is inspected, if feasible. Most debris can be removed by hand or with hand tools (e.g., shovel). Some larger objects, such as fallen tree limbs, may have to be cut up by hand before removal, if possible.

Nonroutine Maintenance

Eroded areas should be filled and compacted, if necessary, and reseeded as soon as possible. Eroded areas near the inlet or outlet should be revegetated and, if necessary, be filled, compacted, and reseeded or lined with rip-rap. Damaged side slopes in retention basins should be repaired using fill dirt of adequate permeability. Major damage to inlet/outlet structures and the embankment (retention basin) should be repaired as soon as possible.

For retention basins, significant sediment accumulations in the basin are likely to require removal (followed by tilling) at a frequency of about once every 5 years.

In order to eliminate clogging problems in a retention trench or a dry well backfilled with aggregate, the surface layer of aggregate and the filter fabric covering the top of the trench should be replaced. First, the old aggregate should be carefully removed. Then, the filter cloth overlaying the top of the trench or well should be cut on either side of the trench and replaced with a new strip, with a minimum overlap between old and new cloth of 1.0 ft. Clean aggregate should then be laid on top of the new filter fabric layer until flush with the finished grade. Based upon typical sediment discharge rates, it is estimated that surface clean-out operations and replacement of the filter fabric cover could be required on the order of once every 2 to 5 years. The frequency of clean-out operations will depend, to a large extent, upon whether satisfactory pretreatment areas are included in the retention system design.

When the inspector determines that the trench or dry well is completely clogged, the entire trench should be rehabilitated, starting with excavation of all aggregate, removal of all filter cloth, and reclarification of the bottom and sides of the trench. New filter fabric and clean aggregate should be laid in the trench. It is estimated that these major rehabilitation projects could be required on the order of once every 10 to 15 years for trenches and dry wells backfilled with aggregate.

D. WETLAND SYSTEMS

General O&M guidelines have been developed for artificial wetland systems used for wastewater treatment. Typical O&M activities include harvesting and other controls to maintain a suitable vegetative cover, spraying for the control of mosquitos and other pests, monitoring, and periodic replacement of substrate and vegetation if the assimilative capacity of the system should be depleted.

However, the hydraulic regime of a wetland used to treat a wastewater effluent is essentially different from the wetland that is used to treat highway runoff. For the former, there is a constant flow of water whose range of variation is predictable and can be accommodated in the design of the wetland. In the case of highway runoff, inflow will: (1) coincide with rainfall, (2) be intermittent and random, and (3) depend upon the intensity and duration of a particular storm. Excessive rainfall may cause erosion in a wetland, or may damage the vegetative cover if inundation should last longer than can be tolerated. If there is too little rainfall, plants may die and require replacement.

An O&M program should be established for wetland systems designed to provide treatment of highway runoff. The O&M program may include the following activities:

- Periodic sediment removal within wetland.
- Introduction of certain vegetative species.
- Harvesting or burning of vegetation.
- Toxic monitoring.
- Mosquito control.

3. MANAGEMENT MEASURES EFFECTIVENESS AND APPLICABILITY

A. EFFECTIVENESS OF MANAGEMENT MEASURES

Management measures were rated on the basis of their pollutant removal effectiveness for specific pollutants, relative capital costs, land requirements, and operation and maintenance costs. Ratings are based on information gathered from the review of literature. Efficiencies inferred from other than specific data in the literature. Qualitative ratings are used because effectiveness is dependent on the design of the management measure and site-specific factors that determine runoff characteristics and pollutant loads. The ratings are shown in table 26.

Table 26. Effectiveness ratings of management measures.[1]

		Removal Efficiencies						O & M Costs	
Management Measure	Type	Particulates	Metals	Pesticides	Organics	Relative Capital Costs Per Acre[2]	Additional Land Requirements	Routine	Nonroutine
Grassed Channels	Post Runoff	H	H	M	H	L	L	L	L
Overland Flow	Post Runoff	H	H	M	H	L	M to H	L	L
Dry Detention Basins	Post Runoff	L to H	L to H	L ro M	L to M	M	M	L	L
Wet Detention Basins	Post Runoff	H	H	H	H	H	H	L	L
Infiltration Systems	Post Runoff	H	H	H	H	M to H	L to M	H	H
Wetlands	Post Runoff	H	H	M to H	M to H	M to H	M to H	L	L

Ratings: H = High, M = Medium, L = Low, 0 = None, N/A = Non Applicable.

[1] Based on additional capital costs required for nonpoint pollution management, per acre.

B. HIGHWAY APPLICATIONS

All effective measures require space for construction and maintenance. Since the need for mitigation is usually associated with high-traffic volumes, and high-traffic volumes occur in or near urban areas, the costs of management measures could be high. In many locations, the most practical and cost-effective approach to stormwater runoff management may be cooperation with local government in installations that serve the purpose of both levels of government. Table 27 shows the applicability of the specific management measures for use in different highway configurations.

4. SELECTION OF MANAGEMENT MEASURES

The primary management measure for highway runoff pollution is vegetative controls because of their relatively low costs (compared to the other measures) and their widespread applicability. However, considering that stormwater runoff management for pollution abatement is principally needed in high-traffic corridors, vegetative controls may be impractical in many locations. The second choice for a management measure is wet detention. Detention typically costs more than the vegetative controls and less than infiltration systems or wetlands. Infiltration systems and wetlands are variations on detention and are considered as special subsets of detention. Figure 7 presents a selection process for identifying a management measure that is suitable for a specific site. Each measure has minimum conditions that must be met for the measure to be effective. If these minimum conditions are not met, then another measure should be used, or the site and/or runoff characteristics that do not meet the minimum conditions should be altered.

Combinations of measures may be used to compensate for certain site limitations and to increase pollutant-removal effectiveness. An example would be use of infiltration wells in a detention basin to increase pollutant removal while decreasing long-term runoff storage requirements. Another example is the use of overland flow to filter suspended sediments from runoff upstream of an infiltration basin or trench.

In general, grassed waterways should be used to collect and transport highway runoff where practical. Where additional treatment is necessary, wet detention basins are the most readily adaptable and cost-effective management measure applicable to a wide range of site and runoff conditions. Wetlands, which are a variation on the wet detention basin measure, are used to provide additional pollutant removal potential in areas of high groundwater. Infiltration measures are only used after pretreatment of runoff to remove sediment and are used in place of wet detention basins only when there is a need for groundwater recharge or a reduction in runoff volume or peak flow rate.

Table 27. Applicability of pollution management measures to highway configurations.

Management Measure	Planned Highway Construction				Existing Highway Retrofit			
	Interchange	Elevated Highway	At-grade Highway	Depressed Highway	Interchange	Elevated Highway	At-grade Highway	Depressed Highway
Vegetative Controls								
Grassed channel	High	Low	High	Low	Medium	Low	High	Low
Overland Flow	Medium	Low	High	Low	High	Low	High	Low
Detention Basins	High	Medium	Medium	Low	Medium-High	Medium	Medium	Low
Infiltration Measures								
Basin	High	Medium	Low	Low	Medium-High	Medium	Medium	Low-Medium
Trench	Low	Medium	Medium	Medium	Medium	Low-Medium	Medium	Low-Medium
Well	Medium	Low	Low	Low	Low-Medium	Low-Medium	Low	Low
Wetlands	Medium	Low	Low	Low	Low-Medium	Medium	Medium	Low

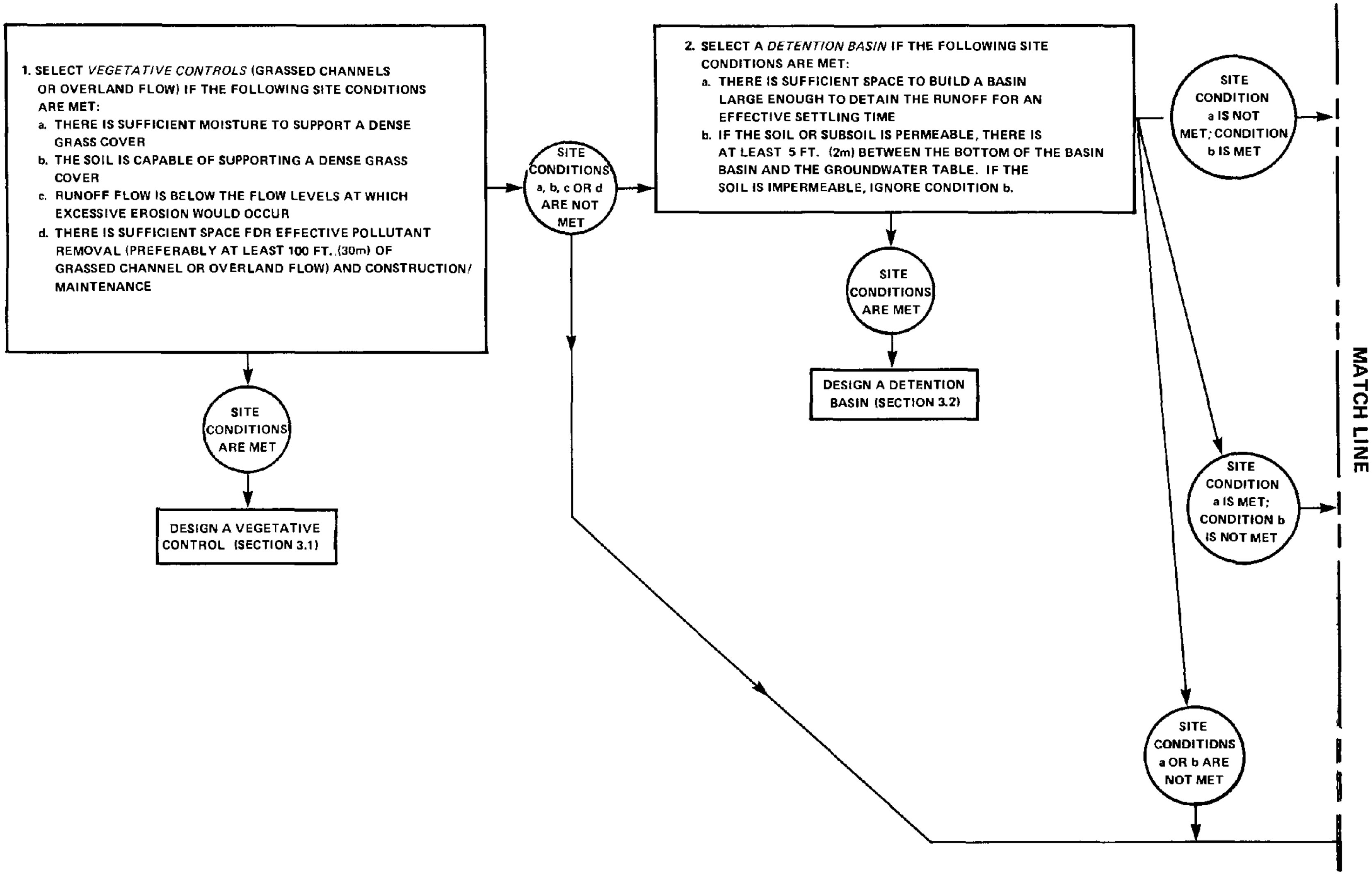


Figure 7. Selection of effective management measures for mitigation of highway stormwater runoff pollution problems.

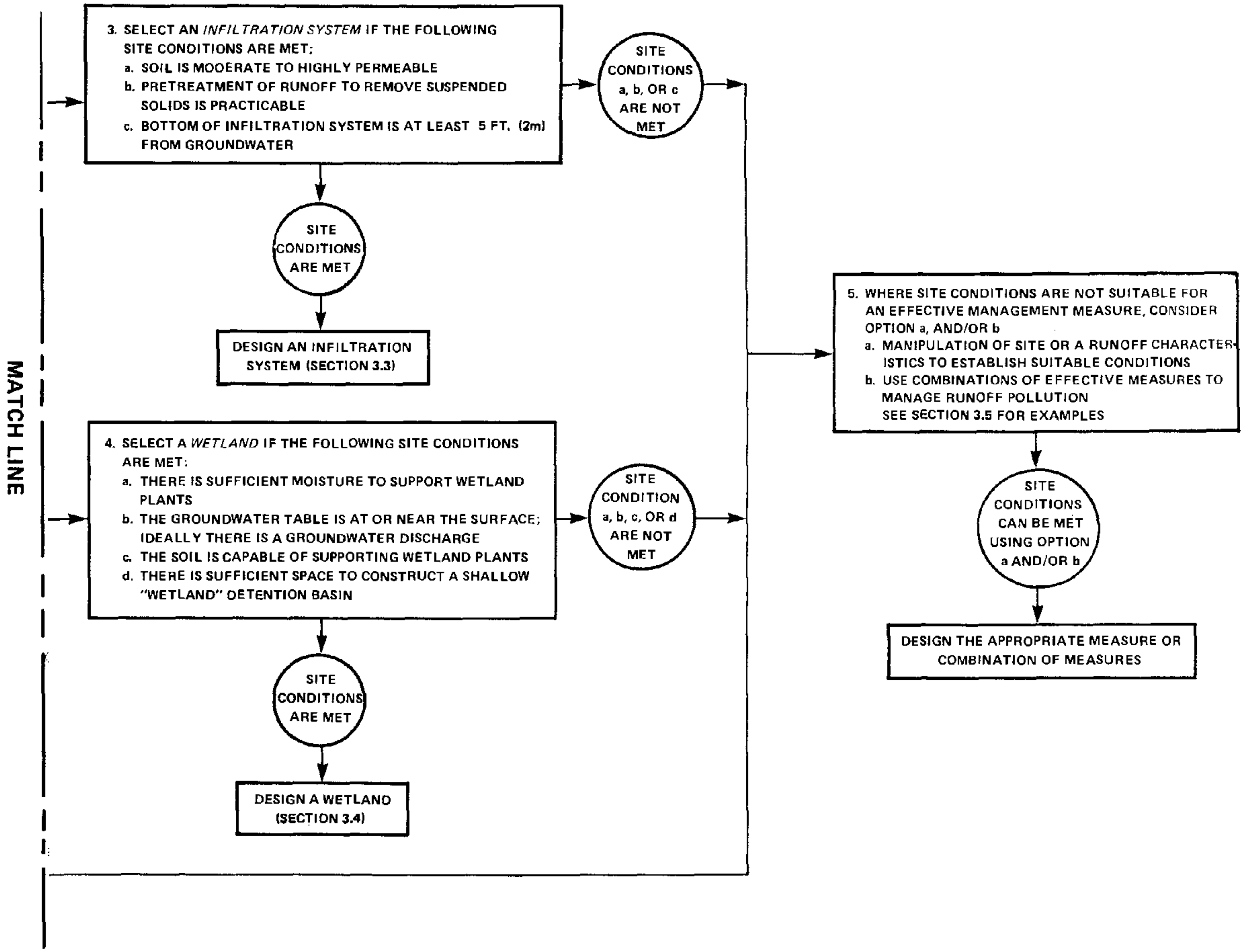
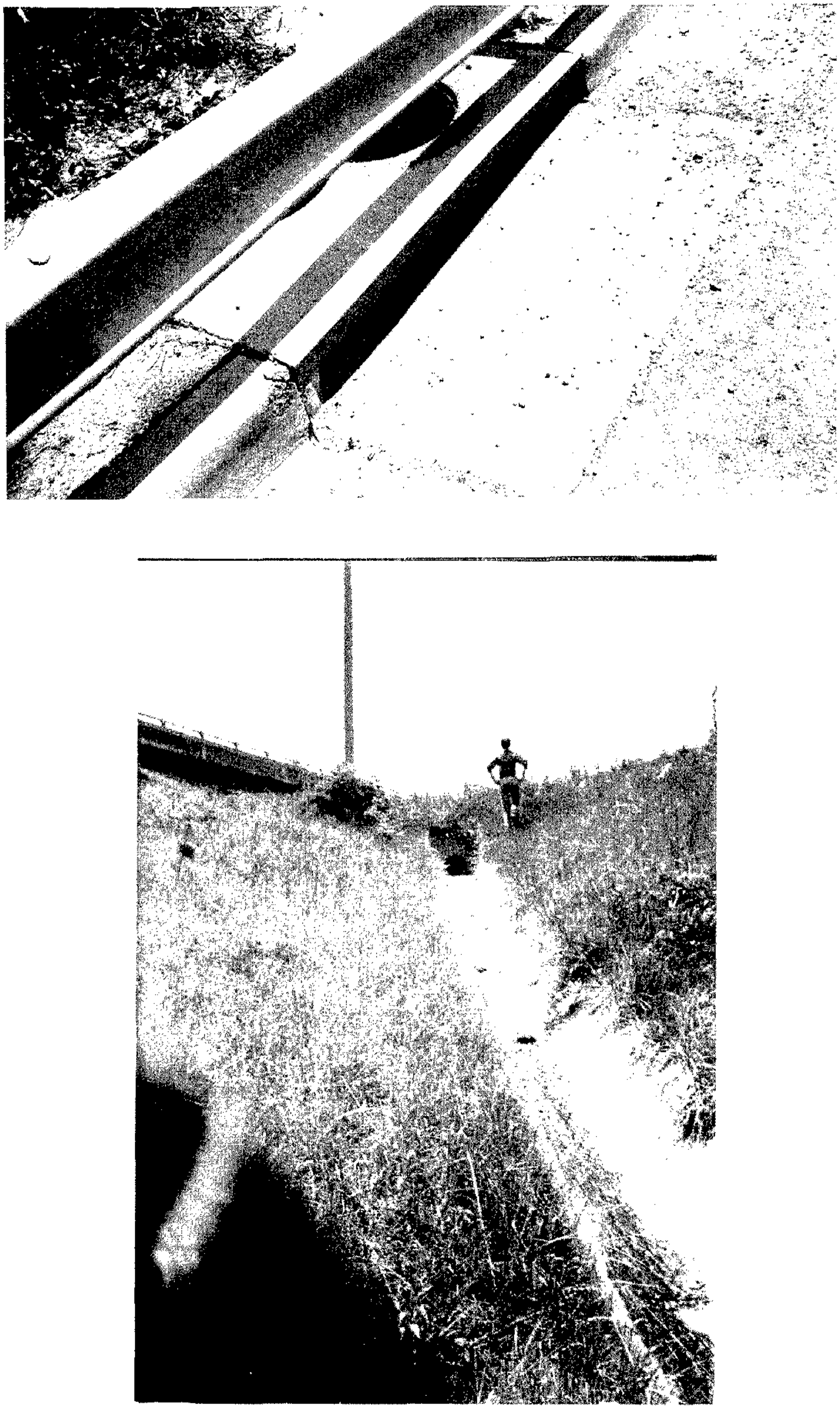


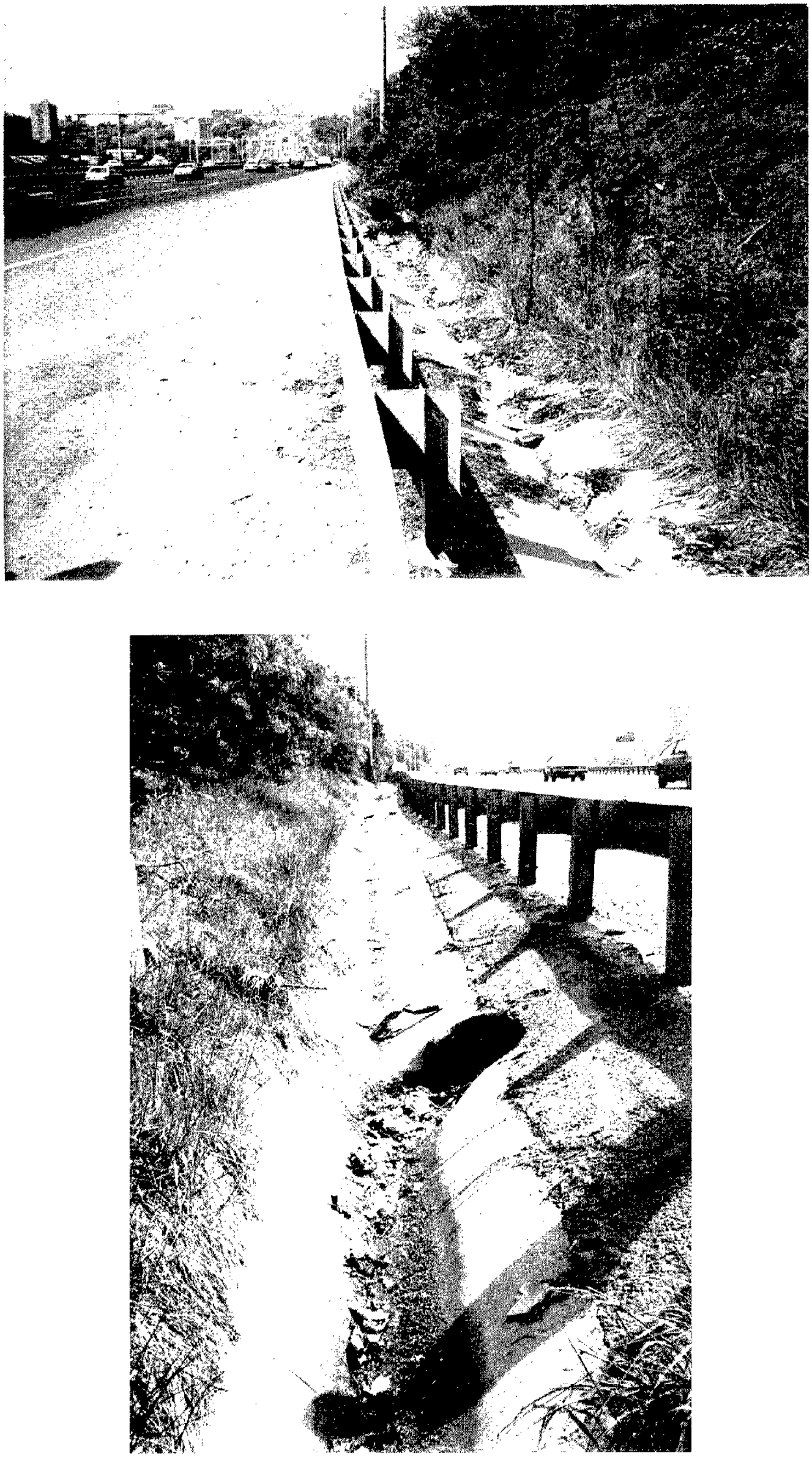
Figure 7. Selection of effective management measures for mitigation of highway stormwater runoff pollution problems. (continued)

Infiltration basins also require specific site conditions to be effective. Thus, the primary management measures are vegetative controls and wet detention basins, with wetland treatment systems and infiltration systems considered as special cases.

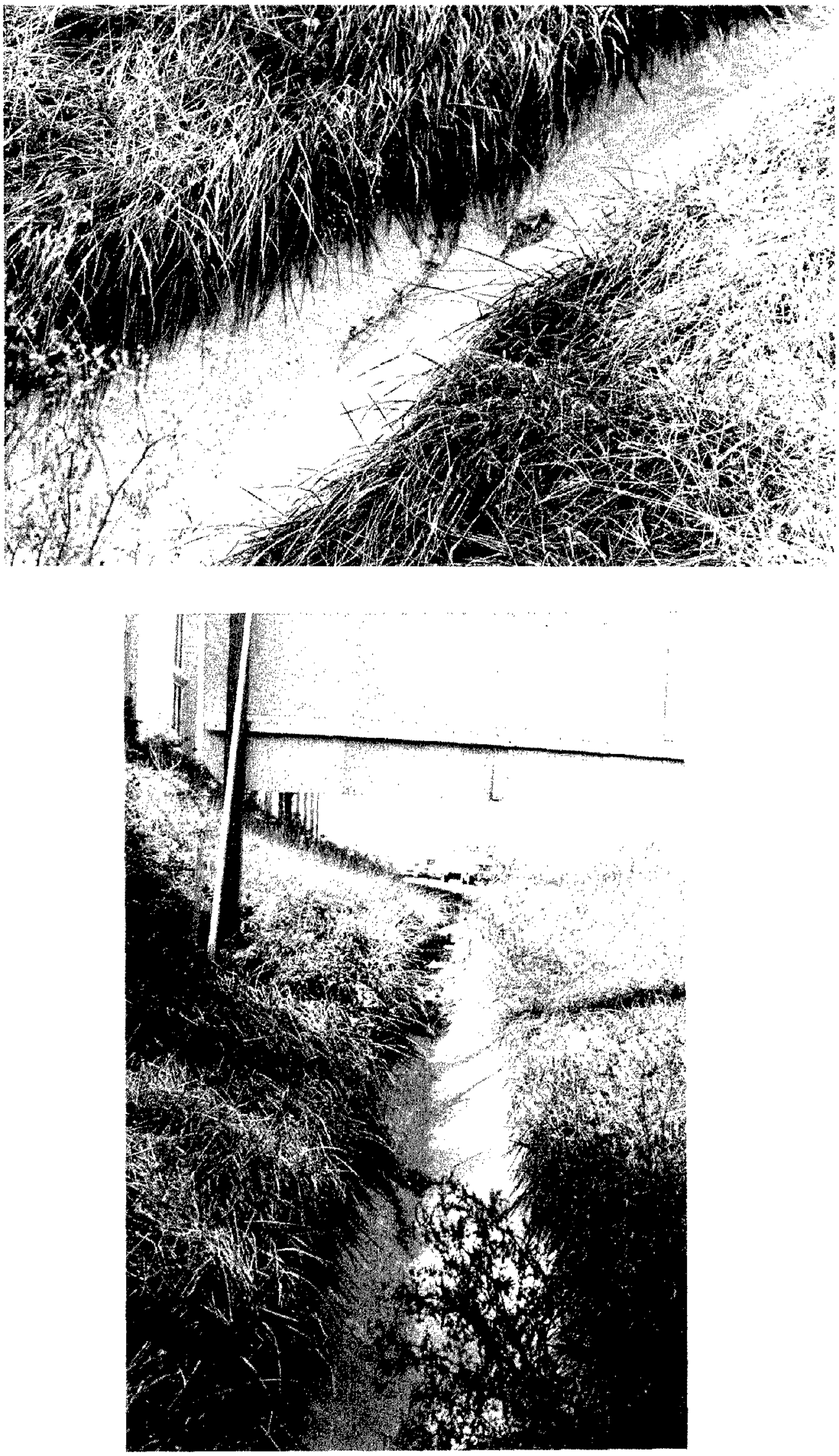
Appendix A. Photographs of laboratory phase sample collection sites.



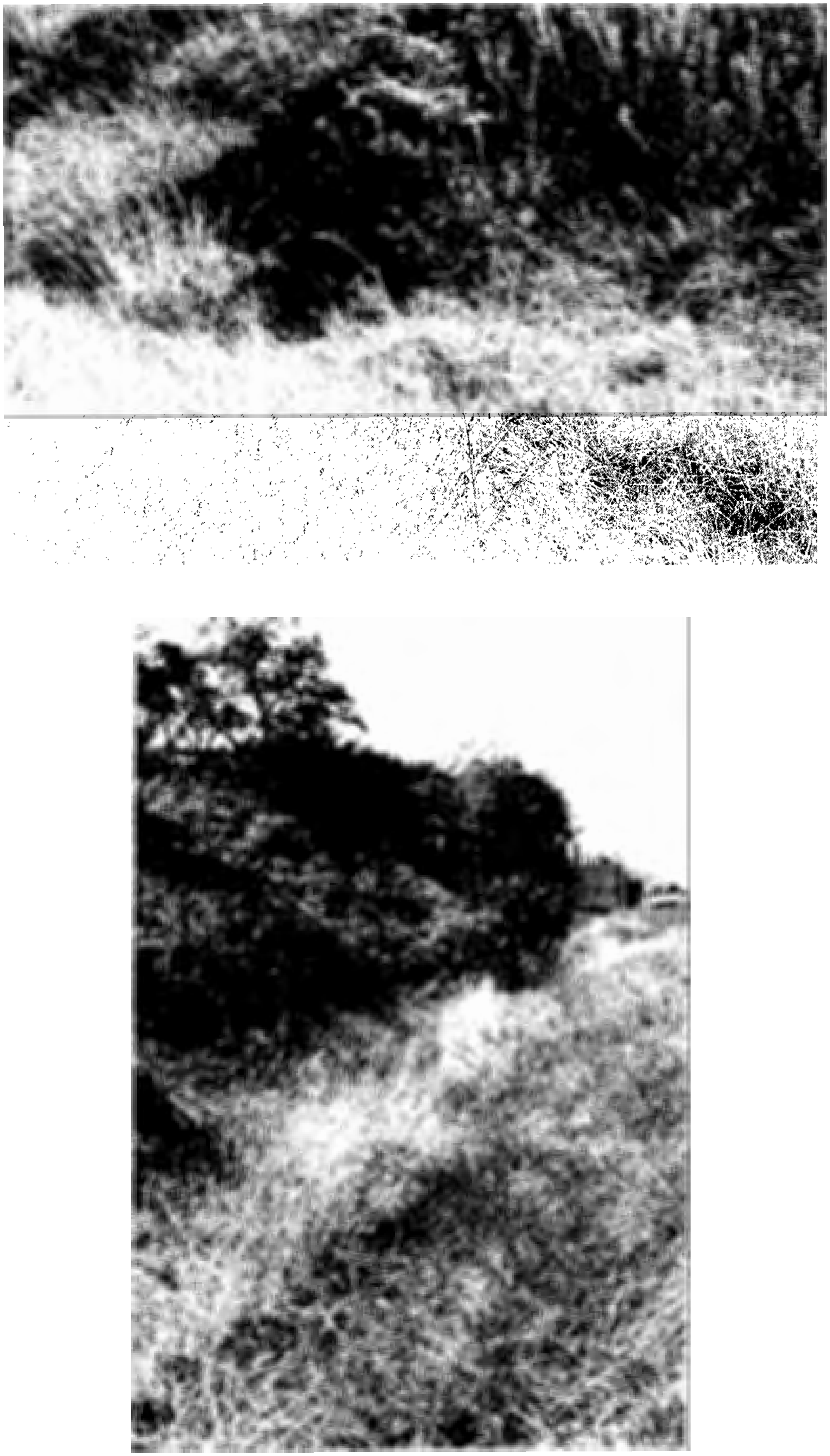
Site A: I-395 North at the intersection of I-495.



Site B: I-395 South approximately one-half mile south of Seminary Road.

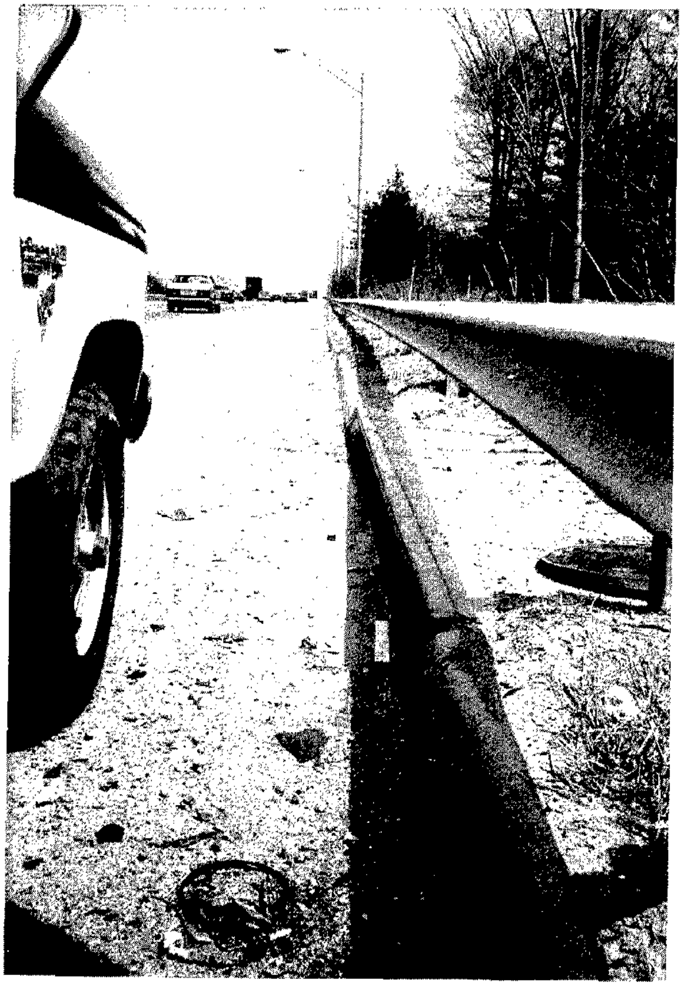


Site C: I-495 East near I-395.



Site D: I-495 East near I-395.

Site E: I-495 South at Gallows Road.



Site F: I-395 North approximately one mile south of Duke Street.

Appendix B. Laboratory analyses of settling column data.

Storm #1
Site: A
Date: June 12, 1986

		Total (hrs)						Diss (hrs)	
Parameter	Port	0	2	6	12	24	48	0	48
Cd (ug/l)	3	11	<10	<10	<10	<10	<10	-	-
	2	11	<10	<10	<10	<10	<10	<10	<10
	1	11	<10	<10	<10	<10	<10	-	-
Cr (ug/l)	3	67	23	<20	22	<20	<20	-	-
	2	67	24	<20	<20	<20	<20	<20	<20
	1	67	26	<20	<20	<20	<20	-	-
Cu (ug/l)	3	213	90	65	48	47	35	-	-
	2	213	92	67	61	55	39	26	11
	1	213	91	68	61	48	43	-	-
Pb (ug/l)	3	878	333	278	189	138	101	-	-
	2	878	334	248	205	178	133	<50	<50
	1	878	358	309	202	188	147	-	-
Zn (ug/l)	3	2600	1480	1280	1300	1110	960	-	-
	2	2600	1440	1250	1220	1210	1080	970	890
	1	2600	1500	1280	1190	1260	1070	-	-
TSS (mg/l)	3	1120	305	169	92	83	37	-	-
	2	1120	314	202	156	103	74	352	652
	1	1120	351	199	146	104	62	-	-
NO2+NO3 (mg/l)	3	4.23	4.55	4.26	3.35	1.81	0.09	-	-
	2	4.23	4.53	4.07	2.92	1.60	0.12	-	-
	1	4.23	4.50	4.03	3.07	1.58	0.07	-	-
TKN (mg/l)	3	12.38	8.04	7.59	6.86	7.42	7.03	-	-
	2	12.38	10.75	9.79	7.76	6.86	6.52	-	-
	1	12.38	10.64	8.33	-	8.16	8.49	-	-
Phos. (mg/l)	3	3.40	1.43	0.96	0.71	0.56	0.43	-	-
	2	3.40	1.38	1.03	0.87	0.69	0.52	0.13	0.10
	1	3.40	1.50	1.16	0.91	0.71	0.54	-	-
Ortho P (mg/l)	3	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	<0.01	<0.01
	1	-	-	-	-	-	-	-	-
Temp (C)	-	24.3	24.4	24.9	24.6	23.6	23.8	-	-
pH	-	6.66	-	-	-	-	7.18	-	-

Storm #2
Site: A
Date: June 28, 1986

		Total (hrs)						Diss (hrs)	
Parameter	Port	0	2	6	12	24	48	0	48
Cd (ug/l)	3	<10	<10	<10	<10	<10	<10	-	-
	2	<10	<10	<10	<10	<10	<10	<10	<10
	1	<10	<10	<10	<10	<10	<10	-	-
Cr (ug/l)	3	<5	<5	<5	<5	<5	<5	-	-
	2	<5	<5	<5	<5	<5	<5	<5	<5
	1	<5	<5	<5	<5	<5	<5	-	-
Cu (ug/l)	3	11	10	<5	<5	<5	<5	-	-
	2	11	9	6	<5	<5	<5	<5	<5
	1	11	12	<5	<5	<5	<5	-	-
Pb (ug/l)	3	<50	<50	<50	<50	<50	<50	-	-
	2	<50	<50	<50	<50	<50	<50	<50	<50
	1	<50	52	<50	<50	<50	<50	-	-
Zn (ug/l)	3	296	243	214	179	192	171	-	-
	2	296	251	235	180	171	-	150	154
	1	296	279	225	185	-	161	-	-
TSS (mg/l)	3	100	39	18	14	3	<1	-	-
	2	100	53	28	16	3	<1	42	40
	1	100	56	31	15	5	5	-	-
NO2+NO3 (mg/l)	3	0.89	0.90	0.90	0.96	0.91	0.83	-	-
	2	0.89	0.90	0.90	0.90	0.90	0.88	-	-
	1	0.89	0.87	0.90	0.89	0.90	0.83	-	-
TKN (mg/l)	3	1.67	2.02	0.65	0.88	0.85	0.75	-	-
	2	1.67	1.33	0.96	0.76	0.83	-	-	-
	1	1.67	1.52	1.09	0.93	0.86	0.72	-	-
Phos. (mg/l)	3	0.08	0.12	0.05	0.04	0.03	0.03	-	-
	2	0.08	0.08	0.15	0.05	0.03	0.04	0.03	0.02
	1	0.08	0.07	0.07	0.07	0.03	0.03	-	-
Ortho P (mg/l)	3	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	<0.01	<0.01
	1	-	-	-	-	-	-	-	-
Temp (C)	-	24.4	24.4	25.3	25.3	23.3	22.3	-	-
pH	-	6.63	-	-	-	-	7.36	-	-

Storm #3
Site: B
Date: July 16, 1986

		Total (hrs)						Diss (hrs)	
Parameter	Port	0	2	6	12	24	48	0	48
Cd (ug/l)	3	<10	<10	13	<10	<10	<10	-	-
	2	<10	<10	<10	<10	<10	<10	<10	<10
	1	<10	<10	<10	<10	<10	<10	-	-
Cr (ug/l)	3	17	<10	<10	<10	<10	<10	-	-
	2	17	<10	<10	<10	<10	<10	<10	<10
	1	17	<10	<10	<10	<10	<10	-	-
Cu (ug/l)	3	92	50	53	38	34	31	-	-
	2	92	53	47	43	32	34	38	29
	1	92	60	46	39	32	28	-	-
Pb (ug/l)	3	406	164	114	53	-	<50	-	-
	2	406	150	112	75	<50	<50	<50	<50
	1	406	209	117	63	50	<50	-	-
Zn (ug/l)	3	3380	2900	3190	3080	2930	2920	-	-
	2	3380	2850	3100	2680	2830	3050	3420	3350
	1	3380	3140	2920	2870	2720	2860	-	-
TSS (mg/l)	3	160	154	66	44	32	20	-	-
	2	160	174	108	88	48	28	256	276
	1	160	172	88	80	70	66	-	-
NO2+NO3 (mg/l)	3	2.28	2.14	2.31	2.28	1.75	-	-	-
	2	2.28	2.39	2.50	2.31	1.89	1.13	-	-
	1	2.28	2.21	2.20	2.36	1.95	1.12	-	-
TKN (mg/l)	3	4.58	3.70	3.67	3.57	-	3.12	-	-
	2	4.58	3.88	3.84	3.31	3.41	3.06	-	-
	1	4.58	3.80	4.00	3.99	3.34	2.70	-	-
Phos. (mg/l)	3	0.15	0.08	0.05	0.03	0.03	0.03	-	-
	2	0.15	0.08	0.06	0.04	0.03	0.03	0.05	0.01
	1	0.15	0.10	0.06	0.04	0.04	0.04	-	-
Ortho P (mg/l)	3	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	0.06	<0.02
	1	-	-	-	-	-	-	-	-
Temp (C)	-	24.0	23.8	24.6	25.5	24.0	24.8	-	-
pH	-	5.89	-	-	-	-	6.33	-	-

Storm #4
Site: B
Date: August 2, 1986

		Total (hrs)						Diss (hrs)	
Parameter	Port	0	2	6	12	24	48	0	48
Cd (ug/l)	3	<10	<10	<10	<10	<10	<10	-	-
	2	<10	<10	<10	<10	<10	<10	<10	<10
	1	<10	<10	<10	<10	<10	<10	-	-
Cr (ug/l)	3	19	<10	<10	<10	<10	<10	-	-
	2	19	<10	<10	<10	<10	<10	<10	
	1	19	<10	<10	<10	<10	<10	-	-
Cu (ug/l)	3	59	29	23	20	18	20	-	-
	2	59	34	20	19	12	9	20	17
	1	59	31	24	21	15	18	-	-
Pb (ug/l)	3	210	78	50	<50	<50	<50	-	-
	2	210	82	51	57	<50	<50	<50	<50
	1	210	94	<50	66	<50	<50	-	-
Zn (ug/l)	3	1410	990	901	882	848	818	-	-
	2	1410	1040	903	868	812	811	1150	1140
	1	1410	1040	858	914	842	798	-	-
TSS (mg/l)	3	438	152	84	64	46	32	-	-
	2	438	133	83	55	48	26	192	264
	1	438	142	82	71	32	36	-	-
NO2+NO3 (mg/l)	3	1.31	1.40	1.45	1.43	1.36	1.07	-	-
	2	1.31	1.37	1.38	1.38	1.37	1.08	-	-
	1	1.31	1.39	1.40	1.40	1.00	1.08	-	-
TKN (mg/l)	3	3.58	2.76	2.48	2.42	2.25	2.08	-	-
	2	3.58	2.81	2.54	2.50	2.31	2.01	-	-
	1	3.58	2.68	2.60	2.42	2.01	2.01	-	-
Phos. (mg/l)	3	0.89	0.61	0.39	-	0.18	0.08	-	-
	2	0.89	0.60	0.37	0.28	0.20	0.10	0.05	<0.02
	1	0.89	0.62	0.35	0.36	0.18	0.08	-	-
Ortho P (mg/l)	3	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	0.02	<0.01
	1	-	-	-	-	-	-	-	-
Temp (C)	-	24.9	25.4	25.8	25.2	22.4	23.0	-	-
pH	-	6.70	-	-	-	-	6.59	-	-

Storm #5
Site: C
Date: August 6, 1986

		Total (hrs)						Diss (hrs)	
Parameter	Port	0	2	6	12	24	48	0	48
Cd (ug/l)	3	<10	<10	<10	<10	<10	<10	-	-
	2	<10	<10	<10	<10	<10	<10	<10	<10
	1	<10	<10	<10	<10	<10	<10	-	-
Cr (ug/l)	3	<10	<10	<10	<10	<10	<10	-	-
	2	<10	<10	<10	<10	<10	<10	<10	<10
	1	<10	<10	<10	<10	<10	<10	-	-
Cu (ug/l)	3	29	22	17	18	18	15	-	-
	2	29	26	18	17	20	18	20	16
	1	29	22	20	66	19	20	-	-
Pb (ug/l)	3	135	85	66	<50	<50	<50	-	-
	2	135	93	88	<50	<50	51	<50	<50
	1	135	71	69	<50	<50	<50	-	-
Zn (ug/l)	3	191	133	136	114	124	112	-	-
	2	191	150	120	114	120	127	113	115
	1	191	133	120	115	109	114	-	-
TSS (mg/l)	3	142	60	35	29	20	6	-	-
	2	142	120	68	28	24	60	58	58
	1	142	58	40	27	16	<10	-	-
NO2+NO3 (mg/l)	3	1.68	1.73	1.77	1.77	1.73	1.39	-	-
	2	1.68	1.73	1.79	1.73	1.71	1.38	-	-
	1	1.68	1.39	1.77	1.73	1.73	1.36	-	-
TKN (mg/l)	3	2.98	2.67	2.33	2.36	2.32	1.80	-	-
	2	2.98	2.63	2.15	2.32	2.10	2.40	-	-
	1	2.98	2.08	1.95	1.85	3.50	1.54	-	-
Phos. (mg/l)	3	0.62	0.42	0.32	0.24	0.19	0.15	-	-
	2	0.62	0.43	0.30	0.26	0.19	0.14	0.14	0.05
	1	0.62	0.41	0.34	0.29	0.22	0.15	-	-
Ortho P (mg/l)	3	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	0.16	0.08
	1	-	-	-	-	-	-	-	-
Temp (C)	-	26.0	26.4	26.4	25.8	24.0	22.9	-	-
pH	-	6.21	-	-	-	-	6.09	-	-

Storm #6
Site: D
Date: August 6, 1986

		Total (hrs)						Diss (hrs)	
Parameter	Port	0	2	6	12	24	48	0	48
Cd (ug/l)	3	<10	<10	<10	<10	<10	<10	-	-
	2	<10	<10	<10	<10	<10	<10	<10	<10
	1	<10	<10	<10	<10	<10	<10	-	-
Cr (ug/l)	3	<10	<10	<10	<10	<10	<10	-	-
	2	<10	<10	<10	<10	<10	<10	<10	<10
	1	<10	<10	<10	<10	<10	<10	-	-
Cu (ug/l)	3	24	19	19	26	17	16	-	-
	2	24	21	14	21	15	18	50	<10
	1	24	47	16	15	14	20	-	-
Pb (ug/l)	3	57	<50	<50	<50	<50	<50	-	-
	2	57	<50	<50	<50	<50	<50	<50	<50
	1	57	<50	<50	<50	<50	<50	-	-
Zn (ug/l)	3	71	<20	<20	<20	<20	<20	-	-
	2	71	74	<20	61	<20	<20	<20	<20
	1	71	65	<20	<20	<20	65	-	-
TSS (mg/l)	3	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	210	200
	1	-	-	-	-	-	-	-	-
NO2+NO3 (mg/l)	3	0.77	0.77	0.78	0.77	0.75	0.69	-	-
	2	0.77	0.77	0.78	0.77	0.75	-	-	-
	1	0.77	0.76	0.77	0.77	0.75	0.71	-	-
TKN (mg/l)	3	1.72	1.49	1.42	1.31	1.13	1.08	-	-
	2	1.72	1.76	1.45	1.39	1.47	1.39	-	-
	1	1.72	1.81	1.58	1.45	1.34	1.39	-	-
Phos. (mg/l)	3	0.86	0.72	0.63	0.59	0.56	0.51	-	-
	2	0.86	0.80	0.72	0.59	0.53	0.49	0.37	0.36
	1	0.86	0.79	0.68	0.65	0.56	0.53	-	-
Ortho P (mg/l)	3	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	0.51	0.47
	1	-	-	-	-	-	-	-	-
Temp (C)	-	26.0	26.4	26.4	25.8	24.0	22.9	-	-
pH	-	6.57	-	-	-	-	6.31	-	-

Storm #7
Site: C
Date: August 27, 1986

		Total (hrs)						Diss (hrs)	
Parameter	Port	0	2	6	12	24	48	0	48
Cd (ug/l)	3	<10	<10	<10	<10	<10	<10	-	-
	2	<10	<10	<10	<10	<10	<10	<10	<10
	1	<10	<10	<10	<10	<10	<10	-	-
Cr (ug/l)	3	<10	<10	<10	<10	<10	<10	-	-
	2	<10	<10	<10	<10	<10	<10	<10	<10
	1	<10	<10	<10	<10	<10	<10	-	-
Cu (ug/l)	3	31	23	20	18	11	14	-	-
	2	31	27	20	42	15	18	17	25
	1	31	25	18	20	16	22	-	-
Pb (ug/l)	3	115	84	<50	<50	<50	<50	-	-
	2	115	67	54	<50	<50	<50	<50	<50
	1	115	68	<50	<50	<50	<50	-	-
Zn (ug/l)	3	178	136	113	120	113	100	-	-
	2	178	135	117	126	106	111	98	88
	1	178	146	115	113	108	100	-	-
TSS (mg/l)	3	220	96	38	22	14	16	-	-
	2	220	98	42	34	24	18	72	121
	1	220	116	52	36	30	17	-	-
NO2+NO3 (mg/l)	3	2.81	3.00	2.95	2.92	2.89	2.28	-	-
	2	2.81	2.92	2.95	2.37	2.67	2.37	-	-
	1	2.81	2.97	2.86	2.92	2.51	2.20	-	-
TKN (mg/l)	3	5.26	4.37	-	4.80	4.55	3.59	-	-
	2	5.26	4.04	4.98	4.49	4.26	4.12	-	-
	1	5.26	4.26	4.36	3.93	4.19	-	-	-
Phos. (mg/l)	3	0.88	0.62	0.44	0.42	0.33	0.30	-	-
	2	0.88	0.69	0.53	0.39	0.34	0.27	0.18	0.15
	1	0.88	0.71	0.51	0.42	0.32	0.29	-	-
Ortho P (mg/l)	3	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	0.14	0.15
	1	-	-	-	-	-	-	-	-
Temp (C)	-	22.4	21.7	21.2	22.1	21.9	22.3	-	-
pH	-	6.29	-	-	-	-	6.44	-	-

Storm No.: 87-1
Site: A
Date: May 3, 1987

		Total (hrs)						Diss (hrs)	
Parameter	Port	0	2	6	12	24	48	0	48
Cd	3	0.006	<.003	<.003	<.003	<.003	<.003		
(mg/L)	2	0.006	<.003	<.003	0.006	<.003	<.003	<.003	<.003
	1	0.006	0.004	0.003	0.006	0.005	<.003		
Cr	3	0.015	0.006	0.007	0.013	0.007	0.005		
(mg/L)	2	0.015	0.008	0.010	0.009	0.005	0.006	0.005	0.006
	1	0.015	0.008	0.007	0.005	0.008	0.006		
Cu	3	0.145	0.091	0.081	0.080	0.065	0.054		
(mg/L)	2	0.145	0.098	0.087	0.080	0.069	0.055	0.060	<.004
	1	0.145	0.097	0.086	0.081	0.066	0.055		
Pb	3	0.291	0.130	0.084	0.080	<.043	0.056		
(mg/L)	2	0.291	0.110	0.103	0.067	0.060	0.080	0.046	<.043
	1	0.291	0.153	0.085	0.077	0.072	0.060		
Zn	3	2.67	1.70	1.56	1.50	1.44	1.39		
(mg/L)	2	2.67	1.74	1.56	1.46	1.40	1.39	1.62	1.3
	1	2.67	1.82	1.62	1.57	1.48	1.38		
TSS	3	942	276	155	122	89	61		
(mg/L)	2	942	299	189	142	88	71		
	1	942	298	195	166	99	68		
NO2+NO3	3	8.29	8.70	8.76	8.11	6.21	1.46		
(mg/L)	2	8.29	8.58	9.00	7.75	5.73	1.46		
	1	8.29	7.99	8.23	8.11	6.09	1.37		
TKN	3	28.3	19.5	19.8	19.6	19.0	18.5		
(mg/L)	2	28.3	21.4	19.7	19.4	19.6	19.4		
	1	28.3	27.1	27.1	27.7	26.9	26.9		
TP	3	0.396	0.07	0.3	0.334	0.408	0.289		
(mg/L)	2	0.396	0.168	0.428	0.232	0.224	0.634	0.27	0.178
	1	0.396	0.31	0.137	0.481	0.386	0.392		
pH	2	5.88					7.09		

Storm No.: 87-2
Site: E
Date: May 3, 1987

		Total (hrs)						Diss (hrs)	
Parameter	Port	0	2	6	12	24	48	0	48
Cd	3	0.010	0.004	0.006	0.008	0.007	<.003		
(mg/L)	2	0.010	0.006	0.005	0.004	0.007	0.007	0.007	<.003
	1	0.010	0.006	<.003	0.004	<.003	0.004		
Cr	3	0.051	0.031	0.021	0.019	0.010	0.010		
(mg/L)	2	0.051	0.035	0.029	0.021	0.014	0.010	<.004	0.005
	1	0.051	0.037	0.032	0.027	0.014	0.016		
Cu	3	0.206	0.158	0.132	0.141	0.120	0.118		
(mg/L)	2	0.206	0.169	0.150	0.127	0.123	0.117	0.090	0.095
	1	0.206	0.163	0.155	0.145	0.124	0.110		
Pb	3	0.562	0.377	0.288	0.268	0.158	0.155		
(mg/L)	2	0.562	0.434	0.359	0.300	0.178	0.165	0.081	0.108
	1	0.562	0.458	0.346	0.270	0.223	0.180		
Zn	3	1.08	0.831	0.645	0.632	0.558	0.553		
(mg/L)	2	1.08	0.823	0.707	0.618	0.588	0.549	0.485	0.506
	1	1.08	0.824	0.683	0.636	0.601	0.561		
TSS	3	944	487	271	213	110	105		
(mg/L)	2	944	542	373	261	157	100		
	1	944	548	394	291	208	130		
NO2+NO3	3	5.55	4.66	3.47	2.09	2.09	1.52		
(mg/L)	2	5.55	5.26	3.35	2.12	1.88	1.57		
	1	5.55	3.35	3.53	2.00	1.64	1.48		
TKN	3	29.5	22.9	14.5	17.4	15.9	13.2		
(mg/L)	2	29.5	25.8	18.9	20.8	16.0	23.9		
	1	29.5	25.7	18.4	20.1	19.6	16.0		
TP	3	1.970	2.014	1.553	1.788	1.611	1.342		
(mg/L)	2	1.970	1.768	2.041	1.634	1.534	1.230	0.910	1.074
	1	1.970	1.902	2.012	2.043	1.648	1.621		
pH	2	6.57	-	-	-	-	5.31		

Storm No.: 87-3
Site: A
Date: May 12, 1987

		Total (hrs)						Diss (hrs)	
Parameter	Port	0	2	6	12	24	48	0	48
Cd	3	0.007	<.003	<.003	0.007	0.005	0.004		
(mg/L)	2	0.007	0.006	0.004	0.003	<.003	<.003	0.005	<.003
	1	0.007	0.008	0.005	0.004	0.006	0.006		
Cr	3	0.034	0.019	0.013	0.009	0.007	0.005		
(mg/L)	2	0.034	0.027	0.013	0.010	0.007	0.008	<.004	<.004
	1	0.034	0.024	0.013	0.009	0.006	0.007		
Cu	3	0.204	0.170	0.149	0.140	0.126	0.102		
(mg/L)	2	0.204	0.176	0.147	0.145	0.132	0.123	0.123	0.070
	1	0.204	0.177	0.151	0.140	0.137	0.126		
Pb	3	0.471	0.273	0.168	0.130	0.098	0.057		
(mg/L)	2	0.471	0.305	0.132	0.131	0.090	0.078	<.043	<.043
	1	0.471	0.318	0.169	0.111	0.115	0.073		
Zn	3	1.240	0.959	0.841	0.833	0.760	0.706		
(mg/L)	2	1.240	1.010	0.819	0.811	0.793	0.764	0.812	0.660
	1	1.240	0.998	0.828	0.788	0.808	0.754		
TSS	3	845	576	178	105	86	42		
(mg/L)	2	845	621	451	417	378	355		
	1	845	327	162	82	51	72		
NO2+NO3	3	8.79	10.00	9.72	9.27	8.32	7.14		
(mg/L)	2	8.79	9.38	9.78	7.59	8.09	6.29		
	1	8.79	9.16	9.10	8.60	8.04	5.56		
TKN	3	20.0	18.5	18.0	18.1	17.4	16.9		
(mg/L)	2	20.0	18.7	17.3	17.0	17.1	17.7		
	1	20.0	18.0	16.7	16.9	16.9	17.0		
TP	3	0.618	0.332	0.352	0.448	0.348	0.428		
(mg/L)	2	0.618	0.430	0.432	0.384	0.468	0.408	0.532	0.432
	1	0.618	0.374	0.330	0.318	0.332	0.384		
pH	2	6.13					6.67		

Storm No.: 87-4
Site: F
Date: May 12, 1987

		Total (hrs)						Diss (hrs)	
Parameter	Port	0	2	6	12	24	48	0	48
Cd	3	0.010	0.003	<.003	<.003	<.003	<.003		
(mg/L)	2	0.010	0.004	0.005	0.005	<.003	0.006	<.003	<.003
	1	0.010	0.006	0.006	0.005	0.006	<.003		
Cr	3	0.057	0.019	0.009	0.007	0.007	0.006		
(mg/L)	2	0.057	0.018	0.011	0.007	0.008	0.005	<.004	<.004
	1	0.057	0.018	0.011	0.007	0.005	0.006		
Cu	3	0.218	0.099	0.083	0.064	0.060	0.051		
(mg/L)	2	0.218	0.094	0.077	0.069	0.046	0.029	0.023	0.010
	1	0.218	0.095	0.078	0.065	0.043	0.030		
Pb	3	0.371	0.104	0.076	<0.042	<0.042	<0.042		
(mg/L)	2	0.371	0.097	0.078	<0.042	0.044	<0.042	<.042	<.042
	1	0.371	0.088	0.069	<0.042	0.046	<0.042		
Zn	3	2.540	1.200	1.050	0.922	0.923	0.945		
(mg/L)	2	2.540	1.130	1.030	0.933	0.909	0.883	1.250	0.928
	1	2.540	1.200	1.110	0.952	0.908	0.874		
TSS	3	1066	214	112	67	49	28		
(mg/L)	2	1066	187	117	73	70	45		
	1	1066	188	108	74	50	35		
NO2+NO3	3	9.06	9.83	9.16	8.09	5.56	0.337		
(mg/L)	2	9.06	10.40	9.44	4.66	5.56	0.403		
	1	9.06	9.95	9.16	7.59	5.84	0.247		
TKN	3	19.1	17.7	17.2	17.6	16.4	15.5		
(mg/L)	2	19.1	17.4	16.3	18.2	16.0	14.9		
	1	19.1	18.6	18.0	16.6	16.9	15.6		
TP	3	0.398	0.184	0.228	0.264	0.364	0.400		
(mg/L)	2	0.398	0.212	0.264	0.286	0.336	0.370	0.180	0.092
	1	0.398	0.248	0.204	0.344	0.258	0.362		
pH	2	6.77					7.34		

Storm No.: 87-5
Site: F
Date: June 12, 1987

		Total (hrs)						Diss (hrs)	
Parameter	Port	0	2	6	12	24	48	0	48
Cd	3	0.009	0.005	0.010	0.008	0.005	<.003		
	2	0.009	0.005	0.003	0.006	0.010	0.008	<.003	<.003
	1	0.009	0.007	0.008	0.004	0.008	0.004		
Cr	3	0.025	0.020	0.014	0.012	0.008	0.005		
	2	0.025	0.015	0.014	0.015	0.011	0.013	0.004	<.004
	1	0.025	0.019	0.014	0.011	0.011	0.011		
Cu	3	0.179	0.135	0.103	0.091	0.075	0.058		
	2	0.179	0.134	0.112	0.098	0.082	0.060	0.010	<.004
	1	0.179	0.125	0.112	0.094	0.073	0.060		
Pb	3	0.227	0.132	0.099	0.050	<0.043	<0.043		
	2	0.227	0.113	0.086	0.100	0.081	<0.043	<.04	<.04
	1	0.227	0.134	0.054	0.070	0.052	<0.043		
Zn	3	1.040	0.850	0.804	0.766	0.723	0.699		
	2	1.040	0.860	0.792	0.749	0.728	0.686	0.80	0.58
	1	1.040	0.782	0.777	0.758	0.722	0.697		
TSS	3	502	184	111	80	65	48		
	2	502	228	132	96	68	54		
	1	502	215	140	103	77	69		
NO2+NO3	3	6.24	5.56	4.72	3.64	0.449	0.085		
	2	6.24	5.54	4.67	3.44	0.446	0.088		
	1	6.24	5.19	4.50	3.62	0.460	0.085		
TKN	3	24.5	25.1	25.0	25.2	24.4	23.9		
	2	24.5	24.5	23.5	23.5	25.2	21.7		
	1	24.5	25.1	24.2	25.7	22.9	18.8		
TP	3	1.14	0.968	0.968	1.710	1.740	1.690		
	2	1.14	0.716	0.880	0.962	1.760	1.690	1.85	1.46
	1	1.14	0.870	1.360	1.710	1.690	1.710		
pH	2	5.95					6.89		

Storm No.: 87-6
Site: E
Date: June 12, 1987

Parameter	Port	Total (hrs)						Diss (hrs)	
		0	2	6	12	24	48	0	48
Cd	3	<.003	<.003	<.003	<.003	<.003	<.003		
	2	<.003	<.003	<.003	<.003	<.003	<.003	<.003	<.003
	1	<.003	<.003	<.003	<.003	<.003	<.003		
Cr	3	0.007	0.006	<.004	<.004	0.006	<.004		
	2	0.007	<.004	0.008	0.009	0.009	0.005	<.004	<.004
	1	0.007	<.004	0.008	<.004	<.004	0.007		
Cu	3	0.072	0.044	0.040	0.045	0.040	0.044		
	2	0.072	0.056	0.058	0.045	0.045	0.044	0.044	<.004
	1	0.072	0.043	0.045	0.045	0.044	0.044		
Pb	3	0.111	0.050	0.047	0.045	<.043	<.043		
	2	0.111	0.063	0.064	0.047	0.052	0.048	0.051	<.043
	1	0.111	0.061	0.047	0.050	0.046	<.043		
Zn	3	0.360	0.273	0.268	0.270	0.256	0.267		
	2	0.360	0.299	0.278	0.256	0.267	0.271	0.341	0.24
	1	0.360	0.273	0.260	0.277	0.280	0.269		
TSS	3	452	181	123	103	91	80		
	2	452	158	121	111	113	79		
	1	452	149	116	97	81	59		
NO2+NO3	3	1.510	1.390	0.671	0.419	0.283	0.113		
	2	1.510	1.370	0.703	0.404	0.271	0.101		
	1	1.510	1.430	0.689	0.420	0.243	0.043		
TKN	3	12.4	11.0	12.6	12.1	12.1	12.3		
	2	12.4	12.0	11.8	10.9	11.4	11.0		
	1	12.4	11.3	11.2	11.8	12.1	10.7		
TP	3	0.600	0.605	0.680	0.645	0.820	0.790		
	2	0.6D0	0.490	0.535	0.720	0.595	0.630	0.854	0.622
	1	0.600	0.495	0.605	0.725	0.755	0.815		
pH	2	6.11					5.17		

Appendix C. Pollutant removal efficiencies for settling column data.

Storm No.: 86-1
Site: A
Date: June 12, 1986

		% Removal				
Parameter	Port	2	6	12	24	48
Cd (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cr (ug/l)	3	66%	-	-	-	-
	2	64%	-	-	-	-
	1	61%	-	-	-	-
Cu (ug/l)	3	58%	69%	77%	78%	84%
	2	57%	69%	71%	74%	82%
	1	57%	68%	71%	77%	80%
Pb (ug/l)	3	62%	68%	78%	84%	88%
	2	62%	72%	77%	80%	85%
	1	59%	65%	77%	79%	83%
Zn (ug/l)	3	43%	51%	50%	57%	63%
	2	45%	52%	53%	53%	58%
	1	42%	51%	54%	52%	59%
TSS (mg/l)	3	73%	85%	92%	93%	97%
	2	72%	82%	86%	91%	93%
	1	69%	82%	87%	91%	94%
NO2+NO3 (mg/l)	3	0%	0%	21%	57%	98%
	2	0%	4%	31%	62%	97%
	1	0%	5%	27%	63%	98%
TKN (mg/l)	3	35%	39%	45%	40%	43%
	2	13%	21%	37%	45%	47%
	1	14%	33%	-	34%	31%
Phos. (mg/l)	3	58%	72%	79%	84%	87%
	2	59%	70%	74%	80%	85%
	1	56%	66%	73%	79%	84%
Ortho P (mg/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-

Storm No.: 86-2
Site: A
Date: June 28, 1986

Parameter	Port	% Removal 2	6	12	24	48
Cd (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cr (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cu (ug/l)	3	9%	-	-	-	-
	2	18%	45%	-	-	-
	1	0%	-	-	-	-
Pb (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Zn (ug/l)	3	18%	28%	40%	35%	42%
	2	15%	21%	39%	42%	-
	1	6%	24%	38%	-	46%
TSS (mg/l)	3	61%	82%	86%	97%	-
	2	47%	72%	84%	97%	-
	1	44%	69%	85%	95%	95%
NO2+NO3 (mg/l)	3	0%	0%	0%	0%	7%
	2	0%	0%	0%	0%	1%
	1	2%	0%	0%	0%	7%
TKN (mg/l)	3	0%	61%	47%	49%	55%
	2	20%	42%	54%	51%	-
	1	9%	35%	44%	48%	57%
Phos. (mg/l)	3	-	44%	48%	60%	67%
	2	0%	-	46%	60%	57%
	1	17%	20%	12%	65%	64%
Ortho P (mg/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-

Storm No.: 86-3
Site: B
Date: July 16, 1986

		% Removal				
Parameter	Port	2	6	12	24	48
Cd (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cr (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cu (ug/l)	3	46%	42%	59%	63%	66%
	2	42%	49%	53%	65%	63%
	1	35%	50%	58%	65%	70%
Pb (ug/l)	3	60%	72%	87%	-	-
	2	63%	72%	82%	-	-
	1	49%	71%	84%	88%	-
Zn (ug/l)	3	14%	6%	9%	13%	14%
	2	16%	8%	21%	16%	10%
	1	7%	14%	15%	20%	15%
TSS (mg/l)	3	4%	59%	73%	80%	88%
	2	0%	33%	45%	70%	83%
	1	0%	45%	50%	56%	59%
NO2+NO3 (mg/l)	3	6%	0%	0%	23%	-
	2	0%	0%	0%	17%	50%
	1	3%	4%	0%	14%	51%
TKN (mg/l)	3	19%	20%	22%	-	32%
	2	15%	16%	28%	26%	33%
	1	17%	13%	13%	27%	41%
Phos. (mg/l)	3	44%	68%	78%	79%	78%
	2	44%	62%	74%	79%	79%
	1	34%	60%	72%	76%	77%
Ortho P (mg/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-

Storm No.: 86-4
Site: B
Date: August 2, 1986

		% Removal				
Parameter	Port	2	6	12	24	48
Cd (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cr (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cu (ug/l)	3	51%	61%	66%	69%	66%
	2	42%	66%	68%	80%	85%
	1	47%	59%	64%	75%	69%
Pb (ug/l)	3	63%	76%	-	-	-
	2	61%	76%	73%	-	-
	1	55%	-	69%	-	-
Zn (ug/l)	3	30%	36%	37%	40%	42%
	2	26%	36%	38%	42%	42%
	1	26%	39%	35%	40%	43%
TSS (mg/l)	3	65%	81%	85%	89%	93%
	2	70%	81%	87%	89%	94%
	1	68%	81%	84%	93%	92%
NO2+NO3 (mg/l)	3	0%	0%	0%	0%	18%
	2	0%	0%	0%	0%	18%
	1	0%	0%	0%	24%	18%
TKN (mg/l)	3	23%	31%	32%	37%	42%
	2	22%	29%	30%	35%	44%
	1	25%	27%	32%	44%	44%
Phos. (mg/l)	3	31%	56%	-	80%	91%
	2	33%	59%	68%	78%	89%
	1	30%	61%	60%	80%	91%
Ortho P (mg/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-

Storm No.: 86-5
Site: C
Date: August 6, 1986

		% Removal				
Parameter	Port	2	6	12	24	48
Cd (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cr (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cu (ug/l)	3	24%	41%	38%	38%	48%
	2	10%	38%	41%	31%	38%
	1	24%	31%	-	34%	31%
Pb (ug/l)	3	37%	51%	-	-	-
	2	31%	35%	-	-	62%
	1	47%	49%	-	-	-
Zn (ug/l)	3	30%	29%	40%	35%	41%
	2	21%	37%	40%	37%	34%
	1	30%	37%	40%	43%	40%
TSS (mg/l)	3	58%	75%	80%	86%	96%
	2	-	-	80%	83%	-
	1	59%	72%	81%	89%	-
NO2+NO3 (mg/l)	3	0%	0%	0%	0%	17%
	2	0%	0%	0%	0%	18%
	1	17%	0%	0%	0%	19%
TKN (mg/l)	3	10%	22%	21%	22%	40%
	2	12%	28%	22%	30%	19%
	1	30%	35%	38%	-	48%
Phos. (mg/l)	3	32%	49%	62%	69%	77%
	2	31%	52%	59%	69%	77%
	1	34%	46%	54%	64%	76%
Ortho P (mg/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-

Storm No.: 86-6
Site: D
Date: August 6, 1986

Parameter	Port	% Removal 2	6	12	24	48
Cd (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cr (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cu (ug/l)	3	21%	21%	0%	29%	33%
	2	13%	42%	13%	38%	25%
	1	0%	33%	38%	42%	17%
Pb (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Zn (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
TSS (mg/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
NO2+NO3 (mg/l)	3	0%	0%	0%	0%	10%
	2	0%	0%	0%	2%	-
	1	1%	0%	0%	2%	7%
TKN (mg/l)	3	13%	17%	24%	34%	37%
	2	0%	16%	19%	15%	19%
	1	0%	8%	16%	22%	19%
Phos. (mg/l)	3	17%	26%	32%	35%	41%
	2	7%	17%	31%	38%	43%
	1	8%	21%	25%	35%	38%
Ortho P (mg/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-

Storm No.: 86-7
Site: C
Date: August 27, 1986

		% Removal				
Parameter	Port	2	6	12	24	48
Cd (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cr (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cu (ug/l)	3	26%	35%	42%	65%	55%
	2	13%	35%	-	52%	42%
	1	19%	42%	35%	48%	29%
Pb (ug/l)	3	27%	-	-	-	-
	2	42%	53%	-	-	-
	1	41%	-	-	-	-
Zn (ug/l)	3	24%	37%	33%	37%	44%
	2	24%	34%	29%	40%	38%
	1	18%	35%	37%	39%	44%
TSS (mg/l)	3	56%	83%	90%	94%	93%
	2	55%	81%	85%	89%	92%
	1	47%	76%	84%	86%	92%
NO2+NO3 (mg/l)	3	0%	0%	0%	0%	19%
	2	0%	0%	16%	5%	16%
	1	0%	0%	0%	11%	22%
TKN (mg/l)	3	17%	-	9%	13%	32%
	2	23%	5%	15%	19%	22%
	1	19%	17%	25%	20%	-
Phos. (mg/l)	3	30%	50%	52%	63%	66%
	2	22%	40%	56%	61%	69%
	1	19%	42%	52%	64%	67%
Ortho P (mg/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-

Settling Column Study
Highway Runoff

Storm No.: 87-1
Site: A
Date: May 3, 1987

Parameter	Port	% Removal 2	6	12	24	48
Cd	3	-	-	-	-	-
(mg/L)	2	-	-	-	-	-
	1	29%	46%	0%	11%	-
Cr	3	62%	51%	13%	53%	64%
(mg/L)	2	45%	33%	42%	64%	57%
	1	49%	52%	69%	49%	63%
Cu	3	37%	44%	45%	55%	63%
(mg/L)	2	32%	40%	45%	52%	62%
	1	33%	41%	44%	54%	62%
Pb	3	55%	71%	73%	-	81%
(mg/L)	2	62%	65%	77%	79%	73%
	1	47%	71%	74%	75%	79%
Zn	3	36%	42%	44%	46%	48%
(mg/L)	2	35%	42%	45%	48%	48%
	1	32%	39%	41%	45%	48%
TSS	3	71%	84%	87%	91%	94%
(mg/L)	2	68%	80%	85%	91%	92%
	1	68%	79%	82%	89%	93%
NO2+NO3	3	0%	0%	2%	25%	82%
(mg/L)	2	0%	0%	7%	31%	82%
	1	4%	1%	2%	27%	83%
TKN	3	31%	30%	31%	33%	35%
(mg/L)	2	24%	30%	31%	31%	31%
	1	4%	4%	2%	5%	5%
TP	3	82%	24%	16%	0%	27%
(mg/L)	2	58%	0%	41%	43%	0%
	1	22%	65%	0%	3%	1%

Settling Column Study
Highway Runoff

Storm No.: 87-2
Site: E
Date: May 3, 1987

		Total (hrs)				
Parameter	Port	2	6	12	24	48
Cd	3	58%	37%	16%	26%	-
(mg/L)	2	42%	52%	59%	26%	26%
	1	37%	-	58%	-	58%
Cr	3	39%	59%	63%	80%	80%
(mg/L)	2	31%	43%	59%	73%	80%
	1	27%	37%	47%	73%	69%
Cu	3	2 3%	36%	32%	42%	43%
(mg/L)	2	18%	27%	38%	40%	43%
	1	21%	25%	30%	40%	47%
Pb	3	33%	49%	52%	72%	72%
(mg/L)	2	23%	36%	47%	68%	71%
	1	19%	38%	52%	60%	68%
Zn	3	23%	40%	41%	48%	49%
(mg/L)	2	24%	35%	43%	46%	49%
	1	24%	37%	41%	44%	48%
TSS	3	48%	71%	77%	88%	89%
(mg/L)	2	43%	60%	72%	83%	89%
	1	42%	58%	69%	78%	86%
NO2+NO3	3	16%	37%	62%	62%	73%
(mg/L)	2	5%	40%	62%	66%	72%
	1	40%	36%	100%	70%	73%
TKN	3	22%	51%	4		

Storm No.: 87-1
Site: A
Date: May 3, 1987

Parameter	Port	% Removal 2	6	12	24	48
Cd	3	-	-	-	-	-
(mg/L)	2	-	-	-	-	-
	1	29%	46%	0%	11%	-
Cr	3	62%	51%	13%	53%	64%
(mg/L)	2	45%	33%	42%	64%	57%
	1	49%	52%	69%	49%	63%
Cu	3	37%	44%	45%	55%	63%
(mg/L)	2	32%	40%	45%	52%	62%
	1	33%	41%	44%	54%	62%
Pb	3	55%	71%	73%	-	81%
(mg/L)	2	62%	65%	77%	79%	73%
	1	47%	71%	74%	75%	79%
Zn	3	36%	42%	44%	46%	48%
(mg/L)	2	35%	42%	45%	48%	48%
	1	32%	39%	41%	45%	48%
TSS	3	71%	84%	87%	91%	94%
(mg/L)	2	68%	80%	85%	91%	92%
	1	68%	79%	82%	89%	93%
NO2+NO3	3	0%	0%	2%	25%	82%
(mg/L)	2	0%	0%	7%	31%	82%
	1	4%	1%	2%	27%	83%
TKN	3	31%	30%	31%	33%	35%
(mg/L)	2	24%	30%	31%	31%	31%
	1	4%	4%	2%	5%	5%
TP	3	82%	24%	16%	0%	27%
(mg/L)	2	58%	0%	41%	43%	0%
	1	22%	65%	0%	3%	1%

Storm No.: 87-2
Site: E
Date: May 3, 1987

		Total (hrs)				
Parameter	Port	2	6	12	24	48
Cd	3	58%	37%	16%	26%	-
(mg/L)	2	42%	52%	59%	26%	26%
	1	37%	-	58%	-	58%
Cr	3	39%	59%	63%	80%	80%
(mg/L)	2	31%	43%	59%	73%	80%
	1	27%	37%	47%	73%	69%
Cu	3	23%	36%	32%	42%	43%
(mg/L)	2	18%	27%	38%	40%	43%
	1	21%	25%	30%	40%	47%
Pb	3	33%	49%	52%	72%	72%
(mg/L)	2	23%	36%	47%	68%	71%
	1	19%	38%	52%	60%	68%
Zn	3	23%	40%	41%	48%	49%
(mg/L)	2	24%	35%	43%	46%	49%
	1	24%	37%	41%	44%	48%
TSS	3	48%	71%	77%	88%	89%
(mg/L)	2	43%	60%	72%	83%	89%
	1	42%	58%	69%	78%	86%
NO2+NO3	3	16%	37%	62%	62%	73%
(mg/L)	2	5%	40%	62%	66%	72%
	1	40%	36%	100%	70%	73%
TKN	3	22%	51%	41%	46%	55%
(mg/L)	2	13%	36%	29%	100%	19%
	1	13%	38%	32%	34%	100%
TP	3	0%	21%	9%	18%	32%
(mg/L)	2	10%	0%	17%	22%	38%
	1	3%	0%	0%	16%	18%

Storm No.: 87-3
Site: A
Date: May 12, 1987

Parameter	Port	Total (hrs)				
		2	6	12	24	48
Cd	3	-	-	6%	28%	47%
(mg/L)	2	12%	51%	57%	-	-
	1	0%	38%	47%	12%	15%
Cr	3	44%	62%	72%	79%	85%
(mg/L)	2	21%	62%	71%	79%	76%
	1	29%	62%	73%	83%	79%
Cu	3	17%	27%	31%	38%	50%
(mg/L)	2	14%	28%	29%	35%	40%
	1	13%	26%	31%	33%	38%
Pb	3	42%	64%	72%	79%	88%
(mg/L)	2	35%	72%	72%	81%	83%
	1	32%	64%	76%	76%	85%
Zn	3	23%	32%	33%	39%	43%
(mg/L)	2	19%	34%	35%	36%	38%
	1	20%	33%	36%	35%	39%
TSS	3	32%	79%	88%	90%	95%
(mg/L)	2	27%	47%	51%	55%	58%
	1	61%	81%	90%	94%	91%
NO2+NO3	3	0%	0%	0%	5%	19%
(mg/L)	2	0%	0%	14%	8%	28%
	1	0%	0%	2%	9%	37%
TKN	3	8%	10%	9%	13%	16%
(mg/L)	2	7%	13%	15%	14%	12%
	1	10%	17%	16%	16%	15%
TP	3	46%	43%	28%	44%	31%
(mg/L)	2	30%	30%	38%	24%	34%
	1	39%	47%	49%	46%	38%

Storm No.: 87-4
Site: F
Date: May 12, 1987

Parameter	Port	Total (hrs) 2	6	12	24	48
Cd	3	66%	-	-	-	-
(mg/L)	2	60%	51%	51%	-	37%
	1	37%	42%	45%	40%	-
Cr	3	67%	84%	87%	88%	89%
(mg/L)	2	68%	81%	88%	86%	91%
	1	68%	81%	88%	91%	89%
Cu	3	55%	62%	71%	72%	77%
(mg/L)	2	57%	65%	68%	79%	87%
	1	56%	64%	70%	80%	86%
Pb	3	72%	80%	-	-	-
(mg/L)	2	74%	79%	-	88%	-
	1	76%	81%	-	88%	-
Zn	3	53%	59%	64%	64%	63%
(mg/L)	2	56%	59%	63%	64%	65%
	1	53%	56%	63%	64%	66%
TSS	3	80%	89%	94%	95%	97%
(mg/L)	2	82%	89%	93%	93%	96%
	1	82%	90%	93%	95%	97%
NO2+NO3	3	0%	0%	11%	39%	96%
(mg/L)	2	0%	0%	49%	39%	96%
	1	0%	0%	16%	36%	97%
TKN	3	7%	10%	8%	14%	19%
(mg/L)	2	9%	15%	5%	16%	22%
	1	3%	6%	13%	12%	18%
TP	3	54%	43%	34%	9%	0%
(mg/L)	2	47%	34%	28%	16%	7%
	1	38%	49%	14%	35%	9%

Storm No.: 87-5
Site: F
Date: June 12, 1987

Parameter	Port	Total (hrs)				
		2	6	12	24	48
Cd	3	44%	0%	11%	44%	-
(mg/L)	2	44%	67%	33%	0%	11%
	1	22%	11%	56%	0%	56%
Cr	3	20%	44%	52%	68%	80%
(mg/L)	2	40%	44%	40%	56%	48%
	1	24%	44%	56%	56%	56%
Cu	3	25%	42%	49%	58%	68%
(mg/L)	2	25%	37%	45%	54%	66%
	1	30%	37%	47%	59%	66%
Pb	3	42%	56%	78%	-	-
(mg/L)	2	50%	62%	56%	64%	-
	1	41%	76%	69%	77%	-
Zn	3	18%	23%	26%	30%	33%
(mg/L)	2	17%	24%	28%	30%	34%
	1	25%	25%	27%	31%	33%
TSS	3	63%	78%	84%	87%	90%
(mg/L)	2	55%	74%	81%	86%	89%
	1	57%	72%	79%	85%	86%
NO2+NO3	3	11%	24%	42%	93%	99%
(mg/L)	2	11%	25%	45%	93%	99%
	1	17%	28%	42%	93%	99%
TKN	3	0%	100%	0%	0%	2%
(mg/L)	2	0%	4%	4%	0%	11%
	1	0%	1%	0%	7%	23%
TP	3	15%	15%	0%	0%	0%
(mg/L)	2	37%	23%	16%	0%	0%
	1	24%	0%	0%	0%	0%

Storm No.: 87-6
Site: E
Date: June 12, 1987

Parameter	Port	Total (hrs)				
		2	6	12	24	48
Cd	3	-	-	-	-	-
(mg/L)	2	-	-	-	-	-
	1	-	-	-	-	-
Cr	3	14%	-	-	14%	-
(mg/L)	2	-	0%	0%	0%	29%
	1	-	0%	-	-	0%
Cu	3	39%	44%	38%	44%	39%
(mg/L)	2	22%	19%	38%	38%	39%
	1	40%	38%	38%	39%	39%
Pb	3	55%	58%	59%	-	-
(mg/L)	2	43%	42%	58%	53%	57%
	1	45%	58%	55%	59%	-
Zn	3	24%	26%	25%	29%	26%
(mg/L)	2	17%	23%	29%	26%	25%
	1	24%	28%	23%	22%	25%
TSS	3	60%	73%	77%	80%	82%
(mg/L)	2	65%	73%	75%	75%	83%
	1	67%	74%	79%	82%	87%
NO2+NO3	3	8%	56%	72%	81%	93%
(mg/L)	2	9%	53%	73%	82%	93%
	1	5%	54%	100%	84%	97%
TKN	3	11%	0%	2%	2%	1%
(mg/L)	2	3%	5%	12%	8%	11%
	1	9%	10%	5%	2%	14%
TP	3	0%	0%	0%	0%	0%
(mg/L)	2	18%	11%	0%	1%	0%
	1	18%	0%	0%	0%	0%

Appendix D. Mean efficiencies for 1986 and 1987 settling column data.

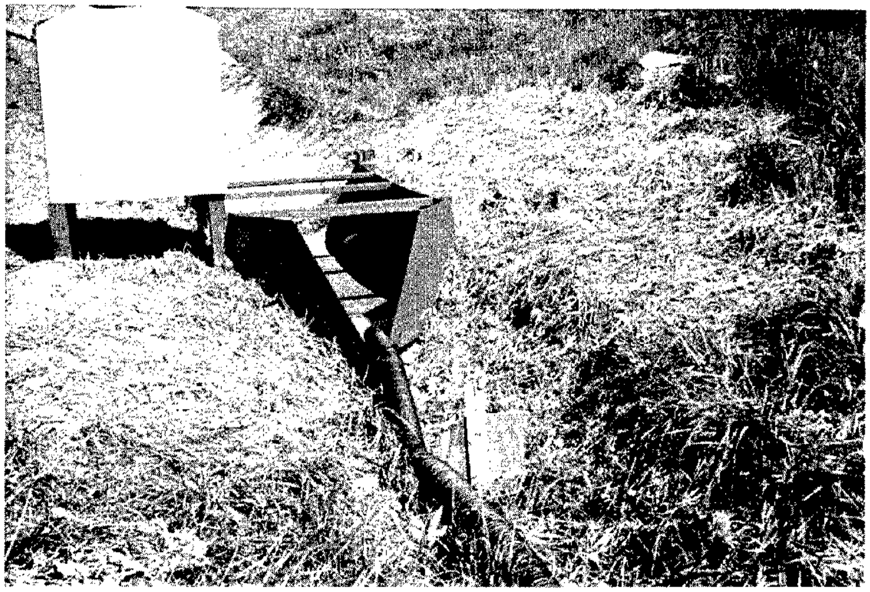
Summary of Percent Removal vs Time
1986 Storms

		% Removal				
Parameter	Port	2	6	12	24	48
Cd (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cr (ug/l)	3	-	-	-	-	-
	2	-	-	-	-	-
	1	-	-	-	-	-
Cu (ug/l)	3	33%	45%	47%	57%	59%
	2	28%	49%	49%	57%	56%
	1	26%	47%	53%	57%	49%
Pb (ug/l)	3	50%	67%	83%	84%	88%
	2	52%	62%	77%	80%	74%
	1	50%	62%	77%	83%	83%
Zn (ug/l)	3	26%	31%	35%	36%	41%
	2	25%	31%	37%	39%	36%
	1	22%	33%	36%	39%	41%
TSS (mg/l)	3	53%	77%	84%	90%	93%
	2	49%	70%	78%	87%	90%
	1	48%	71%	78%	85%	86%
NO2+NO3 (mg/l)	3	1%	0%	3%	12%	28%
	2	0%	1%	7%	12%	33%
	1	4%	1%	4%	16%	32%
TKN (mg/l)	3	17%	32%	29%	33%	40%
	2	15%	22%	29%	31%	31%
	1	16%	24%	28%	33%	40%
Phos. (mg/l)	3	35%	52%	58%	67%	72%
	2	28%	50%	58%	66%	71%
	1	28%	45%	50%	66%	71%

Summary of Percent Removal vs Time
1987 Storms

Parameter	Port	% Removal 2	6	12	24	48
Cd (ug/l)	3	56%	18%	11%	33%	47%
	2	40%	55%	50%	13%	25%
	1	25%	34%	41%	19%	43%
Cr (ug/l)	3	41%	60%	57%	64%	80%
	2	41%	44%	50%	60%	64%
	1	40%	46%	67%	70%	59%
Cu (ug/l)	3	33%	43%	44%	52%	56%
	2	28%	36%	44%	50%	56%
	1	32%	38%	43%	51%	56%
Pb (ug/l)	3	50%	63%	67%	76%	80%
	2	48%	59%	62%	72%	71%
	1	43%	65%	65%	72%	77%
Zn (ug/l)	3	30%	37%	39%	43%	44%
	2	28%	36%	40%	42%	43%
	1	29%	36%	39%	40%	43%
TSS (mg/l)	3	59%	79%	85%	89%	91%
	2	57%	71%	76%	81%	85%
	1	63%	76%	82%	87%	90%
NO2+NO3 (mg/l)	3	6%	20%	32%	51%	77%
	2	4%	20%	41%	53%	78%
	1	11%	20%	33%	53%	81%
TKN (mg/l)	3	13%	17%	15%	18%	21%
	2	9%	17%	16%	19%	18%
	1	8%	13%	11%	12%	20%
Phos. (mg/l)	3	33%	24%	14%	12%	15%
	2	33%	16%	23%	18%	13%
	1	24%	27%	10%	17%	11%

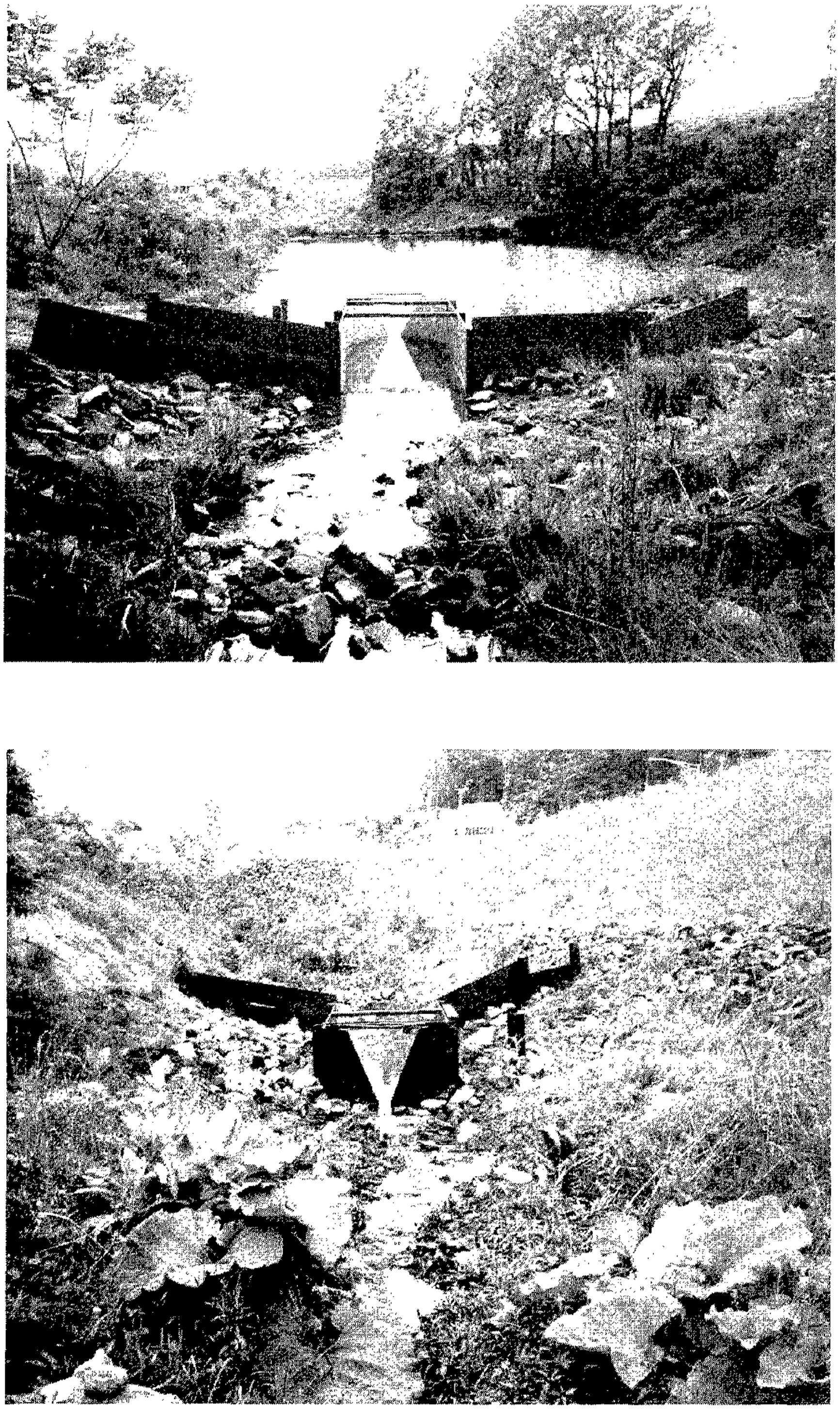
Appendix E. Photographs of field monitoring sites.



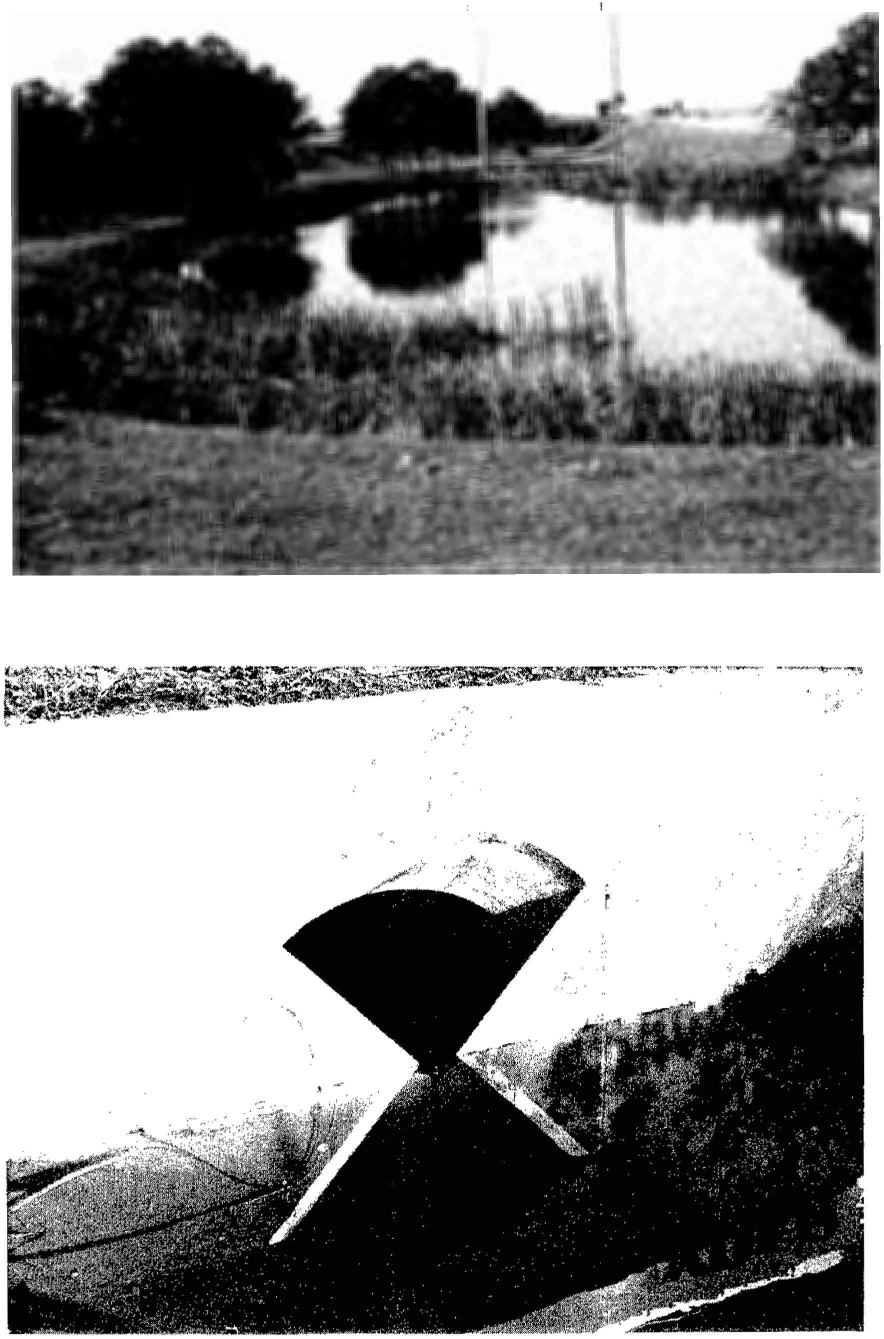
Virginia grassed channel site.

Maryland grassed channel site.

Florida grassed channel site.



Connecticut wet detention basin.



Florida wet detention basin.

Minnesota wet detention basin.

Appendix F. Stormwater monitoring data for field sites.

Field Monitoring Program: Virginia Channel Site Summary

Parameter	Storm #1 *		Storm #2		Storm #3		Storm #4		Storm #5		Storm #6		Storm #7	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Duration (min)	110	128	65	80	90	92				60				50
Total flow (gal)	46100	64100	32100	32100	16600	16600	3100	1700	9500	6800	13700	8200	4000	4000
Average flow (gps)	7.0	8.3	8.2	6.7	3.1	3.0				1.9				1.3
TSS (mg/l)	266	268	794	182	224	154	44	16	648	344	112	54	278	160
TOC (mg/l)	15.8	18.8	233.3	17.6	22.4	28.6	28.8	29	42.6	26	13.3	12.4	14.4	12.8
TKN (mg/l)	2.51	2.75	2.38	2.39	1.93	2.23	2.21	1.84	3.69	2.61	1.6	1.32	1.93	1.14
NO2+NO3 (mg/l)	0.777	0.94	1.39	1.44	0.828	1	2.26	1.81	2.12	2.2	0.834	0.801	0.45	0.482
TP (mg/l)	0.12	0.17	1.74	0.728	0.65	0.524	0.498	0.394	0.373	0.316	0.29	0.151	0.241	0.23
Cd (ug/l)	<3	3.4	<4	<4	<4	<4	5.2	5	<4	<4	<4	<4	<4	<4
Cr (ug/l)	<4	<4	22	12	13	9.3	<7	<7	<7	45	<7	<7	8.4	9
Cu (ug/l)	53	42	51	29	25	22	24	22	31	26	13	8.6	16	18
Pb (ug/l)	119	157	266	119	132	80	<51	<51	271	203	<51	<51	98	87
Zn (ug/l)	135	148	259	129	134	114	79	42	223	159	52	36	89	85
Al (ug/l) **	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ba (ug/l) **	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B (ug/l) **	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe (ug/l) **	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mg (ug/l) **	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mn (ug/l) **	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sr (ug/l) **	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ti (ug/l) **	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Runoff Event Date	6/27/87		7/12/87		7/14/87		8/16/87		8/28/87		9/5 and 9/6/87		9/8/87	
No. of Events	1		1		1		1		1		4		1	

* Storm 1 appeared to be affected by the seeding operation prior to the storm. It is believed that the channel had not yet restabilized before this storm and, therefore, had a substantial amount of erosion along the channel length.

** Parameters analyzed for only 1 runoff event.

Field Monitoring Program: Virginia Channel Site Summary (continued)

	Storm #8		Storm #9		Storm #10		Storm #11		Storm #12	
Parameter	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Duration (min)	135	125	120	135	unk	315	235	259	200	180
Total flow (gal)	24700	24700	3300	3300	23200	23200	50200	41200	12000	12000
Average flow (gps)	3.0	3.3	0.5	0.4		1.23	3.6	2.7	1.0	1.1
TSS (mg/l)	183	127	92	44	218	51	59	29	17	10
TOC (mg/l)	15.2	11.3	33.6	31	15.8	16	11.6	12.7	19.6	19.9
TKN (mg/l)	1.32	1.28	4.67	2.42	2.46	1.64	0.106	0.125	1.31	1.45
NO2+NO3 (mg/l)	0.801	0.644	0.581	0.519	0.972	1	0.142	0.154	0.962	1.02
TP (mg/l)	0.452	0.092	1.32	0.895	0.427	0.199	0.534	0.669	0.436	0.398
Cd (ug/l)	<4	<4	<4	<4	<4.0	<4.0	<4	<4	<4	<4
Cr (ug/l)	11	11	9.3	7.1	8.3	8.6	8	9	17	16
Cu (ug/l)	12	12	13	13	13	13	12	14	15	10
Pb (ug/l)	<51	52	<51	<51	70	<51	<51	<51	<51	<51
Zn (ug/l)	81	57	67	60	76	42	49	41	49	35
Al (ug/l) **	-	-	-	-	504	347	-	-	-	-
Ba (ug/l) **	-	-	-	-	28	23	-	-	-	-
B (ug/l) **	-	-	-	-	22	30	-	-	-	-
Fe (ug/l) **	-	-	-	-	624	405	-	-	-	-
Mg (ug/l) **	-	-	-	-	1180	1360	-	-	-	-
Mn (ug/l) **	-	-	-	-	124	54	-	-	-	-
Sr (ug/l) **	-	-	-	-	54	63	-	-	-	-
Ti (ug/l) **	-	-	-	-	13	9.6	-	-	-	-
Runoff Event Date	9/11/87		9/20/87		10/3/87		10/27/87		11/11/87	
No. of Events	1		1		1		1		1	

* Storm 1 appeared to be affected by the seeding operation prior to the storm. It is believed that the channel had not yet restabilized before this storm and, therefore, had a substantial amount of erosion along the channel length.

** Parameters analyzed for only 1 runoff event.

Field Monitoring Program: Maryland Channel Site Summary

	Storm #1		Storm #2		Storm #3		Storm #4	
Parameter	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Begin flow	14:33	14:38	23:30	23:35	6:30	NA	16:00	16:24
End flow	17:00	17:40	23:55	0:30	12:28	NA	16:53	17:23
Duration (min)	147	182	25	55	368	NA	53	59
Peak flow (gps)	13.5	9.8	5	10	1.67	NA	0.56	0.83
Total flow (gal)	3750	5030	3250	3540	1930	0	890	1150
Average flow (gps)	0.4	0.5	2.2	1.1	0.1	NA	0.3	0.3
TSS (mg/l)	45	127	20	19	46	0	8	22
TOC (mg/l)	14.2	14.7	11.1	12.1	23.8	0	12.5	12.6
TKN (mg/l)	1.81	1.81	0.925	1.41	1.29	0	1.62	0.928
NO2+NO3 (mg/l)	0.158	0.71	0.262	0.615	0.303	0	0.273	0.536
TP (mg/l)	0.235	0.215	0.17	0.22	0.223	0	0.087	0.147
Cd (ug/l)	36	5.4	27	<4	15	0	5.3	<4
Cr (ug/l)	<4	<4	<7	<7	<7	0	20	16
Cu (ug/l)	18	18	6.1	8.2	13	0	15	12
Pb (ug/l)	<43	<43	<51	<51	<51	0	<51	<51
Zn (ug/l)	75	35	47	30	32	0	31	48
Runoff Event Date	6/22/87		7/7/87		9/6/87		9/20/87	
No. of Events	1		1		1		1	

Field Monitoring Program: Florida Channel Site Summary

Parameter	Storm #1		Storm #2		Storm #3		Storm #4		Storm #5		Storm #6		Storm #7	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Total flow (gal)	5500	14800	2600	3900	10600	12600	4200	6400	3300	2700	8800	9300	3300	5400
TSS (mg/l)	46	22	50	7	26	1	82	1	8	8	18	<1	137	9
TOC (mg/l)	11.6	10.4	24.8	14.6	7.77	3.25	11.3	7.96	8.75	7.42	7.79	2.38	19.3	7.55
TKN (mg/l)	0.9	1	0.95	1.19	0.83	0.47	1.56	0.74	0.82	1.4	0.88	0.46	1.43	1.2
NO2+NO3 (mg/l)	0.053	<0.01	0.743	0.685	0.319	0.188	0.549	0.596	0.583	0.727	0.486	0.319	0.567	0.852
TP (mg/l)	0.122	0.131	0.428	0.831	0.173	0.229	0.218	0.248	0.178	0.422	0.336	0.264	0.174	0.156
Cd (ug/l)	8.2	6.9	17	22	5.7	9.3	9.2	9.8	3.5	17	7.9	9.8	7.3	10
Cr (ug/l)	11	9.2	5.6	6.6	<5	<5	6.6	5.6	5.7	<5	6.5	9.3	7.4	6.2
Cu (ug/l)	9.1	<4	15	10	19	18	11	6.3	13	11	6.6	11	17	11
Pb (ug/l)	160	<32	<32	<32	44	<27	29	<27	<27	<27	29	<27	<27	37
Zn (ug/l)	96	31	153	62	94	32	147	32	84	59	71	28	168	61
Runoff Event Date	3/13/88		4/11/88		5/2/88		5/13/88		5/21 - 5/22/88		5/25/88		5/27/88	
No. of Events	1		1		1		1		1		1		1	

Field Monitoring Program: Florida Channel Site Summary (continued)

Parameter	Storm #8		Storm #9		Storm #10		Storm #11		Storm #12		Storm #13	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Total flow (gal)	6300	14100	2400	2400	1600	1400	8500	19500	4700	12100	4600	16200
TSS (mg/l)	71	4	123	7	66	<1	21	4	10	3	82	4
TOC (mg/l)	26.1	10.2	22.8	3.88	21.1	4.88	5.29	4.42	5.3	7	12.7	6.29
TKN (mg/l)	0.18	1.06	0.65	0.62	1.26	0.59	0.62	0.47	0.51	0.78	0.64	0.68
NO2+NO3 (mg/l)	0.55	0.42	0.309	0.235	0.878	1.12	0.269	0.271	0.181	0.271	0.567	0.347
TP (mg/l)	0.274	0.622	0.329	0.636	0.216	0.368	0.229	0.304	0.171	0.282	0.617	0.822
Cd (ug/l)	<3	3.6	<5	<5	<5	<5	<5	<5	<5	13	<5	<5
Cr (ug/l)	<5	<5	17	4	11	4.9	<4	<4	<4	<4	9.7	<4
Cu (ug/l)	10	<6	22	5.7	14	7.3	7.9	8.7	14	7.5	16	11
Pb (ug/l)	<27	<27	108	<38	79	<38	<38	<38	<38	<38	81	<38
Zn (ug/l)	196	32	252	32	168	36	77	36	55	36	160	31
Runoff Event Date	6/30/88		7/15/88		7/18/88		7/25/88		8/4/88		10/4/88	
No. of Events	1		1		1		1		1		1	

Field Monitoring Program: Connecticut Wet Detention Basin Summary

	Storm #1		Storm #2		Storm #3		Storm #4		Storm #5		Storm #6		Storm #7	
Parameter	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Flow duration (min)	165	27	253	180	352	714			1545	1215	477		780	
Peak flow (gps)	83	29	50	22	23	11	24		76.5	83	27		83	
Total flow (gal)	187,695	67,830	130,470	55,890	70,980		131,385		587,790		137,400		456,630	
TSS (mg/l)	320	118	226	68	28	54	2	10	32	36	67	33	47	27
TOC (mg/l)	23.6	12.1	14.5	14.4	13.6	13.2	6.9	5.19	6.47	6.33	10	9.51	5.33	5.06
TKN (mg/l)	3.63	3.5	1.5	1.23	1.23	1.92	0.939	0.983	0.811	0.846	1.48	1.48	0.7	0.68
NO2+NO3 (mg/l)	1.59	1.98	1.12	1.35	2.03	1.81	1.21	1.37	1.74	1.3	1.53	1.91	0.748	0.593
TP (mg/l)	1.9	1.01	0.745	1.33	0.118	0.234	0.069	0.102	0.258	0.195	0.247	0.138	0.129	0.19
Cd (ug/l)	54	148	20	64	18	41	<4.0	11	<4.0	<4.0	<4.0	11	<4.0	5.8
Cr (ug/l)	30	24	<30	<30	<7.0	<7.0	<7.0	<7.0	11	14	9.2	8.6	<7.0	<7.0
Cu (ug/l)	30	15	14	14	15	12	19	6.3	10	9.8	12	8.9	9.9	8.4
Pb (ug/l)	<51	<51	<51	<51	<51	<51	<51	<51	<51	53	<51	<51	<51	<51
Zn (ug/l)	173	98	55	62	49	32	24	26	28	20	30	17	14	13
VSS (mg/l)											17	9	9	11
Runoff Event Date	7/25 - 7/26/87		8/3/87		8/9 - 8/10/87		8/22 - 8/29/87		9/18 - 9/19/87		9/30/87		10/4/87	
No. of Events	2		3		2		5		3		3		1	

Field Monitoring Program: Florida Wet Detention Basin Summary

Parameter	Storm #1		Storm #2		Storm #3		Storm #4		Storm #5		Storm #6		Storm #7	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Total flow (gal)	90,000	250,903	120,300	336,600	37,600	14,620	119,700	25,440	47,700	2,600	18,900		73900	75,280
TSS (mg/l)	23	26	1	21	7	8	2	6	7	7	10	8	10	8
TOC (mg/l)	6.35	7.9	5.12	8.32	16.9	9.33	4.81	6.3	10.4	9.1	14.6	8.7	14.2	6.32
TKN (mg/l)	0.56	0.71	0.5	0.44	1.35	0.82	0.77	1.03	1.3	1.06	1.35	1.21	2.33	1.27
NO2+NO3 (mg/l)	0.037	0.01	0.028	0.594	0.567	0.01	0.265	0.015	0.659	0.034	0.072	0.022	0.43	0.01
TP (mg/l)	0.212	0.116	0.142	0.2	0.525	0.175	0.198	0.091	0.272	0.066	0.252	0.096	0.326	0.1
Cd (ug/l)	12	5	8.7	5	16	5	8.1	5.3	15	4.6	13	8.4	9.8	3
Cr (ug/l)	5	8.6	11	11	8.4	5	5	5	5.7	6.8	5	5.3	5.1	5
Cu (ug/l)	4	4	6.5	6.6	14	4	20	6	15	6	13	6	22	11
Pb (ug/l)	32	32	32	32	32	32	28	27	27	27	27	27	40	27
Zn (ug/l)	51	46	42	32	66	16	52	26	63	15	68	17	90	39
Runoff Event Date	3/13/88		3/20/88		4/10 - 4/11/88		5/1/88		5/13/88		5/16/88		5/21 - 5/22/88	
No. of Events	1		1		1		1		1		1		1	

Field Monitoring Program: Florida Wet Detention Basin Summary (continued)

Parameter	Storm #8		Storm #9		Storm #10		Storm #11		Storm #12		Storm #13		Storm #14	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Total flow (gal)	7,400	19,134	50,300	37,251	87,600	60,054	20,800	30,599	52,400	88,350	177,300	286,033	2,900	230,723
TSS (mg/l)	6	9	52	22	11	11	6	16	12	22	6	21	4	15
TOC (mg/l)	13.1	7.1	10.1	13.1	16.9	19.7	6.42	14.4	11.7	11	7.21	13.3	5.5	12.2
TKN (mg/l)	1.2	1.35	3.29	2.12	2.25	1.01	0.83	2.39	1.32	2.48	1	2.74	0.75	3.07
NO2+NO3 (mg/l)	0.01	0.01	0.554	0.037	0.524	0.027	0.353	<0.01	0.649	0.037	0.195	0.095	0.226	<0.01
TP (mg/l)	0.165	0.12	0.187	0.17	0.474	0.279	0.351	0.166	1.5	0.168	0.208	0.155	0.431	0.127
Cd (ug/l)	3	3	6.3	6.4	8	20	6.6	5	5	5	5	5	5	5
Cr (ug/l)	5.7	5.2	5	5	5	5	4.2	4.6	64.3	6.4	4	4	4	4
Cu (ug/l)	12	6	20	6	6	6	15	5	12	5	11	6.3	5.2	5
Pb (ug/l)	27	27	27	27	27	27	28	28	38	38	50	38	38	38
Zn (ug/l)	38	18	77	64	51	16	51	10	47	21	50	22	45	19
Runoff Event Date	5/25/88		5/26 - 5/27/88		6/29 - 6/30/88		7/15 - 7/16/88		7/18 - 7/19/88		7/23 - 7/25/88		8/2 - 8/4/88	
No. of Events	1		1		1		1		1		1		1	

Field Monitoring Program: Florida Wet Detention Basin Summary (continued)

	Storm #15	
Parameter	Inflow	Outflow
Total flow (gal)	103,000	45,700
TSS (mg/l)	8	19
TOC (mg/l)	9.12	12.7
TKN (mg/l)	0.97	1.58
NO2+NO3 (mg/l)	0.304	0.018
TP (mg/l)	0.636	0.254
Cd (ug/l)	5	5
Cr (ug/l)	4	4
Cu (ug/l)	14	5
Pb (ug/l)	38	38
Zn (ug/l)	42	15
Runoff Event Date	10/4/88	
No. of Events	1	

Field Monitoring Program: Minnesota Wet Detention Basin Summary

	Storm #1		Storm #2		Storm #3		Storm #4 *		Storm #5		Storm #6		Storm #7	
Parameter	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Total flow (gal)	119000	171000	90000	167000	97000	156000	571000	963000	82000	94000	83000	116000	73000	137000
TSS (mg/l)	23	23	126	11	140	24	13	36	63	19	15	4	38	22
TOC (mg/l)	18	21.7	11	15.6	30.1	16.8	7.5	13.4	29.1	14.2	18.8	17.3	12.4	17.2
TKN (mg/l)	2.24	1.85	1.89	1.84	3.19	2.72	1.16	1.7	2.56	1.4	1.44	1.25	1.68	1.58
NO2+NO3 (mg/l)	0.912	0.598	0.729	0.321	0.915	0.461	0.469	0.297	1.2	0.525	0.9	0.143	0.329	0.049
TP (mg/l)	0.518	0.488	0.281	0.544	1.16	0.649	0.3	0.55	0.152	0.224	0.18	0.4	0.49	0.379
Cd (ug/l)	<5	6.2	8.6	<5	8.6	<5	<5	<5	<5	<5	<3	<3	<5	<5
Cr (ug/l)	6.1	5.5	7	7.7	10	4	5.4	<4	5.2	<4	6.1	<5	4.5	<4
Cu (ug/l)	16	9.1	17	9.9	30	13	20	15	18	15	<16	<16	12	11
Pb (ug/l)	<38	<38	<38	<38	58	38	<38	<38	<38	<38	19	<16	<38	<38
Zn (ug/l)	65	31	101	37	163	46	38	44	90	23	65	20	52	22
Runoff Event Date	7/13/88		7/20/88		8/2 - 8/3/88		8/3 - 8/4/88		8/11/88		8/22 - 8/23/88		8/27/88	
No. of Events	1		1		1		1		1		1		1	

* Inflow structure developed major leak during this storm event, therefore inflow data is not reliable. Also, neither station sampled entire storm event (data not used in any analysis).

Field Monitoring Program: Minnesota Wet Detention Basin Summary (continued)

Parameter	Storm #8		Storm #9 **		Storm #10		Storm #11		Storm #12		Storm #13	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Total flow (gal)	166000	184000	77000	133000	557000	785000	80000	103000	15000	27000	78000	119000
TSS (mg/l)	59	22	48	451	52	23	72	28	90	44	33	32
TOC (mg/l)	15.5	17.3	16.5	46.1	9.59	9.13	19.9	11.9	24.2	17.8	10.7	12.6
TKN (mg/l)	2.41	1.93	1.23	2.14	0.9	0.98	1.73	1.29	3.15	1.95	2.27	1.45
NO2+NO3 (mg/l)	0.679	0.447	0.567	0.079	0.142	0.063	0.769	0.178	1.04	<0.01	0.439	0.224
TP (mg/l)	0.173	0.28	0.209	0.287	0.118	0.133	0.55	0.342	0.975	0.468	1.06	0.628
Cd (ug/l)	<5	<5	<3	<3	<3	<3	<5	<5	4.3	<4	4	<4
Cr (ug/l)	5.1	<4	<5	11	<5	17	8.4	<4	9.2	4.9	9.8	4.7
Cu (ug/l)	14	<5	12	22	17	14	20	12	30	16	27	19
Pb (ug/l)	39	<38	<16	<16	17	<16	<38	<38	<90	<90	<90	<90
Zn (ug/l)	76	30	65	97	44	26	96	35	149	31	104	48
Runoff Event Date	9/1/88		9/19/88		9/19 - 9/20/88		9/29/88		10/18/88		10/21/88	
No. of Events	1		2		1		1		1		1	

** Beaver packed mud on outflow sample strainer and partially clogged weir (data not used in any analysis).

Appendix G. Sediment data for field sites.

Sediment Analysis - Virginia Grassed Channel

Distance From Start of Channel (ft)			Dry Weight Concentrations (mg/kg)													
	Percent Solids		Total Phos.		TKN		NO2 + NO3		Cr		Cu		Pb		Zn	
	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk
0	77.6	90.4	868	1,708	925	231	0.132	0.257	22	17	37	52	61	69	97	42
10	71.7		1,138		897		0.679		21		33		169		95	
20	71.9	79.3	993	874	951	792	0.164	0.324	28	21	85	30	211	100	234	66
30	72.9		1,249		1,025		0.130		25		33		66		92	
40	76.4	75.6	1,314	931	932	1,077	3.060	1.340	26	20	42	33	137	61	147	62
50	75.8		1,132		977		0.055		29		40		103		133	
75	75.3	78.2	902	1,499	1,156	626	0.153	1.320	25	31	41	43	113	134	84	105
100	84.0		948		871		0.167		26		35		73		90	
125	81.9	78.0	1,170	802	849	642	0.173	0.679	29	24	32	27	88	88	88	68
150	80.0		1,201		1,269		0.667		25		23		46		61	
185	77.4	80.6	714	1,112	561	664	0.220	0.339	28	21	30	31	35	38	50	53
Average:	76.8	80.4	1,057	1,154	947	672	0.509	0.710	26	22	39	36	100	82	106	66

Note: Cadmium concentrations where generally below detection ((0.30 mg/kg).

Key

Ch - grassed channel sample
Bk - background sample

Sediment Analysis - Maryland Grassed Channel

Distance From Start of Channel			Dry Weight Concentrations (mg/kg)															
	Percent Solids		Total Phos.		TKN		NO2 + NO3		Cd		Cr		Cu		Pb		Zn	
(ft)	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk
0	77.7	76.2	1,006	1,312	669	2,837	16.3	4.3	0.7	(0.3	68	66	27	16	270	64	203	163
10	74.2		914		1,365		7.2		2.0		40		42		578		357	
20	82.0	74.1	645	1,126	993	3,140	15.9	7.8	1.2	0.7	33	80	24	19	312	78	199	309
30	77.5		898		824		10.7		1.0		25		25		354		201	
40	71.9	76.2	1,157	1,242	2,736	3,635	5.1	0.4	1.7	(0.3	53	77	43	22	581	83	350	244
50	68.0		1,087		2,240		8.5		1.6		47		44		513		360	
75	84.7	75.1	1,054	1,040	689	2,530	2.8	1.9	1.2	(0.3	35	59	26	16	314	80	196	153
100	78.2		1,185		1,874		5.1		0.8		54		27		379		199	
125	78.8	79.1	1,019	1,310	1,673	2,848	4.9	0.1	1.4	(0.3	56	63	23	18	332	86	209	140
150	73.2	75.1	1,077	1,247	2,581	2,914	10.7	2.7	1.6	(0.3	60	55	31	17	508	88	281	128
175	74.2		1,407		2,907		20.2		1.3		55		28		341		212	
193	72.2		2,167		2,979		16.1		3.7		62		43		547		245	
Average:	76.1	76.0	1,135	1,213	1,794	2,984	10.3	2.9	1.5	(0.3	49	67	32	18	419	80	251	190

Key

Ch - grassed channel sample
Bk - background sample

Sediment Analysis - Florida Grassed Channel

Distance From Start of Channel (ft)	Percent Solids		Dry Weight Concentrations (mg/kg)															
			Total Phos.		TKN		NO2+NO3		Cd		Cr		Cu		Pb		Zn	
	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk	Ch	Bk
0.0	80.1	91.2	35	273	1,513	570	7.7	0.5	1.1	<0.5	18.7	4.6	25.0	3.3	208.5	59.2	370.8	25.2
10.0	85.1		779		1,640		11.8		0.6		10.9		15.3		156.3		204.5	
20.0	82.4	86.5	772	266	1,360	785	10.0	1.8	0.9	<0.5	10.0	4.0	14.6	2.9	163.8	31.2	150.5	9.8
30.0	86.4		1,920		654		8.5		0.9		13.9		13.9		133.1		170.1	
40.0	84.5	88.0	837	266	1,140	454	8.2	0.4	1.3	<0.5	11.2	3.2	11.1	1.7	137.3	35.2	124.3	14.8
50.0	87.3		488		855		6.0		<0.5		5.5		3.1		69.9		72.2	
75.0	81.0	92.1	514	302	2,110	1,000	8.2	5.4	<0.5	<0.5	4.7	2.7	3.3	2.0	60.5	41.3	35.8	23.9
100.0	79.8	86.4	1,110	317	2,260	1,080	25.1	3.7	<0.5	<0.5	10.4	3.2	9.0	2.7	139.1	45.1	106.5	54.4
125.0	72.3		2,200		3,097		13.0		1.0		22.1		13.8		207.5		148.0	
150.0	61.8	92.0	3,670	429	4,570	927	31.7	3.0	1.0	<0.5	16.2	4.0	17.8	3.3	218.4	47.8	216.8	34.8
175.0	71.9		672		2,550		13.7		<0.5		5.8		6.4		132.1		90.4	
185.0	78.5	90.6	348	297	1,050	698	5.0	3.0	<0.5	<0.5	4.2	3.1	2.9	1.9	90.4	32.0	40.8	17.7
Average:	79.3	89.5	1,112	307	1,900	788	12.4	2.5	0.6	<0.5	11.1	3.6	11.4	2.5	143.1	41.7	144.2	25.8

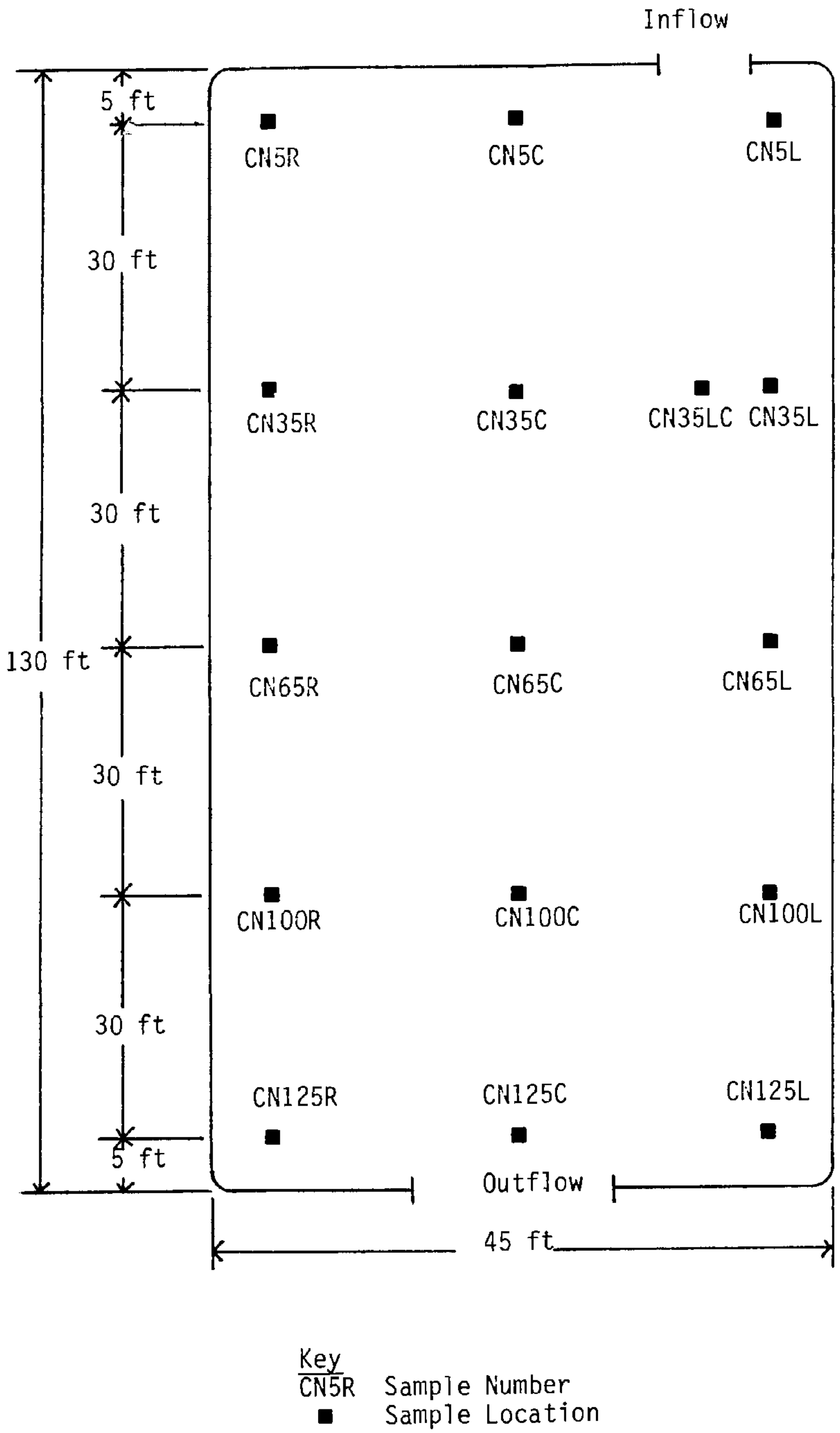
Key

Ch - grassed channel sample
Bk - background sample

Sediment Analysis - Connecticut Wet Detention Basin

Sample Location	Percent Solids	pH	Total Phos.	TKN	NO2&NO3	Cd	Cr	Cu	Pb	Zn
			Dry Weight Concentrations (mg/kg)							
CN5R	67.0	6.22	444	156	0.57	<0.40	11	18	30	36
CN5C	77.2	6.91	167	209	1.86	<0.40	10	7	13	23
CN5L	75.9	7.12	116	46	0.69	<0.40	4	7	13	20
CN35R	76.0	7.17	321	46	2.49	<0.40	11	16	36	42
CN35C	81.0	7.13	241	72	2.43	<0.40	6	8	14	20
CN35L	75.6	7.16	295	135	1.22	<0.40	8	10	21	30
CN65R	65.5	6.86	588	307	0.66	<0.40	12	17	31	46
CN65C	68.0	7.12	589	125	0.69	<0.40	15	22	53	69
CN65L	69.3	7.17	415	120	0.60	<0.40	8	12	23	30
CN100R	63.2	6.85	530	161	0.68	<0.40	15	21	41	62
CN100C	64.4	6.95	843	320	1.87	<0.40	20	23	51	67
CN100L	66.3	6.95	689	289	1.01	<0.40	15	23	62	59
CN125R	60.0	6.90	802	419	0.93	<0.40	23	30	63	83
CN125C	54.4	6.77	760	114	0.57	<0.40	26	35	74	94
CN125L	64.4	6.86	689	201	1.44	<0.40	22	31	57	71
CN35LC	62.0	6.83	500	780	0.68	<0.40	12	19	48	73
Average:	68.1		499	219	1.15	<0.40	13	19	39	52

See accompanying map for sample locations.



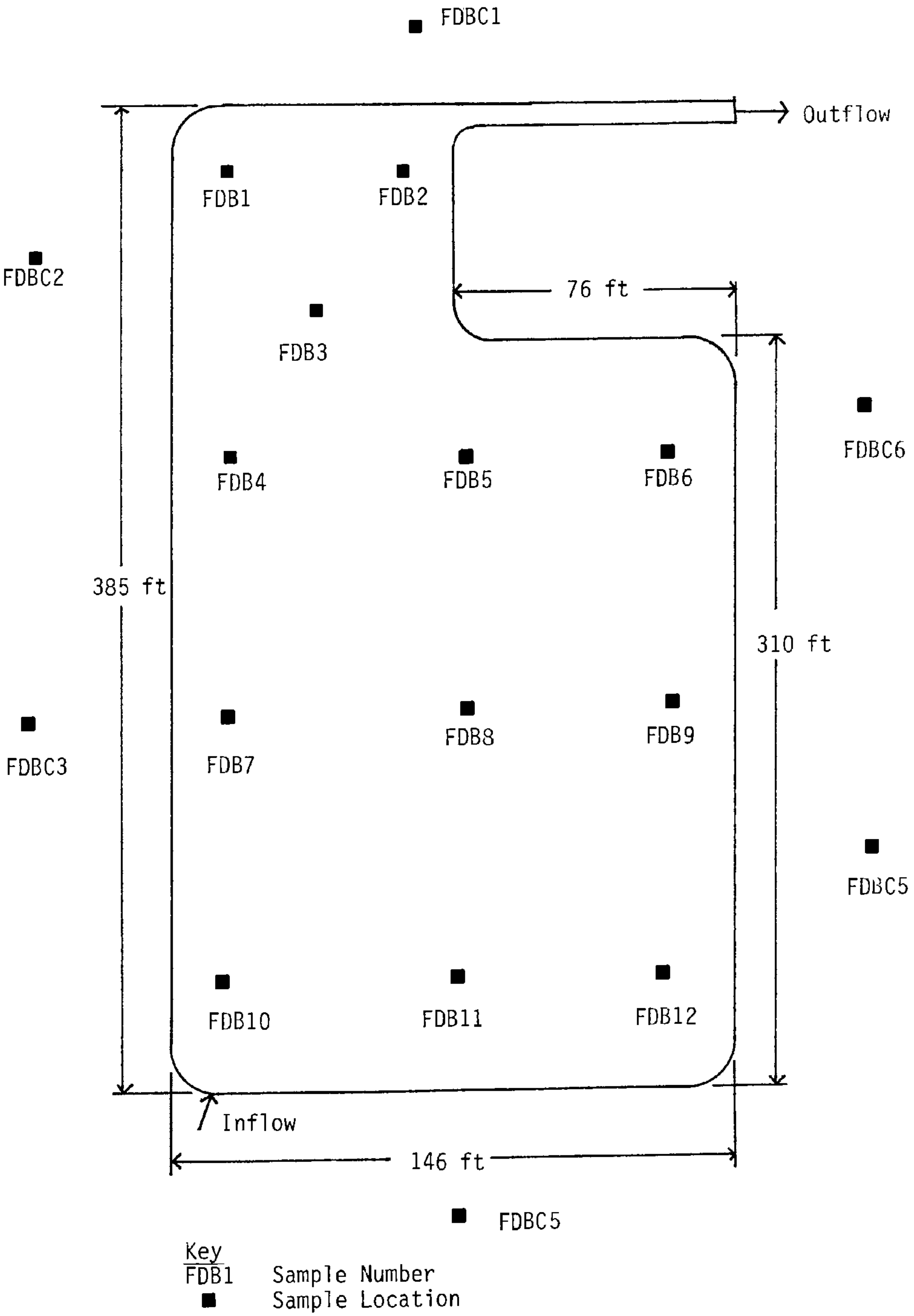
Schematic of Connecticut Basins Sediment Sample Locations.

Sediment Analysis - Florida Wet Detention Basin

Sample Location	Percent Solids	Dry Weight Concentrations (mg/kg)						
		Total Phos.	TKN	NO2+NO3	Cr	Cu	Pb	Zn
Basin Samples								
FDB1	9.2	5,660	8,830	2.4	54.6	37.1	294.8	349.3
FDB2	31.9	1,180	1,790	0.6	7.8	5.6	28.8	59.6
FDB3	49.6	2,260	1,430	0.6	17.5	5.8	48.4	38.3
FDB4	27.8	4,100	2,490	1.7	46.8	13.7	158.3	97.1
FDB5	33.7	6,260	1,060	1.3	41.5	12.5	151.3	89.0
FDB6	24.1	5,270	2,820	1.2	33.6	12.0	120.3	99.6
FDB7	56.5	2,550	810	0.9	26.5	6.7	90.3	47.8
FDB8	25.5	9,610	2,200	1.6	43.1	16.9	164.7	117.6
FDB9	65.0	2,140	892	1.1	18.5	5.2	52.3	35.4
FDB10	20.9	2,860	2,880	0.4	29.2	20.1	157.9	186.6
FDB11	48.3	2,630	1,120	0.5	33.1	10.6	153.2	76.6
FDB12	41.4	1,840	1,350	0.7	15.7	9.2	77.3	72.5
Background Samples								
FDBC1	75.4	1,210	1,220	4.7	7.4	2.7	19.9	18.6
FDBC2	86.9	1,750	456	0.8	12.7	0.9	26.5	9.8
FDBC3	89.5	1,360	181	1.1	10.1	0.0	19.0	4.2
FDBC4	88.6	1,530	513	0.9	10.4	1.5	14.7	14.7
FDBC5	84.3	565	1,300	10.4	4.4	2.4	24.9	14.2
FDBC6	82.5	776	1,300	4.4	7.5	2.5	30.3	11.8
Average Basin:	36.2	3,863	2,306	1.1	30.7	13.0	124.8	105.8
Average Background:	84.5	1,199	828	3.7	8.7	1.7	22.5	12.2

Note: Cadmium levels were all below 0.50 mg/kg detection limit.

See accompanying map for sample locations.



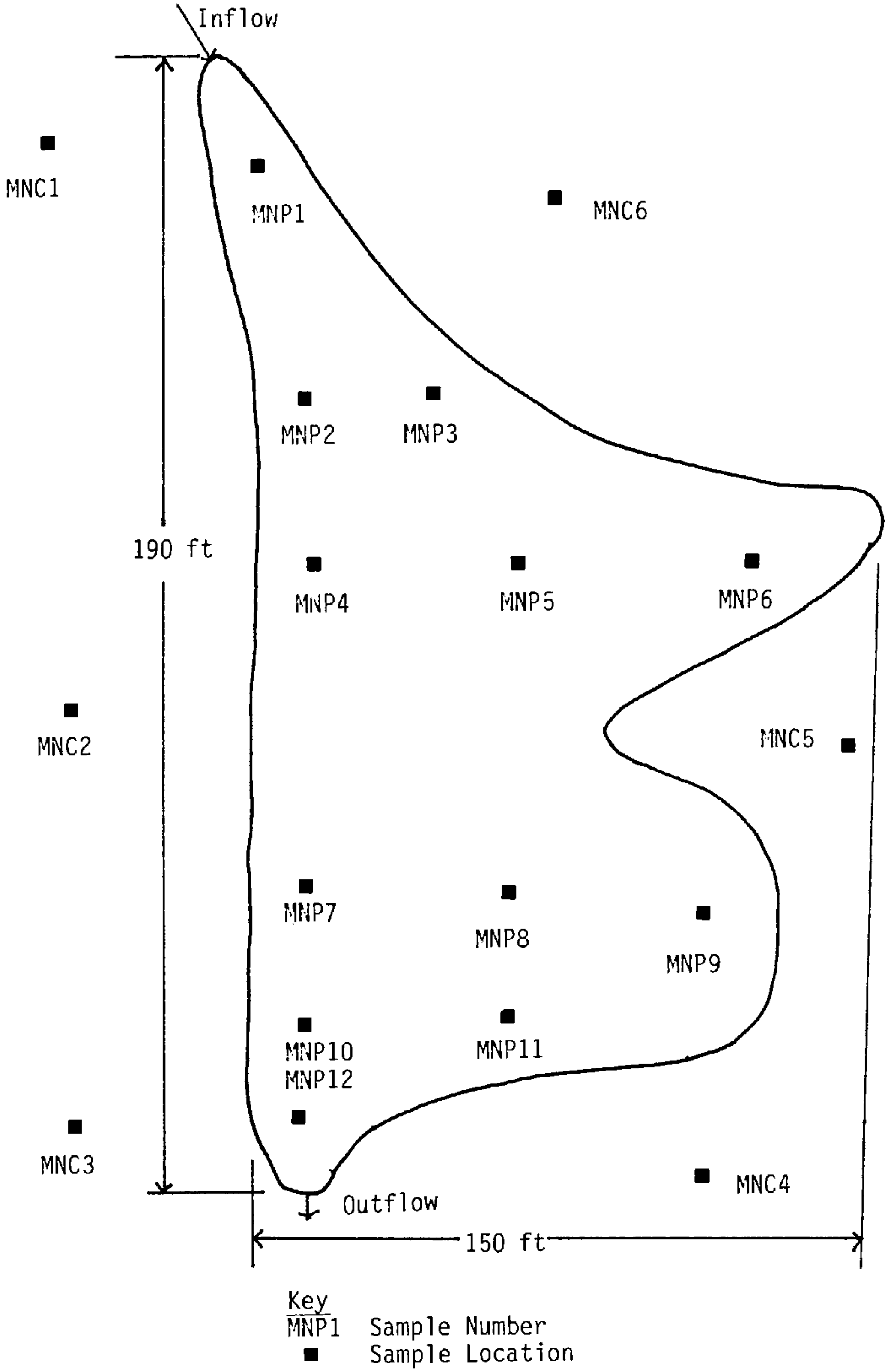
Schematic of Florida Basin Sediment Sample Locations.

Sediment Analysis - Minnesota Wet Detention Basin

Sample Location	Percent Solids	pH	Dry Weight Concentrations (mg/kg) Total Phos.	TKN	NO2+NO3	Cr	Cu	Pb	Zn
Basin Samples									
B1	88.4%	8.11	318	615	0.79	12	15	24	60
B2	56.9%	7.93	420	1,590	1.06	33	26	130	134
B3	67.9%	7.35	395	1,100	0.52	18	18	87	93
B4	36.8%	6.87	821	4,770	0.98	60	63	106	266
B5	37.4%	7.11	727	4,310	0.99	72	88	259	382
B6	40.5%	7.62	881	3,600	2.07	77	94	232	331
B7	35.8%	7.44	749	4,600	2.08	67	67	148	271
B8	40.9%	7.00	939	4,270	0.97	56	61	139	281
B9	71.2%	7.62	316	1,130	0.54	17	18	52	81
B10	37.9%	7.24	982	4,570	1.75	77	92	190	388
B11	33.4%	7.21	1,140	5,300	1.07	78	90	192	413
B12	46.5%	7.27	654	3,400	0.84	47	52	112	426
Background Samples									
C1	71.1%	7.73	632	1,840	11.40	31	28	77	127
C2	69.7%	7.60	752	2,620	6.59	30	34	66	119
C3	66.0%	7.34	859	1,620	12.80	44	42	133	176
C4	42.6%	7.57	843	-	-	52	47	56	155
C5	72.4%	8.05	548	1,280	1.52	25	21	43	90
C6	88.9%	8.63	534	1,880	7.86	15	16	31	90
Average Basin:	49.5%		695	3,271	1.14	51	57	139	261
Average Backgound:	68.5%		695	1,540	6.70	33	31	68	126

Note: Cadmium samples were all below detection limit.

See accompanying map for sample locations.



Schematic of Minnesota Basin Sediment Sample Locations.

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