Grass Swales: Gauging Their Ability to Remove Pollutants From Highway Stormwater Runoff

Prepared for
Bureau of Equity and Environmental Services
Division of Transportation System Development

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June 5, 2007

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Request for Report

Stormwater runoff from highways can contain metals, organic materials and other pollutants that pose a threat to the health of the nation's water resources. Federal and state transportation agency responsibilities for effective stormwater management are guided by a series of environmental laws, executive orders and policies that have been developed to address this risk. Wisconsin DOT has employed several structural best management practices for removing contaminants from stormwater runoff, including roadside swales—broad, shallow channels with a dense stand of vegetation that promote infiltration and trap pollutants. The Bureau of Equity and Environmental Services asked us to locate recently completed and ongoing research studies that quantify the effectiveness of grass swales at removing contaminants from highway runoff.

Summary

We located a number of research studies performed by state DOTs, the U.S. Environmental Protection Agency, NCHRP and other entities that quantify grass swales' effectiveness at removing pollutants from roadway runoff. Overall, the results of these studies suggest that properly designed and sited grass swales can be effective tools for removing pollutants from highway runoff. For example, a September 2004 U.S. EPA study notes:

> "In general, the current literature reports that a well-designed, well-maintained swale system can be expected to remove 70% of total suspended solids, 30% of total phosphorus, 25% of total nitrogen, and 50 to 90% of trace metals (Barret et al., 1993, and GKY and Associates Inc., 1991). The nitrogen removals may be fairly optimistic, given that studies conducted by Yousef et al. (1985) and others produced negative nitrogen removal in many cases. It is theorized that the outwelling of nitrogen from grass clippings and other organic materials from the swale produced these results… (Swale) removal efficiencies reported in the literature vary, but generally fall into the low to medium range, with some swale systems recording no water quality effects at all… Pollutant removal efficiencies for many constituents can be markedly different during the growing and dormant periods (Driscoll and Mangarella, 1990)."

We present our findings in two sections. **State DOT Research** summarizes recent studies by seven DOTs that quantify the effectiveness of grass swales. One of these studies, performed by the Western Transportation Institute

for Montana DOT, also discusses the advantages and limitations of vegetative biofiltering in cold regions. In the **Additional Resources** section, we call out several recent studies by EPA, NCHRP and academia that document the effectiveness of grass swales. We also point readers to an informational Web site, the International Stormwater Best Management Practices (BMP) Database. This site provides a variety of practical tools for stormwater managers that include:

- **Analysis of Treatment System Performance report.** This study provides an overview of the performance of various BMP types with regard to individual pollutants based on BMP data entered through December 2005.
- **Online Data Search Engine.** Users can retrieve BMP studies based on state or country, BMP type, water quality parameter, watershed size area range and average storm volume. The search retrieves summary data for BMPs including test site information, analytical parameters for the BMP, a summary of key design data for the site, a detailed statistical analysis of BMP performance, and a summary of precipitation and flow data for the BMP.

State DOT Research

Alabama

Alabama Highway Drainage Conservation Design Practices—Particulate Transport in Grass Swales and Grass Filters

University Transportation Center for Alabama, November 2005
http://rpitt.eng.ua.edu/Publications/UTCA/UTCA%20final%20swales%20report.pdf
The objective of this project was to demonstrate how a common ALDOT design and maintenance practice—the use of grass drainage swales—can help meet the requirements of the EPA's new Phase II Stormwater Regulations (http://cfpub.epa.gov/npdes/stormwater/swphases.cfm#phase2). As part of the study, 69 sediment samples were collected at an outdoor grass swale located adjacent to Tuscaloosa City Hall, Alabama, during 13 storm events from August to December 2004. The samples were analyzed for turbidity, total solids, total suspended solids, total dissolved solids and particle size distributions. The total suspended solids concentrations observed during different rain events showed significant sediment reductions as a function of the length of the swale. The particle size distributions of the suspended solids at the swale showed preferential transport of small particles for all lengths of the swale and preferential trapping of large particles.

California

BMP Retrofit Pilot Program: Final Report

Caltrans Division of Environmental Analysis, Report CTSW-RT-01-050, January 2004
http://www.dot.ca.gov/hq/env/stormwater/special/newsetup/_pdfs/new_technology/CTSW-RT-01-050.pdf

Excerpts from the Executive Summary:

> Litigation between Caltrans and the Natural Resources Defense Council, Santa Monica BayKeeper, the San Diego BayKeeper, and the U.S. Environmental Protection Agency resulted in a requirement that Caltrans develop a Best Management Practice (BMP) Retrofit Pilot Program in Caltrans districts 7 (Los Angeles) and 11 (San Diego). The objective of this program was to acquire experience in the installation and operation of a wide range of structural BMPs for treating stormwater runoff from existing Caltrans facilities and to evaluate the performance and costs of these devices. Each BMP was designed, constructed and maintained at what was state-of-the-art at the time the project began (in 1997).
>
> Biofiltration swales and biofiltration strips were among the BMP types included in the study. These practices are considered technically feasible depending on site-specific considerations. Overall, the reduction of concentration and load of the constituents monitored was comparable to the results reported in other studies, except for nutrients. Nutrient removal was compromised by the natural leaching of phosphorus from the salt grass vegetation used in the pilot study. This condition was not known at the start of the project but was discovered later in the program.
>
> Biofiltration swales and strips were among the least expensive devices evaluated in this study and were among the best performers in reducing sediment and heavy metals in runoff. Removal of phosphorus was less than that reported by Young et al. (1996) but may be related to leaching of nutrients from the salt grass during its dormant season. The swales are easily sited along highways and within portions of maintenance stations, and do not require specialized maintenance. In addition, the test sites were similar in many ways to the vegetated shoulders and conveyance channels common along highways in many areas of the state. Consequently, these

areas, which were not designed as treatment devices, could be expected to offer water quality benefit comparable to these engineered sites. More research is needed to investigate this possibility.

Related links:

- **BMP Retrofit Pilot Program—Final Report Appendices**
  http://www.dot.ca.gov/hq/env/stormwater/special/newsetup/_pdfs/new_technology/CTSW-RT-01-05a.pdf
- **BMP Retrofit Pilot Program—Technical review Web site**
  http://www.dot.ca.gov/hq/env/stormwater/ongoing/pilot_studies/index.htm
- **Caltrans Storm Water Treatment BMP Technology Report (April 2007)**
  Includes assessments of potential permanent BMPs.
  http://www.dot.ca.gov/hq/env/stormwater/annual_report/2007/Annual_Report_05-06/Attachments/TreatmentBMPTechnologyReport.pdf
- **Storm Water Monitoring and BMP Development Status Report (March 2007)**
  Describes Caltrans monitoring activities, action plans and treatment research status.
  http://www.dot.ca.gov/hq/env/stormwater/annual_report/2007/Annual_Report_05-06/Attachments/SWMonitoringBMPStatusReport.pdf
- **Stormwater Pollutant Removal in Roadside Vegetated Buffer Strips**
  This study found that buffer strips consistently reduced the concentration of suspended solids and total metals in stormwater runoff from freeways. See Appendix A.
- **Using Reinforced Native Grass Sod for Biostrips, Bioswales, and Sediment Control**
  Research in progress that will evaluate the effectiveness, efficiency and cost of using reinforced native grass sod for erosion and sediment control on land near the California highway system.
  http://rip.trb.org/browse/dproject.asp?n=11795

Maryland

Grassed Swale Pollutant Removal Project
AASHTO Region 1 RAC Research Highlights 2005—Maryland Research Highlights
http://www.nh.gov/dot/bureaus/materialsandresearch/research/documents/2005RAC1Sampler.pdf
From page 16 of the PDF:

> In Maryland, grassed swales are routinely incorporated into highway medians and right-of-way as an aesthetically pleasing method for conveying highway runoff. This project evaluated the performance of grass swales as a stormwater management technology that can remove surface runoff contamination through sedimentation, filtration by the grass blades, infiltration to the soil, and some likely biological processes. Three storm events were monitored to evaluate pollutant removal effects of two grassed swales receiving highway runoff, and of the pollutant removal efficiencies of grassed swales. The researchers observed significantly reduced concentrations of many pollutants.
>
> Results confirm the positive event mean concentration (EMC) removal (35 to 84%) of most pollutants of interest, including total suspended solids, nitrate, nitrite, total Kjeldahl nitrogen, copper, lead and zinc. The EMC was calculated by combining the flow and concentration data, a total pollutant mass. However, the swales demonstrated some export of phosphorus and chloride. Export of phosphorus in a natural system like a grass swale is understandable because this element is present in all organic material.

Minnesota

Improving the Design of Roadside Ditches to Decrease Transportation-Related Surface Water Pollution
Minnesota Department of Transportation Research Services Section, June 2003
http://www.mrr.dot.state.mn.us/research/pdf/200411.pdf
Abstract: A field monitoring program began in spring 2000 to test the ability of a grassy roadside swale to remove pollutants in stormwater. A check dam was designed and installed into the vegetative swale. The check dam system incorporated some unique design features, including a peat filter to trap nutrients and metals and a low rock pool to trap water for the settling of suspended solids and for biological processing. The check dam was cost effective and simple to install. The system was quantified and evaluated hydrologically and qualitatively before and after the check dam installation. Pollutants monitored included total suspended solids, total phosphorus, and ortho-phosphorus. The average pollutant removal rates for the three storms following the installation of the check dam

were 54% total phosphorus, 47% ortho-phosphorus, and 52% total suspended solids. Metals were also analyzed for two storm events, one before and one after installation of the check dam. Peat soil samples were analyzed for nutrients, organic content, water capacity, metals and pH before and after check dam installation. The results suggest that properly designed short vegetative strips and swales can reduce pollutant levels from the stormwater that drains off roadways.

From Recommendations (page 27 of the PDF):

> Further research is also needed to determine the efficiency of the check dam at removing large pollutant loadings similar to those exiting highly traveled roads. The pollutant loadings in this research were relatively small. Greater removal efficiency values may be realized with the addition of a series of check dams in longer roadside swales. Also, more research needs to be performed analyzing the check dam efficiency at reducing heavy metals.

Montana

Recommendations for Winter Traction Materials Management on Roadways Adjacent to Bodies of Water
Western Transportation Institute, Report No. FHWA/MT-04-008/8117-19, December 2004
http://www.mdt.mt.gov/research/docs/research_proj/traction/final_report.pdf

From the abstract:

> Wherever possible, a combination of both structural and non-structural best management practices should be employed to minimize the environmental impacts of winter traction materials. This report focuses on the cold region and rural transportation perspective, and discusses the structural BMPs potentially applicable in Montana in greater detail, including applicability, site criteria, engineering characteristics, safety concerns, maintenance issues, costs, effectiveness in the presence of snow, and sediment removal efficiency. Despite the challenges of winter conditions, structural BMPs such as vegetated swales and filter strips, ponds and wetlands can still remove high levels of sediment from runoff if designed, sited, installed and maintained properly. This report also summarizes the primary non-structural BMPs used to reduce the use, and thereby minimize the environmental impacts of, winter traction materials.

Points of interest in the report include:

- From **Section 3.1, Terminology, Dry Swale** (page 19 of the PDF):
  Dry swales (also known as grassy swales or vegetated channels) require minimal modifications for use in cold climates.
- From **Section 3.6, Biofiltration** (page 39 of the PDF):
  The effectiveness of biofiltration treatment in Montana is limited by the short growing season when vegetation actively removes nutrients, and this limitation may also extend the time to establish a biofiltration BMP. Other limitations of applying biofiltration methods in cold climates include vegetation damage, reduced drainage due to buildup of salt and other deicers, impacts from snow storage, roadway scrapes from plowing, and heavy accumulations of sand (Watson 1994, Caraco and Claytor 1997, Davis et al. 1998). However, biofiltration methods have many advantages that make them a viable option in Montana. The advantages of implementing natural materials in biofiltration practices include enhancement of roadside aesthetics and prevention of erosion while effectively treating runoff. Biofiltration is most effective when combined with other BMPs. As part of a system, a biofiltration BMP can be used as a conveyance structure that provides treatment. For instance, vegetated swales can be combined with detention ponds, infiltration trenches, constructed wetlands etc. (Watson 1994).
- From **Section 3.6.1, Vegetated Swales, Site Criteria** (page 40 of the PDF):
  Swales are useful for runoff control on highway medians. Performance diminishes significantly for areas with higher concentrations of runoff, which consequently have higher runoff velocities (Watson 1994). To provide for additional runoff capacity, the vegetative swale could be used in addition to a pond type facility.
- From **Section 3.6.1, Vegetated Swales, Effectiveness in Snow** (page 42 of the PDF):
  Accumulation of sediment along road shoulders will prevent runoff from properly entering a swale or may bypass a filter strip (Watson 1994). Therefore, swales should be designed to account for an accumulation of sediment. The use of salt-tolerant vegetation should be considered. Despite the loss of effectiveness of vegetated swales in the winter, they can remain effective if they have adequate vegetative cover, and they can act as permeable snow storage areas when located adjacent to highways (Caraco and Claytor 1997). Although grass in vegetated swales can be dormant for most of the winter, it can still provide resistance to flow and cause

the deposition of suspended solids. Vegetative swales can also provide some level of infiltration if located in well-drained soils (Jokela and Bacon 1990).

- From **Section 3.6.1, Vegetated Swales, Sediment Removal Efficiency** (page 43 of the PDF):
  A nine-minute residence time in vegetated swales generally provides slightly higher pollutant reductions over a five-minute residence time and resulted in an 83% removal of total suspended solids (Watson 1994). In addition, vegetated swales can provide up to 99% erosion reduction (Barr Engineering Company 2001). One study found the greatest factor for sediment removal in vegetated swales to be the addition of check dams, which increase the detention time of runoff and increase sedimentation. The same study also found that swales longer than 75 meters did not increase sediment removal regardless of slope (Yu et al. 2001).

- From **Section 3.7.7, Example Selection of Structural BMP** (page 53 of the PDF):
  Scenario B: A segment of a two-lane rural route through a broad valley.

  Possible BMP: In a broad valley with gentle topography, vegetated swales and filter strips could provide sufficient treatment of highway runoff. Potentially better soils, lower flow velocities and lower amounts of sand would all allow relatively easy use of vegetated structural BMPs. These BMPs are expected to achieve high levels of sediment removal, as even unconstructed vegetative areas were estimated to provide an average 69% sediment removal efficiency by respondents to our survey.

- From **Chapter 5, Conclusions and Recommendations, Best Management Practices** (page 72 of the PDF):
  The most applicable structural BMPs for use along Montana's highways seem to be dry ponds, wet ponds, wet extended detention ponds, constructed wetlands, vegetated swales and vegetated filter strips. It is mainly because of their resistance to freezing conditions and their ability to effectively trap suspended solids…

- From **Chapter 5, Conclusions and Recommendations, Benefits of This Report** (page 74 of the PDF):
  Scenario B: Low dilution potential, low runoff velocities and volumes, slow discharge to water body; similar to a two-lane roadway passing through an area of low elevation and gentle topography with low precipitation.

  Possible BMPs: Vegetated swales and filter strips could effectively capture much of the sand and suspended particles in highway runoff from this scenario. This section of roadway may already have such features that would only need slight modifications to meet the design specifications such as sheet flow across a filter strip. With minimal investments in BMPs, the effects of traction materials in this scenario could be effectively minimized.

Texas
Storm Water Management Guidelines for Construction Activities Manual (2002 revised)
Texas DOT Environmental Affairs Division, Water Resources Management Branch, and Division of Bridges and Structures, Hydraulics Section

Section 5, Sediment Control BMPs
http://www.dot.state.tx.us/publications/environmental_affairs/storm/5sedimentationcontrol.pdf

From Section 5.2.1, Grass Swales (Borrow Ditches and Median Swales), Design Requirements (page 26 of the PDF):

> The primary factors that will determine the suitability of a grass swale or channel as a water quality structure are soil type, slope of the contributing drainage basin, imperviousness of the drainage basin, and the cross section of the swale. Grass channels can be used to service drainage areas of as much as 10 acres (4 ha). Specific criteria for improved grass swales to be used as water quality BMPs include:
> - The average slope of the watershed should be 5% or less.
> - Soils should have infiltration rates of 0.18 in/hr (4.5 mm/hr). Heavy clays typical of NRCS Hydrologic Soil Group D are generally not acceptable.
> - The seasonal high groundwater table should be at least 10 feet (three meters) below the surface of the channel.
> - A longitudinal slope of 1% is preferred. The Lower Colorado River Authority allows slopes of up to 4% or where a velocity of 1.5 ft/sec is exceeded. Greater slopes are acceptable with the introduction of check dams to reduce velocity and increase detention times.
> - Channel bottom width should be between two and six feet. Channels may be wider but it is difficult to achieve uniform flow over the channel bottom at low flows which can reduce the overall water quality effectiveness.

From Section 5.2.1, Grass Swales (Borrow Ditches and Median Swales), Pollutant Removal Performance (page 29 of the PDF):

> The pollutant removal performance depends on whether or not a grass swale or channel has been designed to specifically provide water quality functions. In general, any channel that meets the four basic design criteria related to slope, soil type, vegetative cover and length will provide some sediment control. It is important to remember that vegetated BMPs have variable performance with respect to the removal of nutrients. The primary removal of nutrients will be due to infiltration or detention of the runoff in the swale. Therefore, the use of check dams is very important to overall success where nutrients are concerned. Likewise, a good vegetative cover and mowing heights maintained above four inches will further enhance the performance of a grass channel.

Use of Vegetative Controls for Treatment of Highway Runoff
Report No. FHWA/TX-7-2954-2, revised September 1998
http://www.utexas.edu/research/ctr/pdf_reports/2954_2.pdf
This study investigated the capability of two vegetative controls—grassed swales and vegetated buffer strips—to treat highway runoff. A grassed swale was constructed in an outdoor channel to investigate the impacts of swale length, water depth, and season of the year on pollutant removal efficiency, and two vegetated strips treating highway runoff in the Austin area were monitored to determine removal capabilities.

From Section 3.5.6, Summary of Channel Swale Results (page 57 of the PDF):

> A grassed swale constructed in a steel channel removed over 50% of the suspended solids, zinc, and lead after 40 meters of swale treatment. COD (chemical oxygen demand) concentrations decreased 25 to 79% after 40 meters of treatment, while the reduction of nutrient concentrations varied from negative to 45%. In general, the majority of pollutant removal occurred in the first 20 meters of swale. Increasing the water depth and velocity of surface flow of runoff in the swale reduced the removal efficiency of the swale.
>
> More suspended solids were removed in the channel swale in the growing season than in the dormant season. During the growing season, new grass stood alongside dormant grass that increased the grass blade density in the swale. This increase in removal is attributed to the combined filtering capacity of the dead material and live grasses. The removal of nutrients and organic material may decline in the growing season, when decay of vegetation from the previous season contributes to the constituents in the runoff.
>
> The concentrations of constituents in runoff that had percolated through the soil in the swale were generally lower than the concentrations in surface runoff after 40 meters of treatment by the swale. However, the impact of swales on groundwater quality in the field will vary with thickness of soil to groundwater, permeability of the soil, and the constituents in the highway runoff.

Evaluation of the Performance of Permanent Runoff Controls: Summary and Conclusions
Center for Research in Water Resources, University of Texas at Austin, CRWR Online Report 97-3, November 1997
http://www.crwr.utexas.edu/reports/pdf/1997/rpt97-3.pdf

From the Summary (page 11 of the PDF):

> Pollutants found in runoff from highways may produce adverse impacts in receiving waters under some conditions. The Edwards Aquifer is particularly vulnerable to this type of nonpoint source pollution and concern about the potential impact on the aquifer has led to the construction of stormwater controls on highways in the Austin area. This study was designed to help Texas DOT identify the types of runoff control systems that are most applicable for highways in this area. The study investigated the capability of vegetative controls (grassed swales and vegetated buffer strips) and sedimentation/filtration systems for treating stormwater runoff.

Section 4.2, Conclusions and Recommendations, Channel Swale (page 45 of the PDF):

- Removal of total suspended solids, chemical oxygen demand, total phosphorus, total Kjeldahl nitrogen, zinc and iron was highly correlated with swale length. No trend was observed for nitrate.
- Most of the reduction in the concentration of constituents in runoff occurred in the first 20 meters of the swale. Little improvement in water quality was observed during the last 20 meters.

- The removal efficiency for suspended solids, organic material and most metals decreased with increased water depth. No relationship between water depth and removal efficiency was observed for nitrate and total Kjeldahl nitrogen.
- The removal efficiency of the grassed swale was about the same during the dormant and growing season for all constituents except for total suspended solids. Total suspended solids experienced the highest removal during the growing season, when there is a combination of new grass and remaining dormant grass.
- Percolation of runoff through layers of soil and gravel into the underdrain reduced concentrations of all constituents except nitrate.
- Excellent pollutant removal occurred in the channel swale when the hydraulic residence time was approximately nine minutes. The removal was similar to that of a site monitored in Seattle that had about the same residence time, but differed in other aspects. Hydraulic residence time appears to be an appropriate design criterion for grassed swales.

From Section 4.5.1, Recommendations, Vegetative Controls (page 47 of the PDF):

- 2. Avoid curb-and-gutter systems on new highways and roadways. Instead, allow the runoff to exit the pavement as sheet flow into grassy medians or shoulder areas.
- 3. Medians with a V-shaped cross-section should have a maximum side slope of 9 to 12% and a minimum distance from roadway to median centerline of eight meters for effective pollutant removal.
- 5. Channel erosion was a significant problem in the median of the MoPac Expressway, which was designed to current standards. A storm drain system with drop inlets can be used in conjunction with vegetated channels to minimize erosion and maintain shallow water depths.

Washington
2006 Stormwater Report
Washington State DOT
http://www.wsdot.wa.gov/NR/rdonlyres/09450DED-E0BC-4568-BFF6-341BD96434C9/0/2006StormwaterReport.pdf
WSDOT submits annual reports to the Washington State Department of Ecology summarizing activities undertaken to comply with its National Pollution Discharge Elimination System municipal permits and evaluate the effectiveness of its stormwater management program. This report documents the progress made by WSDOT to protect water quality within the NPDES permit areas between July 1, 2005 and June 30, 2006.

From Chapter 6, Stormwater Treatment Effectiveness Testing and Research, What Do the Results Tell Us? (page 45 of the PDF):

> Data from several years of monitoring has been combined to show all BMP effectiveness data collected from 2003 through 2006. The data has been summarized in graphs so readers can quickly compare the quality of treated water to applicable water quality standards, and can view the effectiveness of different BMPs, including bioswales and vegetated filter strips, in relation to each other.
>
> Two graphs are presented for each pollutant—average pollutant concentration reduction, and pollutant concentration reduction per storm. The graphs include (see next page):

Exhibit 6-13
Overall Average Total Phosphorus Removal by BMP

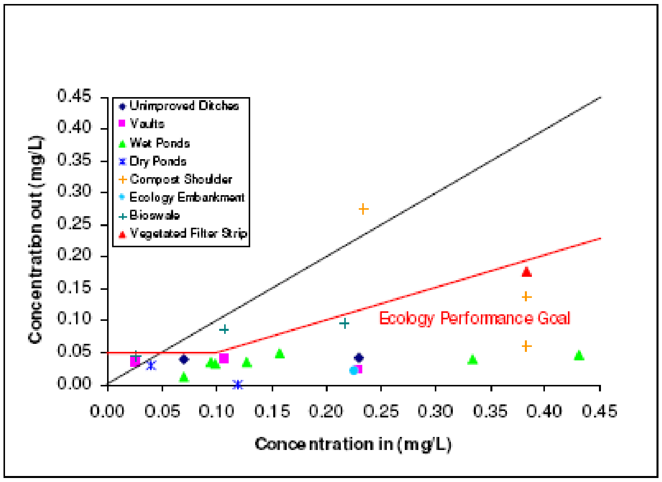
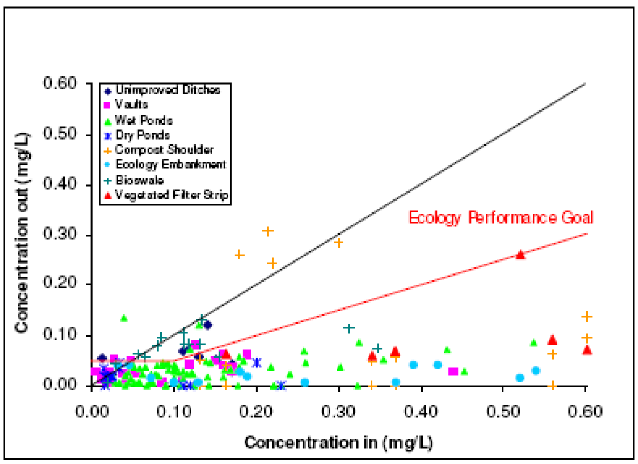


Exhibit 6-14
Total Phosphorus Removed Per Storm



Contaminant Detention in Highway Grass Filter Strips
Washington State Transportation Center, Report No. WA-RD 474.1, January 2000
http://www.wsdot.wa.gov/research/reports/fullreports/474.1.pdf
Abstract: A 17-month sampling campaign was initiated to investigate the potential for vegetated highway shoulders to retain suspended solids, metals and total petroleum hydrocarbons (TPH). A site along SR 8 in Western Washington was selected and three full-scale test plots constructed for evaluation of contaminant retention capability. The data indicated that TPH and suspended solids were effectively removed. Metal concentration reduction was also effective when consideration was given to inadvertent pretreatment afforded by the highway runoff collection system. Consequently, the vegetated highway shoulder, located along hundreds of miles of highway, can afford a cost effective means of contaminant retention.

From Section 3.2.1, Grassy Swales (pages 9 to 10 of the PDF):

> Yousef et al. determined that pollutants could be retained in a swale by adsorption, precipitation and/or biological uptake (Yousef, Y. A. et al., 1985). He also discovered better removal with a newly constructed swale prior to the establishment of vegetation. His conclusion was that soluble metals are mainly removed by adsorption due to the adsorptive capacity of soil. Plant material growing in the swale decreased the contact area between the metals and the soil, reducing the number of adsorptive sites. In contrast, a study completed by Bell and Wanielista determined that an increased concentration of organic material (mainly humic substances) and vegetation increased the removal of metals from runoff (Bell, J. H. and Wanielista, M. P. 1979). Therefore, the presence of decaying plant material in a swale may increase the removal potential by the addition of a greater number of adsorption sites for metals.

Sediment and Contaminant Removal by Dual Purpose Detention Basins: Draft Final Report
Washington State University, May 1993
http://www.wsdot.wa.gov/research/reports/fullreports/336.1.pdf
The purpose of this project was to generate a database that could be used in the development of a rational design approach for stormwater sedimentation basin design. The investigation included a review of the pollutant removal efficiencies of grass swales.

From Chapter 1, Introduction, Removal Efficiencies of Grassy Swales and Grass Lined Channels (pages 14 and 15 of the PDF):

> Yousef reports metal removal rates of grass lined swales for Pb, Zn, Cu, and Cd of 2.61, 5.76, 0.60, and 0.26 $mg/m^2.hr$, respectively. In another study, respective removals for Pb, Zn, and Cu were reported as 1.14, 1.85, and 0.42 $mg/m^2.hr$.[18] It is important to note that removal efficiencies are related to many site specific conditions including stormwater characteristics and swale design. For example, removal as a function of swale length for TSS, VSS, Pb, Cu, Cd, and Zn reported by Wang[9] are summarized in Tables 2 and 3.
>
> Table 2. Grass channel removal as a function of length for TSS and VSS.
>
> | Swale Length (m) | TSS[1] | VSS[2] |
> |---|---|---|
> | 21 | 90.4 | 90.9 |
> | 43 | 93.2 | 86.4 |
> | 67 | 94.5 | 100 |
>
> [1] total suspended solids
> [2]volatile suspended solids

Table 3. Grass channel removal efficiencies.

Site	Distance (m)*	number of samples	Cadmium Removal (percent)	Copper Removal (percent)	Lead Removal (percent)	Zinc Removal (percent)
1	15-21	6	51.4	24.6	59.3	35.5
	31.0	1	60	53.5	70.4	31.4
	40-50	6	80	39.2	72.0	69.7
	67.0	6	100	63.1	83.8	69.7
2	15-20	2	100**	40.1	37.5	23.6
	30-40	2	100**	51.1	54.1	50.8
	50-60	2	34.8**	20.3	66.9	64.2
	67.0	1	**	43.4	90.2	65.4
	77.0	2	**	57.5	80.6	72.1
3	2.5	1	**	<0	2.9	2.1
	10.0	1	**	29.3	58.6	16.6
	15.0	1	**	51.9	68.1	19.4
	20.0	1	**	63.7	77.3	45.9
	25.0	1	**	70.7	86.7	57.1
4	2.5	1	<0	<0	2.1	12.9
	5.0	1	45.8	34.4	72.4	60.2
	15.0	1	100	68.1	78.5	93.2
	25.0	1	100	53.3	82.4	94.0

* - distance in channel from beginning of vegetated area.
** - One or more values were below detectable limit.

Low Impact Stormwater Treatment Methods
Washington State DOT, research in progress
http://rip.trb.org/browse/dproject.asp?n=7763
Abstract: In many places stormwater flows off highways into vegetated areas before entering surface or ground water. These areas include ditches, embankments, landscaping, medians and bioswales. Currently there is not adequate methodology to account for the treatment benefits that these areas provide. This forces projects to address stormwater by constructing unnecessarily large BMPs, often in natural areas, resulting in high cost and further environmental degradation. Several states have recently completed, or are close to completing, studies on this subject intended to provide a basis for accounting for benefits. This project will both assess that work's applicability to Washington and tailor an approach for the state. It is anticipated that the project will attract partnership funds.

Additional Resources

International Stormwater Best Management Practices Database
http://www.bmpdatabase.org/index.htm
The International Stormwater BMP Database project provides scientifically sound information to improve the design, selection and performance of BMPs. To accomplish this, the project team has developed tools to promote scientifically based collection and management of the data needed to evaluate the effectiveness of stormwater runoff BMPs. The tools include standardized BMP monitoring and reporting protocols, a stormwater BMP database, BMP performance evaluation protocols and BMP monitoring guidance. Resources available at the site include:

- **Analysis of Treatment System Performance report** (http://www.bmpdatabase.org/DB_Download/BMP Performance Summaries Feb 2006.zip). This study provides a comprehensive analysis of BMP performance on a pollutant-by-pollutant basis using the statistical protocols developed for the project. The report provides an overview of the performance of various BMP types with regard to individual pollutants based on BMP data entered through December 2005.
- **Online Data Search Engine** (http://www.bmpdatabase.org/cgi-bin/DataEntry.asp). Users can retrieve BMP studies based on five search criteria: state or country, BMP type, water quality parameter, watershed size area

range, and average storm volume. Searches retrieve summary data for the BMP, including basic test site information, a list of analytical parameters for the BMP, and these three PDF files: a summary of key design data for the site, a detailed statistical analysis of BMP performance, and a summary of precipitation and flow data for the BMP.

Stormwater Best Management Practice Design Guide: Volume 2, Vegetative Biofilters
EPA/600/R-04/121A, September 2004
http://www.epa.gov/nrmrl/pubs/600r04121/600r04121a.pdf
This is the second in a series of three volumes that provide guidance on the selection and design of stormwater management BMPs. This volume provides specific design guidance for a group of on-site BMP control practices referred to as vegetative biofilters and includes the following BMP control practices: grass swales, filter and buffer strips, and bioretention cells. Section 6 focuses on design guidelines and considerations for grass swales and includes discussion of pollutant removal capability.

Section 6: Grass Swales, Pollutant Removal
http://www.epa.gov/nrmrl/pubs/600r04121/600r04121asect6.pdf
From pages 5 and 6 of the PDF:

Pollutants are removed in swales by the filtering action of grass, deposition in low velocity areas, or by infiltration into the subsoil. The primary pollutant removal mechanism is through sedimentation of suspended materials. Therefore, SS (suspended solids) and adsorbed metals are most effectively removed through a grassed swale. Removal efficiencies reported in the literature vary, but generally fall into the low to medium range, with some swale systems recording no water quality effects at all.

Table 6-2 presents the pollutant removal efficiencies for swale lengths of 61 meters (200 feet) and 30 meters (100 feet). Although research results varied, these data clearly indicate greater pollutant removal at longer swale lengths.

Table 6-2 Swale Pollutant Removal Efficiencies (Barret et al., 1993, Schueler et al, 1991, Yu,1993, and Yousef et al., 1985)

Design	Pollutant Removal efficiencies (%)							
	Solids	Nutrients		Metals			Other	
	TSS	TN	TP	Zn	Pb	Cu	Oil & Grease	COD**
61-m (200-ft) swale	83	25*	29	63	67	46	75	25
30-m (100-ft)swale	60	-*	45	16	15	2	49	25

*Some swales, particularly 100-ft systems, showed negligible or negative removal for TN.
**Data is very limited.

In general, the current literature reports that a well-designed, well-maintained swale system can be expected to remove 70% of total suspended solids (TSS), 30% of total phosphorus (TP), 25% of total nitrogen (TN), and 50 to 90% of trace metals (Barret et al., 1993 and GKY and Associates Inc., 1991). The nitrogen removals may be fairly optimistic, given that studies conducted by Yousef et al. (1985) and others produced negative nitrogen removal in many cases. It is theorized that the outwelling of nitrogen from grass clippings and other organic materials from the swale produced these results.

Seasonal differences in swale performance can be important. In temperate climates fall and winter temperatures force vegetation into dormancy, thereby reducing uptake of runoff pollutants, and removing an important mechanism for flow reduction. Decomposition in the fall and the absence of grass cover in the winter can often produce an outwelling of nutrients, and exposes the swale to erosion during high flows, increasing sediment loads downstream. Pollutant removal efficiencies for many constituents can be markedly different during the growing and dormant periods (Driscoll and Mangarella, 1990).

Several other factors may influence expected removal rates, including soil and vegetation type, runoff pollutant constituents, flow rate and runoff contact with the swale, and swale enhancements.

The Use of Best Management Practices in Urban Watersheds
EPA/600/R-04/184, 2004
http://www.epa.gov/ORD/NRMRL/pubs/600r04184/600r04184.htm
This report provides general information on the most commonly used structural BMP options, the design considerations involved, and the general guidelines for monitoring, selection, implementation and associated costs of BMPs in urban watersheds.

Chapter 5, Effective Use of BMPs in Stormwater Management
http://www.epa.gov/ORD/NRMRL/pubs/600r04184/600r04184chap5.pdf

From Chapter 5, Section 5.1.4.2, Approximate Pollutant Removals of Structural BMPs (pages 24 to 26 of the PDF):

> The pollutant removal of structural BMPs has been the subject of many studies. The majority of reported data is presented in percent removals. This method of evaluating BMPs is widely criticized, however, a proven better measure for evaluating BMP pollutant removal efficiencies is not available and/or widely accepted (Urbonas, 2000; GeoSyntec and ASCE, 2002; U.S. EPA, 2002a; Clar et al., 2003). Recently some have suggested that observed effluent quality is a more robust method for characterizing BMP performance (Strecker et al., 2004). The approximate pollutant removals of the most common structural BMPs are presented in terms of observed effluent quality in Table 5-6 for a select group of pollutants.

Table 5-6. Observed Effluent Quality Performance for Common Structural BMPs[1]

BMP Type	Effluent Quality of Select Parameters							
	TSS (mg/L)	TP (mg/L as P)	TN (mg/L)	NO_x (mg/L as N)	Total Cu (µg/L)	Total Pb (µg/L)	Total Ni (µg/L)	Total Zn (µg/L)
Detention pond	32 ± 12 (2.5 - 140)	0.32 ± 0.04 (0.02 - 0.86)	1.8 ± 0.88 (0.45 - 6.0)	0.28 ± 0.05[2] (0.25 - 0.60)	20 ± 2.6 (0.5 - 82)	27 ± 6.4 (1.3 - 200)	4.8 ± 0.82 (0.5 - 11)	110 ± 18 (0.70 - 610)
Retention pond	24 ± 3.9 (0.03 - 250)	0.39 ± 0.15 (0.01 - 22)	1.1 ± 0.09 (0.10 - 4.1)	0.12 ± 0.03 (0.00 - 2.0)	11 ± 1.7 (0.13 - 130)	14 ± 2.5 (0.13 - 130)	4.0 ± 0.96 (0.11 - 23)	24 ± 2.9 (1 - 350)
Infiltration trench	240 ± 260[2] (120 - 420)	NI[3]	2.0 ± 0.76[2] (1.4 - 2.3)	0.57 ± 0.32[2,4] (0.36 - 0.73)	NI	26 ± 25[2] (12 - 42)	NI	90 ± 84[2] (50 - 150)
Porous pavement	24 ± 20[2] (0.55 - 52)	0.03 ± 0.01[2] (0.02 - 0.04)	2.9[5]	0.55[4,5]	8.4 ± 17[2] (0.24 - 30)	14 ± 12[2] (0.91 - 33)	NI	11 ± 8.8[2] (1.5 - 26)
Sand/Media filter	11 ± 7.4 (2.5 - 55)	0.24 ± 0.04 (0.002 - 2.3)	NI	0.26 ± 0.01[2] (0.25 - 0.34)	17 ± 2.7 (1.2 - 150)	8.4 ± 1.6 (1.0 - 110)	4.5 ± 8.7 (2.0 - 22)	120 ± 22 (1.0 - 960)
Wetland Basin	22 ± 8.1 (0.14 - 730)	0.13 ± 0.02 (0.00 - 1.4)	2.0 ± 0.60 (0.01 - 51)	0.22 ± 0.10 (0.00 - 8.1)	3.9 ± 0.53 (0.50 - 16)	1.6 ± 0.29 (0.10 - 10)	NI	47 ± 13 (2.0 - 500)
Grassed swale	26 ± 23 (5.0 - 56)	0.28 ± 0.08 (0.04 - 2.7)	0.62 ± 0.10 (0.06 - 2.7)	0.85 ± 0.86 (0.08 - 3.7)	6.5 ± 1.3 (0.30 - 56)	4.3 ± 1.1 (0.50 - 33)	NI	34 ± 3.7 (4.0 - 150)
Vegetated filter strip	37 ± 47[2] (5.0 - 56)	0.91 ± 0.62 (0.15 - 9.3)	NI	NI	7.2 ± 1.7 (1.0 - 17)	15 ± 12 (1.0 - 150)	2.4 ± 0.76[2] (2.0 - 4.3)	44 ± 11 (3.0 - 150)

[1] all data from the National Stormwater BMP Database (http://www.bmpdatabase.org/): mean ± 95% confidence level (minimum - maximum)
[2] based on one study only
[3] No Information
[4] nitrate only
[5] one data point only

Low Impact Development (LID): A Literature Review
U.S. Environmental Protection Agency, October 2000
http://www.epa.gov/owow/nps/lid/lid.pdf
This literature review was conducted to determine the availability and reliability of data to assess the effectiveness of Low Impact Development practices for controlling stormwater runoff volume and reducing pollutant loadings to receiving waters.

From Section 4.6, Grass Swales Field Study, Highway Grass Channels in Northern Virginia, Maryland and Florida (pages 35 and 36 of the PDF):

> FHWA conducted a field study to determine the pollutant removal efficiencies of grassed channels and swales along highways in Northern Virginia, Maryland and Florida. Sampling was conducted at the inflow and outflow areas of the channels, which provided data for quantity and quality of waters entering and leaving the channels.

The samples were analyzed for total suspended solids (TSS), heavy metals (cadmium, copper, lead and zinc), nitrogen (total Kjeldahl nitrogen and nitrite/nitrate), total phosphorus and total organic carbon. All three locations showed some effectiveness with regard to pollutant removals, although results varied depending on the method of analysis and the location. The results for all three locations are represented in Table 8. Sediment core samples were obtained from the channels and compared to samples from adjacent, upland areas to determine pollutant removal effectiveness of the grass channels. Based on the data from the analysis the following conclusions were made:

- Removal of metals appears to be directly related to the removal of TSS, whereas nutrient removal is not.
- Removal of TSS can be estimated using flow depth and travel time relationships.
- Relatively low nutrient removal may be observed in channels that are effective in removing other pollutants.
- The controlling factors in pollutants removal of grass channels are length, channel geometry, channel slope and average flow.
- Both metals and nutrients are removed in grass channels, but metal removal is more reliable.

Table 8: Long Term Pollutant Removal Estimates for Grassed Swales

	TSS	TOC	TKN	NO_2/NO_3	TP	Cd	Cr	Cu	Pb	Zn
VA	65%	76%	17%	11%	41%	12-98%	12-16%	28%	41-55%	49%
MD	-85%	23%	9%	-143%	40%	85-91%	22-72%	14%	18-92%	47%
FL	98%	64%	48%	45%	18%	29-45%	51-61%	62-67%	67-94%	81%

Evaluation of Best Management Practices for Highway Runoff Control
NCHRP Report 565, 2006
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_565.pdf

From the Foreword (page v of the PDF):

> This report presents guidance for the selection of BMPs for highway runoff control. These practices provide means of avoiding or mitigating the negative impacts of various pollutants that can be carried by rainfall into the groundwater and receiving waters. These pollutants include materials discharged by vehicles using the highway system, pesticides and fertilizers from adjacent landscapes, and particulates from breakdown of the pavements themselves.

Points of interest in the report include:

- From **Section 4.4.5, Nutrients** (page 34 of the PDF):
  In the study by Yonge et al. (2002), in which two wet ponds in differing areas of Washington State were studied for removal performance, bioswales and grass strips that employed more filtration and infiltration removal unit processes tended to show a higher net removal of nutrients than systems primarily utilizing sedimentation for removal. In a study by Walsh et al. (1997), vegetated swales in Texas were found to exhibit an average total phosphorus removal of 35% and a total nitrogen (sum of nitrate, nitrite and TKN) removal of 37%. A study by Yu and Stopinski (2001) found that for three storms in Virginia, total phosphorus removal exceeded 98%, while a controlled test site in Taiwan showed total phosphorus removal of 54% and a total nitrogen removal of 19%. A number of studies have found that swale length, as a function of residence time and hydraulic loading, as well as soil sorption characteristics, are important parameters when looking at the removal of nutrients via filtration and infiltration unit processes (Fletcher et al. 2002,Walsh et al. 1997,Yu et al. 2001).

- From **Section 8.6.2, Volume Reduction** (page 73 of the PDF):
  There is certainly a basis for factoring in runoff volume and resulting pollutant load reductions into performance estimates, particularly when TMDLs are involved. (A TMDL—total maximum daily load—specifies the maximum amount, either as a load or concentration, of a pollutant that a water body can receive and still meet water-quality standards and allocates pollutant loadings or concentration limits among point and nonpoint pollutant sources.) The limited study data available show an average volume reduction of 30% and 38% in dry detention basins and biofilters, respectively, while wet ponds (retention ponds) and wetland basins achieve an average volume reduction of 7% and 5%, respectively (Strecker et al. 2004a, 2004b). Based on this analysis, detention basins (dry ponds) and biofilters (vegetated swales, overland flow etc.)

appear to contribute significantly to volume reductions, even though it is likely that they are not designed specifically for this purpose.

- From **Section 8.7, Methodology Options Using Process Simulation Models** (pages 76 and 77 of the PDF): Simulation models provide an opportunity to analyze details of several BMP options, including treatment trains and the ability of some BMPs to evapotranspire and/or infiltrate runoff. Simulation models also allow one to evaluate a long-term rainfall record to assess how much stormwater is treated by the BMP and how much is bypassed or processed by the BMP at the lower, water-quality design flow rate, and the higher, flood control rate at which higher flows (and resulting short detention times) will result in minimal or ineffective treatment. For example, swales are not effective at flow rates above a certain level (often the flow rate that results in a flow depth which covers the vegetation). Any flows with rates above the design flow rate should be considered as a "bypass" during a BMP performance analysis. Thus, evaluations of the performance of a BMP must take into consideration how much of the rainfall record is treated, controlled or eliminated.

Identification of Research Needs Related to Highway Runoff Management
NCHRP Report 521, 2004
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_521.pdf
This report summarizes significant stormwater management practices and research efforts, and identifies the most pressing gaps and needs in the current state of knowledge in more than 30 subject areas. The report includes full research project statements for the topics considered to be of highest priority.

Points of interest in the report include:

- From **Section 3.2.7, Design Variables Affecting BMP Performance** (page 80 of the PDF):
  A study performed by Walsh et al. in 1997 investigated the effect of a swale underdrain on pollutant removal efficiency. During nine experiments, simulated highway runoff was sampled on the surface of a swale and from the swale's underdrain pipe after percolating through a top layer of grass sod, 16 centimeters of topsoil, and six centimeters of gravel. Concentrations of constituents in runoff that had percolated through the soil in the swale generally were lower than the concentrations in surface runoff after 40 meters of treatment by the swale. The underdrain water quality demonstrated the filtering capability of the soil and reflected water quality of recharge for groundwater in situations with shallow soils.

- From **Section 3.2.11, Maintenance and Longevity** (pages 87 and 88 of the PDF):
  A study by Galli (1992) in Prince George's County, Maryland, evaluated the performance and longevity of 11 types of BMPs. The BMPs studied included infiltration trenches and basins, dry wells, porous pavement, vegetated swales, extended detention dry ponds, wet ponds, constructed marshes, pocket wetlands, oil and grit separators and dry ponds. Assessment criteria used in the study included design strengths and weaknesses, maintenance issues, and environmental considerations for each of the 156 sites included in the study. The results of the study suggested that infiltration basins, porous pavement, grass filters, swales and "pocket" wetlands generally required modifications or improvements in order to provide reliable pollutant removal.

  A King County (Washington) study evaluated the effects of mowing on the performance of vegetated swales (Colwell et al., 2000). Two mowing regimes—mowing at both the beginning and at the end of the growing season and mowing only at the end of the growing season—were evaluated to determine impacts to swale treatment efficiencies. Total suspended solids and turbidity mitigation were significantly higher for the unmowed swale showing that mowing did not provide increased treatment. The two mowing strategies were found to be equivalent with respect to water quality benefits. The authors cautioned that the test systems may not be representative of all swales.

- From **Section 3.2.14, Economic Analysis and Assessment** (page 91 of the PDF):
  Sear et al. (1996) explained the development of equations used to estimate BMP cost as a function of pollutant removal. The functions were used to evaluate nine alternatives for five stormwater treatment technologies in Lakeland, Florida. Production cost functions, with respect to TSS removal percentages, were developed for street sweeping, infiltration systems, wet ponds, dry ponds and wetlands. The cost functions do not include property acquisition costs or operation and maintenance costs. The authors concluded that wet detention ponds and wetlands are more economical than dry detention bonds and curb-cut swales, if the cost of property acquisition is taken into account.

Field Test of Grassed-Swale Performance in Removing Runoff Pollution
S. Yu and E. Fassman, University of Virginia-Charlottesville, and J. Kuo and H. Pan, National Taiwan University. *Journal of Water Resources Planning and Management,* May/June 2001, pages 168 to 171. See Appendix B.

Abstract: The paper presents results of field tests, conducted in Taiwan and Virginia, of the pollutant removal efficiencies of grassed swales. The Virginia experiments tested a highway median swale, while the Taiwan experiments were conducted on an agricultural test farm. Average pollutant removal efficiencies reported for the test swales vary from 14 to 99% for total suspended solids, chemical oxygen demand, total nitrogen and total phosphorus. The wide range of performance results indicates the importance of such design parameters as length, longitudinal slope and the presence of check dams.

Stormwater Pollutant Removal in Roadside Vegetated Buffer Strips

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Abstract: The Roadside Vegetated Treatment Sites Study was a two-year water quality monitoring project undertaken to evaluate the removal of storm water contaminants by existing vegetated slopes adjacent to freeways. The objectives of this study were to determine if standard roadway design requirements result in biofilter strips with treatment equivalent to those specifically engineered for water quality performance, and to generate design criteria. Variables such as width, slope, vegetation density, and hydraulic loading were evaluated by studying the runoff through existing vegetated slopes at four locations in northern California and four locations in southern California. At each location, concrete channels, approximately 30 m long, were constructed to capture freeway runoff after it passes through existing vegetated strips of varying widths. The quantity and quality of the runoff discharged from the buffer strip was compared to freeway runoff collected at the edge of pavement. The study found that buffer strips consistently reduced the concentration of suspended solids and total metals in stormwater runoff. The strips were generally less effective at removing dissolved metals and essentially no change in concentration was observed for nitrogen and phosphorus. Concentrations of organic carbon, dissolved solids, and hardness were observed to increase. For the constituents exhibiting a decrease in concentration, steady state levels were generally achieved within 5 meters of the pavement edge for slopes commonly found on highway shoulders and when the vegetation coverage exceeded 80%. Slope, vegetation type and height, highway width, and hydraulic residence time had little or no impact on the final concentrations.

INTRODUCTION

The Clean Water Act, which was enacted in 1972 and amended in 1987 to include storm water discharges, requires that states assess the condition of surface waters within their jurisdiction to determine whether they support their designated beneficial uses. A total maximum daily load (TMDL) must be developed for each of the segments designated as impaired for the constituents that are contributing to the impairment. The TMDL is the maximum pollutant load that can be assimilated by the waterbody without impairing its beneficial uses. When TMDLs are developed each of the dischargers to these impaired segments, including transportation agencies, may have to implement Best Management Practices (BMPs) to reduce the discharge of pollutants.

BMPs include vegetative stormwater controls such as grassed swales and vegetated filter strips. Vegetated filter strips, also known as buffer strips are relatively smooth vegetated areas with moderate slopes that accept stormwater runoff as overland sheet flow. The mechanisms of pollutant removal are filtration by grass blades or other vegetation, sedimentation, adsorption, infiltration into the soil, and biological and chemical activity in the grass/soil media. Although not designed specifically for water quality treatment and often not recognized by regulatory agencies, vegetated areas, such as medians and shoulders may provide substantial pollutant reduction; consequently, evaluation of the degree to which these areas reduce the adverse impacts that might be caused by discharging untreated runoff directly to receiving waters is important. Vegetated areas may mitigate the impact of highway runoff in two major ways, reduction of the concentrations of pollutant and reduction of the amount stormwater discharged to surface waters as a result of infiltration into the soil.

LITERATURE REVIEW

Vegetated swales and filter strips have not always been accepted as primary controls for the treatment of stormwater runoff. This is mainly the result of the wide range of pollutant removals reported for vegetative controls in various studies (Schueler et al, 1992; Young et al, 1996). Consequently, a lack of confidence emerged among regulatory agencies that vegetative controls could provide reliable and consistent removal of pollutants in stormwater. Some design manuals recommend vegetative controls only for pretreatment to reduce sediment loading to filtration systems or other structural stormwater controls. Unfortunately, many of the studies in which lower removal efficiencies were observed were not well designed and significant removal of the pollutants occurred before the runoff entered the test sections that were monitored.

One example is the evaluation of a grassy swale in Austin, Texas, by Welborn and Veenhuis (1988). The authors reported low or negative removals for many stormwater constituents; however, the runoff had traveled through a grassy swale for more than 200 feet *before* reaching the influent to the site that was monitored. The median influent total suspended solids concentration (TSS) was less than 20 mg/L, even though the drainage was derived from an area of medium density townhouses. Unpublished data collected by the City of Austin indicate that TSS concentrations in stormwater runoff from this type of land use are typically above 100 mg/L. The low influent concentration indicates that most of the removal occurred before entering the test section; therefore, the removals reported understate the potential improvement in water quality resulting from use of vegetative controls.

Kaighn and Yu (1996) recognized that the quality of highway runoff entering two test swales was considerably better than that observed at an edge of pavement site located nearby. For example, average TSS concentrations in runoff entering the swale were 38.7 and 32.8 mg/L, while runoff sampled from the pavement nearby had a TSS concentration of 112.9 mg/L. Additional monitoring indicated that much of the removal occurred in the vegetated filter strip crossed by the runoff before entering the swale test section.

Dorman et al (1996) analyzed the performance of three vegetated channels for treating highway runoff and reported TSS removal efficiencies ranging from 98% to negative 7 %. Operational problems and erosion of the channel were reported at the Virginia site. The influent TSS concentrations were as low as 8 mg/L at the Maryland site, and the average was less than 30 mg/L. The third site in Florida was extremely effective in removing suspended solids. The wide range of reported removal efficiencies reinforces the belief that small changes in channel characteristics cause large changes in pollutant removal effectiveness; however, only the data from the Florida site is indicative of the pollutant removal that might be expected in grassy channels.

The stormwater discharged from the vegetated controls in many of these studies contained 20 mg/L or less of TSS, which is well below the concentrations that would be expected based on the land use in the watershed. However, the impression conveyed by these published reports is that the vegetative controls are unreliable or worse, do nothing at all. In the studies described above, the monitored vegetative controls generally operated to polish the quality of the discharge rather than as the primary treatment device. A more efficient and consistent performance would be expected when the concentrations in the influent to the controls are similar to what might be encountered in untreated urban or highway runoff. The TSS concentrations might range from 100-200 mg/L, which is almost an order of magnitude higher than the influent concentrations reported in the cited studies.

There was a relatively recent study of the performance of vegetated areas adjacent to highways funded by the Texas Department of Transportation (TxDOT) that tried to resolve some of the misconception produced by earlier studies. This study was conducted in Austin, Texas by Barrett et al. (1998). The study determined the efficiency of a grassy median for mitigating highway runoff by measuring concentrations of pollutants in samples of stormwater runoff that were collected directly off the road surface and in samples of stormwater discharged from the median. The sites were selected to investigate the potential for variation in performance between vegetated areas with different characteristics compared the differences in quality and volume of runoff between the edge of pavement and after flowing down a grassy median.

Barrett et al. reported that vegetated channels designed solely for stormwater conveyance can be as effective as sedimentation/filtration systems for reducing the concentrations and loads of constituents in highway runoff. The percent reduction in pollutant mass transported to receiving waters was greater than the concentration reduction because of runoff lost to infiltration. These data indicate that filter strips are effective for treating runoff from 3-lane (each direction) highways at average daily traffic counts greater than 50,000.

There remain a number of important site-specific questions regarding the pollutant removal that can be expected. Because of differences in rainfall patterns, soils, typical road cross-sections and other factors, additional data needs to be collected to ensure that the full benefit of vegetated shoulders and channels is recognized by regulatory agencies. In addition, there is little documentation on maximum slopes and minimum widths for effective stormwater treatment.

METHODOLOGY

Eight study locations were selected across California that represented the range of slopes, climate, vegetation coverage, soil characteristics, and other regional factors that might impact pollutant removal in roadside vegetated buffer strips. Concrete collection channels were constructed at various distances from the edge of pavement so that the effect of buffer width on pollutant removal could be quantified. The locations of the study sites are shown in Figure 1 and the characteristics of each site are show in Table 1. A photograph of a typical system is presented in Figure 2.

The monitoring occurred over two wet seasons, generally from October to April 2001-2002 and 2002-2003. Monitoring of the RVTS sites began shortly after the completion of construction of the collection systems and installation of the monitoring equipment. The number of sampled storm events ranged from nine at Yorba Linda in southern California to 23 events at the San Rafael site in northern California. Flow weighted composite samples were collected at all locations in accordance with Caltrans guidelines (Caltrans, 2000). Precipitation during each storm event was characterized by total rainfall, duration of rainfall, rainfall intensity, days since last rainfall and antecedent rainfall depth. Most sampled storm events were preceded by at least 24 hr without rainfall, meeting the minimum required antecedent dry period.

Flow monitoring was conducted during each monitored storm event and continually throughout the storm season at each of the RVTS biofilter strips. Flow was measured using bubbler flow meters in conjunction with trapezoidal flumes. During several events, particularly in southern California, flow did not discharge through the biofilter strips due to infiltration.

Vegetation plays an important role in the concentration reduction in buffer strips by slowing the velocity of runoff, stabilizing the slope, and stabilizing accumulated sediment in the root zone of the plants. A vegetation assessment was conducted at all the test sites on a quarterly basis throughout the study duration to characterize the vegetation condition of the test sites. The vegetation was characterized by percent vegetation cover/density, height, plant species composition, and indication of maintenance activity.

Analysis of variance (ANOVA) was used to determine whether concentrations measured at each buffer width differed significantly. The purpose of this was to determine whether statistically significant differences exist between constituent concentrations at different buffer strip widths, and whether steady-state concentrations were achieved at any distance away from the edge of pavement. The constituent data were log-transformed prior to applying ANOVA. Initially, ANOVA was applied to the edge of pavement and all buffer widths at each site simultaneously. If there was no statistically significant difference in the means, then it was concluded that the vegetated area had no effect on runoff concentrations. If there was a difference, ANOVA was applied to the concentrations measured at adjacent collection channels to determine the minimum distance from the edge of pavement the greatest change was observed.

Equilibrium concentrations were determined to exist when the following conditions were met: 1) the mean concentration at a given length was significantly different (alpha = 0.05) than the edge of pavement mean concentration. 2) all mean concentrations at greater distances were not significantly different (alpha = 0.05) from the mean at the aforementioned length. When these conditions are satisfied, it can be inferred that the pollutant concentration has stabilized, and will not significantly change regardless of length away from the pavement. For some constituents the greatest change was observed to occur at the farthest distance monitored from the edge of pavement. In these cases, no judgment about whether these represent equilibrium concentrations can be made.

RESULTS

Water Quality Performance

There are a number of possible measures of performance of storm water BMPs. The two most common report performance as a removal efficiency (i.e., a percentage change between the influent and effluent quality) or focus on the effluent quality achieved. A boxplot of observed TSS data at Sacramento is presented in Figure 3 and suggests that an irreducible minimum concentration occurs that is relatively insensitive to concentrations at the edge of pavement. Consequently, the primary measure of performance among the sites in this report is the minimum concentration for each constituent at each site and the distance at which it first becomes manifest.

Summary statistics for each of the monitored sites are presented in Tables 2 through 9. The tables contain the summary statistics (arithmetic mean, range, and standard deviation) of the monitoring data collected. The rows have been color coded to indicate whether the observed concentrations at various distances from the edge of pavement exhibit statistically significant increases (shown in red) or decreases (shown in green) in concentration at the 95% confidence level. If the colored cell is located at the far right then the lowest/highest concentration occurs at the greatest distances from the edge of pavement. If multiple cells are colored, such as for TSS in Table 2, then the lowest concentration occurs at the distance of the first colored cell (4.2 m) and no further statistically significant change occurs at greater distances. Constituents in rows with no colored cells did not exhibit any statistically significant change in concentration at the test site. For the constituents exhibiting a statistically significant decrease in concentration, the lowest concentration for all is achieved within 4.6 meters of the edge of pavement and those that increase achieve their highest concentration farthest from the edge of pavement.

A summary of the shortest length observed to produce a constant (best) discharge quality for all constituents that decrease in concentration is presented in Table 10. For the sites with relatively few samples (Irvine and San Onofre) the distance presented is where the lowest concentrations are observed rather than where no statistical difference was demonstrated. The only site not to produce significant reductions was Moreno Valley, which is located in an arid region and only had an average of about 25% vegetation coverage. Table 11 presents the TSS edge of pavement and average discharge concentrations for each of the sites. In general a substantial reduction is observed, except for the sites with abundant gophers and Moreno Valley.

Infiltration

Each length of the buffer strips was evaluated for the amount of infiltration that occurred at each distance based on all events during the study period (not just those monitored for water quality). The load reduction for each of the sites for selected constituents is shown in Table 12. This is the load reduction calculated from the edge of pavement concentration at each site, the discharge concentration, and the runoff coefficient at the buffer widths shown in Table 10. In general, infiltration is responsible for a greater portion of the load reduction than the change in concentration. Only Moreno Valley which was ineffective at reducing concentrations and which had a relatively high runoff coefficient (about 50%) did not have substantial load reductions for all constituents.

Vegetation

Vegetation type and relative quantity is similar at all the California sites except for Moreno Valley, which had less than 25% vegetation coverage for most of the study period. Non-native grasses (Italian rye and brome grasses primarily) dominate and comprise between 65% and 100% of the vegetative cover type. Consequently, there is little basis for relating type of ground cover to performance. Average vegetation height varied between 11 and 22 cm, and was not correlated with performance. The vegetation at Redding, which produced runoff with the lowest constituent concentrations, consisted of 73% grasses with an average height of about 15 cm. This height is near the conventional recommendation for vegetated storm water controls.

Redding and Sacramento have average vegetation coverage exceeding 80% and with moderate slopes achieve irreducible minimum concentrations within 5 meters of the edge of pavement. Sites in southern California such as Irvine, Yorba Linda, and San Onofre have coverages of about 75% or less and with similar slopes require about 10 meters to achieve minimum concentrations. This suggests that performance falls off rapidly as the vegetation coverage declines below 80%.

Performance of existing vegetated areas adjacent to highways was also reported by Barrett et al. (1998). They monitored two sites in the Austin, Texas area, which had substantially different types of vegetation. Despite the differences, average TSS concentrations discharged from the two sites were very similar, 21 mg/L and 29 mg/L. These concentrations are similar to those observed in this study, again suggesting that vegetation type is not an important factor in performance. This conclusion is reinforced by the results of an earlier unpublished study conducted by the California Department of Transportation (Caltrans) of buffer strips engineered and operated specifically for stormwater treatment. The average minimum concentration of TSS observed at these sites, which had a monoculture of salt grass was about 27 mg/L.

Regression Analysis

Multiple (stepwise) regression was performed with the monitoring data from the biofilter strips except for Moreno Valley, which was eliminated because little pollutant removal occurred. Initially five predictors were used strip width, slope, grass coverage, peak discharge and influent concentration. These five predictors gave physically unreasonable results, indicating that the steeper slopes resulted in lower discharge concentrations and that wider buffer strips increased concentrations compared to narrow ones. Slope and width were also combined using design storm rainfall rates and roadway width to determine resulting runoff velocity and buffer residence time. It was hoped that residence time would be a better predictor of discharge quality than the individual factors. Unfortunately, the southern California sites tended to have the longest residence times, but the worst discharge quality.

There were several factors that lead to the disappointing results of the regression analysis. The two steepest sites (San Rafael and Cottonwood) outperformed sites at some locations with much flatter slopes (San Onofre and Yorba Linda). Additionally sites with lower average vegetation density (Irvine) performed much better than sites with higher coverage (San Onofre) even though both suffered about the same gopher damage. Finally, high effluent concentrations at San Onofre tended to skew the results of all the regression analysis since the site characteristics were similar to others, but all effluent concentrations were far higher.

Soil Chemistry

There is a common concern that constituents removed from highway runoff in vegetated buffer strips will accumulate in the soil and vegetation to the extent that the material could eventually be classified as a hazardous waste and require special handling. Consequently, the soils at each of the sites were evaluated at the end of the study period using the Toxicity Characteristic Leaching Procedure (TCLP). The results of this test for metals that have concentration limits are summarized in Table 13. Soil samples were collected from each of the buffer widths at each of the test sites. The average concentration is the mean for all the sites combined and the maximum is the highest concentration observed. Even the highest concentrations observed at the study sites were two to three orders of magnitude below the level where these soils would be classified as hazardous waste. Consequently, no special handling of roadside soils is required. In addition, accumulation rates of leachable metals must be very low since many of these sites have been subject to high traffic conditions for many years.

CONCLUSIONS

Based on evaluation of the data collected during the 2-year monitoring study, a summary of findings of the water quality performance of vegetated highway shoulders are listed below:

- Concentration reductions consistently occur for TSS and total metals and frequently for dissolved metals.
- Nutrient concentrations were generally unchanged by the buffer strips.
- Water quality performance declines rapidly when the vegetative cover falls below about 80%.
- Vegetation species and height was similar at most sites and no effect on performance was observed.
- A substantial load reduction is evident for almost all constituents even those that exhibit no change in concentration because of the large amount of infiltration that occurred at most of the sites.
- At sites with greater than 80% vegetation coverage, the following buffer widths result in irreducible minimum concentrations for those constituents whose concentrations decrease:
    - 4.2 meters for slopes less than 10%
    - 4.6 meters for slopes greater than 10% and less than 35%
    - 9.2 meters for slopes between 35% and 50%
- At sites with less than 80% coverage, the following buffer widths result in irreducible minimum concentrations:
    - No data for slopes less than 10%
    - 10 meters for slopes greater than 10%
- The minimum concentration produced varied among the sites, but could not be shown to be a function of buffer width, highway width, vegetation coverage, hydraulic residence time, vegetation type, or slope.
- For selected constituents whose concentrations were lowered by the buffer strips the median of the average values for all of the sites except Moreno Valley were:
    - TSS – 25 mg/L
    - Copper – 8.6 μg/L
    - Lead – 3.0 μg/L
    - Zinc – 25 μg/L
    - Dissolved Copper – 5.2 μg/L
    - Dissolved Lead – 1.3 μg/L
    - Dissolved Zinc – 12 μg/L

- Study sites with sufficient vegetation produced an effluent quality that was equal to or better than that observed from vegetated buffer strips that were engineered and operated specifically for water quality improvement.
- Toxicity Characteristic Leaching Procedure (TCLP) testing of soils at the study sites indicated that metals concentrations were far below levels that would require classification as hazardous waste, so removal or disposal of roadside soils would not be subject to any special requirements even after years of runoff treatment.
- Existing routine maintenance activities for vegetated shoulders were sufficient to establish conditions favorable for substantial pollutant removal.

In summary, the constituents exhibiting a decrease in concentration achieved steady state levels within 5 meters of the pavement edge for slopes commonly found on highway shoulders and when the vegetation coverage exceeded 80%. Slope, vegetation type and height, highway width, and hydraulic residence time had little or no impact on the final concentrations. The presence of gophers at all of the sites with lower levels of vegetation appeared to affect the monitoring results, so additional study of sites with less vegetation may lead to stronger conclusions regarding the minimum vegetation coverage required for substantial pollutant reduction. Nevertheless, the results of this study indicate that substantial reduction of pollutants in highway runoff occurs in roadside vegetated areas that were neither designed nor maintained specifically for stormwater treatment.

ACKNOWLEDGEMENTS

This research effort was funded by the California Department of Transportation under Contract No. 43A0051. Prime contractor for the study was RBF Consulting and monitoring and operation of the tests sites were conducted by KLI and URS Corporation. Technical oversight was provided by David Alderete and Misty Scharff at the Office of Water Projects at California State University at Sacramento. Special thanks to Laura Larsen for assembling the data and to Blaine Linkous for his help in data analysis.

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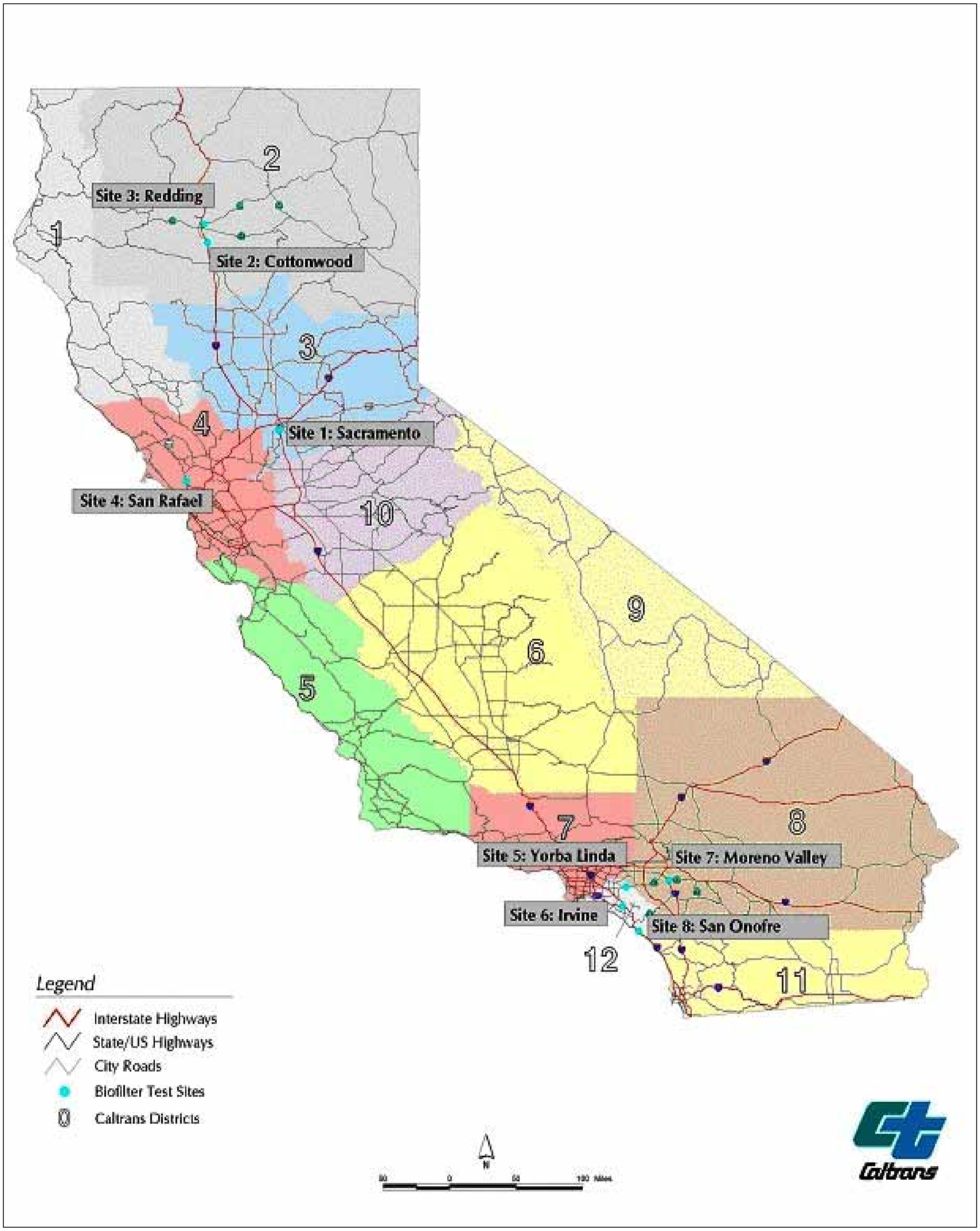

FIGURE 1. RVTS Buffer Strip Test Site Map

FIGURE 2. Redding, California Test Site

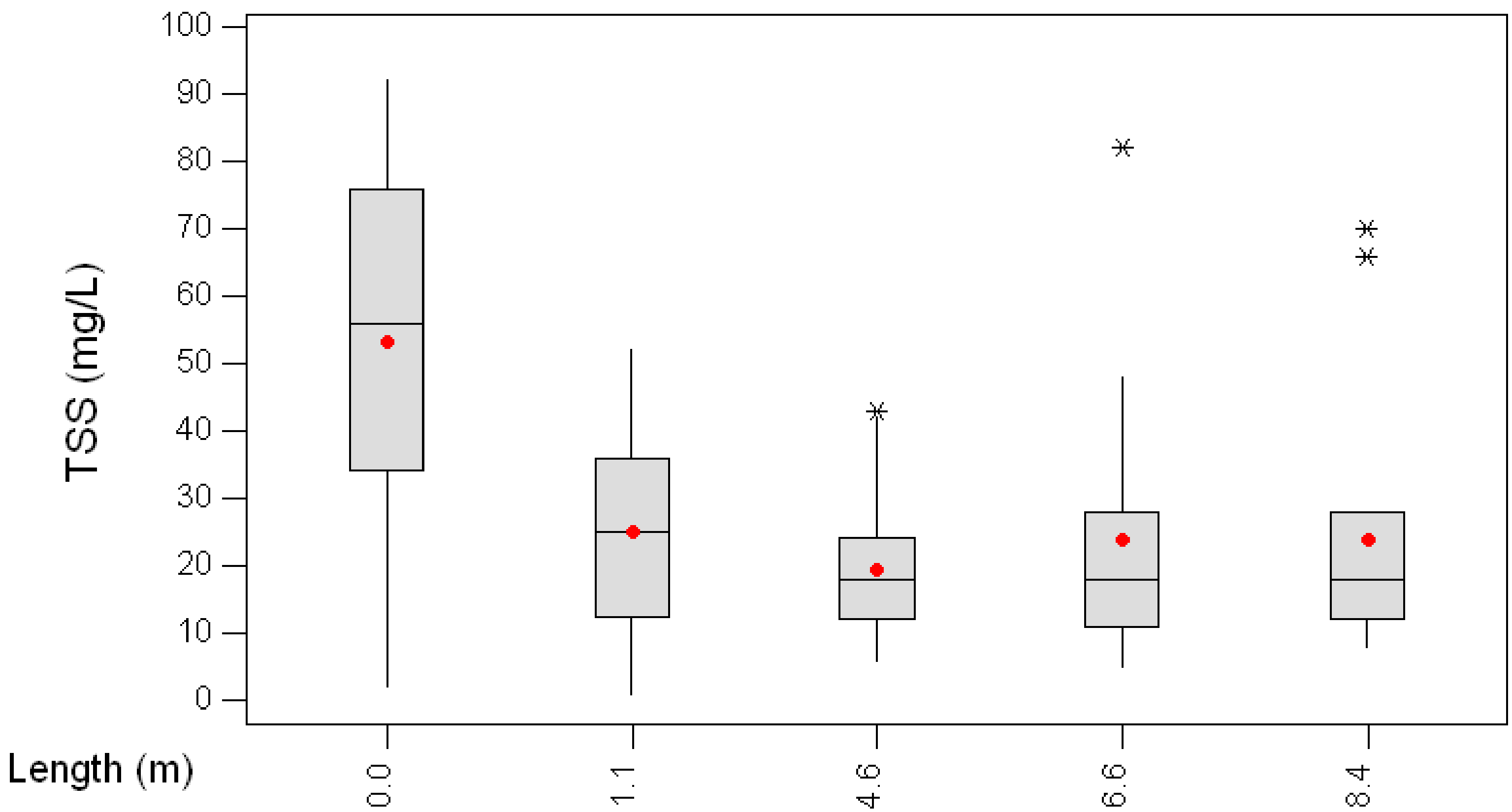

FIGURE 3. Boxplot of TSS EMCs at Sacramento

TABLE 1. Characteristics of the Test Sites

Site	System	Slope	Drainage Area [b] (m^2)	Strip Width (m)	Hydrologic Soil Type [c]
Sacramento					D
	System 1	EP	332	0.0	
	System 2	5%	376	1.1	
	System 3	33%	453	4.6	
	System 4	33%	498	6.6	
	System 5	33%	538	8.4	
Cottonwood					C
	System 1	EP	210	0.0	
	System 2	52%	546	9.3	
Redding					C
	System 1	EP	295	0.0	
	System 2	10%	372	2.2	
	System 3	10%	425	4.2	
	System 4	10%	478	6.2	
San Rafael					C/D
	System 1	EP	590	0.0	
	System 2	50%	890	8.3	
Yorba Linda					B
	System 1	EP	910	0.0	
	System 2	14%	1080	2.3/1.4 [d]	
	System 3	14%	1160	5.4/4.4 [d]	
	System 4	14%	1090	7.6	
	System 5	14%	1840	13.0	
Irvine					B
	System 1	EP	630	0.0	
	System 2	11%	710	3.0	
	System 3	11%	780	6.0	
	System 4	11%	1040	13.0	
Moreno Valley					C
	System 1	EP	368	0.0	
	System 2	13%	460	2.6	
	System 3	13%	518	4.9	
	System 4	13%	610	8.0	
	System 5	13%	672	9.9	
San Onofre					B/C
	System 1	EP	530	0.0	
	System 2	8%	558	1.3	
	System 3	10%	700	5.3	
	System 4	16%	840	9.9	

TABLE 2 Summary Statistics of EMCs at Sacramento Test Site

Constituent	**EOP** Mean Range Std. Dev.	**1.1 m** Mean Range Std. Dev.	**4.6 m** Mean Range Std. Dev.	**6.6 m** Mean Range Std. Dev.	**8.4 m** Mean Range Std. Dev.
TSS (mg/L)	53 2 - 92 24	25 1 - 52 14	19 6 - 43 11	24 5 - 82 21	24 8 - 70 19
TDS (mg/L)	64 32 - 170 33	57 1 - 120 31	99 49 - 150 33	135 82 - 250 45	153 58 - 300 92
TOC (mg/L)	8.7 2 - 21 5.4	11 3 -23 6.2	13 5 - 25 5.9	13 3 - 30 7.9	16 2 - 32 9.1
Total Cu (µg/L)	12 3 - 26 6.4	8.5 2 - 16 4.2	6.3 2 - 19 3.9	6.0 2 - 13 3.1	6.0 3 - 10 2.5
Total Pb (µg/L)	4.0 0.5 - 8.8 2.7	2.2 1.0 - 4.6 1.3	1.6 1.0 - 6.0 1.4	1.5 1.0 - 3.9 0.88	1.3 1.0 - 3.9 0.77
Total Zn (µg/L)	65 5 - 170 41	34 8 - 65 17	26 10 - 100 22	30 7 - 63 18	21 5 - 67 17
Dissolved Cu (µg/L)	4.0 1.4 - 11 2.4	4.3 1.0 - 10 2.5	3.5 1.0 - 9.3 2.1	3.4 1.0 - 11 2.7	4.2 1.0 - 9.8 2.7
Dissolved Pb (µg/L)	1.0 none 0.0	1.0 1.0 - 1.4 0.09	1.0 1.0 - 1.4 0.10	1.0 none 0.0	1.0 none 0.0
Dissolved Zn (µg/L)	14 5 - 40 11	17 5 - 41 13	12 5 - 29 8.3	8.5 5 - 28 6.9	7.9 5 - 23 6.1
NO_3-N (mg/L)	0.44 0.1 - 1.2 0.35	0.35 0.07 - 0.72 0.21	0.25 0.02 - 0.72 0.23	0.45 0.08 - 0.87 0.26	0.46 0.1 - 1.6 0.44
TKN (mg/L)	1.7 0.7 - 4.3 1.1	1.5 0.5 - 2.9 0.61	1.5 0.8 - 3.3 0.68	1.8 1.1 - 3.6 0.74	1.5 0.7 - 2.7 0.57
Total P (mg/L)	0.40 0.03 - 1.7 0.37	0.27 0.03 - 0.62 0.14	0.35 0.09 - 0.60 0.15	0.34 0.08 - 1.1 0.28	0.26 0.08 - 0.55 0.15
Dissolved P (mg/L)	0.17 0.03 - 0.41 0.11	0.21 0.08 - 0.45 0.12	0.25 0.05 - 0.43 0.12	0.17 0.03 - 0.37 0.12	0.17 0.03 - 0.44 0.14

TABLE 3 Summary Statistics of EMCs at Redding

Constituent	**EOP** Mean Range Std. Dev.	**2.2 m** Mean Range Std. Dev.	**4.2 m** Mean Range Std. Dev.	**6.2 m** Mean Range Std. Dev.
TSS (mg/L)	49 8 - 260 55	26 1 - 220 50	5.0 1 - 22 5.2	10 1 - 54 15
TDS (mg/L)	27 1-150 35	47 6 - 96 28	42 6 - 90 25	79 6 - 190 53
TOC (mg/L)	7.3 1 - 23 6.2	12 2 - 29 8.9	11 3 - 20 5.6	19 8 - 33 8.7
Total Cu (µg/L)	5.8 1.5 - 18 4.1	4.6 1.5 - 18 3.9	2.4 1 - 4.9 1.2	4.5 1.2 - 16 3.5
Total Pb (µg/L)	3.5 1 - 13 2.9	4.0 1 - 13 3.8	1.4 1 - 5.5 1.2	1.8 1 - 6.1 1.6
Total Zn (µg/L)	39 7 - 130 30	12 6 - 25 6.2	10 5 - 32 7.1	20 5 - 110 28
Dissolved Cu (µg/L)	2.8 1 - 12 2.8	1.9 1 - 4.1 1.0	1.8 1 - 4.1 1.0	2.6 1 - 6.7 1.7
Dissolved Pb (µg/L)	1.0 1 - 1.4 0.09	1.0 1 - 1.3 0.07	1.0 none 0.0	1.0 none 0.0
Dissolved Zn (µg/L)	16 6 - 50 11	13 5 - 43 13	8.2 5 - 26 5.4	12 2 - 51 13
NO_3-N (mg/L)	0.45 0.10 - 1.2 0.37	0.30 0.08 - 0.9 0.25	0.22 0.03 - 0.8 0.22	0.20 0.04 - 0.56 0.17
TKN (mg/L)	1.32 0.38 - 5.2 1.1	0.87 0.26 -2.0 0.50	0.84 0.27 - 1.9 0.40	1.2 0.49 - 3.6 0.80
Total P (mg/L)	0.14 0.03 - 0.67 0.18	0.09 0.03 - 0.26 0.07	0.10 0.03 - 0.31 0.07	0.17 0.03 - 0.61 0.17
Dissolved P (mg/L)	0.04 0.003 - 0.24 0.06	0.06 0.011 - 0.25 0.07	0.05 0.02 - 0.12 0.03	0.07 0.03 - 0.24 0.05

TABLE 4 Summary Statistics of EMCs at San Rafael

Constituent	EOP Mean Range Std. Dev.	8.3 m Mean Range Std. Dev.
TSS (mg/L)	70 5 - 210 50	19 1 - 38 11
TDS (mg/L)	71 10 - 290 60	142 80 - 230 47
TOC (mg/L)	16 5 - 41 10	13.5 3 - 33 9.4
Total Cu (µg/L)	38 7 - 82 19	6.6 1 - 16 3.4
Total Pb (µg/L)	14.5 1 - 45 11	2.7 1 - 11 2.7
Total Zn (µg/L)	123 33 - 330 69	25 6 - 110 26
Dissolved Cu (µg/L)	16 5 - 34 6.7	3.8 1.0 - 7.8 1.9
Dissolved Pb (µg/L)	1.2 1.0 - 2.7 0.45	1.0 1.0 - 1.3 0.07
Dissolved Zn (µg/L)	43 8 - 79 18	10 5 - 36 7.4
NO_3-N (mg/L)	1.9 0.1 - 4.6 1.2	0.61 0.08 - 2.2 0.48
TKN (mg/L)	2.3 0.6 - 4.7 1.1	1.2 0.6 - 4.8 0.94
Total P (mg/L)	0.21 0.04 - 0.81 0.17	0.13 0.03 - 0.31 0.08
Dissolved P (mg/L)	0.07 0.01 - 0.49 0.10	0.06 0.02 - 0.19 0.04

TABLE 5 Summary Statistics of EMCs at Cottonwood

Constituent	**EOP** Mean Range Std. Dev.	**9.2 m** Mean Range Std. Dev.
TSS (mg/L)	88 26 - 260 69	19 4 - 50 14
TDS (mg/L)	34 1 - 88 25	85 32 - 180 44
TOC (mg/L)	12 3 - 51 10	12 2 - 25 5.2
Total Cu (µg/L)	33 8 - 85 19	8.6 3 - 33 7.7
Total Pb (µg/L)	11 0.5 - 54 12	3.0 1.0 - 9.5 2.6
Total Zn (µg/L)	127 17 - 310 72	22 5 - 120 32
Dissolved Cu (µg/L)	12 4 - 33 7.6	5.2 2 -16 3.8
Dissolved Fe (µg/L)	172 22 - 949 229	476 50 - 1100 367
Dissolved Pb (µg/L)	1.4 1.0 - 5.8 1.1	1.3 1.0 - 3.6 0.78
Dissolved Zn (µg/L)	40 6 - 84 21	12 5 - 52 14
NO_3-N (mg/L)	0.81 0.1 - 3.4 0.78	1.4 0.1 - 5.2 1.3
TKN (mg/L)	1.9 0.8 - 4.6 0.98	1.9 0.7 - 7.4 1.7
Total P (mg/L)	0.19 0.03 - 0.85 0.23	0.15 0.03 - 0.67 0.19
Dissolved P (mg/L)	0.05 0.01 - 0.28 0.06	0.05 0.01 - 0.29 0.07

TABLE 6 Summary Statistics of EMCs at San Onofre

Constituent	**EOP** Mean Range Std. Dev.	**1.3 m** Mean Range Std. Dev.	**5.3 m** Mean Range Std. Dev.	**9.9 m** Mean Range Std. Dev.
TSS (mg/L)	104 12 - 206 58	66 7 - 150 51	50 11 - 140 40	90 18 - 216 83
TDS (mg/L)	118 16 - 360 95	131 10 - 360 124	112 40 - 278 66	90 14 - 278 39
TOC (mg/L)	31 8 - 84 24	25 9 - 73 18	30 11 - 86 22	29 11 - 86 17
Total Cu (µg/L)	58 13 - 110 28	31 9 - 75 19	26 10 - 46 13	18 8 - 46 7.3
Total Pb (µg/L)	68 15 - 190 46	34 8 - 100 26	41 11 - 110 33	41 3 - 110 28
Total Zn (µg/L)	265 46 - 510 142	81 20 - 160 47	78 21 - 250 73	57 20 - 250 30
Dissolved Cu (µg/L)	26 9 - 54 13	19 7 - 58 14	17 8 - 39 8.6	12 6 - 39 4.5
Dissolved Pb (µg/L)	16 3 - 75 20	8.5 1 - 21 6.2	11 3 - 24 6.8	14 1 - 32 11
Dissolved Zn (µg/L)	77 27 - 170 41	33 5 - 85 22	32 16 - 58 13	34 15 - 64 17
NO_3-N (mg/L)	1.5 0.2 - 4.6 1.4	1.6 0.2 - 5.7 1.8	0.72 0.1 - 1.9 0.61	0.60 0.1 - 10 0.68
TKN (mg/L)	1.8 0.4 - 4.2 1.2	2.0 0.1 - 5.2 1.6	1.6 0.6 - 2.7 0.94	1.7 1 - 10 0.52
Total P (mg/L)	0.35 0.03 -1.2 0.27	0.57 0.2 - 1.5 0.37	0.83 0.3 - 1.8 0.46	0.78 0.6 - 10 0.17
Dissolved P (mg/L)	0.11 0.03 - 0.36 0.10	0.37 0.06 - 1.4 0.35	0.67 0.3 - 1.6 0.39	0.59 0.4 - 10 0.17

TABLE 7 Summary Statistics of EMCs at Irvine

Constituent	**EOP** Mean Range Std. Dev.	**3.0 m** Mean Range Std. Dev.	**6.0 m*** Mean Range Std. Dev.	**13.0 m** Mean Range Std. Dev.
TSS (mg/L)	127 40 - 320 86	52 8 - 110 36	NA	25 14 - 38 11
TDS (mg/L)	164 1 - 350 96	135 44 - 292 85	NA	104 65 - 166 45
TOC (mg/L)	39 13 - 94 27	31 10 - 92 31	NA	21 14 - 34 8.9
Total Cu (µg/L)	84 37 - 130 27	41 11 - 74 25	NA	12 8 - 17 4.0
Total Pb (µg/L)	85 27 - 210 51	23 5 - 45 14	NA	4.8 2.7 - 6.3 1.5
Total Zn (µg/L)	286 110 - 480 113	99 40 - 200 57	NA	25 15 - 34 8.3
Dissolved Cu (µg/L)	35 15 - 75 18	19 5 - 50 17	NA	9.6 7 - 13 2.6
Dissolved Pb (µg/L)	11 2 - 38 12	3.8 1.0 - 7.4 2.6	NA	2.0 1.3 - 2.6 0.62
Dissolved Zn (µg/L)	80 40 - 170 36	36 13 - 94 31	NA	20 13 - 26 6.0
NO_3-N (mg/L)	2.6 0.7 - 5.2 1.6	1.5 0.2 - 4.4 1.6	NA	0.21 0.10 - 0.27 0.08
TKN (mg/L)	3.6 0.9 - 8.0 2.0	2.8 0.5 - 9.0 3.2	NA	1.0 0.7 - 1.7 0.45
Total P (mg/L)	0.48 0.2 - 1.0 0.26	0.70 0.4 - 1.3 0.40	NA	0.65 0.4 - 1.1 0.34
Dissolved P (mg/L)	0.22 0.03 - 0.49 0.15	0.37 0.04 - 1.1 0.38	NA	0.35 0.03 - 0.75 0.30

*Only a single sample collected at this distance

TABLE 8 Summary Statistics of EMCs at Yorba Linda

Constituent	EOP Mean Range Std. Dev.	1.8 m Mean Range Std. Dev.	4.9 m Mean Range Std. Dev.	7.6 m Mean Range Std. Dev.	13.0 m Mean Range Std. Dev.
TSS (mg/L)	114 24 - 221 73	222 47 - 670 189	119 28 - 400 115	124 19 - 330 116	42 15 - 108 45
TDS (mg/L)	68 19 - 149 44	87 8 - 190 58	67 1 - 182 49	91 20 - 150 49	80 44 - 124 34
TOC (mg/L)	20 9 - 48 13	21 3 - 44 13	24 8 - 57 16	24 9 - 50 16	21 11 - 32 8.8
Total Cu (µg/L)	43 16 - 100 22	44 25 - 85 19	31 9 - 77 20	16 7 - 26 7.2	10 7 - 14 3.7
Total Pb (µg/L)	23 4 - 45 11	29 17 - 47 11	24 8 - 55 16	19 7 - 42 15	7.3 3 - 17 6.5
Total Zn (µg/L)	321 94 - 640 208	224 95 - 550 154	105 31 - 250 69	54 21 - 96 29	33 20 - 58 17
Dissolved Cu (µg/L)	17 6 - 38 11	15 6 - 31 7.8	17 6 - 47 13	9.3 6 - 14 3.1	6.9 5.2 - 8.3 1.5
Dissolved Pb (µg/L)	5.2 1 - 12 4.0	4.3 1.0 - 9.0 2.6	4.5 1 - 11 3.0	2.9 1.0 - 7.4 2.4	2.2 1.0 - 4.3 1.5
Dissolved Zn (µg/L)	139 31 - 490 135	39 5 - 83 26	40 11 - 140 39	17 11 - 24 4.6	21 11 - 31 8.4
NO_3-N (mg/L)	0.83 0.1 - 2.2 0.67	1.8 0.4 - 6.0 1.7	1.3 0.3 - 3.9 1.2	0.84 0.2 - 2.0 0.70	0.26 0.14 - 0.41 0.11
TKN (mg/L)	2.2 0.9 - 4.9 1.4	2.4 0.8 - 5.0 1.2	1.9 0.7 - 3.8 1.1	1.7 0.4 - 3.7 1.3	1.3 0.8 - 2.3 0.70
Total P (mg/L)	0.26 0.18 - 0.46 0.09	0.40 0.24 - 0.99 0.23	0.40 0.19 - 0.65 0.16	0.54 0.2 - 1.2 0.38	0.67 0.5 - 1.2 0.34
Dissolved P (mg/L)	0.06 0.03 - 0.16 0.04	0.06 0.03 - 0.13 0.03	0.19 0.03 - 0.43 0.13	0.31 0.03 - 0.67 0.25	0.51 0.38 - 0.81 0.21

TABLE 9 Summary Statistics of EMCs at Moreno Valley

Constituent	**EOP** Mean Range Std. Dev.	**2.6 m** Mean Range Std. Dev.	**4.9 m** Mean Range Std. Dev.	**8.0 m** Mean Range Std. Dev.	**9.9 m** Mean Range Std. Dev.
TSS (mg/L)	71 11 - 257 81	161 34 - 680 213	330 56 - 1300 419	280 77 - 538 167	626 50 - 2600 812
TDS (mg/L)	66 26 - 110 34	100 16 - 230 74	81 14 - 172 52	81 12 - 163 54	59 8 - 100 38
TOC (mg/L)	31 9 - 96 30	33 9 - 83 26	30 9 - 90 27	31 9 - 85 27	26 9 - 73 22
Total Cu (µg/L)	38 16 - 100 27	36 20 - 72 18	37 14 - 71 19	32 18 - 53 12	40 21 - 67 15
Total Pb (µg/L)	8.4 4 - 13 3.2	12 4 - 32 8.8	16 5 - 42 13	16 6 - 31 9.0	27 6 - 52 17
Total Zn (µg/L)	349 150 - 800 237	184 62 - 640 188	196 44 - 630 190	191 79 - 510 139	404 120 - 1800 570
Dissolved Cu (µg/L)	26 11 - 87 25	24 12 - 61 16	23 14 - 62 16	19 10 - 40 9.3	18 10 - 39 9.5
Dissolved Pb (µg/L)	2.6 1.0 - 5.5 1.4	2.0 1.0 - 3.4 0.79	3.0 1.0 - 3.9 0.89	3.4 1.0 - 5.8 1.3	3.0 1.0 - 6.3 1.7
Dissolved Zn (µg/L)	261 99 - 700 206	55 29 - 140 36	49 18 - 120 31	53 25 - 94 21	56 21 - 110 28
NO_3-N (mg/L)	0.94 0.3 -3.6 1.1	1.1 0.4 - 2.5 0.77	1.1 0.5 - 2.7 0.72	0.88 0.3 - 1.9 0.59	0.65 0.2 - 1.6 0.48
TKN (mg/L)	3.7 1 - 13 4.0	3.5 1.4 - 8.0 2.3	3.8 1.2 - 9.1 2.9	4.8 2 - 13 4.0	4.6 2 - 14 4.3
Total P (mg/L)	0.57 0.1 - 2.3 0.72	0.52 0.2 - 1.1 0.30	0.69 0.2 - 1.8 0.58	0.48 0.09 - 0.84 0.25	0.80 0.5 - 1.1 0.26
Dissolved P (mg/L)	0.18 0.03 - 0.54 0.20	0.26 0.03 - 0.69 0.24	0.27 0.03 - 0.86 0.30	0.27 0.04 - 0.72 0.25	0.28 0.05 - 0.81 0.30

TABLE 10 Shortest Effective Length for each RVTS

Site	Distance (m)
Redding	4.2
Sacramento	4.6
San Rafael	8.3*
Cottonwood	9.2*
San Onofre	9.9
Irvine	13
Yorba Linda	13
Moreno Valley	Not Effective

*shortest distance monitored

TABLE 11 TSS Equilibrium Concentration for Each Test Site

Site	Edge of Pavement (mg/L)	Discharge Concentration (mg/L)
Redding	49	5
Sacramento	53	24
San Rafael	70	19
Cottonwood	88	19
San Onofre*	104	90
Irvine*	127	25
Yorba Linda*	114	42
Moreno Valley	71	626

*Gophers present in test strip

TABLE 12 Total Load Reduction (%) at Minimum Effective Width

Site	TSS	Copper	Lead	Zinc
Redding	97	76	84	90
Sacramento	85	83	87	87
Camp Pendleton	77	88	83	92
San Rafael	96	98	98	97
Cottonwood	96	95	95	97
Irvine	97	98	99	99
Yorba Linda	94	96	95	98
Moreno Valley	-450	46	-63	68

TABLE 13 Summary of TCLP Tests of Roadside Soils

Constituent	Average Concentration (μg/L)	Maximum Concentration (μg/L)	Hazardous Waste Threshold (μg/L)
As	2.2	4.7	5,000
Cd	0.5	0.5	1,000
Cr	8.2	19	5,000
Cu	24.5	210	25,000
Ni	8.4	31	20,000
Pb	45.6	240	5,000
Zn	44.5	120	250,000

FIELD TEST OF GRASSED-SWALE PERFORMANCE IN REMOVING RUNOFF POLLUTION

By Shaw L. Yu,[1] Jan-Tai Kuo,[2] Members, ASCE, Elizabeth A. Fassman,[3] and Henry Pan[4]

ABSTRACT: The paper presents results of field tests, conducted in Taiwan and Virginia, of the pollutant removal efficiencies of grassed swales. Swales are a low-cost storm-water best management practice (BMP) that have been reported as a cost-effective method for controlling runoff pollution from land surfaces, especially highways and agricultural lands. The Virginia experiments tested a highway median swale, while the Taiwan experiments were conducted on an agricultural test farm. Average pollutant removal efficiencies reported for the test swales vary from 14 to 99% for total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP). The wide range of performance results indicates the importance of such design parameters as length, longitudinal slope, and the presence of check dams. Minimum design guidelines for use of swales as a BMP are suggested.

INTRODUCTION

Grassed swales are increasingly being employed as a storm-water best management practice (BMP) for runoff quantity and quality control. The primary mechanisms for pollutant removal in swales are filtration by the vegetation, settling of particulates, and infiltration into the subsurface zone. As runoff travels through a swale, the vegetation reduces peak velocity while infiltration reduces flow volume. Attenuation of runoff flow promotes pollutant removal. In practice, check dams are sometimes placed in grassed swales to increase the detention time and to create a ''mini-storage'' effect.

Effectiveness of a swale as a BMP is therefore highly dependent on design characteristics such as length, longitudinal slope, and the presence of check dams. Each factor influences detention time, and hence treatment efficiency. Most studies show that long swales with gradual slopes are more effective at removing pollutants because of increased time for settling and physical sites for infiltration. (Kaighn and Yu 1996; Watershed Protection Techniques 1996; Patron 1998). Ponding of water behind check dams further enhances infiltration and settling by temporarily blocking the flow of water. Yu et al. (1994) presented a compilation of various studies' design guidelines, which recommended maximum 5% longitudinal slope; 30 to 60 m length; 0.6 m bottom width; soil with high infiltration rate; dense, deep-rooted, flood-tolerant vegetation; and the inclusion of check dams.

Kaighn and Yu (1996) compared swales of equal length but having different slopes. One of the swales also contained a check dam. Results indicated that pollutant removal was impacted more by the presence of the check than by changes in slope. Yousef et al. (1985) also concluded that inclusion of check dams in swale design would have a significant impact on pollutant removal performance.

Pollutant removal efficiencies of swales reported in the literature covers a wide range. (Yousef et al. 1985; Kaighn and Yu 1996; Watershed Protection Techniques 1996; Barrett et al. 1998; Patron 1998). In general, swales show good performance for removal of large particles, such as suspended solids (TSS); however, during intense storms, settled particles are potentially subject to resuspension, resulting in net export of pollutant. Export of pollutants has also been reported for nutrients. Investigation of total phosphorus (TP) and total nitrogen (TN) removal for swales has indicated that the vegetation itself or fertilization might contribute to nutrient loads, particularly after mowing (Patron 1998).

Even though not all studies show positive results in terms of water quality improvement, swales are an attractive option for agencies such as departments of transportation since they are easily incorporated into the landscape, such as in highway medians. Minimal maintenance requirements include mowing and periodic inspection to assess vegetative health and fill in eroded paths. Swale construction costs are estimated at \$5 to \$15 per linear foot, which makes them a cost-effective option for storm-water management if performance is acceptable (Patron 1998). An analysis of design criteria, therefore, is warranted to render swale applications as effective as possible for storm-water management.

CASE STUDIES

Site Descriptions

Taiwan

The Taiwan experiments were conducted in 1997 on an agricultural experiment farm site of the National Taiwan University. The test swale (Fig. 1) was 30 m with a longitudinal slope of 1%. A triangular weir was placed at the swale midpoint and outlet to facilitate flow measurement. The midpoint weir also served as a check dam. Synthetic runoff with prescribed pollutant concentrations and flow rate was fed to the swale from two 5-ton storage tanks. Tests were run with and without the midpoint check dam. Automatic and manual sampling techniques were employed in the experiments.

Virginia

Field testing of swales occurred in the summer of 1997 in Northern Virginia. The Goose Creek (heretofore referred to as GC) swale is located in the median of State Route 7, which is subject to an average daily traffic (ADT) of approximately 39,000 vehicles per day. Swale testing was performed during highway construction in the immediate drainage area, as shown in Fig. 2. The total length of the GC swale is 274.5 m, with a 3% longitudinal slope and check dams located at 175 and 237.5 m from the swale inlet. Runoff that does not infiltrate into the swale is conveyed via storm sewer at the swale outlet for ultimate discharge to a scenic river.

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Note. Discussion open until November 1, 2001. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on November 20, 2000; revised January 10, 2001. This paper is part of the ***Journal of Water Resources Planning and Management***, Vol. 127, No. 3, May/June, 2001. ©ASCE, ISSN 0733-9496/01/0003-0168–0171/\$8.00 + \$.50 per page. Paper No. 22345.

FIG. 1. 30 m Test Swale with 1 Check Dam at Taiwan Site

FIG. 2. Goose Creek Swale and Check Dam System

Methodology

Taiwan

As described above under ''Site Descriptions,'' synthetic runoff with prescribed pollutant concentrations and flow rate was used in the swale experiments. Samples were taken manually and with automatic samplers at 5–10 min intervals. Each water sample was collected and analyzed individually in accordance with the QA/QC requirements specified by the Taiwan Environmental Protection Administration, which were based mainly on the *Standard Methods for the Examination of Water and Waste Water.*

Virginia

Site conditions permitted only manual sampling techniques. Storm samples were collected June 18, July 22, and August 4, 1997, at four locations along the swale—at the edge of pavement near the inlet, downstream of each check dam, and at the outlet. For each storm event monitored, sampling began after 0.25 cm (0.1 in.) of rainfall accumulation, provided runoff was generated. For every 0.25 cm of accumulation thereafter, samples were taken at each location above where runoff occurred and the time was recorded. Samples were analyzed for TSS according to *Standard Methods for the Examination of Water and Wastewater,* 19th Edition, Method 2450D Total Suspended Solids Dried at 103–105°C (1995). Total phosphorus was analyzed according to Hach Method 8190, equivalent to U.S. EPA Method 365.2 and *Standard Methods* 4500-PB (5) and 45000-PE for wastewater.

Highway runoff flow into the swale was calculated using the rational formula, which is appropriate for small watersheds. Lateral flow into the swale was included in calculation of total runoff volume. Flow through the swale was determined using Manning's Equation, with the coefficient of roughness as prescribed from results of other swale studies (Yousef et al. 1985) and the continuity equation. It is important to note that since actual flow measurement was not possible, because of site limitations, calculation of flow through the swale does not account for runoff volume reduction due to infiltration. Therefore, pollutant mass removal for storms that were large enough to discharge runoff to the outlet is most likely underestimated. Mass removal was calculated according to flow weighting of sample concentration and the total flow through the swale. One hundred percent mass removal was assumed for storms that did not produce flow at the outlet (i.e., all runoff was infiltrated into the soil).

Precipitation data was collected on-site for most storms. Equipment failure during one storm resulted in inaccurate measurements. Precipitation data collected at Dulles International Airport (approximately 11.3 km from the site) was substituted for on-site data for this storm.

RESULTS

Results of field tests are found in Table 1. Mass balance calculations were calculated for all events where accurate flow measurements were possible. Four scenarios (TA, TB, TC, TD) were tested at the Taiwan site. TA and TC were conducted with inlet flows of 4.2×10^{-3} m^3s^{-1} and 4.0×10^{-3} m^3s^{-1}, resulting in detention times of 7 min and 5.5 min, respectively. TB and TD were conducted with inlet flows of 0.86×10^{-3} m^3s^{-1} and 0.9×10^{-3} m^3s^{-1} and detention times of 18 min and 10 min, respectively. The Virginia data represent average pollutant removal efficiencies at the GC swale for three storms. The extensive length and presence of several check dams al-

TABLE 1. Pollutant Mass Removal for Test Swales: TSS, COD, TN, and TP

	Experiment	Length (m)	Mass Removal (%) TSS	COD	TN	TP
TA	check dam	15	75.2	55.7	24.2	41.2
	outlet	30	69.7	62.9	20.9	76.9
TB	check dam	15	74.4	48.0	13.6	34.0
	outlet	30	86.3	45.6	23.1	58.1
TC	outlet	30	47.7	33.9	20.0	50.3
TD	outlet	30	67.2	42.7	13.8	28.8
GC	upper	238	29.7	NT	NT	73.4
GC	lower	99	97.2	NT	NT	96.8
GC	entire swale	274.5	94.0	NT	NT	98.6

Note: ''T'' designates Taiwan Swale; ''GC'' designates Virginia Swale; NT = not tested.

lowed for analysis of shorter segments of the swale, which reflect lengths more often reported in the literature. The upper GC swale was considered as the segment of the swale from the inlet to the second check dam for a total length of 238 m. The lower GC swale was the segment from the first check dam to the swale outlet for a total length of 99 m.

DISCUSSION

Taiwan Swale

Inspection of the table reveals several performance characteristics of the test swale. The most prominent swale feature that enhanced pollutant removal was the presence of the check dam in experiments TA and TB. For all pollutants tested, removal over the entire length of the swale was higher than for tests without the check dam (TC and TD). Comparison of tests performed at equal inflow rates (TA and TC, paired, and TB and TD, paired) indicates that mass removal at the check dam in most cases was higher than at the outlet for the no–check dam experiments. Flow retardation due to the check dam increases detention time, thereby enhancing sedimentation and contact time, and hence pollutant removal. For the low-flow case (TB and TD), detention time is almost doubled with the check dam. The check dam cases showed the greatest improvement TP reduction. Outlet removals less than check dam location removals are most likely due to resuspension of settled particles near the outlet or export of plant detritus, such as grass clippings. There was no significant difference in mass removal for COD between check dam and no–check dam cases.

Since the mass balance analysis incorporates flow volume, removal of pollutants can also indicate volume reduction. As runoff travels the length of the swale, runoff volume and pollutant concentration decreases because of infiltration and settling. Check dams enhance the amount of reduction.

Virginia Swale

Of the sections of the GC swale presented in table, the upper GC swale showed the poorest average pollutant removal efficiency. Edge of pavement samples collected at the site revealed high pollutant concentrations, particularly for TP. The upper section was subject to the greatest loads and, hence, one would expect reduced performance for this type of BMP. Short-circuiting of the system via lateral inflow may have also contributed to export of TP during the August storm and export of TSS during the June and August storms. The mass balance presented herein is a conservative estimate of performance since calculation of volume reduction was not possible. Therefore, actual export of pollutants during these storms may be less than as indicated, thereby reflecting overall improved performance of the system.

The lower section and the entire swale showed good performance as a stormwater BMP. The trend demonstrates the significance of swale length and the presence of check dams in terms of quantity and quality of improvements.

An important feature of the GC swale was its ability to infiltrate larger volumes of runoff, compared with other swales. The longer-than-average length and the presence of two check dams caused complete infiltration of runoff (and therefore 100% removal of pollutants) for storms with less than approximately 12.7 mm total precipitation. Complete infiltration of runoff was reported for two 30 m swales from storms with less than 5 and 7 mm total precipitation (Kaighn and Yu, 1996). Kercher et al. (1983) reported 99% removal of pollutants measured for an extensive swale system, with only 3 out of 13 storms producing outflow. For geographic regions subject to frequent light rainfall, which results in long-duration, low-intensity storms, swales can be highly effective for pollutant removal.

SWALE DESIGN AND POLLUTANT REMOVAL

Often regulations are written in terms of sediment and phosphorus removal. The data presented in this report were combined with results of eight studies found in the literature to demonstrate the theoretical relationship between swale design characteristics and pollutant removal (Urban Best Management Practices 1994, 1996; Yu et al. 1994; Kaighn and Yu 1996) Figs. 3 and 4 show TSS and TP removal with respect to swale length and slope. While a specific equation describing performance was prevented because of significant scatter of data points, combining field observation with engineering judgment leads to several conclusions worthy of note.

As previously stated, it is generally agreed that swale length and slope are important parameters leading to pollutant removal. Consideration of these design parameters is shown in Fig. 4 by a theoretical family of curves based on longitudinal slope. It is important to note that curves indicated on the figure are meant to show estimated trends; they are not meant as absolute relationships. More data is required to substantiate a definitive relationship. The figure does show, however, that in

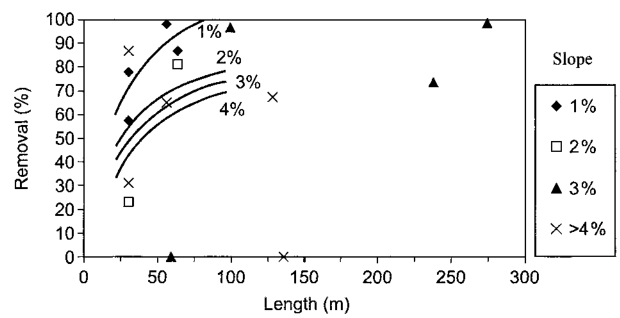

FIG. 3. Relationship between Swale Total Suspended Solids Removal Efficiency, Length, and Slope (Important: Curves Are Meant to Show Estimated Trends; They Are Not Absolute Relationships)

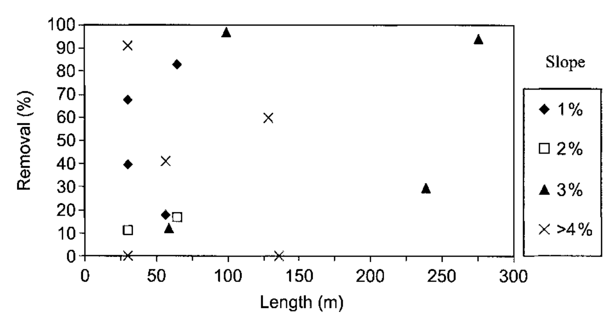

FIG. 4. Relationship between Swale Total Phosphorous Removal Efficiency, Length, and Slope

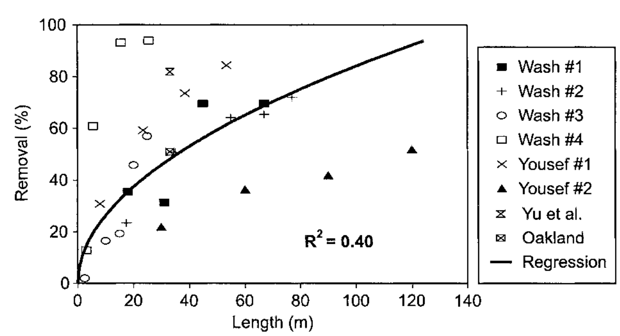

FIG. 5. Regression Curve Showing Relationship between Swale Length and Zinc Pollutant Removal (Kaighn and Yu 1996)

addition to generally improved performance with increased length, swales with a more gradual slope reported better removal of suspended particles. The rate of improvement reaches a plateau when swales are longer than approximately 75 m regardless of slope. A relationship between swale length and zine (Zn) removal, as shown in Fig. 5 and presented by Kaighn and Yu (1996), also shows that the rate of increasing pollutant removal with length decreases after a sharp initial rise. The regression equation was reported as $R_{Zn} = 8.302L^{0.50}$, where R_{ZN} represents zinc removal and L is swale length. Significant scatter of data led to an R^2 value of only 0.40; however, the figure shows a theoretical relationship similar to that found for TSS in this study.

Trends based on slope and length are not evident for removal of TP, as shown in Fig. 4. Swales generally are not considered efficient for removal of nutrients, due to the tendency to be effected by vegetation characteristics. The figure does demonstrate that increased swale length beyond approximately 75 m again does not result in a similar increase in pollutant reduction. Average TP mass removal for swales less than 75 m was approximately 42.3%, whereas swales greater than 75 m long showed only increased mass removal by 4.5% on average.

Field test data for buffer strip performance have been used for detecting trends and developing design recommendations. For example, Desbonnet et al. (1994, after Jones, unpublished, 1997) compiled literature data for 35 buffer strips and found that removal efficiency for TSS, TP, and TN, in general, increases over buffer width but at a diminishing rate after approximately 10 to 50 m, although the data were quite scattered. Also, Fan et al. (1998) used regression analysis to derive functional relationships between buffer strip pollutant removal efficiency and hydraulic loading rate and slope. The general form of the equation is as follows:

$$R = A \times S^b \times \left(\frac{q}{L}\right)^c \tag{1}$$

where R is pollutant removal rate; S the buffer strip slope; q the flow rate across the strip; L the buffer length; and A, b, c are regression coefficients. Since the key parameters—i.e., slope, length, and flow rate—are also applicable to swales, similar equations could be derived for the latter. The growing interest in implementation of infiltration techniques for storm-water management gives rise to a demand for effective design criteria. Further research in the application of swales for removing runoff pollution can lead to empirical relationships such as described by (1) for use by water quality professionals.

CONCLUSIONS

1. Properly engineered grassed swales can be an effective storm-water BMP, particularly for areas subject to low-intensity storms.
2. Swales should be a minimum of 75 m in length and have a maximum 3% longitudinal slope.
3. The presence of check dams generally improves swale performance.

ACKNOWLEDGMENTS

The writers would like to thank Estela Patron for her assistance with this project.

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