Research Report
Research Project T1803, Task 07
Veg Stormwater

VEGETATED STORMWATER FACILITY MAINTENANCE

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Prepared for

Washington State Transportation Commission
Department of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

December 2000

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
WA-RD 495.1		

4. TITLE AND SUBTITLE

VEGETATED STORMWATER FACILITY MAINTENANCE

5. REPORT DATE

December 2000

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)

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8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Washington State Transportation Center (TRAC)
University of Washington, Box 354802
University District Building; 1107 NE 45th Street, Suite 535
Seattle, Washington 98105-4631

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

Agreement T1803, Task 07

12. SPONSORING AGENCY NAME AND ADDRESS

Research Office
Washington State Department of Transportation
Transportation Building, MS 47370
Olympia, Washington 98504-7370
Jim Schafer, Project Manager, 360-407-0885

13. TYPE OF REPORT AND PERIOD COVERED

Research report

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

This study had three objectives and associated work components: Component 1—assess routine highway ditch cleaning alternatives ("Service Levels") for water quality benefits; Component 2—survey biofiltration swales to evaluate conditions promoting water quality benefits; and Component 3—assess restabilization and revegetation options for use after ditch cleaning and for restoring biofiltration swale vegetation.

Component 1 tested the water quality effects of three Service Levels in freeway ditches: (1) excavated to original elevation and shape along the upstream three-quarters of the length and then sodded, (2) excavated along the entire length and straw-covered, and (3) excavated along the upstream three-quarters of the length and then straw-covered. Component 2 surveyed representative swales along central Puget Sound area highways for a variety of geometric, hydraulic and vegetative characteristics. Survey data were analyzed to develop maintenance, design, and construction guidelines. In Component 3 vegetation establishment from seed was assessed in replicate plots in a freeway ditch with the assistance of restabilization aids: (1) coconut fiber blanket, (2) straw held in place with stapled jute mat, (3) straw without covering, and (4) polyacrylamide (PAM). Cost-benefit analyses were performed in Components 1 and 3.

The overall best Service Level for water quality benefits was excavating the first three quarters and retaining vegetation in the remainder. The ditch treated in this manner was capable of reducing TSS by approximately 40 percent, total phosphorus by about 50 percent, and total and dissolved Cu and Zn each by roughly 20 to 25 percent. It is recommended as the standard procedure when cleaning ditches that discharge to a natural receiving water. Analysis of survey data showed that biofiltration swales with broad side slopes, wide bases, and total storage volumes equivalent to 3 inches of runoff from the impervious drainage area consistently supported good vegetation cover and showed few signs of damage. For assisting grass growth, straw held in place with stapled jute mat had a clear advantage in effectiveness over the alternatives and a slight economy advantage over the coconut mat.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Stormwater facility, maintenance, biofiltration swales, revegetation, water quality	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
None	None		

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EXECUTIVE SUMMARY

BACKGROUND

This summary describes a one-year study of roadside ditches and biofiltration swales along Washington State Department of Transportation (WSDOT) freeways and state highways. In the study's context, ditches were considered to be drainage courses built with water conveyance as the primary or sole objective. In contrast, biofiltration swales were considered to be channels built more recently to improve the water quality of highway runoff, usually while also conveying it, through filtering by vegetation and other mechanisms that capture and hold water pollutants. The study considered several questions pertaining mainly to the maintenance of ditches and swales. While the design of these drainage facilities has been the subject of several previous studies, the way they should be maintained has received little attention.

The WSDOT drainage system was traditionally built with ditches for water conveyance. Depending on how they are maintained (and designed and built originally), ditches have the potential to be either sinks or sources of water pollutants. If they can be well vegetated and still serve their conveyance function, ditches can provide the same type of water quality benefits as biofiltration swales. On the other hand, if they are bare and eroding, ditches add solids and the other pollutants they transport to runoff. Most critical for water quality are the way ditches are cleaned and the way they are treated following cleaning.

While the pollutant removal effectiveness of biofiltration swales has been well demonstrated, establishing and retaining the essential vegetation has sometimes proven to be a problem. The problem stems from maintenance, as well as initial design and construction. With this study's emphasis on maintenance, it also produced information that can improve design and construction. Progress in all of these areas will improve not only biofiltration swales but also ditches that retain vegetation. At this point the distinction between ditches and swales is fading in the WSDOT system, as many new drainage courses are being built large enough that conveyance is assured with full vegetation cover.

The best ways to maintain existing drainage systems and ways to build new ones to protect aquatic ecosystems are instrumental issues in WSDOT's Endangered Species Act (ESA) and Clean Water Act (CWA) responses. The prominence of these issues is due to the recognition that highway drainage systems have potential either to degrade or to improve water quality. The study's general goal was to maximize the water quality benefits that can be gained from both traditional ditches, which will exist for years to come, and biofiltration swales, which will become more and more conspicuous as new highways are built and old ones renovated.

With these observations, three needs were identified to achieve the goals of maximizing water quality benefits and minimizing detriments associated with highway ditches and swales. These needs became components of the research program:

- Component 1—Assess routine ditch cleaning alternatives ("Service Levels," SL) for water quality benefits
- Component 2—Survey biofiltration swales to evaluate conditions that promote water quality benefits
- Component 3—Assess restabilization and revegetation options for use after ditch cleaning and for restoring biofiltration swale vegetation.

COMPONENT 1—ASSESSMENT OF DITCH CLEANING SERVICE LEVELS

Work Plan

Study Design and Sites

Component 1 was performed in three phases:

- Phase 1: Identify and characterize study ditch segments. Identify and implement cleaning alternatives. Install monitoring equipment.
- Phase 2: Collect water quality data. Determine treatment costs.
- Phase 3: Analyze results to provide practical operating recommendations.

Potential study sites were screened to identify ditches with similar physical, drainage catchment, and hydraulic characteristics and to provide safe access. Those selected were as follows:

- Ditch A—Northbound I-405 at mile posts 14-15 (draining 20,000 ft^2 of highway)
- Ditch B—Northbound I-405 at mile posts 15-16 (draining 27,000 ft^2 of highway)
- Ditch C—Southbound I-405 at mile posts 15-16 (draining 140,000 ft^2 of highway).

For testing, the following Service Levels were applied to the selected ditches:

- Ditch A—Excavated to original elevation and shape along upstream three-fourths of the length
  - remaining length left intact
  - transition graded to reduce potential for pooling upstream of intact length
  - excavated portion resodded with 100 percent perennial rye in 18-inch wide rolls with no pinning, watering, or soil preparation.
- Ditch B—Excavated to original elevation and shape along entire length; ~3 inches of straw hand-applied

- Ditch C—Excavated to original elevation and shape along upstream three-fourths of the length
    - remaining length left intact
    - ~3 inches of straw hand-applied to excavated portion.

Monitoring

Continuous composite samples of the runoff entering and exiting each ditch were collected to determine total runoff volumes and relative water quality. Flow-splitter samplers were installed to collect flow-weighted composite samples at each point. The samplers consisted of an entrance section, in which flow became super-critical and spread uniformly across the channel bed, and vanes that collected a known portion of the runoff and discarded the remainder. The fractions split were determined by calibration with known flow volumes.

The collected runoff was conveyed to 64-ft^3 covered plywood tanks with disposable plastic liners. The total runoff volume produced by each monitored rainfall event was estimated by sounding the tanks and calculating volume according to the split fractions. Tank contents were mixed every 10 seconds as samples were drawn off for analysis of water quality variables. Analyses for temperature, pH, turbidity, and conductivity were performed in the field. Samples were taken to the University of Washington Department of Civil and Environmental Engineering's environmental laboratory for analysis of total suspended solids (TSS), total phosphorus (TP), and soluble reactive phosphorus (SRP). Aquatic Research, Inc., analyzed samples for total and dissolved copper (Cu) and zinc (Zn).

A formal qualification procedure was employed to decide whether data from each ditch in each rainfall event should be accepted in the data set. Rainfall data and runoff coefficients were used to estimate storm runoff volumes and determine whether sampling systems were relatively effective in collection. If so, an event was designated as qualifying for inclusion in the data set.

A variety of other data were collected in and near the ditches. Ditch dimensions and slopes were measured at five transects along their lengths. Vegetation composition, cover, and biomass were assessed in quadrats spaced along the ditches. Soil samples were collected for determination of particle size distribution and organic content. Hydraulic residence times were established by timed dye travel measurements with known flow rates. Hourly rainfall records were obtained from a nearby City of Bellevue gauge.

Data Analysis

The water quality effects of ditch Service Levels were expressed in terms of annual pollutant loading reductions between inlet and outlet. Annual pollutant loading reductions were estimated by multiplying the pollutant loading (concentration x flow volume) difference between inlet and outlet in qualifying events times the ratio of the total annual average precipitation to the cumulative precipitation in qualifying events. This computation was performed for total pollutant mass, mass per unit length of ditch per year, and mass per unit length of ditch per unit depth of rainfall. The results for total mass were then expressed as efficiencies by calculating the proportions of total annual loadings removed to total annual influent loadings.

A Service Level cost-benefit analysis was conducted with the use of three indices computed as follows:

- Relative Economy Index = [1- (Unit cost of SL - Minimum unit cost)/Unit cost of SL] x 100

  where: Unit cost of SL = Total SL cost/Length of ditch treated

Minimum cost = Lowest cost among all SLs

- Relative Effectiveness Index = [Pollutant loading reduction efficiency/Highest efficiency among all SLs] x 100
- Relative Cost-Effectiveness Index = [1-(Cost-to-benefit ratio – Minimum cost-to-benefit ratio)/Cost-to-benefit ratio] x 100

where: Cost-to-benefit ratio = Unit cost/ Pollutant loading reduction efficiency

Minimum cost-to-benefit ratio = Lowest cost-to-benefit ratio among all SLs

A simple mathematical model was developed to approximate the ditch cleaning interval necessary to keep accumulated sediments below a selected depth. The model estimates annual depth of sediment buildup based on inlet TSS loading from measurements, TSS removal in ditch from measurements, and road and ditch geometries.

Results

General Results

The monitoring program collected runoff from 18 storms with ≥ 0.2 inches of rain between January 9 and May 24, 2000. Of these events, seven qualified for inclusion in the data set from Ditch A, four from Ditch B, and ten from Ditch C.

Mean hydraulic residence times, normalized to common length, for the three ditches were as follows:

- Ditch A (75 percent excavated, resodded)—4.68 minutes
- Ditch B (100 percent excavated)—2.72 minutes
- Ditch C (75 percent excavated)—4.87 minutes.

Pollutant reduction is generally a function of how long flow stays in contact with vegetation and the soil surface. Therefore, Ditches A and C would be expected to decrease pollutants more than Ditch B.

Pollutant Loading Reductions

Table ES-1 summarizes pollutant loading reductions in terms of efficiency of total mass reduction and mass removal per unit length per year. All ditches had negative reductions of soluble reactive phosphorus, meaning that more of this pollutant exited than entered. Of the six remaining pollutants reported, Ditch C (75 percent excavated) exhibited the highest efficiencies in three cases and the highest unit length removals in all six; it had the lowest efficiency in one instance. Ditch A (75 percent excavated and resodded) had two of the highest efficiencies but no instances of leading in unit length removals; it was lowest in efficiency in one case and lowest in unit length removal in three. Ditch B (100 percent excavated) had the lowest efficiency in three of six cases and the lowest unit length removal in two; it registered highest in only one efficiency.

The overall best Service Level for water quality benefits was excavating the first three-fourths and retaining vegetation in the remainder. The ditch treated in this manner was capable of reducing TSS by approximately 40 percent, total phosphorus by about 50 percent, and total and dissolved Cu and Zn each by roughly 20 to 25 percent. Per foot of total length, this ditch could capture more than 1.5 kg of TSS each year, about 5 g of TP, 1 g of total Zn, 0.5 g of dissolved Zn, and a lesser amount of Cu. This ditch, and the others tested, released more soluble reactive phosphorus than entered.

Table ES-1. Summary of Pollutant Loading Reductions in I-405 Ditches with Three Different Maintenance Service Levels

MEASURE OF LOADING REDUCTION	UNIT	DITCH A[a]	DITCH B[a]	DITCH C[a]
TSS removal efficiency	g/g	0.495	0.128	0.401
TSS unit length annual removal	g/ft-yr	235	147	1671
Total Zn removal efficiency	g/g	0.224	0.225	0.237
Total Zn unit length annual removal	mg/ft-yr	153	307	1012
Dissolved Zn removal efficiency	g/g	0.239	0.257	0.222
Dissolved Zn unit length annual removal	mg/ft-yr	70	132	520
Total Cu removal efficiency	g/g	0.204	0.216	0.233
Total Cu unit length annual removal	mg/ft-yr	36	49	184
Dissolved Cu removal efficiency	g/g	0.252	0.065	0.177
Dissolved Cu unit length annual removal	mg/ft-yr	23	5	75
TP removal efficiency	g/g	0.216	0.175	0.515
TP unit length annual removal	mg/ft-yr	265	400	5162
SRP removal efficiency	g/g	-0.545	-0.051	-0.088
SRP unit length annual removal	mg/ft-yr	-57	-5	-28

[a] A—75 percent excavated, resodded, B—100 percent excavated, C—75 percent excavated; heavier shading—highest of three values, lighter shading—lowest of three values.

Cost-Benefit Analysis

Table ES-2 summarizes the results of the cost-benefit analysis in terms of the three indices defined previously. Ditch C (75 percent excavated) had the lowest per-foot cost for the Service Level and, hence, the highest relative economy index. Ditch A (75 percent excavated and resodded) ranked lowest in relative economy. In terms of relative effectiveness results mirrored the pollutant loading reductions described above, with Ditch C ranking highest and B

(100 percent excavated) lowest overall. Ditch C exhibited clear superiority to the other options in relative cost effectiveness.

Table ES-2. Summary of Cost-Benefit Analysis for I-405 Ditches with Three Different Maintenance Service Levels

COST-BENEFIT ANALYSIS METRICS:	ROADSIDE DITCH SITE[a]		
	A	B	C
WSDOT Cost for treatments	$1,141	$697	$587
Length (ft)	154	114	128
Per ft cost	$7.41	$6.12	$4.59
Relative Economy Index	62	75	100
Fraction TSS Reduction	0.50	0.13	0.40
Relative TSS Effectiveness Index	100	26	81
Fraction TZn Reduction	0.22	0.22	0.24
Relative TZn Effectiveness Index	92	92	100
Fraction TP Reduction	0.22	0.18	0.52
Relative TP Effectiveness Index	42	35	100
Relative Cost Effectiveness Index—TSS	77	24	100
Relative Cost Effectiveness Index—TZn	57	68	100
Relative Cost Effectiveness Index—TP	26	26	100

[a] A—75 percent excavated, resodded, B—100 percent excavated, C—75 percent excavated; heavier shading—highest of three values, lighter shading—lowest of three values.

Conclusions and Recommendations

Retaining an intact vegetated section in the last quarter of the ditch is clearly the most effective, least costly, and most cost-effective strategy among those tested. This strategy should be implemented for maintaining WSDOT ditches that discharge to natural receiving waters. After the cleaned section revegetates, the last quarter can then be maintained. Vegetation should be restored there as quickly as possible, using techniques demonstrated in the third component of the research. Cleaning should be scheduled to coincide with reduced storm runoff but sufficient moisture to support revegetation (April through June and October are best).

Model calculations showed that the cleaning interval necessary to prevent more than 4 inches of sediment accumulation is about 2 to 3 years. The interval can be increased by encouraging sedimentation upstream or reduced by an undersized ditch or excessive sediment loads.

High energy inflows to ditches should be dissipated by rough inlet sections, stilling basins, or flow spreaders. Check dams or "pocket ponds" should be installed to trap sediments in cleaned sections, especially in ditches with much slope (> 2.5 percent).

COMPONENT 2—BIOFILTRATION SWALE SURVEY

Work Plan

Study Design and Sites

Component 2 was performed in three phases:

- Phase 1: Develop survey and data management protocol. Identify representative bioswales to survey.
- Phase 2: Interview maintenance personnel. Conduct field survey. Develop bioswale metrics.
- Phase 3: Define Service Levels and Performance Measures for a bioswale Maintenance Accountability Process (MAP) module. Provide specific recommendations on all Department activities pertinent to bioswales.

Candidate biofiltration swales were screened and the study sites were selected to offer a range of conditions (geometry, drainage catchment, vegetation, hydraulic) representative of WSDOT's Northwest Region Maintenance Areas 3, 4, and 5 (central Puget Sound area). Twenty swales were selected, evenly split between freeways and arterial highways (two were later found to be off WSDOT property, although in the inventory).

Survey Observations and Measurements

The work began with development of a survey procedure and related data sheets. These instruments were used on site visits during the summer of 2000. One set of observations and measurements involved swale attributes that do not change over time, unless the swale is modified, and need be performed only once. This set included drainage catchment area and description, means of flow introduction, dimensions and slopes at transects spaced along the length, location with geopositioning satellite (GPS) equipment, and slope measurement with automatic level and rod. A second set of observations involved changeable features and would have to be repeated in any future surveys. This set included weather; photography of key features; hydraulic conditions; presence of bare areas and other problems; and vegetation type, cover, height, and condition at transects.

Maintenance Areas 3, 4, and 5 supervisors were interviewed according to a questionnaire developed to obtain their experience with and opinions about biofiltration swales and their maintenance. Questions involved swale maintenance priorities and problems; maintenance activities, frequencies, and costs; and recommendations for improvement.

Data Analysis

Survey data were analyzed to develop maintenance (and design and construction) guidelines for biofiltration swales. The analysis entailed the following:

- qualitative 1-5 rankings of swales based on current conditions—sufficiency of cross-sectional area for flow conditions, side slope, plant growth substrate, plant suitability, vegetation maintenance, effects of litter

- analysis of survey data to identify performance measures consistently associated with rankings
- screening of performance measures and guidelines in terms of implementation feasibility and relevance to water quality and conveyance objectives
- spreadsheet analysis of swale size in relation to runoff production potential, using SCS TR-55 hydrologic modeling methods.

Guidelines were specifically formulated to contribute to the *Maintenance Manual for Water Quality and Habitat Protection*, which was developed as part of WSDOT's ESA response. In addition, the results were applied to formulate a descriptive module compatible with the Service Level hierarchy scheme in the WSDOT Maintenance Accountability Process (MAP), using identified performance measures, photographs, and descriptions.

Results and Recommendations

Field Survey Data Analysis

Qualitative rankings and identification of performance measures showed that swales with broad side slopes, wide bases, and potential treatment volumes (PTVs) equivalent to 3 inches of runoff from the impervious drainage area consistently supported good vegetation cover and showed few signs of damage (e.g., side rilling, channel incision, toe slumping, vegetation washout). Poor vegetation cover appeared to be mainly the result of poor soil preparation and detrimental maintenance activities. The eight "best" swales in the survey had several common characteristics:

- longitudinal slopes of less than 2.8 percent
- gradual side slopes and/or wide beds
- generally no point inlets

- nearly uniform distribution of stormwater to the swale bed via sheet flow off the road surface that then passed through a low gradient (<30 percent) filter strip before flowing down the swale bank.

Spreadsheet analysis showed that many swales had PTVs that were two or more times the water quality design event (runoff from 6-month, 24-hour rainfall) and significant fractions of the 100-year, 24-hour rainfall runoff volume, thus affording water quantity as well as quality control.

Maintenance Supervisor Interview Results

Nine specific recommendations were drawn from the maintenance supervisor interviews. Various WSDOT offices were identified to implement these recommendations. In brief, they are as follows (with suggested implementing office[s]):

- Expand the *Inspection and Maintenance of Permanent Stormwater Facilities* section in the Stormwater Site Plan (SSP) into a detailed operation and maintenance (O&M) manual template (Northwest Region Environmental).
- Use the O&M manual template to prepare a *Permanent Stormwater Facilities O&M Manual* for each project (Project Design Office, Maintenance Area Office).
- Design permanent stormwater management facilities with maintenance access as a high priority (Project Design Office, Maintenance Area Office).
- Create as-built plans for permanent stormwater management facilities after project construction (Project Construction Office).
- Formally transfer responsibility for maintenance of permanent stormwater management facilities from the Project Construction Office to the Maintenance Area Office after

project construction (Project Design Office, Project Construction Office, Maintenance Area Office, Northwest Region Environmental).

- Develop a geographic information system (GIS) database of permanent stormwater management facilities (Northwest Region Environmental).
- Develop biofiltration swale maintenance routines and schedules (Maintenance Area Office).
- Include biofiltration swale maintenance history as a GIS layer (Maintenance Area Office, Northwest Region Environmental).
- Develop a funding package for environmental maintenance (Environmental Affairs Office)..

Maintenance, Design, and Installation Guidelines

Many maintenance, design, and installation guidelines came from analysis of the survey measurements and observations. The report presents these guidelines in tables that list the issues (present problems) and recommendations to address each problem. Maintenance guidelines address such issues as follows (with recommended intervention):

- non-uniform distribution of flow along shoulder edge and thus to biofiltration swale (regrade edge)
- steep slope (check dams)
- mowing equipment damage (reconfigure to accommodate mowing)
- solids accumulation (source controls)
- herbicide damage (alter spraying patterns or eliminate)
- poor vegetation (remedial site preparation and reseeding with herbaceous mix)
- non-stormwater flows (investigate source and eliminate)

- shading (remove growth shading herbaceous plants).

Design and installation issues (with recommended intervention) include the following:

- mowing equipment damage (configure to accommodate mowing)
- side slope failure (do not exceed 3:1 horizontal:vertical)
- excessive velocity and erosion (specific quantitative guidelines on geometry and slope)
- standing water (careful grading)
- undesirable vegetation (proper site preparation and mix of plants appropriate for conditions).

In addition to these guidelines, the analysis produced some programmatic maintenance guidelines and a proposed Maintenance Accountability Process (MAP) module. The MAP module is compatible with the overall set of modules used by WSDOT, including five Service Level categories and, associated with each service action, a description of appearance and functionality, as well as photographs of representative sites.

COMPONENT 3—ASSESSMENT OF RESTABILIZATION AND REVEGETATION OPTIONS

Work Plan

Study Design and Site

Component 3 was performed in three phases:

- Phase 1: Identify study ditch and measures to compare performance. Select and install stabilization technologies.
- Phase 2: Monitor study plots. Determine treatment costs.
- Phase 3: Analyze results and recommend specific ditch stabilization treatment(s).

The site of the work was a 350-ft ditch draining eastbound I-90 near milepost 10. Thirteen 3-ft x 10-ft plots (long axis perpendicular to flow) were established along the ditch centerline, each separated by 16 feet of undisturbed ditch. Each plot was cleared of all vegetation and soil containing viable seed (typically, to a depth of 4 inches below original grade). Then, the original grade was reestablished. Each plot was seeded in March 2000 with the standard Western Washington WSDOT seed mix (10 percent *Agrostis tenuis*, 40 percent *Festuca rubra*, 40 percent *Lolium perenne*, and 10 percent pre-inoculated *Trifolium repens*) at a rate of 3/8 oz per 10 ft^2.

Plots were randomly allocated to the following stabilization treatments:

- 100 percent coconut fiber (Coir) blanket (Greenfix #CFO72RR)—3 plots
- ANTI-WASH /GEOJUTE over 1.5-in-thick straw—3 plots
- 1/3 gallon of anionic polyacrylamide (PAM) mixture (at 4/5 oz per 100 gallon water concentration)—3 plots
- controls (1.5-in-thick straw, common WSDOT post-ditching treatment)—4 plots.

Assessment Methods

An initial grass blade count was performed six weeks after seeding. Blades >½ inch high were counted within two randomly placed 0.673-ft^2 sampling grids. Total and individual vegetation species cover was assessed with the Daubenmire cover class system in both early June and mid-July 2000. Vegetation biomass was measured on the first occasion.

Data Analysis

A relative growth measure (RGM) was defined to integrate the various quantitative expressions of plant establishment made on three occasions and to allow objective comparisons:

RGM = Σ [(April 24th plot stem count/April 24th mean plot stem count) + (June 9th plot cover/June 9th mean plot cover) + (July 18th plot cover/July 18th mean plot cover) + (June 9th plot biomass/June 9th mean plot biomass)]

A cost-benefit analysis was performed in a manner similar to that outlined for Component 1. In this case the RGM was the basis of the Relative Effectiveness Index, while the Relative Economy Index was based on per-unit length costs for the restabilization treatments.

Results and Recommendations

Relative Growth Measures for the various treatments were

- jute mat with straw—2.87
- coconut fiber mat—2.14
- PAM—1.95
- control—1.29

Table ES-3 summarizes the cost-benefit analysis. The straw held in place with stapled jute mat had a clear advantage in effectiveness over the alternatives and a slight economy advantage over the coconut mat. Straw with no means of attachment was the least effective in promoting vegetation development. PAM was essentially equal to jute mat/straw in relative cost effectiveness, owing mainly to its low cost.

The jute mat/straw combination is most highly recommended for assisting vegetation establishment in highway ditches after cleaning and in biofiltration swales when constructed or renovated. This treatment should be applied where a bare ditch would otherwise discharge directly to a natural receiving water. One instance would be where the principal recommendation arising from Component 1 of this project is applied. After the first three-fourths of the ditch revegetates following cleaning and the remainder is cleaned, that portion should be reseeded and stabilized with spread straw covered by stapled jute mat.

PAM is less highly recommended than jute mat/straw but could be used if the exposure is short-term (e.g., more work will be done after a short interval) or there is some mitigating feature between the bare ditch and the receiving water (e.g., a relatively long run of another vegetated drainage course with at least partial vegetation). There was no advantage seen for coconut mat in this application, and its use is not warranted because of cost. Straw without jute mat attachment should not be used in ditches, where the concentrated flow quickly moves it and exposes the soil. Use of straw alone is now a common practice in WSDOT ditch maintenance operations and should be abandoned.

Table ES-3. Summary of Cost-Benefit Analysis of Four Ditch Restabilization Treatments

COST-BENEFIT ANALYSIS MEASURE	TREATMENT [a]			
	JUTE MAT/ STRAW	STRAW	COCONUT MAT	PAM
WSDOT Cost for treatments	$880.59	$641.35	$928.59	$602.19
Length (ft)	100	100	100	100
Per ft cost	$8.81	$6.41	$9.29	$6.02
Relative Economy Index	68	94	65	100
Relative Growth Measure	2.87	1.29	2.14	1.95
Relative Effectiveness Index	100	45	75	70
Relative Cost-Effectiveness Index	100	62	71	99

[a] Heavier shading—highest of four values, lighter shading—lowest of four values.

1 INTRODUCTION

1.1 STATEMENT OF RESEARCH PROBLEM

The Washington State Department of Transportation (WSDOT) has developed a storm water management plan in accordance with the Washington State Department of Ecology's discharge standards for permitted water dischargers established under the National Pollutant Discharge Elimination System (NPDES). In addition, most WSDOT construction and maintenance activities within storm water control facilities will need to follow regulations approved by the National Marine Fisheries Service under section 4(d) and section 9 rules of the Endangered Species Act (ESA) related to threatened and endangered salmonids. Therefore, WSDOT must develop and implement an "adequate and active program for the conservation" of these species. Pursuant to this objective, the *Maintenance Manual for Water Quality and Habitat Protection* was developed in early 2000 to outline an implementation plan for specific actions and organizational processes by WSDOT maintenance groups.

In light of the renewed emphasis on preserving aquatic habitat in the central Puget Sound region, as well as WSDOT's ongoing efforts to reduce downstream pollutant loading from existing storm water management facilities, the current study was funded between July 1999 and November 2000. The primary goal of the research was to develop improved maintenance practices for storm water conveyance facilities that would minimize the water quality impacts of highway runoff on receiving bodies. The study's explicit objectives were twofold:

1) Identify the best management practices regarding the maintenance and design of vegetated roadside ditches and biofiltration swales.

2) Identify the best technologies to stabilize and re-vegetate recently excavated roadside drainage channels.

The exact scope of WSDOT maintenance activities that will be modified to meet ESA rules is dependent on budgetary constraints, administrative decisions, and the findings of other WSDOT research projects. Therefore, the final products of this project were developed to provide guidance to WSDOT personnel at a variety of levels. Recommendations address issues from site-specific maintenance activities to department-wide management of storm water facilities.

1.2 RESEARCH COMPONENTS AND TASKS

The goal of this project is to provide specific recommendations for maintaining vegetated storm water facilities to enhance water quality. The research focused on roadside ditches and biofiltration swales (bioswales) maintained by WSDOT—Northwest Region personnel. The work comprised three components defined by sequenced phases:

Component One: Pollutant Control Alternatives Following Routine Drainage Ditch Excavation

Phase One: Identify and characterize study ditch segments. Identify and implement treatment alternatives. Install on-site monitoring equipment.

Phase Two: Collect water quality data. Determine costs associated with each treatment.

Phase Three: Analyze results and provide practical operational recommendations.

Component Two: Survey of Biofiltration Swales

Phase One: Develop field survey and data management protocols. Identify representative bioswales for survey.

Phase Two: Interview maintenance personnel. Conduct field survey. Develop metrics that describe the functionality of a bioswale as a water quality management practice.

Phase Three: Define service levels and performance measures for a new bioswale maintenance accountability process (MAP) module. Provide specific recommendations regarding WSDOT activities that affect bioswales.

Component Three: Re-stabilization Alternatives Following Routine Drainage Ditch Excavation

Phase One: Identify and characterize study ditch. Develop comparative metrics for treatment evaluations. Select and install soil stabilization technologies.

Phase Two: Conduct monthly site visits to evaluate the vegetation at study plots. Determine costs associated with each plot treatment.

Phase Three: Analyze results and recommend specific ditch stabilization treatment(s).

1.3 RESEARCH HYPOTHESES

The hypotheses posed by this research project are as follows:

1) In comparison with spreading straw mulch, providing some level of live vegetation cover to a recently excavated roadside drainage ditch is a cost-effective method of reducing downstream sediment loading

2) Relative to unprotected straw mulch or polyacrylamide treatments, erosion control matting is a cost-effective method of establishing seeded grasses in a recently excavated roadside drainage ditch.

3) Easy to implement maintenance practices can improve the water quality function of existing WSDOT bioswales.

2 REVIEW OF PREVIOUS WORK

2.1 OPEN CHANNEL CONCEPTS FOR VEGETATED STORM WATER FACILITIES

2.1.1 Flow and Resistance Relationships

A full discussion of the fundamental concepts of open channel flow can be found elsewhere (Chanson 1999; Henderson 1966). For the reader's convenience the concepts underlying current design procedures for storm water drainage channels are presented below.

Sloped vegetated storm water facilities are generally designed as prismatic channels that convey storm flow through partially submerged vegetation. The nature and magnitude of the interactions of the fluid flow with the channel boundary are essential to describing the transport of sediment, as well as the characteristics of local bed forms. Flow velocity, flow resistance, and stream energy are parameters that are often used to describe these interactions. To relate flow velocity and resistance, several equations have been developed, of which the Manning equation (Equation 2.1) is widely used in open channel applications and the Darcy-Weisbach equation (Equation 2.2) is considered the most theoretically sound (Knighton 1998). The coefficients in these equations are empirical and can be manipulated to account for grain and bed form roughness. Mean bed shear stress is calculated with Equation 2.3. These equations typically assume steady, uniform, fully turbulent flow conditions.

(U.S. Customary units): $U = 1.49 \times R_h^{0.667} \times S_f^{0.5} / n$ (Eqn 2.1)

$$U = \sqrt{(8 \times g / F)} \times \sqrt{(R_h \times S_f)} \qquad \text{(Eqn 2.2)}$$

$$\tau_o = \gamma \times R_h \times S_f \qquad \text{(Eqn 2.3)}$$

where U = mean downstream velocity

R_h = hydraulic radius

n = Manning's roughness coefficient

F = Darcy-Weisbach roughness coefficient

τ_o = mean bed shear stress

S_f = friction slope

γ = specific weight of water

Chen (1976) pointed out that flow resistance coefficients for densely vegetated channels may be several orders of magnitude higher than those for open channel situations where bed resistance is solely responsible for friction losses. From work on overland flow through Kentucky Blue Grass, Chen refined Horton's original equation for friction slope (Equation 2.4).

$$Q/W = 28.5 \times 10^8 \times d_{max}^{3.75} \times S_f^{0.5} \qquad \text{(Eqn 2.4)}$$

where Q = flow rate

W = width of flow

d_{max} = maximum depth of flow in channel

For low gradient (<0.1 percent) overland flow situations, Kadlec (1990) argued that, in many vegetated flow situations, the assumption of turbulent conditions is not accurate. He presented a more complete formulation than the Manning equation to account for laminar and transition flows, which are possible in low-gradient, well-vegetated facilities (Equation 2.5).

$$S_f = (3 \times U \times \nu)/(g \times d^2) + (n^2 \times U^2)/d^{1.33} \qquad \text{(Eqn 2.5)}$$

where ν = kinetic viscosity

A report on experiments by Wu et al. (1999) presents a full description of the variation in the roughness coefficient and mean flow velocity due to changes in flow depth. Confirming earlier modeling efforts by Barfield and Kao (1977), the researchers found that roughness coefficients do not vary with bed slope in unsubmerged conditions and are very weakly correlated under submerged conditions. The research found that for unsubmerged conditions the roughness coefficient *decreases* with increasing flow depth. Wu's functional relationship between flow depth, d, and roughness, n, for unsubmerged grass is given by Equation 2.6.

$$n_2 = n_1 \times (d_2/d_1)^{-1.970} \qquad \text{(Eqn 2.6)}$$

where n_1 can be approximated by $[d_1^{0.667}/\sqrt{(2 \times g)}] \times \sqrt{[(3.44 \times 10^6) \times S^{0.5} / \mathbb{R}_{flow}^{1.45}]}$

2.1.2 Dimensionless Numbers in Open Channel Flow

To characterize the inertial forces of the flow, several dimensionless numbers can be calculated. The relative magnitude of inertial to viscous forces within the overall flow field is described by the flow Reynold's number, $\mathbb{R}_{flow}$ (Equation 2.7). A bed Reynold's number ($\mathbb{R}_{bed}$) characterizes the level of turbulence occurring along a particular boundary of an open channel (Equation 2.8).

$$\mathbb{R}_{flow} = U \times (4 \times R_h)/\nu \quad \text{turbulent flow regime when } \mathbb{R}_{flow} > 3000 \qquad \text{(Eqn 2.7)}$$

$$\mathbb{R}_{bed} = u_* \times d_s/\nu \quad \text{"fully rough" turbulent flow when } \mathbb{R}_{bed} > 100 \qquad \text{(Eqn 2.8)}$$

where $u_* = \sqrt{(f/8)} \times U$

$u_* = \sqrt{(g \times R_h \times S_o)}$ (under uniform flow assumption)

d_s = characteristic grain or bedform dimension

The dimensionless Froude number, $\mathbb{F}$, is evaluated to determine the nature of oscillatory surface wave patterns in open channel flow (Equation 2.9). The value of the $\mathbb{F}$ defines the type of flow as subcritical ($\mathbb{F} < 1$) or supercritical ($\mathbb{F} > 1$), where surface disturbances are able to or inhibited from migrating upstream, respectively.

$$\mathbb{F} = U/\sqrt{(g \times d)} \qquad \text{(Eqn 2.9)}$$

where g = gravitational acceleration

d = flow depth for rectangular channels (d = flow area/flow top width, for nonrectangular channels)

2.2 SEDIMENT TRANSPORT AND EROSIONAL THRESHOLDS

2.2.1 Conceptual Model of Sediment Transport and Deposition

A basic scheme for classifying sediment transport in open channels is shown in Figure 2.1. In most storm water applications, vegetated storm water facilities are designed to settle a portion of the suspended load in the influent, retain most of the bed load, and prevent erosion from disrupting the existing bed material. A variety of numerical models have been developed to predict the erosional threshold of vegetated facilities, the rate of sediment deposition, and the vertical growth of the sedimentation layer (see section 2.3).

<table>
<tr><th></th><th>Location in Flow</th><th>Origin</th><th>Transport Mechanism</th></tr>
<tr><td rowspan="4">Sediment Load</td><td rowspan="2">Suspended Load</td><td>Wash Material</td><td rowspan="2">Suspended</td></tr>
<tr><td rowspan="3">Bed Material</td></tr>
<tr><td rowspan="2">Bed Load</td><td>Saltating</td></tr>
<tr><td>Rolling</td></tr>
<tr><td colspan="4">Sedimentation Layer</td></tr>
<tr><td colspan="4">Stable Bed</td></tr>
</table>

Figure 2.1 Classification scheme for sediment transport terminology

2.2.2 Determination of Erosional Threshold

A common deterministic method for predicting the stability of cohesionless bed material requires the calculation of the Shield's parameter, θ (Equation 2.10). Plots of various forms provide a straightforward method for evaluating the stability of the channel bed as a function of the Shield's parameter and $\mathbb{R}_{bed}$.

$$\theta = \tau_o/[\gamma \times (s-1) \times d_s] \qquad \text{(Eqn 2.10)}$$

where s = specific gravity of d_s material

For $\mathbb{R}_{bed} > 500$, θ would need to be less than 0.06 for d_s to be considered a stable bed material.

2.3 MODELS OF FLUID FLOW AND SEDIMENT TRANSPORT IN VEGETATED CHANNELS

The order-of-magnitude scatter of predictions generated by current sediment transport equations (Nakato 1990; van Rijn 1984) indicates the necessity of applying models developed and validated with flow, load, and bed material similar to the channel of interest. Many researchers have developed physical models to predict the sediment transport rates in partially or fully submerged vegetated channels. Following tests on the removal of suspended sediment by artificial grass media, the GRASSF model was developed by researchers at the University of Kentucky (Tollner 1976). Wilson et al. (1984) modified GRASSF into SEDIMOT II, and recent work by Diletic (1999) may lead to further refinements. These models are frequently used to predict the deposition and movement of bed material in vegetation filters. Munoz-Carpena et al. (1998) and Srivastanura (1998) have developed numerical models that couple a finite-element overland flow model, a Green-Ampt infiltration submodel, and the aforementioned University of Kentucky sediment transport model to better capture the multiple removal mechanisms at work in a vegetated filter strip.

2.4 STORMWATER POLLUTANTS AND REMOVAL MECHANISMS

2.4.1 General Findings from Earlier Studies

Highway runoff quality is highly variable, and mean national values may be poor predictors of site-specific pollutant concentrations and loads (see Table 2.1). The observed variability is often attributed to local differences in pollutant sources and transport mechanisms (Bannerman 1993; Pirrone and Keeler 1993; Kobriger 1984; Asplund 1980; Gupta 1981).

A study commissioned by WSDOT between 1977 and 1982 (Mar et al. 1982) characterized the runoff from western Washington highways. A model was developed to estimate runoff total suspended solids (TSS) on the basis of highway segment length, the average runoff coefficient, and vehicles traveling during the storm. By using an assort-

Table 2.1 Values of storm water parameters from studies on highways and urbanized areas

		Driscoll (1990)		WSDOT (2000)		(1993)	WSDOT (1995-1996)	Farris (1973)	Gupta (1981)
Parameter	units	SR-5	SR-520	SR-8, MP15.80	SR-5, MP2.80	Oregon, SR-30	Olympia, SR-5	S. Bellevue Interchange	Wisconsin, I-794
Site ADT	count	106000	84000	18000	101000				53,000
% Pavement		100	100						100
TSS	mg/L	93	244	53.6	208.6	119	49.7	246	138
TDS	mg/L			49.4	92.1				240
VSS	mg/L	26	59					57	53
VDS	mg/L								74
Zn	ug/L	382	280		278.1	253	54	170	350
Cd	ug/L			0.27	1.06	1.4	4		40
Pb	ug/L	451	1065	5.64	49.68	36	19	1160	1500
Cu	ug/L	37	72	20.69	41.25	39	12	152	100
Soluble P	mg/L	0.217	0.415						
Total P	mg/L			0.05	0.31	0.3		0.31	
COD	mg/L	106	145	26.2	19.7	123		123	
TPH	mg/L			1.46	4.45				
pH		6.1	5.6						
Hardness	mg/L			14.4	93.4				
Conductivity									
NO3 + NO2	mg/L	0.83	0.79	0.15	5			0.75	
TKN	mg/L	0.9	1.09			1.6		0.5	

ment of ratios, COD, nutrient, and trace metal loadings can then be predicted on the basis of TSS loads in the runoff. Researchers have raised concerns about the consistency of these correlations during individual storms (Sansalone 1997); therefore, the models are most appropriate for annual load calculations.

In the King County area, Stuart et al. (1988) determined that lead, copper, polycyclinc aromatic hydrocarbons (PAHs), and phthalic acid esters (PAEs) were the storm water constituents of most concern. Of these, lead was the only storm water constituent in concentrations high enough to degrade the water column and sediment in the large urban lakes investigated.

A study in Tacoma, Washington, by Norton (1997) found that the particulate matter from storm sewer flows draining from I-5 (identified as the Hosmer and S. Tacoma sampling site) had 6 percent gravel (>2 mm), 74 percent sand (62 μm to 2 mm), and 20 percent fines (<62 μm). Dry weight analysis of the collected sediments found acceptable levels of inorganic toxicants (lead at 89 mg/kg, mercury at 0.15 mg/kg, and zinc at 170 mg/kg). However, runoff sediment concentrations of high molecular weight PAHs, phenanthrene, and several phthalates were found to exceed EPA guidelines that had been set for the sediments of the receiving water body.

"Priority pollutants," a term that refers to 115 organic compounds and 14 metal elements designated by the U.S. Environmental Protection Agency, can be removed from a storm water stream by six main processes (from Scholze 1993; Dorman 1988):

1) adsorption on suspended solids followed by particle sedimentation or filtration
2) adsorption on an adsorbing medium such as peat or other organic material

3) biodegradation (aerobic and anaerobic)

4) volatilization (common during aeration processes)

5) photodegradation via photolysis

6) bioassimilation.

2.4.2 Sediment Sources and Removal

Direct vehicular sources of roadway particulates include tire wear, pavement degradation, engine and brake abrasion, and settlable emissions (Kobriger 1984). Additional on-site sources of solids include construction activities, maintenance operations (including grit and sand application), littering, and spillage (Sansalone 1999).

As noted above, total suspended solids is a water quality parameter that is believed to correlate reasonably well with the concentrations of heavy metals and nutrients in the storm water. Turbidity can be used as a surrogate measure of nonsettlable solids when a full evaluation of the particle size distribution is not conducted. Removal of suspended solids from the flow and reduction in turbidity primarily occur via sedimentation, filtration, and adsorption (Wilson 1967). Grass filters retard local velocities and enhance particle settling. Filtration of infiltrated flow is more complicated, consisting of interception, straining, flocculation, and sedimentation as the water percolates through the granular subsurface (Viessman and Hammer 1998). The process is augmented as clay particles are adsorbed to positively charged organic matter, which can enhance settling in surface flows and improve retention in the subsurface. However, in vegetated storm water channels the sorption mass rate is quite low relative to sedimentation rates.

2.4.3 Nutrient Sources and Removal

Poor storm water facility maintenance can result in soil erosion, decomposition of plant biomass, and fertilizer washout, which can lead to significant nutrient loads to downstream waters (Horner 1994). The majority of total phosphorus removed by a vegetated storm water facility is believed to be associated with sedimentation of the larger particulates. Extended contact time (on the order of hours to days) can result in biological uptake, adsorption, and precipitation. Coarse-textured, acidic, and organic soils have the lowest capacity for phosphorus removal. However the presence of iron and aluminum in peat often produces organic soils with high phosphorus sorption potential (Reed et al. 1995).

2.4.4 Trace Metal Sources and Removal

Heavy metal species are associated with both particulate and dissolved material. In general, over 90 percent by mass of heavy metal contamination in highway runoff is affiliated with deposited and abraded particulate matter (Wilber 1979). Larson et al. (1975) in Washington and Yousef et al. (1985) in Florida found sites where atmospheric characteristics can lead to higher than expected concentrations of dissolved Cu, Pb, Zn, and Cd in rainfall. Sansalone and Buchberger (1997) found that for rain event runoff, total metal concentrations of Zn, Pb, and Cu were significantly higher for particles in the 25-250 μm diameter range than for those in the 250-9500 μm range. Sansalone and Tribouillard (1999) found a similar pattern emerge in runoff from an interstate roadway with an ADT of 110,000. However, on a total mass basis, the majority of total Zn, Pb, Cu, and Cd was associated with particles exceeding 200 μm in diameter. On the basis of 35 CSO measurements, researchers in Germany (Michelbach and Wohrle 1993) developed a set of charts relating particle settling velocity, particle density, and threshold sheer stress.

Metal elements partition into different phases depending on pH, solids composition, and residence times. The phase and form of the metal has important implications in terms of removal processes. The mechanisms for the precipitation and complexation of heavy metal species include the following (Salomons and Förstner 1984):

1) oxidation of reduced components such as iron, manganese, and sulfides
2) reduction of higher valency metals (selenium, silver) by interaction with organic matter
3) reduction of sulfate to sulfide, causing precipitation of metal sulfides
4) alkaline type reactions in which many metallic elements are precipitated by increased alkalinity
5) adsorption or co-precipitation of metallic ions with iron and manganese oxides, clays, and particulate organic matter
6) ion-exchange reactions, primarily with clays.

Generally, under aerobic conditions, process 5 is the dominant immobilization process, whereas in anaerobic environments process 3 is most prevalent (Scholze 1993). Metal species can desorb from particulates into an aqueous phase as conditions within the micro-environment change.

High metals removal and retention rates occur naturally as subsurface flows pass through alkaline substrates. Therefore, it is common practice to amend acidic soils with organic matter to enhance metals removal (Dorman 1988). Yonge (2000) and Kobriger

(1984) provided concise reviews of the observed retention and migration patterns of heavy metals in roadside soils.

2.5 ECOLOGICAL AND HYDROLOGICAL EFFECTS OF STORM WATER RUNOFF

Under the current National Pollutant Discharge Elimination System (NPDES) program, the Washington State Department of Ecology (WSDOE) has approved WSDOT's standard maintenance operating procedures that affect waters discharging from state highways. These discharges must meet the general surface water criteria established by WSDOE (see Table 2.2).

2.5.1 Storm Water Field Studies

The complicated interactions between pollutants and the local environment make conclusions about the specific effects of storm water runoff on aquatic organisms difficult to draw. In general, loadings of highway pollutants from storm events are not acutely toxic (Horner 1994).

The sediments transported in runoff often serve as a source of contaminants that can affect the local ecology near outfalls. For instance, studies by Willemsen et al. (1990) and Gast et al. (1990) characterizing the aquatic ecology near urban outfalls found that the most degraded populations of sessile diatoms, phytoplankton, and zooplankton occurred in low flow or small stagnant water bodies that received high nutrient storm water inflows. Furthermore, the studies concluded that the impact on macro-invertebrates was less noticeable, since these species were able to temporarily migrate and then re-colonize affected areas as conditions improved.

Table 2.2 Washington State Department of Ecology's regulations for discharges to surface freshwater bodies (from WAC 173-201A)

Parameter (units)	Exposure Condition	Discharge quality threshold for Class AA Freshwaters	Discharge quality threshold for Puget lowland lakes
Turbidity (NTU)		If background <= 50 NTU: Not to exceed 5 NTU over background. If background > 50 NTU: Not to exceed 110% of background level	Not to exceed 5 NTU over background
Dissolved Zinc (µg/L)	Chronic: 4 day average not to be exceeded once every 3 years on average	$<= 0.986 \times (e^{0.8473(\ln(\text{hardness})+0.7614)})$	same as AA freshwaters
	Acute: 1 hour average not to be exceeded once every 3 years on average	$<= 0.978 \times (e^{0.8473(\ln(\text{hardness}))+0.8604})$	same as AA freshwaters
Dissolved Copper (µg/L)	Chronic: 4 day average not to be exceeded once every 3 years on average	$<= 0.960 \times (e^{0.8545(\ln(\text{hardness})-1.465)})$	same as AA freshwaters
	Acute: 1 hour average not to be exceeded once every 3 years on average	$<= 0.960 \times (e^{0.9422(\ln(\text{hardness})-1.464)})$	same as AA freshwaters
Fecal coliforms		geometric mean value of less than 50 colonies/100 mL; less than 10% of these samples to exceed 100 colonies/100mL	same as AA freshwaters
Total Dissolved Gas		not to exceed 110% of saturation	same as AA freshwaters
Dissolved Oxygen		over 9.5 mg/L	same as natural conditions
Temperature		not to exceed 16°C (unless natural condition is higher)	same as natural conditions
pH		6.5 to 8.5; less than 0.2 unit change due to human effects	same as natural conditions
Total Phosphorus (ug/L)	**Ambient TP**	Not applicable	**Criteria**
	0 to 4 ug/L		<= 4 ug/L
	4 to 10 ug/L		<= 10 ug/L
	10 to 20 ug/L		<= 20 ug/L

Dupuis et al. (1985) studied a variety of storm water runoff conditions in North Carolina. In one watershed, an interstate with an ADT load of 120,000 drained directly to a 270-acre natural lake. Tests on cattails and bottom sediments near outfalls showed higher than baseline concentrations of metals and salts. However, no toxic response was detectable in the cattails, and elevated metal concentrations in plant biomass were not present at distances greater than 65 feet from the outfalls. In bench tests with the undiluted runoff, no discernible effects were observed in isopod, amphipod, or mayfly species. Qualitative analyses of fathead minnow and cladocerans behavior displayed minor chronic effects. Algal (*Selenastrum spp.*) assays showed no acute toxicity; however, incubation for 14 days in undiluted runoff significantly reduced algal growth rates, possibly because of the phosphorus limitations caused by chelated heavy metals in the water.

The work of Portele et al. (1982) indicated that concentrations of dissolved pollutants are the most relevant to aquatic biota health. The study found that the biological effects varied tremendously between sampling sites within King County, Washington. For six monitored storms, runoff from a site along I-5 in north Seattle consistently had significantly higher concentrations of soluble copper (13-24 μg/L) and soluble zinc (96-316 μg/L) than runoff from SR 520 in Seattle with an equivalent traffic volume. In 14-day algal bioassays (with *Selenastrum capricornutum*), biomass production dropped 85 percent for filtered storm water from the I-5 site and as much as 70 percent for 3:1 dilutions (lake water:storm water). *Daphnia spp.* showed a similar pattern, with 83 to 100 percent mortality after 48 hours with either filtered or unfiltered I-5 storm water. Experiments on very young rainbow trout fry (*Salmo gairdneri*) found no harmful effects with filtered or 50 percent dilutions. However, unfiltered runoff at 0 percent and 50 percent dilutions yielded significant mortality after 96-hour exposures. The TSS concentrations were only 35-97 mg/L, but the author argued that the angular particulates associated with abraded highway material can readily obstruct the mouthparts of young, unacclimated fish.

2.5.2 Effects of Specific Storm Water Pollutants on Fish

The effects on fish physiology varies considerably by species and environmental conditions. For a thorough account of the effects of pollutants on fish physiology and behaviour see Heath (1995). The following discussion highlights some of the most pronounced changes in fish species attributable to the water pollutants analyzed in the present study.

2.5.2.1 Suspended Solids

In his artificial stream experiments with wild juvenile salmonids, Noggle (1978) found that avoidance of sediment-laden flows was not observed until TSS concentrations exceeded 4000 mg/L. In general, research has found that fish prefer low- to medium-level turbidity relative to clear water over the short term, and avoidance behavior is not noticed until TSS concentrations exceed 2000-4000 mg/L (Mizunuma 1965; Noggle 1978). Noggle (1978) found that feeding of coho smolts on aquatic insects decreased significantly when suspended solids exceeded 300 mg/L, presumably because of the reduction in their visual field. This value should be used cautiously as a threshold, since TSS concentration does not reflect the optic characteristics of the suspended sediment nor the possibility of individuals employing alternative prey search mechanisms (i.e., olfactory or lateral line detection). The 96-hour LC50 of salmonids for TSS varies greatly from 1,200 to 55,000 mg/L (Smith 1978; Noggle 1978). Most studies point out that the acute effects of suspended material on fish is due to gill damage and oxygen exchange inhibition. Behaviorial reactions to high TSS values are identical to responses by fish in hypoxic waters (Smith 1978).

Morrill (1994) found highly variable survivability rates of coho and steelhead up to the alevin stage in Olympic peninsula streams. He concluded that "egg shock" due to shifting bedload was the most likely explanation for the differences in survivability. In general, neither reduced dissolved oxygen concentrations, elevated metabolite levels, nor physical entrapment correlated with mortality rates. However, when the amount of fine sediment (<0.85 mm in diameter) in the bed material exceeded 17.5 percent, egg survival decreased markedly.

2.5.2.2 Nutrients

One of the most common causes of hypoxia in surface waters of western Washington is cultural eutrophication due to high nutrient loading in thermally stratified lakes. The effects on fish physiology and behavior due to environmental hypoxia are well-documented (Barnes and Mann 1991). In general, salmonids and pelagic species are less adapted to conditions of low dissolved oxygen and, therefore, exhibit more pronounced physiological symptoms.

2.5.2.3 Trace Metals

Behavioral modifications of fish due to metals exposure has been evaluated in several studies. Many metals, especially copper, appear to increase metabolic rates in non-muscular tissues, reducing the spontaneous muscular movements (locomotor activity) of fish. Hartwell et al. (1987) found that fish can lose the ability to avoid extremely high concentrations of metals following acclimation to moderately contaminated water. In the study, fathead minnows were acclimated by continual exposure to an industrial effluent containing copper, arsenic, chromium, and selenium at a total concentration of 48 ug/L. The specimen lost the ability to avoid concentrations of 245 ug/L after three months and 480 ug/L after nine months. Control populations readily avoided waters with these concentrations. These results point to risks of significant metal bioaccumulation in fish habitating waters chronically exposed to high concentrations of heavy metals.

In other studies, the effect of sub-lethal concentrations of copper has been shown to depress feeding rates of brook trout (Drummond et al. 1973), change schooling behavior in Atlantic silversides (Koltes 1985), and inhibit the uptake of electrolytes in salmonids, thereby disrupting their osmoregulatory functions (Lorz and MacPherson 1976).

Changes in the sensory receptors of fish can result from metal exposure. In studies with salmon and trout, individuals exposed to sublethal concentrations of inorganic mercury (> 0.10 mg/L) or copper (> 0.008 mg/L) exhibited a marked depression in response to common olfactory stimulants after just two hours of exposure (Heath 1995). Copper concentrations as low as 0.044 mg/L can affect the affinity of migrating salmonids for home stream waters (Sutterlin and Gray 1973).

Concerns over the possibility of cell and tissue damage to fish by environmental toxicants have existed since the 1930s (Macek 1980). Except for methylmercury, fish absorb metals in ionic form or in food. The rate of uptake for a particular toxicant is highly variable, dependent on the form of the pollutant, pH, hardness, the microenvironment of the gill lamallae, and the condition of the gill epithelium. It also should be noted that particulate-bound metals on gill tissue or in the gut can desorb in response to pH changes. Since there is no known function for cadmium and mercury in the cells of fish, much attention has been given to these elements. The inhibition of cellular enzymatic activity due to exposure to these metals at high concentrations is well documented (Heath 1995). Interestingly, many species appear to have little inclination to avoid cadmium, selenium, and mercury (Giattina et al. 1982; Hartwell et al. 1989). Gill lamellae are very sensitive in comparison to the rest of the external tissue of fish. Many inorganic and organic compounds cause histological damage to these structures; however, the impacts vary by contaminant. For example, nickel and zinc are much more damaging than cadmium and other priority metals (Hughes et al. 1979).

On the basis of experiments with rainbow trout, Davies (1986) concluded the following regarding the effects of metals:

- Hard, well-buffered waters dampen toxic impacts better than soft waters.
- Increasing temperatures enhance toxic effects because of higher metabolic rates.
- Younger individuals are more sensitive. Fish are more sensitive than macro-invertebrates.
- Long-term exposure to very low levels of certain trace metals in soft water can protect fish from the effects of short-term acute exposures.
- Toxicity increases as exposure time lengthens.
- Complexation processes can take several days, so high acute exposures can be toxic regardless of the buffering capacity of the receiving water.

- Realistic water quality criteria need to account for toxic forms that may solubilize over time.

2.5.3 Effects of Landscape Disturbances on Stream Hydrology and Ecology

The impacts on lowland streams by watershed development have been well documented by researchers in western Washington (Richey 1982; Scott 1982; Booth and Jackson 1997; Taylor 1993). The changes in stream hydrology in a typical, moderately developed watershed were summarized by Schueler (1987):

- larger peak discharges in comparison to predevelopment levels (Leopold 1968)
- larger volume of storm runoff produced by each storm in comparison to predevelopment conditions
- less time needed for runoff to reach the stream (Leopold 1968), particularly if extensive drainage improvements have been made
- increased frequency and severity of flooding
- less stream flow during prolonged periods of dry weather because of the reduced level of infiltration in the watershed
- greater runoff velocity during storms caused by the combined effects of higher peak discharges, rapid time of concentration, and the smoother hydraulic surfaces that occur as a result of development.

Horner (1994) concluded that the main ecological impacts attributable to changes in high flows are stream habitat degradation due to siltation, direct health effects on biota, loss of healthy vegetation in riparian buffers, and loss of protective qualities of woody debris. In addition, reduced dry weather flows can increase summer water temperatures, decrease dissolved oxygen levels, offer less dilution of discharged waters, and impede biota mobility.

2.6 VEGETATION AND EROSION CONTROL

The processes of infiltration, surface sealing, erosion, and runoff define the hydrology and sediment transport of the hill slope. Contemporary models describe particle detachment and transport by both raindrop and overland flow forces. Recent work by Huang (1998) highlights the complicated interplay between these mechanisms. For instance, increasing slope does not necessarily produce greater surface runoff. Flows that remain on the surface move faster, pore sealing is reduced, and consequently, a larger proportion of rainfall may be able to infiltrate.

Agricultural researchers have long reported on the use of vegetation and organic litter to deter soil erosion. Oades (1993) provided a summary of the role of biological agents in the formation and stabilization of soil structure. Vegetation encourages the development of water-stable aggregates at many scales. Fibrous roots press soil particles together, which are then bound by polysaccharides supplied by the decomposition of vegetal matter. At the most basic structural level, the formation of soil micro-aggregates depends on polyvalent metal linkages between clay minerals and humic complexes derived from microbial and plant material (Edwards and Bremner 1967).

Bare soil with neither aerial nor immediate surface cover is vulnerable to damage by falling rain. The mechanical breakdown of aggregates into finer particles by rain impact can seal the immediate surface and significantly reduce infiltration rates (Marshall et al. 1996). Alternatively, these finer particles are prone to down-slope transport by overland flow. Therefore, both elevated and at-surface vegetation cover are important.

The canopy intercepts raindrops, and the immediate surface cover prevents the formation of erosive overland flows. At the macro-scale, hill slope vegetation creates roughness elements that prevent rill initiation and down gradient transport of suspended material.

2.7 TREATMENT OF STORM WATER USING VEGETATED CHANNELS

One of the earliest works dealing specifically with the potential of grass-lined swales for storm water pollutant removal was by Wanielista et al. (1988). The study emphasized the importance of infiltration to reduce outlet loading. The specific findings included the following:

- The infiltration rates of operating swales may only be 4 to 15 percent of the infiltrometer test rates.
- No runoff was observed at the outlet of a 550-foot swale for flows of less than 0.12 ft^3/ft^2-hr, and infiltration rates never exceeded 0.29 ft^3/ft^2-hr.
- To determine the length, L (in ft), of a trapezoidal cross-sectional swale to allow complete infiltration, Equation 2.11 was developed.

$$L = (K \text{ x } Q^{0.625} \text{ x } S_o^{0.188}) / (n^{0.375} \text{x } I) \qquad \text{(Eqn. 2.11)}$$

where

K = a constant that is a function of a side slope parameter (see Wanielista and Yousef 1993)

Q = maximum flow rate ft^3/s

I = infiltration rate in/h

Few well-designed studies to quantify the effects of grassy swales on runoff from heavily travelled highways have been conducted. Wang's (1981) study of highway sites in western Washington found that the removal of most solids and heavy metals occurred within the first 200 to 260 feet of the swale. Removal efficiences of suspended solids (90 percent) and lead (80 percent) were particularly impressive, the latter possibly due to its low solubility and affinity for particulate matter. Studies of vertical metal profiles also indicate that the gradient for lead removal is the most pronounced of all the heavy metal species (Newberry and Yonge 1996).

Barrett et al. (1998) performed a 34-storm study of two V-shaped grassy swales with median influent concentrations of 130 mg/L TSS and 44 to 59 NTU turbidity. Load reductions exceeded 80 percent for TSS and 70 percent for turbidity. Reductions of lead and nutrients were less than 50 percent, while zinc and iron removals exceeded 75 percent. The most interesting findings were that 1) infiltration losses accounted for less than 15 percent of TSS load reduction and 2) the overwhelming majority of influent sediment was captured by the 25-ft-wide side slopes of the swale (Walsh 1997). This confirmed earlier findings by Yu et al. (1995) that removal of most pollutants occurs in the first 10 feet of vegetated buffer and that the finer particulate and dissolved forms were the only materials reaching the swale invert (90 percent zinc and 60 percent total phosphorus were dissolved). Athayde et al. (1983) and Horner (1988) presented results that supported the use of biofiltration swales to improve the quality of storm water runoff. The range of removal efficiencies in these studies pointed to the importance of site-specific flow conditions, influent concentrations and forms, physical geometry, and vegetation in the effectiveness of the facility.

Several western Washington studies have looked at the use biofiltration swales in residential and commercial settings. The findings of these regional studies are summarized in Table 2.3 (Municipality of Metropolitan Seattle 1992; Goldberg 1993;

Koon 1995). These findings tend to support the use of swales for storm water quality control in new developments.

Table 2.3 Removal efficiencies of biofiltration swales in King County, Washington.

		Sites				
Parameter	**unit**	**Mountlake Terrace**		**Sammamish Plateau**	**Dayton Avenue**	**Interstate**
Sampling Dates		winter '91-'92	summer '91	1993	1992	1981
Length	ft	100	200	350	570	
Total Drainage	ac	15.0	15.0	17.0		
Impervious Drainage	ac	6.5	6.5			
TSS	%	60	83	67	68	
Turbidity	%	60	65			
Total P	%	45	29	39	4.5	
BAP	%	-73	40	-31	31.9	
SRP	%	-280	0	-45	35.3	
NO3 + NO2	%	-24	-81	9	31.4	
NH3	%			16		
Total Cu	%	2	46	-35	41.7	60
Total Pb	%	15	67	6	62.1	80
Total Zn	%	16	63	-3		70
Total Fe	%	5	72			70
Total Al	%	16	63			

A storm water quality best management practice closely related to the bioswale is the vegetated filter strip (VFS). These systems have been studied extensively for decades (Reed and Palmer 1949; Wilson 1967; Dillaha 1989; Yonge 2000). Wilson (1967) found that as the depth of deposited sediment decreased and distance from infall increased, the fraction of clay in the sediment increased dramatically. The deposition rate was highest within the first 50 feet of the vegetated filter; however, at downstream sections where local slope decreased, deposition rates often increased accordingly.

In experiments on agricultural land, Dillaha (1989) found that a 15-foot VFS removed 53 to 86 percent of incoming sediment, and a 30-foot VFS removed 70 to 98 percent. A site with a 16 percent slope had lower reduction rates than sites with slopes of 5 and 11 percent. However, the improvement in overall removal efficiency due to lengthening of the filter was most significant for the steepest site. Total phosphorus and nitrogen reductions ranged between 49 and 95 percent. In many of the plots removal rates dropped significantly during the later trials as the deposition layer increased in depth and progressed down slope, leading to the inundation of the grass stems.

Jenkins et al. (1985) looked at overland flow systems for the removal of toxic volatile organics. For seepage flow conditions through a Palouse topsoil with 15 percent organic matter, Newberry and Yonge (1996) found >99 percent retention for Cu and Cd, 84 percent for zinc, and 93 percent for lead. Schmitt et al. (1999) found that in plots of switchgrass (*Panicum virgatum*) and tall fescue (*Festuca arundinacea*), doubling the length from 25 to 50 feet was most important for difficult to remove pollutants, in particular, nitrate-nitrite and dissolved phosphorus. The researchers described the mechanisms of removal, explaining that sediment bound P is not removed as effectively as TSS because of its association with the finer fraction. A 25-year-old grass plot had higher infiltration rates than a 2-year-old grass plot. The authors discussed the possibility of greater dilution as canopy interception decreases and surface area increases.

No direct information is available on projects that specifically modified road ditches to function as water quality BMPs, although findings from vegetated filter strips and grassy channels are certainly indicative of the water quality management potential of vegetated road drainage systems.

Kulzer (1990) provided a thorough review of literature related to the use of aquatic plants to manage storm water quality. She summarized that in terms of nutrient removal, species with both high growth rates and high biomass:surface area are most efficient. Metals tend to accumulate in the roots and older tissues of aquatics. In comparison to other elements, lead and mercury seem to accumulate readily; however, the possibility of these elements leaching from the biomass needs to be researched. As a precaution against re-introducing pollutants to storm water, proper maintenance and the harvesting of standing biomass is suggested. Care should be taken to avoid aggressive species such as reed canarygrass (*Phalaris arundinacea*), giant reed (*Phragmites communis*), purple loosestrife (*Lythrum salicaria*), and possibly cattail (*Typha latifolia*), which may choke waterways and disrupt the local ecology.

Salt and Kramer (2000) pointed out that true hyper-accumulators of metals have a shoot:root ratio of metal concentrations above 1.0. While this appears to contradict Kulzer's literature review, it may simply indicate that the aquatic species of her study were not true hyper-accumulators. Newberry and Yonge (1996), demonstrated that WSDOT's western Washington seed mix does not contain any hyper-accumulators. They found far larger concentrations of heavy metals in root biomass than in the above-ground biomass, and all these species had metal concentrations below that of the growing media. Most research to date has involved *Thlaspi spp*. and *Alyssum spp*. Salt and Kramer (2000) identified four mechanisms by which these species accumulate metals: enhanced rhizosphere mobility (chelators), enhanced root metal uptake system, root to shoot translocation, and sequestration in specific cellular locations of leaf cells.

A report by Koon et al. (1995) discussed some concerns about using wetland species in biofiltration swales. A qualitative analysis indicated that the structure of cattail communities appeared to distribute flow better than the clumping nature of soft rush. In areas of the study swale where slope exceeded 2 percent, a defined channel appeared bordered by soft rush. Although the study was not conclusive, the researchers noted that the swale was only effective at removing dissolved nutrients during the spring and summer, presumably because of biological activity. In general, the facility was just as effective as similar grass-lined swales in reducing TSS and total phosphorus (TP); however, design and maintenance modifications could possibly improve performance. In lab studies with bulrush, cattail, and reed, Yu and Liao (1995) found that containers with plants were much more efficient than those with only substrate at removing soluble nutrients. Bulrush was the species most responsive to increased nutrient loads.

2.8 VEGETATED CHANNEL FACILITY DESIGN

General drainage channel design guidance can be found in *FHWA Hydraulic Design Series #3: Design Charts for Open Channel Flow* and *FHWA Hydraulic Design Series #4: Design of Roadside Drainage Channels*. Specific attention is given to vegetation lined channels in *Stability Design of Grass-Lined Channels* (Temple et al. 1987) and *Open Channel Hydraulics* (Chow 1959).

A complete summary of biofiltration swale design procedures for western Washington is discussed in *Biofiltration Swale Performance, Recommendations, and Design Considerations* (Municipality of Metropolitan Seattle 1992), *Biofiltration Systems for Storm Runoff Water Quality Control* (Horner 1988), and *Water Quality Best Management Practices Manual* (Resource Planning Associates 1989). The findings concerning swale design and maintenance from *Biofiltration Swale Performance, Recommendations, and Design Considerations* are summarized in Appendix A. Design methodologies developed by Horner (1988), Resource Planning Associates (1989), and King County (1990) are presented in the Metropolitan Seattle report.

Normann (1975) developed a series of nomographs relating velocity, slope, hydraulic radius, and species-specific retardance. A separate set of plots for each retardance rating is available to aid in drainage channel design.

Current WSDOT guidelines for designing roadside ditches are based primarily on the expedient conveyance of the design storm event, whereas biofiltration swales are designed to both enhance pollutant removal processes and provide storage/conveyance for the design storm. WSDOT specifications recommend the use of the U.S. Natural Resource Conservation Service's Rational method or the Santa Barbara Urban Hydrograph method for the hydrologic analysis of catchments of less than 1000 acres. For conveyance analysis the 10-year, 24-hour mean recurrence storm is suggested for ditches. Biofiltration swales are sized as a treatment facility for the 6-month, 24-hour storm and to pass the 100-year, 24-hour storm to downstream facilities. The hydraulic analysis of roadside ditches (except where downstream controls require a backwater analysis approach) employs the Manning equation with n values selected from pages 4-1-4 through 4-1-5 of the WSDOT *Hydraulics Manual* (01/97). (The reader is referred to Appendix C for study-specific findings on Manning's n.) A velocity of 1 ft/s is selected for ditches lined solely with earth and grass. The process is iterative, with typical design constraints consisting of mean longitudinal slope, maximum top width, and maximum stable velocity. The WSDOT design criteria for biofiltration swales imposes the following additional constraints (WSDOT *Highway Runoff Manual* (02/95)):

1) Swale length should exceed 200 feet.
2) The shape should have a bottom width of greater than 1 foot and less than 10 feet while maintaining a flow depth not to exceed 4 inches and 1 fps during the 6-month, 24-hour storm,
3) Cross-section should be trapezoidal, with side slopes no steeper than 3:1.
4) If flow is introduced through curb cuts, the pavement should be placed slightly above biofilter elevation. The cut should be at least 1 foot wide to prevent clogging.
5) Low-flow biofiltration swales should be installed within ponds where space is unavailable to accommodate both.
6) Biofilters must be vegetated. In general fine, close-growing, water resistant grasses should be selected.
7) Heavy flows and sediment loads from construction projects and during vegetation establishment should be avoided.
8) Roadside ditches should be regarded as potential biofiltration sites and should be utilized for this purpose when appropriate.
9) After the design for maximum water treatment has been calculated, Manning's Equation should be used to find the depth of flow for the 100-year, 24-hour storm. The depth of the channel should exceed this flow depth by at least 1 foot.

A review of design specifications from other state DOTs where biofiltration studies have occurred (California, Florida, Virginia, and Texas) yielded few additional recommendations beyond WSDOT's guidelines for biofiltration swales and roadside ditches. CalTrans recommends rounding all angles of earthen channel cross sections (California Department of Transportation 1995). Furthermore, its design procedure allows the water surface span, during maximum design flow (25-year, 24-hour storm) to cover the road shoulder. This provision allows for the construction of a smaller facility than the WSDOT design process would generate. Both Virginia and California have tables outlining the maximum permissible velocities for unlined channels of various soil types. For ungraded, recently seeded soils these range from 1.5 feet per second for silt to 3.75 feet per second for stiff clays. For easily eroded soils, a survey of earlier findings by the Municipality of Metropolitan Seattle (1992) reported permissible swale velocities of 2.5 ft/sec for red fescue and 5 ft/sec for Kentucky bluegrass and tall fescue for sites with slopes of less than 5 percent.

2.9 VEGETATED CHANNEL FACILITY MAINTENANCE

Of the 70 water quality control swales surveyed in studies by Koon (1995) and Horner (1988), the problem most frequently encountered was that of poor vegetation coverage. This was usually attributable to poor installation and early care, poor soil conditions, shading, or chronic saturation due to grading or water table levels. Less frequent problems included channelization by either base or storm flows, siltation, and poor inflow distribution.

Historically, department-wide WSDOT guidance on maintenance practices within vegetated ditches and swales has been limited. The current operating policy within the Northwest Region maintenance offices is to excavate, or “clean,” a ditch every few years to prevent overtopping during high flows. The cleaning interval varies with hydraulic conditions, ditch geometry, activities within the catchment, and traffic characteristics.

Sediment control practices include minimizing cleaning operations during the wet season, protecting buffer strips, and installing some type of trap to reduce downstream sediment loading while establishing new vegetation. These preventative measures usually consist of check dams, straw mulch, or the placement of a silt fence transverse to the channel.

WSDOT's *Maintenance Manual for Water Quality and Habitat Protection (08/00 revision)*, emphasizes the following points:

1) Excavation of ditches and channels should occur to the original gradeline when the sediment exceeds 50 percent of the facility volume or when pooling occurs.
2) Structural and non-structural BMPs following excavation work should be stringently followed to reduce the downstream impacts of these activities.
3) Routine facility inspections and field personnel training should be implemented to ensure that drainage facilities are not detrimental to downstream waters.

The following maintenance guidelines for biofiltration swales come from WSDOT's *Maintenance Manual* (01/86) and *Highway Runoff Manual* (02/95, section 8, page 49):

1) Groomed biofilters planted with grasses shall be mowed during the summer to promote growth and pollutant uptake.
2) Remove sediments during summer months when they build up to 4 inches, cover biofilter vegetation, or otherwise interfere with optimal operation. Reseed any bare spots following sediment removal operations.

3) Inspect biofilters periodically, especially after periods of heavy runoff. Remove sediments, fertilize, and reseed as necessary. Be careful to avoid introducing fertilizer to surface or ground waters.
4) Clean curb cuts when soil and vegetation buildup interferes with flow introduction.

Additional Departmental resources revise portions of the aforementioned manuals. Excerpts are provided for reference in Appendix B. The *WSDOT Maintenance Manual for Water Quality and Habitat Protection (08/00 revision)*, provides specific guidance on minimizing the water quality impacts of ditch/channel maintenance activities. The WSDOT *Storm water Management Plan v5.3 (03/97)*, provides guidance on bioswale/drainage maintenance and bioswale-related experimental BMPs. See the Field Operations Support Service Center's (FOSSC) Maintenance Office Web site at <wsdot.wa.gov/fossc/maint/> for the latest information on WSDOT BMP policies.

2.10 SEDIMENT CONTROL WITH ROLLED EROSION CONTROL PRODUCTS (RECPS) AND SOIL STABILIZERS

A WSDOT study (1990) compared several slope covering techniques to reduce sediment export from construction sites. The study team found that treatments of straw, straw/grass seed/manure/fertilizer, and wood fiber mulch/grass seed/fertilizer were the most cost effective slope erosion control methods. The possibility of high nutrient and organics export with straw and manure decay was noted, as were the limitations of each treatment, given specific site and access conditions. Woven straw matting, jute matting, and synthetic fiber blanket performed satisfactorily but were not recommended because of cost. Chemical agents and shaved wood blankets performed poorly overall. The study pointed out the importance of inhibiting particle detachment in the first place to reduce the turbidity of the site effluent and that the combination of straw with jute matting might yield the best results.

Field trials by CalTrans provide additional guidance on the effectiveness of bare ground treatments for erosion control and vegetation establishment. Following seeding/fertilization, two over-treatments of mechanically rolled straw at rates of 4000 lb/acre yielded the best results relative to hydraulic mulching, PVA treatment, and certain RECP applications. Success with RECPs was often enhanced by an initial application of weed-free straw at 3000 lb/acre (Dorman 1987).

Sanders et al. (1990) and Israelson and Urroz (1991) tested the sediment retention of several different types of RECPs in unvegetated conditions. The findings indicated that the rate of soil loss for any given product remains constant under increasing overland flow rates until a threshold shear stress is exceeded (Gharabaghi et al. 1999).

The Hydraulics and Erosion Control Laboratory of the Texas Department of Transportation and the Texas Transportation Institute have tested RECPs on vegetated plots since 1991. RECPs intended for *embankment protection* are tested on a variety of bed grades and soil types. These slope protection products are evaluated on the basis of vegetation cover and sediment yields. The products designed as *flexible channel liners* are rated on the basis of vegetation cover and sediment movement at a four flow rates, which produce boundary shear stresses of 2, 4, 6, and 8 psf. Evaluation cycles are completed each December at the end of the Texas growing season, and the results are posted on-line at <dot.state.tx.us/insdtdot/orgchart/cmd/erosion/content.htm >.

Gharabaghi et al. (1999) argued that the most important erosion control properties of a flexible channel liner are permeability according to ASTM D4491 and initial tensile modulus according to ASTM D4595. Long duration, moderate intensity flow events can lead to poor overall product performance because of chronic soil losses caused by high liner permeability. During short-term, high intensity flow events, liner deformation caused by the exceedance of product yielding shear stress can result in excessive erosional events. Table 2.4 summarizes the trade-offs of key properties of RECPs.

Less costly alternatives to erosion control nettings, meshes, blankets, and mattings include the use of hydraulic mulches and soil stabilizers. Of particular interest to WSDOT is the use of large, linear, anionic polyacrylamide (PAM) polymers as both an erosion control technique on bare land and as a flocculant to reduce turbidity in waters with poor settlability. As an erosion control treatment in agricultural settings, these polymers have been shown to reduce surface erosion rates by over 90 percent and increase infiltration rates by 5 to 25 percent in comparison to untreated plots (Sojka and Lentz 1997). Further information on polyacrylamides can be found at <wsdot.wa.gov/eesc/environmental/PAM.htm> and <Kimberly.ars.usda.gov/pamPage.shtml>.

Table 2.4. Trade-offs of REC product properties (from Allen 1996).

Parameter Value	Advantage	Disadvantage	Performance Measure
High strength and stiffness	Material not damaged by installation Resistance to flow stresses	Excessive stiffness inhibits conformation with surface during installation leading to underflow channels	liner deformation and durability
Low light penetration	Corresponds to a denser material able to protect germinating vegetation	May indicate less open volume and void space	vegetation growth
High porosity	May enhance sedimentation due to infilling	Excessive light penetration, raindrop compaction, and water flow across soil surface	soil loss

3 RESEARCH METHODOLOGY

3.1 ROADSIDE DITCH MAINTENANCE COMPONENT

3.1.1 Facility Selection and Characterization

All roadside ditch facilities were located within rights-of-way maintained by Washington State Department of Transportation's Northwest Region, Maintenance Area 5 (Figure 3.1). Ditches were screened to identify facilities with similar physical parameters, catchment characteristics, and hydraulic conditions (see Appendix D). Furthermore, the selected sites provided safe access for workers and protection of field equipment.

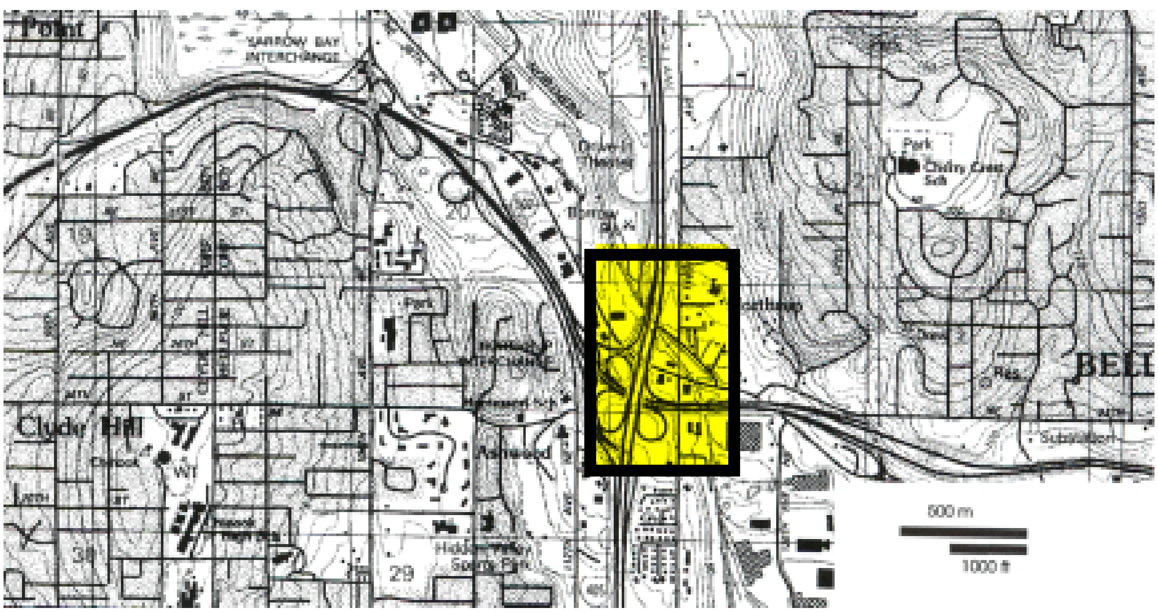


Figure 3.1. Vicinity map of roadside ditch study sites

Site A was located along the northbound lanes of I-405 between mileposts 14 and 15. The catchment was approximately 20,000 ft^2 (0.46 ac), consisting exclusively of asphalt and concrete pavement. The roadway runoff drained to a right shoulder catch basin connected to a 12-in culvert. The culvert outlet drained into the distal upstream end of Ditch A. Site B was located along the northbound lanes of I-405 between mileposts 15 and 16. The catchment comprised 27,000 ft^2 (0.62 ac) of asphalt roadway that collected along the right shoulder jersey barrier and was delivered directly to the upstream end of Ditch B from the paved shoulder surface. Site C was located along the southbound lanes of I-405 between mileposts 15 and 16. A series of right shoulder catch basins, connected via a 12-in culvert, collected runoff from approximately 140,000 ft^2 (3.21 ac) of road surface and drained into the upstream end of Ditch C.

To prevent the introduction of roadway runoff other than the initial upstream inflow, the selected ditch segments were located behind concrete jersey barriers with plugged weepholes, and the grating to any additional catch basin discharging into the ditch segment was blocked with 4-mm polyethylene sheeting.

At all sites, the catchment areas other than WSDOT maintained road surfaces amounted to less than 5 percent of the total catchment area. These areas were either small sections of maintained landscape beds or the extended side slopes of the study ditches, upslope of the wetted perimeters.

Field surveys of physical geometry, vegetation condition, and soils were performed to characterize ditches. Survey points were located along transects at 0, 25, 50, 75, and 100 percent of the total ditch segment length. Appendix E contains the survey protocol that was developed by the University of Washington's Center for Urban Water Resource Management.

The vegetation survey of each ditch was made during early June of 2000. The appearance of seed heads or flowers on most roadside plants during this period aided in the identification of vegetation species. The methodology, based on that developed by Mazer (1998) for vegetated swales, was as follows:

- The location and size (approximate dimensions) of isolated bare areas were recorded. The location and size of each extended bare channel were recorded. Any conditions that might have accounted for a lack of vegetation cover (e.g., flow concentration at the inlet, channel erosion, lateral bed slope, poor drainage, droughty soil, slope slumping, stoniness, shading, or human activity) were noted.
- To assess plant species composition and cover, two adjacent 0.25m^2 (2.69-ft^2) square quadrats were situated along the ditch centerline at each transect. Within each quadrat, total cover, species, composition, and relative cover by species were recorded. Vegetation cover was evaluated according to the Daubenmire cover class system (Barbour et al. 1987).
- To assess live plant and surface litter biomass, all aboveground growth and surface organic litter, within an open 11.5-cm (4.53-in) diameter cylinder, was collected from each quadrat of the preceding step. On the basis of the Mazer (1998) method, growth exceeding 10 cm (3.94 in) above the bed surface was cut and discarded. The dry mass of each sample was determined to the nearest 0.0001 g after the sample was fully dried in an oven at 105 °C.

When soil moisture conditions permitted, two soil cores were collected from each vegetation quadrat following cover assessment and biomass sampling. A 1.25-in diameter soil auger was bored into the ditch bed. Typical cores consisted of material from the top 8 in of the bed; however, at times rocky material prevented sampling fully to this depth. Additionally, at the completion of the sampling campaign, surface soil samples were collected at two locations within each ditch. These samples appeared to represent the settled material that had been transported by stormflows during the study period. For all soil samples, a standard sieve analysis was preferred to determine particle size distribution (ASTM D 421 and ASTM D 422). Volatile solids were determined by using a loss-on-ignition procedure (Council on Soil Testing and Plant Analysis 1992) from which the percentage of organic content of the soil sample was determined. At the completion of the sampling campaign, surface soil samples were collected at two locations within each ditch that appeared to represent settled material that had been transported by storm flows during the study period.

To determine the mean hydraulic residence time (HRT) of each ditch segment, a field approach outlined by Horner (1998) was followed (Appendix F). Municipal fire hydrants were accessed, and a flow meter recorded the total discharge volume, from which flow rates were calculated. A pulse input of a conservative-tracer (0.5 oz of rhodamine dye) was added to the flow at the head of each study ditch (immediately downstream of the flow splitter). A constant flow rate, similar to typical high storm flow, was maintained throughout the duration of the HRT test. Samples were withdrawn at the downstream end of the treatment length (immediately upstream of the flow splitter) with 12-mL polyethylene bottles and stored for no more than 24 hours in a 4°C refrigerator.

Samples were analyzed with a Shimadzu UV-1601 spectrophotometer at 556 nm according to the procedure in Appendix F. The adjusted absorbance readings, A_i, were derived by subtracting the absorbance reading of the water before the addition of the tracer from the actual reading of each sample.

At the HRT test flow rate, observations of the cross-sectional flow geometry (Figure 3.2) were recorded at each transect line.

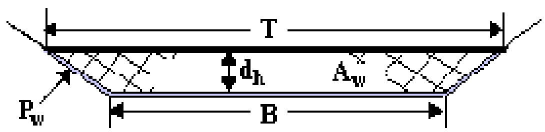


Figure 3.2 Cross-sectional flow dimension notation

Flow geometry of each ditch was characterized by using length-weighted means defined as,

$$d_x = (\Sigma d_i \times L_i)/ L_k \qquad \text{(Eqn 3.1)}$$

where d_x = mean ditch dimension

d_i = dimension measurement at transect i

L_i = length of ditch represented by transect i

L_k = length of ditch k

3.1.2 Experimental Treatment Selection, Description, and Implementation

Following site selection, experimental ditch excavation and follow-up maintenance treatment strategies were defined by WSDOT's Olympia Maintenance Office of the Field Operations Support Service Center. The term "treatments" refers to maintenance activities that could be conducted after routine ditch excavation to assist vegetation return. Ditch excavations and treatment applications followed typical operating procedures of the Northwest District's Maintenance Area 5.

All fieldwork occurred between November 1999 and June 2000 (Table 3.1). Treatments were applied in November of 1999. Mowing the ditch channel and slopes was not necessary, as vegetation was dormant at this time of year. All ditch segments were excavated with a bucketed trackhoe, and spoils were hauled off-site by dump truck.

Table 3.1 Work timeline for roadside ditch maintenance component

Field task	Dates	Personnel
Excavate and apply treatments	11/12/99	UW and WSDOT
Install sampling equipment and site adjustments	11/15/99-01/07/00	UW and WSDOT
Sampling campaign	01/09/00-05/24/00	UW
Segment surveys	06/08/00	UW
Hydraulic residence time tests	07/21/00-07/24/00	UW
On-site splitter calibration	07/21/00-07/24/00	UW

Ditch A was excavated to its original elevation and shape along the upstream three-quarters of the length. The remaining length was left intact, consisting of mature 24-in. tall, dense grass. The transition between the two lengths was graded to reduce the potential for pooling at the upstream end of the intact segment. The excavated portion was then resodded with 18-in.-wide rolls of perennial ryegrass (*Lolium perenne*).

Lengths of sod (approximately 7 ft long) were laid edge to edge to cover the cleared portion of the ditch bed and side slopes. No watering or soil preparation was performed. Pinning to stabilize sod was only done, as necessary, on steeper side slopes. Blade height was 1 in. at the time of installation and was not observed to grow beyond 3 in. high during the sampling campaign. Ditch B was excavated to its original elevation and shape along its entire length. Ditch C was excavated to its original configuration along the upstream three-quarters of the length. The remaining length was left intact and consisted of mature, 24-in tall dense grass. The cleared areas of Ditch B and Ditch C were covered with well-separated, hand-applied agricultural straw with a uniform, 3-in. loft.

3.1.3 Monitoring Equipment Design and Installation

Composite flow samplers were constructed to divert a representative fraction of the total flow passing through each treatment ditch into a collection tank (Figure 3.3). The design was based on that developed by Clark and Mar (1980).

The flume-like splitter structure was constructed of ¾-in. medium density overlay (MDO) board and fastened together with sub-floor adhesive and stainless steel wood screws (Figure 3.4). The 9-in.-tall diversion vanes are constructed of 1/8-in.-thick aluminum sheets set into slots routed into the MDO baseboard (Figure 3.5)

All exposed joints were sealed with silicone caulking to prevent leakage and flow disturbances. At the downstream end of the small diversion channel, an end cap for 6-in. PVC line was notched to fit securely to the downstream edge of the MDO baseboard and the aluminum vanes (Figure 3.6). The contact points were then sealed with silicone caulking. Through a series of unions and reducers, a 4-in. PVC line was attached to convey the separated water downstream to the collection box. The 4-in. PVC lines were

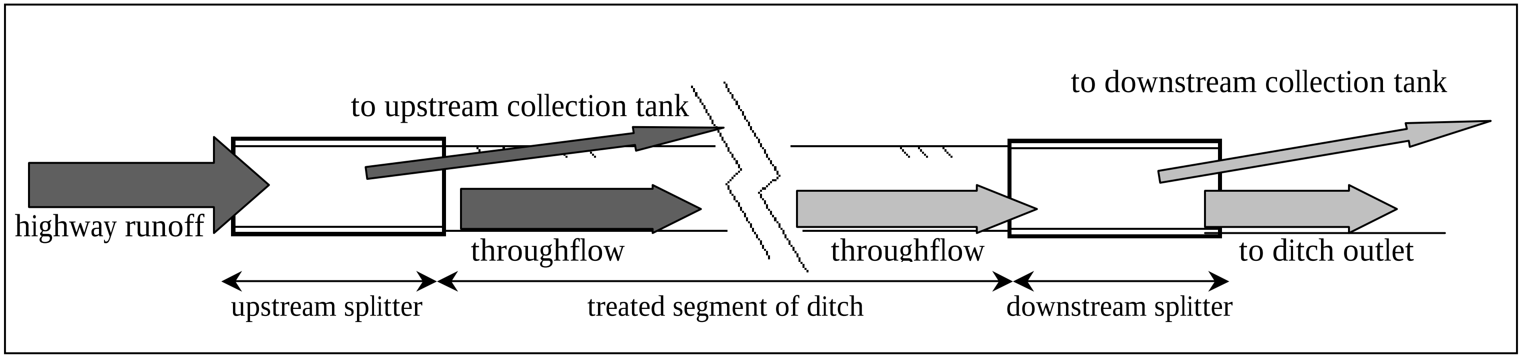


Figure 3.3 Plan view schematic of ditch site layout

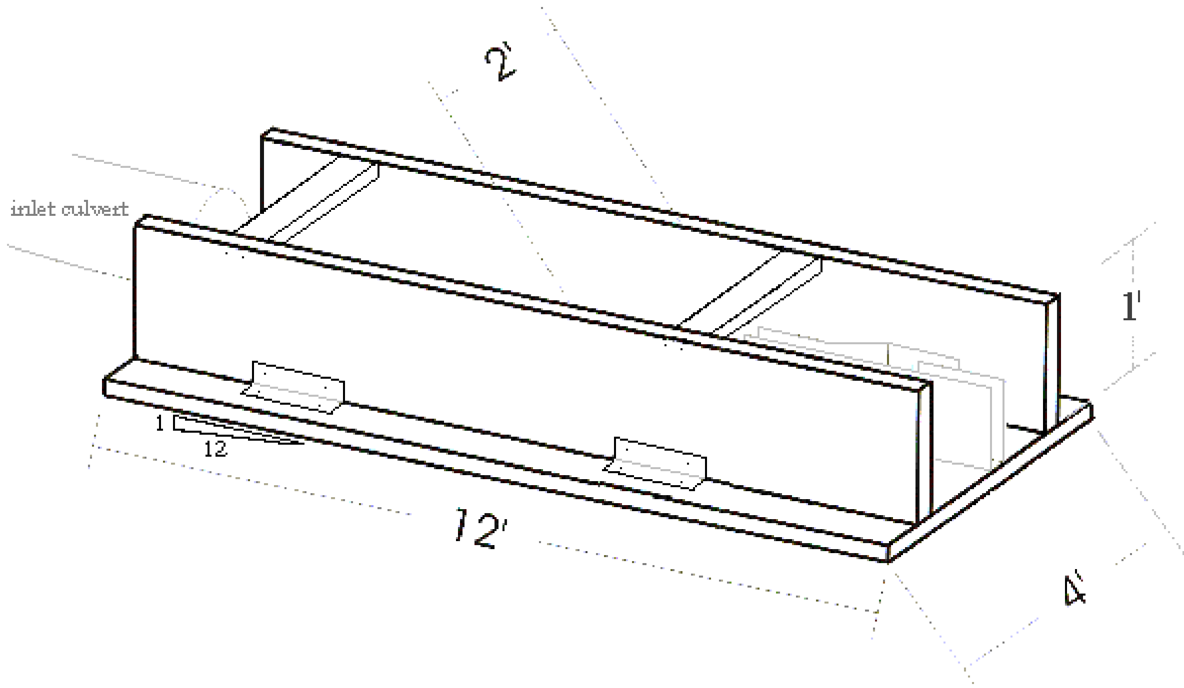


Figure 3.4 Schematic of typical composite flow splitter (inlet debris traps not shown)

Figure 3.5 Diversion channel at downstream end of composite flow splitter

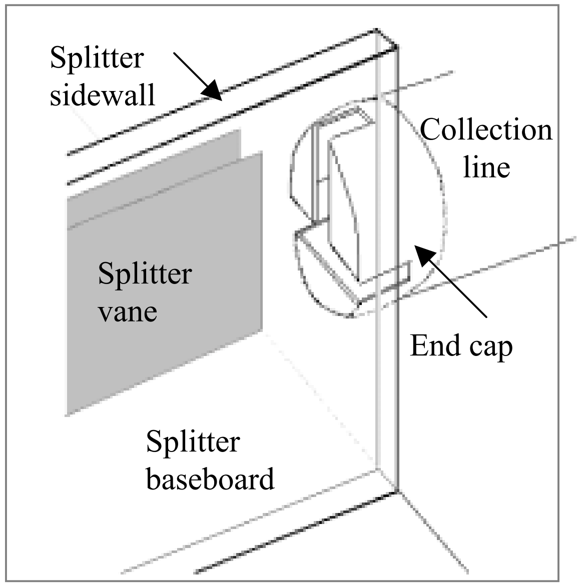


Figure 3.6 Connection between diversion channel outlet and collection line

set to reduce contact with the wetted area of the ditch segment while maintaining a gradient to maximize the velocity of the diverted water. The 10-ft-long line segments were connected together by slipping the 4-in. end of one into the slightly larger bell-end of the adjacent downstream member. Where the line might come in contact with storm water in the ditch, connection seams were sealed with silicone caulking.

The 64-ft^3 cube-shaped collection tanks were constructed of ¾-in. exterior-grade plywood. The sidewalls and bottom were lap-jointed and fastened with stainless steel wood screws. To support the bottom member, masonry blocking was set underneath each tank. To reduce the likelihood of tank failure, 2-in. x 4-in. lumber collars were set 1 ft and 3 ft from the tank base along the outside of the sidewalls. To optimize the collection capacity of the system, tanks were set so that inflows from the 4-in. conveyance line entered near the top (Figure 3.7).

Figure 3.7 Storm water conveyance lines and collection tanks

The tank bases were leveled and the sidewalls were plumbed to ensure that the depth of collected water from the tank bottom to the water surface was equal across the entire surface of the tank. The depth from the bottom of the tank to the top edge was recorded on the outside of the tank so that during data collection, the sampler need only measure the distance from the top edge of the tank to the water. This kept the measuring tape dry and reduced the possibility of contaminating the collected storm water.

The tanks were lined with 50-in. x 48-in. x 108-in. 4-mm polyethylene bags. This size allowed the bags to be folded over the top edges of the tank and provided the necessary capacity to accommodate the full tank if it were to fill with storm flow. The top of the bag was held in place by the ¾-in. plywood cover, which was sized to extend at least 1 in. beyond the tank sidewalls. One sidewall of the tank was notched to receive the 4-in. conveyance line and a small, 3-in. slit was cut into the plastic liner, through which the end of the line could be slipped.

Setting the tank bases above the existing grade facilitated sampling and draining the tanks after each sampling period. A 2-in.-diameter access hole was bored near the base of one sidewall. Through this hole, sampling personnel were able to cut a small hole into the collection tank liner for both withdrawing water samples and draining the tank.

The width of the diversion channel relative to the overall splitter width was based on calculations of total ditch through-flow for an isolated 12-hour, 1-inch rain event. The total storm flow volume was estimated with the rational method (Equation 3.2). A global value of 0.90 for the runoff coefficient, C, was selected, since each drainage catchment was over 95 percent impervious.

$$V = 0.0833 \times C \times (I \times t) \times A \qquad \text{(Eqn 3.2)}$$

where

V = total runoff volume past sampling point ft^3

C = runoff coefficient (= 0.90 for design purposes)

I = intensity of storm in/hr

t = length of storm hr

A_k = area of catchment k above sampling station ft^2

With V solved and a useable collection tank capacity of 57 ft^3, the width of the diversion channel was set to ensure that a full composite sample could be collected, without overflow losses, from the design storm.

To reduce the likelihood of splitter malfunction, a series of debris traps was installed to prevent obstruction of the diversion channel. Immediately downstream of the splitter inlet, an inclined netting trap (½-in. openings) and an inverted "rake" (consisting of three 5-in.-high rows of 1/8-in.-diameter aluminum rod) were installed in a series to trap coarse debris 1 in. or larger (Figure 3.8A). Attached to the inlet of the diversion channel, a 20-gauge aluminum wire rack was arranged to lift any passing debris above the flow area (Figure 3.8B).

Figure 3.8 (A) Inclined netting and inverted rake at splitter inlet
(B) Aluminum wire rack immediately upstream of diversion channel

To separate a consistent fraction of the total flow, the splitters were set at a minimum slope of 1:12 (V:H) to ensure that supercritical conditions occurred across the expected range of flow rates without the possibility of hydraulic jumps developing (Clark and Mar 1980). The splitters were then leveled in the lateral direction with masonry blocks and cedar shims. It was essential that the downstream outfall of the splitter be set several inches above the ditch bed. This ensured that flow disturbances and water surface elevations of the ditch flow would not interfere with the development of uniform, supercritical flow within the splitter.

3.1.4 Field Instrument Calibration

Doell (1995) found that the actual fraction of flow split by samplers, f, constructed according to the Clark and Mar (1980) design, differed significantly (by up to 87 percent) from the design spilt fraction based on splitter geometry. Therefore, calibration was necessary to determine the fraction of total ditch through-flow that was collected within the holding tanks. Initially, flow splitters were calibrated in the fall of 1999 at the Harris Hydraulics Laboratory of the University of Washington. Because of concerns that f varied with both discharge rate and inlet configuration, additional calibrations were conducted in conjunction with the on-site HRT tests (section 3.1.1). Each of six splitters was calibrated at three different flow rates (approximately 0.06, 0.15, and 0.30 ft^3/s) to bracket the range of possible storm flows. Fire hose discharges were distributed to simulate hydraulic patterns that had been observed during storm events. To account for any conveyance lines losses that may have been present in the system, diverted water was collected at the tank locations during the calibration trials. The proportion split, f, was determined by using Equation 3.3.

$$f = V_c/V_h \qquad \text{(Eqn 3.3)}$$

where f = split fraction collected in tank

V_c = collected volume from diversion channel ft^3

V_h = known discharge from hydrant ft^3

To simulate flow disturbances frequently observed during site visits, small twigs were placed between the aluminum separation vanes following the calibrations. The obstructed flow data provided information to evaluate the error associated with study results. Event ditch flow totals were based on the unobstructed calibration results.

Equations 3.4 to 3.6 were used to convert the height of water measured in the collection tank to total storm water flow of a particular series of storms. A *storm series* is defined as the collection of all storm events occurring between sampling visits.

$$V_c = (h \times A)/1728 \qquad \text{(Eqn 3.4)}$$

where V_c = volume in collection tank ft^3

h = height of water in tank in

A = surface area of water column in collection tank in^2

$$V_{T,j} = V_c / f \qquad \text{(Eqn 3.5)}$$

where $V_{T,j}$ = total storm series flow *into splitter* during event j ft^3

$$V_{d,j} = V_{T,j} \times (1-f) \qquad \text{(Eqn 3.6)}$$

where $V_{d,j}$ = total storm flow conveyed *downstream of splitter* during event j ft^3

3.1.5 Field Sampling Protocol

Samples were collected after eighteen storm series between January 9 and May 24, 2000. Generally, a "storm series" was considered to be one or more storm events totalling at least 0.3 in. of precipitation. Date, time, and current weather conditions were recorded for each site visit. Upon removing the collection tank cover, the height of the water was recorded (see section 3.1.3), and a large paddle was used to mix the tank water. A small slit was cut in the bag near the bottom through the pre-drilled drain hole. Samples were withdrawn via a 1-in. polyethylene tube slipped through the slit and were collected in polyethylene bottles. The tank was re-stirred every 10 seconds to obtain samples representative of the overall storm water influent. Bottles for the metals analysis samples were both provided and cleaned by the analytical laboratory contracted for the study. All other samples were stored in bottles previously cleaned with reagent grade water and a dilute acid wash. For each tank, three 250-mL bottles (two for TSS analysis, one for phosphorus analysis), one 125-mL bottle for metals analyses, and two 500-mL Pyrex beakers were filled. On-site measurements of temperature, pH, turbidity, and conductivity were taken using the beaker of water. A Sper scientific thermometer with 1°C gradations, a Beckman pH meter, a Hach 2100P Turbidmeter, and a Hanna Instruments HI 9033 Multi-Range Conductivity meter were used for these field measurements, respectively. (See Appendix G for detailed field sampling and analysis protocol.)

Following sample collection, the tank was allowed to drain, and a new plastic liner was installed. General site observations were recorded, with particular attention given to conditions that may have interfered with proper functioning of the flow splitters or conveyance lines.

A thorough site inspection was conducted monthly to ensure that splitters remained level, splitter outlet connections and PVC conveyance lines were securely fastened, collection tanks were supported properly, and the system was functioning as designed. Treated segments of ditch were left unaltered, and human encroachment was restricted throughout the duration of the field sampling campaign.

3.1.6 Lab Analysis Protocol

Field samples withdrawn for metals analyses were kept at ambient outdoor temperatures and delivered to the analytic laboratory (Aquatic Research, Inc. Seattle, Wash.) within six hours of collection. Total zinc and dissolved zinc were analyzed following EPA method 200.7. Total copper and dissolved copper were analyzed following EPA method 220.2. Digestion involved in the analyses of total metal species was typically performed within 18 hours of field collection. Samples were tested for total phosphorus (TP), soluble reactive phosphorus (SRP), and total suspended solids (TSS) in laboratory facilities of the Department of Civil and Environmental Engineering at the University of Washington (Seattle, Wash.). These samples were maintained at ambient outdoor temperatures during transport and transferred to a refrigerator (4°C) within 6 hours of field collection. Before refrigeration, approximately 50 mL of sample from each collection tank were filtered through a rinsed, 0.45-µm-pore-diameter membrane for SRP analysis. TSS analysis was performed within five days, and TP and SRP analyses were performed within 30 days from sample collection time. TSS analysis was performed in accordance with procedure 2540 D from Standard Methods for the Examination of Water and Wastewater (1998). TP and SRP analyses followed a colorimetric ascorbic acid method developed by the Tahoe Research Group of University of California at Davis (February 1993).

Typical quality assurance/quality control (QA/QC) procedures were followed during all laboratory work. This included field duplicates of 5 to 10 percent of the sub-samples, laboratory duplicates on 5 to 10 percent of the analyses, one spiked sample, and one method blank per batch of analyses.

3.1.7 Data Analysis and Statistical Techniques

3.1.7.1 Soil Particle Size Distribution

Cumulative frequency diagrams of soil grain size were developed by using the sieve data. The d_{50} value corresponds to the effective grain size, the size at which 50 percent of the soil sample is smaller by weight. This grain size is read directly from a cumulative frequency diagram (see Appendix I). The coefficient of uniformity, C_u, is a parameter that describes the gradation distribution of the sample (Equation 3.7). Values of 2 to 3 represent poorly graded soils, whereas values of 15 or higher are typical of very well graded material (Holtz and Kovacs 1981).

$$C_u = D_{60}/D_{10} \qquad \text{(Eqn 3.7)}$$

where D_{60} = grain diameter at which 60 percent of sample is smaller

D_{10} = grain diameter at which 10 percent of sample is smaller

Another descriptor of the grain size distribution is the geometric standard deviation, σ_g. Low values of σ_g imply a nearly uniform distribution of sediment sizes. Assuming that the grain size distribution is log-normal, σ_g can be defined by,

$$\sigma_g = \sqrt{(D_{84.1}/D_{15.9})} \qquad \text{(Eqn 3.8)}$$

where $D_{84.1}$ = grain diameter at which 84.1 percent of sample is smaller

$D_{15.9}$ = grain diameter at which 15.9 percent of sample is smaller

3.1.7.2 Hydraulic Residence Time

From the HRT tests, the mean residence time of the segment, t_h, can be defined as the time to the centroid of the distribution approximated by Equation 3.9.

$$t_h = \Sigma\, t_i \times A_i \,/\, \Sigma\, A_i \qquad \text{(Eqn 3.9)}$$

where t_i = time of absorbance reading i sec

A_i = adjusted absorbance reading at t_i

To scale mean residence time by length, Equation 3.10 was used.

$$t_s = t_h \times (L_{min}/L_k) \qquad \text{(Eqn 3.10)}$$

where t_s = length scaled mean residence time

L_{min} = length of shortest ditch

L_k = length of treatment ditch k

Mean segment flow velocity at the HRT test discharge, U_h, is derived from,

$$U_h = L_k / t_h \qquad \text{(Eqn 3.11)}$$

An approximation of the maximum velocity, U_{max}, is given by,

$$U_{max} = L_k / t_o \qquad \text{(Eqn 3.12)}$$

where t_o = time at which tracer first appears in downstream sample

If uniform flow is present, a roughness coefficient can be determined using U_h. Solving Equation 3.13 is a typical approach to obtaining a site-specific value of Manning's roughness coefficient n for the HRT test discharge rate.

$$n = 1.49/U_h \times R_h^{0.667} \times S_o^{0.5} \qquad \text{(Eqn 3.13)}$$

where S_o = mean longitudinal bed slope of the ditch

To compare HRT results among multiple sites, a representative rainfall intensity of 0.32 in/hr was selected. The fire hydrant discharge was set to simulate the representative runoff rate that a storm of this intensity would produce. At site C, the representative discharge exceeded the maximum flow rate of the fire hydrant. As with the other sites, Manning's n was derived from Equation 3.13 using the mean velocity of the HRT test discharge rate. However, this n coefficient was then used in an expanded form of Equation 2.1, to solve for U_h at the representative runoff rate.

A(t) is a higher order polynomial fitted to the plot of the adjusted spectrophotometric absorption readings as a function of time. The shape of curve A(t) provides information on whether an assumption of plug flow conditions is valid within the ditch segments. In an ideal plug flow system, all the particles of fluid enter and discharge the system in the same sequence (see Figure 3.10). In these systems the theoretical detention time, t_R, (Equation 3.14) equals t_h. In the analyses of non-uniform open channel flows, the level of accuracy of Equation 3.14 is highly dependent on accurately accounting for longitudinal changes in A_w.

$$t_R = V/Q \qquad \text{(Eqn 3.14)}$$

where $V = L_k \times A_w$

A_w = mean wetted cross-sectional area (see Figure 3.2)

Q = flow rate through channel

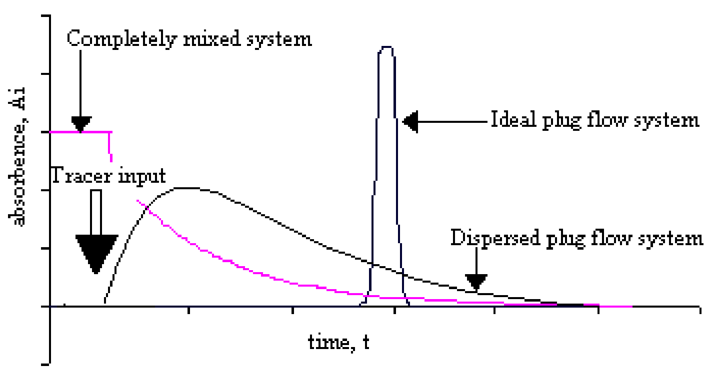


Fig 3.10 Residence time distributions, A(t), for various levels of longitudinal dispersion (from Viesmann and Hammer, 1998)

All real flows deviate from ideal plug flow, but the model is appropriate for systems with low to intermediate longitudinal dispersion numbers, δ (Equation 3.15). These systems are described as dispersed plug flows, which result from minor back-mixing and intermixing due to non-uniform velocity distributions.

$$\delta = \Gamma / (u_n \text{ X } L_K) \qquad \text{(Eqn 3.15)}$$

where Γ = longitudinal dispersion coefficient ft^2/sec

To solve for Γ, the variance of the tracer response curve, σ^2, is required (Equation 3.16). The relationship between Γ and σ^2 is given by Equation 3.17.

$$\sigma^2 = [\Sigma\, t_i^2 \text{ x } A_i / \Sigma\, A_i] - t_h^2 \qquad \text{(Eqn 3.16)}$$

where t_h is from Equation 3.9

$$\sigma^2 / t_h^2 = 2 \text{ x } \Gamma / (u_h \text{ x } L_k) - [2 \text{ x } (\Gamma / (u_h \text{ x } L_k))^2 \text{ x } (1 - e^{(-u_h \text{ x } L_k / \Gamma)})] \qquad \text{(Eqn 3.17)}$$

For most flow systems, the following ranges of δ characterize the level of longitudinal dispersion in the flow due to axial intermixing (Viesmann and Hammer 1998):

- low level of dispersion $\delta < 0.01$
- intermediate level of dispersion $0.01 < \delta < 0.10$
- high level of dispersion $\delta > 0.10$

3.1.7.3 Rainfall Data

Hourly rainfall data were from measurements recorded by a rain gage located at the Bellevue Service Center, 2901 115th Ave NE, Bellevue, Wash. Measurements from additional City of Bellevue and King County gages were reviewed to identify periods of possible sampling errors by the Service Center gage.

3.1.7.4 Flow Variables

The ditch survey and HRT test data, in conjunction with the meterological data, allowed the development of flow variables that described the theoretical flow and sediment behavior of the ditches during runoff events. These variables, discussed in section 1.1, included $\mathbb{R}_{flow}$, $\mathbb{R}_{depth}$, $\mathbb{F}$, τ_o, and θ. To characterize flow conditions that might exist during different rainfall intensities (expressed as an equivalent runoff rate, Q) Equation 3.18 was evaluated (an alternative presentation of Equation 3.13). A constant Manning's n, derived from HRT test data (see Equation 3.13), was assigned to each ditch.

$$(n \times Q) / (1.49 \times S_o^{0.5}) = (A_w/P_w)^{0.667} \times A_w \qquad \text{(Eqn 3.18)}$$

The only unknown is the flow depth, d, which defines A_w and P_w in Equation 3.18 on the basis of the cross-sectional geometry (Figure 3.1). Once the approximate d has been found iteratively, the mean velocity can be determined for each runoff rate. All of the variables are now known to solve for τ_o and θ (see sections 2.1.1 and 2.2.2), from which a theoretically stable d_{50} bed material can be approximated.

3.1.7.5 Water Quality Data

All pollutant concentration, loading, and removal efficiency values are based on storm series that meet the minimum criterion of at least one fully functioning splitter and collection system. Site-specific water quality data were used in inter-treatment analyses if both site collection tanks held a volume that represented at least 50 percent of the total estimated effective storm runoff. In the following discussion, all events, flows, and water samples meeting the above stipulations will be referred to as *qualifying.*

A key assumption behind the proceeding pollutant load reduction calculations is that the cumulative qualifying sampled storm flow of a particular treatment represents a composite sample of runoff quality characteristics that would typify the total annual runoff.

Two methods were employed to evaluate the water quality data. Method One is based on the modified direct average method developed by Marsalek (1990). Assuming that the event mean concentrations (EMCs) of the monitored water constituents for each sampling point are lognormally distributed (Driscoll 1990), the distribution of the natural logarithms of each EMC data point is normally distributed with mean μ and variance s^2. Gilbert (1987) developed the following formulas to estimate the mean $\hat{C}$ and variance b^2 of the original lognormally distributed EMCs,

$$\hat{C} = \exp(\mu + s^2/2) \qquad \text{(Eqn 3.19)}$$

$$b^2 = \mu^2 \times (\exp(s^2) - 1) \qquad \text{(Eqn 3.20)}$$

The lower and upper bounds of the 95 percent confidence interval, $\hat{C}_{lower}$ and $\hat{C}_{upper}$, for mean $\hat{C}$ are determined using Equation 3.21 (Horner et al. 1994).

95% confidence limits for lognormal mean $\hat{C}$ =

$$\hat{C} \times \exp(+/-1.96 \times [(s^2/n) + (2 \times (s^2)^3)/(n-1)]^{0.5} \qquad \text{(Eqn 3.21)}$$

where n = number of EMC data points used to determine μ

The load factor F is necessary to annualize the load data from the 5-month sampling period (Equation 3.22). The estimated total annual storm flow V_{A1} passing through a particular ditch can then be defined by Equation 3.23.

$$F = (P_T / P_S) \qquad \text{(Eqn 3.22)}$$

where P_T = average annual precipitation in

P_S = total cumulative precipitation of qualifying events in

$$V_{A1} = F \times V_{T1} \qquad \text{(Eqn 3.23)}$$

where V_{T1} = total storm flow from all qualifying storm series ft^3

To develop a probabilistic estimate of annual load X_{A1}, Equation 3.24 is appropriate (Marsalek 1991). Assuming relatively little error exists in the volume measurements, the 95 percent confidence interval for annual loading (or load removal) is given by Equation 3.25.

$$X_{A1} = V_{A1} \times \hat{C} \quad \text{(Eqn 3.24)}$$

$$V_{A1} \times \hat{C}_{lower} < X_{A1} < V_{A1} \times \hat{C}_{upper} \quad \text{(Eqn 3.25)}$$

The annual removal efficiency e_1 of a treatment for a particular storm water pollutant is determined by Equation 3.29.

$$e_1 = (V_{A1,in} \times \hat{C}_{in} - V_{A1,out} \times \hat{C}_{out})/(V_{A1,in} \times \hat{C}_{in}) \quad \text{(Eqn 3.26)}$$

where "in" refers to influent and "out" refers to effluent

and the numerator is equivalent to the annual load removal

Method Two is a modified version of the midpoint subinterval method (City of Bellevue 1995). The summation of all storm loads is calculated to determine the total load for the sampling period, X_{T2} (Equation 3.27). The sampling period load is annualized using Equation 3.28.

$$X_{T2} = \Sigma(V_i \times C_i) \text{ for all qualifying storm series} \quad \text{(Eqn 3.27)}$$

where V_i = storm runoff from sample series i

C_i = EMC of sample series i

$$X_{A2} = (P_T/P_S) \times (X_{T2}) \quad \text{(Eqn 3.28)}$$

where X_{A2} = annual load

Treatment efficiency and annual load reduction are defined as in Method One.

The annual unit load reduction, Δx, is in units of mass of pollutant foot of treatment k/year and is calculated with Equation 3.29.

$$\Delta x = [P_T \times P_S^{-1}] \times X_{T2} \times L_k^{-1} \qquad \text{(Eqn 3.29)}$$

Mean values of turbidity, conductivity, and pH were determined using Equation 3.30.

mean value of water parameter over sampling period =

$$\Sigma (Y_i \times V_i)/V_T \qquad \text{(Eqn 3.30)}$$

where Y_i = mean parameter value for storm series i

3.1.7.6 Statistical Analysis

To evaluate whether any significant differences existed between inflow and outflow water quality concentrations for a particular treatment, the Wilcoxon paired-sample test was applied. The null hypothesis, H_0, was that the effluent is the same as the influent with respect to a particular water quality parameter. The alternate hypothesis, H_A, stated that the two were significantly different.

Tests for statistical differences among treatments based on both storm loadings as well as inflow and outflow event mean concentrations were conducted. To examine the nature of the data distributions (normality, variances, and additivity), skewness and kurtosis measures, q-q plots, p-p plots, and goodness-of-fit tests were developed. When datasets were determined to fall reasonably close to normality, evaluation procedures consisted of an initial Model I one-way ANOVA to test for the presence of significant differences ($\alpha <= 0.05$) and, if necessary, Tukey's Honestly Significant Difference Test was used for multiple comparison testing ($\alpha <= 0.05$). If dataset transformations proved unsuccessful in improving normality or equalizing variances, non-parametric analysis of variance and multiple comparison techniques were employed. The Kruskal-Wallis test was conducted to determine whether any significant differences existed among the three treatments. If a significant difference ($\alpha <= 0.05$) was found to exist, the application of a nonparametric Tukey-type multiple comparisons test identified the treatments between which a significant difference existed (Zar 1999).

3.1.7.7 Cost-Benefit Analysis

A cost-benefit analysis offered an additional method of comparing the relative efficiency of each treatment. The indices used in this method (equations 3.31 to 3.33) are typically used when many options are being considered and assist in the identification of those that represent the optimum balance between financial cost and water quality benefit.

Relative Cost Index = [1-(unit cost of treatment - minimum unit cost)/ unit cost of treatment] x 100 (Eqn 3.31)

where unit cost of treatment = total treatment cost/length of ditch treated

minimum unit cost = cost of least expensive treatment

Relative Effectiveness Index = [treatment effectiveness measure/highest treatment effectiveness measure] x 100 (Eqn 3.32)

where the treatment effectiveness measure quantifies the ability of the treatment to remove a pollutant of interest (i.e., efficiency of pollutant mass loading reduction between ditch inlet and outlet for a treatment over monitoring period)

highest treatment effectiveness measure = calculated value of the most efficient treatment

Relative Cost-Effectiveness Index = [1-(cost to benefit ratio – minimum cost to benefit ratio)/cost to benefit ratio] x 100 (Eqn. 3.33) where cost to benefit ratio = unit cost/treatment effectiveness measure

minimum cost to benefit = lowest cost to benefit ratio among all treatments

3.1.7.8 Model for Estimating Ditch Cleaning Intervals

The findings regarding TSS load removal and the typical sedimentation grain size permitted the development of a simple model of bed aggradation that can be used to estimate ditch cleaning intervals. While site inspections are certainly more reliable, this model can provide an estimate of cleaning intervals to assist with scheduling and budgeting. The deterministic model presented in Equation 3.34 assumes a ditch with a rectangular cross-section.

annual depth of sediment buildup ditch {in} = [[loading to ditch inlet{lbs TSS/ft^2 of roadway/yr}] x [fraction of load removed] x [curb length of highway draining to ditch {ft}/ length of ditch {ft}] x [12 {in/ft}]] /[[dry density of sediment layer {lbs/ft^3}]$^-$ x [mean width of roadway draining to ditch {ft}] x [width of ditch {ft}]] – [Z {in}] (Eqn 3.34)

where Z accounts for losses due to infiltration or downstream movement of previously settled solids

Equation 3.35 can be used to estimate the time interval between ditch cleaning.

cleaning interval {yr} = [depth threshold {in}] x [fraction of ditch length where sediment accumulates] /[annual depth of sediment buildup ditch {in}] (Eqn 3.35)

where depth threshold = depth of sediment at which proper hydraulic and water quality functions of ditch are impaired

For most practical purposes equations 3.34 and 3.35 can be simplified by the following assumptions:

- loading to ditch inlet (western Washington, no sanding or nearby construction activity) = 0.02 lbs TSS/ft^2 of roadway/yr
- dry density of sediment layer = 110 lbs/ft^3
- depth threshold for vegetated channels (Washington State Department of Transportation 1995) = 4 in
- fraction of ditch length where "stable" sediment layer accumulates < 0.25

3.2 BIOFILTRATION SWALE SURVEY COMPONENT

3.2.1 Site Selection

Facility selection was based on brief site visits between March and April 2000 to bioswales within the current WSDOT inventory. These facilities varied in length, cross-sectional geometry, shape, slope, catchment characteristics, vegetation cover, inflow distribution, and hydraulic control features. Nineteen biofiltration swales designed to treat highway runoff were selected to represent the range of existing facilities in WSDOT's Northwest Region maintenance areas 3, 4, and 5.

3.2.2 Field Survey

Facilities were surveyed between June and August of 2000. The survey instrument was adapted from a roadside ditch survey procedure developed earlier for King and Snohomish counties. The revised procedures and survey form are presented in Appendix H. Both physical aspects and vegetation were characterized at a number of transects (between five and nine, depending on swale length) laid across the swale width. The complete facility survey consisted of two parts. First, during the initial site visit a physical survey was performed. This portion of the survey recorded drainage area characteristics, swale morphology, and geographic position. Second, a vegetation survey was performed during each site visit to document the current hydraulic and vegetation conditions of the facility. A hand-held GPS unit (Garmin GPS 12) was used to document the location of the upstream end of each surveyed facility. Swale slopes were determined with a Sokkia $C3_2$ auto level and elevation rod.

3.2.3 Maintenance Personnel Interviews

During the spring of 2000, assistant superintendents and supervisors from three of the five maintenance areas within the Northwest Region of WSDOT were interviewed regarding the maintenance of biofiltration swales. The objective of the written questionnaire and follow-up interview was to obtain an understanding of

- how biofiltration swales were maintained
- what impediments to swale maintenance existed
- what was needed to improve swale maintenance.

3.2.4 Data Analysis and Metric Development

The survey procedure was developed to identify the strengths and weaknesses of each facility. It is important to recognize the multiple objectives sought by this representative survey. First, a systematic assessment of current facilities allowed the development of a classification structure that captures the range of facilities within WSDOT's rights-of-way. This structure is presented in section 4.2.4 as a descriptive module compatible with the Maintenance Accountability Process (MAP) service level hierarchy scheme that WSDOT's Maintenance Program has adopted. To develop performance measures that would classify the maintenance Service Level of a particular swale facility, the survey data were analyzed to identify straightforward field measures that would consistently capture the condition of a facility's vegetation, hydraulic competence, and physical structure. The performance measures are presented in a format that can readily be incorporated into the current MAP manual. Photographs and detailed descriptions augment the performance measure-based Service Level classification scheme.

Second, the findings are incorporated into a variety of recommendations to assist in future facility design, maintenance, and decision-making processes. Many of these guidelines may already be followed in the facility design process. They are presented in section 4.2.3 to reinforce the characteristics that are most important to ensuring that a bioswale functions properly.

The development of physical design guidelines for biofiltration swales entailed three basic steps:

1. qualitative ranking of swale facilities based on current conditions
2. analyzing survey data for metrics that were consistently indicative of the qualitative ranking of a facility
3. screening developed metrics and guidelines in terms of implementation feasibility and relevancy to design objectives.

The ranking process (Step One) was based on facility characteristics related to maintenance, structural integrity, and vegetation condition. Each facility was ranked according to a cumulative score based on four factors. Each factor was evaluated on a 1 to 5 scale relative to the following descriptions of the extreme values:

I. Physical stability

5 = No signs of scour or slope failure

1 = Substantial incision and slope failure along majority of length

II. Water flow and distribution

5 = Introduction of runoff appropriate to optimize water treatment benefits.

1 = Poor flow introduction and distribution

III. Vegetation health

5 = Sufficient cover of suitable plants in both bed and side slopes

1 = Minimal plant coverage providing inadequate water treatment

IV. Vegetation maintenance

5 = No plant overgrowth, bed shading, and/or damage by maintenance operations.

1 = Extensive overgrowth inhibiting establishment of bed vegetation and/or significant damage due to maintenance activities.

In general, a surveyed facility with large cross-sectional areas, gentle slopes, stable beds/banks, signs of regular maintenance, and uniformity of vegetation cover would receive a favorable (high) ranking. The siting of a facility is often the underlying factor for its current physical condition. Therefore, design features and configurations that can enhance the durability and vegetation cover of the swale in a difficult setting are identified.

In Step Two, survey results regarding swale geometry and vegetation condition were analyzed to identify the bioswale characteristics that consistently support a well-functioning bioswale, as determined by the rankings of Step One. As part of this process, the potential runoff production of a drainage catchment was determined by using the SCS TR-55 methodology, which was then compared to the size of the swale.

3.3 RE-VEGETATION ENHANCEMENT COMPONENT

3.3.1 Site Characterization and Field Installation

A 350-foot ditch draining the eastbound lanes on I-90 near milepost 10 was selected for the re-vegetation/stabilization experiment. The site vegetation consisted of healthy grasses on both the side slopes and ditch bed before treatment installation. Thirteen 3-ft x 10-ft treatment plots (long axis transverse to flow) were established along the ditch centerline, each separated by 16 ft of undisturbed ditch. Each plot was cleared of all vegetation and soil containing viable seed (typically, to a depth of 4 inches below original grade). A borrow pit was excavated on-site to provide material to regrade plots, as necessary. Care was taken to set the final grades such that following installation of treatments, the ditch conveyed storm water as it had before disturbance. All subgrade was hand tamped. Standard westside WSDOT seed mix (10 percent *Agrostis tenuis*, 40 percent *Festuca rubra*, 40 percent *Lolium perenne*, and 10 percent pre-inoculated *Trifolium repens*) was applied at a rate of 3/8 oz per 10 ft^2. The exact siting of each treatment and control plot was randomly assigned. The following three treatments were applied in triplicate over the grass seed: 100 percent coconut fiber (coir) blanket (Greenfix #CFO72RR), ANTI-WASH /GEOJUTE over 1.5-in.-thick straw, and 1/3 gallon of an anionic polyacrylamide (PAM) mixture (at 4/5 oz per 100 gallon water concentration). Four control plots were established consisting of 1.5-in.-thick straw cover over grass seed.

All site preparation and treatment installation was completed in early March of 2000. An initial watering of the treatments was unnecessary because of the high moisture content of soils at the time of seeding.

3.3.2 Field Sampling

An initial blade count was conducted six weeks after treatment installation. In each plot, all the blades exceeding ½ in. high were counted within two randomly placed 0.673-ft^2 sampling grids. In early June and mid-July additional vegetation success assessments were made by using the Daubenmire cover class system for total cover and species-specific cover (Barbour et al. 1987). During the early June site visit, plant biomass was removed and measured from each treatment plot following the procedure outlined in section 3.1.1.

3.3.3 Data Analysis

Cost benefit indices were calculated following the steps discussed at the end of section 3.1.7. To compare treatment performances, a Relative Growth Measure (RGM) was developed. This measure is a summation of four normalized measures indicative of re-vegetation success based on the various readings taken on those occasions (Equation 3.36).

$$\text{RGM} = \Sigma\ [(\text{April } 24^{th} \text{ plot stem count/April } 24^{th} \text{ mean plot stem count}) + (\text{June } 9^{th} \text{ plot cover/June } 9^{th} \text{ mean plot cover}) + (\text{July } 18^{th} \text{ plot cover/July } 18^{th} \text{ mean plot cover}) + (\text{June } 9^{th} \text{ plot biomass/June } 9^{th} \text{ mean plot biomass})] \quad \text{(Eqn 3.36)}$$

Plot observations made during treatment installation and follow-up sampling visits provided additional guidance regarding both site and treatment characteristics to consider before field implementation by WSDOT personnel.

4 RESULTS AND DISCUSSION

4.1 ROADSIDE DITCH MAINTENANCE COMPONENT

4.1.1 Ditch Soils

4.1.1.1 Findings

The complete set of particle size distribution curves is provided in Appendix I. Table 4.1 summarizes the key aspects of the soil surveys completed 6 months after the application of field treatments.

Table 4.1 Ditch bed and settled storm water sediment data

		Ditch A (sod and intact strip)			Ditch B (straw only—control)			Ditch C (straw and intact strip)		
Parameter	Units	Bed mean	Deposit (1’)	Deposit (34’)	Bed mean	Deposit (3’)	Deposit[1] (86’)	Bed mean	Deposit (3’)	Deposit (77’)
Characteristic sediment size, d_{50} (at inlet)	mm	0.793 (1.57)	0.286	0.222	0.353 (0.323)	0.228	0.695	0.326 (0.271)	0.137	lost sample
Coefficient of uniformity, C_u		19.47	3.21	5.24	11.96	3.54	27.82	4.71	>3.9	
Geometric standard deviation, σ_g		5.95	2.40	3.44	10.85	2.46	>11.51	3.50	3.12	
Soil texture		loamy sand	sand	sand	loamy sand	sand	sand	sand	sandy loam	
Percent combustible		2.61%	2.14%	12.01%	1.78%	3.24%	3.29%	3.18%	5.93%	

[1] adjusted parameters after discarding material from the #4 sieve (4.75 mm openings): d_{50} = 0.29 mm, C_u, = 8.2, and σ_g = 3.5

Statistical analyses of the deposits were not possible because of the small sample sizes. The bed deposits from ditches A and C were taken from regions upstream of the intact vegetation strip. The difference in percentage of combustible material between the mean bed values (2.5 percent) and mean deposit values (5.3 percent) indicate a higher fraction of organic material in the settlable storm water solids. A significant similarity exists between the particle size distributions of three of the five bed deposits values (d_{50} ~0.24, C_u ~ 4, σ_g ~2.77). In Table 4.1, the parameter values of the sediment collected 86 ft from the inlet in ditch B could be due to fine gravel (> 4.75 mm). If this material is discounted and a d_{50}, C_u, and σ_g are recalculated, the values become 0.29, 8.2, and 3.5, respectively. In the proceeding calculations the settlable d_{50} of the three segments was assumed to be 0.25 mm.

It is appropriate to assume that the runoff d_{50} <= 0.25 mm for the duration of the present study. The uniformity of the recent deposits, as well as the lower d_{50} relative to pre-existing bed material, indicates that the likely sources of these deposits were the highway drainage areas rather than eroded portions of the ditch beds. Determination of sediment particle size distributions in ditch influents and effluents could confirm this supposition.

These data do not provide information regarding the size or quality of passing suspended material. It is possible that a large amount of nonsettlable fine material existed in the storm water flows, in which case the d_{50} values calculated above are much too large. As will be discussed later, the intact vegetation strip appeared to filter the finer material quite effectively. Theoretically, the filtration process inhibits the passage of finer suspended solids and prevents the transport of larger material re-suspended during high flow conditions.

According to highway design manuals, the uniform fine sands deposited in the study ditches are stable in flows with velocities of under 1.5 ft/sec. For the majority of sampled storms the calculated flow velocity was well under 1.5 ft/sec. It is important to note that this differs significantly from theoretical formulations, which predict that sediments with d_{50} equal to 0.25 mm would be readily transported as suspended load during most of the storms of the sampling campaign (Table 4.8).

4.1.1.2 Implications

All bed soils and accumulated sediment are larger than fine sands ($d_{50} > 0.25$ mm, $d_{10} > 0.08$ mm). Critical stress and velocity values from the literature suggest that under typical flow regimes this material should remain stable in the channel. Therefore, the key is to prevent downstream migration and bed scour during rare high flow events. Transport is most likely to occur as sediments increase in depth and if the bed plane remains smooth. Vegetation growth through the sediment layers, over planting and/or channel liners, filter strips, check dams, energy dissipaters, armoring/substrate protection (with riprap or polymer treatment), or reduction in longitudinal slope are frequently implemented measures that not only enhance settling but retain imported and native in-channel material.

4.1.2 Ditch Hydraulics

4.1.2.1 Findings

The results of the biophysical surveys and HRT tests provide information to characterize the treatment ditches. Tables 4.2 and 4.3 summarize the key features of each ditch on the basis of mean transect measurements and HRT test flow data.

The measured (and calculated) mean flow velocities through ditches A, B, and C are 0.38 (0.43), 0.71 (0.73), and 0.39 (0.39) ft/s, respectively. Because of the longitudinal changes in vegetation cover within the ditch, it is likely that the velocities of A and C

Table 4.2 Mean flow geometry measurements during HRT tests

Parameter	Units	Ditch A	Ditch B	Ditch C
HRT test discharge, Q_h	ft^3/s	0.147	0.200	0.135[3]
Equivalent runoff rate[1]	in/hr	0.32	0.32	0.17
Longitudinal slope, S_o		2.1%	2.8%	4.6%
Side slope, S_s		0.525	0.642	0.812
Length, L_s	ft	154	114	128
Flow depth, d_h	in	2.6	2.1	3.8
Flow top width, T	in	34.3	25.8	38.2
Bottom width, B	in	11.3	13.7	13.0
Wetted area, A_w	in^2	50.8	39.3	100.4
Wetted perimeter, P	in	34.6	26.4	39.3
Hydraulic radius, R_h	in	1.4	1.5	2.4
Calculated mean velocity[2], U_T	ft/s	0.43	0.73	0.39

[1] Equivalent runoff rate = 0.00333 x Q_h / A_k where A_k = catchment area of site k

[2] Uniform velocity distribution assumption, $U_T = Q_h / A_w$

[3] Inlet flow splitter diverts 50% of inflows around this ditch segment because of the relatively large contributing catchment; therefore, hydrant discharge was set at 0.270 ft^3/s

Table 4.3 Results of HRT tests

Parameter	Units	Ditch		
		A	B	C
Time at which 10% of flow has passed, t_{10}	sec	257	94	254
Time at which 90% of flow has passed, t_{90}	sec	495	204	485
Theoretical detention time, t_R	sec	370	156	331
Mean residence time, t_h	sec	380	163	328[1]
Measured mean velocity, U_h	ft/sec	0.384	0.713	0.390[1]
Approx. max. velocity, U_{max}	ft/sec	0.73	1.27	0.61
Dispersion number, δ		0.053	0.050	0.043
Symmetry parameter, G		1.06	0.98	1.03
Breadth parameter, σ		1.653	1.667	1.686

[1] Adjusted values based on a runoff rate = 0.32 in/hr (at actual HRT test discharge t_h = 378, U_h = 0.327)

differ substantially from the calculated mean, both upstream from and within, the intact vegetation strip. Equation 3.9 yields mean residence times within the treatment segments A, B, and C of 6.33, 2.72, and 5.47 minutes, respectively. If these values are scaled by length (Equation 3.10) they become 4.68, 2.72, and 4.87. Note that field inspections revealed that the filter strip of ditch C had a denser cover than the strip in ditch A because of an accumulation of straw that was transported into the vegetation filter within a month of treatment installation. The finer straw material appears to increase the cover density by infilling between the stems of the intact grass. However, the larger straw pieces tend to create detrimental blockages where it accumulates. This occurred upstream of the intact zones until a large storm event washed the material downstream of the study segments.

The δ and G parameters indicate relatively symmetric time distributions and that plug flow assumptions are reasonable. To statistically compare these parameters would require a significantly decreased sampling time interval to obtain more samples.

The residence time distributions are plotted in Figure 4.1. The mean HRT of the control ditch is significantly shorter than those of the treated sites. The same pattern is observed for the length-adjusted mean HRTs (not shown).

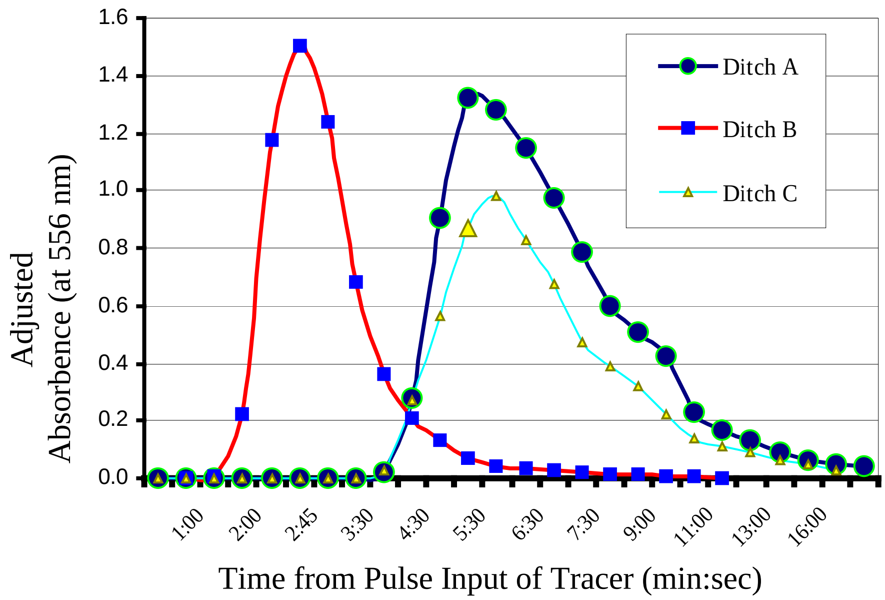


Figure 4.1 Residence time distribution curves at Q_h

4.1.2.2 Implications

The mean HRT, t_h, of both treatments (A and C) is roughly twice as long as that of the control site (B). The similarity between treatments A and C indicates that a dense intact filter strip is more effective at regulating the HRT than the presence of a cover of newly installed, short sod. The effective density of the mature grass filter strip may be enhanced through the upstream application of fine, short straw that “tracks” storm water flow into the vegetated zone and fills gaps between grass stems.

4.1.3 Splitter Calibration

4.1.3.1 Findings

The results of the unobstructed splitter calibration tests are presented in Table 4.4. Each splitter was calibrated at three flow rates. The fraction split, f, varied by as much as 35 percent between trials at different flow rates, with an unclear functional relationship. Therefore, a "representative" discharge and f value were selected using the following criteria:

(1) The approximate equivalent rainfall intensities yielding the calibration test discharges were estimated.

(2) These values were compared to the actual hourly rainfall intensities encountered during the sampling campaign.

(3) These rainfall rates seldom (<95 percent of hours with recorded rainfall) exceeded the rate represented by the minimum calibration discharge.

(4) Therefore, for all six splitters, the representative f value is based on the field trial with the lowest flow rate.

Table 4.4 Data from field calibration tests of splitter and collection system

Parameter	Units	**Splitter**					
		Ditch A		Ditch B		Ditch C	
		Up-stream	Down-stream	Up-stream	Down-stream	Up-stream	Down-stream
Discharge	ft^3/sec	0.063	0.056	0.056	0.041	0.150	0.074
Equivalent rainfall intensity	in/hr	0.151	0.134	0.100	0.073	0.051	0.051
Fraction captured, f		0.035	0.048	0.039	0.048	0.019	0.003
Obstruction related error		-16%	--	--	-4%	--	--

If time permitted during the field calibrations, obstructed flow data were collected. Small obstructions consistently reduced the split volume between 4 percent and 16 percent. These data indicate the level of accuracy associated with collected volumes from storm series when splitter obstructions were observed during the sampling campaign.

4.1.3.2 Implications

The data obtained from the splitter calibration field tests are useful for several reasons. By identifying the fraction of total flow that is diverted by each splitter, the total surface stormflow that enters and exits each experimental ditch segment can be determined. These flow data are required to perform pollutant loading calculations. Furthermore, the differences in flow between inlet and outlet splitter allows for an evaluation of infiltration rates and volumes. In the present study, infiltration rates are not discussed because of the uncertainties associated with the actual volumes of ditchflow collected in the tanks. In no case were all of the splitters fully functioning throughout the complete storm series, so an assumption of saturated soil conditions was made by which ditch inflow equals ditch outflow. By using the measured volumes of the splitter systems that appeared to have been operating properly during sample collection, the runoff volumes for all of the sites could be estimated.

As mentioned in section 3.1.3, debris traps were placed near splitters to collect large litter that could prevent proper splitter functioning. However, fine vegetation material from runoff frequently obstructed a portion of the splitter channel. Calibration tests with similar obstructions (small twigs/grass) indicated that the error resulting from these obstructions could be significant and reduce split volume. Furthermore, split fractions varied with flow rate, so it is vital to obtain a split fraction value (or range of values) that is based on calibration trials at flow rates similar to actual storm water discharge rates.

4.1.4 Storm Series and Storm Flow Data

Tables 4.5 and 4.6 summarize the storm data from the sampling campaign. Storm series 2 through 10 and 15 qualified to be used in subsequent water quality analyses. The total precipitation of these series ranged from 0.24 in. to 1.17 in. (Table 4.5) and rainfall intensities ranged from 0.02 in/hr to 0.07 in/hr (Table 4.6). Series 2, 3, and 8 qualified at all three sites.

Table 4.5 Storm series precipitation by date

Storm Series #	Dates	Series Duration at Site A	Total Precipitation	Effective Precipitation	Qualifying Storm Series (by Site)
Units		hrs	in.	in.	
1	01/09/00-01/11/00	45	0.29	0.20	
2	01/11/00-01/13/00	49	0.24	0.14	A,B,C
3	01/13/00-01/16/00	71	0.67	0.42	A^{d},B,C^{u}
4A	01/23/00-02/01/00	215	1.18	0.34	
4	02/01/00-02/08/00	170	1.17	0.73[1]	A^{d},$C^{d,u}$
5	02/08/00-02/10/00	48	0.26	0.26[1]	A,C
6	02/10/00-02/15/00	119	0.48	0.38	A,C
7	02/15/00-02/22/00	169	0.45	0.23	A,C
8	02/22/00-02/24/00	51	0.31	0.29	A,B,C
9	02/24/00-02/29/00	120	0.97	0.65	B,C
10	03/01/00-03/07/00	141	1.01	0.85	$C^{d,u}$
11	03/07/00-03/15/00	192	0.92	0.58	
12	03/28/00-04/05/00	192	0.60	0.33	
13	04/05/00-04/14/00	218	0.50	0.30	
14	04/14/00-04/24/00	238	0.32	0.11	
15	04/24/00-05/03/00	218	0.76	0.58	$C^{d,u}$
16	05/03/00-05/10/00	170	0.87	0.59	
17	05/10/00-05/24/00	335	0.79	0.37	

[1]On 02/08/00 samples were collected during a heavy rain. Therefore, for series #4 the effective precipitation amounts at site B and site C were 0.94" and 0.88", respectively. For series #5 the effective precipitation at site B and site C was 0.20" and 0.18", respectively.
[d]Overfilled downstream sampler collection tank (but with <50% of split volume lost)
[u]Overfilled upstream sampler collection tank (but with <50% of split volume lost)

Table 4.6 Event characteristics: runoff volumes

Event #	Runoff Volume at A	Runoff Volume at B	Runoff Volume at C	Effective Rainfall Intensity	Antecedent Conditions	Maintenance Activities
	ft^3	ft^3	ft^3	in/hr		
1	333	450	1225		1 day w/o rain	Sweep 1/11
2	217	293	758	0.019	Many storms w/ < 16 hrs of dry	
3	700	945	2450	0.032	Many storms w/ < 16 hrs of dry	
4A	567	765	1983		9 days w/ < 0.1" total preceding 1/21 storm	Vactor 1/19
4	1217	2115	5133	0.041	20% of collected w/o any dry period; 80% preceded by 5.5 days w/ <0.06" cum.	Sweep 2/7 & 2/9
5	433	450	1050	0.050	No dry	
6	633	855	2217	0.038	5.5 days w/o rain	
7	383	518	1341	0.029	6 days w/o rain	Sweep 2/15-2/18
8	483	653	1692	0.074	2 hours w/o rain	
9	1083	1463	3792	0.027	3 storms < 1 day w/o rain	
10	1417	1913	4958	0.035	2 storms < 1 day w/o rain	
11	967	1305	3383		6 days w/o rain then intermittent for 4 days	Possible sweep 3/14
12	550	743	1925		2 storms each with 6 days w/o rain	Sweep 4/4
13	500	675	1750		6 days w/o rain	
14	183	248	642		6 days w/o rain	
15	967	1305	3383	0.038	Intermittent rain < 2 days w/o rain	Vactor 4/25
16	983	1328	3442		Intermittent rain < 2 days w/o rain	
17	617	833	2158		12 days with 3 brief downpours	

The "effective precipitation" values are based on observed differences between total series rainfall and the rainfall volume represented in the collection tanks of functioning samplers. This value is equivalent to the depth of runoff distributed uniformly over the drainage catchment. The qualifying series (defined in section 3.1.7.5) used in the cross-treatment water quality analyses are identified by site in Table 4.5.

The "effective rainfall intensity" values are from Equation 4.1. Runoff is dependent on antecedent conditions and type of storm; in general "effective precipitation" (runoff producing) occurred when rainfall intensities exceeded 0.03 in/hr.

$$I_i = \Sigma P_i / t \qquad \text{(Eqn 4.1)}$$

where I_i = effective rainfall intensity during storm series i in/hr

P_i = total effective precipitation for storm series i in

t = time of effective precipitation for storm series i hr

Table 4.7 summarizes the precipitation data of the qualifying storm series at each treatment site. The qualifying rainfall to total annual rainfall ratio is the inverse of the load factor, F (Equation 3.25), that is used to annualize load values in subsequent calculations. The total qualifying runoff volume can be used with mean concentration data to determine loadings and load removal rates.

Table 4.7 Hydro-meterological summary by treatment site

Ditch	Number of Qualifying Series	Total Qualifying Rainfall	[1]Ratio of Qualifying Rainfall to Total Annual Rainfall	Total Qualifying Runoff Volume
Units		in		ft^3
A	7[A]	3.58	0.092	4083
B	4[B]	2.19	0.056	3354
C	10[C]	6.32	0.162	26774

[1] Based on total annual rainfall of 39"
[A] SRP analysis conducted for 3 series
[B] SRP analysis conducted for 1 series and TP analysis conducted for 3 series
[C] SRP analysis conducted for 5 series and metals analysis conducted for 9 series

Table 4.8 categorizes the source of sampled storm events by storm size class. In order to validate the assumption that the sampled storm series is representative of the annual storm distributions, it is important to consider the distribution of storm sizes.

Table 4.8 Percentage of qualifying storm events by storm size class

Storm Size Class	Site A	Site B	Site C	Typical King County
< 0.3"	20.0%	36.3%	35.0%	41.0%
0.3"-0.6"	43.4%	63.7%	42.2%	33.0%
0.6"-0.9"	13.9%	0.0%	21.6%	13.0%
0.9"-1.2"	22.8%	0.0%	16.6%	5.0%
>1.2"	0.0%	0.0%	0.0%	8.0%

The data in Table 4.8 indicate that the sampled storm events may not be representative of the annual distribution of storm and runoff patterns. This observation, coupled with the fact that pollutant deposition on roadways may vary seasonally, suggests that the annual loading and removal values presented in section 4.1.4 need to be interpreted cautiously.

To evaluate the impact on sediment transport, the PSD data (Table 4.1) and storm intensity data (tables 4.5 and 4.6) can be incorporated into a simple theoretical analysis of bed sediment stability. Table 4.9 summarizes the data required for and generated by an analysis procedure using the Shield's parameter (section 2.2.2).

According to the Shield's criteria, relatively large grain sizes, an order of magnitude higher than both the bed substrate and the deposited sediment within the study ditches, are required for a stable bed. Design manuals for roadside ditches state that 0.25

mm material (fine sand) is stable with velocities of up to 1.5 feet per second (FHWA 1965). Therefore, it appears that the Shield's analysis is an extremely conservative method for determining bed stability.

Table 4.9 Range of flow characteristics based on HRT tests and storm series data (stability analysis)

	Units	Site A		Site B		Site C	
		High flows	Typical flows	High flows	Typical flows	High flows	Typical flows
Storm intensity, I	in/hr	0.15	0.04	0.15	0.04	0.15	0.04
Ditch flow, Q	ft^3/sec	0.07	0.02	0.09	0.03	0.24	0.06
n (from HRT test)	from HRT	0.14	0.14	0.09	0.09	0.33	0.33
d	ft	0.11	0.05	0.09	0.04	0.28	0.13
U	ft/sec	0.32	0.20	0.53	0.33	0.35	0.22
u_*	ft/sec	0.25	0.17	0.26	0.19	0.57	0.41
F		0.19	0.16	0.33	0.29	0.13	0.12
$\mathbb{R}_{depth}$		6898	2158	9749	2987	18090	6057
$\mathbb{R}_{bed}$		296	105	364	123	3749	1323
τ_o	psf	0.118	0.059	0.134	0.067	0.624	0.322
θ		0.057	0.057	0.057	0.059	0.055	0.058
stable grain size based on Shields' analysis, d_{50}	in (mm)	0.24 (6.1)	0.12 (3.0)	0.28 (7.0)	0.13 (3.4)	1.32 (33.5)	0.65 (16.5)
stable grain class		fine gravel	very fine gravel	fine gravel	very fine gravel	very coarse gravel	medium gravel

4.1.5 Water Quality Constituent Analyses

4.1.5.1 Total and Unit Pollutant Load Removal and Removal Efficiency Analysis

Table 4.10 provides the three-site mean EMCs at the ditch inlets based on the qualifying storm series. These values are similar to data from other studies on runoff from heavily traveled highways. Compared with the eight-site average (from Table 2.1), the EMCs of the present study are lower than what would be expected for a highway with such a large daily vehicular volume (study values are 29 percent lower than eight-site mean for TSS, 56 percent lower for total zinc, 61 percent lower for total copper, and 2 percent lower for total phosphorus).

Table 4.10 Highway runoff characteristics based on qualifying storm series—all sites (01/00 to 05/00)

Storm water parameter	Units	EMC	95% Confidence Interval	
			Lower bound	Upper bound
Total suspended solids	mg/L	108.6	72.9	130.9
Turbidity	NTU	132.4	98.8	166.0
Total extractable zinc	µg/L	112.1	86.2	145.7
Dissolved zinc	µg/L	50.6	33.8	64.3
Total extractable copper	µg/L	24.9	16.0	29.6
Dissolved copper	µg/L	9.4	6.3	12.2
Total phosphorus	µg/L	255.1	162.3	313.9
Soluble reactive phosphorus	µg/L	10.2	5.9	13.9
Conductivity	µS/cm	84.1	65.5	102.7
pH		7.20	7.04	7.35

Many of the previous studies were multi-year sampling projects that captured any seasonal changes in pollutant loading and precipitation patterns, which this project was unable to examine.

Table 4.11 summarizes the mean influent data at each of the three sites. The EMC data were developed with Method 1 (section 3.1.7) and the other parameters were derived from Equation 3.33. These data highlight the differences existing between the runoff to ditches A and C. In particular, the TSS and turbidity values at site A were substantially less and exhibited less scatter than those at site C.

Table 4.11 Mean highway runoff values and 95 percent confidence intervals—by site (January-May, 2000)

Parameter	Units	Ditch		
		A	**B**	**C**
TSS	mg/L	**64.8**	**89.2**	**147.1**
		49.0 - 85.6	63.5 - 125.2	76.0 - 284.8
Total extractable zinc	μg/L	**92.9**	**105.1**	**133.5**
		57.2 - 150.9	58.0 – 190.6	92.4 - 192.9
Dissolved zinc	μg/L	**32.6**	**54.6**	**62.8**
		23.7 - 45.0	11.7 - 254.7	43.7 - 90.1
Total extractable copper	μg/L	**24.2**	**21.4**	**27.0**
		12.2 - 48.2	4.8 - 95.8	12.0 - 61.0
Dissolved copper	μg/L	**10.4**	**6.3**	**10.1**
		5.9 - 18.4	5.1 - 7.8	6.2 - 16.2
Total phosphorus	μg/L	**160.1**	**275.6**	**315.5**
		130.9 - 195.7	44.7 - 1699.8	154.3 -645.2
SRP	μg/L	**12.5**	**4.7**	**9.9**
		6.1 – 25.4	--	6.7 - 14.8
Turbidity	NTU	**101.0**	**123.5**	**157.9**
		66.0 -136.0	37.3 - 209.8	91.3 -224.5
Conductivity	μS/cm	**110.6**	**93.7**	**61.7**
		80.2 - 141.0	0.0 - 202.9	49.7 - 73.8
pH		**7.29**	**7.42**	**7.03**
		7.08 - 7.50	7.22 - 7.62	6.74 - 7.31

The ratios of dissolved to total concentration of metal species is indicative of the partitioning characteristics of the heavy metals in the runoff, and typically, relatively high dissolved concentrations are more toxic and difficult to treat. For zinc, the dissolved to total ratio was 0.36 at site A, 0.52 at site B, and 0.48 at site C. For copper, the values were 0.44 at site A, 0.33 at site B, and 0.40 at site C.

Tables 4.12 through 4.19 were developed with Method 1 (section 3.1.7) and summarize the mean EMC differences and removal efficiencies based on influent and effluent concentrations. From the concentration change, an annual load removal value can be calculated (the numerator of Equation 3.29). In Table 4.12, it is evident that both ditch A and ditch C performed better than ditch B at removing TSS loads. In comparison to ditch C, ditch A had a lower EMC reduction but a higher removal efficiency. This is a result of a lower influent TSS concentration into ditch A, whereas TSS influent concentrations to ditch C were the highest among the three sites.

Table 4.12 Total suspended solids: concentration and load reductions

Site	n	Mean EMC Reduction	95% Confidence Interval		Annual Load Removal	95% Confidence Interval		Removal efficiency
			lower bound	upper bound		lower bound	upper bound	
		mg/L	mg/L	mg/L	kg/yr	kg/yr	kg/yr	
Ditch A	7	**33.5**	8.4	61.6	**41.6**	10.5	77.3	**0.52**
Ditch B	4	**10.3**	-46.5	68.7	**16.6**	-78.7	116.2	**0.11**
Ditch C	10	**48.4**	-143.9	240.5	**229.6**	-673.5	1125.2	**0.37**

The combination of resodding and leaving an intact vegetation strip (treatment A) appeared to reduce the effluent TSS *concentration* slightly below that of the using the straw mulch and intact strip treatment (treatment C).

The large difference between TSS load removal values at sites A and C can be explained in part by the high concentrations of suspended solids in the influent of Site C. The high concentration of influent TSS (above 100 mg/L) at site C may be due to sand sized material, which settles out relatively rapidly. This appears to be a reasonable assumption since similar mean influent turbidity measurements (91 NTU and 132 NTU for sites A and C, respectively) were observed, indicating that the finer material associated with turbidity was equivalent across both catchments.

Because of the lack of statistically significant differences between treatments, the results of the metals analysis must be interpreted cautiously. Two points do appear justified. First, neither sites A nor C was a source of metal species to downstream waters. Second, as depicted in tables 4.13 and 4.21, both treatments were able to reduce total zinc concentrations by about 25 percent. This agrees with reports by other researchers that zinc has a relatively high tendency to partition to settlable particulate material.

Ditch A was consistently able to reduce the effluent concentrations a modest amount for all the metal analytes (between 15 to 33 percent), and at lower influent loads, ditch C might have been just as effective. It is interesting to note the high efficiency of the control ditch (see tables 4.15 and 4.21) at removing total zinc and total copper. However, with large confidence intervals, low concentrations, and a small sample size, a single anomalous event could significantly distort the values. Therefore, it would be difficult to characterize the site's annual removal potential.

Table 4.13 Total extractable zinc: concentration and load reductions

Site	n	EMC Removal	95% Confidence Interval		Annual Load Removal	95% Confidence Interval		Removal efficiency
			lower bound	upper bound		lower bound	upper bound	
					g/yr	g/yr	g/yr	
Ditch A	7	**31.1**	-35.5	109.7	**37.5**	-44.5	137.6	**0.33**
Ditch B	4	**21.3**	-150.1	105.3	**39.9**	-114.8	158.8	**0.22**
Ditch C	9	**29.5**[1]	-46.1	114.7	**130.0**	-220.1	547.7	**0.21**

Table 4.14 Dissolved zinc: concentration and load reductions

Site	n	EMC Removal	95% Confidence Interval lower bound	95% Confidence Interval upper bound	Annual Load Removal	95% Confidence Interval lower bound	95% Confidence Interval upper bound	Removal efficiency
					g/yr	g/yr	g/yr	
Ditch A	7	**5.2**	-13.1	24.5	**5.9**	-16.4	30.7	**0.15**
Ditch B	4	**28.0**	-21.0	233.0	**46.5**	-35.5	394.1	**0.59**
Ditch C	9	**11.8**	-19.1	48.7	**53.0**	-91.2	232.6	**0.18**

Table 4.15 Total extractable copper: concentration and load reductions

Site	n	EMC Removal	95% Confidence Interval lower bound	95% Confidence Interval upper bound	Annual Load Removal	95% Confidence Interval lower bound	95% Confidence Interval upper bound	Removal efficiency
					g/yr	g/yr	g/yr	
Ditch A	7	**10.0**	-11.0	39.4	**6.6**	-13.8	49.4	**0.23**
Ditch B	4	**4.0**	-53.3	90.6	**4.9**	-90.2	153.3	**0.16**
Ditch C	9	**3.8**	-34.0	49.3	**16.1**	-162.4	235.4	**0.13**

Table 4.16 Dissolved copper: concentration and load reductions

Site	n	EMC Removal	95% Confidence Interval lower bound	95% Confidence Interval upper bound	Annual Load Removal	95% Confidence Interval lower bound	95% Confidence Interval upper bound	Removal efficiency
					g/yr	g/yr	g/yr	
Ditch A	7	**2.7**	-4.4	12.6	**3.0**	-5.5	15.8	**0.24**
Ditch B	4	**0.8**	-1.0	2.9	**1.3**	-1.7	4.9	**0.12**
Ditch C	9	**0.6**	-6.7	9.3	**4.2**	-32.0	44.4	**0.09**

Because of interferences from particulate matter during spectrophotometric analysis, the concentrations of total and soluble reactive phosphorus in many of the collected samples were highly suspect and therefore not included in the site comparisons (see table notes of Table 4.7). In general, the sites performed quite well at removing total phosphorus from the storm water stream. The positive results indicated in table 4.17 for the control site are due to a single storm event. In the other two events, the site acted as a source of total phosphorus. While both ditches A and C had a positive effect in terms of phosphorus removal, the higher efficiency rate of ditch C should be noted. In the case of metals, both treatments performed similarly, but ditch C was more efficient in terms of total phosphorus removal in both the EMC-based analysis (Method 1) and the summation-based analysis (Method 2). It is possible that the phosphorus compounds were attached to larger particulates, and since ditch C received a higher TSS loading, the rate of removal was higher.

Table 4.17 Total phosphorus: concentration and load reductions

Site	n	EMC Removal	95% Confidence Interval lower bound	95% Confidence Interval upper bound	Annual Load Removal	95% Confidence Interval lower bound	95% Confidence Interval upper bound	Removal efficiency
					g/yr	g/yr	g/yr	
Ditch A	7	**32.7**	-23.4	90.6	**40.7**	-29.4	113.7	**0.20**
Ditch B	3	**140.53**	-162.1	1611.6	**187.1**	-283.8	2821.0	**0.45**
Ditch C	10	**131.67**	-178.1	543.5	**540.4**	-833.1	2542.8	**0.39**

Table 4.18 Soluble reactive phosphorus (SRP): concentration and load reductions

Site	n	EMC Removal	95% Confidence Interval lower bound	95% Confidence Interval upper bound	Annual Load Removal	95% Confidence Interval lower bound	95% Confidence Interval upper bound	Removal efficiency
					g/yr	g/yr	g/yr	
Ditch A	3	**-5.2**	-12.8	8.9	**-7.9**	-17.4	12.1	**-0.49**
Ditch B	1	**-0.2**	-0.2	-0.2	**-0.6**	-0.6	-0.6	**-0.05**
Ditch C	5	**-0.2**	-7.1	7.4	**-1.2**	-38.2	39.7	**-0.02**

Conversely, the affiliation of adsorbed metal species with smaller clay fractions may have limited either facility's ability to reduce metals below a certain concentration. There is evidence of poor fines removal in the turbidity data presented in Table 4.19. The lower influent turbidity at site A did not result in a substantially lower effluent level, relative to site C. This observation is interesting given that the maximum influent readings for sites A and C were 154 NTU and 342 NTU, respectively.

Table 4.19 Flow-weighted mean values of field measured water quality parameters

Parameter	**Symbol**	**Units**	**Site**		
			A	B	C
Mean Influent Turbidity		NTU	91	100	132
Mean Turbidity Difference (in – out)		NTU	23	-2	37
Mean Percent Change			23.4%	-13.3%	22.4%
Mean Influent Conductivity		μS/cm	102.1	71.5	59.3
Mean Conductivity Difference (in – out)		μS/cm	-11.6[1,2]	-1.3[1]	3.4[2]
Mean Percent Change			-11.1%	-3.2%	3.9%
Mean Influent pH			7.2	7.4	7.0
Mean pH Difference (in – out)			-0.2[3]	0.3[3,4]	-0.1[4]
Mean Percent Change			-2.2%	4.6%	-1.2%

[1] significant difference between sites ($\alpha = 0.05$, $p = 0.008$)
[2] significant difference between sites ($\alpha = 0.05$, $p = 0.01$)
[3] significant difference between sites ($\alpha = 0.05$, $p = 0.027$)
[4] significant difference between sites ($\alpha = 0.05$, $p = 0.001$)

Table 4.20 presents a qualitative summary of the effects of each treatment on storm water quality. Numbers in the “-“ and “+” columns are the counts of samples for which the effluent concentration was less than or greater than the influent, respectively. It confirms findings discussed above, primarily the following:

- Both ditches A and C consistently reduced the downstream concentration of total suspended solids and total zinc.
- Both ditches A and C were modestly successful at reducing downstream turbidity and total phosphorus levels.

- Results for other constituents were variable, and treatment success for a particular storm event would likely be related to storm and runoff characteristics.

Table 4.20 Sign analysis of difference between effluent and influent values ("-" means $C_{out} < C_{in}$, "+" means $C_{out} >= C_{in}$)

Water Quality Constituent	Ditch A		Ditch B		Ditch C	
	-	+	-	+	-	+
TSS	7	0	2	2	10	0
Total Zinc	6	1	4	0	9	0
Dissolved Zinc	6	1	2	2	5	4
Total Copper	5	2	4	0	6	3
Dissolved Copper	5	2	3	1	3	6
Total Phosphorus	5	2	1	2	8	2
SRP	1	2	0	1	3	2
Turbidity	6	1	2	2	8	2
Conductivity	0	7	3	1	5	5
pH	2	5	4	0	3	6

Table 4.21 presents the results of the second analysis methodology, discussed in section 3.1.7.5 (Method 2). The patterns in the results discussed above were confirmed in most respects. The anomalous high removal efficiency rate by the control for dissolved copper was not apparent. This is probably because the high concentration reductions occurred during the lower runoff events, and in Method 2 each value is scaled by the corresponding runoff volume it came from. The same is true for total phosphorus load removals and efficiency. These differences point out the weakness of Method 1 when there are few sampling points and the data point distribution is widely scattered or follows a lognormal pattern. The most interesting aspect of the data is the magnitude of pollutants removed by ditch C. The total annual load removal values at site C exceeded those values at sites A and B several fold for all analytes except SRP. Some of these

Table 4.21 Loading, removals, and efficiency for storm water constituents based on qualifying composite samples (01/00 and 05/00) (Method 2)

Parameter	Units	Ditch A	Ditch B	Ditch C
TSS annual loading	g/yr	73079	130825	533883
TSS annual removal	g/yr	36154[1]	16804[2]	213940[1,2]
TSS removal efficiency	g/g	0.495	0.128[A]	0.401
TSS unit length annual removal	g/ft-yr	234.8	147.4	1671.4
Total Zinc annual loading	g/yr	105.3	137.5	546.1
Total Zinc annual removal	g/yr	23.6	35.0	129.5
Total Zinc removal efficiency	g/g	0.224	0.225	0.237
Total Zinc unit length annual removal	mg/ft-yr	153	307	1012
Dissolved Zinc annual loading	g/yr	44.5	58.7	299.3
Dissolved Zinc annual removal	g/yr	10.7	15.1	66.5
Dissolved Zinc removal efficiency	g/g	0.239	0.257	0.222
Dissolved Zinc unit length annual removal	mg/ft-yr	70	132	520
Total Copper annual loading	g/yr	27.1	25.8	101.6
Total Copper annual removal	g/yr	5.5	5.6	23.6
Total Copper removal efficiency	g/g	0.204	0.216	0.233
Total Copper unit length annual removal	mg/ft-yr	36	49	184
Dissolved Copper annual loading	g/yr	14.3	9.8	54.4
Dissolved Copper annual removal	g/yr	3.6	0.6	9.6
Dissolved Copper removal efficiency	g/g	0.252	0.065	0.177
Dissolved Copper unit length annual removal	mg/ft-yr	23	5	75
Total Phosphorus annual loading	g/yr	188.3	260.8	1283.3
Total Phosphorus annual removal	g/yr	40.8	45.6	660.7
Total Phosphorus removal efficiency	g/g	0.216	0.175	0.515
Total Phosphorus unit length annual removal	mg/ft-yr	265	400	5162
SRP annual loading	g/yr	15.9	10.9	41.2
SRP annual removal	g/yr	-8.7	-0.6	-3.6
SRP removal efficiency	g/g	-0.545	-0.051	-0.088
SRP unit length annual removal	mg/ft-yr	-57	-5	-28

[1] Reject H_o at $\alpha = 0.05$ ($p = 0.043$)
[2]Reject H_o at $\alpha = 0.05$ ($p = 0\ 030$)

differences are possibly due to the variability of influent quality characteristics that can exist among sites receiving equivalent traffic flows and rainfall patterns. The observed influent variability could be accounted for by differences in shoulder maintenance or high inputs from a small portion of the drainage area that is landscaped. While it is not possible to predict how sites A and B would have responded to the higher loading, it is reasonable to state that site C is capable of appreciably reducing loading. Ditch C was in a storm water treatment train that was upstream of a small detention pond. The reduction in pollutant loading improves the pond's treatment capabilities and increases the intervals between maintenance to remove excessive sediment accumulation.

4.1.5.2 Discussion of treatment effects

Since many researchers have that found storm water quality parameters display a strong functional relationship to storm event characteristics, two methodologies were used to approximate total load removals for key water quality parameters. In Method 1 (modified direct average method), a representative EMC is defined for each constituent and then multiplied by runoff total for the sampling period and rainfall factor to develop annual values for total loading, removals, and efficiencies. Method 2 (modified midpoint subinterval method) entails calculating the cumulative loading over the sampling period and then multiplying by a factor to produce annual values. The results of the two approaches are quite similar; the key findings are summarized below.

- Both treatments (sod with filter strip and straw with filter strip) reduced *total loads* of TSS in comparison to the control site (straw only).
- Both treatments showed *higher removal efficiences* of TSS loads in comparison to the control site.

- All sites appeared reasonably effective at reducing total phosphorus loads. Both analytical methodologies indicated that the straw with filter strip treatment was 40 to 50 percent effective.
- Successful reduction of dissolved metals and turbidity below a certain level is doubtful because of the association of these constituents with fine particles that may not be settlable under flowing conditions.
- In general, Site C performed quite well relative to Site A. There is concern about which site would perform best under the wide variety of possible solids loading conditions within the WSDOT system. Treatment C handled high loadings well, and the tendency for sod to be smothered by sediments would indicate that sod is not appropriate at a high loading site when installed during the wet season. The other concern is Treatment C's ability to reduce pollutant concentrations when influent EMCs are low. This issue can be addressed by examining series 9, 10, and 15, for which the mean influent TSS at Ditch C was only 45.4 mg/L. However, the facility was able to reduce the mean effluent to 27.1 mg/L, equivalent to a mean removal efficiency of 42 percent. The storms in these series were characterized by large total runoff volume and moderate intensity.

4.1.6 Sedimentation Rates

4.1.6.1 Findings

Stable bed material, sediment settling velocity, and bed aggradation rates were approximated with several widely applied models. The most complete ditch sediment model entails a two-part process. First, the deposition rate of sediment into the channel is predicted, followed by an evaluation of the downstream redistribution rate due to bedload transport and/or resuspension. The second part of this analysis requires an understanding of bed shear stress and suspended load capacitance values, which was beyond the scope of the current study.

Equation 3.35 was used to calculate the approximate intervals between ditch cleanings. On the basis of the sediment found in the ditch beds, the TSS removal rates, and annual flow volumes, an interval on the order of two to three years was calculated. These intervals assume complete retention of settled material within the ditch, which is likely to occur only in facilities with low gradient slopes, check dams, and substantial bottom roughness.

4.1.6.2 Implications

Assuming in-channel retention of settled material, theoretical cleaning intervals are on the order of 2 to 3 years. This interval may decrease if settled material is constrained to a small fraction of total ditch length, if the ditch is undersized for the catchment, or if construction activities introduce loads above typical vehicular inputs. On the basis of these findings and field observations, the following suggestion regarding maintenance procedures are offered:

- Schedule all cleaning during dry weather months when regrowth is apt to be most rapid. This will reduce the likelihood of downstream sediment loading and channel erosion.
- Small adjustments in grade or control structures may significantly reduce the interval of full-length cleaning by enhancing settling. These low-gradient areas can be designed for easy manual cleanout.

- Observations of storm flow characteristics and highway sediment accumulations may provide site-specific solutions to downstream loading issues.

Maintaining a functional filter strip at the time of cleaning can effectively reduce loading to receiving waters or downstream treatment facilities. Additional concerns include preventing scour and establishing regrowth in the cleared segment, encouraging upstream sedimentation so that the functioning filter strip is not overwhelmed with sediment, and retaining this settled sediment between cleanings. To reduce scour and encourage regrowth, the following options exist:

- time cleaning to coincide with reduced flows but sufficient precipitation to enhance germination success of revegetation seed (especially if supplemental irrigation is not an option)
- place energy dissipaters, stilling basins, or flow spreaders where high discharge infalls are present
- use polymers, mulches, or erosion control mattings on side slopes and, possibly, in channel beds
- use temporary check structures (cobble dams, straw bales, transverse silt fencing), especially in facilities where no healthy vegetation exists downstream of the cleaned section.

If vegetation regrowth is successful and inflow energy is dissipated, the most significant remaining concerns are to prevent sediment accumulations from smothering vegetation, retain settled material between cleanings, reduce general maintenance demands, and enhance the filtering capability of the healthy vegetation. An in-channel control structure is proposed to both meet these needs and avoid the difficulties associated with standard check structures. The structure is best described as an in-channel “pocket pond.” Where rights-of-way allow and water tables are deep enough, a below-grade depression could be excavated immediately upstream of the intact vegetation strip. The schematics in figures 4.2 and 4.3 best describe the ideal layout. These structures could be part of a retrofit or original construction. The preference is for vegetation to remain downstream of the “pond” to filter fully suspended material. Since there is a channel transition in the design, careful construction and the use of appropriate soils is required. Areas of high slope and extremely large discharges may not be suitable for use. The pond’s best application may be in areas where low to moderate flows occur (i.e., sites draining less than one-half acre or generating less than 0.5 cfs for the 10 year storm).

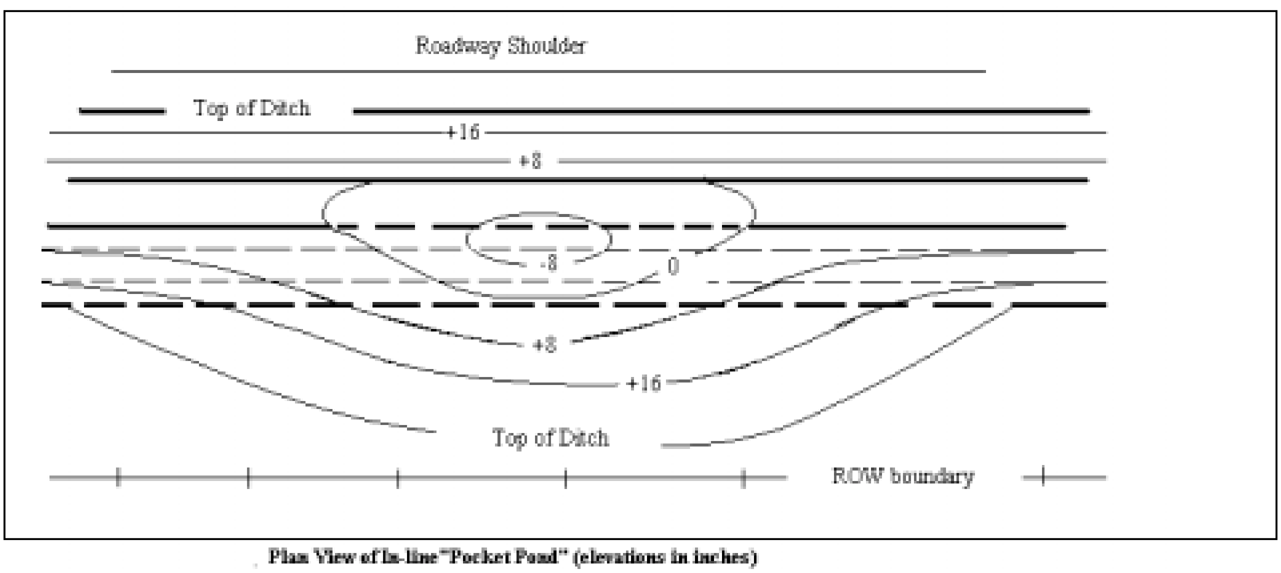


Figure 4.2 Plan view of in-line “pocket pond” (elevation in inches) (dashed lines depict original ditch configuration)

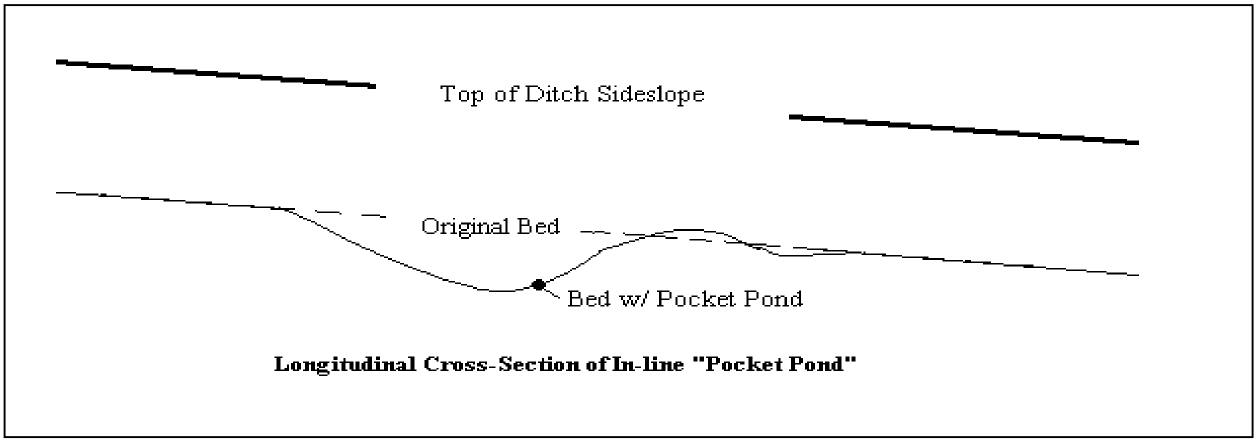


Figure 4.3 Longitudinal view of in-line “pocket pond”

4.1.7 Treatment Cost-Water Quality Benefit Analysis

4.1.7.1 Findings

Table 4.22 summarizes the results of the comparative cost-benefit analysis of study treatments. The key metric of this procedure is the Relative Cost Effectiveness Index (see section 3.1.7), which relates the ditch maintenance operational cost to water quality benefit. In this analysis, the proportion of influent TSS and total zinc removed by a treatment was selected to best represent the water quality enhancement potential of a particular ditch treatment. Efficiencies are based on results from Method 2 (Table 4.21). The development of treatment cost is detailed in Appendix J.

The Relative Cost Effectiveness Index demonstrates that straw with a vegetation strip (site C) is the most cost effective. In terms of TSS removal efficiency, site A with sod and a filter strip performed better than site C, although, as discussed above, that was due to the different solids loading characteristics. The Relative Effectiveness Indices are probably closer under similar loadings. As the Relative Cost Effectiveness Index points out, in comparison to treatment C, the cost associated with re-sodding is not warranted as a pollutant removal strategy following ditching operations. The high score of treatment C relative to treatment B (100 vs. 24) indicates that retention of an intact vegetated strip downstream of a recently cleaned segment affords a level of solids retention that is justified. It is interesting to note that the treatment cost of C is less than that of B, simply because less material is removed during a given cleaning operation. However, this cost does not take into account the possibility that subsequent site work may be necessary to restore the intact portion (the downstream one-quarter of ditch C) to its original shape and elevation following re-vegetation of the recently cleaned segments.

Table 4.22 Roadside ditch maintenance component cost-benefit analysis

Cost-Benefit Analysis Metrics	Roadside Ditch Site		
	A	B	C
WSDOT Cost for Treatments	$1,141	$697	$587
Length (ft)	154	114	128
Per ft cost	$7.41	$6.12	$4.59
Relative Economy Index	62	75	100
Fraction TSS Reduction (Method 2)	0.50	0.13	0.40
Relative TSS Effectiveness Index	100	26	81
Fraction TZn Reduction (Method 2)	0.22	0.22	0.24
Relative TZn Effectiveness Index	92	92	100
Relative Cost Effectiveness Index—TSS	77	24	100
Relative Cost Effectiveness Index—TZn	57	68	100

4.1.7.2 Implications

On the basis of a "cost of treatment to water quality benefit metric," Site C was the superior treatment during wet weather sediment control following ditch cleanout.

4.1.8 Qualitative Site Assessment and Additional Maintenance Considerations

In addition to water quality data collection, visual site observations were made throughout the duration of the sampling campaign. It is important to note that comments were based solely on the three study sites and, therefore, are not necessarily indicative of facility responses to maintenance activities across the range of WSDOT ditch sites.

At site A, a wedge of settled sediment from influent first appeared immediately at the outfall of the upstream splitter. This wedge lengthened in the downstream direction from December 1999 through June 2000. The depth of this sediment layer ranged from 1 ½ in. to 2 in. and consisted of material with an approximate d_{50} of 0.25 mm (see Table 4.1). In most areas the development of this wedge smothered the newly installed sod. This may partially explain the higher velocities (and lower Manning's n values) for site A in comparison with those of site C (which had a slope twice as great as that of site A). It may therefore be appropriate to install a temporary check dam upstream of the sodded length both to dissipate inflow velocity that may resuspend settled material and to allow a portion of settlable solids to fall out behind control structure. This is especially pertinent during re-vegetation treatments applied between late fall and early spring, when the possibility of sediment deposition depths exceeding the height of newly established grasses is greatest.

The cleaned portions of ditches B and C were both covered with 3 in. of straw on the same day of the ditching operations. In ditch B, all of the straw covering the wetted perimeter of the ditch was washed downstream of the treatment segment before the first storm series. In ditch C, a similar washout occurred; however, the intact vegetation portion of the treatment segment captured a large amount of straw material, which remained throughout the duration of the sampling campaign. The side slopes above the wetted perimeter, especially those of ditch B, maintained a moderate cover of straw.

It was apparent that the straw was not sterilized, since by March stems of a species of barley (*Hordeae*) emerged at low densities on the side slopes of ditches B and C. This indicates that care needs to be taken in selecting a supplier of erosion-control straw so that seeds of undesirable species are not introduced. On the other hand, the experience with barley, an annual that will not supplant desirable perennials, points to the potential for straw alone to act as a sufficient mulch in certain re-vegetation applications (possibly in ditches during dry season operations).

While treatment C performed satisfactorily in reducing downstream loadings of suspended solids, several design options exist that may further improve treatment. For instance, erosive velocities probably existed in ditch C upstream of the intact vegetation strip. These velocities would have been unaccounted for in the HRT tests, which simply provided a mean velocity. In fact, areas of scour were apparent in ditch C even where the original underlying rock lining was present. Therefore, the installation of check dams (or a similar bed roughness element that serves to trap sediment and dissipate flow energy) may be necessary, depending on the ditch and flow characteristics.

In regard to actual treatment installation, the following details can improve the water quality function of the ditch after cleaning:

1) Ensure that locally adverse bed slopes are not created from cleaning activities. In particular, care needs to be taken at the transition between the cleaned segment and the intact vegetation segment.

2) Select an intact segment with existing vegetation cover that is dense and uniform throughout the segment.

3) If numerous candidate segments are available to leave intact, use the following selection criteria:

- If the total length of the ditch is less than 500 ft, attempt to leave the downstream one-quarter of the length intact. At a minimum, leave 20 ft intact immediately upstream of the outlet.
- If the ditch is greater than or equal to 500 ft and receives roadway sheet flow along a substantial portion of ditch length, retain 30 ft of intact vegetated segments every 250 ft. Ensure that an intact segment exists immediately upstream of the outlet.
- If the ditch is greater than or equal to 500 ft and receives most of flow from a single point inflow, retain a downstream vegetation strip at least one-tenth of the total ditch length. At a minimum, leave 50 ft intact immediately upstream of the outlet.
- While a system consisting of an intact vegetation preceded by a check dam was not tested in this study, it may be prudent to install one of these downstream of each point of inflow to capture larger material that may fill the ditch bed and inhibit re-growth.
- The key to reducing the TSS loads of ditch effluent is to retain an intact vegetation strip downstream of all significant inflows.

4) The application of straw to ditch beds when wet weather flows are expected is not only unnecessary but can create overflow hazards when

straw dams inadvertently develop at downstream locations. Depending on the site, 2-in-thick straw cover restricted to side slopes of less than 50 percent may reduce slope erosion, inhibit rainfall compaction, and promote grass seed germination.

4.1.9 Component Conclusions

- Preservation of a vegetated filter strip downstream of excavated ditch segments, in conjunction with an application of straw mulch, reduces outfall loadings of total suspended solids (TSS) by 37 percent, total extractable zinc by 21 percent, and total phosphorus by 39 percent.
- This same level of treatment demonstrates a mean turbidity reduction of 22 percent across a wide range of influent conditions. However, it is unlikely that the treatment affords consistent turbidity reduction at influent readings of 30 NTU or less.
- This same level of treatment has minor positive effects on dissolved zinc, dissolved copper, and total extractable copper. With greater confidence, it can be concluded that treatment does not negatively affect storm water in regard to these constituents.
- Data indicate that each ditch, regardless of treatment, acted as a source of soluble reactive phosphorus (SRP) to downstream waters. Total phosphorus (TP) discharge levels from each ditch exceeded the discharge threshold for lakes in the Puget lowlands (WAC 173-201A-03016), as shown by comparison of data in Table 4.11 to criteria in Table 2.2. The bulk of TP loading was not SRP, the most

biologically available portion, as shown by a comparison of SRP and TP data in Table 4.11.

4.2 BIOFILTRATION SWALE FACILITY INVENTORY COMPONENT

4.2.1 Field Survey Findings

The key bio-physical characteristics of 19 WSDOT bioswales are summarized in Table 4.23. The impervious drainage areas (IDA) estimated from measurements of the highway catchments ranged from 7,400 ft^2 to 198,000 ft^2, and catchments drained roadways with annual average daily traffic values (AADTs) of 4,500 to 80,000. In the following discussion, the key findings of the field survey are broken down into four categories: physical structure, vegetation health, general design and maintenance, and facility tracking.

4.2.1.1 Physical Structure

The cross-sectional dimensions of the surveyed facilities were found to vary considerably because of both original construction and ongoing hydraulic impacts. For example, Facility 17 had a mean depth of 4.8 ft and a mean bottom width of 16.3 ft, whereas the mean depth of Facility 18 was only 0.7 ft and the bottom width was 1.5 ft. Swales with broad side slopes, wide bases, and large volumes typically supported healthy vegetation cover and showed few signs of damage (side rilling, channel incision, toe slumping, or vegetation washout) from storm runoff. The minimum "potential treatment volume" (as defined by Equation 4.2) that consistently supports a well-functioning swale is equivalent to at least two times the runoff from the impervious draingage area (IDA) generated by the 6-month, 24-hour storm (see Table 4.23).

Table 4.23 Key physical characteristics of surveyed biofiltration swale facilities

			Parameters								
Facility #	AADT	Swale ID	Length	Bed Width	Cross-sectional Area	Bed Slope	Bank Slope	Impervious Drainage Area (IDA)	Potential Treatment Volume (PTV)	[2]PTV to $V_{6mo., 24hr}$	[2]PTV to $V_{100yr, 24hr}$
			ft	ft	ft^2	%	%	ft^2	ft^3		
1	10,000	SR18(1)	912	3.5	11.4	1.21	15.4	31232	10362	2.5	0.4
2	10,000	SR18(2)	792	3.0	7.2	4.33	13.9	25344	5666	2.1	0.4
3	10,000	SR18(3)	813	1.1	3.1	2.59	24.4	31707	2546	0.9	0.2
4	43,000	SR167(1)	1584	12.3	41.6	0.70	47.6	197708	65920	3.7	0.9
5	43,000	SR167(2)	1278	6.0	13.9	0.36	18.9	70356	17776	2.6	0.8
6 & 7	8,500	SR900(1,2)	381	2.5	4.9	2.77	32.3	34440	1876	0.6	0.2
8	22,000	SR90	234	2.2	5.6	0.16	32.3	7488	1300	2.0	0.7
9	39,000	SR520	2250	5.7	8.1	0.20	15.2	90030	18324	2.1	0.4
10	12,500	SR527(4)	445	2.2	5.1	1.40	31.3	11100	2265	2.3	0.7
11	25,000	SR527(3)	995	2.5	12.8	2.56	52.6	33200	12699	3.8	0.7
12	12,500	SR527(2)	1250	2.9	12.3	1.32	45.5	37900	15413	3.9	0.7
13	8,000	SR527(5)	500	0.7	3.0	2.42	32.3	10185	1484	1.4	0.3
14	12,500	SR527(1)	840	2.2	15.3	1.60	37.0	26340	12818	5.5	1.7
15	80,000	SR5	1030	2.1	12.8	2.69	23.3	55000	13148	2.6	0.6
16	10,000	SR96	1050	9.1	23.5	0.54	32.3	116250	24645	5.2	1.3
17	4,800	SR202	555	16.3	120.3	0.44	52.6	8700	66763	82.2	18.5
18	39,000	SR526	565	1.5	2.0	3.99	41.7	65000	1150	0.2	0.0
19[1]	14,000	SR522	330	3.9	25.4	2.07	40.0	78000	8374	2.4	0.8
20	4,500	SR203	not constructed or maintained by WSDOT								

[1]inflows solely from several point inlets draining elevated bridge deck

[2] $V_{6mo., 24hr}$ and $V_{100yr, 24hr}$ refer to the volume generated by the 6-month, 24 hour storm and 100-year, 24 hour storm, respectively

Potential Treatment Volume (PTV) =
(mean cross-sectional area of facility) x (length of facility) (Eqn 4.2)

While site conditions varied tremendously, the eight “best” sites had several common characteristics:

- longitudinal slopes of less than 2.8 percent
- broad side slopes and/or a wide bed
- no point inlets (at six of the eight facilities)
- near-uniform distribution of storm water to the swale bed via sheet flow through a low gradient (< 30 percent) vegetated filter strip.

The sites that displayed the best overall structure were facilities 1, 5, 6/7, 9, and 14 through 17. In some cases the physical geometry was found to be appropriate, but overall vegetation conditions were poor because of installation and maintenance activities. For example, Facility 15 was sized and shaped appropriately. However, sparse vegetation cover was the result of poor soils and detrimental maintenance activities. The common structural features that differentiated these fully functioning facilities from the more degraded sites yielded the design recommendations listed in item 3 in Table 4.28.

Wide swale beds (flat or slightly concave) are desirable for several reasons. First, where cross-culverts discharge into narrow, confined swales, scour and slumping can occur along the far bank. While outfall energy dissipaters and bank armoring can be effective, failure is common because of improper installation or erosional flow disturbances. By maximizing the distance to the far embankment, the detrimental effects of cross-culvert discharges can be attenuated. Transverse bed scour may occur, but this tends be less severe than bank erosion and the resulting slope failure. Second, wide beds allow flow channels to migrate, which is generally preferable to the incision patterns found in highly confined channels. Swales are exposed to a diverse array of discharges and loadings, with associated alterations in wetted areas, velocities, and transport rates. A wide bed allows the system to adjust form in response to these variations. Third, if flow is distributed across width, flow depths are reduced and erosive energy is correspondingly decreased.

Facility 16, with a 9-ft-wide bed along its entire length, serves as an example of the preceding discussion. The discharge points from two cross-culverts, each draining a 30,000-ft^2 parking lot, had not affected the swale structure because of effective installation of riprap pads, as well as the relatively large distance to the toe of the far bank. In zones of dense cattail growth, both high sinuosity and significant braiding occurs during low flows. This indicates that the vegetation may not only filter and adsorb particulates but can alter the flow path of the active channel.

4.2.1.2 Vegetation Health

Table 4.24 summarizes the key findings of the bioswale vegetation assessment. The development of appropriate vegetation composition and structure is a function of several hydrologic and environmental variables. Runoff intensity, substrate composition, duration of soil saturation, embankment slopes, competition, and anthropogenic disturbances appear to have the most pronounced influence on the relative success of desirable vegetation. Facility 18 had a low ratio of PTV to $V_{6mo,24hr}$, indicating an undersized facility that afforded little water quality enhancement. Because of detrimental storm flows (as evidenced by damage at culvert outlets), a relatively small cross-sectional flow area, and a high longitudinal slope (4.0 percent), this facility was no more than an

Table 4.24 Key vegetation characteristics of surveyed biofiltration swale facilities

Swale ID	Vegetation Conditions				
	Mean Bed Cover Class	Dominant bed species	Mean Side Slope Cover Class	Dominant side slope species	Problems
1	1.5	grass, some other herbaceous (aster)	3	grass, some other herbaceous	drought damage
2	1 (upstream); 3.5 (downstream)	grass, some other herbaceous (aster)	2	grass, some other herbaceous (aster)	some incision; drought damage
3	5	grass, some other herbaceous (aster)	2	grass, some other herbaceous (aster)	incision and most of bed bare; bed widening
4	3 (variable depending on bank canopy)	reed canarygrass, duckweed, himalayan blackberry	1	reed canarygrass, Himalayan blackberry, hardhack, willow	canopy shading; stagnant water in places
5	1 (except at outlet)	reed canarygrass, aster, grass	3	willow, reed canarygrass, ornamental shrubs	lanscaped side slopes
6/7	1	reed canarygrass, willow	1	reed canarygrass, willow	
8	4	grass	2.5	reed canarygrass, grass, ivy, himalayan blackberry	poor bed cover due to shading & rocky soil
9	2 (variable depending on bank canopy)	reed canarygrass, grass	1	reed canarygrass, grass, himalayan blackberry	tall bank vegetation smothering bed
10	5	buttercup, rush, spike rush, veronica	2	grass, buttercup, aster	non-storm flow and bare channel bed, clippings left
11	2	grass (agrotis/holocus), aster, medic, clovers	2	grass (agrotis/holocus), buttercup, clovers, small blackberry/alder	newest swale on 527 with barest side slopes
12	4 (varies)	rush, emergents, buttercup/plantain in drier areas	1.5	grass, buttercup, aster	500 ft with continuous flow and bare channel
13	1	grass, some other herbaceous	1	grass, some other herbaceous	mowed regularly

Table 4.24 Key vegetation characteristics of surveyed biofiltration swale facilities (continued)

14	1	grass	1	grass	mowed regularly
15	3	grass, some other herbaceous	2	grass, some other herbaceous	
16	2	juncus, typha	1.5	grass, buttercup, rumex, clover	saturated bed, mowed side slopes
17	1	grass, clover, aster, moss	1	grass, clover, aster, moss	
18	4	agrostis, holocus, festuca	2	agrostis, holocus, festuca	high flows & bed shading resulting in poor bed cover
19	2	lolium, agrotis, orchardgrass	2	lolium, agrotis, reed canarygrass	
20	1.5	horsetail, lolium, holocus, bromus	1.5	horsetail, lolium, holocus	poor soil prep

Cover percentages corresponding to cover class designations: = 0-5%, 2 = 5-25%, 3 = 25-50%, 4 = 50-75%, 5 = 75-95%, 6 = 95-100%

earthen ditch with very low plant densities on the active bed. Facilities 8 and 15 were both constructed well; however, the stoniness and poor soil quality prevented establishment of dense, fine grass cover.

The effectiveness of a biofiltration swale as a water-quality control facility is highly dependent on in-swale plant community composition and densities. Current WSDOT swale specifications call for vegetation consisting of "fine, close-growing, water-resistant grasses" appropriate for regional climate and site conditions (WSDOT *Highway Runoff Manual* February 1995). Most of the best performing sites did support vegetation of this type. However, at sites exposed to long periods of saturation, establishment of wetland species may be more appropriate. Throughout the length of Facility 16 a suitable pattern of grass, emergent, and wetland species was established that was unique among the survey sites. Bank coverage exceeded 95 percent at six of nine transects; however, as with many wetland plantings, bed coverage was considerably lower (four of eight transects were classified as 40 percent to 70 percent coverage). Because of the low longitudinal slope (0.5 percent), presence of non-storm inflows, organic muck layer, and bed shading by tall herbaceous material (primarily *Typha spp*. and *Juncus spp*.), the full width of the bed was saturated during four dry-weather site visits (May through August). It is interesting to note the similarities in form between Facility 16 and a WSDOT nutrient-control wet pond or narrow treatment wetland.

The decision to install a facility such as that described above must be considered carefully. Continual base flow or irrigation is required during dry weather to support many wetland species. The use of these wetland type swales is yet unproven in situations with a single highway runoff inlet and high discharges. Ideally, runoff is intercepted by a vegetated filter strip (VFS) and introduced as sheet flow along much of the swale's length. The VFS both (1) reduces the load of coarser, inorganic sediments that could alter bottom elevation, thereby inundating desirable species and (2) prevents the inlet scour common in high discharge situations.

The success and complexity of plant communities appears to correlate with the intensity and duration of flows, as well as infiltration rates of bed depressions during interflow periods. Facilities 10 and 12 both had experienced significant non-storm inflows that had altered the vegetation composition. Emergent and aquatic species were present (Table 4.24); however since the plantings had not been installed and maintained, these colonizing communities did not offer significant water quality benefits. Furthermore, saturated conditions had allowed the establishment of aggressive weeds that neither grew as densely as typical meadow grasses nor provided the structural stability of desirable wetland species.

In situations where dense bed coverage is not possible, vegetation planted on the side slopes can be useful. Certain species of grasses (*Phalaris spp*. and *Agrotis spp*.), if left uncut, will fall over and lie prostrate on the bed of the channel, which can serve as an effective biofiltration medium. However, the undesirable consequences of vegetation in this condition must be considered (e.g., bed shading, flow blockages).

4.2.1.3 General Design and Maintenance

The preceding discussion emphasizes the potential benefits of several bioswale characteristics to ensure facility stability and treatment efficiency. In conjunction with low gradient side slopes and wide beds, curved transverse transitions can reduce the damage caused by routine maintenance work. Wetter, grassy sites with narrow beds (< 3 ft), sharp transitions, and side slopes exceeding 30 percent are the most likely to display signs of mower deck scalping, uneven cutting height, and tire rutting. Sites with wide beds and gentle side slopes provide several benefits in regard to mowing activity:

1) Tire rutting is ameliorated because variable mowing patterns are possible from visit to visit.
2) Clumping of clippings is less prevalent, since the ground surface is unlikely to impinge directly on the outlet of the mower deck chute.
3) The height of the vegetation following mowing is more uniform since mower decks are better suited to these configurations.

It was apparent that many sites had not been cut for several years (facilities 4, 6/7, 9, 16, and 19). In these cases, long-term maintenance plans need to be carefully considered. As a general rule, if woody weed species predominate, removal is suggested to prevent excessive crowding and shading of finer material, which provides better filtering. If cutting of reeds and grasses can only occur at yearly (or longer) intervals, then it is advisable to not cut at all. The large amount of cut herbaceous material, when not removed, can smother any undergrowth, act as a source of nutrients to receiving waters, and even form dams that prevent the passage of storm flows.

If the intention is to routinely monitor and maintain the site, then a target condition (see Service Level information in section 4.2.4) should be identified. The target vegetation structure should consider the observed flow conditions, the surrounding environment, and the accessibility and availability of maintenance services. At these routinely maintained facilities a situation may occur in which the bed does not support any growth, but tall grass species emerging from the channel banks fall over into the active flow path at maturity. This condition does afford a level of filtration that otherwise would not be present if the side slopes were mowed regularly. If the establishment of swale bed vegetation proves unsuccessful, then maintenance should follow practices that will allow side vegetation to mature and fall over during the wet season.

Surveys of several facilities revealed that the total swale volume (equivalent to the PTV) exceeded the runoff volume generated by the majority of storm events. With WSDOT's current focus on reducing total discharge quantity, as well as preventing flows with excessive turbidity levels from entering receiving bodies, it is logical to consider the potential for existing swales to serve as infiltration facilities. The design depicted in Figure 4.4 provides for significant retention capacities, biofiltration through fine grasses on the exposed berm surfaces and on the upper portions of the side slopes, infiltration along the majority of the swale's wetted perimeter, and beneficial biological activities due to wetland plants and microbial species within the retention zone. Site-specific modifications may include designs for enhanced under-drainage or high flow bypass.

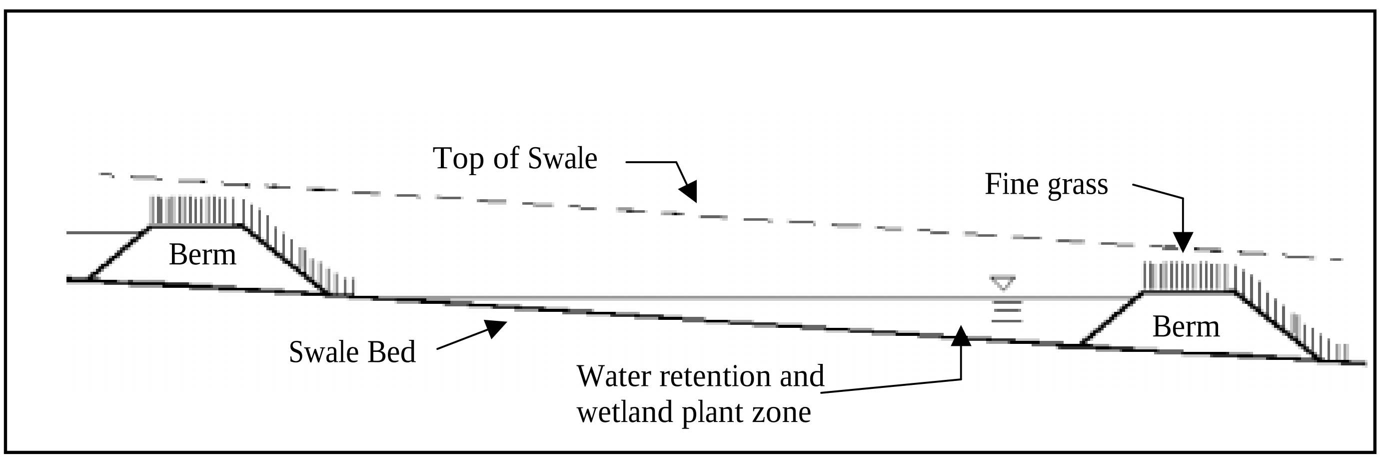


Figure 4.4 Bermed swale to enhance storm water infiltration (modified from Wanielista et al. 1986)

The proposed “infiltration swale” has several limitations. Although the optimal design of the proposed facility requires no additional space than a *properly constructed* biofiltration swale, retrofits of *existing sub-optimal* bioswales (or possibly large ditches) may require additional right-of-way space. Sites with extremely low infiltration rates and low swale volume to discharge volume ratios would not be appropriate for the proposed design.

4.2.1.4 Facility Tracking

Several on-going projects (i.e., BMP Inventory and Outfall Inventory databases under development by the Northwest Regional Office) within WSDOT are focused on developing a more accurate inventory of WSDOT storm water facilities/outfalls as well as improving facility tracking and management systems. The current survey identified several facilities where routine maintenance and flow sources were from non-WSDOT entities. Other facilities appear to have no maintenance activities performed at all. The occurrence of these problems will diminish with the implementation of well-designed facility management systems.

4.2.2 Interview Observations

The following response summaries are based on the results of interviews with assistant superintendents and supervisors from three of the five maintenance areas within the Northwest Region of WSDOT

How are biofiltration swales currently maintained?

The approach to biofiltration swale maintenance is either incidental to higher priority projects, corrective, or not at all. When maintenance is done, it entails mowing and possibly some revegetation. Minimal resources are available for swale maintenance, and minimal maintenance is provided.

<u>What impediments to biofiltration swale maintenance exist?</u>

Impediments to swale maintenance are threefold. First, minimal requirements and guidance have been available from the regional design, construction, and environmental offices and from the Environmental Affairs Office. Second, minimal resources (funding = equipment and personnel) have been committed to swale maintenance. Third, the design and construction of swales have not always considered ease of maintenance (e.g., accessibility) to be a high priority.

<u>What is needed to improve biofiltration swale maintenance?</u>

The following items are recommended to help improve biofiltration swale maintenance, as well as the maintenance of all permanent storm water management facilities.

Table 4.25 Recommendations developed from interviews with maintenance personnel concerning general storm water facility management

Recommendation	Responsibility
Expand the section in the Storm Water Site Plan (SSP) template entitled *Inspection and Maintenance of Permanent Stormwater Facilities* into a detailed operation and maintenance (O&M) manual template. The format should be such that this project-specific manual can be a stand-alone document that is easily extracted from the main SSP document for maintenance office use.	NWR Environmental
For each project requiring permanent storm water management facilities, use the O&M manual template to prepare a *Permanent Stormwater Management Facilities O&M Manual*. This should include clear, concise descriptions of the rationale, design parameters, operation, and maintenance of the site-specific permanent storm water management facilities, including biofiltration swales. Include plan and profile drawings and any other pertinent supporting information. Work with the maintenance office to ensure that requirements and methods are practicable.	Project Design Office Maintenance Area Office
Design permanent storm water management facilities, including biofiltration swales, with ease of maintenance access as a high priority. Work with the maintenance office to ensure that proposed access is acceptable.	Project Design Office Maintenance Area Office
After project construction is complete, create as-built plans for permanent storm water management facilities, including biofiltration swales. Amend the project-specific *Stormwater Management Facilities O&M Manual* with these as-built plans.	Project Construction Office
After project construction is complete, ensure that a formal handoff (from the Project Construction Office to the Maintenance Area Office) of responsibility for maintenance of the permanent storm water management facilities, including biofiltration swales, takes place. Resolve any remaining maintenance concerns.	Project Design Office Project Construction Office Maintenance Area Office NWR Environmental
Develop a GIS database of permanent storm water management facilities, including biofiltration swales. Include a Biofiltration Swale Survey Database as one of the GIS layers (this database would include GPS coordinates for the location of each swale).	NWR Environmental
Develop biofiltration swale maintenance routines and schedules.	Maintenance Area Office
Include biofiltration swale maintenance history as a GIS layer for use in maintenance tracking and scheduling.	Maintenance Area Office NWR Environmental
Develop a funding package specifically for environmental main-tenance. Provide support to the maintenance offices for commit-ting equipment and personnel to environmental maintenance activities, including maintenance of biofiltration swales.	Environmental Affairs Office

4.2.3 Bioswale Maintenance and Design Recommendations

Several general recommendations, stemming from observations collected during the survey, are detailed in Table 4.26. Specific problems prevalent throughout many of the surveyed swales and corresponding maintenance recommendations are outlined in Table 4.27.

The findings of the field survey indicated that, in addition to maintenance practices, several design characteristics were essential to ensure that a bioswale facility is capable of providing benefit to storm water quality. The key elements of good bioswale design and construction are outlined in Table 4.28.

Table 4.26 Recommendations for general maintenance operations to address systematic problems of existing biofiltration swale facilities.

Issue	**Recommendation**
1) Inconsistent levels of maintenance service among similar facilities.	1) Set up approximately quarterly drive-by inspections of swales to determine the need for and timing of corrective maintenance work. Particular attention should be given to bare areas; unhealthy vegetation; standing water; deposits of sediments, yard waste, litter, and other solids that are harming plant growth; and vegetation clippings.
2) Many minor problems appear to be overlooked or are not addressed by maintenance personnel.	2a) Provide the needed employee training and management oversight to implement the recommended maintenance tasks effectively. Training, probably best be offered as on-the-job sessions, should explain the benefits of new procedures, as well as teach techniques. These sessions could be conducted by "maintenance crew environmental leaders," a position recommended under the Level 2 funding option proposed in the Maintenance Manual for Water Quality and Habitat Protection (May 2000 revision). 2b) Provide field crews with equipment and supplies that are appropriate for mowing/raking, seeding, planting, amending, and minor grading/excavating.
3) The existing facility database does not provide accurate information about the status of many facilities. Several facilities appear to be maintained by non-WSDOT entities, from which liability and monitoring issues may arise.	3) Provide managers and field personnel with facility tracking tools to record detailed work history, site problems/successes, and location. Continue current WSDOT initiatives geared toward facility tracking and more efficient database management.

Table 4.27 Recommendations for field maintenance activities to improve conditions of existing biofiltration swale facilities

Issue	**Recommendation**
1) Concentrated flow along the shoulder edge often results in silt/litter buildup. May reduce the effectiveness of the swale because of the non-uniform distribution of inflows.	1) Periodically grade to allow sheet-flow off of the pavement along the entire length of the filter strip/swale. Alternatively, re-grade the earthen edge to ensure that the elevation of the mature vegetation and accumulated sediment is lower than the pavement edge.
2) Swales on steep slopes are eroding because of high velocity flows.	2) Retrofit with check dams to prevent erosion in the channel and energy dissipaters if erosion is occurring at a point inlet.
3) Mechanical damage by mowing equipment that encourages rutting and/or scalping. For example, the inability of the mower operator to alter the alignment of equipment tires between visits results in permanent wear marks that prevent the establishment of healthy vegetation.	3) Configure the swale access points and cross-sectional area to allow proper mowing techniques that reduce scalping, non-uniform cutting heights, and repeated passes that foster rut development.
4) Buildup of deposits of sediments, yard waste, litter, and other solids that suppress plant growth.	4) Source control options: Sediments—in cooperation with the agency in charge of grading permit oversight, ensure proper installation of erosion and sediment controls to prevent soil loss from construction sites. Yard waste/litter—place “No Dumping” signs, distribute flyers discouraging dumping, consider other public education measures. If residents mow roadside ditches and leave substantial clippings, encourage them to remove and dispose of them in a manner that does not release nutrients to the receiving waters.
5) General herbicide application prevents development of a healthy vegetated filter strip and roadside side slope.	5) Alter spraying patterns to encourage healthy vegetation within the filter strip. Alternatively, abandon maintenance of a clear zone along roadways where swale vegetation cover is severely impacted by herbicide treatments.
6) Areas of poor or unhealthy vegetation.	6) Prepare an appropriate seed bed and plant a mix of herbaceous species, including grasses and other forms. Obtain a qualified botanist’s or landscape professional’s advice to select the species and specify the preparation. Remedial preparation may include local grading, topdressing, soil amending, and removal of poor planting medium.

7) Non-storm related inflows and pools keep portions of the swale saturated throughout much of the year. May decrease vegetation density and select for undesirable species.	7) Investigate the cause of persistent water. Depending on site conditions, subsequent remedial actions include the following: Discharge from non-WSDOT pipe or channel connection: Check records to determine whether the connection and discharge pattern are approved by WSDOT. Take appropriate corrective action. For continual saturated conditions: Prepare soils and install appropriate plantings. To determine the herbaceous plants that the site can support may require assistance from a qualified wetland botanist or landscape professional. Local depressions and persistent pools: Grade to create suitable hydraulic conditions, then install vegetation
8) Shading of bed by tall vegetation with low stem densities	8) Mow, spray, or prune/grub to remove undesirable woody species as necessary.

Table 4.28 Recommendations regarding swale design and installation standards

Issue	**Recommendation**
1) Minor slumping and mower scalping associated with cross-sectional geometry of the swale.	1) Eliminate sharp lateral transitions from design.
2) Side slope failure leading to sediment inputs and reduced ability to support healthy vegetation.	2) Follow current specifications of 3:1 (preferably less) side slope, particularly in areas prone to high flows and/or saturated conditions.
3) Hydraulic conditions that promote rill formation, erosion, high velocities, etc.	3) Incorporate the following into the configuration: • Swale Depth:Top Width < 0.15 • Minimum Bed Width = 3 ft • For Depth >3 ft, Bed Width > Depth + 1 • Side Slopes < 33% (never >50%) • Potential Treatment Volume: Impervious Drainage Area >0.30 • Mean Longitudinal Slope < 2.5%
4) Downcutting and toe erosion	4) Provide a wide bed to promote variable flow patterns. Generally, problems are not prevalent in swales with a wetted bed that exceeds 36 inches. Specify armoring and control structures in areas prone to erosive or continual flows. Erosion at a steeply sloping point inlet can be avoided with an energy dissipater (e.g., a rip-rap pad) and, within the channel, by using check dams (see biofiltration guidance in the King County Surface Water Design Manual for specifics).
5) Standing water	5) Attempt to avoid standing water by careful grading to avoid depressions in ditch beds and compaction of the soil. Finish the construction by tilling if the soil has become compacted.
6) Undesirable vegetation composition	6a) In ditches without a surface or subsurface base flow source, plant a mix of herbaceous species including grasses and other forms, after preparing an appropriate seed bed. Obtain a qualified botanist's or landscape professional's advice to select the species and specify the preparation.
	6b) In ditches with a surface or subsurface base flow source, determine whether conditions will support wetland herbaceous plants. Establish them if the determination is positive, with the help of a qualified wetland botanist or landscape professional.

4.2.4 Maintenance Accountability Process (MAP) Service Levels and Performance Measures: Group 2B (proposed) – Storm Water Control Facilities– Biofiltration Swale

Detailed descriptions of bioswale service actions and facility conditions at different serivce levels are provided below. Table 4.29 summarizes the proposed service level scheme in the standard MAP format. Table 4.30 outlines proposed performace measures for these facilities.

4.2.4.1 Level A

Service Actions

Routine catch basin and culvert cleaning to ensure efficient system operation. Minor grading and silt removal to promote both uniform sheet-flow off of road surfaces and in-swale hydraulic conditions that enhance vegetation growth and soil stabilization. Mowing and supplemental care to maintain healthy cover of fine grasses on slopes and bed. Infill planting of desirable woody and herbaceous plant species to achieve desired densities. Hand removal of accumulated silt, thatch/clippings, and trash to maintain vegetation cover and design flow conditions while preventing damage that the use of equipment may cause. Regular herbicide application and manual actions as per weed management program. Site maintenance and inspection visits on a weekly to monthly basis. Maintain the facility and surrounding right-of-way at Treatment Level 3, as outlined in the Roadside Maintenance Manual (M 25-30). These represent priority facilities where retrofitting, repair, overseeding, and planting should be performed to ensure the best possible treatment of runoff.

Appearance and Functionality

Visually compatible with natural landscape. May provide habitat for desirable fauna and offer habitat continuity with adjacent natural areas. Design and maintenance objectives emphasize the aesthetic appeal of the facility. Pro-active maintenance activities optimize facility treatment and conveyance potential while enhancing the health of desirable vegetation. Scour, slope failure, and heavy siltation seldom occurs. Conditions do not threaten driver or pedestrian safety. Allows convenient access for WSDOT maintenance personnel.

4.2.4.2 Level B

Service Actions

Routine catch basin and culvert cleaning to ensure efficient system operation. Minor grading and silt removal to promote uniform sheet-flow off of drainage area and in-swale hydraulic conditions that enhance vegetation growth and soil stabilization. Turf mowing and care to maintain healthy cover of fine grasses on slopes and bed. Replacement of desirable woody and herbaceous plant species as necessary. Hand removal of accumulated silt, thatch/clippings, and trash to maintain vegetation cover and design flow conditions while preventing damage that the use of equipment may cause. Regular herbicide application and manual actions as per weed management program.

Appearance and Functionality

Visually compatible with the natural landscape or adjacent right-of-way areas. Most frequently dense grassy vegetation maintained to foster healthy growth. May entail landforms constructed for safety or aesthetic reasons. Fully capable of treating and conveying variable flows while maintaining the health of desirable species. Hydraulic damage is infrequent and manageable by small field crews.

4.2.4.3 Level C

Service Actions

Routine catch basin and culvert cleaning to ensure efficient system operation. Annual "zone 2" brush cutting as well as herbicide treatments for weed control and/or clear zone maintenance. Repair of major slope failures. Seasonal mowing of filter strip, swale, and grassed areas of catchment where appropriate. Regular herbicide application and manual actions as per weed management program.

Appearance and Functionality

May exhibit many of the features of Service Level B facilities but lower rating because of one or more performance indicators. Capable of conveying large storms during which little overall treatment may occur. Treatment effectiveness reduced by either poor vegetation development or physical structure of facility. Alternatively, may be represented by a generally poorly designed and maintained facility that is oversized to such an extent that it is capable of significant water treatment. Sub-optimal performance may simply be the result of siting problems rather than design/maintenance issues.

4.2.4.4 Level D

Service Actions

Annual catch basin and culvert cleaning to prevent hazards. Annual "zone 2" brush cutting as well as herbicide treatments for weed control and/or clear zone maintenance. Repair of major slope failures. Seasonal mowing of filter strip, swale, and grassed areas of catchment where appropriate.

Appearance and Functionality

Not designed well or simply a well-vegetated ditch that affords some level of treatment. Basic maintenance and remedial actions would provide immediate benefit to facility.

4.2.4.5 Level F

Service Actions

No routine maintenance by WSDOT beyond minimal annual zone 1 and zone 2 activities such as herbicide application and brush control. For non-freeway locations, agreements may exist with adjacent landowners for mowing, planting, and brush control.

Appearance and Functionality

Lack of monitoring and maintenance inhibits early identification of facility problems. Appearance similar to an unvegetated earthen ditch because of high-energy storm flows or long periods of saturation. Storm flows frequently overtop the side slopes. May see deep scour, slope failures, litter/debris dams, ponding, non-storm flows, and very little vegetation. Culverts and catch basins may be blocked or damaged. Debris and silt on the shoulder are often present and inhibit uniform sheet-flow into the swale. Mechanical damage from vehicles or equipment is left unrepaired. Access for maintenance is limited by design, hydraulic damage, or woody vegetation growth. May present driver and pedestrian safety hazards because of visual obstruction by vegetation or the condition of the channel

Table 4.29 Proposed bioswale MAP module: service levels

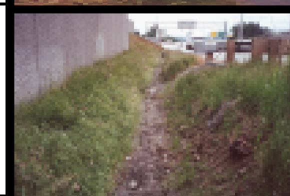
Service Level	Service Actions	Appearance and Functionality	Representative Sites	
			Overall	**Details/Alternatives**
A	Regular mowing (monthly Grades maintained to prevent ponding/slides Hydraulic structures maintained for optimal performance Pro-active facility management	Dense, healthy vegetation (95+% of area) Uniform cover and clippings not accumulated Well-drained & fully capable of passing high flows		
B	Regular mowing (monthly) Grades maintained to prevent ponding/slides Hydraulic structures maintained for optimal performance during wet season	Dense, healthy vegetation (80+% of area) Uniform cover, limited clippings apparent, and weedy growth not dominant Fully capable of passing high flows		
C	Regular mowing (seasonally) Slope failures repaired Culverts/catchbasins/grates cleaned (seasonally)	Healthy vegetation cover by desirable forms over 50% of area Invasive plant species controlled to allow stormflow conveyance		
D	Mowing and pruning to reduce safety hazards (annually) Armoring of bank and outfalls as necessary No concern for water quality treatment potential	Significant bed scour and minor slope failures prevalent Vegetation forms dependent on site & invasive species dominate		
F	Maintenance of clear zone (annually) No concern for water quality treatment potential	Little bed cover (<15%) due to hydraulic conditions or shading Side slopes overgrown and may be exclusively of weedy species		

Table 4.30 Proposed bioswale MAP module: performance measures

Group 2B – Storm Water Control Facility Maintenance				Service Level and Threshold				
Biofiltration Swale Maintenance				A	B	C	D	F
Number	Activities	Condition Indicators	Outcome Measures					
2B1	Edge of Pavement Sediment Removal	Sediment buildup along edge of pavement inhibits uniform sheet flow of roadway runoff into swale facility	% of swale length parallel to roadway where sediment buildup exceeds 1/4"	5%	10%	30%	50%	>50%
2B2	Side Slope Maintenance	Side slope failure impedes flow, increases sediment loads, and inhibits healthy vegetation growth	# of failures exceeding 2' in length/1000' of swale length	2	4	10	20	>20
2B3a	Vegetation Structure: grasses dominant	Low grass densities in flow path generally reduce hydraulic residence time, reduce sediment trapping and retention capabilities, and allow higher flow velocities to develop. Reduction in root biomass may increase erosion and reduce infiltration processes.	% bare area (see note 1)	3%	10%	20%	30%	>30%
2B3b	Vegetation Structure: emergent and aquatic plants dominant	Low grass densities in flow path generally reduce hydraulic residence time, reduce sediment trapping and retention capabilities, and allow higher flow velocities to develop.	% of open area (water or soil) at elevation of normal storm flow surface (assume 3" if elevation indeterminate)	10%	20%	40%	50%	>50%

Table 4.30 Proposed bioswale MAP module: performance measures (continued)

2B4	Vegetation Care	Overlying plant material can smother surrounding growth, reducing overall stem density	# of 6–ft^2 areas where vegetation growth is inhibited by clippings or shading because of unmanaged overgrowth (typically woody material or grasses exceeding 3 ft in height) per 1000 ft of swale length	2	4	10	20	>20
2B5	Inflow Control	Point inflows can erode swale bed/sides which may increase sediment loads and likelihood of slope failure	# of erosive point inflows/1000' of swale	0	0	2	3	>3
2B6	Flow conditions	Swale does not retain healthy vegetation cover and designed configuration due to base or storm flow characteristics	% of total length displaying flow related damage (scour, poor drainage, overflows, etc.)	1%	3%	5%	20%	>20%
2B7	Downstream receiving body	Poor outfall protection or flow introduction into downstream control facility	Rating of outlet conditions	Excel-lent	Good	Fair	Poor	Hazard-ous

Note 1: The term "bare area" is quite subjective. The researchers in this study primarily looked at bare ground exceeding several inches in one horizontal dimension. However, the cross-sectional flow area also needs to be considered.

4.2.5 Component Conclusions

The following conclusions are based on the findings of the bioswale survey and interview process:

- The accounts of maintenance personnel, as well as field observations, indicated that an inconsistent level of maintenance has been conducted at existing bioswale facilities. An adaptable, regularly updated database system would alleviate many of these problems. This system could provide WSDOT personnel with information on facility work history, work requests, precise location, inspection/monitoring findings, and scheduling isssues.
- Recommendations for improved maintenance and design of WSDOT bioswales is provided in tabular format. In general, several straightforward actions are proposed that will significantly improve the biological and hydraulic conditions at many of the Department's bioswale facilities.
- The proposed MAP module can serve as a valuable planning tool for maintenance personnel. Specific field actions are suggested to attain a targeted service level for a facility. The performance measures will allow field personnel to efficiently identify functionality of facility in terms of water quality management.

4.3 ROADSIDE DITCH STABILIZATION COMPONENT

4.3.1 Re-Vegetation Success Data

Table 4.31 and Figure 4.5 summarize the results of the stabilization study following plot-scale ditch cleaning. The mean blade count was conducted after the emergence of individual grass stems through the erosion control products. This initial survey was conducted to assess the relative efficacy of products at promoting early growth. The June and July vegetation cover assessments were based on areal coverage and grouped by vegetation cover class (section 3.1.1). Dry biomass was based on a two-sample mean from the June site visit. The poor growth in plots 9 through 13, relative to plots 1 through 8, was due both to extended periods of soil saturation as well as to significant mole damage. In light of this, the relative growth measure (RGM) (section 3.3.3) for each treatment was based on results from plots 1 through 8, which are believed to better represent the typical conditions of a high-gradient (longitudinal slope >4 percent) roadside ditch.

Table 4.31 Stabilization treatment results

Plot #	**Treatment**	**April 24th mean blade count**[1]	**June 9th % vegetation cover**	**July 18th % vegetation cover**	**June 9th dry biomass (g)**
1	**Coir**	80.5	15%	13%	0.56
2	**Jute & Straw**	154.5	27%	30%	0.66
3	**PAM**	23.0	15%	15%	0.75
4	**Straw**	91.0	38%	30%	0.41
5	**Jute & Straw**	139.0	38%	25%	0.31
6	**PAM**	55.5	33%	18%	0.60
7	**Straw**	31.5	3%	20%	0.07
8	**Coir**	86.0	38%	35%	0.46
9	**PAM**	*71.0*	*39%*	*33%*	*0.36*
10	**Straw**	*9.0*	*3%*	*5%*	*0.00*
11	**Coir**	*6.0*	*3%*	*5%*	*0.00*
12	**Straw**	*25.0*	*3%*	*10%*	*0.03*
13	**Jute & Straw**	*15.0*	*3%*	*5%*	*0.01*
	Means	**81.3**	**27%**	**24%**	**0.46**

[1] the two plot mean of Jute/Straw and PAM blade counts are significantly different by Tukey's HSD comparison ($\alpha = 0.05$, $p = 0.04$)

Italicized numbers are not used in developing means or treatment performance indices due to the continual saturation of these sites

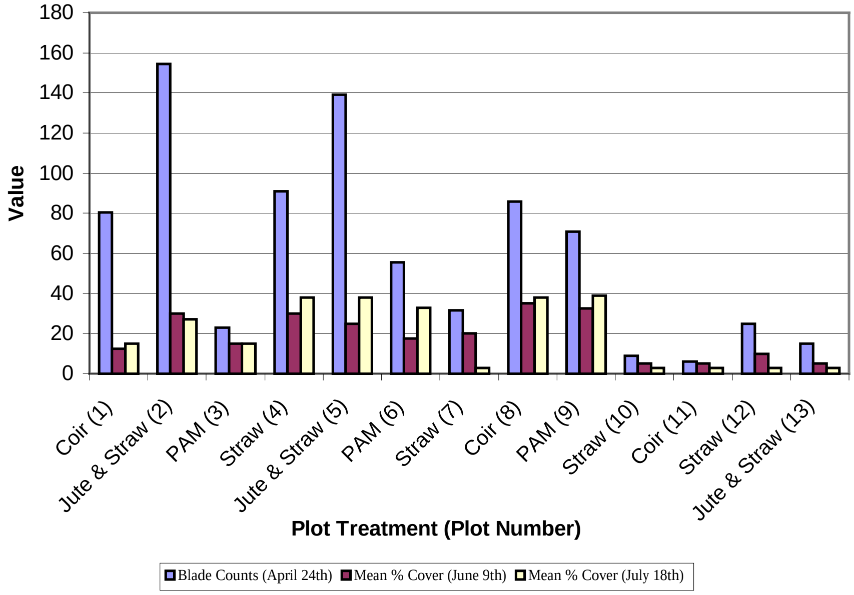


Figure 4.5 Stabilization treatment results

On the basis of the data presented above, the Relative Growth Measure by treatment type is as follows:

- Jute mat with straw 2.87
- Straw 1.29
- Coconut fiber mat 2.14
- Polyacrylamide 1.95

This measure indicates that jute mat with straw was the best performing erosion control product at the study site (characterized by low storm flows, 6 percent longitudinal slope, 40 percent side slope, and established grasses surrounding treatment plots). Below are comments regarding the findings of the field survey analysis:

- Early revegetation was not uniform across any of the plots. It appears that storm flow washout of seed and periods of extended saturation prevented grass species from germinating within the ditch bed.
- Vegetation establishment was the criterion used for success. In certain channel applications, bed sediment retention and side slope stability may be of primary concern. All technologies in this study were designed to support vegetation growth. The coir blanket used at the site also functions as a channel liner, with a failure threshold exceeding 8 lbs/ft^2 according to the manufacturer. Therefore, product selection must consider possible trade-offs between vegetation enhancement and substrate protection (see Table 2.4).
- Consideration of field logistics is essential. Site-specific issues such as ease of installation, available material widths, follow-up maintenance, rate of material degradation, and access need to be addressed before product selection. Unit costs for an identical treatment could vary substantially between sites because of differences in channel dimensions and additional labor requirements. For coverage of large planar slopes, these issues are not a concern. In the case of drainage channels, consideration of cross-sectional geometry is as important as total areal coverage to ensure treatment success and affordability. A sample worksheet is provided in Appendix J, which details variations in unit treatment cost among typical channel widths.

The following suggestions for field application of erosion control technologies are based on observations from the plot scale installations of the present study:

- To reduce the possibility of undermining, the upstream edge of any blanket product should be set at or just below the grade of the existing channel invert. This may require setting and tamping the bed by shovel at transitions between excavated and intact ditch line sections.
- Placement of transverse check slots, additional ground staples, and covering edges of blankets along side slopes with soil are procedures that may be necessary for the channel lining applications. These may differ from those followed on typical slope applications.
- As mentioned in section 2.10, PAM as a sediment retention technology offers great promise. The ease of application, affordability, and successful use in agricultural channels indicate that these polymers will prove useful in certain settings. In this study it was not as successful in promoting seed germination and channel re-vegetation as the blanket products. However, since no quantitative measurements of soil surface condition or sediment yield were taken, it would not be prudent to speculate on the relative sediment control performance of the treatments.

4.3.2 Treatment Cost-Regrowth Benefit Analysis

The treatment of straw and jute matting over grass seed had the highest relative effectiveness (RE) and was identical to the relative cost effectiveness (RCE) of the PAM treatment (see Table 4.32). The high RCE rating of the PAM treatment was primarily a function of its extremely low relative cost, whereas the high RCE index of jute/straw was a result of its high RGM value. In light of WSDOT's ongoing efforts to reduce sediment and pollutant loadings to surface waters, the jute/straw treatment for recently cleaned ditches is recommended over the other two treatments and the control.

Table 4.32 Roadside ditch stabilization component cost-benefit analysis

Cost-Benefit Analysis Measures	Treatment			
	Jute Mat/Straw	Straw	Coconut Mat	PAM
WSDOT Cost for treatments	$880.59	$641.35	$928.59	$602.19
Length	100	100	100	100
Per lf cost	$8.81	$6.41	$9.29	$6.02
Relative Economy Index	68.38	93.89	64.85	100.00
	minimum lf cost			$6.02
Relative Growth Measure	2.873	1.285	2.142	1.954
Relative Effectiveness Index	100.00	44.85	75.37	69.90
	maximum relative growth measure			3.964
Cost Effectiveness	3.06	4.99	4.34	3.08
Relative Cost Effectiveness Index	100.00	61.72	70.97	99.35
	minimum cost effectiveness			3.08

The cost-benefit results presented in Table 4.32 were developed for ditch dimensions at the study site. Soil stabilization matting is available in a limited number of widths; therefore, the Relative Cost Effectiveness Index for a particular treatment can vary substantially simply because of the dimensions of the exposed area of the ditch that requires protection against erosion. To assist with subsequent stabilization projects, completed cost-benefit analysis worksheets for common ditch dimensions other than the one studied are presented in tabular form in Appendix J.

A full discussion of considerations for selecting stabilization technologies is presented above. The findings of this study confirm those of other projects (WSDOT 1999 and Texas Department of Transportation 1999) that discuss the trade-offs among the approaches to channel stabilization. The present study indicates that a straw mulch overlain with jute blanketing supports the most rapid and densest development of grassy vegetation in steep, low flow ditches. In large channels with higher discharges, a sturdier material, such as 100 percent coir with mesh reinforcement, is apt to retain its structure longer.

Furthermore, there are considerations beyond the relative ratings of technologies based on vegetation success and sediment retention. Technologies such as PAM need to be considered because of their low cost and time investment. Circumstances in which combinations of methods are most practical are sure to exist (combining two mattings—one for a large side slope, the other for channel lining—or using straw or hydraulic mulches to protect seed and maintain proper bed environments underneath protective mat products).

5 RECOMMENDATIONS AND IMPLEMENTATION

5.1 ROADSIDE DITCH TREATMENTS FOLLOWING ROUTINE EXCAVATION

On the basis of the findings from the study of roadside ditch treatments following routine excavation, the following recommendations are offered.

- In comparison to the control site, preservation of a vegetated filter strip downstream of excavated ditch segments, in conjunction with an application of straw mulch, improved outfall water quality of all measured parameters except soluble reactive phosphorus.
- Given comparative removal efficiencies and cost-benefit analysis, as well as poor vegetation success, sodding is not recommended over straw mulching to cover an exposed ditch perimeter following wet weather ditch excavation. Instead, if concerns exist about channel degradation due to high flows, infall energy dissipaters, stilling basins, mulching, and/or channel liner treatments should be considered.
- Siting of a vegetation strip downstream of all point inflows is recommended to provide maximum treatment potential and reduce loading to receiving waters/downstream facilities. In addition, an upstream strip situated just below the region of high-energy discharges can trap coarse particles within a short distance and prevent sediment inundation along the full length of the ditch.
- Selection of a vegetation strip with a healthy stand of dense, tall grasses in a relatively low gradient segment appears to work well.

- Field observations during the sampling campaign suggest that the following maintenance strategies may further improve upon storm water quality:
  - Retention of settled sediments on the channel bed may be enhanced by incorporating one of more of the following strategies: stilling basins immediately downstream of infalls; application of anionic PAM before sediment overseeding; settling sump configurations such as the proposed on-line “pocket pond” to prevent downstream migration of bedload material and provide points for easy sediment removal without disturbing the remaining ditch length; and providing temporary check structures (riprap dams, straw bales traps, or transverse silt fencing) to capture anticipated high solids loadings from short-term construction activities or seasonal sanding operations.
  - Improved pollutant control may result from applying fine straw or other appropriate material to an intact vegetation filter strip with insufficient vegetation density. To apply, personnel could distribute small piles of material upstream of the strip (or spaced along its length) and allow storm flows to distribute the material throughout the vegetation. This technique was not tested, and care would need to be taken to ensure that the material neither inundates existing stands of vegetation nor impedes safe drainage of the runoff.

5.2 BIOFILTRATION SWALES

Comprehensive summary tables of the key findings of the biofiltration swale survey can be found in section 4.2.3. The following recommendations address the most frequently encountered problems of biofiltration swales.

- Priority maintenance operations require focus on the following:
  - Remove sediment deposits on the shoulder edge that inhibit the uniform introduction of storm water along the full length of the bioswale.
  - Install vegetation appropriate for site-specific soil moisture conditions. Alternatively, regulation of dry weather discharges or localized grade alterations may modify the soil environment to improve the growth of existing vegetation.
  - Develop site-specific vegetation management plans that promote high densities among areas that receive storm flows (side slopes and wetted areas). Pay particular attention to (1) controlling over-canopies that inhibit the development of suitable vegetation densities within effective flow areas and (2) encouraging maximum densities during the wet season (for example, retaining dense, tall grasses on side slopes in zones of poor bed coverage until the following growing season).
  - Protect the channel in areas of high-energy flows to reduce erosion and foster seedling establishment.
- New facility and retrofit designs should incorporate the following characteristics:
  - longitudinal slopes of less than 2.8 percent (consider increasing channel sinousity if possible)

  - broad, gradual side slopes and/or wide beds
  - a limited number of point inlets
  - longitudinally uniform introduction of storm flows to the swale bed via low gradient filter strips and swale side slopes
  - cross-sectional geometry and site configuration that are amenable to the routine activities associated with facility maintenance.

- Efficient and effective facility management requires the following refinements to current organizational practices:
  - Prepare a project-specific *Stormwater Management Facilities O&M Manual* that is readily accessible by maintenance personnel. This comprehensive document should be developed in conjunction with input from the responsible maintenance office and amended if as-built plans warrant any changes.
  - Ensure that a formal handoff occurs between the Project Construction Office and the Maintenance Area Office for the care of the storm water management facility. Any remaining maintenance concerns should be addressed during this process
  - Develop a GIS database of permanent storm water management facilities. The primary components of this system would entail map coordinates, work history, facility condition, and scheduling layers.
  - Commit equipment and personnel to environmental maintenance operations. Develop a funding package specifically targeting these activities.

5.3 CHANNEL STABILIZATION AND RE-VEGETATION STUDY

On the basis of the findings from the channel stabilization/re-vegetation study, the following recommendations are offered:

- Grass seed covered by straw mulch and woven jute blanket provides superior grass establishment success in comparison to grass seed with over-treatments of coir blanket, PAM, or straw alone in newly excavated, moderate flow roadside ditches.
- For RECPs, substantial tradeoffs may exist between the hydraulic stability and vegetation enhancement characteristics of products. Hydrologic, hydraulic, technology combinations and treatment train considerations are essential to selecting the most appropriate management practice.
- Channel stabilization budgeting needs to account for product width availability and the labor cost requirements of the site and product. Assumption of standard unit costs and coverage calculations can lead to significant errors in estimates of budgets and time allotments.

6 ACKNOWLEDGMENTS

The authors wish to thank the many dedicated individuals at the Washington State Department of Transportation who actively participated in this project and who continue to work toward improving the quality of our water resources. The personnel of the Northwest Region's maintenance areas 4 and 5 spent many hours assisting with the project during both its field and data analysis phases. We would like to mention Michael Golden, Mike Katzer, Jim McBride, Don Nelson, John Stecher, and Nancy Thompson in particular for their enthusiasm and efforts.

Individuals of the Northwest Region and Olympia offices have been active participants throughout the course of the project. Special thanks go to Rick Johnson, Ed Molash, Doug Pierce, and Jim Schafer.

This report would not have been possible without the editorial efforts of Amy O'Brien at the Washington State Transportation Center. Her many hours of work are sincerely appreciated.

Tony McKay, of the University of Washington, deserves recognition for his tireless dedication to assisting students working at the Harris Hydraulics Lab. His practical skills and insight greatly improved the quality of construction and operation of the sampling equipment.

REFERENCES

Allen, S.R. 1996. Evaluation and standardization of rolled erosion control products. Geotextiles and Geomembranes. 14(3-4):207-221.

American Public Health Association. 1998. Standard Methods for the Examination of Water and Wastewater. 20th Ed. Published jointly by American Public Health Association, American Water Works Association, and Water Pollution Control Federation. New York.

Asplund, R. 1980. Characterization of Highway Stormwater Runoff in Washington State. Master of Science Thesis. Department of Civil Engineering, University of Washington, Seattle, Washington.

Athayde, D.N., P.E. Shelley, E.D. Driscoll, D. Gaboury, G. Boyd. 1983. Results of the Nationwide Urban Runoff Program. Volume I—Final Report. USEPA, Washington, D.C. NTIS #PB84-185552

Bannerman, R.T., D.W. Owens, R.B. Dodds, and N.J. Hornewer. 1993. Sources of pollutants in Wisconsin stormwater. Water Science and Technology. 28(3-5):241-259.

Barbour, M.G., J.H. Bruk, and W.D. Pitts. 1987. Terrestrial Plant Ecology. The Benjamin/Cummins Publishing Co. Menlo Park, CA.

Barfield, B.J., and D.T.Y. Kao. 1977. Hydraulic residence of grass media as shallow overland flow. University of Kentucky Water Resource Research Institute, Lexington, Kentucky.

Barnes, R.S.K. and Mann, K.H., Eds. 1991. Fundamentals of Aquatic Ecology. Blackwell Scientific. London.

Barrett, M.E., P.M. Walsh, J.F. Malina, and R.J. Charbeneau. 1998. Performance of vegetative controls for treating highway runoff. Journal of Enviromental Engineering. 124(11):1121-1128.

Bellevue, City of. 1995. Characterization and Source Control of Urban Stormwater Quality. Volume 1—Technical Report. City of Bellevue Utilities Department.

Booth, D.B., and C.R. Jackson. 1997. Urbanization of aquatic systems: degradation thresholds, stormwater detention, and the limits of mitigation. Journal of the American Water Resources Association. 33(5):1076-1090.

California State Department of Transportation. 1995. Highway Design Manual. Sacramento, California.

Chanson, H. 1999. The Hydraulics of Open Channel Flow: An Introduction. John Wiley & Sons. New York.

Chen, C.L. 1976. Flow resistance in broad shallow grassed channels. Journal of the Hydraulics Division, ASCE. 102(3):307-322.

Chow, V.T. 1959. Open-channel Hydraulics. McGraw-Hill. New York.

Clark, D.L. and Mar, B.W. 1980. Composite Sampling of Highway Runoff: Year 2. Washington State Department of Transportation. Report No. WA-RD-39.4.

Council on Soil Testing and Plant Analysis. 1992. Handbook on Reference Methods for Soil Analysis. Soil and Plant Analysis Council. Athens, Georgia.

Davies, P.H. 1986. Toxicology and chemistry of metals in urban runoff. Pages 60-78 *in* B. Urbonas and L.A. Roesner, eds. Urban Runoff Quality—Impacts and Quality Enhancement Technology. ASCE. New York.

Diletic, A. 1999. Sediment behaviour in grass filter strips. Water, Science, and Technology. 39(9):129-136.

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, D. Lee. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. Transactions of the ASAE. 32(2):513-519.

Doell, D.V. 1995. Development of a stormwater collection system to evaluate the quality and quantity of urban runoff from road shoulder treatments. Master of Science in Civil Engineering Thesis. University of Washington, Seattle, Washington.

Dorman, M.E., H. Hartigan, F. Johnson, and B. Maestri. 1988. Retention, Detention, and Overland Flow for Pollutant Removal from Highway Stormwater Runoff: Interim Guidelines fro Management Measures. Report FHWA/RD-87/056 (PB89-133292). FHWA, U.S. Department of Transportation, Washington, D.C.

Driscoll, E.D., P.E. Shelley, and E.W. Strecker. 1990. Pollutant Loadings and Impacts from Highway Stormwater Runoff. Volume 3: Analytical Investigation and Research Report. Report FHWA/RD-88/008. FHWA, U.S. Department of Transportation, Washington, D.C.

Drummond, R.A., W.A. Spoor, and G.F. Olson. 1973. Some short-term indicators of sublethal effects of copper on brook trout, *Salvelinus fontinalis*. Journal of Fisheries Research Board Canada 698.

Dupuis, T., J. Kaster, P. Bertram, J. Meyer, and M. Smith. 1985. Effects of Highway Runoff on Receiving Waters. Vol II: Research Report. Report FHWA/RD-84/063 (PB86-228202). FHWA, U.S. Department of Transportation, Washington, D.C.

Edwards, A.P. and Bremner, J.M. 1967. Microaggregates in soil. Journal of Soil Science. 18:64-73.

Farris, G., D. Ray, and P. Machno. 1973. Freeway runoff from the I-90 corridor. Municipality of Metropolitan Seattle, Washington.

Federal Highway Administration. 1965. Design of Roadside Drainage Channels. Report FHWA/EPD-86/103, Hydraulic Design Series #4. Washington, D.C.

Federal Highway Administration. 1961. Design Charts for Open-Channel Flow. Report FHWA/EPD-86/102, Hydraulic Design Series #3. Washington, D.C.

Gast, H.F., R.E.M. Suykerbuyk, and R.M.M. Roijackers. 1990. Urban storm water discharges: Effects upon plankton communities. Water, Science, and Technology. 22(10-11):155-162.

Gharabaghi, B., W.T. Dickinson, R.P. Rudra, W.J. Snodgrass, and B.G. Krishnappan. 1999. Performance analysis of reinforced vegetative channel lining systems. Computers and Structures. 72:149-164.

Giatinna, J.D., R.R. Garton, and D.G. Stevens. 1982. The avoidance of copper and nickel by rainbow trout as monitored by a computer-based data acquisition system. Transactions of the American Fisheries Society. 111:491.

Gilbert, R.O. 1987. Statistical Methods for Environmental Pollution Monitoring. Van Nostrand Reinhold. New York.

Goldberg, J.S. 1993. Dayton Avenue Swale Biofiltration Study. Seattle Engineering Department.

Gupta, M.K., R.W. Agnew, D. Gruber, and W. Kreutzberger. 1981. Constituents of Highway Runoff. Vol. IV, Research Report. Report FHWA/RD-81/045 (PB81-241929). FHWA, U.S. Department of Transportation, Washington, D.C.

Hartwell, S.I., D.S. Cherry, and J. Cairns. 1987. Avoidance response of schooling fathead minnows (*Pimephales promelas*) to a blend of metals during a 9-month exposure. Environmental Toxicology and Chemistry 6:177.

Hartwell, S.I., J. Jin, D.S. Cherry, and J. Cairns. 1989. Toxicity versus avoidance response of golden shiner, Notemigonus crysoleucas, to five metals. Journal of Fish Biology. 35:447.

Heath, A.G. 1995. Water Pollution and Fish Physiology. CRC Press. Boca Raton, Florida.

Henderson, F.M. 1966. Open Channel Flow. Macmillan, New York.

Holtz, R.D. and Kovacs, W.D. 1981. An Introduction to Geotechnical Engineering. Prentice-Hall. Englewood Cliffs, New Jersey.

Horner, R.R., J.J. Skupien, E.H. Livingston, and H.E. Shaver. 1994. Fundamentals of Urban Runoff Management: Technical and Institutional Issues. Terrene Institute. Washington, D.C.

Horner, R.R., J. Guedry, and M.H. Kortenhof. 1990. Highway construction site erosion and pollution control manual. Washington State Department of Transportation. Report # WA-RD-200.2. Olympia, Washington.

Horner, R.R. 1988. Biofiltration systems for storm runoff water quality control. Washington State Department of Ecology.

Huang, C. 1998. Sediment regimes under different slope and surface hydrologic conditions. Soil Science Society of America Journal 62:423-430.

Hughes, G.M., Perry, S.F., and Brown, V.M. 1979. A morphometric study of effects of nickel, chromium, and cadmium on the secondary lamellae of rainbow trout gills. Water Resources. 13:665.

Israelsen, C.E. and Orroz, G. 1991. High velocity flow testing of turf reinforcement mats and other erosion control materials. UWRL, USU, Logan, Utah.

Jenkins, T.F., D.C. Leggett, L.V. Parker, and J.L. Oliphant. 1985. Toxic organics removal kinetics in overland flow land treatment. Water Research. 19(6):707-718.

Kadlec, R.H. 1990. Overland flow in wetlands: Vegetation resistance. Journal of Hydraulic Engineering. 116(5):691-706.

King County Surface Water Design Manual. 1990. King County Surface Water Management Division, Seattle, Washington.

Knighton, D. 1998. Fluvial Forms & Processes: A New Perspective. John Wiley & Sons. New York.

Kobriger, N.P. and A. Geinopolos. 1984. Sources and Migration of Highway Runoff Pollutants. Research Report, Vols. III. Report FHWA/RD-84/059 (PB86-227915). FHWA, U.S. Department of Transportation, Washington, D.C.

Koltes, K. 1985. Effects of sublethal copper concentrations on the structure and activity of Atlantic silverside schools. Transactions of the American Fisheries Society. 114:413.

Koon, J. 1995. Evaluation of water quality ponds and swales in the Issaquah/East Lake Sammamish Basins. Final Report for Task 5 of Grant Agreement No. TAX90096-Issaquah/East Lake Sammamish Nonpoint Plans. King County Surface Water Management Division. Seattle, Washington.

Kulzer, L. 1990. Water pollution control aspects of aquatic plants: Implications for stormwater quality management. Municipality of Metropolitan Seattle. Seattle, Washington.

Larson, T.V., R.J. Charlson, E.J. Knudson, G.D. Christian, H. Halstead. 1975. Influence of a sulfur dioxide point source on the rain chemistry of a single storm in the Puget Sound region. Water, Air, and Soil Pollution. 4(3-4):319-328.

Leopold, L.B. 1968. Hydrology for Urban Land Planning: A Guidebook on the Hydrologic Effects of Land Use. Circular 554. U.S.G.S., Menlo Park, California.

Lorz, H.W. and McPherson, B.P. 1976. Effects of copper or zinc in fresh water on the adaptation to seawater and ATPase activity, and the effects of copper on migratory disposition of coho salmon (Oncorhynchus kisutch). Journal of Fisheris Research Board of Canada. 33:2023.

Macek, K.J. 1980. Aquatic toxicology: fact or fiction? Environmental Health Perspective 34:159.

Mar, B.W., R.R. Horner, J.F. Ferguson, D.E. Spyridakis, E.B. Welch. 1982. Summary—Highway Runoff Water Quality Study 1977-1982. Washington State Department of Transportation, Olympia, Washington.

Marsalek, J. 1990. Evaluation of pollutant loads from urban nonpoint sources. Water Science and Technology. 22(10-11):23-30.

Marshall, T.J., J.W. Holmes, and C.W. Rose. 1996. Soil Physics. Cambridge University Press. Cambridge.

Mazer, G. 1998. Environmental limitations to vegetation establishment and growth in vegetated stormwater biofilters. Master of Science Thesis. University of Washington, Seattle, Washington.

Michelbach, S. and C. Wöhrle. 1993. Settleable solids in a combined sewer system, settling characteristics, heavy metals, and efficiency of storm water tanks. Water, Science, and Technology. 27(5-6):153-164.

Mizunuma, E. 1965. Discussion during conference. Advances in Water Pollution Research. Proceedings of the Second International Conference. Tokyo 1964. Pergamon Press, Oxford. 1:35-38.

Morrill, D.C. 1994. Spawning gravel quality, salmonid survival, and watershed characteristics of five Olympic Peninsula watersheds. Master of Science Thesis. College of Fisheries, University of Washington, Seattle, Washington.

Municipality of Metropolitan Seattle. 1992. Biofiltration swale performance, recommendations, and design considerations. Seattle, Washington.

Muñoz-Carpena, R., J.E. Parsons, and J.W. Gilliam. 1999. Modeling hydrology and sediment transport in vegetative filter strips. Journal of Hydrology. 214:111-129.

Nakato, T. 1990. Tests of selected sediment-transport formulas. Journal of Hydraulic Engineering. 116(3):362-379.

Newberry, G.P. and Yonge, D.R. 1996. The retardation of heavy metals in stormwater runoff by highway grass strips. Washington State Department of Transportation. Report No. WA-RD 404.1.

Noggle, C.C. 1978. Behavioral, Physiological, and Lethal Effects of Suspended Sediment on Juvenile Salmonids. Master's Thesis. College of Fisheries, University of Washington, Seattle, Washington.

Normann, J.M. 1975. Design of Stable Channels with Flexible Linings. Report FHWA/EPD-86/111, Hydraulic Engineering Circular #15. Washington, D.C.

Norton, D. 1997. Stormwater Sediment Trap Monitoring of Discharges to Thea Foss Waterway. Ecology Report #97-322. Washington State Department of Ecology, Olympia, Washington.

Oades, J.M. 1993. The role of biology in the formation, stabilization, and degradation of soil structure. Geoderma. 56:377-400.

Pirrone, N. and G.J. Keeler. 1993. Deposition of trace metals in urban and rural areas in the Lake Michigan basin. Water, Science, and Technology. 28(3-5):261-270.

Portele, G.J., B.W. Mar, R.R. Horner, and E.B. Welch. 1982. Effects of Seattle Area Highway Stormwater Runoff on Aquatic Biota. Washington State Department of Transportation. Report No. WA-RD-39.11.

Ree, W.O. and V.J. Palmer. 1949. Flow of water in channels protected by vegetative linings. U.S. Department of Agriculture Technical Bulletin 967. Washington, D.C.

Reed, S.C., R.W. Crites, and E.J. Middlebrooks. 1995. Natural Systems for Waste Management and Treatment. McGraw-Hill. New York, New York.

Resource Planning Associates. 1989. Water Quality Best Management Practices Manual. City of Seattle. Seattle, Washington.

Richey, J.S. 1982. Effects of Urbanization on a lowland stream in western Washington. Ph.D. dissertation. University of Washington, Seattle, Washington.

Salomons, W. and Foerstner, U. 1984. Metals in the Hydrocycle. In: Berlin-FRG-Springer-Verlag. pp. 291-332.

Salt, D.E. and U. Kramer. 2000. Mechanisms of metal hyperaccumulation in plants. In Phytoremediation of Toxic Metals: Using Plants to Clean Up the Environment, I. Raskin and B.D. Ensley, (eds.) John Wiley & Sons. New York. pp. 231-242.

Sanders, T.G., S.R. Abt, and P.E. Clopper. 1990. A quantitative test of erosion control materials. In: IECA, 21st Annual Conference, Washington, D.C. pp. 209-212.

Sansalone, J.J. and S.G. Buchberger. 1997. Characterization of solid and metal element distributions in urban highway stormwater. Water, Science, and Technology. 36(8-9):155-160.

Sansalone, J.J. and T. Tribouillard. 1999. Variation in characteristics of abraded roadway particles as a function of particle size: implications for water quality and drainage. In Transportation Research Record 1690, TRB, National Research Council, Washington, D.C., pp. 153-163.

Scholze, R., V. Novotny, R. Schonter. 1993. Efficiency of best management practices for controlling priority pollutants in runoff. Water Science and Technology 28(3-5):215-224.

Schueler, T.R. 1987. Controlling Urban Runoff: A practical manual for planning and designing urban BMPs. Metropolitan Washington Council of Governments, Washington, D.C.

Scott, J.B. 1982. The potential and realized impacts of urban nonpoint source pollution upon the fish populations of Kelsey Creek, Bellevue, Washington. Master of Science Thesis. University of Washington, Seattle, Washington.

Seattle, City of. 1995. Characterization and source control of urban stormwater quality. Volume 1—Technical Report. City of Bellevue Utilities Department.

Smith, D.W. 1978. Tolerance of juvenile chum salmon (*Oncorhynchus keta*) to suspended sediments. Master of Science Thesis. College of Fisheries, University of Washingtion, Seattle, Washington.

Sojka, R.E. and Lentz, R.D. 1997. A PAM primer: a brief history of PAM and PAM-related issues. Online at: http://kimberly.ars.usda.gov/Pamprim.shtml

Srivastanura, P., T.A. Costello, D.R. Edwards, and J.A. Ferguson. 1998. Validating a vegetated filter strip model. Transactions of the ASAE. 41(1):89-95.

Stuart, R.E., R.D. Cardwell, and S.F. Munger. 1988. Toxicants in Urban Stormwater Runoff and Combined Sewer Overflows: An Ecological and Human Health Risk Assessment. Prepared by Envirosphere Company and Municipality of Metropolitan Seattle, Washington.

Sutterlin, A.M. and Gray, R. 1973. Chemical basis for homing of Atlantic salmon (Salmo salar) to a hatchery. Journal of Fisheries Research Board of Canada. 30:985

Taylor, B.L. 1993. The influences of wetland and watershed morphological characteristics on wetland hydrology and relationships to wetland vegetation communities. Master of Science Thesis. University of Washington, Seattle, Washington.

Temple, D.M., K.M. Robinson, R.M. Ahring, and A.G. Davis. 1987. Stability Design of Grass-Lined Open Channels. USDA, ARS, Agriculture Handbook 667. Washington, D.C.

Tollner, E.W., B.J. Barfield, C.T. Haan, and T.Y. Kao. 1976. Suspended sediment filtration of simulated vegetation. Transactions of the ASAE. 19(4):678-682.

van Rijn, L.C. 1984. Sediment transport, Part I: Bed load transport. Journal of Hydraulic Engineering. 110(10):1431-1456.

Viessman, W. and M.J. Hammer. 1998. Water Supply and Pollution Control. Addison-Wesley. Menlo Park, California.

Walsh, P.M., M.E. Barrett, J.F. Malina Jr., R.J. Charbeneau. 1997. Use of vegetative controls for treatment of highway runoff. Online Report No. 97-5, Center for Research in Water Resources, University of Texas, Austin, Texas.

Wang, T.S., D.E. Spyridakis, B.W. Mar, and R.R. Horner. 1981. Transport, Deposition, and Control of Heavy Metals in Highway Runoff. Report FHWA-WA-RD-39.10. Report to Washington State Department of Transportation by Department of Civil Engineering, University of Washington, Seattle, Washington.

Wanielista, M.P., Y.A. Yousef, L. Van DeGraaff, and S. Rehmann-Kuo. 1986. Best Management Practices for Highway Runoff Erosion and Sediment Control. Florida Department of Transportation, Tallahassee, Florida.

Wanielista, M.P., Y.A. Yousef, and E. Avellaneda. 1988. Alternatives for the Treatment of Groundwater Contaminants: Infiltration Capacity of Roadside Swales. Report FL-ER-38-88. Florida Department of Transportation, Tallahassee, Florida.

Wanielista, M. and Y. Yousef. 1993. Stormwater Management. John Wiley and Sons. New York, New York.

Washington State. Water Quality Standards for Surface Waters of the State of Washington. Chapter 173-201A WAC. Olympia, Washington.

Washington State Department of Transportation. 1996. Maintenance Manual. Manual No. M 51-01. FOSSC, Maintenance Office, Olympia, Washington.

Washington State Department of Transportation. 2000. Maintenance Manual for Water Quality and Habitat Protection. FOSSC, Maintenance Office, Olympia, Washington.

Washington State Department of Transportation. 1997. Stormwater Management Plan v5.3. EESC, Olympia, Washington.

Washington State Department of Transportation. 1997. Hydraulics Manual. Manual No. M 23-03. EESC, Olympia, Washington.

Washington State Department of Transportation. 1995. Highway Runoff Manual. Manual No. M 31-16. EESC, Olympia, Washington.

Washington State Department of Ecology. 1997. Stormwater Sediment Trap Monitoring of Discharges to Thea Foss Waterway. Ecology Report #97-322. Olympia, Washington.

Wilber, W.G. and J.V. Hunter. 1979. Impact of urbanization on the distribution of heavy metals in bottom sediments of the Saddle River. Water Resources Bulletin. 15(3):790-800.

Willemsen, G.D., H.F. Gast, R.O.G. Franken, and J.G.M. Cuppen. 1990. Urban storm water discharges: Effects upon communities of sessile diatoms and macro-invertebrates. Water, Science, and Technology. 22(10-11):147-154.

Wilson, L.G. 1967. Sediment removal from flood water by grass filtration. Transactions of the ASAE. :35-37

Wilson, B.N., B.J. Barfield, A.D. Ward, and I.D. Moore. 1984. Hydrology and sedimentology watershed model. Part I: Operational format and hydrologic component. Transactions of the ASAE. 27(5):1370-1377.

Wu, F.-C., W.S. Hsieh, and Y.-J. Chou. 1999. Variation of roughness coefficients for unsubmerged and submerged vegetation. Journal of Hydraulic Engineering. 125(9):934-941.

Yonge, D.R. 2000. Contaminant Detention in Highway Grass Filter Strips. Washington State Department of Transportation. Report No. WA-RD 474.1.

Yu, S.L., R.J. Kaighn, S.-H. Liao, C.E. O'Flaherty. 1995. The control of pollution in highway runoff through biofiltration, Vol I: Executive Summary. Virginia Transportation Research Council, Report VTRC 95-R28.

Zar, J.H. 1999. Biostatistical Analysis. Prentice-Hall. Upper Saddle River, New Jersey.

APPENDIX A:
BIOSWALE RECOMMENDATIONS FROM MUNICIPALITY OF METRO SEATTLE REPORT (10/92)

Project Phase		Recommendation	Benefits	Concerns
Planning	Siting	consider several complementary facilities in treatment train		
		make use of natural drainage courses and topographic features		
		provide for access	monitoring and maintenance	
Design & Installation	Planting	fine, dense, stiff bladed grasses such as Tall fescue, Bentgrass, and Red fescue	•provide excellent filtering •many species such as beach grasses able to grow up through sediment deposits	
		mosses	•can be beneficial for metal removal	•may outcompete grass
		Juncus tenuis, Juncus ensifolius, Scirpus microcarpus, Eleocharis, Sparganium euycarpum	•successful species in area of continual inundation	•not as finely divided as meadow grasses in area water contact
		perimeter trees and shrubs	•barrier to pets • support slope soil	•shading (so plant on north and east sides of facility) •litter drop can be detrimental to swale •heavily mulched and fertilized beds can create water quality problems •not appropriate for planting in swale bed
		consider desirability of creating healthy habitat		
	Hydraulics	max design velocity 0.9 fps		
		Manning's n of 0.200 to 0.235		
		flow spreaders such as weirs, stilling basin, or perforated pipe	avoid high local velocity and scour	increased maintenance
		check dams with flat tops	inhibits channelization	mowing and clean out more difficult
		high flow bypass	•avoid vegetation damage and high material inputs associated with high flows •provides bypass system if work needs to occur in swale	costs, may be unnecessary if upstream treatment facility exists
	Hydraulic Residence Time	optimal is at least 9 minutes and in no case should it be less than 5 minutes		

	Base Flow	where high water table, slight slopes, or winter base flows exist use finely-divided wetland vegetation		
	Geometry	length of 200 feet		treatment area and hydraulic residence are as important
		width between 2 to 8 feet	avoid channelization, ease of maintenance	
		longitudinal slope of 2-4%	if slope exceeds 6% design swale to traverse slope or install small (~1') drop structures	
		side slopes of 3:1	ease of maintenance, reduces problems with rock armoring, increases treatment area	
		minimize lateral slopes by careful grading	prevents channelization and distributes flow evenly	
		use 6-9" rock riprap pads for energy dissipation at infall as needed		
		water depth not to exceed 1/3 of vegetation height for grassy biofilters 2 to 3 inches is recommended		
	Soil	ideal composition varies by site and purpose		clays may not support vegetation coarse material may promote excessive infiltration
		avoid use of manure due to leaching		
		line bed with clay and geotextile if groundwater contamination is a concern		
Operation and Maintenance		keep inlets and flow spreaders clear of debris	improves flow introduction and distribution	
		negotiate access easements as needed	allows for anticipated monitoring, maintenance, and inspection	
		regular mowing of grass facilities	to keep vegetation at design height for best filtration	clippings can clog and add nutrients to water
		remove excessive sediment with flat shovels	allows vegetation to re-establish	
		reseed any bare areas and fill scour holes		need to divert flow to avoid washout, may need supplemental irrigation
		dispose of clippings as yard waste unless contaminated		

	perform chemical testing on sediments and dispose accordingly (Model Toxics Control Act)		
	avoid entry of animal waste into flow area		
	clean only as necessary for hydraulic capacity	reduces impact on established vegetation	
Institutional and Enforcement	greater flexibility within regulatory and institutional settings	promote more creative and effective designs allows for site-specific designs	
	have maintenance personnel review designs for capital projects		
	ensure proper guidelines if maintenance performed by private contracted parties		
	require construction/maintenance bonds	ensures proper installation by contractor which is single greatest factor in success of facility	
	proactive planning based on soils, hydrology, and maintenance commitments		

APPENDIX B:
WSDOT BIOSWALE, DITCH, AND CHANNEL GUIDELINES
(excerpts from Department manuals)

From *WSDOT Maintenance Manual for Water Quality and Habitat Protection (08/00)*

Group 2 - Drainage Maintenance & Slope Repair: Group 2 practices in the following areas are targeted for higher spending levels under the proposed ESA Maintenance M-2 program: ditch and channel maintenance, catch basin cleaning, culvert, retention/detention basins, and slope repairs. These WSDOT group 2 work activities total $9.3 million annually. Cost will increase about 23.6%. The estimated cost increase for Group 2 totals $2.2 million.

BMPs required will depend on site conditions and will include any or all of the following:

- Carry spill kit in all vehicles.
- Routinely inspect open ditches for accumulation of sediment and other pollutants.
- Proper erosion/sediment control BMPs.
- Prevent tracking out of soils onto public roads.
- Follow up with hydroseeding, straw bales and/or planting.
- Installation of appropriate water diversions.
- Appropriate removal of fish that are trapped.
- Bank stabilization using bioengineering.

2A1a--Maintain Ditches

Ditches are a feature, typically parallel to the road, that carries surplus surface water or ground water from the WSDOT facility and adjacent properties. They are not a channelized stream, or fish bearing stream. Channel impacts will be addressed in the channel maintenance section of this document.

Ditches are maintained and preserved to the line, grade, depth and cross section to which they were originally designed and constructed. Includes all work necessary to remove soil and rock that have built up over time to restore the originalhydraulic capacity of ditches. Work may include appropriate erosion control BMPs (e.g., seeding, mats, riprap), where there is the potential for continued erosion. Reshaping ditches which are designed to enhance motorist safety andimprove water quality (e.g., by regrading the drainage ditch with gentler slopes,which can reduce erosion, increase growth of vegetation, increase uptake of nutrients and other substances by vegetation, etc.) will be considered. Materialthat is removed from the ditch must be hauled to a suitable disposal site.

Crewsdoing this work may vary from 1 to more than 7 people depending on the size ofthe repair and amount of equipment needed to accomplish the work. Ditches donot require Corps and HPA permits if WSDOT's BMPs are followed.

Timing: Year round depending on weather. Generally will occur during drier times of the year when stormwater flows are low. Work may occur at any time of day or night, any day of the week.

Equipment: may include dump trucks, front end loader, motor grader, belt loader,excavator, or backhoe.

General Conditions: Statewide which are 1) conducted entirely within the existing right of way or on WSDOT properties, 2) removes low-growing grasses and forbs and expose soils, 3) do not increase drainage beyond original project boundaries or expand the area drained by the ditch as originally designed, 4) remains in approximately the same location, and 5) are located within 300 feet of riparian habitat or discharges into surface waters of the state

Avoidance and Minimization

Erosion and Sediment Control BMPs utilized by WSDOT are detailed in the WSDOT Highway Runoff Manual (M31-16, February 1995 - see appendix 20). The Highway Runoff Manual has been formally approved for use by Ecology under provisions of the Puget Sound Highway Runoff Program (Chapter 173-270 WAC). WDFW has also concurred with the provisions of the Highway Runoff Manual.

The protection of water quality for a variety of drainage maintenance activities is provided for in the WSDOT/Ecology Implementing Agreement for Surface Water Quality Standards (see appendix 19). Applicable maintenance activities are conducted in accordance with the conditions of this agreement and any subsequent revisions.

Best Management Practices

Appropriate BMPs will be used on all activities within 300-feet of surface water or potential riparian habitat. These practices must ensure that no foreign material such as side cast soils or oil and grease enter waters of the state.

Open ditches are routinely checked for accumulation of sediment and other pollutants (e.g., organic debris, oil and grease). If there is any standing water on shoulder or if deposits fill >50 % of the capacity of the basin, as measured by depth of accumulation, they require cleaning.

- Plan and schedule activities in dry conditions, except in emergency situations.

Where ditch maintenance is required within sensitive area boundaries, desirable vegetation will be retained on the inside shoulder slope to the greatest extent possible.

Leave vegetative buffer outside of work zone to provide bio-filtration and shading on back slope of ditch.

Leave vegetative buffer of grasses and small forbs between the shoulder and ditch if the area is wide enough.

Leave vegetated sections in ditchline, where sediment buildup does not impede flow or infiltration. Leaving vegetation in the last 50 feet of a ditch produces less sediments and other pollutants in runoff than complete ditching.

Remove slides from ditches and roadway.

If cleaning is required they are maintained to the line and grade and depth and cross section to which they were constructed. Ditches may be reshaped to produce shallower side slopes, to enhance motorist safety and improve water quality by trapping sediments and increasing vegetation.

Erosion and sediment control devices such as check dams, silt fences, and other acceptable techniques, will be used so that sediment or other materials do not enter waters of the state.

When surface water is flowing, a flow bypass system such as flow bypass (pump and pipe), diversion berm, diversion channel, pump to gutter or temporary channel, and other acceptable techniques, will be used so that sediment or other materials do not enter waters of the state.

Hydroseed or replant disturbed areas.

All exposed and erosive soils will be stabilized by application of effective erosion control BMP's, which protect the soil from the erosive forces of rain impact and flowing water.
Vegetation can be effectively restored after ditching by seeding, covering with straw, and holding the straw in place with stapled jute mat. West of the summit of the Cascade Range - March 1 to May 15 and August 15 to October 1. Seeding, fertilizing, and mulching will be accomplished during the spring and fall period listed above. East of the summit of the Cascade Range - August 15 to November 15. Seeding, fertilizing, and mulching will be accomplished during this period only.

Excavated materials will be disposed upland and not in any waters or wetland.

Excavated materials will be recycled when suitable.

All fueling and maintenance of equipment will occur at locations greater than 300 feet from the nearest wetland, ditches, flowing or standing water.

Carry spill kit in vehicle.

2A1b- Channel Maintenance

A Channel is different from a ditch in that a channel is a feature that collects drainage water, can be parallel or perpendicular to the highway facility, and may or may not be a natural stream. This action includes the same tasks performed on ditches and/or stormwater facilities within WSDOT right of way includes cleaning, reshaping/regrading, erosion control/slope stabilization, vegetation management, removing debris, trash, yard waste, sediment and repairing channels. Maintenance of ditches and/or stormwater features which are channels is performed when sediment, debris, or vegetation impedes flows or storage of water and sediments to a point where safety or structural integrity are jeopardized. Features which are not properly functioning, can cause:

- Hazardous driving conditions, particularly during cold weather.
- Roadway washouts during storm events.
- Flooding of adjacent property.
- Saturation of the road sub-base.
- Large quantities of sediment transport.

Material that is removed from the channel must be hauled to a suitable disposal site. Crews doing this work may vary from 1 to more than 7 people depending on the size of the repair and amount of equipment needed to accomplish the work. Channel maintenance may require permits. A checklist will be developed by OSC with consultation with Corps to clarify their policy on drainage ditches/channel maintenance activities and Section 404 permits. Any activity that requires a Corps permit will not be covered under the 4(d) exemption.

Timing: Year round depending on weather. Generally will occur during drier times of the year when stormwater flows are low. Work may occur at any time of day or night, any day of the week and limited to preferred in water work windows by WDFW (Appendix 10).

Equipment: may include dump trucks, front end loader, motor grader, belt loader, excavator, or backhoe.

General Conditions: Statewide which are 1) conducted entirely within the existing right of way, 2) removes low-growing grasses and forbs and expose soils, 3) do not increase drainage beyond original project boundaries or expand the area drained by the channel as originally designed, 4) remains in approximately the same location, and 5) are located within 300 feet of riparian habitat or discharges into surface waters of the state.

Avoidance and Minimization

Erosion and Sediment Control BMPs utilized by WSDOT are detailed in the WSDOT Highway Runoff Manual (M31-16, February 1995 - see appendix 20). The Highway Runoff Manual has been formally approved for use by Ecology under provisions of the

Puget Sound Highway Runoff Program (Chapter 173-270 WAC). The WDFW has also concurred with the provisions of the Highway Runoff Manual.

The protection of water quality for a variety of drainage maintenance activities is provided for in the WSDOT/Ecology Implementing Agreement for Surface Water Quality Standards (see appendix 19). Applicable maintenance activities are conducted in accordance with the conditions of this agreement and any subsequent revisions.

All drainage maintenance and slope repair activities must meet the conditions of the applicable HPA. Check with AHB for work falling under the regulatory jurisdiction of WDFW's HPA permit program. Tidegate maintenance activities will also be conducted according to HPA conditions as negotiated with NMFS/USFWS.

A 5-year, GHPA (Appendix 21) currently provides for the removal or modification of newly constructed beaver dams within WSDOT owned and/or maintained "manufactured drainage systems" and from WSDOT owned and/or maintained bridge piers. WSDOT adheres to the conditions in this permit in the conduct of beaver dam removal activities. Older, well-established beaver dams which must be modified or removed for roadway/structure safety reasons will be addressed under the conditions of a separate HPA.

A 5-year, GHPA (Appendix 22) currently provides for the removal from and/or repositioning of debris within WSDOT owned and/or maintained "manufactured drainage systems" as well as from WSDOT owned and/or maintained bridges and ferry terminals. WSDOT adheres to the conditions in this permit in the conduct of debris removal activities.

WSDOT, WDFW, and Ecology are cooperatively developing a document entitled "The Integrated Stream bank Protection Guidelines" (ISPG) which provides guidance on stream bank erosion assessment and remedial action technique selection. The most recent version of the ISPG (Appendix 23), is currently being used by WSDOT Maintenance in an "evaluative" manner. It is anticipated that the ISPG will become an increasingly-used resource for stream bank stabilization HPA conditions.

Channels that contains fish or contributes resources that support fish will be identified at the annual WDFW Maintenance Meetings. Channels identified will be tracked as an environmental deficiency. These projects will be forward to WSDOT's Regional Program Management Office for consideration into a scope of a proposed capital project to be separated from the channel. Identified projects which fall within the scope of other projects in WSDOT's 2 and 6 year plans, may be considered in conjunction with the scheduled project in an attempt to reduce the number of channels being used as drainage systems.

Best Management Practices

Appropriate BMPs will be used on all activities within 300-feet of surface water or potential riparian habitat. These practices must ensure that no foreign material such as side cast soils or oil and grease enter waters of the state.

Open channels are routinely checked for accumulation of sediment and other pollutants (e.g., organic debris, oil and grease). If there is any standing water on shoulder or if deposits fill >50 % of the capacity of the basin, as measured by depth of accumulation, they require cleaning.

Plan and schedule activities in dry conditions, except in emergency situations.

- Leave vegetative buffer outside of work zone to provide bio-filtration and shading on back slope of channel.

- Leave vegetative buffer of grasses and small forbs between the shoulder and channel if the area is wide enough.

Leave vegetated sections in channel, where sediment buildup does not impede flow or infiltration.

- Remove slides from channels and roadway.

- If cleaning is required they are maintained to the line, grade, depth and cross section to which they were constructed.

All permit conditions will be followed.

- If fish are present, work will only be performed in emergency situations. (See Timing limitations/Notification Requirement page 28). Fish will be excluded from area using appropriate methods such as the use of nets, dewatering at a controlled rate, and removal of stranded fish according to HPA permit conditions as negotiated with NMFS/USFWS.

- Captured fish shall be immediately and safely transferred to free flowing water downstream of the work area.

Erosion and sediment control devices such as check dams, silt fences, and other acceptable techniques, will be used so that sediment or other materials do not enter waters of the state.

- When surface water is flowing, a flow bypass system such as flow bypass (pump and pipe), diversion berm, diversion channel, pump to gutter or temporary channel, and other acceptable techniques, will be used so that sediment or other materials do not enter waters of the state.

- Hydroseed or replant disturbed areas.

- All exposed and erosive soils will be stabilized by application of effective erosion control BMP's, which protect the soil from the erosive forces of rain impact and flowing water. Vegetation can be effectively restored after ditching by seeding, covering with straw, and holding the straw in place with stapled jute mat. West of the summit of the Cascade Range - March 1 to May 15 and August 15 to October 1. Seeding, fertilizing, and mulching will be accomplished during the spring and fall period listed above. East of the summit of the Cascade Range - August 15 to November 15. Seeding, fertilizing, and mulching will be accomplished during this period only.

- Excavated materials will be disposed upland and not in any waters or wetland.

Excavated materials will be recycled when suitable.

All fueling and maintenance of equipment will occur at locations greater than 300 feet from the nearest wetland, ditches, flowing or standing water.

- Carry spill kit in vehicle.

From *WSDOT Stormwater Management Plan v5.3 (03/97)*

Grading and Cleaning Drainage System Ditches

Drainage facilities are maintained to preserve the condition and capacity for which they were originally designed and constructed. Maintenance practices for erosion and sediment control best management practices (BMPs), water quality and quantity BMPs, and construction site pollution control BMPs, are found in Chapter 8 of the Highway Runoff Manual.

Maintenance Criteria for Grading and Cleaning of Drainage System Ditches:

1. Maintenance of ditches uses the hydraulic performance of the drainage facility as an surrogate indicator for its water quality functions.

2. Ditches should be inspected twice each year to identify sediment accumulations, localized erosion and other problems. Ditches should be cleaned on an annual basis or frequently if needed.

3. Ditches and gutters must be kept free of rubbish and debris. Cracks and breaks must be repaired as required.

4. Water should not pond in ditches and a ditch should never be deeper than the culvert flow lines, unless the ditch is designed for storage.

5. Vegetation in ditches often prevents erosion and cleanses runoff waters. Remove vegetation only when flow is blocked or excess sediments have accumulated. Emphasis shall be placed performing ditch maintenance in late spring to enable the vegetation the opportunity to re-establish by the next wet season thereby minimizing erosion of the ditch as well making the ditch effective as a biofilter.

6. Open ditches must be routinely checked and maintained to the line, grade, depth, and cross section to which they were constructed. Where practical, ditches should be modified to produce a relatively flat shallow ditch to enhance motorist safety.

7. Diversion ditches on top of cut slopes that are constructed to prevent slope erosion by intercepting surface drainage must be maintained to retain their diversion shape and capability.

8. Surplus material derived from regular maintenance of ditch cleaning can often be used for shoulder widening, as long as the material placed into adjacent portions of the highway or disposal areas and does not obstruct impair other roadside drainage areas. Care must be taken to avoid causing erosion problems or loose unstable fills.

9. Ditch cleanings are not to be bladed across the roadway surfaces. Dirt and debris remaining on the pavement after the ditch cleaning operations shall be swept from the pavement.

10. Culverts shall be inspected on a regular basis for scour around the inlet and outlet, and repaired as necessary. Priority shall be given to those culverts near streams in areas of high sediment load, such as near construction activities. *Implementation Reference(s*): Ch. 5 MM; Ch. 7 & 8 HRM

Maintaining Biofiltration Swales

1. Maintenance: Swales are mowed during summer. Remove sediments during summer months when they build up to 4 inches at any spot, cover biofilter vegetation, or other wise interfere with biofilter operation. Focus is to have a level surface to provide even flow - to the pond bottom.

2. Inspect biofilters periodically, especially after heavy runoff. Remove sediments, fertilize and reseed as necessary. Be careful to avoid introducing fertilizer to receiving waters or groundwater. Remove litter to keep biofilters free of external pollution.

Mowing

1. Mechanical mowers are used to selectively remove undesirable trees, brush and weeds as part of an integrated vegetation management program.

2) Turf and erosion control grasses are managed by mowing. Only roadside areas level enough to accommodate mechanical mowing will be mowed.

3. Not more than one-third of the total grass height should be removed in a single mowing activity, unless the grass has produced seed and died.

4. Mowing frequency is dictated by height of mowing for grasses shall not be less than two inches, and preferably between 4 and 6 inches.

5. Newly seeded erosion control grass stands are not to be mowed until the grass has been in place one full year.

Implementation Reference(s): Ch. 7 MM

Additional Maintenance Excavation Practices

All material excavated from roadside ditches or streams shall be completely removed and disposed of at an upland location. No material shall be side cast into adjacent wetlands or other waters of the state, unless authorized by WDFW for stream habitat improvement. If material is placed on the upland to dewater, it shall be contained or placed in such a way that the runoff will not flow into nearby storm drains, or waterbodies, including wetlands occurring adjacent to the ditch. Any flow of slurry water shall be controlled to reduce suspended sediment levels prior to discharge back into any adjacent waterbody. This return water shall not exceed the standards.

Experimental BMPs

The findings from WSDOT work on the following Experimental BMPs may be applicable to bioswale and ditch maintenance operations.

Ecology Ditch

(i) Description of the experimental BMP. The ecology ditch is a modification of the standard biofiltration swale design for use in areas with very flat gradients (<2%). To provide sufficient drainage in these flat areas, the ecology ditch is constructed with a substrata consisting of highly pervious sand/gravel soils (ecology mix), and a perforated pipe subsurface drainage system. In addition to allowing the ecology ditch to drain sufficiently to maintain vegetation, the underdrain system acts as a sand filter during low intensity precipitation events.

(ii) Why the experimental BMP is being requested and HRM techniques are not appropriate. In many cases in areas with very flat gradients, the depth of flow in a standard biofiltration swale will exceed 4 inches in depth for a 6 mo. / 24 hour storm event. This exceeds HRM design standards. In order to facilitate the transport of stormwater, enhanced infiltration rates are required. The ecology ditch design was developed to facilitate this modification.

(iii) Special construction provisions for the ecology ditch. Cross sections of the ecology ditch are shown in Appendix C. The ecology ditch has a substrate that acts as filtration media. The ecology mix will consist of a mixture of soil amendments and mineral aggregate in accordance with the requirements of Section 8-02 and these specifications:

Soil Amendment	Unit	Quantity (rate)
Perlite	cubic yard (CY)	1 CY per 3 CY of mineral aggregate
Dolomite Lime, #0, #16 to #8 gradation	pound	10 pounds per CY of perlite
Gypsum	pound	1.5 pounds per CY of perlite

The ecology mix will be covered with an erosion control blanket. The ecology mix will then be seeded, fertilized, and mulched and then mulched a second time.

(iv) Ecology ditch testing site(s) and characteristics. An ecology ditch was originally planned to be constructed at SR 167 (Valley Highway), MP 25.35 in Auburn, Washington, but it was eliminated from the project because the road alignment was altered such that space to construct the proposed ecology ditch became unavailable. WSDOT will seek alternate locations for ecology ditch monitoring.

(v) Design criteria. A typical ecology ditch contains a 8 inch PVC underdrain pipe in a 2-foot-wide trench bedded with gravel. Pipe bedding material is a gravel backfill for drains with a maximum size of 1 inch and only 2 percent passing the number 200 sieve. Above the pipe trench the ditch widens to 8 feet and contains a 1 foot layer of gravel aggregate. The aggregate has a gradation of 3/8 inch to number 10 sieve. The surface of the ditch consists of gypsum and alder sawdust mixed onto the top 2 inches of the aggregate. The gypsum is number 0 grade and has a gradation of number 8 to number 16 sieve.

Other necessary design and site criteria for installation of an ecology ditch:

A minimum length of 200 feet, the maximum bottom width is 10 feet, The bottom width will be specified so that depth of flow does not exceed 4 inches during the 6-month storm;

- Low longitudinal slopes (<2%), which precludes the installation of a standard biofiltration swale;

The ecology ditch should be sized both as a water quality treatment facility for the 6-month storm and as a conveyance system to pass the peak hydraulic flows of the 100-year storm;

A minimum of three feet of soil between the bottom of ditch to the highest ground water level;

- In-situ soil infiltration rates of at least 2.0 inches per hour;

- Low intensity precipitation events, 50% of the 6-month storm, shouldn't overtop the installed erosion control blanket (dependent on bottom width and side slopes);

The ideal cross-section of the ditch should be a trapezoid with side slopes no steeper than 3:1.

(vi) Proposed maintenance procedures.

Remove sediments during summer months when they build up to 4 inches at any spot, cover vegetation, or otherwise interfere with hydraulic performance of the ditch.

- Inspect ecology ditch periodically, especially after periods of heavy runoff. Remove sediments, mulch, fertilize, and reseed as necessary. Be careful avoid introducing fertilizer to receiving waters or ground water.

- Clean curb cuts when soil and vegetation buildup interferes with flow introduction.

- Remove litter to keep the ecology ditch free of external pollution sources.

(vii) Cost estimates. Because of additional excavation, fill, and materials requirements, ecology ditches should cost 50-100% greater than an equivalently sized biofiltration swale. This amounts to (roughly) $7,500 to $20,000 per acre of impervious surface drained. Using this as an basis for estimation, the cost of an ecology ditch could range from $10,000 to over $200,000, depending on the size of the drainage area and the amount of right of way that would have to be acquired.

(viii) Anticipated results. It is anticipated that the ecology ditch will remove suspended solids and constituents associated with solids at rates which vary between 25% and 90%, depending on the intensity of the precipitation event. Higher removal rates is anticipated to be associated with low intensity (<0.25 inch/24 hour) events. Dissolved constituents (nutrients or dissolved-phase metals) are anticipated to be removed at rates which range between 0% and 50%. Concentrations of nutrients in stormwater may actually increase after passing through the ecology ditch in its early life-cyclebecause of the application of fertilizer during construction to establish vegetation. Consideration should be given to sodding, mulching without fertilizer, or other vegetation methods which do not use fertilizer in drainages discharging to lake basins or water quality limited water bodies because of excessive nutrients.

(ix) Approved BMP(s) that can be used if the experimental BMP fails. Depending on the characteristics of the drainage basin, soil characteristics, and available right of way, biofiltration swales, wet ponds, infiltration ponds, or wet vaults may be suitable alternatives to the ecology ditch.

(x) BMP status. Based on the results of the monitoring program for the ecology ditch, WSDOT will evaluate the BMP for effectiveness in protecting water quality and beneficial uses, its reliability, cost, ease of construction, and maintenance requirements. After evaluation of the results of a monitoring program designed to evaluate the BMP's constituent removal effectiveness, WSDOT may then propose that the ecology ditch be included as a standard BMP in the Highway Runoff Manual.

Biofiltration Swale Design Enhancements

(i) Description of the experimental BMP. Biofiltration swales have been found to have highly variable constituent removal efficiencies (Koon, 1995). But, because of the narrow, linear nature of biofiltration swales, they fit the spatial constraints that are common along state highways. Virginia DOT (1994) and FHWA (1996) conducted independent studies that suggest that the incorporation of level spreaders with wetland plants into biofiltration swales may improve their constituent removal performance. The incorporation of "pocket wetlands" create greater detention time, increase infiltration rates, and create low velocity zones which allow for increased sediment removal.

WSDOT plans to investigate modifying biofiltration swale design criteria so that they are based on detention times rather than using predetermined physical dimensions. modifications to empirically determine whether they provide performance improvements over conventional designs between1997 and 2000.

(ii) Why the experimental BMP is being requested and HRM techniques are not appropriate:

Currently, biofiltration swales designs are determined by physical dimensions, rather than detention time. Using detention time as a primary design criteria, which can be modified by the installation of check dams, may be more appropriate criteria affecting the constituent removal efficiency of swales.

(iii) Special construction provisions for biofiltration swale design enhancements: None.

*(iv) Biofiltration swale sites and characteristic*s: None has been identified as of the drafting of this document. Grant funding and internal funding will be requested to facilitate the applicability of biofiltration swale design enhancements.

(v) Design criteria for biofiltration swales design enhancements: The side slopes for the check dams should be between 5 and 10 to 1 to facilitate mowing operations. The berm height should not exceed 2 ft. and water ponded behind the berm should infiltrated into the soils within 24 hours. Check dams should be spaced so that the toe of the upstream dam is at the same elevation as the top of the downstream dam. Check dams should be constructed using quarry spall. For best performance, check dams should have a level upper surface. The number of check dams required for maximum ponding needs to be computed, by first determining the length behind each check dam:

> L_d = H/s, where L_d is the length behind the check dam, H is the depth of the swale, and s = slope
>
> Number of check dams = L/L_d , where L is the total swale length.
>
> The top width (wt) for each check dam is computed by: wt = wb + 3ds z, where wb is the check dam bottom width (corresponding to swale bottom width, calculated using standard HRM criteria), and 3 is the side slope ratio.

(vi) Proposed maintenance procedures: Same as standard biofiltration swales, section 3.3.6.11.

(vii) Cost estimates. Typically, vegetated swales cost less to construct than curb, gutters, and underground pipe, and may run from $5 to $15 per linear foot. Quarry spall used to create detention structures and level spreaders costs and additional $12 per cubic yard and it between 5 and 60 cubic yards of spall would be needed per swale.

(viii) Anticipated results. VDOT reported an additional 40% solids removal rate when check dams are incorporated into swale designs. WSDOT expect similar improvements in constituent removal efficiency.

(ix) Approved BMP(s) that can be used if the experimental BMP fails: None

(x) BMP status. Funding sources are being identified to conduct tests on this experimental BMP. Testing is dependent on acquiring funding.

From *WSDOT Highway Runoff Manual (02/95)*

BMP RB.05 — Biofiltration Swale

Definition

Biofiltration is the simultaneous process of filtration, particle settling, adsorption, and biological uptake of pollutants in stormwater that occurs when runoff flows over and through vegetated areas. A biofiltration swale is a sloped, vegetated channel or ditch that provides both conveyance and water quality treatment to stormwater runoff. It does not provide stormwater quantity control but can convey runoff to BMPs designed for that purpose.

General Criteria

1. The swale should have a length of 200 feet (61.0 m). The maximum bottom width is 10 feet (3.1 m). The depth of flow must not exceed 4 inches (100 mm) during the 6-month storm.
2. The channel slope should be at least 1 percent and no greater than 5 percent.

3. The swale can be sized as both a treatment facility for the 6-month storm and as a conveyance system to pass the peak hydraulic flows of the 100-year storm if it is located "on-line."

4. The ideal cross-section of the swale should be a trapezoid. The side slopes should be no steeper than 3:1.

5. Roadside ditches should be regarded as significant potential biofiltration sites and should be utilized for this purpose whenever possible.

6. If flow is to be introduced through curb cuts, place pavement slightly above the biofilter elevation. Curb cuts should be at least 12 inches (300 mm) wide to prevent clogging.

7. Install low-flow biofiltration swales within ponds where sufficient land does not exist for both.

8. Biofilters must be vegetated in order to provide adequate treatment of runoff.

9. It is important to maximize water contact with vegetation and the soil surface. For general purposes, select fine, close-growing, water-resistant grasses. Consult the district or headquarters Landscape Section for specific vegetation selection recommendations.

10. Biofilters should generally not receive construction-stage runoff. If they do, presettling of sediments should be provided (see BMPs E3.35 and E3.40). Such biofilters

should be evaluated for the need to remove sediments and restore vegetation following construction.

11. If possible, divert runoff (other than necessary irrigation) during the period of vegetation establishment. Where runoff diversion is not possible, cover graded and seeded areas with suitable erosion control materials.

Design Procedure

1. Determine the peak flow rate to the biofilter from the 6-month 24 hour design storm.

2. Determine the slope of the biofilter. This will be somewhat dependent on where the biofilter is placed. The slope should be at least 1 percent and shall be no steeper than 5 percent. When slopes less than 2 percent are used, the need for underdrainage must be evaluated.

3. Select a swale shape. Trapezoidal is the most desirable shape; however, rectangular and triangular shapes can be used. The remainder of the design process assumes that a trapezoidal shape has been selected.

4. Use Manning's Equation to estimate the bottom width of the biofilter.

Manning's Equation for English units is as follows:

$$Q = (1.486 \times A \times R^{0.667} \times S^{0.5}) / n$$

where: Q = flow (cfs)
A = cross sectional area of flow (ft^2)
R = hydraulic radius of flow cross section (ft)
S = longitudinal slope of biofilter (ft/ft)
n = Manning's roughness coefficient = 0.20 for typical biofilter

For a trapezoid, this equation cannot be directly solved for bottom width. However, for trapezoidal channels that are flowing very shallow the hydraulic radius can be set equal to the depth of flow. Using this assumption, the equation can be altered to:

$$b = ((0.135 \times Q) / (y^{1.667} S^{0.5})) - z \times y$$

where: y = depth of flow
z = the side slope of the biofilter in the form of z:1

Typically the depth of flow is selected to be 4 inches (100 mm). It can be set lower but doing so will increase the bottom width. Sometimes when the flow rate is very low the equation listed above will generate a negative value for b. Since it is not possible to have a negative bottom width, the bottom width should be set to 1 foot when this occurs. Biofilters are limited to a maximum bottom width of 10 feet. If the required bottom width is greater than 10 feet, parallel biofilters should be used in conjunction with a device that splits the flow and directs the proper amount to each biofilter.

5. Calculate the cross sectional area of flow for the given channel using the calculated bottom width and the selected side slopes and depth.

6. Calculate the velocity of flow in the channel using:

$V = Q / A$

If V is less than or equal to 1 ft/sec, the biofilter will function correctly with the selected bottom width. Proceed to design step 7. If V is greater than 1 ft/sec, the biofilter will not function correctly. Increase the bottom width, recalculate the depth using Manning's Equation and return to design step 5.

7. Select a location where a biofilter with the calculated width and a length of 200 feet (61 m) will fit. If a length of 200 feet (61 m) is not possible, the width of the biofilter must be increased so that the area of the biofilter is the same as if a 200 foot (61 m) length had been used.

8. Select a vegetation cover suitable for the site. Refer to the district or headquarters landscape architect or the headquarters horticulturist.

9. Determine the peak flow rate to the biofilter during the 100-year 24-hour storm. Using Manning's Equation, find the depth of flow (typically n = 0.04 during the 100-year flow). The depth of the channel shall be 1 foot (300 mm) deeper than the depth of flow.

Construction and Maintenance Criteria

1. Groomed biofilters planted in grasses shall be mowed during the summer to promote growth and pollutant uptake.

2. Remove sediments during summer months when they build up to 4 inches (100 mm) at any spot, cover biofilter vegetation, or otherwise interfere with biofilter operation. If the removal equipment leaves bare spots, reseed those spots.

3. Inspect biofilters periodically, especially after periods of heavy runoff. Remove sediments, fertilize, and reseed as necessary. Be careful to avoid introducing fertilizer to receiving waters or ground water.

4. Clean curb cuts when soil and vegetation buildup interferes with flow introduction.

5. Remove litter to keep biofilters free of external pollution.

Channel Conveyance

Maintenance of ditches has focused historically on the hydraulic performance of drainage facilities. In some instances, vegetation within the ditches may provide an opportunity for water quality enhancement but could interfere with the hydraulic capacity. Cleaning of the ditches resulting in exposed soils may result in increased sediment load and the subsequent downstream impact.

The preservation of the hydraulic capacity of ditches must be recognized in the maintenance approach. The following recommendations are intended to augment the existing WSDOT ditch maintenance program.

Ditches should be inspected by WSDOT maintenance staff twice each year to identify sediment accumulations, localized erosion and other problems. Ditches should be cleaned on an annual basis or more frequently if needed. Ditches and gutters must be kept free of rubbish and debris and all cracks and breaks must be repaired as required.

Water should not pond in ditches and a ditch should never be deeper than the culvert flow lines, unless the ditch is designed for storage. Vegetation in ditches often prevents erosion and cleanses runoff waters. Vegetation should be removed only when flow is blocked or excess sediments have accumulated. Emphasis shall be placed on performing maintenance in late spring to enable the vegetation the opportunity to reestablished by the next wet season thereby minimizing erosion of the ditch as well as making the ditch effective as a biofilter.

Open ditches will be routinely checked and maintained to the line, grade, depth, and cross section to which they were constructed. Where practicable, ditches should be modified to produce a relatively flat, shallow ditch to enhance motorist safety.

Diversion ditches on top of cut slopes that are constructed to prevent slope erosion by intercepting surface drainage must be maintained to retain their diversion shape and capacity.

Surplus material derived from regular maintenance of ditch cleaning can often be used for widening, as long as the material placed into the adjacent portions of the highway or disposal areas and does not obstruct or impair other roadside drainage areas. Care must be taken to avoid causing erosion problems or loose unstable fills.

Ditch cleanings are not to be bladed across roadway surfaces. Dirt and debris remaining on the pavement after the ditch cleaning operations will be swept from the pavement.

Culverts will be inspected on a regular basis for scour around the inlet and outlet, and repaired as necessary. Priority will be given to those culverts located in perennial or salmonid-bearing streams, and culverts near streams in areas of high sediments load, such as those near construction activities.

APPENDIX C:
FIELD MEASUREMENTS OF MANNING'S N VALUES FOR VEGETATED CHANNELS

Authors	Soils and Vegetation		Flow conditions	Geometry	Manning's n coefficient values
Ree and Palmer (later modified by Wanielista)	Reed canary grass			slope 0 to 5%	• 0.40 (for vR[1] = 0.1) • 0.250 (for vR = 1.0) • 0.070 (for vR = 10)
	Tall fescue			slope 5 to 10%	
Ree and Crow	clay subsoil; good cover of 16" lovegrass and crabgrass; 165 stems/ft2		2.8 to 99.5 cfs	Trapezoidal with 20 wide beds on a 0.1% slope	• for R < 1.50 and vR < 0.30 n = 0.332 to 0.383 • for R > 1.50 and vR > 0.30 and unsubmerged n = 0.232 to 0.325 • after submergence n = 0.077 to 0.144
Engman (1983) and FDOT (1986)	Dense grass mix				0.17 to 0.30 (for vR < 1.0)
	Bermudagrass				0.30 to 0.48 (for vR < 1.0)
Metro	67% tall fescue, 16% seaside bentgrass, 17% other grass and herbs. Density ranged from 600 to 1600 stems/ft2	unmowed (12" grass)	0.33 to 0.51 cfs	3–4% slope, trapezoidal, 5 foot bottom width	0.193 to 0.206
		mowed (6" grass)	0.60 to 1.1 cfs	3–4% slope, trapezoidal, 5 foot bottom width	•0.235 (at 0.6 cfs) •0.164 (at 1.1 cfs)

[1]vR = mean velocity ft/s x hydraulic radius ft

APPENDIX D:
SITE SELECTION METHODOLOGY FOR EXPERIMENTAL ROADSIDE DITCHES

VEGETATED STORMWATER FACILITY MAINTENANCE PROJECT

Detailed Site Selection Criteria

DESCRIPTION

Ditches are roadside channels designed only for water conveyance but can be either beneficial (if well vegetated) or detrimental (if eroding) to water quality. Biofiltration **swales** are vegetated channels designed to capture pollutants from runoff. Three ditch segments and three swale segments will be selected for investigation of the cost effectiveness of alternative maintenance actions to address common problems in each that negatively affect water quality. The term **segment** is used to signify that an entire ditch or swale, or a portion thereof, may be selected for the investigation, depending on the fit of a potential site with these criteria.

A key part of the investigation will be monitoring of highway runoff entering and exiting the segments. Monitoring will be accomplished by deploying flow-splitting devices at the segment inlet and outlet points that direct a known fraction of the total runoff into collection tanks for determination of total influent and effluent volumes and for obtaining composite water samples to analyze for water quality variables.

CRITERIA APPLICABLE TO BOTH DITCHES AND BIOFILTRATION SWALES

<u>Essential Conditions</u>

Assured safety from traffic hazards for personnel during site construction and monitoring.

Highway runoff as the only source of water conveyed through the segment.

Contributing highway catchment representative of facilities where maintenance decisions will be made using the study's results and not so large that it produces runoff volumes in frequent storms that would be hard to handle in the flow-splitter system. (Note: A practical maximum catchment size is roughly 1 acre.)

Ditch or swale representative of facilities where maintenance decisions will be made using the study's results.

Ability to direct entering highway runoff into the flow splitter without its contacting media that may change its quantity and quality, such as earth, vegetation, gravel, etc.

Surface water entering only at the point designated as the segment inlet and exiting only at the point designated as the segment outlet. (Note: Infiltration may occur and will be registered by comparing influent and effluent volumes.)

Substantial similarity among the contributing catchments of the three selected ditch segments and of the three selected swale segments in:

- Highway configuration (in terms of pavement and presence of mainline, overpasses, ramps, etc.)
- Traffic volume and type
- Absence of construction
- Maintenance practices
- Pollutant spill history

Substantial similarity among the three selected ditch segments and among the three selected swale segments in:

- Approximate age and maturity (A mix of newly constructed and older segments will be avoided, especially.)
- Vegetation type and initial cover
- Soil characteristics (primarily, origin, grain size distribution, organic content)
- Soil moisture condition
- Longitudinal slope
- Shading
- Energy dissipation and flow distribution of entering runoff
- Previous maintenance

Minimum of 1:12 (rise:run) slope for approximately 10-15 ft immediately upslope of designated inlet and immediately downslope of designated outlet for installation of flow splitters, or ability to place flow splitter elsewhere and get water to and from it by gravity and without any modification. (Note: Flow splitters must be placed on this minimum slope to produce supercritical flow and, consequently, uniform flow distribution across the flow path).

Slope configuration appropriate for flow splitter installation. (Note: The device is rectangular in cross section and approximately 1.5 ft high by 2-3 ft wide, depending on contributing catchment; confining spaces like narrow V-shaped channels may be problematic.)

Space for 4 x 4 x 4 ft collection tank.

Accessibility and physical characteristics that allow proposed maintenance actions to be conducted in accordance with standard roadside maintenance procedures.

Secondary Conditions

An ideal case would be to have three ditch segments and three swale segments each with identical contributing catchments, each of the same size and shape, and all close to one another for ease of monitoring. Therefore, a premium will be placed on candidates in the same complex that are similar in size. If such sites can not be found, the three segments in each group should have at least approximately the same ratio of treatment volume (wetted cross-sectional area for design storm x length) to design storm peak flow rate.

Accessible via local street, avoiding going on the highway.

Fire hydrant within 500 ft to provide water for hydraulic residence time measurement. If this becomes problematic, WSDOT will be requested to provide water trucks..

In the contributing watershed of a high priority salmon-bearing stream.

CRITERIA APPLICABLE TO DITCHES

Appropriate to apply alternative ditch cleaning and revegetation measures.

CRITERIA APPLICABLE TO SWALES

Functioning sub-optimally but potentially reparable by maintenance action short of major reconstruction. Therefore, preferred sites will be swales that are properly sited and designed but have a problem that decreases performance, such as bare spots, for which more limited actions have a high probability of success.

APPENDIX E: ROADSIDE DITCH SURVEY DIRECTIONS AND FORMS

VEGETATED STORMWATER FACILITY MAINTENANCE

DITCH SURVEY DATA RECORDING

GENERAL INFORMATION

Assigned number

Location: Thomas Bros. map and alphanumeric grid

Address or road and nearest crossroads (to N and S or E and W)

Length (ft)

Connection (record for upstream and downstream): Ul--connected to additional natural bottom ditch upstream; U2--connected to pipe or culvert upstream; U3--connected to paved ditch upstream; U4--not connected to any other conveyance upstream; Dl--connected to additional natural bottom ditch downstream; D2--connected to pipe or culvert downstream; D3--connected to paved ditch downstream; D4--not connected to any other conveyance downstream

Land use along roadside and in drainage area visible from survey location (list in order of dominance): SFR--single-family residential; MFR--multi-family residential; Co--commercial; I- institutional (e. g., school, church); OP--office park; LI--light industrial; HI--heavy industrial; P-pasture; Cr--cropland; DP--"developed pervious" (e. g., park lawn, cemetery); G--grassland; CF-coniferous forest; DF--deciduous forest; W--wetland

Hydraulics (flow and drainage conditions during survey): 1--dry; 2--flowing but apparently intermittent; 3--flowing and apparently continuous; 4--flowing, continuity not apparent; 5-substantial standing water; 6--isolated pooling

Disturbance (record all that apply and give approximate location in ft relative to upstream end): 1--minor litter; 2--substantial litter; 3--minor siltation (record average depth); 4--substantial siltation (record average depth); 5--minor scour (record average depth); 6--substantial scour (record average depth); 7--visible oil; 8--visible pollutant other than silt or oil; 9--mowed grass not removed; 10--yard waste disposed; 11--soil buildup at curb cuts; 12--other (describe)

Design plans available: Yes/No?

If design plans available:

- Design flow rate (cfs)
- Manning's n
- Age (years)
- Planting plan
- Structural data (see below)
- Transect geometric date (see below)

Maintenance schedule available: Yes/No?

If maintenance schedule available:

Type (record all that apply): 1--mowing or other plant harvesting; 2--silt removal; 3-ditch cleaning by backhoe; 4--ditch cleaning by Ditch Master; 5--curb cut cleaning; 6-other (describe)

Frequency

Monitoring potential (describe)

STRUCTURAL DATA

Inflow (record all that apply): Pt.--at single point; CC--curb cut; Free--over-the-shoulder sheet flow

Inflow structure (if inflow Pt.): 1--culvert pipe; 2--catch basin; 3--other (describe)

Energy dissipation (if inflow Pt. or CC): 1--none; 2--rip-rap; 3--stilling well; 4--other (describe)

Flow distribution (if inflow Pt. or CC): 1--none; 2--level spreader; 3--perforated pipe; 4--stilling well; 5--other (describe)

Check dams (number, spacing in ft)

TRANSECT GEOMETRIC DATA (specify spacing; e. g., 0, *50,...* ft from upstream end)

Shape: T--trapezoidal; P--parabolic; V--V-shaped; U--U-shaped

Top width (any shape;ft)

Bottom width (T; ft)

Ditch depth (any shape, inches)

Water depth, if any (any shape; inches)

Side slope (T, P, V; H:V)

Longitudinal slope (any shape; %)

TRANSECT VEGETATION DATA (specify spacing; e. g., 0, *50,* ft from upstream end; answer for a 1-meter long quadrant around the transect point)

Bed vegetation type: MH--mixed herbaceous (apparently volunteers without evidence of seeding); GS--grass seeding; WT--woody terrestrial plants; EW--emergent herbaceous wetland plants; WW--woody wetland plants; N--none (describe surface)

Side slope vegetation type: MH--mixed herbaceous (apparently volunteers without evidence of seeding); GS--grass seeding; WT--woody terrestrial plants; EW-emergent herbaceous wetiand plants; WW--woody wetiand plants; N--none (describe surface)

Bed vegetation cover: 1--fully or nearly fully covered (95-100% covered); 2--some bare area (70-95% covered); 3--substantial bare area (40-70% covered); 4--mostly bare (5-40% covered); 5-bare (0-5% covered)

Side slope vegetation cover: 1--fullyornearlyfullycovered(95-100%covered);2--somebare area (70-95% covered); 3--substantial bare area (40-70% covered); 4--mostly bare (5-40% covered); 5--bare (0-5% covered)

Bed vegetation average height (inches)

Side slope vegetation average height (inches)

Bed vegetation status (% erect)

Side slope vegetation status (% erect)

Bed vegetation condition: 1--healthy; 2--some damage due to human intrusion; 3--substantial damage due to human intrusion; 4--some damage probably due to drought; 5--substantial damage probably due to drought; 6--some damage probably due to other causes (describe if possible); 7-substantial damage probably due to other causes (describe if possible)

Side slope vegetation condition: 1--healthy; 2--some damage due to hw-nan intrusion; 3-substantial damage due to human intrusion; 4--some damage probably due to drought; 5-substantial damage probably due to drought; 6--some damage probably due to other causes (describe if possible); 7--substantial damage probably due to other causes (describe if possible)

Roadside Ditch Survey Form

Number:
Location:

General Information

Length (ft): | Connection (U,D-1,2,3,4) : | Land Use (SFR,MFR,Co,I, OP,LI
Hydraulics (1-6): | Disturbance (1-12): | HI,P,Cr,DP,G,CF,DF,W):

Design Plans Available? | Design Flow Rate(cfs): | Manning's n:
Age (yrs): | Planting Plan:
Structural Data: | Transect Geometric Date:

Maintenance Schedule Available? | Type of Maintenance:
Frequency:

Monitoring Potential:

Structural Data

Inflow (Pt,CC,Free): | Inflow Structure (1-3):
Energy Dissipation (1-3): | Flow Distribution (1-5):
Check Dams (#,spacing '):

Transect Geometry/Vegetation Data

Location (x' from upstream end): | Shape (T,P,V,U): | **#1**
Top Width (any shape,ft): | Bottom Width (T,ft):
Ditch Depth (any shape, in): | Water Depth (any shape,in):
Side Slope (T,P,V;H:V): | Longitudinal Slope (any shape%):

Location (x' from upstream end): | BED | Side Slope
Vegetation Type (MH,GS,WT,EW,WW,N):
Vegetation Cover (1-5):
Vegetation Average Height (in):
Vegetation Status (% erect):
Vegetation Condition:

NOTES:

Location (x' from upstream end): | Shape (T,P,V,U): | **#2**
Top Width (any shape,ft): | Bottom Width (T,ft):
Ditch Depth (any shape, in): | Water Depth (any shape,in):
Side Slope (T,P,V;H:V): | Longitudinal Slope (any shape%):

Location (x' from upstream end): | BED | Side Slope
Vegetation Type (MH,GS,WT,EW,WW,N):
Vegetation Cover (1-5):
Vegetation Average Height (in):
Vegetation Status (% erect):
Vegetation Condition:

NOTES:

Location (x' from upstream end):	Shape (T,P,V,U):	**#3**
Top Width (any shape,ft):	Bottom Width (T,ft):	
Ditch Depth (any shape, in):	Water Depth (any shape,in):	
Side Slope (T,P,V;H:V):	Longitudinal Slope (any shape%):	
Location (x' from upstream end):	BED	Side Slope
Vegetation Type (MH,GS,WT,EW,WW,N):		
Vegetation Cover (1-5):		
Vegetation Average Height (in):		
Vegetation Status (% erect):		
Vegetation Condition:		
NOTES:		

Location (x' from upstream end):	Shape (T,P,V,U):	**#4**
Top Width (any shape,ft):	Bottom Width (T,ft):	
Ditch Depth (any shape, in):	Water Depth (any shape,in):	
Side Slope (T,P,V;H:V):	Longitudinal Slope (any shape%):	
Location (x' from upstream end):	BED	Side Slope
Vegetation Type (MH,GS,WT,EW,WW,N):		
Vegetation Cover (1-5):		
Vegetation Average Height (in):		
Vegetation Status (% erect):		
Vegetation Condition:		
NOTES:		

Location (x' from upstream end):	Shape (T,P,V,U):	**#5**
Top Width (any shape,ft):	Bottom Width (T,ft):	
Ditch Depth (any shape, in):	Water Depth (any shape,in):	
Side Slope (T,P,V;H:V):	Longitudinal Slope (any shape%):	
Location (x' from upstream end):	BED	Side Slope
Vegetation Type (MH,GS,WT,EW,WW,N):		
Vegetation Cover (1-5):		
Vegetation Average Height (in):		
Vegetation Status (% erect):		
Vegetation Condition:		
NOTES:		

Notes, Comments...

Vegetation Cover Quantification

1. Schedule in June, based on Mazer's (1998) experience that vegetation forms were difficult to identify in swales in September.

2. Make a careful assessment of and describe bare areas. Record the number of isolated bare areas and their locations and sizes (approximate length and width or diameter). Record the number of extended bare channels and their locations and sizes. Note any conditions that may account for lack of vegetation cover (e. g., flow concentration at the inlet, erosion, sloping laterally (perpendicular to flow direction), stoniness, poor drainage, shading).

3. Assess plant species composition and relative cover according to the same procedure used by Mazer (1998, p. 53, 57-58). Mazer's procedure established two adjacent 0.25 m^2 square quadrants 10 in from the swale inlet and then every 15 m to the end. In each quadrant he identified each species and its relative cover according to the Daubemnire cover class system.

4. Assess plant biomass and surface organic litter mass according to the same procedure used by Mazer (1998, p. 57). In Mazer's procedure all above-ground vegetation and surface organic litter within an open cylinder 11.5 cm in diameter and 10 cm high was removed from each quadrant after cover assessment. Cut off and discard any growth taller than 10 cm. Determine the oven-dry mass of samples by weighing to 0.0001 g on an analytical balance after fully drying in a 105 °C oven.

VEGETATION ASSESSMENT

Site:_____________ **Date:**____________

Isolated bare areas: locations and sizes			
Extended bare channels: locations and sizes			
Channel conditions (flow concentration at inlet, erosion, sloping laterally, stoniness, poor drainage, shading, etc.)			
Plant species composition and relative cover (Daubenmire cover class - 1: 0-5%, 2: 5-25%, 3: 25-50%, 4: 50-75%, 5: 75-95%, 6: 95-100%)			
Station 1 Quadrant 1 (10m from inlet) Class:___	Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___	**Station 1 Quadrant 2 (10m from inlet) Class:___**	Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___
Station 2 Quadrant 1 (15m from Station 1) Class:___	Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___	**Station 2 Quadrant 2 (15m from Station 1) Class:___**	Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___ Species___ Class:___

Station 3 **Quadrant 1** **(15m from Station 2)** **Class:___**	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___	**Station 3** **Quadrant 2** **(15m from** **Station 2)** **Class:___**	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___
Station 4 **Quadrant 1** **(15m from Station 3)** **Class:___**	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___	**Station 4** **Quadrant 2** **(15m from** **Station 3)** **Class:___**	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___
Station 5 **Quadrant 1** **(15m from Station 4)** **Class:___**	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___	**Station 5** **Quadrant 2** **(15m from** **Station 4)** **Class:___**	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___
Station 6 **Quadrant 1** **(15m from Station 5)** **Class:___**	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___	**Station 6** **Quadrant 2** **(15m from** **Station 5)** **Class:___**	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___	Species___ Species___ Species___ Species___ Species___	Class:___ Class:___ Class:___ Class:___ Class:___

Notes:

APPENDIX F:
HRT TEST AND SPLITTER CALIBRATION FORMS

Hydraulic Residence Time Measurement

1. Schedule for a period when soil saturation is similar to the period during which most runoff passes through the swales. The best scheduling, considering this condition and the project's current status, is late winter.

2. Arrange for the use of a nearby **fire** hydrant and flow meter, if possible, or, if there is no nearby hydrant, a King County Roads Division water truck with a flow meter.

3. Estimate the design flow rate (Q, $m^{3/S}$ or cfs) of the swale assuming the design basis is equivalent to the current King County standard. Back-calculate hypothetical design flow rate according to Manning's equation from swale width and length dimensions, longitudinal slope, and Manning's n from the design literature. Attempt to establish the depth of relatively high flows (as from the 6-month, 24 hour rainfall event) from visual signs in the swale. If these signs do not exist or are inconclusive, assume a depth of 3 inches.

4. Apply a flow rate that is a significant fraction of the design rate but does not exceed it in a manner as much like the introduction of natural runoff as possible. In particular, be careful not to introduce flow from a hose at a higher entrance velocity than would occur with natural runoff.

5. After flow reaches a steady state in the-swale, set a transect every 6 in (20 ft) from the inlet to the outlet. At each transect measure the width of the water surface (w, m or ft) and the water depth (y, m or ft, converted from cm or inches) every 15 cm (6 inches) along the transect.

6. Take a sample of the effluent for later measurement of background light absorbence in a spectrophotometer.

7. At the swale inlet add to the flow a small quantity (determined by experience and then kept constant for all tests) of non-toxic, biodegradable dye. Distribute the dye evenly into the flow over a short period of time (determined by experience and then kept constant for all tests). Record the time of dye addition.

8. Move to the swale outlet. Take a sample for later light absorbance reading at 2 or 3 minutes after dye addition. The time interval should be relatively short if travel time from inlet to outlet is observed to be quite short and vice versa. Continue to collect samples at recorded time intervals for later reading until no dye has been visually evident for at least 15 minutes.

9. As soon as possible, measure the light absorbence of all samples in a spectrophotometer. Subtract absorbence before dye addition measured in step 6 to get adjusted absorbence. Plot adjusted absorbence versus time after first introduction of dye.

Calculations

1. If the plot of light absorbence versus time is essentially symmetrical, take mean hydraulic residence time (HRT, minutes) as the time about which the plot is symmetrical. If the plot deviates from symmetrical, take the centroid of the area under the curve as mean HRT.

2. Calculate mean flow velocity (v, m/s or ft/s):

$$v = L/HRT$$

3. Calculate the flow cross-sectional area (A, m^2 or ft^2) and hydraulic radius (R_h, m or ft) at each point where water depth and surface width were measured during the hydraulic residence time experiments. Consult a table for the correct formula for the these quantities for the swale shape. Average A and R for the overall swale.

4. For each swale test compute Manning's n (dimensionless):

$$n = [(1.49)(A)(R^{0.67})(s^{0.5})]/Q$$

in the English system, or equivalent metric system equations. Use average values of A and R from the transect measurements.

5. For each swale test calculate Reynold's Number (Re, dimensionless):

$$Re = [(v)(y)]/\nu$$

where ν= kinematic viscosity of water (consistent units)

6. For each swale test calculate shear stress (τ, kg/cm^2 or psi):

$$\tau = (9810)(y)(s) \qquad \text{(with y in meter)}$$

7. For each swale test compute unit stream power (P, kg/cm-s or lb/ft-s), the power of the flow to move solids per unit area of channel bed:

8. For each swale test calculate Froude Number (Fr, dimensionless):

$$Fr = v/[(9.81)(y)]^{0.5} \qquad \text{(with y in meter)}$$

9. For each swale test calculate hydraulic loading rate (HLR, m/day or ft/day), the daily flow rate per unit area of the swale bed. Calculate HLR in m/day by converting Q to m^3/day and dividing by the product of the swale length (L, in) and bed width (b, in):

$$HLR = Q/[(L)(b)]$$

Splitter Calibration Form

Date		Notes:
Samplers		
Soil Conditions		
Weather		
Site ID		
Splitter ID		

Run Number	Total Volume	Elapsed Time	Flow Rate	Split Volume	Elapsed Time	Split
#	ft3	sec	cfs	ft3	sec	%

APPENDIX G:
FIELD AND LABORATORY PROCEDURES FOR ROADSIDE DITCH WATER QUALITY ANALYSES

Roadside Ditch Stormwater Sampling, Analysis, & Site Inspection Protocol – December 1999

Total Suspended Solids dried at 104°C

Prior to sample analysis:

1) The day before analysis, prepare & weigh glass fiber filter disks according to Section 2540 D, 3a from Standard Methods.

Sample analysis:

2) Agitate water in plastic lined collection tanks for 30 seconds.
3) Dip two 250 mL HDPE containers to obtain stormwater samples.
4) Store in refrigerator at 4°C for no more than two days.
5) Assemble filtering apparatus and filter, and then begin suction.
6) Wet weighed glass-fiber filter to seat in filtering apparatus with reagent-grade water.
7) Pipet 50 mL of stirred sample water onto seated glass-fiber filter.
8) Wash with 3 successive 10-mL volumes of DD water. Allow complete drainage between washings.
9) Continue suction for 3 minutes after filtration is complete.
10) Remove filter and transfer to aluminum weighing dish for support.
11) Dry for at least 1 hour at 104°C, cool in desiccator, and weigh.
12) Repeat cycle of drying, cooling/desiccating, and weighing until constant weight is obtained or weight change is less than 4% of preceding weight.

Turbidity Determination using nephelometric method

Prior to field analysis:

1) Use process nephelometer that meets criteria of Section 2130 B, 2a from Standard Methods.
2) Check that instrument sample cells are extremely clean, colorless, and unscratched. Handle cells only where light beam will not strike. Clean all sample cells with lab soap, rinse with deionized water, and allow to air dry. Apply thin, uniform coat of silicone oil (of same refractive index as cell material) to outside of cell.
3) Check calibration of instrument using new secondary standards from instrument manufacturer to represent range of possible storm water turbidity levels.

In field:

4) Agitate sample, degas with non-foaming surfactant if necessary, and pour from polyethylene bottle into sample cell.
5) Ensure that condensate does not form on outside of cell prior to instrument reading.

pH determination using electrometric method

Prior to field analysis:

1) Prepare or purchase three standard buffer solutions according to Standard Methods 4500 B, 3. If prepared then, store in 1-L HDPE bottle for up to four weeks.
2) Calibrate instrument periodically using prepared buffers to establish isopotential point and ensure accurate readings occur across range of possible sample pH values.
3) Store electrodes according to manufacturer's recommendations.

In field:

4) Collect sample in polyethylene beaker prior to stirring collection tank and agitate gently with Teflon coated stir bar.
5) Set electrodes in this sample.
6) Blot electrodes dry and repeat steps 4 & 5 with new sample to measure pH.

Conductivity laboratory method

Prior to field analysis:

1) Prepare standard 0.01 M potassium chloride solution by dissolving 745.6 mg anhydrous KCl in DD water and dilute to 1000 mL at 25°C. Store in glass stoppered glass bottle. This reference solution has a conductivity of 1412 μmhos/cm at 25°C.

Note—Do not need to calculate a cell constant if instrument reads temperature-compensated conductivity directly.

In field or lab:

2) Analyze samples within 28 days of rain event.
3) Rinse cell with two portions of sample.
4) Adjust temperature of final portion to about 25°C.
5) Measure conductivity directly from instrument readout and note temperature of final portion.

Total and soluble reactive phosphorus

Note: Recommended to use glass bottles that are cleaned with hot dilute HCl and rinsed thoroughly with distilled water, however can replace with HDPE bottles if samples are stored near freezing. UC-Davis recommends that TP assay performed within one month and SRP assay within ten days from collection time

Filtration:

1) Wash 0.45 μm membrane filters by soaking 20 filters in 2L of distilled water for 24 hours (day before filtration).
2) Filter sample immediately after collection. Store at 4°C. May add 40 mg $HgCl_2$ per liter if they are to be stored for long period of time.

Digestion and colorimetric analysis:

see attached University of California-Davis procedures

Collection and transfer procedure for metals determination

1) Obtain sterilized HDPE bottles from Aquatic Research lab and label accordingly.

2) Complete COC document at time of sample collection.
3) Deliver water samples to Aquatic Research lab within 24 hours of sample collection.
4) Aquatic Research lab to perform total zinc, dissolved zinc, total copper, and dissolved copper analyses.

Basic examination of field equipment prior to sample collection:

1) Check for impedances to flow in splitters as well as possible leakages at PVC unions.
2) Check upstream end of splitters to ensure that all ditch flow is entering splitter
3) Re-level splitter if necessary.
4) Check collection lines for grade and leak problems.
5) Clean debris traps and rinse with storm water.
6) Check collection bags for leakage.
7) Measure height of water in collection tanks
8) Drain collection bags and replace after sample collection.
9) Record any site problems and work performed during each visit.
10) Note any other variables: weather, air & water temperature, approximate rainfall duration, site anomalies, etc.
11) Cover collection tanks and replace any drain hole covers.

APPENDIX H:
VEGETATED STORMWATER FACILITY MAINTENANCE PROJECT

BIOFILTRATION SWALE FIELD SURVEY

TRANSECT LOCATIONS

1. If the total continuing swale length is <500 ft, locate transects across the swale (perpendicular to the flow direction) at 0, 25, 50, 75, and 100% of its length.

2. If the total continuing swale length is 500-1000 ft, identify two segments each 1/3 of the full length at the upstream and downstream ends. Locate transects in each at 0, 50, and 100% of the segment length.

3. If the total continuing swale length is > 1000 ft, identify three segments each 1/5 of the full length at the upstream end, approximate middle, and downstream end. Locate transects in each at 0, 50, and 100% of the segment length.

4. Assign an identification code to each swale and each transect within each swale.

5. Place a marker at the top of the swale s side slope to indicate each transect s location for future visits. A painted stake would be an appropriate marker.

NOTE: Measure all locations in the swale in terms of absolute distance from the upstream end. However, consider the length of the swale to be only the portion that has vegetation or is intended to have vegetation (i.e., do not consider as part of the length portions in a culvert or sections that are paved, covered with gravel, etc.)

TASKS TO PERFORM ON FIRST SURVEY VISIT ONLY

Note: **Bold** signifies code for recording on data sheet.

<u>Time, Personnel, and Location Information</u>

Date and time
Surveyor
Highway
Mile post, **MP**, at beginning and end of each segment (inlet and outlet if <500 ft long)
Location within right of way (alongside of **EB**, **WB**, **NB**, or **SB** lane[s]; or in median, **M**)

General Information

Length (ft)

Connection (record for upstream and downstream): **U1**--connected to additional natural bottom conveyance upstream; **U2**--connected to pipe or culvert upstream; **U3**--connected to paved conveyance upstream; **U4**--not connected to any other conveyance upstream; **D1**--connected to additional natural bottom conveyance downstream; **D2**--connected to pipe or culvert downstream; **D3**--connected to paved conveyance downstream; **D4**--discharges to receiving water (name water body); **D5**--not connected to any other conveyance downstream but does not discharge to receiving water

Drainage catchment consists of:

__ mainline traffic lanes each __ ft wide and __ ft long;
paved right shoulder __ ft wide and __ ft long;
unpaved right shoulder __ ft wide and __ ft long (shoulder material: __);
paved left shoulder __ ft wide and __ ft long;
unpaved left shoulder __ ft wide and __ ft long (shoulder material: __);
paved median __ ft wide and __ ft long;
unpaved median __ ft wide and __ ft long (shoulder material: __);
on-ramp __ ft wide and __ ft long;
off-ramp __ ft wide and __ ft long;
transition lane from highway (name: __) __ ft wide and __ ft long;
transition lane to highway (name: __) __ ft wide and __ ft long;
right of way outside of areas described above __ ft wide and __ ft long (land cover: __);
area outside of WSDOT right of way __ ft wide and __ ft long (land cover: __)

Monitoring potential (describe)

Structural Data

Inflow (record all that apply): **Pt.**--at single point; **CC**--curb cut; **Free**--over-the-shoulder sheet flow

Inflow structure (if inflow Pt.): **1**--culvert pipe; **2**--catch basin; **3**--other (describe)

Energy dissipation (if inflow Pt. or CC): **1**--none; **2**--rip-rap; **3**--stilling well; **4**--other (describe)

Flow distribution (if inflow Pt. or CC): **1**--none; **2**--level spreader; **3**--perforated pipe; **4**--stilling well; **5**--other (describe)

Check dams (number, spacing in ft, material of construction)

Transect Geometric Data (for each transect)

Distance from upstream end of segment (ft)

Shape: **T**--trapezoidal; **P**--parabolic; **V**--V-shaped; **U**--U-shaped

Top width (for any shape; ft)

Bottom width (for T shape; ft)

Depth (any shape, inches)

Side slope (for T, P, and V shapes; H:V ratio)

Longitudinal slope (parallel to flow; %)

Lateral slope (perpendicular to flow; %)

TASKS TO PERFORM ON EACH SURVEY VISIT

Note: **Bold** signifies code for recording on data sheet.

Time, Personnel, and Location Information

Date and time
Surveyor
Highway
Mile post, **MP**, at beginning and end of each segment (inlet and outlet if <500 ft long)
Location within right of way (alongside of **EB**, **WB**, **NB**, or **SB** lane[s]; or in median, **M**)

General Tasks

Weather:

1. Record date and time (starting and ending) of survey.

2. Record weather conditions during survey.

3. Record rainfall for the 6, 12, 24, and 48 hours preceding the start of the survey.

4. Record minimum and maximum temperatures on the day of the survey and the preceding two days.

Photography:

1. Take photographs looking along the swale s length from the beginning and end of each segment (inlet and outlet if <500 ft long).

2. Photograph the local vicinity of each transect.

3. Record the roll number, frame number, and view of each photograph.

Water Quality Measurements (if water flowing):

1. Measure and record the temperature of the swale influent and effluent.

2. Sample the influent and effluent and measure and record turbidity in the field.

Maintenance:

Describe any evidence of maintenance that has been done since the previous visit.

<u>Hydraulic Conditions</u>

Present:

1--fully wet and flowing at approximately __ ft/second and approximately __ inches deep; **2**--fully wet at approximately __ inches deep but not flowing;
3--not fully wet but pooled approximately __ inches deep from __ to __ ft downstream from inlet;
4--not fully wet but more than one distinct pool (specify approximate depths and positions from __ to __ ft downstream from inlet);
5--dry

Signs of previous wetness:

Record the presence of any drift lines, water marks, discoloration, bent or matted vegetation, etc. that signify the presence and location of water that has receded.

Problems

1. Make a careful assessment of and describe bare areas. Record the number of isolated bare areas and their locations and sizes (approximate length and width or diameter). Record the number of extended bare channels and their locations and sizes. Note any conditions that may account for lack of vegetation cover (e. g., flow concentration at the inlet, erosion, sloping laterally [perpendicular to flow direction], stoniness, poor drainage, shading).

Record all that apply and give approximate location in ft relative to upstream end:
1--minor litter;
2--substantial litter;
3--minor siltation (record average depth);
4--substantial siltation (record average depth);
5--minor scour (record average depth);
6--substantial scour (record average depth);
7--visible oil;
8--visible pollutant other than silt or oil;
9--mowed grass not removed;
10--other vegetative matter disposed;
11--soil buildup at curb cuts;
12--other (describe)

Transect Vegetation Data (answer for a 3-ft long quadrat around each transect)

Distance from upstream end (ft)

Bed and side slope vegetation type(s) note all present: **G** grasses; **OH** herbaceous plants other than grasses; **WT** woody terrestrial plants; **EW** emergent herbaceous wetland plants; **WW** woody wetland plants; **N** none (describe surface)

Bed and side slope vegetation cover note overall cover and amount provided by each separate type:
1--fully or nearly fully covered (95-100% covered);
2--some bare area (70-95% covered);
3--substantial bare area (40-70% covered);
4--mostly bare (5-40% covered);
5--bare (0-5% covered)

Bed and side slope forms: Name in order of abundance the vegetation forms present. Give the best description you can, the species or genus (or equivalent common name) if possible. If unknown, record, for example, unknown grass.

Bed vegetation average height (inches)

Side slope vegetation average height (inches)

Bed vegetation status (% erect)

Side slope vegetation status (% erect)

Bed vegetation condition:
1--healthy;
2--some damage due to human intrusion;
3--substantial damage due to human intrusion;
4--some damage probably due to drought;
5--substantial damage probably due to drought;
6--some damage probably due to other causes (describe if possible);
7--substantial damage probably due to other causes (describe if possible)

Side slope vegetation condition:
1--healthy;
2--some damage due to human intrusion;
3--substantial damage due to human intrusion;
4--some damage probably due to drought;
5--substantial damage probably due to drought;
6--some damage probably due to other causes (describe if possible);
7--substantial damage probably due to other causes (describe if possible)

Highway Swale Survey Data Sheet 1:
First Survey Visit

Highway:
Upstream MP: Downstream MP:
Right-of-way location (EB, WB, NB, SB, M):

Date: Starting time:
Ending time:
Surveyor:

General Information

LENGTH (ft): CONNECTION (U1, 2, 3, 4; D-1, 2, 3, 4, 5) :

DRAINAGE CATCHMENT:

__ mainline traffic lanes each ____ ft wide and ____ ft long
Paved right shoulder ____ ft wide and ____ ft long
Unpaved right shoulder ____ ft wide and ____ ft long (shoulder material: __;
Paved left shoulder ____ ft wide and ____ ft long
Unpaved left shoulder ____ ft wide and ____ ft long (shoulder material: __)
Paved median ____ ft wide and ____ ft long
Unpaved median ____ ft wide and ____ ft long (shoulder material: ________________________________)
On-ramp ____ ft wide and ____ ft long
Off-ramp ____ ft wide and ____ ft long
Transition lane from highway (route: ___) ____ ft wide and ____ ft long
Transition lane to highway (route: ___) ____ ft wide and ____ ft long
Right of way outside of areas described above ____ ft wide and ____ ft long (land cover: ______________)
Area outside of WSDOT right of way ____ ft wide and ____ ft long (land cover: _____________________)

MONITORING POTENTIAL:

NOTES:

Structural Data

Inflow (Pt, CC, Free): Inflow structure (1-3):
Energy dissipation (1-3): Flow distribution (1-5):
Check dams (#; spacing, ft; material):

NOTES:

Transect Geometry Data

Transect #1	Location (ft from upstream end): Top width (any shape, ft): Ditch depth (any shape, in): Side slope (T, P, V; H:V):	Shape (T, P, V, U): Bottom width (T, ft): Lateral slope (any shape, %): Longitudinal slope (any shape, %):

NOTES:

Transect #2	Location (ft from upstream end): Top width (any shape, ft): Ditch depth (any shape, in): Side slope (T, P, V; H:V):	Shape (T, P, V, U): Bottom width (T, ft): Lateral slope (any shape, %): Longitudinal slope (any shape, %):

NOTES:

Transect #3	Location (ft from upstream end): Top width (any shape, ft): Ditch depth (any shape, in): Side slope (T, P, V; H:V):	Shape (T, P, V, U): Bottom width (T, ft): Lateral slope (any shape, %): Longitudinal slope (any shape, %):

NOTES:

Transect #4	Location (ft from upstream end): Top width (any shape, ft): Ditch depth (any shape, in): Side slope (T, P, V; H:V):	Shape (T, P, V, U): Bottom width (T, ft): Lateral slope (any shape, %): Longitudinal slope (any shape, %):

NOTES:

Transect #5	Location (ft from upstream end): Top width (any shape, ft): Ditch depth (any shape, in): Side slope (T, P, V; H:V):	Shape (T, P, V, U): Bottom width (T, ft): Lateral slope (any shape, %): Longitudinal slope (any shape, %):

NOTES:

Transect #6	Location (ft from upstream end):	Shape (T, P, V, U):
	Top width (any shape, ft):	Bottom width (T, ft):
	Ditch depth (any shape, in):	Lateral slope (any shape, %):
	Side slope (T, P, V; H:V):	Longitudinal slope (any shape, %):

NOTES:

Transect #7	Location (ft from upstream end):	Shape (T, P, V, U):
	Top width (any shape, ft):	Bottom width (T, ft):
	Ditch depth (any shape, in):	Lateral slope (any shape, %):
	Side slope (T, P, V; H:V):	Longitudinal slope (any shape, %):

NOTES:

Transect #8	Location (ft from upstream end):	Shape (T, P, V, U):
	Top width (any shape, ft):	Bottom width (T, ft):
	Ditch depth (any shape, in):	Lateral slope (any shape, %):
	Side slope (T, P, V; H:V):	Longitudinal slope (any shape, %):

NOTES:

Transect #9	Location (ft from upstream end):	Shape (T, P, V, U):
	Top width (any shape, ft):	Bottom width (T, ft):
	Ditch depth (any shape, in):	Lateral slope (any shape, %):
	Side slope (T, P, V; H:V):	Longitudinal slope (any shape, %):

NOTES:

Add any additional notes or comments:

Highway Swale Survey Data Sheet 2: Each Survey Visit

Highway:
Upstream MP: Downstream MP:
Right-of-way location (EB, WB, NB, SB, M):

Date: Starting time:
Ending time:
Surveyor:

General Tasks:

SOIL SAMPLE COLLECTED?

WEATHER: Present conditions--
Rainfall (in) preceding--6 hours ____ 12 hours ____ 24 hours ____ 48 hours ____
Min./max. temp. (° F)--Day of survey ___/___ Day before ___/___ 2 days before ___/___

PHOTOGRAPHY:
Roll/frame--___/___ View-- Roll/frame--___/___ View--
Roll/frame--___/___ View-- Roll/frame--___/___ View--
Roll/frame--___/___ View-- Roll/frame--___/___ View--
Roll/frame--___/___ View-- Roll/frame--___/___ View--
Roll/frame--___/___ View-- Roll/frame--___/___ View--
Roll/frame--___/___ View-- Roll/frame--___/___ View--

WATER QUALITY MEASUREMENTS:
Water temp. (unit, ° C or ° F)--______ Influent ______ Effluent ______
Turbidity (NTU)--Influent ______ Effluent ______

EVIDENCE OF MAINTENANCE:

NOTES:

Hydraulic Conditions

PRESENT (circle those applying):
1--Fully wet and flowing at approximately ____ ft/second and approximately ____ inches deep
2--Fully wet at approximately ____ inches deep but not flowing
3--Not fully wet but pooled approximately ____ inches deep from ____ to ____ ft downstream from inlet
4--Not fully wet but more than one distinct pool (specify approximate depths and positions from ____ to ____ ft downstream from inlet)
5--Dry

SIGNS OF PREVIOUS WETNESS (observation, location):

NOTES:

Problems

BARE AREAS (give dimensions as appropriate to shape of area; i.e., length and width or diameter):

Location Relative to Upstream End (ft)	Dimensions (ft)	Possible Causes

EXTENDED BARE CHANNELS (give dimensions as length and width):

Location Relative to Upstream End (ft)	Dimensions (ft)	Possible Causes

OTHER PROBLEMS (circle those applying):	Location Relative to Upstream End (ft)
1--Minor litter	
2--Substantial litter	
3--Minor siltation (average depth, in) ____	
4--Substantial siltation (average depth, in) ____	
5--Minor scour (average depth, in) ____	
6--Substantial scour (average depth, in) ____	
7--Visible oil	
8--Visible pollutant other than silt or oil (describe)	
9--Mowed grass not removed	
10--Other vegetative matter disposed	
11--Soil buildup at curb cuts	
12--Other (describe)	

NOTES:

Transect Vegetation Data

Transect #1

		Bed	Side Slope
	Location (ft from upstream end):		
	Vegetation type (G, OH, WT, EW, WW, N):		
	Vegetation cover (1-5)--overall:		
	for each type:		
	Vegetation forms in order of abundance:		
	Vegetation average height (in):		
	Vegetation status (% erect):		
	Vegetation condition:		

NOTES:

Transect #2

		Bed	Side Slope
	Location (ft from upstream end):		
	Vegetation type (G, OH, WT, EW, WW, N):		
	Vegetation cover (1-5)--overall:		
	for each type:		
	Vegetation forms in order of abundance:		
	Vegetation average height (in):		
	Vegetation status (% erect):		
	Vegetation condition:		

NOTES:

Transect #3

		Bed	Side Slope
	Location (ft from upstream end):		
	Vegetation type (G, OH, WT, EW, WW, N):		
	Vegetation cover (1-5)--overall:		
	for each type:		
	Vegetation forms in order of abundance:		
	Vegetation average height (in):		
	Vegetation status (% erect):		
	Vegetation condition:		

NOTES:

Transect #4

		Bed	Side Slope
	Location (ft from upstream end):		
	Vegetation type (G, OH, WT, EW, WW, N):		
	Vegetation cover (1-5)--overall:		
	for each type:		
	Vegetation forms in order of abundance:		
	Vegetation average height (in):		
	Vegetation status (% erect):		
	Vegetation condition:		

NOTES:

Transect #5		Bed	Side Slope
	Location (ft from upstream end):		
	Vegetation type (G, OH, WT, EW, WW, N):		
	Vegetation cover (1-5)--overall:		
	for each type:		
	Vegetation forms in order of abundance:		
	Vegetation average height (in):		
	Vegetation status (% erect):		
	Vegetation condition:		

NOTES:

Transect #6		Bed	Side Slope
	Location (ft from upstream end):		
	Vegetation type (G, OH, WT, EW, WW, N):		
	Vegetation cover (1-5)--overall:		
	for each type:		
	Vegetation forms in order of abundance:		
	Vegetation average height (in):		
	Vegetation status (% erect):		
	Vegetation condition:		

NOTES:

Transect #7		Bed	Side Slope
	Location (ft from upstream end):		
	Vegetation type (G, OH, WT, EW, WW, N):		
	Vegetation cover (1-5)--overall:		
	for each type:		
	Vegetation forms in order of abundance:		
	Vegetation average height (in):		
	Vegetation status (% erect):		
	Vegetation condition:		

NOTES:

Transect #8		Bed	Side Slope
	Location (ft from upstream end):		
	Vegetation type (G, OH, WT, EW, WW, N):		
	Vegetation cover (1-5)--overall:		
	for each type:		
	Vegetation forms in order of abundance:		
	Vegetation average height (in):		
	Vegetation status (% erect):		
	Vegetation condition:		

NOTES:

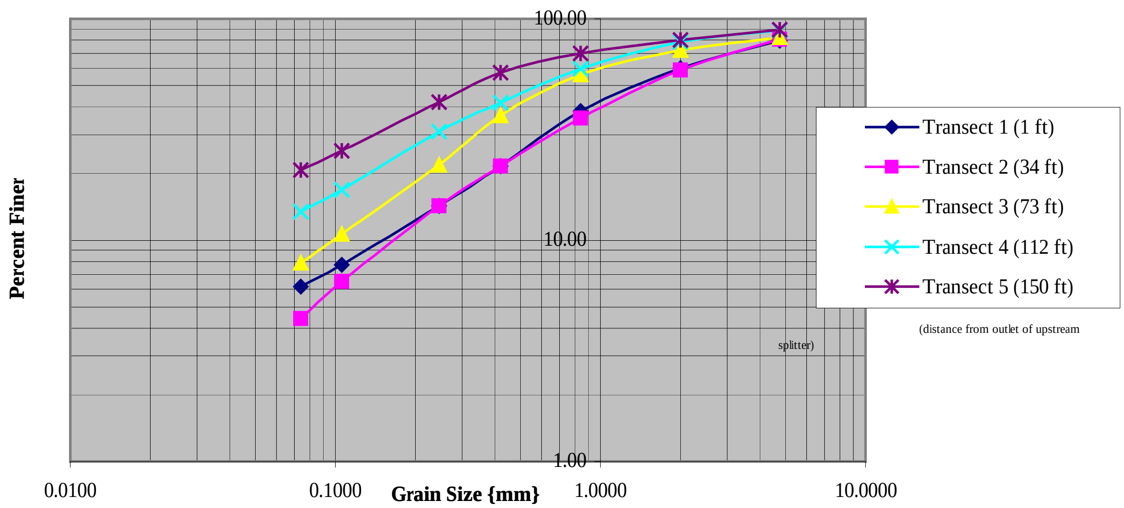
		Bed	Side Slope
Transect #9	Location (ft from upstream end):		
	Vegetation type (G, OH, WT, EW, WW, N):		
	Vegetation cover (1-5)--overall:		
	for each type:		
	Vegetation forms in order of abundance:		
	Vegetation average height (in):		
	Vegetation status (% erect):		
	Vegetation condition:		

NOTES:

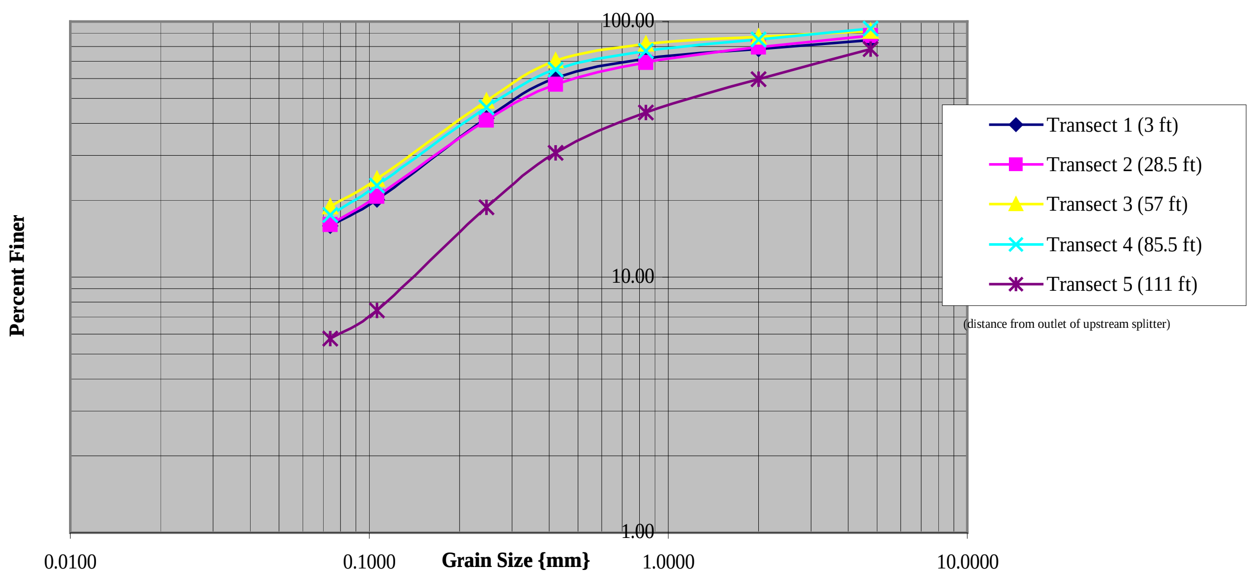
Add any additional notes or comments:

APPENDIX I:
CUMULATIVE FREQUENCY PLOT OF SOILS IN EXPERIMENTAL ROADSIDE DITCHES

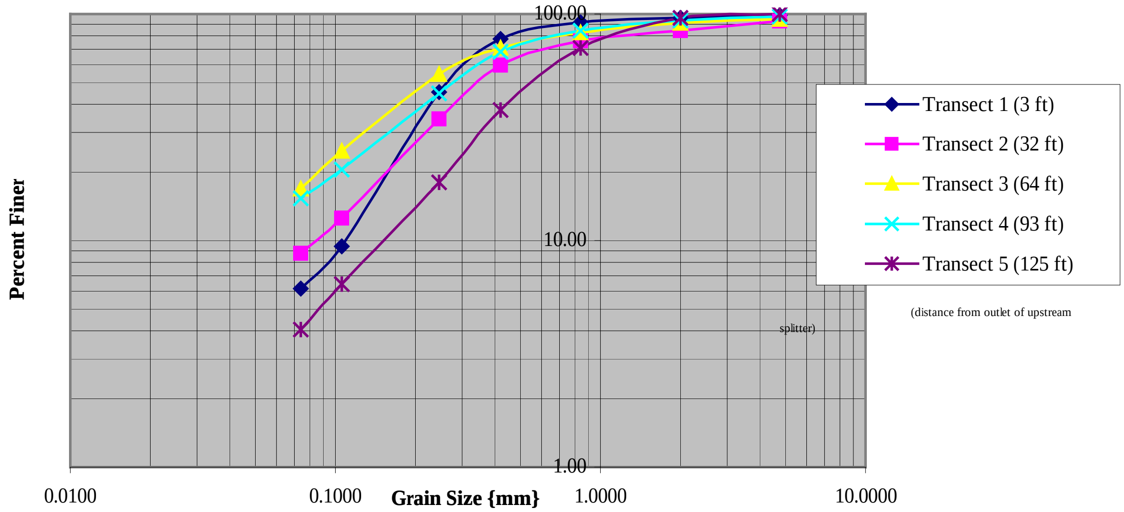
Particle Size Distribution Curves for Site A



Particle Size Distribution Curves for Site B



Particle Size Distribution Curves for Site C



APPENDIX J:
COST SPREADSHEETS FOR RE-VEGETATION TREATMENTS IN TYPICAL DRAINAGE CHANNELS

100’ x 8’ Re-vegetation Area					
Item	unit cost	unit qty	ft2	total	waste factor
Straw (150sf coverage/bale)	$7.00	bale	800	$39.20	1.05
Jute	$0.45	yd2	800	$42.00	1.05
Coconut	$0.95	yd2	800	$129.20	1.53 (uncorrected total = $84.44)
PAM--per visit	$4.00	lbs	800	$0.04	1.10
PAM application by water truck--per visit	$0.02	yd2	800	$2.02	1.10
Staples	$0.04	staple	800	$12.44	1.00
Backfill	$0.00	on-site	800	$0.00	
Topsoil salvage	$0.00	yd2	800	$0.00	
Seeding--per visit	$0.09	yd2	800	$8.40	1.05
Supplemental Water--per visit	$0.02	yd2	800	$2.02	1.10

100’ x 10’ Re-vegetation Area					
Item	unit cost	unit qty	ft2	total	waste factor
Straw (150' coverage/bale)	$7.00	bale	1000	$49.00	1.05
Jute	$0.45	yd2	1000	$60.00	1.20
Coconut	$0.95	yd2	1000	$141.44	1.34
Pam	$35.00	lbs	1000	$0.44	1.10
PAM application by water truck--per visit	$0.02	yd2	1000	$2.53	1.10
Staples	$0.04	staple	1000	$15.56	1.00
Backfill	$0.00	on-site	1000	$0.00	
Topsoil salvage		yd2	1000	$0.00	
Seeding	$0.09	yd2	1000	$10.50	1.05
Supplemental Water??		cf	1000		

100’ x 12’ Re-vegetation Area					
Item	unit cost	unit qty	ft2	total	waste factor
Straw (150' coverage/bale)	$7.00	bale	1200	$58.80	1.05
Jute	$0.45	yd2	1200	$63.00	1.05
Coconut	$0.95	yd2	1200	$141.87	1.12
Pam	$35.00	lbs	1200	$0.53	1.10
PAM application by water truck--per visit	$0.02	yd2	1200	$3.03	1.10
Staples	$0.04	staple	1200	$18.67	1.00
Backfill	$0.00	on-site	1200	$0.00	
Topsoil salvage		yd2	1200	$0.00	
Seeding	$0.09	yd2	1200	$12.60	1.05
Supplemental Water??		cf	1200		

100’ x 6.67’ Re-vegetation Area					
Item	unit cost	unit qty	ft2	total	waste factor
Straw (150' coverage/bale)	$7.00	bale	667	$32.68	1.05
Jute	$0.45	yd2	667	$39.69	1.19
Coconut	$0.95	yd2	667	$73.93	1.05
Pam	$35.00	lbs	667	$0.29	1.10
PAM application by water truck--per visit	$0.02	yd2	667	$1.69	1.10
Staples	$0.04	staple	667	$10.38	1.00
Backfill	$0.00	on-site	667	$0.00	
Topsoil salvage		yd2	667	$0.00	
Seeding	$0.09	yd2	667	$7.00	1.05
Supplemental Water??		cf	667		