Compost-Amended Biofiltration Swale Evaluation

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TECHNICAL EVALUATION REPORT

Compost-Amended Biofiltration Swale Evaluation

Prepared for

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16. ABSTRACT

From May 2009 through June 2010, Herrera Environmental Consultants conducted hydrologic and water quality monitoring of a compost-amended biofiltration swale and a standard (control) biofiltration swale in the median of State Route 518 for the Washington State Department of Transportation. Herrera conducted this monitoring to obtain performance data that supports the issuance of a General Use Level Designation (GULD) for the compost-amended biofiltration swale from the Washington State Department of Ecology. This monitoring was performed in accordance with procedures described in *Guidance for Evaluating Emerging Stormwater Treatment Technologies; Technology Assessment Protocol – Ecology (TAPE)* (Ecology 2008). This document is a technical evaluation report on the compost-amended biofiltration swale, prepared by Herrera and based on results of the monitoring described above. The goal of this report is to demonstrate satisfactory performance of the compost-amended biofiltration swale for issuance of a GULD for basic, enhanced (dissolved metals removal) and oil treatment.

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Executive Summary

From May 2009 through June 2010, Herrera Environmental Consultants conducted hydrologic and water quality monitoring of a compost-amended biofiltration swale and a standard (control) biofiltration swale in the median of State Route 518 for the Washington State Department of Transportation. Herrera conducted this monitoring to obtain performance data that supports the issuance of a General Use Level Designation (GULD) for the compost-amended biofiltration swale from the Washington State Department of Ecology. This monitoring was performed in accordance with procedures described in *Guidance for Evaluating Emerging Stormwater Treatment Technologies; Technology Assessment Protocol – Ecology (TAPE)* (Ecology 2008).

This document is a technical evaluation report on the compost-amended biofiltration swale, prepared by Herrera and based on results of the monitoring described above. The goal of this report is to demonstrate satisfactory performance of the compost-amended biofiltration swale for issuance of a GULD for basic, enhanced (dissolved metals removal) and oil treatment.

Technology Description

The compost-amended biofiltration swale is identical to the standard (control) biofiltration swale design described in the WSDOT *Highway Runoff Manual*, except for a 3-inch compost blanket. Both biofiltration swales were hydroseeded with a seed mix consisting of red fescue, meadow foxtail, and white dutch clover. Fertilizer was added to the hydroseed mix for the control biofiltration swale, but was not added to the mix for the compost-amended biofiltration swale.

Sampling Procedures

Two biofiltration swales (compost-amended and control) were installed in the median of SR 518 (Figure 1) to facilitate performance monitoring pursuant to the TAPE procedures. Automated monitoring equipment was installed at the same time to characterize influent and effluent flow volumes over a 19-month period, extending from March 2009 through September 2010. Water quality was sampled from May 2009 through June 2010. A total of 23 separate storm events were sampled during this 13-month period, resulting in a total of 15 grab samples and 16 composite samples from each swale (15 of which were paired events at both biofiltration swales).

Automated samplers were used to collect flow-weighted composite samples of the influent and effluent during discrete storm events for subsequent water quality analyses. Based on this monitoring data, removal efficiency estimates were computed for targeted monitoring parameters, and compared to goals identified in Ecology's TAPE guidelines, to support the issuance of a GULD for the compost-amended biofiltration swale.

Grab samples were analyzed for total petroleum hydrocarbons (TPH). Collected flow-weighted composite samples were analyzed for the following water quality parameters:

- Total suspended solids (TSS)
- Total and dissolved copper
- Total and dissolved zinc
- Total phosphorus
- Soluble reactive phosphorus
- Hardness
- pH
- Particle size distribution
- Total Kjeldahl nitrogen
- Nitrate + Nitrite nitrogen

These data were subsequently evaluated in the following ways:

- Computation of pollutant removal efficiencies
- Statistical comparisons of influent and effluent concentrations
- Statistical comparisons of effluent concentrations and removal efficiencies between the compost-amended and control biofiltration swales
- Calculation of bootstrap confidence intervals
- Correlation analysis to examine the influence of storm characteristics
- Statistical comparisons of removal rates for the compost-amended biofiltration swale relative to basic treatment facilities

Hydrologic Performance

The water quality treatment goal for both biofiltration swales was to capture and treat 91 percent of the average annual runoff volume. Due to the design of the biofiltration swales, no overflow was included on the swales; thus all influent water must pass through both biofiltration swales.

Some infiltration of stormwater did occur on a storm-by-storm basis; however, when looking at the overall dataset, the biofiltration swales did not show a substantial reduction in flow volumes. The compost-amended biofiltration swale tended to hold stormwater for a longer duration during a storm event than the control biofiltration swale, resulting in longer flow durations observed at the outlet of the compost-amended biofiltration swale. Both biofiltration swales had the capacity to attenuate peak discharge rates.

Water Quality Performance

Conclusions derived from the monitoring data are summarized below for each treatment goal addressed in this report.

Basic Treatment

The basic treatment goal listed in the TAPE guidelines is 80 percent removal of TSS for influent concentrations ranging from 100 to 200 milligrams per liter (mg/L). A higher treatment goal may be appropriate for influent TSS concentrations greater than 200 mg/L. For influent TSS concentrations less than 100 mg/L, the facilities should achieve an effluent goal of 20 mg/L. There is no specified criterion for influent TSS concentrations less than 20 mg/L.

The TAPE guidelines require a minimum of 12 sampling events for demonstrating satisfactory performance relative to goals specified in TAPE for basic treatment. During the 2009-2010 monitoring period, a total of 15 valid samples were collected at the compost-amended biofiltration swale (one storm event had an influent TSS concentrations less than 20 mg/L). Eight of the 15 samples were in the 20 to 99 mg/L influent TSS range, and the remaining 7 samples were in the 100 to 200 mg/L range. Since the sampled storm events were divided evenly between the two influent ranges, both performance goals were evaluated. The upper 95 percent confidence limit for the mean effluent TSS concentration was 6.0 mg/L, and the lower 95 percent confidence limit for the mean TSS removal was 91 percent. Because the upper confidence limit for effluent TSS concentrations is lower than the effluent goal of 20 mg/L, and the lower confidence limit for TSS removal is higher than the 80 percent removal goal, it can be concluded that the compost-amended biofiltration swale met the basic treatment goal.

There was no significant relationship between flow rate and TSS removal, demonstrating that the measured pollutant removal performance can be applied to the range of flow rates monitored during this study (0.010 to 0.078 cubic feet per second [cfs]). There was a significant positive relationship between the aliquot-weighted average flow rate and effluent TSS concentrations; however, the maximum TSS effluent concentration measured at the compost-amended biofiltration swale was well below the 20 mg/L effluent goal over the range of flow rates monitored during this study.

Enhanced Treatment

The TAPE guidelines indicate that the data collected for an “enhanced” BMP should demonstrate significantly higher removal rates for dissolved metals than basic treatment facilities. The performance goal for enhanced treatment assumes that the facility treats stormwater with dissolved zinc influent concentrations ranging from 0.02 to 0.3 mg/L, and dissolved copper influent concentrations ranging from 0.003 to 0.02 mg/L. The influent dissolved zinc and dissolved copper concentrations from all 16 storm events sampled at the compost-amended biofiltration swale were within the acceptable TAPE ranges, thus all of the data was used to evaluate the enhanced treatment goal.

To evaluate the performance goal for enhanced treatment, the dissolved zinc and dissolved copper data obtained from the compost-amended biofiltration swale were compared to basic treatment facility performance data obtained from the International Stormwater Best Management Practices Database (ISBMPD) (ASCE 2009). These data were obtained from monitoring conducted on the following types of basic treatment facilities: biofiltration systems (e.g., grass strips and grass swales), media filters (e.g., sand filters, peat mixed with sand, StormFilter), retention ponds (e.g., surface wet ponds with a permanent pool), and retention underground vaults or pipes (e.g., surface tanks with impervious liners).

When compared to the ISBMPD data, the compost-amended biofiltration swale had significantly higher removal rates for dissolved zinc than all seven BMP types. The compost-amended biofiltration swale also performed significantly better than the control biofiltration swale (which is classified as a basic treatment facility) in removing dissolved zinc. In addition, the compost-amended biofiltration swale had significantly higher dissolved zinc removal relative to two other facilities that have received a GULD for enhanced treatment (the WSDOT Ecology Embankment and the Filterra Bioretention System).

The compost-amended biofiltration swale also had significantly higher removal rates of dissolved copper than two of the six BMP types (grass swales and sand filters) in the ISBMPD. No significant difference was found between dissolved copper removal in the compost-amended biofiltration swale compared to the remaining four BMP types in the ISBMPD. The WSDOT Ecology Embankment and the Filterra Bioretention System also performed significantly better than the compost-amended biofiltration swale in removing dissolved copper.

It should be noted that low dissolved copper concentrations at the SR 518 site likely influenced dissolved copper removal for the compost-amended biofiltration swale during this study. If the storm events with dissolved copper influent concentrations less than 0.006 mg/L are removed from the valid dataset, the new mean dissolved copper removal is 38 percent, which is comparable to results from the WSDOT Ecology Embankment and Filterra Bioretention System studies. Based on data presented in Strecker et al. (2004), influent dissolved copper concentrations less than 0.006 mg/L range can generally be considered to be an irreducible concentration for biofiltration swales.

Because dissolved copper treatment performance during this study was highly influenced by the low influent dissolved copper concentrations at this particular monitoring site, it is proposed that the treatment goal for dissolved copper be evaluated based on the paired design with the control biofiltration swale serving as the basic treatment facility. Both swales received similar dissolved zinc (median of 0.051 mg/L for both swales) and dissolved copper (median of 0.0060 and 0.0064 mg/L for the compost-amended and control biofiltration swales, respectively) influent concentrations. Despite the same median influent dissolved zinc concentration for both swales, the compost-amended biofiltration swale results demonstrated a significantly higher removal efficiency (corresponding to a median improvement of 64 percent between the two swales). The compost-amended biofiltration swale also demonstrated significantly higher removal efficiency for dissolved copper (corresponding to a median improvement of 31 percent between the two swales). These results indicate the compost-amended biofiltration swale does warrant GULD approval for enhanced treatment.

There was no significant relationship between flow rate and dissolved zinc removal, demonstrating that the measured pollutant removal performance can be applied to the range of flow rates monitored during this study (0.010 to 0.078 cfs). There was a significant relationship between the aliquot-weighted average flow rate and dissolved copper removal; however, dissolved copper percent removal is strongly related to the influent dissolved copper concentration. As the flow rate increases, the influent dissolved copper concentration decreases (i.e., becomes more dilute at higher flow rates). When influent dissolved copper concentrations less than 0.006 mg/L are removed from the dataset, the regression relationship is no longer significant.

Oil Treatment

The oil treatment goal listed in the TAPE guidelines is:

- No ongoing or recurring visible sheen
- A daily average TPH concentration of no greater than 10 mg/L
- A maximum of 15 mg/L for a discrete grab sample

Although only one collected influent sample was higher than the minimum influent concentration of 10 mg/L, all of the results are presented in this report, since they represent typical concentrations found in highway runoff.

Based on the TPH data obtained from 15 storm events sampled at the compost-amended biofiltration swale, influent TPH concentrations ranged from 1.28 to 10.5 mg/L, and effluent TPH concentrations ranged from 0.11 to 1.72 mg/L. TPH removal efficiency estimates ranged from 42 to 97 percent across all sampled storm events at the compost-amended biofiltration swale, with a mean value of 81 percent. The upper 95 percent confidence limit for the mean effluent TPH concentration measured in the compost-amended biofiltration swale was 0.69 mg/L, and the lower 95 percent confidence limit for the mean TPH percent removal was 73 percent. Visible oil sheen was not observed in any effluent sample.

There was no significant relationship between flow rate and TPH removal or effluent TPH concentration, demonstrating that the measured pollutant removal performance can be applied to the range of flow rates monitored during this study (0 to 0.076 cfs).

Despite TPH influent concentrations that were lower than those specified in the oil treatment performance goals, the data presented in this TER shows that the compost-amended biofiltration swale is capable of providing significant treatment for the TPH concentrations found in typical highway runoff.

Introduction

The Washington State Department of Transportation (WSDOT) is interested in evaluating the effectiveness of compost blankets in biofiltration swales to remove pollutants from stormwater runoff and comparing the results to standard biofiltration swales. To meet this objective, Herrera Environmental Consultants (Herrera) was retained by WSDOT to design and implement a monitoring program to compare the treatment performance of a compost-amended biofiltration swale and a standard (control) biofiltration swale. This project involved constructing two biofiltration swales, each 100 feet long by 6.5 feet wide, on WSDOT right-of-way in the median of State Route 518 (SR 518) in SeaTac, Washington (Figure 1). One biofiltration swale received a 3-inch compost blanket and the other served as a control. The biofiltration swales were installed in September and October 2008.

The primary goal of this monitoring program was to assess the performance of compost-amended biofiltration swales in treating common pollutants in highway runoff. During the course of the study, the water quality data for dissolved metals looked promising for enhanced treatment, thus a secondary goal of the study was to apply for a General Use Level Designation (GULD) for enhanced treatment. The monitoring program was also designed to assess the performance of both types of biofiltration swales with regard to reducing the peak discharge rates, flow volumes, and flow durations of highway runoff.

A quality assurance project plan (QAPP) was developed for the project by WSDOT (2008) in accordance with the *Guidelines for Preparing Quality Assurance Project Plans for Environmental Studies* (Ecology 2004) and is included in Appendix K. Monitoring equipment installation at the site occurred from October 2008 through January 2009. Herrera conducted flow monitoring for the project, which occurred over a 19-month period between March 2009 and September 2010. Herrera also conducted water quality sampling for the project, between May 2009 and June 2010.

Pursuant to guidance in *Guidance for Evaluating Emerging Stormwater Treatment Technologies; Technology Assessment Protocol – Ecology (TAPE)* (Ecology 2008), a technical evaluation report (TER) must be completed for any stormwater treatment system under consideration for a GULD. Specifically, the TER should:

- Document treatment performance of a technology to show that it will achieve Ecology's performance goals for target pollutants, as demonstrated by field testing performed in accordance with the TAPE

- Demonstrate the technology is satisfactory with respect to factors other than treatment performance (e.g., maintenance)

This document is a TER for the compost-amended biofiltration swale, prepared by Herrera and based on results of the monitoring described above. The goal of this TER is to demonstrate

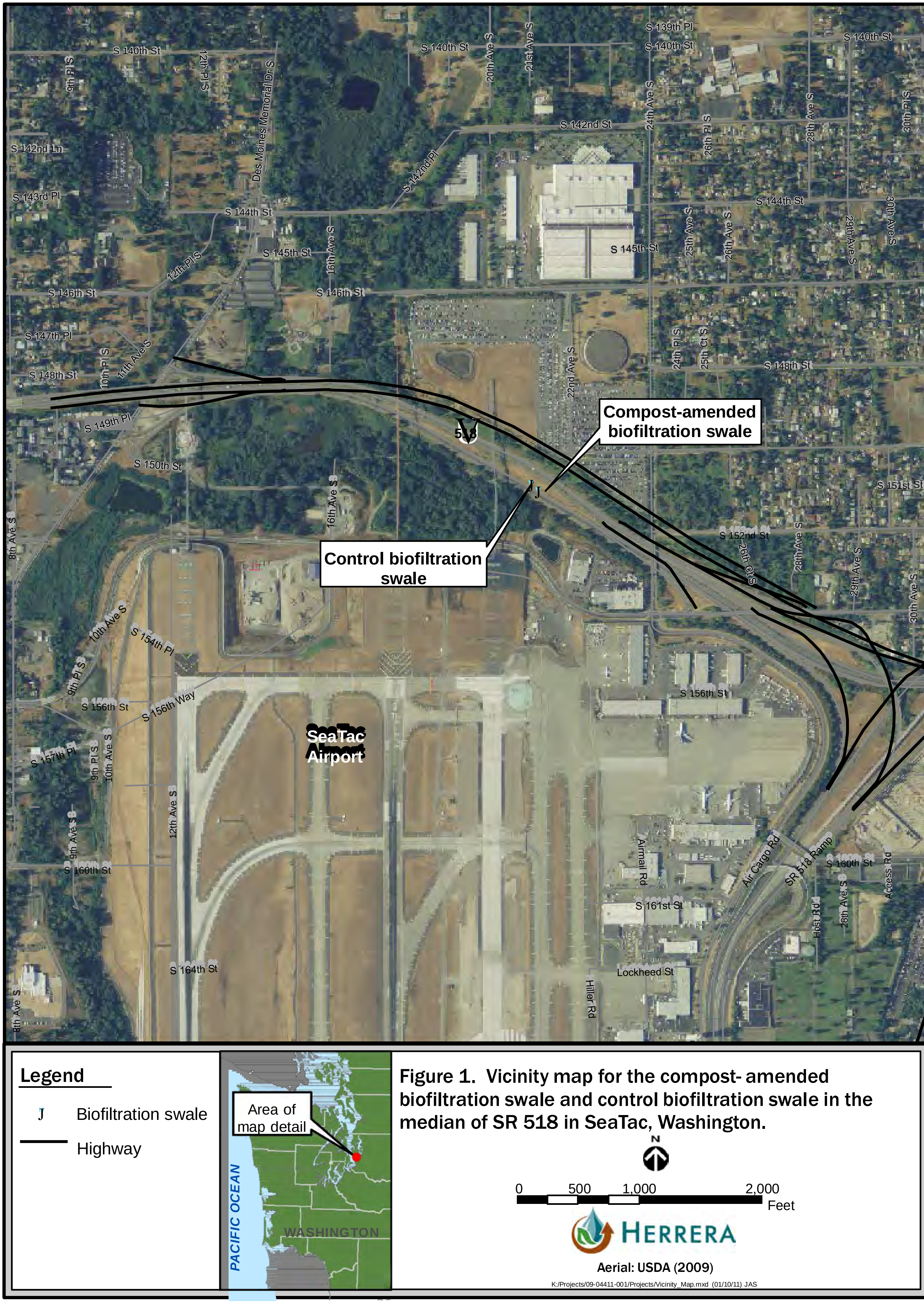

Figure 1. Vicinity map for the compost- amended biofiltration swale and control biofiltration swale in the median of SR 518 in SeaTac, Washington.

satisfactory performance of the compost-amended biofiltration swale for issuance of a GULD for basic, enhanced (dissolved metals removal) and oil treatment.

In accordance with these performance goals, monitoring data from the compost-amended biofiltration swale installation in the median of SR 518 shows that the system achieves the following:

- **Total suspended solids (TSS) removal:** 94 percent
- **Dissolved zinc removal:** 83 percent
- **Dissolved copper removal:** 25 percent (with the influent range specified in the TAPE guidelines) to 38 percent (with influent concentrations greater than or equal to 0.006 milligrams per liter [mg/L])
- T**otal petroleum hydrocarbon (TPH) removal:** 84 percent

These values represent the median removal efficiency for each parameter as calculated using Method #1 in the TAPE guidelines. It should be noted that only one of the influent TPH concentrations was higher than the 10 mg/L minimum influent concentration required by Ecology (2008). However, the TPH data is still discussed in this TER, since highway monitoring in the state of Washington has rarely measured influent TPH concentrations above the 10 mg/L influent threshold.

The data and analyses used to determine performance results are described within this TER. Pursuant to the guidelines in Ecology (2008), information is organized using the following major headings:

- Technology Description
- Sampling Procedures
- Data Summaries
- Evaluation of Performance Goals
- Conclusions

Technology Description

Currently, WSDOT has limited options for meeting end-of-pipe enhanced treatment for stormwater runoff. Constructed wetlands, the primary available stormwater technology, require a large area and ongoing maintenance, both of which are expensive in urban areas. Biofiltration swales require much less area and can easily fit in medians or right-of-way; however, they are currently approved for basic treatment, not for enhanced treatment. This project was designed to evaluate a compost-amended biofiltration swale design to remove dissolved metals from stormwater and achieve enhanced treatment. This section describes the system, treatment processes, sizing methods, and maintenance procedures.

Physical Description

The project constructed two biofiltration swales, each 100 feet long by 6.5 feet wide. The biofiltration swales were designed according to Section 5-4.1.3 (RT.04 – Biofiltration Swale) of the WSDOT *Highway Runoff Manual* (HRM) (WSDOT 2010a); this section is reproduced in Appendix M of this document. Both biofiltration swales were constructed of native soils. The compost-amended biofiltration swale received a 3-inch compost blanket and the standard (control) biofiltration swale received no compost. Both biofiltration swales were hydroseeded with a seed mix that consisted of red fescue, meadow foxtail, and white dutch clover (Table 1).

Table 1. Biofiltration swale hydroseed mix.

Kind and Variety of Seeds	Pure Live Seed (pounds per acre)
Red fescue (*Festuca rubra*)	20
Meadow foxtail (*Alopecurus pratensis*)	14
White dutch clover (*Trifolium repens*) (pre-inoculated)	6
Total	**40**

Fertilizer was also added to the hydroseed mix for the control biofiltration swale, but not the compost-amended biofiltration swale. Fertilizer was applied at a rate of 135 pounds of nitrogen (minimum of 90 pounds in a slow release form with a minimum release time of 6 months), 60 pounds of phosphorus, and 60 pounds of potassium per acre. The compost applied to the compost-amended biofiltration swale conformed to WSDOT Standard Specification 9-14.4(8) for coarse compost.

Site Requirements

The following subsections describe the site requirements, including necessary soil characteristics, hydraulic grade requirements, depth to groundwater limitations, utility requirements, landscaping (planting considerations), and construction criteria.

Necessary Soil Characteristics

Specific underlying soil characteristics are not required for biofiltration swales; however, sites containing soils with high infiltration capacity can be beneficial for flow control and water quality treatment. The SR 518 site was selected due to its low infiltration capacity soils, to ensure that sufficient flow would be present at the outlet of the system to allow a comparison of the influent and effluent water quality characteristics.

Hydraulic Grade Requirements

There are no specific hydraulic grade requirements for biofiltration swales in the WSDOT HRM (WSDOT 2010a); however, the manual does mention considering alterations in the design of a particular stormwater best management practice (BMP) if adequate hydraulic head (generally greater than 3 feet, but depends on BMP type) is not available. Further information about hydraulic requirements is available in the WSDOT *Hydraulics Manual* (WSDOT 2010b).

The recommended longitudinal slope for biofiltration swales is 1.5 to 5 percent. Biofiltration swales with longitudinal slopes less than 1.5 percent require underdrain systems, and slopes greater than 5 percent require energy dissipation. These slopes should be considered when evaluating existing site drainage to determine if sufficient hydraulic grade is present at the selected site.

Depth to Groundwater Limitations

There are no specific requirements for depth to groundwater limitations for biofiltration swales in the WSDOT HRM (WSDOT 2010a); however, the manual does mention considering alterations in the design of a particular stormwater BMP if construction will involve excavating below annual high groundwater levels. The WSDOT HRM also recommends sealing the bed or underdrain area of a biofiltration swale with either a treatment liner or a low-permeability liner if groundwater contamination is a concern at the selected site.

Utility Requirements

Biofiltration swales are designed to be passive systems, thus they do not require power and have a free-draining outfall to an appropriate water conveyance, storm drainage system, or downstream BMP.

To coordinate with existing utilities in the area where a stormwater BMP will be constructed, the WSDOT HRM recommends contacting the Region Utilities Office during the design stage to obtain information about whether existing utilities have franchises or easements within the project limits. Further information about utility elements is available in the WSDOT *Utilities Manual* (WSDOT 2010c).

Landscaping (Planting) Considerations

The following landscaping (planting) considerations are also included in the WSDOT HRM (WSDOT 2010a) for biofiltration swales:

- Consult with the Region Landscape Architect or the Headquarters Roadside and Site Development Section to determine plants for use in the biofiltration swale
- Select fine, turf-forming grasses where moisture is appropriate for growth
- If possible, perform final seeding of the swale during the seeding windows specified in WSDOT's standard specifications. Supplemental irrigation may be required depending on seeding and planting times
- Plant wet-tolerant species in the fall
- Use only sod specified by the Region Landscape Architect
- Stabilize soil areas upslope of the biofiltration swale to prevent erosion and excessive sediment deposition
- Apply seed via hydroseeder or broadcaster

Construction Criteria

The following construction criteria are also included in the WSDOT HRM (WSDOT 2010a) for biofiltration swales:

- Do not put the biofiltration swale into operation until areas of exposed soil in the contributing drainage catchment have been sufficiently stabilized
- Keep effective erosion and sediment control measures in place until the biofiltration swale vegetation is established
- Avoid over-compaction during construction
- Grade biofiltration swales to attain uniform longitudinal and lateral slopes

Treatment Processes

Many studies have shown that compost-amended soil removes metals and other pollutants from stormwater (Pitt et al.1999; Yu et al. 2001; Barrett et al. 2004; Glanville et al. 2004; Hsieh and

Davis 2005; Sun and Davis 2007). However, many of these studies were conducted on sites where stormwater infiltrated into the soil, such as bioretention ponds, biofiltration areas (i.e., rain gardens), or side slopes. The effectiveness of grass-lined swales as a BMP is highly dependent on design characteristics such as length, longitudinal slope, and the presence of check dams (Yu et al. 2001). Grass-lined swales without compost designed to convey highway runoff have shown pollutant removal efficiencies of 77 to 97 percent for TSS and 68 to 90 percent for zinc (Barrett et al. 2004). The primary mechanisms for pollutant removal in biofiltration swales are filtration by vegetation, settling of particulates, and infiltration into the subsurface zone (Yu et al. 2001).

Adding compost to the soil adds organic matter, which increases the number of adsorption sites for metals (Rushton 2001; Sun and Davis 2007), lowers the bulk density of the soil (Pouyat et al. 2002), improves the soil structure (Rushton 2001), and provides conditions conducive to healthy soil microbes (Rushton 2001). Significantly greater infiltration capacity has been measured on highway embankments where compost blankets have been applied (Glanville et al. 2004). Persyn et al. (2007) found that compost blankets increased the plant mass of planted species while controlling the establishment of weeds on highway slopes. Faucette et al. (2006) reported that soils receiving compost blankets averaged 2.7 times more vegetation cover than hydroseed treatments alone. Since plant cover, soil structure, and infiltration rates are all enhanced by compost applications, and these factors also play a key role in pollution removal from stormwater, it suggests that applying a compost blanket to swales can increase their pollution removal capabilities.

Sizing Methods

The biofiltration swales were designed according to Section 5-4.1.3 (RT.04 – Biofiltration Swale) of the WSDOT HRM (WSDOT 2010a) (Appendix M). The following subsections describe the sizing methods for western and eastern Washington.

Western Washington

Four preliminary steps and seven design steps are included in the WSDOT HRM (WSDOT 2010a). The preliminary steps (P) for western Washington biofiltration swale sizing include:

P-1 Determine the runoff treatment design flow rate (Q_{wq}).

P-2 Determine the biofiltration design flow rate (Q_{biofil}).

P-3 Establish the longitudinal slope of the proposed biofiltration swale.

P-4 Select a soil and vegetation cover suitable for the biofiltration swale.

The design steps (D) for western Washington biofiltration swale sizing include:

D-1 Select the design depth of flow.

D-2 Select a swale cross-sectional shape. Trapezoidal is preferred, however, rectangular or parabolic cross sections can be used if site-specific constraints so dictate.

D-3 Use Manning's equation and first approximations relating hydraulic radius and dimensions for the selected swale shape to obtain a value for the width of the biofiltration swale.

D-4 Compute wetted area (A) at Q_{biofil}.

D-5 Compute the flow velocity at Q_{biofil}.

D-6 Compute the swale length (L).

D-7 If there is not sufficient space for the biofiltration swale, consider modifying the design summarized in the WSDOT HRM.

Eastern Washington

The sizing procedure listed for western Washington can also be used in eastern Washington, with a different coefficient (k) value used for step P-2. Alternatively, the following biofiltration swale sizing procedure can also be used in eastern Washington. The preliminary steps (P) for this alternative method include:

P-1 Determine the runoff treatment design flow rate (Q_{wq}); this is also the biofiltration design flow rate (Q_{biofil}).

P-2 Determine the slope of the biofiltration swale.

P-3 Select a swale shape. Trapezoidal is the most desirable shape; however, rectangular and triangular shapes can be used. The remainder of the design process assumes that a trapezoidal shape has been selected.

P-4 Use Manning's equation to estimate the bottom width of the biofiltration swale.

P-5 Calculate the cross-sectional area of flow for the given channel using the calculated bottom width and the selected side slopes and depth.

P-6 Calculate the velocity of flow in the channel.

P-7 Select a location where a biofiltration swale with the calculated width and a length of 200 feet will fit. If a length of 200 feet is not possible, the width of the biofiltration swale must be increased so that the area of the biofiltration swale is the same as if a 200-foot length had been used.

P-8 Select a vegetation cover suitable for the site.

P-9 Using Manning's equation, find the depth of flow.

The design steps (D) for the alternative eastern Washington biofiltration swale sizing procedure include:

D-1 Though the actual dimensions for a specific site may vary, the swale should generally have a length of 200 feet. The maximum bottom width is typically 10 feet. The depth of flow should not exceed 4 inches during the design storm. The flow velocity should not exceed 1 foot per second.

D-2 The channel slope should be at least 1 percent and no greater than 5 percent.

D-3 The swale can be sized as a treatment facility for Q_{biofil}.

D-4 The ideal cross section of the swale should be a trapezoid. The side slopes should be no steeper than 3H:1V.

D-5 Roadside ditches should be regarded as significant potential biofiltration sites and should be utilized for this purpose whenever possible.

D-6 If flow is to be introduced through curb cuts, place pavement slightly above the biofiltration swale elevation. Curb cuts should be at least 12 inches wide to prevent clogging.

D-7 Biofiltration swales must be vegetated to provide adequate treatment of runoff.

D-8 Maximize water contact with vegetation and the soil surface by selecting fine, close-growing grasses (or other vegetation) that can withstand prolonged periods of wetting and prolonged dry periods (to minimize the need for irrigation).

D-9 Biofiltration swales should generally not receive construction-stage runoff. If they do, presettling of sediments should be provided.

D-10 If possible, divert runoff (other than necessary irrigation) during the period of vegetation establishment. Where runoff diversion is not possible, protect graded and seeded areas with suitable erosion control measures.

Maintenance Procedures

Maintenance procedures for biofiltration swales are outlined in Section 5-5 of the WSDOT HRM (WSDOT 2010a) which is reproduced in Appendix M of this report; these maintenance procedures are also summarized in Table 2.

Table 2. Maintenance procedures for biofiltration swales.

Defect or Problem	Condition when Maintenance is Needed	Recommended Maintenance to Correct Problem
Sediment accumulation on grass	Sediment depth exceeds 2 inches.	Remove sediment deposits on grass treatment area of the swale. When finished, swale should be level from side to side and drain freely toward outlet. There should be no areas of standing water once inflow has ceased.
Standing water	Water stands in the swale between storms and does not drain freely.	Any of the following may apply: remove sediment or trash blockages; improve grade from head to foot of swale; remove clogged check dams; add underdrains; or convert to a wet biofiltration swale.
Flow spreader	Flow spreader is uneven or clogged so that flows are not uniformly distributed through entire swale width.	Level the spreader and clean so that flows are spread evenly over entire swale width.
Constant base flow	Small quantities of water continually flow through the swale, even when it has been dry for weeks, and an eroded, muddy channel has formed in the swale bottom.	Add a low-flow pea gravel drain the length of the swale, or bypass the base flow around the swale.
Poor vegetation coverage	Grass is sparse or bare, or eroded patches occur in more than 10% of the swale bottom.	Determine why grass growth is poor and correct that condition. Replant with plugs of grass from the upper slope: plant in the swale bottom at 8-inch intervals; or reseed into loosened, fertile soil.
Vegetation	Grass becomes excessively tall (greater than 10 inches); nuisance weeds and other vegetation start to take over.	Mow vegetation or remove nuisance vegetation so that flow is not impeded. Grass should be mowed to a height of 6 inches. Fall harvesting of very dense vegetation after plant die-back is recommended.
Excessive shading	Grass growth is poor because sunlight does not reach swale.	If possible, trim back overhanging limbs and remove brushy vegetation on adjacent slopes.
Inlet/outlet	Inlet/outlet areas are clogged with sediment/debris.	Remove material so there is no clogging or blockage in the inlet and outlet area.
Trash and debris	Trash and debris have accumulated in the swale.	Remove trash and debris from biofiltration swale.
Erosion/scouring	Swale bottom has eroded or scoured due to flow channelization or high flows.	For ruts or bare areas less than 12 inches wide, repair the damaged area by filling with crushed gravel. If bare areas are large, the swale should be regraded and reseeded. For smaller bare areas, overseed when bare spots are evident, or take plugs of grass from the upper slope and plant in the swale bottom at 8-inch intervals.

Sampling Procedures

This section provides an overview of the monitoring design and describes performance goals Ecology has established for the types of treatment that are being sought under the GULD. Additional sections describe the site location, test system, monitoring schedule, and the procedures used to obtain the hydrologic and water quality data. Analytical methods, quality assurance and control measures, data management procedures, and data analysis procedures are also discussed.

Monitoring Design Overview

Two biofiltration swales (compost-amended and control) were installed in the median of SR 518 (Figure 1) to facilitate performance monitoring pursuant to the TAPE procedures. Automated monitoring equipment was installed to characterize influent and effluent flow volumes over a 19-month period, from March 2009 through September 2010. Automated samplers were employed to collect flow-weighted composite samples of the influent and effluent during discrete storm events for subsequent water quality analyses.

Water quality sampling for this project lasted 13 months, from May 2009 through June 2010. Based on the resulting monitoring data, removal efficiency estimates were computed for targeted monitoring parameters. These removal efficiency estimates were then compared to TAPE performance goals to support issuance of a GULD for the compost-amended biofiltration swale. These performance goals are described below for the three types of treatment that are under consideration for inclusion in the GULD:

- **Basic Treatment** – 80 percent removal of TSS for influent concentrations that are greater than 100 mg/L but less than 200 mg/L. For influent concentrations greater than 200 mg/L, a higher treatment goal may be appropriate. For influent concentrations less than 100 mg/L, the facilities are intended to achieve an effluent goal of 20 mg/L TSS.

- **Enhanced Treatment** – Provide a higher rate of removal of dissolved metals than most basic treatment facilities. The performance goal assumes that the facility is treating stormwater with influent dissolved copper concentrations typically ranging from 0.003 to 0.02 mg/L, and influent dissolved zinc concentrations ranging from 0.02 to 0.3 mg/L. Data collected for an "enhanced" BMP should demonstrate significantly higher removal rates than most basic treatment facilities.

- **Oil Treatment** – No ongoing or recurring visible sheen, a daily average total petroleum hydrocarbon concentration no greater than 10 mg/L, and a maximum of 15 mg/L for a discrete (grab) sample.

Site Location

Two biofiltration swales were installed in WSDOT right-of-way in the median of SR 518 in SeaTac, Washington in September and October 2008. General characteristics of each biofiltration swale are summarized in Table 3. Installation reports and photographs from each monitoring station can be found in Appendix A.

Table 3. General characteristics of the compost-amended and control biofiltration swales.

	Location	Length (ft)	Width (ft)	Basin Area (sf)	Percent Impervious	Longitudinal Slope [a] (percent)
Compost-amended biofiltration swale (CAB)	MP 1.21	100	6.5	5,600	100	1.5
Control biofiltration swale (CON)	MP 1.21	100	6.5	5,600	100	1.5

[a] Slope of biofiltration swale running parallel to the highway.
ft: feet
sf: square feet
MP: milepost

Test System Description

The basis of design for each biofiltration swale is provided below. Note that biofiltration swales are flow-through systems, and do not contain a bypass. Separate subsections also describe construction costs for the SR 518 biofiltration swales and maintenance.

Compost-Amended Biofiltration Swale

The compost-amended biofiltration swale was sized to provide water quality treatment for 91 percent of the average annual runoff volume. Modeling was performed using MGSFlood to determine the water quality flow rate required to provide this level of treatment, based on local precipitation patterns. MGSFlood is a continuous hydrologic model that simulates rainfall runoff based on drainage basin land uses and soil types. Based on the water quality flow rate obtained from the model (0.02 cfs), a WSDOT sizing spreadsheet was used to calculate the required length, width, and longitudinal slope of the biofiltration swale. Since the water quality design flow rate from MGSFlood resulted in a length that was less than the typical biofiltration swale requirement, the water quality flow rate was increased to 0.03 cfs to result in a more typical swale length (99.3 feet), width (6 feet), and longitudinal slope (1.5 percent) (Appendix N). Based on the available space at the SR 518 site, a compost-amended biofiltration swale that was 100 feet long and 6.5 feet wide was constructed, providing slightly more water quality treatment than required. A cross section of the compost-amended biofiltration swale installed at the SR 518 monitoring site is provided in Figure 2.

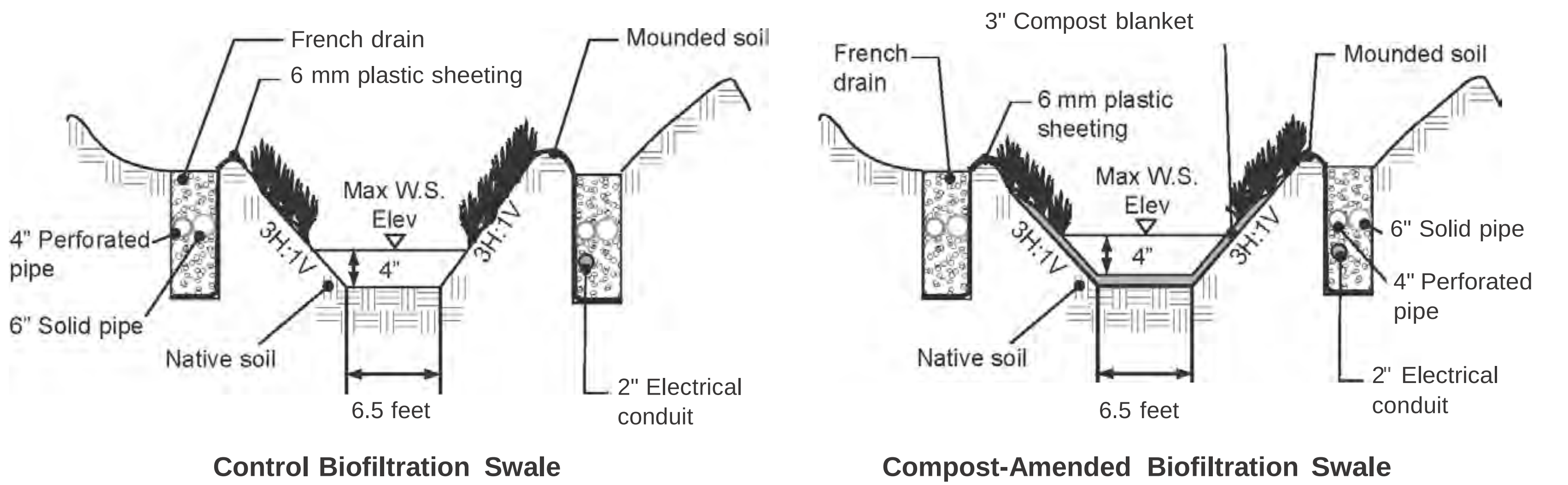

Figure 2. Cross-sectional view of the control and compost-amended biofiltration swales.

Control Biofiltration Swale

The control biofiltration swale has the same drainage basin area as the compost-amended biofiltration swale, thus it was determined to have the same dimensions as the compost-amended biofiltration swale (100 feet long by 6.5 feet wide), based on the MGSFlood model run and the WSDOT sizing spreadsheet. A cross section of the control biofiltration swale installed at the SR 518 monitoring site is provided in Figure 2.

Construction Costs

The installation of both biofiltration swales cost approximately $30,000; however, this cost also included the concrete pads, the piping, and electrical work that were installed to facilitate monitoring; these components would not be required for a conventional biofiltration swale installation. Without these additional components, the cost for a 100-foot long compost-amended biofiltration swale would be approximately $2,800 (approximately $4.30 per square foot) compared to a 100-foot long standard biofiltration swale at approximately $2,500 (approximately $3.80 per square foot). The costs for the SR 518 site included:

- Layout
- Removing asphalt lined ditch
- Reshaping ditch
- Earthwork (a small excavator with a blade was used and cut and fill were balanced)
- Fine grading (small hand tool work)
- Compost blanket (compost-amended biofiltration swale only)
- Inlet pipe (trenching, curb cuts and concrete work at inlet, pipe costs, pipe placement and cover, and splash protection at pipe outlet)
- Hydroseeding (including seed, fertilizer [for the control biofiltration swale only], and mulch)

No outlet catch basin or piping was installed since there was already a catch basin located downstream of the biofiltration swales.

Maintenance

None of the maintenance activities identified in Table 2 were performed during the monitoring period at the control or the compost-amended biofiltration swale. In general, operation and maintenance costs would typically be minimal since the primary maintenance consists of mowing the biofiltration swales once a year. WSDOT estimates indicate that mowing costs are typically between $180 and $300 for an acre. Taking the higher estimate of the cost range, it would only cost $9 to mow the biofiltration swale if maintenance was performed while the adjacent roadside was being mowed. However, if the biofiltration swale mowing and trash pickup occurred independently of the roadside mowing schedule, it would cost approximately $260 for an hour of work (including two WSDOT staff, travel time, loading and unloading equipment, mowing, and trash pickup).

It should be noted that the procedures in Table 2 do not present any specific maintenance requirements for compost-amendment in biofiltration swales. Due to the short duration of this study, the long-term pollutant removal performance of the compost amendment biofiltration swale and related maintenance implications could not be assessed. However, WSDOT will be monitoring the compost-amended biofiltration swale over the next 3 years to obtain additional data for determining these maintenance requirements. In general, there are few studies that have focused specifically on the long-term pollutant removal of compost amendment biofiltration swale; however, there have been more detailed studies of bioretention systems. For example, Davis (2003) studied the removal of total copper, lead, and zinc from stormwater flowing through a 5-year old bioretention system in Greensboro, North Carolina and found removal rates of 95, 97, and 97 percent, respectively. The influent concentrations were on average very high and the effluent concentrations very close to or at the reporting limit. Specifically, influent concentrations of total copper, lead, and zinc averaged 66, 42, and 530 micrograms per liter (μg/L), respectively; while effluent concentrations averaged 2, <2, and <25 μg/L, respectively. If the influent concentrations from the study period are indicative of influent concentrations prior to study, then it appears that the system received a high loading of metals for the 4 years prior to study and still performed well in the fifth year.

Monitoring Schedule

Hydrologic monitoring was conducted at the SR 518 site over a 19-month period from March 2009 through September 2010. Water quality monitoring occurred over a 13-month period from May 2009 through June 2010. During this monitoring period, a total of 23 separate storm events were sampled, resulting in a total of 15 grab samples and 16 composite samples from each swale (15 of which were paired events at both biofiltration swales).

Hydrologic Monitoring Procedures

A generalized schematic of the equipment layout at the site is provided in Figure 3. Equipment installation was completed in January 2009. Continuous hydrologic monitoring was performed at four monitoring stations: CAB In, CAB Out, CON In, and CON Out. Three crest gauges were installed in each biofiltration swale to monitor the distance stormwater had traveled if it infiltrated into the ground before reaching the effluent monitoring station; however, these crest

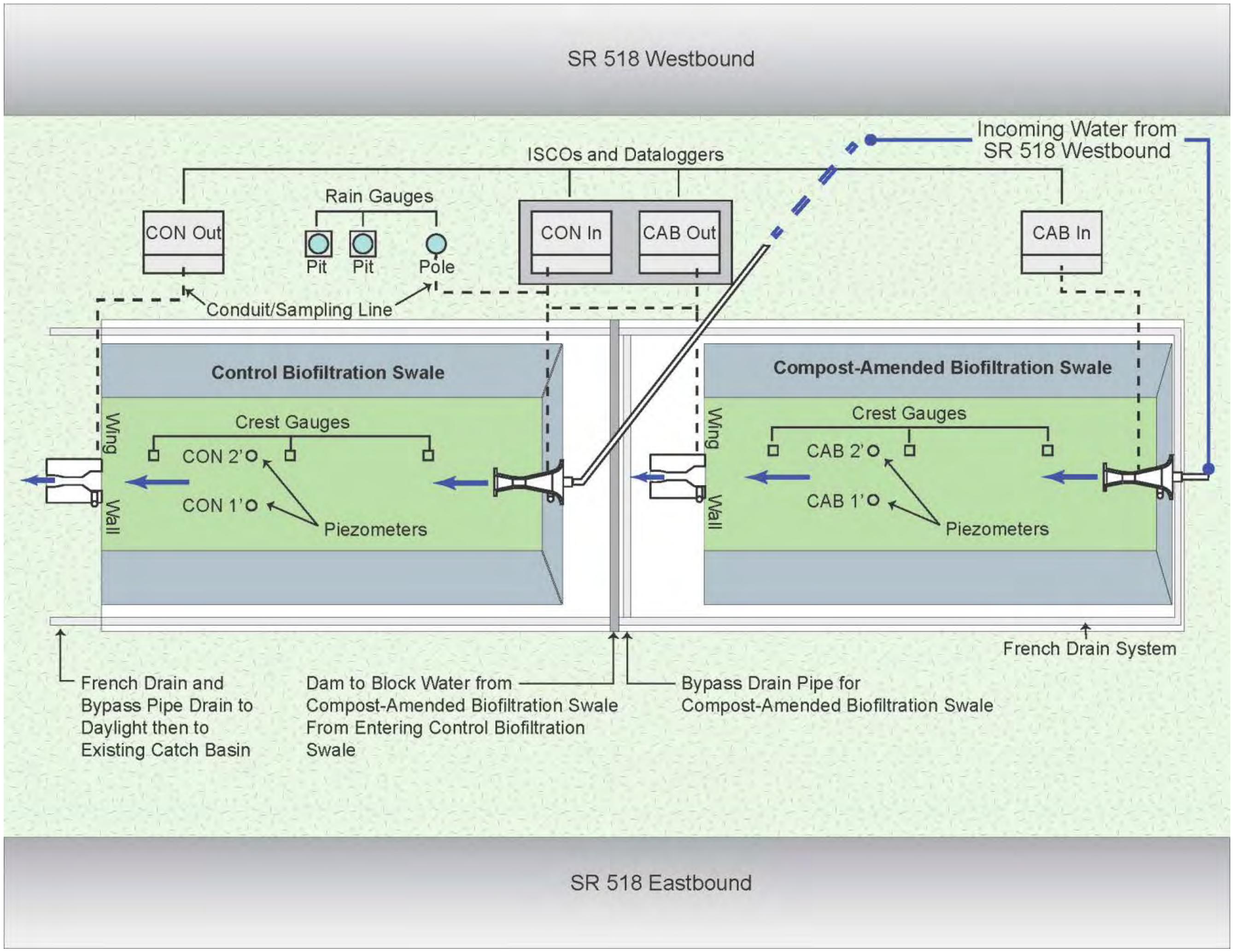

Figure 3. Site schematic for the compost-amended and control biofiltration swales.

gauges were not monitored frequently after it was determined that minimal infiltration occurred and stormwater reached the effluent monitoring station during a majority of the monitored storm events.

Two piezometers were also installed in each biofiltration swale at 1-foot and 2-foot depths to monitor pollutant concentrations passing into the groundwater beneath the biofiltration swales. The influent, effluent, and precipitation monitoring at both biofiltration swales are discussed below, including a summary of equipment maintenance procedures. These monitoring procedures are also described in greater detail in the QAPP that was prepared for this study (WSDOT 2008).

Influent Monitoring

Stormwater runoff from the westbound lanes of SR 518 was captured at curb cuts and piped via gravity to the inlet of each biofiltration swale (CAB In and CON In). To facilitate continuous flow monitoring, a 1-inch Parshall flume was installed at each influent station to derive accurate estimates of discharge from the water level measurements (Figure 3). Automated flow monitoring equipment (i.e., stilling wells, Druck 1830 pressure transducers, and CR1000 Campbell Scientific dataloggers) was installed at each station to continuously record water levels at 5-minute intervals. These measurements were converted to estimates of discharge using standard hydraulic equations. Power for all the equipment was provided using rechargeable batteries connected to the highway lighting system. The batteries were recharged every night when the lighting system was operational.

Effluent Monitoring

To facilitate continuous flow monitoring at the effluent monitoring stations (CAB Out and CON Out), a 60-degree trapezoidal flume was installed to monitor flow (Figure 3). Automated flow monitoring equipment (i.e., stilling wells, Druck 1830 pressure transducers, and CR1000 Campbell Scientific data loggers) was installed at each station to continuously record water levels at 5-minute intervals. These measurements were converted to estimates of discharge using standard hydraulic equations. Power for all the equipment was maintained using rechargeable batteries connected to the highway lighting system. The batteries were recharged every night when the lighting system was operational.

Precipitation Monitoring

Precipitation was measured near the outlet of the compost-amended biofiltration swale and the inlet of the control biofiltration swale using an ISCO 674 Rain Gauge installed on a pole. This rain gauge was programmed to continuously measure precipitation totals at 5-minute intervals, and was integrated with the automated monitoring equipment described in the previous sections. The resulting data was used to determine if rainfall totals measured during sampled storm events met minimum thresholds identified in the TAPE guidelines for acceptance. These data were also used to facilitate interpretation of the flow monitoring data obtained from the stations described above.

Two additional rain gauges were installed at ground level in pits. Calibration and data management from these rain gauges was performed by WSDOT. Accumulated water from both pit gauges were collected to check the overall accuracy of the rain gauges.

Monitoring Equipment Maintenance

After each storm event, flow and precipitation data was uploaded remotely using telemetry systems (i.e., Raven cell link modem) that were integrated with the automated monitoring equipment. Automated field data was stored and managed using LoggerNet and Aquarius software programs. Information obtained from this system was used to determine when field personnel should be mobilized to collect grab samples for water quality and pick up flow-weighted composite samples after a storm event.

Site visits were performed at least every month, or as necessary to address operational problems and perform routine maintenance on the automated monitoring equipment, rain gauges, and flow monitoring equipment. Maintenance procedures and frequencies are summarized in Table 4. Instrument maintenance and calibration activities were documented on standardized field forms (Appendix B). Rain gauge and level calibration data can be found in the hydrologic data quality assurance memorandum in Appendix C.

Table 4. Equipment maintenance schedule for the SR 518 biofiltration swale evaluation.

Equipment	Item	Procedure	Frequency
Batteries	Voltage	Check voltage using volt meter or recorded values from the data logger	Every visit
	Charger	Check connections to wall charger	Every visit
Rain gauge	Level check	Verify level with bubble indicator	Monthly
Automated samplers	Sample tubing	Check integrity; verify no obstructions at opening	Every visit
	Debris	Remove any debris that may be blocking the flumes	Every visit
	Humidity indicator	Check surface indicator	Every visit
Campbell Scientific data logger	Desiccant	Check humidity indicator – when pink, exchange desiccant	Every visit
Pressure transducers	Level calibration	Manually measure water level and recalibrate	Monthly
	Desiccant	Check desiccant – when color changes from orange to gray, exchange desiccant	Every visit

Water Quality Monitoring Procedures

To evaluate the water quality treatment performance of the compost-amended and control biofiltration swales, sampling was conducted at the associated influent and effluent stations. To facilitate sampling, each station was equipped with automated sampling equipment (i.e., ISCO 6712 Full Size Portable Samplers) interfaced with the flow monitoring equipment (described in the Hydrologic Monitoring Procedures section). These monitoring procedures are described in greater detail in the in the QAPP that was prepared for this study (WSDOT 2008).

The sampler intakes for the influent stations were suspended in an inlet box mounted at the entrance to each influent flume. At the effluent stations, the sampler intakes were positioned on the upstream side of the effluent flume inlet. In each case, the sampler intakes were positioned to ensure the homogeneity and representativeness of the collected samples. Specifically, sampler intakes were installed to make sure adequate depth was available for sampling and to avoid capture of litter, debris, and other gross solids that might be present at the base of the channel. The sampler suction lines consisted of 3/8-inch inner diameter Teflon-lined tubing.

The following conditions served as guidelines in defining the acceptability of specific storm events for sampling:

- **Target storm depth:** A minimum of 0.15 inches of precipitation over a 24-hour period
- **Antecedent conditions:** A period of at least 6 hours preceding the event with less than 0.04 inches of precipitation
- **End of storm:** A continuous 6-hour period with no measurable rainfall

Antecedent conditions and storm predictions were monitored via the Internet, and a determination was made as to whether to target an approaching storm. Once a storm was targeted, field staff visited each station to verify that the equipment was operational and to start the sampling program. A clean polyethylene carboy and crushed ice were also placed in the sampling equipment at this time. The speed and intensity of incoming storm events were tracked using Internet-accessible Doppler radar images. Actual rainfall totals during sampled storm events were quantified on the basis of data from the rain gauge installed at the site.

During the storm event sampling, each automated sampler was programmed to enable in response to a predefined increase in flow at the respective station. The automated samplers were then programmed to collect 150-milliliter sample aliquots at preset flow increments. The particular flow increments varied by station and the expected storm magnitude. The typical programming scheme for the automated samplers at each station is provided in Table 5. Based on the expected size of the storm, the flow increment was adjusted to ensure that the following criteria for acceptable composite samples were met at each station:

- A minimum of 10 aliquots was considered optimal; however, a total of 18 aliquots was required to meet the sample volume requirements to analyze all of the targeted parameters.
- For storm events lasting less than 24 hours, sampling was targeted to capture at least 75 percent of the storm event hydrograph. For storm

events lasting longer than 24 hours, sampling was targeted to capture at least 75 percent of the hydrograph of the first 24 hours of the storm.

- Due to sample holding time considerations, the maximum duration of automated sample collection at all stations was 36 hours. **Note:** The maximum duration of automated sample collection specified in the QAPP was 48 hours (WSDOT 2008).

Table 5. Programming parameters for the SR 518 biofiltration swales.

Parameter	Input Value
Data interval	5 minutes
Number of sample bottles	1
Sample bottle size	9.4 liters
One part program	NA
Once enabled, stay enabled	NA
Pauses and resumes	0
Number of samples at start	NA
Run continuously?	No
Sample at beginning?	No
Sample at enable?	No
Number of samples	60 samples/bottle
Sample volume	150 mL (60 samples x 150 mL = 9 liters)
Rinse Cycles	3
Enable	Flow
Units	Length = feet; volume = cf; flow = cfs

cf = cubic feet mL = milliliters
cfs = cubic feet per second NA = not applicable

After each targeted storm event, field personnel returned to each station, made visual and operational checks of the sampling equipment, and determined the total number of aliquots composited. Pursuant to the sampling goals identified above, the minimum number of composites that constituted an acceptable sample was 10; this yielded a total sample volume of 1.5 liters. (A minimum sample volume of 2.7 liters was required to perform all the targeted analytes in this study with the associated laboratory quality control requirements.) If the sample was determined to be acceptable, the carboy was immediately capped, removed from the automated sampler, and kept at 4 degrees Celsius using ice during transport to the laboratory. All samples were delivered to the laboratory with appropriate chain-of-custody documentation. Collected flow-weighted composite samples were then analyzed for the following parameters:

- Total suspended solids (TSS)
- Copper, total and dissolved
- Zinc, total and dissolved
- Total phosphorus (TP)

- Soluble reactive phosphorus (SRP)
- Hardness
- pH
- Particle size distribution (PSD)
- Total Kjeldahl nitrogen (TKN)
- Nitrate + Nitrite nitrogen

In addition to the flow-weighted composite samples described above, samples for total petroleum hydrocarbons (TPH) analysis were collected as grab samples from each station during storm events. Once collected, the TPH samples were kept at 4 degrees Celsius in a cooler and transported to the laboratory.

Analytical Methods

Analytical methods for this project are summarized in Table 6. Aquatic Research, Inc. in Seattle, Washington was the primary laboratory used for this project. This laboratory is certified by Ecology and participates in audits and inter-laboratory studies by Ecology and EPA. These performance and system audits have verified the adequacy of the laboratory’s standard operating procedures, which include preventive maintenance and data reduction procedures. Analytical Resources, Inc. in Tukwila, Washington was used for PSD analysis. Both laboratories provided sample and quality control data in standardized reports suitable for evaluating project data. The laboratory reports also included a case narrative summarizing any problems encountered in the analyses.

Quality Assurance and Control Measures

Field and laboratory quality control procedures used for the compost-amended biofiltration swale evaluation are discussed in the following sections. Quality assurance memorandums discussing hydrologic and water quality data can be found in Appendices C and D, respectively.

Field Quality Assurance/Quality Control

This section summarizes the quality assurance/quality control (QA/QC) procedures that were implemented by field personnel to evaluate sample contamination and sampling precision.

Field Blanks

Automated samplers were cleaned using the rinse and purge-pump-purge cycle. Field blanks were collected on May 4, 2009 prior to the first sampled storm event at both monitoring locations. A second set of field blanks was collected on October 28, 2009 after a few storm events had been sampled and the duplicate automated sampler was set up. One additional set of field blanks was collected towards the end of the monitoring season (May 7, 2010). The

Table 6. Methods and detection limits for water quality analyses for the compost-amended biofiltration swale evaluation.

Analyte	Analytical Method	Method Number [a]	Holding Time [b]	Preservation	Reporting Limit/Resolution	Units
Hardness	Persulfate	SM 2340C	28 days	Cool, 4°C; H_2SO_4 to pH<2	2.0	mg/L
Total suspended solids	Gravimetric, 103°C	SM 2540D	7 days	Cool, 4°C	0.50	mg/L
Total phosphorus	Automated ascorbic acid	EPA 365.1	28 days	Cool, 4°C; H_2SO_4 to pH<2	0.002	mg/L
Soluble reactive phosphorus	Automated ascorbic acid	EPA 365.1	Filter - 12 hours; Analyze - 48 hours	Cool, 4°C; filtration, 0.45 µm	0.001	mg/L
Total Kjeldahl nitrogen	Colorimetric	EPA 351.1	28 days	Cool, 4°C; H_2SO_4 to pH <2	0.200	mg/L
Nitrate + nitrite nitrogen	Automated cadmium reduction	SM 4500 NO_3-F	2 days	Cool, 4°C; H_2SO_4 to pH<2	0.010	mg/L
Copper, dissolved	GFAA	EPA 200.8	6 months[c]	Cool, 4°C; filtration, 0.45 µm; HNO_3 to pH<2	0.0010	mg/L
Copper, total			6 months	Cool, 4°C; HNO_3 to pH<2		
Zinc, dissolved	ICP	EPA 200.8	6 months[c]	Cool, 4°C; filtration, 0.45 µm; HNO_3 to pH<2	0.0050	mg/L
Zinc, total			6 months	Cool, 4°C; HNO_3 to pH<2		
pH	Potentiometric	SM 4500-H+	24 hours	Cool, 4°C	0.10	std. units
TPH (diesel)	GC/FID	NWTPH-Dx [d]	Extract – 14 days; Analyze – 40 days	Cool, 4°C; HCL to pH<2	0.05	mg/L
TPH (motor oil)					0.10	mg/L
Particle size distribution	TAPE Method	NA	7 days	Cool, 4°C	1	micron

[a] SM method numbers are from APHA et al. (1992); EPA method numbers are from U.S. EPA (1983, 1984). The 18th edition of *Standard Methods for the Examination of Water and Wastewater* (APHA et al. 1992) is the current legally adopted version in the *Code of Federal Regulations*.

[b] Holding time specified in EPA guidance or referenced in Standard Methods for equivalent method.

[c] Sample filtration or preservation will occur within 24 hours of sample collection.

[d] Ecology (1997) method includes silica gel extract cleanup step.

GFAA = graphite furnace atomic absorption
ICP/AES = inductively coupled plasma/atomic emission spectrometry
ICP/MS = inductively coupled plasma/mass spectrometry
GC/FID = gas chromatography/flame ionization detection
NA = not applicable
mg/L = milligrams per liter
std. units = standard units
C = Celsius

field blanks were collected by pumping reagent-grade water through the intake tubing into a pre-cleaned sample container. The volume of reagent grade water pumped through the sampler for the field blank was similar to the volume of water collected during a typical storm event.

Field Duplicate Samples

Field duplicates were collected for 10 percent of the samples. The station where the field duplicates were collected was chosen at random in advance of the storm event. To collect the field duplicates, a separate automated sampler (i.e., ISCO 6712 Full Size Portable Sampler) with a 9.4-liter bottle was set up at the selected monitoring station with a separate set of sample tubing. The automated sampler was wired to the Campbell Scientific datalogger and each time the flow trigger occurred, both samplers would draw a stormwater sample at the same time. Sample tubing was staggered, so the two pumps would not affect sample volume if sufficient flow was present. The resultant data from these samples was used to assess variation in the analytical results that is attributable to environmental (natural) and analytical variability.

Flow Measurements

The accuracy and precision of the automated flow measurement equipment were tested prior to the first monitoring round and periodically throughout the project. Level calibration data can be found in the hydrologic data quality assurance memorandum in Appendix C.

Laboratory Quality Control

Accuracy of the laboratory analyses was verified through the use of blank analyses, duplicate analyses, laboratory control spikes, and matrix spikes in accordance with the analytical methods employed. Aquatic Research, Inc. and Analytical Resources, Inc. were responsible for conducting internal quality control and quality assurance measures in accordance with their own quality assurance plans.

Water quality results were first reviewed at the laboratory for errors or omissions and to verify compliance with acceptance criteria. The laboratories also validated the results by examining the completeness of the data package to determine whether method procedures and laboratory quality assurance procedures were followed. The review, verification, and validation by the laboratory were documented in a case narrative that accompanied the analytical results.

Data were also reviewed and validated by Herrera within 7 days of receiving the results from the laboratory. This review was performed to ensure that all data were consistent, correct, and complete, and that all required quality control information was provided. Specific quality control elements for the data were also examined to determine if the method quality objectives (MQOs) for the project were met. Results from these data validation reviews were summarized in quality assurance worksheets were prepared for each sample batch. Values associated with minor quality control problems were considered estimates and assigned *J* qualifiers. Values associated with major quality control problems were rejected and qualified with an *R*. Estimated values were used for evaluation purposes, but rejected values were not used.

Data Management Procedures

Flow and precipitation data was uploaded after each storm event remotely using telemetry systems (i.e., Raven cell link modem) and transferred to a database (LoggerNet and Aquarius software) for all subsequent data management tasks.

Aquatic Research, Inc. and Analytical Resources, Inc. reported the analytical results within 30 days of receipt of the samples. The laboratories provided sample and quality control data in standardized reports suitable for evaluating project data. These reports included all quality control results associated with the data, a case narrative summarizing any problems encountered in the analyses, corrective actions taken, any changes to the referenced method, and an explanation of data qualifiers.

Laboratory data was subsequently entered into a Microsoft Access database for all subsequent data management and archiving tasks. An independent review was performed to ensure that the data were entered without error. Specifically, all of the sample values in the database were cross-checked to confirm they were consistent with the laboratory reports.

Data Analysis Procedures

Analysis procedures that were used for the hydrologic and water quality data are summarized below.

Hydrologic Data

The compiled hydrologic data were analyzed to obtain the following information for each sampled and unsampled storm during the monitoring study:

- Precipitation depth
- Average precipitation intensity
- Peak precipitation intensity
- Antecedent dry period
- Precipitation duration
- Influent flow duration
- Effluent flow duration
- Influent peak discharge rate
- Effluent peak discharge rate
- Influent discharge volume
- Effluent discharge volume

This information was subsequently used to assess the differences between the compost-amended and control biofiltration swales. In addition, a subset of this information was examined in conjunction with sample collection data to determine if individual storm events met the TAPE guidelines for valid storm events.

Differences in discharge volume, flow duration, and peak discharge rates between the influent and effluent and between biofiltration swales were evaluated using a Wilcoxon signed-rank test (Helsel and Hirsh 2002). The Wilcoxon signed-rank test is a nonparametric analogue to the paired *t*-test. The Wilcoxon signed-rank test was required because the paired differences of the data generally exhibited an asymmetrical distribution as opposed to a normal or symmetrical distribution. One-tailed Wilcoxon signed-rank tests were used to evaluate the following:

- Specific hypothesis that discharge volumes, flow durations, and peak discharge rates were significantly lower in the effluent than in the influent
- Specific hypothesis that discharge volumes, flow durations, and peak discharge rates in the compost-amended biofiltration swale were significantly lower than the control biofiltration swale

In all cases, the statistical significance of these tests was evaluated at an alpha level (α) of 0.05.

Water Quality Data

Data analysis procedures are described in separate subsections below for the following seven water quality related study objectives:

1. Computation of pollutant removal efficiencies
2. Statistical comparisons of influent and effluent concentrations
3. Statistical comparisons of effluent concentrations and removal efficiencies between the compost-amended and control biofiltration swales
4. Calculation of bootstrap confidence intervals to determine if the percent removal and concentration goals had been met
5. Correlation analysis to examine the influence of storm characteristics
6. Statistical comparisons of removal rates for the compost-amended biofiltration swale relative to basic treatment facilities
7. Pollutant removal as a function of flow rate

Computation of Removal Efficiencies

Pursuant to guidance from Ecology (2008), pollutant removal efficiencies for individual storm events were calculated as the reduction (in percent) in pollutant concentration during each individual storm (ΔC):

$$\Delta C = 100 \times \frac{(C_{in} - C_{eff})}{C_{in}}$$

where:

C_{in} = influent pollutant concentration

C_{eff} = effluent pollutant concentration

Statistical Comparisons of Influent and Effluent Concentrations

Pollutant concentrations were compared for paired influent and effluent across all storm events using a Wilcoxon signed-rank test (Helsel and Hirsh 2002). Through the use of a paired test, differences in the influent and effluent concentrations could be more efficiently assessed, because the noise (or variance) associated with monitoring over a range of storm sizes can be factored out of the statistical analyses. One- or two-tailed Wilcoxon signed-rank tests were employed for specific sampling parameters, depending on the following criteria:

- A one-tailed test was used to evaluate the specific hypothesis that effluent pollutant concentrations were significantly lower than those in the influent. This test was used to evaluate data for pollutants that should potentially be removed by the compost-amended biofiltration swale (e.g., TSS, zinc, and copper); however, tests were run on data from both biofiltration swales.

- A two-tailed test was used to evaluate the specific hypothesis that effluent pollutant concentrations were significantly different than those in the influent, regardless of whether they were higher or lower. This test was used to evaluate data for pollutants that generally should not be affected by the compost-amended biofiltration swale (e.g., hardness, pH); however, tests were run on data from both biofiltration swales.

In all cases, the statistical significance of these tests was evaluated at an alpha level (α) of 0.05.

Statistical Comparisons of Effluent Concentrations and Removal Efficiencies Between the Compost-Amended and Control Biofiltration Swales

Effluent pollutant concentrations and removal efficiencies were compared for paired compost-amended and control biofiltration swale samples using a Wilcoxon signed-rank test (Helsel and Hirsh 2002). One- or two-tailed Wilcoxon signed-rank tests were employed for specific sampling parameters, depending on the following criteria:

- A one-tailed test was used to evaluate data for pollutants that should have lower effluent concentrations and higher removal efficiencies in the compost-amended biofiltration swale compared to the control biofiltration swale (e.g., TSS, zinc, and copper).

- A two-tailed test was used to evaluate data for pollutants that generally should not be affected by differences between the compost-amended and control biofiltration swales (e.g., hardness, pH).

In all cases, the statistical significance of these tests was evaluated at an alpha level (α) of 0.05.

Bootstrap Confidence Intervals

To evaluate the goals for basic and oil treatment, bootstrapping was used to compute confidence intervals around the mean effluent concentration or pollutant removal efficiency. Bootstrapping offers a distribution-free method for computing confidence intervals around a measure of central tendency (Efron and Tibshirani 1993). The generality of bootstrapped confidence intervals means they are well-suited to non-normally distributed data or datasets not numerous enough for a powerful test of normality (Porter et al. 1997).

In its simplest form, bootstrapping a summary statistic of a dataset of sample size *n* consists of drawing *n* elements from the dataset randomly with replacement and equal probabilities of drawing any element. The statistic of interest is then calculated on this synthetic dataset, and the process is repeated for many repetitions. Repetition generates a distribution of possible values for the statistic of interest. Percentiles of this distribution are confidence intervals of the statistic. For example, if the mean is calculated for 1,000 synthetic datasets, after sorting the replications, the mean result for ranks 2.5 and 97.5 are the lower and upper 95 percent confidence intervals, respectively, around the mean.

For the basic treatment goal expressed as a minimum removal efficiency (i.e., 80 percent TSS removal), bootstrapping was used to compute the 95 percent confidence interval around the mean removal efficiency. (Individual removal efficiency values were computed using the equation provided in *Computation of Removal Efficiencies*.) The lower 95 percent confidence limit was then compared to the applicable treatment goal. If the lower confidence limit was higher than the treatment goal, it was concluded that the system met the treatment goal with the required 95 percent confidence.

For basic and oil treatment goals expressed as a maximum effluent concentration (i.e., 20 mg/L TSS and 10 mg/L TPH), bootstrapping was used to compute the 95 percent confidence interval around the mean effluent concentration. The upper 95 percent confidence limit was then compared to the applicable treatment goal. If the upper confidence limit was lower than the treatment goal, it was concluded that the system met the treatment goal with the required 95 percent confidence.

Correlation Analysis to Examine Influence of Storm Characteristics

Kendall's tau correlation coefficients were also used to evaluate whether the following storm event characteristics influenced system performance in any way:

- Precipitation depth
- Average precipitation intensity
- Peak precipitation intensity

- Antecedent dry period
- Precipitation duration
- Sample date

These tests examined potential relationships between these storm event characteristics and the following variables that either directly measure or indirectly influence system performance: influent concentration, effluent concentration, and pollutant removal efficiency estimates. In all cases, the statistical significance of these tests was evaluated at an alpha level (α) of 0.05. For storm event characteristics that were correlated with influent concentration, effluent concentration, and pollutant removal efficiency estimates, correlation plots were prepared and are presented in Appendix G.

Statistical Comparisons of Removal Rates for the Compost-Amended Biofiltration Swale Relative to Basic Treatment Facilities

As described above, the TAPE guidelines indicate that the data collected for an "enhanced" BMP should demonstrate significantly higher removal rates for dissolved metals than basic treatment facilities. To determine if this goal was met with a specific level of statistical confidence, a one-tailed Mann-Whitney U test was used to compare removal efficiencies for dissolved zinc and dissolved copper in the compost-amended biofiltration swale to the removal efficiencies calculated for basic treatment facilities in the International Stormwater Best Management Practices Database (ISBMPD) maintained by the American Society of Civil Engineers (ASCE 2009). The specific null (H_o) and alternate (H_a) hypotheses that were assessed in these tests are as follows:

H_o: Compost-amended biofiltration swale removal ≤ Basic treatment removal

H_a: Compost-amended biofiltration swale removal > Basic treatment removal

Pursuant to the TAPE guidelines, statistical significance in these tests was evaluated at an alpha (α) level of 0.10.

Pollutant Removal as a Function of Flow Rate

A regression analysis was conducted to evaluate pollutant removal performance as a function of flow rate. The goal of this analysis is to determine if the applicable treatment goal for a given parameters is being met at the design flow rate for the treatment system. To perform this analysis, an "aliquot-weighted influent flow rate" was determined for each composite sample and an instantaneous influent flow rate was determined for each grab sample. A regression analysis was then performed to determine whether the treatment performance increases, decreases, or remains unchanged as function of influent flow rate. More detailed information on these steps is provided in the following subsections.

Flow Rate Determination

For composite sampling, an aliquot-weighted influent flow rate was calculated based on the time that each aliquot was collected. Specifically, the influent flow rate at the time each aliquot was collected was determined for each storm event based on the continuous flow measurements from the influent monitoring station; these values were then averaged to obtain an aliquot-weighted flow rate for the sampled storm event. For grab sampling, the sample was matched up with a specific inlet flow rate based on the time that the sample was collected.

Regression Analysis

Linear regression models were developed using the influent flow rates described in the previous subsection as the independent variable and pollutant removal performance data (from the composite samples or grab samples) as the dependent variable. The suitability of the regression equation was evaluated using the following diagnostics:

- **Outliers** – extreme outliers were evaluated and removed if they imparted undue influence on the regression relationship.
- **Linearity** – scatter plots were used to determine if a linear regression model provided a good fit to the data; as necessary, data transformations were performed to improve the linear fit.
- **Constant variance** – to obtain a valid linear regression model, the variance of the dependent variable should remain relatively constant across the range of values for the independent variable; as necessary, data transformations were performed to remove or reduce this problem.
- **Other explanatory variables** – other explanatory variables that are correlated with the independent variable can influence the dependent variable. For example, influent concentrations of "source limited" parameters can decrease as the influent flow rate increases; this can lead to an overall decrease in system performance. To evaluate this and other potential confounding factors, residuals from the linear regression model were plotted against other likely explanatory variables.

After performing these diagnostics to obtain the best linear regression model for the data, the p-value of the associated regression line was evaluated to determine the statistical significance of the associated slope coefficient. If the p-value was greater than 0.05, the slope coefficient was deemed insignificant (i.e., not significantly different from zero); in these instances it was assumed that there was no relationship between flow and pollutant removal performance over the range of flow rates measured. If the p-value was greater than zero, the slope coefficient was deemed significant; in these instances, the linear regression model was used to estimate system performance at the design flow rate.

Data Summaries

This section summarizes data collected during the 2009-2010 monitoring period. The presentation of these data is organized under separate subsections for the hydrologic and water quality monitoring results, respectively. Additional supporting information can also be found in Appendices C through J.

Hydrologic Data

To provide some context for interpreting the data, this section begins with a comparison of rainfall totals measured during the monitoring period relative to historical data. A separate section then evaluates the performance of the biofiltration swales for reducing flow volumes, peak discharge rates, and flow durations. Appendix C summarizes results from the quality assurance review that was performed on hydrologic data prior to their analysis herein.

Historical Rainfall Data Comparison

To provide some context for interpreting the hydrologic performance of the biofiltration swales, an analysis was performed on rainfall data collected at the Western Regional Climate Center (WRCC) rain gauge at SeaTac Airport to determine if rainfall totals from the monitoring period (i.e., May 1, 2009 through April 30, 2010) were anomalous. The WRCC rain gauge is located on the east side of SeaTac Airport, approximately 1.4 miles southeast of the SR 518 rain gauge. The analysis specifically involved a comparison of rainfall totals measured at the SeaTac rain gauge over the monitoring period to averaged totals for the same gauge from the past 62 years. These data are summarized in Table 7 along with data from the rain gauge associated with the SR 518 monitoring site.

Results from this analysis showed the average annual rainfall total at the SeaTac Airport rain gauge from 1948 through 2009 was 38.12 inches (WRCC 2010). In comparison, the rainfall total at the SeaTac Airport rain gauge over the monitoring period was 40.95 inches. This value is within the normal range of rainfall (i.e., 25th to 75th percentile) for the SeaTac Airport rain gauge based on the 62-year rainfall record, thus the rainfall total during the monitoring year can generally be considered representative of rainfall during an average year.

Despite the generally average rainfall total for the monitoring period, monthly precipitation totals from the SeaTac Airport rain gauge in June, July, and December 2009 were all lower than the 25th percentile value from the 62-year record (Table 7). However, monthly precipitation totals from the SeaTac Airport rain gauge in May, October, and November 2009 and April 2010 were higher than the 75th percentile value from this record (Table 7). The rainfall data collected at the SR 518 monitoring site followed a similar pattern with the exception of the April 2010 data which was within the 25th to 75th percentile range compared to the historical record. The rainfall data suggests that the summer months of 2009 (June and July) were drier than average; however, no sampling was conducted between May 13 and September 19, 2009, so this should not impact the collected data. The winter months of October and November 2009 were wetter than average, resulting in more opportunities for stormwater sampling; 8 of the 23 storm events were sampled during these 2 months. The rainfall in December was lower than average and significant rainfall did not occur until later in the month.

Table 7. Monthly and annual precipitation totals (in inches) for 2009-2010 at the SR 518 monitoring site, compared to historical totals at SeaTac Airport.

Month	SR518 Monitoring Site Rainfall Data (2009-2010) [a]	SeaTac Airport Station #457473 Rainfall Data (2009-2010)	SeaTac Airport Station #457473 Historical Rainfall Data (1948-2009) [b]
May	**3.46**	**3.61**	1.72
June	*0.07*	*0.18*	1.44
July	*0.03*	*0.06*	0.75
August	1.01	1.16	1.10
September	1.59	1.75	1.73
October	**4.92**	**5.54**	3.48
November	**8.52**	**8.96**	6.15
December	*2.43*	*2.75*	5.81
January	5.96	6.17	5.76
February	3.22	3.52	3.93
March	3.60	3.76	3.73
April	**3.34**	**3.49**	2.52
Total	38.15	40.95	38.12

[a] Source: SR 518 monitoring site rain gauge

[b] Source: SeaTac Airport rain gauge (WRCC 2010). Based on average monthly and annual precipitation totals measured over the period from 1948 to 2009.

Values in *italics* are below the 25th percentile value from the historical monthly or annual precipitation totals.

Values in **bold** are above the 75th percentile value from the historical monthly or annual precipitation totals.

Discharge Data Evaluation

Table C-2 in Appendix C presents the flow volumes, peak discharge rates, and flow durations measured at each monitoring station during individual storm events during the monitoring period. This section begins with an overview of the discharge data that were collected at each monitoring station and is followed by a short discussion of the biofiltration swale performance in relation to the design treatment goal. Separate sections then evaluate the performance of the biofiltration swales for reducing flow volumes, peak discharge rates, and flow durations.

Monitoring Data Overview

A total of 156 runoff-producing storm events were observed at the biofiltration swales during the 19-month flow monitoring period (Appendix C, Table C-2). The calculated runoff volume from the 156 runoff-producing storms based on the total precipitation (49.5 inches) and the drainage area for a single biofiltration swale (5,600 sf) was approximately 23,000 cubic feet (cf). The measured flow volume was approximately 56,000 cf at the compost-amended biofiltration swale inlet and approximately 32,000 cf at the control biofiltration swale inlet. This suggests that the actual drainage area to the compost-amended biofiltration swale may be two or more times larger than the estimated 5,600 sf drainage area used for facility sizing. Since the contributing drainage area to the biofiltration swales was located on a sloped roadway (i.e., downhill slope when travelling west on SR 518), the additional flow measured at the compost-amended biofiltration swale inlet (i.e., the westernmost of the two biofiltration swales) may have been a result of bypass occurring at the catch basin located upslope. Qualitative observations made during storm events verified that some bypass did occur around this catch basin; the bypassed water was subsequently captured at the inlet to the compost-amended biofiltration swale. The drainage area for the control biofiltration swale may also be slightly larger than estimated 5,600 sf.

Both biofiltration swales were slightly oversized and did not have a problem handling the volume of water passing through them, thus the drainage basin size issue is not a substantial concern for this study. Larger drainage basins corresponded to an increase in flow to each biofiltration swale, resulting in an underestimation of pollutant removal performance due to the decreased hydraulic residence time and increased water depth. Based on these observations, a conservative estimate of pollutant removal performance for each biofiltration swale is presented in this TER based on the monitoring data collected as part of this study. Statistical comparisons of event-based flow volumes, peak discharges, and flow durations at each station are provided in the following sections.

Performance in Relation to Design Treatment Goal

The water quality treatment goal for both biofiltration swales was to capture and treat 91 percent of the average annual runoff volume. Due to the design of the biofiltration swales, no overflow was included on the swales, thus all of the influent water must pass through each of the biofiltration swales.

Biofiltration Swale Performance in Reducing Runoff Volumes

To examine the potential benefits of compost amendment for improving biofiltration swale performance, a one-tailed Wilcoxon signed-rank test was performed on the flow volumes from the compost-amended and control biofiltration swales (Appendix G, Table G-1). The results indicated that there was not a statistically significant decrease in flow volume between the inlet and the outlet of the compost-amended biofiltration swale despite a median difference of 10.1 cf measured between the two monitoring stations (Appendix G, Table G-1). The results did indicate a statistically significant ($p < 0.0001$) decrease in flow volume between the inlet and the outlet of the control biofiltration swale, corresponding to a median difference of 17.9 cf between the two monitoring stations (Appendix G, Table G-1).

Differences in flow volumes between the two biofiltration swales were also evaluated. These results indicated that the compost-amended biofiltration swale received a significantly larger ($p < 0.0001$) volume of water at the inlet and outlet of the swale compared to the control biofiltration swale. This is most likely due to the larger contributing area for the compost-amended biofiltration swale as discussed in the previous section. The median difference in flow volumes between the compost-amended and control biofiltration swales was 58.0 cf at the inlet and 81.6 cf at the outlet (Appendix G, Table G-1).

On a storm-by-storm basis, some storms showed an increase in flow volume while others showed a decrease in flow volume. This occurred at both the compost-amended and control biofiltration swales. Precipitation falling directly on the biofiltration swales was evaluated as one possible mechanism for the increase in flow from the inlet to the outlet due to the large size of the swales in comparison to their drainage areas. The top area of each swale was approximately 1,200 sf, which is 20 percent of the estimated drainage area of 5,600 sf. This could account for some of the variability during storm events with lower precipitation depths and lower precipitation intensities; however, there did not appear to be a consistent pattern based on precipitation depth or intensity. Due to the flow volume discrepancies, pollutant removal performance based on loads was not evaluated for this TER. Evaluating pollutant removal based on concentrations also provides a more conservative estimate of pollutant removal performance. The influent and effluent hydrographs appeared to track well for the sampled storm events, thus the differences in flow volumes did not appear to be an issue in terms of flow pacing the effluent samplers during the storm events.

Some infiltration of stormwater did occur on a storm-by-storm basis; however, when looking at the overall dataset, the biofiltration swales did not show a substantial reduction in flow volumes. Over the course of the 19-month monitoring period, approximately 3.3 and 8.7 percent of the total influent volume was infiltrated into the compost-amended and control biofiltration swales, respectively. This low reduction in flow volume is most likely due to the low infiltration capacity of the native soils at the SR 518 site. This site was selected for this reason to ensure that sufficient flow would be present at the outlet of the system to allow a comparison of the influent and effluent water quality characteristics.

Biofiltration Swale Performance in Reducing Flow Durations

To examine the potential benefits of compost amendment for improving biofiltration swale performance, a one-tailed Wilcoxon signed-rank test was performed on the flow durations from the compost-amended and control biofiltration swales (Appendix G, Table G-1). The results indicated that there was a statistically significant ($p = 0.0173$) increase in flow duration between the inlet and the outlet of the compost-amended biofiltration swale, corresponding to a median difference of 0.92 hours measured between the two monitoring stations (Appendix G, Table G-1). The results also indicated a statistically significant ($p < 0.0001$) decrease in flow duration between the inlet and the outlet of the control biofiltration swale, corresponding to a median difference of 2.6 hours between the two monitoring stations (Appendix G, Table G-1). These results indicate that the compost-amended biofiltration swale tended to hold stormwater for a longer duration during a storm event than the control biofiltration swale. The control biofiltration swale acted as more of a flow-through system with shorter flow durations at the outlet than the inlet, showing an increase in infiltration toward the end of a storm event.

Differences in flow durations between the two biofiltration swales were also evaluated. These results indicated that the compost-amended biofiltration swale had a significant increase ($p < 0.0001$) in flow duration at the inlet of the swale and a significant decrease ($p < 0.0001$) in flow duration at the outlet of the swale compared to the control biofiltration swale. The median difference in flow durations between the compost-amended and control biofiltration swale inlets was an increase of 0.29 hours at the inlet and a decrease of 3.0 hours at the outlet (Appendix G, Table G-1). The longer duration at the inlet was most likely due to the larger contributing area and larger flow volume for the compost-amended biofiltration swale as discussed previously. The decrease in flow duration at the outlet was attributed to the compost-amended biofiltration swale tending to hold stormwater for a longer duration during a storm event than the control biofiltration swale.

Biofiltration Swale Performance in Reducing Peak Discharge Rates

To examine the potential benefits of compost amendment for improving biofiltration swale performance, a one-tailed Wilcoxon signed-rank test was performed on the peak discharge rates from the compost-amended and control biofiltration swales (Appendix G, Table G-1). The results indicated that there was a statistically significant ($p = 0.0026$) decrease in peak discharge rates between the inlet and the outlet of the compost-amended biofiltration swale, corresponding to a median difference of 0.005 cfs measured between the two monitoring stations (Appendix G, Table G-1). The results also indicated a statistically significant ($p < 0.0001$) decrease in peak discharge rates between the inlet and the outlet of the control biofiltration swale, corresponding to a median difference of 0.004 cfs between the two monitoring stations (Appendix G, Table G-1). These results indicated that both biofiltration swales had the capacity to attenuate peak discharge rates which could result in reduced impacts on downstream receiving waters and BMPs.

Differences in peak discharge rates between the two biofiltration swales were also evaluated. These results indicated that the compost-amended biofiltration swale had significantly higher ($p < 0.0001$) peak discharge rates at the inlet and outlet of the swale compared to the control biofiltration swale. This is most likely due to the larger contributing area and larger flow volume for the compost-amended biofiltration swale as discussed in previously. The median difference in peak discharge rates between the compost-amended and control biofiltration swales was 0.014 cfs at the inlet and outlet (Appendix G, Table G-1).

Water Quality Data

This section summarizes water quality data collected during the 2009-2010 monitoring period at the SR 518 monitoring site, including a comparison of data compiled over this period with guidelines identified by Ecology (2008) for assessing data acceptability. Monitoring results for each parameter are summarized and discussed in separate sections.

Comparison of Data to TAPE Guidelines

Ecology (2008) provides guidelines for determining data acceptability based on the characteristics of sampled storm events and the collected samples. The data collected through this monitoring effort are evaluated relative to these guidelines in the following subsections.

Storm Event Guidelines

During the 2009-2010 monitoring period, a total of 23 storm events were sampled to characterize the water quality treatment performance of the compost-amended biofiltration swale. The majority of the water quality sampling for this project occurred during the wet season (October through May): all of the composite samples at the compost-amended biofiltration swale, all but one composite sample at the control biofiltration swale, and 13 out of 15 of the TPH grab samples (at both CAB and CON). Dry season (June through September) water quality sampling included one composite sample at the control biofiltration swale and two TPH grab samples (at both CAB and CON). Only 2.7 inches of rain (7 percent of the annual precipitation) fell during the summer of 2009, which was a drier summer than average (Table 7). Summer storms are often more difficult to track and sample than winter storms and are not as representative of the typical weather patterns in the Pacific Northwest, thus monitoring typically focuses on sampling during the wet season. Dry season water quality sampling is not a requirement of the TAPE guidelines (Ecology 2008).

Precipitation data from the sampled storm events was compared to the following TAPE storm event guidelines:

- **Minimum precipitation depth:** 0.15 inches
- **Minimum antecedent dry period:** 6 hours with less than 0.04 inches of rain
- **Minimum post storm dry period:** 6 hours with less than 0.04 inches of rain
- **Minimum storm duration:** 1 hour
- **Minimum average storm intensity:** 0.03 inches per hour for at least half the sampled storms

Summary data related to these guidelines are presented in Table 8 for each of the 23 sampled storm events. Piezometer grab samples were collected during two additional storm events for a total of 25 sampled storm events; however, since this grab sampling is not a TAPE requirement, the results are not summarized in the main text of this TER, but are presented in Appendix J. Figures showing sample collection times in relation to influent and effluent hydrographs are also presented in Appendix E for all sampled storm events. (**Note**: each storm in Table 8 was sequentially numbered in order of occurrence. These numbers will be used to reference each storm event throughout the remainder of this document.)

These data show the guideline for minimum precipitation depth (0.15 inches) was met during all sampled storm events. The median and maximum precipitation depths across all 23 sampled storm events were 0.59 and 1.26 inches, respectively. The guidelines for minimum antecedent dry period (6 hours with less than 0.04 inches of rain), post-storm dry period (6 hours with less

Table 8. Comparison of precipitation data from sampled storm events at the SR 518 biofiltration swales with TAPE storm event guidelines.

Water Quality Storm ID	Storm Start Date & Time	Storm Stop Date & Time	Precipitation Depth (inches)	Antecedent Dry Period (hours)	Post Storm Dry Period (hours)	Precipitation Duration (hours)	Average Precipitation Intensity (inches/hour)
1	5/13/2009 13:25	5/14/2009 8:10	0.72	61.7	107.9	19	0.038
2	9/19/2009 2:45	9/19/2009 7:10	0.28	292.3	271.8	4	0.063
3	10/13/2009 20:10	10/14/2009 13:25	0.59	9.3	11.8	17	0.034
4	10/16/2009 7:45	10/16/2009 23:50	0.85	30	9.8	16	0.053
5	10/17/2009 5:15	10/17/2009 19:55	1.05	9.8	6.5	15	0.072
6	10/22/2009 23:00	10/23/2009 14:10	0.34	36.3	60.2	15	**0.022**
7	10/26/2009 2:25	10/26/2009 15:30	1.06	60.2	57.5	13	0.081
8	10/28/2009 19:40	10/29/2009 10:30	0.30	57.5	39	15	**0.020**
9	11/5/2009 11:05	11/6/2009 14:45	0.77	126.9	6.8	28	0.028
10	11/16/2009 7:35	11/17/2009 10:00	1.26	16.6	18.5	26	0.048
11	12/21/2009 0:50	12/21/2009 8:40	0.50	6.2	203.7	8	0.060
12	12/31/2009 12:00	1/1/2010 10:40	0.42	38.3	4.8	23 [a]	0.033
13	1/4/2010 2:25	1/5/2010 9:55	1.04	38.8	64.2	32	0.033
14	1/10/2010 21:10	1/11/2010 14:00	1.02	41.7	9.6	17	0.061
15	1/14/2010 11:10	1/14/2010 18:40	0.28	16	12	8	0.037
16	1/24/2010 12:30	1/25/2010 00:45	0.38	28.8	38.9	12	0.031
17	2/15/2010 21:45	2/16/2010 6:35	0.23	26.2	176.2	9	**0.026**
18	2/26/2010 1:20	2/26/2010 6:55	0.24	20	7.1	6	0.043
19	3/11/2010 2:00	3/12/2010 11:00	1.05	23.4	99	33	0.032
20	3/25/2010 2:30	3/25/2010 8:50	0.21	197.5	6.5	6	0.033
21	3/25/2010 14:20	3/25/2010 20:20	0.36	6.5	54.9	6	0.060
22	3/28/2010 13:40	3/29/2010 11:45	0.79	9.3	4.2	22	0.036
23	3/29/2010 15:00	3/30/2010 7:10	0.60	4.2	13.3	16	0.037

Values in **bold** do not meet storm event guidelines recommended in the TAPE (Ecology 2008).

[a] A precipitation gap of 7.7 hours occurred during Storm 12.

than 0.04 inches of rain) and storm duration (1 hour) were met during all 23 storm events. Actual antecedent dry periods during the sampled storm events ranged from 4.2 to 292 hours, with a median value of 29 hours. Although the antecedent dry period for Storm 23 was less than 6 hours, there were less than 0.04 inches of rain in the 6 hours preceding the storm. Post-storm dry periods during the sampled storm events ranged from 4.2 to 272 hours, with a median value of 18.5 hours. Although the post-storm dry periods for Storms 12 and 22 were less than 6 hours, there were less than 0.04 inches of rain in the 6 hours following the storm. Precipitation durations ranged from 4 to 33 hours, with a median value of 15 hours.

One of the sampled storm events had a precipitation gap longer than 6 hours (Storm 12). Since the gap was only 7.7 hours, and all other storm and sampling criteria were met, this storm was considered valid for inclusion and analysis within this TER.

The minimum average storm intensity of 0.03 inches per hour was achieved for 87 percent of the sampled storm events. The TAPE storm event guidelines recommend this threshold for at least half of the sampled storms, thus this criterion was met.

Based on these comparisons to the TAPE storm event guidelines, the data from all 23 sampled storms were considered valid for inclusion and analysis within this TER.

Sample Collection Guidelines

As described in the methods section, automated samplers were programmed with the goal of meeting the following criteria for acceptable composite samples that are identified by Ecology (2008):

- A minimum of 10 aliquots was considered optimal; however, a total of 18 aliquots was required to meet the sample volume requirements to analyze all of the targeted parameters.
- For storm events lasting less than 24 hours, sampling was targeted to capture at least 75 percent of the storm event hydrograph. For storm events lasting longer than 24 hours, sampling was targeted to capture at least 75 percent of the hydrograph of the first 24 hours of the storm.

The guideline for minimum number of sample aliquots (10) was met for all of the sampled storm events except for one. The CON Out monitoring station only collected nine aliquots during Storm 12 (see Table 9). Since there was sufficient sample volume to analyze all of the required parameters except for PSD, this sample was considered valid for inclusion and analysis within this TER.

The criterion for minimum portion of storm volume covered by sampling (75 percent) was met for all but three of the sampled storm events (see Table 9). To meet this criterion, a storm event was required to have the minimum portion of storm volume covered for both the influent and effluent sample. Although three samples collected during two storm events (Storm 3, CAB In and CON Out; Storm 7, CON Out) did not meet the 75 percent criterion specified in the TAPE,

Table 9. Comparison of flow-weighted composite data from sampled storm events at the SR 518 biofiltration swales with TAPE guidelines.

Water Quality Storm ID	Compost-Amended Biofiltration (CAB) Swale				Control (CON) Biofiltration Swale			
	Influent Sample Aliquots (#)	Effluent Sample Aliquots (#)	Influent Storm Coverage (%)	Effluent Storm Coverage (%)	Influent Sample Aliquots (#)	Effluent Sample Aliquots (#)	Influent Storm Coverage (%)	Effluent Storm Coverage (%)
2	ND	ND	ND	ND	26	22	96.7%	92.1%
3	60	56	**64.9%**	98.0%	56	63	98.7%	**71.9%**
4	43	34	97.1%	99.6%	32	58	94.2%	98.0%
6	16	21	92.9%	95.3%	25	22	95.6%	97.0%
7	47	63	98.1%	75.6%	60	63	84.5%	**68.4%**
8	16	20	89.9%	90.3%	29	13	94.1%	90.6%
11	18	28	96.4%	97.0%	23	19	96.7%	96.6%
12	14	12	93.8%	91.5%	14	**9**	93.7%	95.1%
13	74	106	97.3%	98.4%	72	79	93.2%	84.0%
14	57	76	98.4%	98.5%	64	64	98.2%	97.5%
15	12	11	87.7%	87.8%	17	18	98.4%	97.8%
16	41	43	86.5%	89.3%	51	46	94.4%	94.0%
17	63	27	88.0%	91.5%	63	17	90.0%	89.5%
18	15	18	92.9%	96.8%	ND	ND	ND	ND
19	31	36	95.1%	97.1%	33	25	95.2%	92.3%
21	30	59	87.0%	97.0%	33	39	91.5%	95.6%
22	23	28	85.7%	94.4%	26	22	85.4%	88.7%

Values in **bold** do not meet storm event guidelines recommended in the TAPE (Ecology 2008); however, the percent coverage for Storm 3 was 93-97 percent of first 24 hours of the storm, thus this storm met the requirement outlined in the QAPP that states: "For storm events lasting longer than 24 hours, sampling will be targeted to capture at least 75 percent of the hydrograph of the first 24 hours of the storm" (WSDOT 2008). The storm coverage for Storm 7 was 68 percent; however, all other storm and sampling criteria were met, so this sample was included in further analysis.

Grab samples were the only samples collected for Storms 1, 5, 9, 10, 20, and 23, thus are not presented in this table.

ND = no data

two storm events did meet the requirement outlined in the QAPP that states: "For storm events lasting longer than 24 hours, sampling will be targeted to capture at least 75 percent of the hydrograph of the first 24 hours of the storm" (WSDOT 2008). The storm coverage for Storm 3 at CAB In and CON Out was 97 and 93 percent of the first 24 hours of the storm, respectively; thus, these samples were used for further analysis in this TER. The percent coverage at CON Out during Storm 7 was 68 percent (see Table 9). Since all of the other storm and sampling criteria were met, this sample was considered valid for inclusion and analysis within this TER.

Monitoring Results by Parameter

Water quality data collected from the biofiltration swales are summarized by parameter in this section. A memorandum describing the water quality data quality assurance review can be found in Appendix D. The data for each parameter are also summarized in separate summary sheets that can be found in Appendix F. Finally, results from the statistical analyses that are discussed herein are also presented in Appendix G. Field data and laboratory data sheets can be found in Appendices B and H, respectively.

This section is organized as follows:

- Parameters required for the GULD evaluation (TSS, dissolved zinc, dissolved copper, and TPH)
- TAPE-required parameters (total zinc, total copper, TP, SRP, hardness, pH, and PSD)
- Non TAPE-required parameters (TKN and nitrate + nitrite)

Total Suspended Solids

Based on the data obtained from 16 storm events sampled at the compost-amended biofiltration swale, influent TSS concentrations ranged from 11 to 159 mg/L, with a median value of 91 mg/L (Table 10, Figure 4). Across the same storm events, effluent TSS concentrations ranged from 0.83 to 7.5 mg/L, with a median value of 5.0 mg/L. Across all sampled storm events at the compost-amended biofiltration swale, TSS removal efficiency estimates ranged from 84 to 98 percent, with a median value of 94 percent (Table 10).

Figure 4 shows each sampled storm as a point on the graph based on the influent TSS concentration (bottom x-axis) and the effluent TSS concentration (left y-axis). The median percent reduction for each biofiltration swale is depicted as a line running from zero to the appropriate percentage on the right y-axis. The 95 percent confidence limits around the percent reduction are also shown for each biofiltration swale. If a biofiltration swale exported a pollutant instead of removing it (i.e., phosphorus), the lines on this figure will connect with the median percent export (top x-axis) instead of the right y-axis (median percent reduction). Similar figures are presented in the following sections for each water quality parameter monitored.

Table 10. Total suspended solids concentrations and removal efficiency estimates for individual sampling events at the SR 518 biofiltration swales.

	Compost-Amended Biofiltration (CAB) Swale			Control (CON) Biofiltration Swale		
Event No.	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal
2	ND	ND	ND	27	7.5	72
3	141	7.5	95	77	10	87
4	159	7.5	95	133	12	91
6	24	2.3	90	32	5.5	83
7	51	5.0	90	39	6.0	85
8	11	0.83	92	22	5.3	76
11	102	6.5	94	109	14	87
12	93	2.7	97	118	20	83
13	64	5.8	91	70	12	83
14	107	4.8	96	116	12	90
15	107	2.5	98	97	18	81
16	89	5.8	93	104	17	84
17	31	4.5	85	141	16	89
18	46	7.3	84	ND	ND	ND
19	79	4.8	94	144	14	90
21	105	5.0	95	148	14	91
22	146	5.7	96	203	11	95
Mean	85	4.9	93	99	12	85
Median	91	5.0	94	107	12	86
Minimum	11	0.83	84	22	5.3	72
Maximum	159	7.5	98	203	20	95

Grab samples were the only samples collected for Storms 1, 5, 9, 10, 20, and 23.
ND: no data was collected for this storm event
mg/L: milligram/liter

Influent TSS concentrations at the control biofiltration swale ranged from 22 to 203 mg/L with a median value of 107 mg/L, based on the data obtained from 16 sampled storm events (Table 10). Effluent TSS concentrations for the control biofiltration swale ranged from 5.3 to 20 mg/L, with a median value of 12 mg/L. Across all sampled storm events at the control biofiltration swale, TSS removal efficiency estimates ranged from 72 to 95 percent, with a median value of 86 percent (Table 10).

The minimum influent TSS concentration allowed in the TAPE guidelines is 20 mg/L. Only one influent concentration less than 20 mg/L was measured during this study (Storm 8, 11 mg/L at CAB In), thus only one storm event was excluded from further analysis of the basic treatment performance goal.

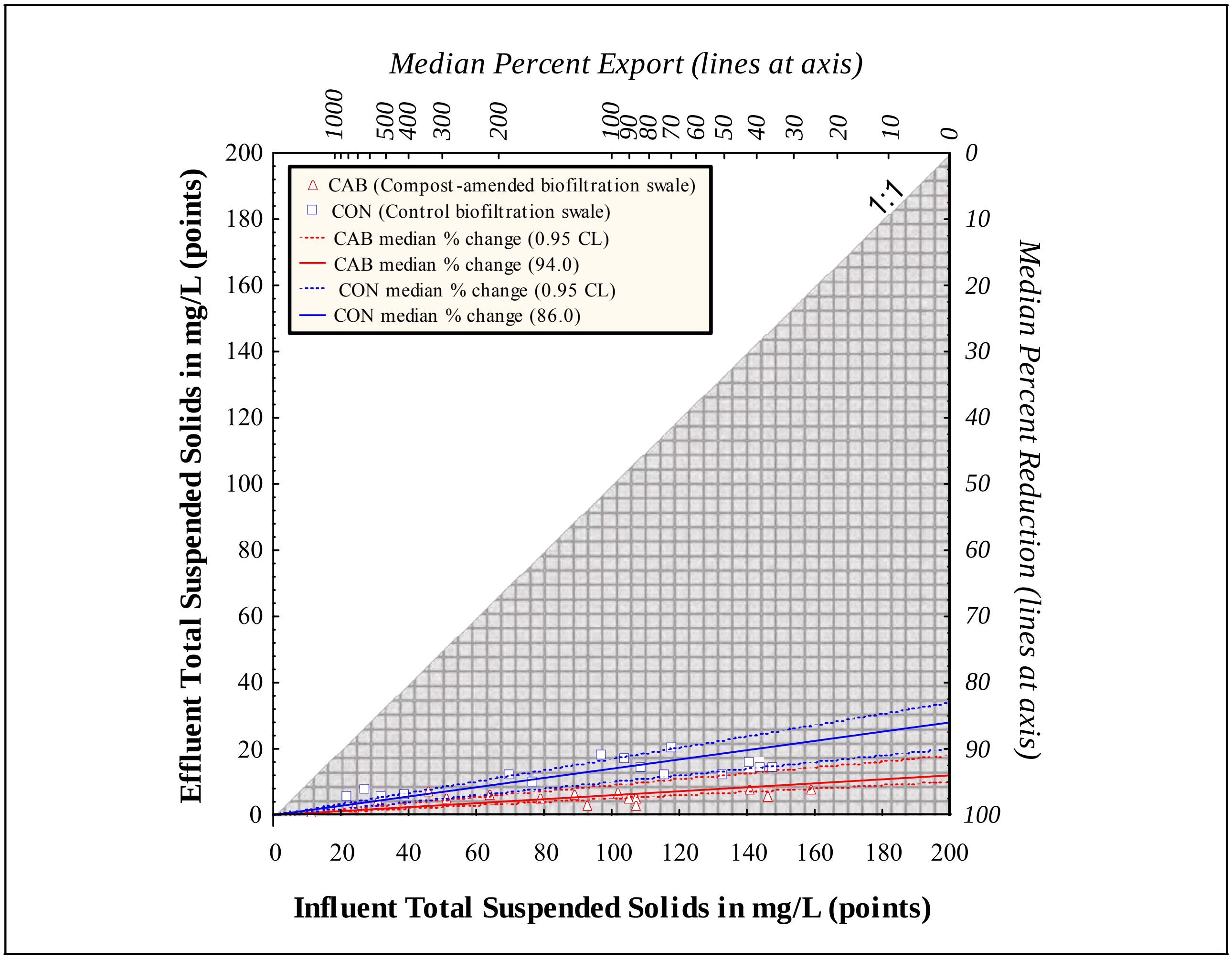

Figure 4. Total suspended solids data collected at the SR 518 monitoring site during the 2009-2010 monitoring year.

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-2) was performed on the TSS data from the compost-amended and control biofiltration swales. The results indicated there was a statistically significant ($p = 0.0002$) decrease in effluent TSS concentrations compared to influent TSS concentrations for both biofiltration swales.

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-3) was also used to compare the effluent TSS concentrations and removal efficiencies between the compost-amended and control biofiltration swales. The results indicated there was a statistically significant ($p = 0.0003$) decrease in effluent TSS concentrations in the compost-amended biofiltration swale compared to the control biofiltration swale, corresponding to a median difference of 7.0 mg/L. There was also a statistically significant ($p = 0.0005$) increase in TSS removal efficiency in the compost-amended biofiltration swale compared to the control biofiltration swale, corresponding to a median difference of 8.0 percent.

A Kendall's tau correlation analysis was performed to determine if treatment performance of the biofiltration swales varied in relation to different storm event characteristics (e.g., storm precipitation depth, average intensity, peak intensity, antecedent dry period, storm duration) or sampling date (i.e., did performance improve or decrease over time). Influent TSS concentrations from the compost-amended biofiltration swale showed a significant positive correlation, with average precipitation intensity ($\tau = 0.414$, $p = 0.025$) and peak precipitation intensity ($\tau = 0.372$, $p = 0.044$) (Appendix G; Table G-4, Figures G-1 and G-3). Effluent TSS concentrations from the compost-amended biofiltration swale also showed a significant positive correlation with peak precipitation intensity ($\tau = 0.535$, $p = 0.004$) (Appendix G, Table G-5 and Figure G-2). Removal efficiency estimates from the compost-amended biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Table G-6).

Influent TSS concentrations and removal efficiency estimates from the control biofiltration swale showed a significant negative correlation with antecedent dry period ($\tau = -0.477$, $p = 0.010$ and $\tau = -0.393$, $p = 0.034$, respectively) and a significant positive correlation with sample date ($\tau = 0.583$, $p = 0.002$ and $\tau = 0.400$, $p = 0.031$, respectively) (Appendix G; Tables G-7 and G-9, Figures G-4 through G-7). Removal efficiency estimates from the control biofiltration swale also showed a significant positive correlation with peak precipitation intensity ($\tau = 0.376$, $p = 0.042$) (Appendix G, Table G-9 and Figure G-8). Effluent TSS concentrations from the control biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Table G-8).

Dissolved Zinc

Based on the metals data obtained from the 16 storm events sampled at the compost-amended biofiltration swale, influent dissolved zinc concentrations ranged from 0.039 to 0.111 mg/L, with a median value of 0.051 mg/L (Table 11, Figure 5). Across the same storm events, effluent dissolved zinc concentrations ranged from less than the detection limit (i.e., 0.005 mg/L) to 0.016 mg/L, with a median value of 0.009 mg/L. Across all sampled storm events at the compost-amended biofiltration swale, dissolved zinc removal efficiency estimates ranged from 69 to 91 percent, with a median value of 83 percent (Table 11).

Based on the metals data obtained from 16 storm events sampled at the control biofiltration swale, influent dissolved zinc concentrations ranged from 0.038 to 0.108 mg/L, with a median value of 0.051 mg/L (Table 11, Figure 5). Effluent dissolved zinc concentrations at the control biofiltration swale ranged from 0.013 to 0.151 mg/L, with a median value of 0.037 mg/L. Dissolved zinc removal efficiency estimates for the control biofiltration swale ranged from -71 to 72 percent, with a median value of 20 percent (Table 11). Thus, despite the same median influent dissolved zinc concentration as the compost-amended biofiltration swale, the control biofiltration swale results show much lower consistency in the removal efficiency, and even resulted in the export of dissolved zinc in three storm events (Storms 11, 12, and 17).

The performance goal for enhanced treatment assumes that the facility can treat stormwater with dissolved zinc influent concentrations ranging from 0.02 to 0.3 mg/L. All of the influent dissolved zinc concentrations measured at the compost-amended biofiltration swale and the control biofiltration swale fell within the acceptable TAPE ranges, thus all of the data presented in Table 11 will be used in further analysis of the enhanced treatment goal.

Table 11. Dissolved zinc concentrations and removal efficiency estimates for individual sampling events at the SR 518 biofiltration swales.

	Compost-Amended Biofiltration (CAB) Swale			Control (CON) Biofiltration Swale		
Event No.	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal
2	ND	ND	ND	0.089	0.027	70
3	0.067	0.012	82	0.074	0.021	72
4	0.051	0.016	69	0.041	0.022	46
6	0.054	0.005 U	91	0.051	0.021	59
7	0.050	0.008	84	0.043	0.013	70
8	0.057	0.006	89	0.054	0.022	59
11	0.044	0.007	84	0.052	0.089	-71
12	0.111	0.014	87	0.108	0.151	-40
13	0.064	0.010	84	0.056	0.043	23
14	0.047	0.008	83	0.038	0.028	26
15	0.054	0.008	85	0.056	0.053	5.4
16	0.053	0.011	79	0.051	0.048	5.9
17	0.039	0.008	79	0.043	0.046	-7.0
18	0.043	0.010	77	ND	ND	ND
19	0.047	0.006	87	0.038	0.038	0.0
21	0.045	0.012	73	0.049	0.049	0.0
22	0.039	0.011	72	0.043	0.036	16
Mean	0.054	0.010	82	0.055	0.045	21
Median	0.051	0.009	83	0.051	0.037	20
Minimum	0.039	0.005 U	69	0.038	0.013	-71
Maximum	0.111	0.016	91	0.108	0.151	72

Note: Grab samples were the only samples collected for Storms 1, 5, 9, 10, 20, and 23.
ND: no data was collected for this storm event
mg/L: milligram/liter
U: undetected at the detection limit noted

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-2) was performed on the dissolved zinc data from the compost-amended and control biofiltration swales. The results confirmed that dissolved zinc effluent concentrations were significantly lower ($p = 0.0002$) than influent concentrations for the compost-amended biofiltration swale. The dissolved zinc effluent concentrations were also significantly lower ($p = 0.0450$) than dissolved zinc influent concentrations for the control biofiltration swale.

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-3) was also used to compare the effluent dissolved zinc concentrations and removal efficiencies between the compost-amended and control biofiltration swales. The results indicated there was a statistically significant ($p = 0.0003$) decrease in effluent dissolved zinc concentrations in the compost-amended biofiltration swale compared to the control biofiltration swale, corresponding to a median difference of 0.028 mg/L. There was also a statistically significant (p = 0.0003) increase in dissolved zinc removal efficiency in the compost-amended biofiltration swale compared to the control biofiltration swale, corresponding to a median difference of 64 percent.

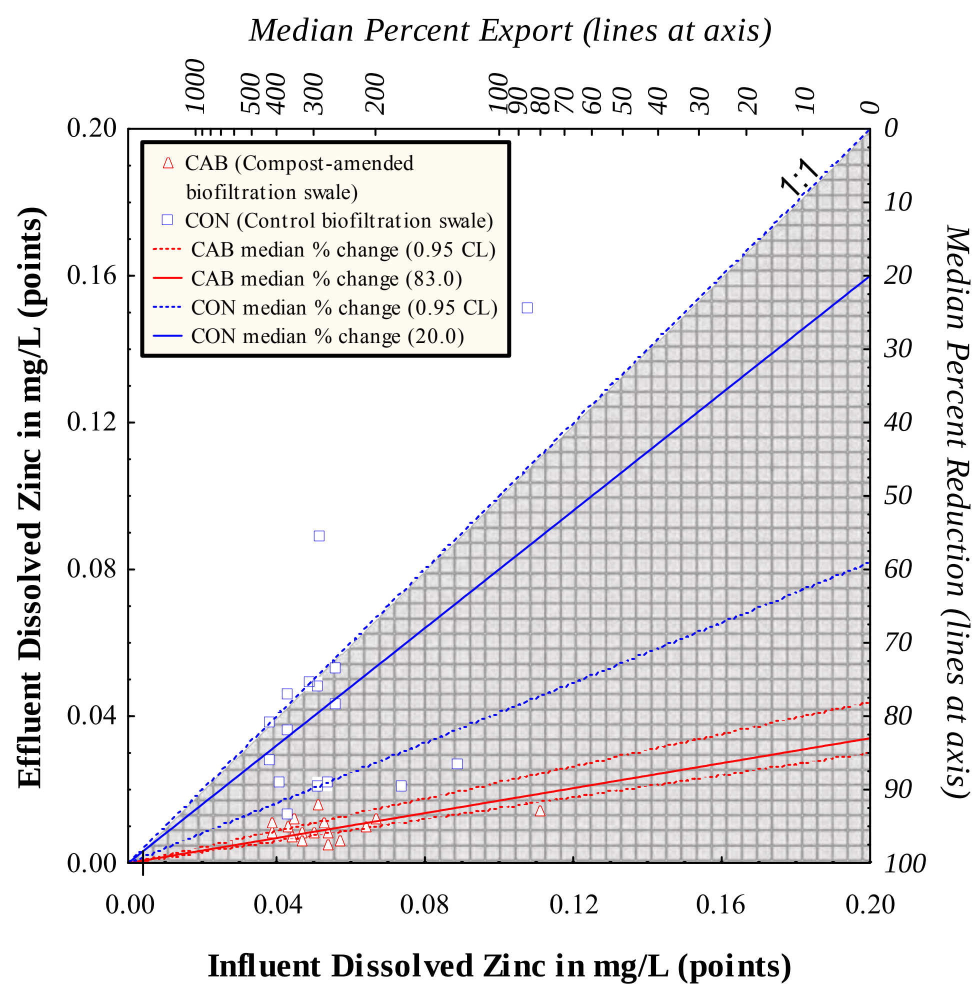

Figure 5. Dissolved zinc data collected at the SR 518 monitoring site during the 2009-2010 monitoring year.

A Kendall Tau correlation analysis was performed to determine if treatment performance of the biofiltration swales varied in relation to different storm event characteristics. Influent dissolved zinc concentrations from the compost-amended biofiltration swale showed a significant negative correlation with sample date (τ = -0.464, p = 0.012) (Appendix G; Table G-4 and Figure G-9). Effluent dissolved zinc concentrations and removal efficiency estimates from the compost-amended biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Tables G-5 and G-6).

Dissolved zinc removal efficiency estimates from the control biofiltration swale showed a significant positive correlation with antecedent dry period (τ = 0.437, p = 0.018) and a significant negative correlation with sample date ($\tau = -0.444$, $p = 0.017$) (Appendix G; Table G-7, Figures G-10 and G-11). Influent and effluent dissolved zinc concentrations from the control biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Tables G-8 and G-9).

Dissolved Copper

Based on the metals data obtained from 16 storm events sampled at the compost-amended biofiltration swale, influent dissolved copper concentrations ranged from 0.0036 to 0.0145 mg/L, with a median value of 0.0060 mg/L (Table 12, Figure 6). Across the same storm events, effluent dissolved copper concentrations ranged from 0.0031 to 0.0068 mg/L, with a median value of 0.0044 mg/L. Across all sampled storm events at the compost-amended biofiltration swale, dissolved copper removal efficiency estimates ranged from -44 to 74 percent, with a median value of 25 percent (Table 12).

Table 12. Dissolved copper concentrations and removal efficiency estimates for individual sampling events at the SR 518 biofiltration swales.

	Compost-Amended Biofiltration (CAB) Swale			Control (CON) Biofiltration Swale		
Event No.	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal
2	ND	ND	ND	0.0195	0.0112	43
3	0.0127	0.0068	46	0.0144	0.0107	26
4	0.0079	0.0060	24	0.0059	0.0076	-29
6	0.0070	0.0042	40	0.0070	0.0061	13
7	0.0036	0.0052	-44	0.0043	0.0046	-7.0
8	0.0060	0.0031	48	0.0085	0.0049	42
11	0.0054	0.0035	35	0.0064	0.0071	-11
12	0.0145	0.0037	74	0.0159	0.0116	27
13	0.0053	0.0047	11	0.0056	0.0064	-14
14	0.0060	0.0045	25	0.0037	0.0043	-16
15	0.0060	0.0038	37	0.0063	0.0069	-9.5
16	0.0067	0.0043	36	0.0083	0.0072	13
17	0.0047	0.0037	21	0.0058	0.0055	5.2
18	0.0051	0.0048	5.9	ND	ND	ND
19	0.0042	0.0043	-2.4	0.0046	0.0053	-15
21	0.0076	0.0065	14	0.0092	0.0098	-6.5
22	0.0040	0.0045	-13	0.0037	0.0055	-49
Mean	0.0067	0.0046	22	0.0081	0.0073	0.74
Median	0.0060	0.0044	25	0.0064	0.0067	-6.7
Minimum	0.0036	0.0031	-44	0.0037	0.0043	-49
Maximum	0.0145	0.0068	74	0.0195	0.0116	43

Note: Grab samples were the only samples collected for Storms 1, 5, 9, 10, 20, and 23.
ND: no data was collected for this storm event
mg/L: milligram/liter

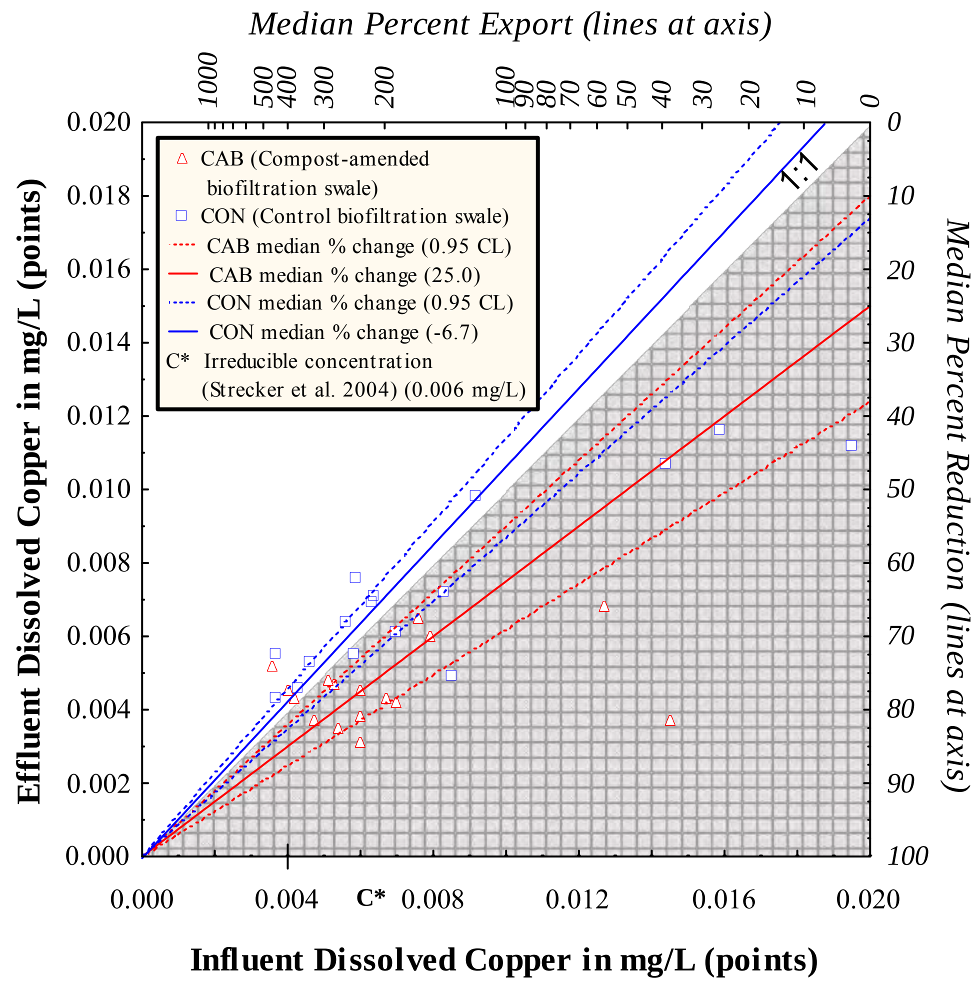

Figure 6. Dissolved copper data collected at the SR 518 monitoring site during the 2009-2010 monitoring year.

Based on the metals data obtained from 16 storm events sampled at the control biofiltration swale, influent dissolved copper concentrations ranged from 0.0037 to 0.0195 mg/L, with a median value of 0.0064 mg/L (Table 12, Figure 6). Across the same storm events, effluent dissolved copper concentrations ranged from 0.0043 to 0.0116 mg/L, with a median value of 0.0067 mg/L. Across all sampled storm events at the control biofiltration swale, dissolved copper removal efficiency estimates ranged from -49 to 43 percent, with a median value of -6.7 percent (Table 12).

The performance goal for enhanced treatment assumes that the facility can treat stormwater with dissolved copper influent concentrations ranging from 0.003 to 0.02 mg/L. All influent dissolved copper concentrations measured at the compost-amended and control biofiltration swales fell within acceptable TAPE ranges, thus all data presented in Table 12 will be used in further analysis of the enhanced treatment goal. However, it is important to note that all of the dissolved copper "export" from the compost-amended biofiltration swale occurred in samples with influent dissolved copper concentrations less than 0.006 mg/L.

Strecker et al. (2004) analyzed data from 14 biofiltration swales in the ISBMPD and found that the median effluent concentration for dissolved copper was approximately 0.006 mg/L, consequently dissolved copper concentrations less than 0.006 mg/L can generally be considered an irreducible concentration for biofiltration swales. Even though they are on the low end of the acceptable range for TAPE, the influence of these low influent dissolved copper concentrations should be considered when evaluating system performance relative to the TAPE goals for enhanced treatment.

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-2) was performed on the dissolved copper data from the compost-amended and control biofiltration swales. The results confirmed that dissolved copper effluent concentrations were significantly lower ($p = 0.0019$) than influent concentrations for the compost-amended biofiltration swale; however, there was no statistically significant decrease ($p = 1.0$) in influent dissolved copper concentrations compared to effluent concentrations measured at the control biofiltration swale.

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-3) was also used to compare the effluent dissolved copper concentrations and removal efficiencies between the compost-amended and control biofiltration swales. The results indicated there was a statistically significant ($p = 0.0006$) decrease in effluent dissolved copper concentrations in the compost-amended biofiltration swale compared to the control biofiltration swale, corresponding to a median difference of 0.0023 mg/L. There was also a statistically significant ($p = 0.0023$) increase in dissolved copper removal efficiency in the compost-amended biofiltration swale compared to the control biofiltration swale, corresponding to a median difference of 31 percent.

A Kendall's tau correlation analysis was performed to determine if treatment performance of the biofiltration swales varied in relation to different storm event characteristics. Influent dissolved copper concentrations and removal efficiency estimates from the compost-amended biofiltration swale showed a significant negative correlation with sample date ($\tau = -0.363$, $p = 0.0499$ and $\tau = -0.400$, $p = 0.031$, respectively) (Appendix G; Tables G-4 and G-6, Figures G-12 and G-13). Effluent dissolved copper concentrations from the compost-amended biofiltration swale showed a significant positive correlation with average precipitation intensity ($\tau = 0.400$, $p = 0.031$) (Appendix G, Table G-5 and Figure G-14). The decrease in dissolved copper removal efficiency in the compost-amended biofiltration swale can be attributed to the lower dissolved copper influent concentrations, since dissolved concentrations on the lower end of the range required by TAPE can be difficult to treat.

Dissolved copper influent concentrations and removal efficiency estimates from the control biofiltration swale showed a significant negative correlation with precipitation depth ($\tau = -0.387$, $p = 0.037$ and $\tau = -0.377$, $p = 0.042$, respectively) (Appendix G; Tables G-7 and G-9, Figures G-15 and G-16). Effluent dissolved copper concentrations from the control biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Table G-8).

Total Petroleum Hydrocarbons

This section focuses on the motor oil (i.e., gasoline fraction) of TPH, since all diesel fraction samples collected were less than the detection limit (i.e., 0.05 mg/L). Based on TPH data obtained from 15 storm events sampled at the compost-amended biofiltration swale, influent TPH concentrations ranged from 1.28 to 10.5 mg/L, with a median value of 2.29 mg/L (Table 13, Figure 7). Across the same storm events, effluent TPH concentrations ranged from 0.11 to 1.72 mg/L, with a median value of 0.38 mg/L. As shown in Table 13, effluent TPH concentrations were lower than influent TPH concentrations across all sampled storm events. Across all sampled storm events at the compost-amended biofiltration swale, TPH removal efficiency estimates ranged from 42 to 97 percent, with a median value of 84 percent (Table 13).

Table 13. Total petroleum hydrocarbon (motor oil) concentrations and removal efficiency estimates for individual sampling events at the SR 518 biofiltration swales.

	Compost-Amended Biofiltration (CAB) Swale			Control (CON) Biofiltration Swale		
Event No.	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal
1	2.96	1.72	42	3.39	2.55	25
2	2.80	0.30	89	3.70	0.29	92
4	1.94	0.11	94	1.74	0.68	61
5	2.29	0.42	82	4.78	0.71	85
6	1.90	0.31	84	1.60	1.48	7.5
7	3.74	0.34	91	1.53	0.36	76
9	1.97	0.66	66	2.18	1.30	40
10	3.14	0.51	84	4.13	1.59	62
12	4.70	0.38	92	4.52	1.25	72
13	1.44	0.35	76	1.43	0.57	60
14	1.28	0.39	70	0.95	0.47	51
15	2.62	0.44	83	3.49	0.89	74
19	1.86	0.15	92	3.58	1.34	63
20	1.88	0.62	67	4.25	1.44	66
23	10.5	0.29	97	2.93	2.50	15
Mean	3.00	0.47	81	2.95	1.16	57
Median	2.29	0.38	84	3.39	1.25	62
Minimum	1.28	0.11	42	0.95	0.29	7.5
Maximum	10.5	1.72	97	4.78	2.55	92

Note: Grab samples were not collected for Storms 3, 8, 11, 16, 17, 18, 21, and 22.
mg/L: milligrams/liter

TPH concentrations obtained from 15 sampled storm events at the control biofiltration swale ranged from 0.95 to 4.78 mg/L, with a median value of 3.39 mg/L (Table 13). Effluent TPH concentrations for the control biofiltration swale ranged from 0.29 to 2.55 mg/L, with a median value of 1.25 mg/L. Across all sampled storm events at the control biofiltration swale, TPH removal efficiency estimates ranged from 7.5 to 92 percent, with a median value of 62 percent (Table 13).

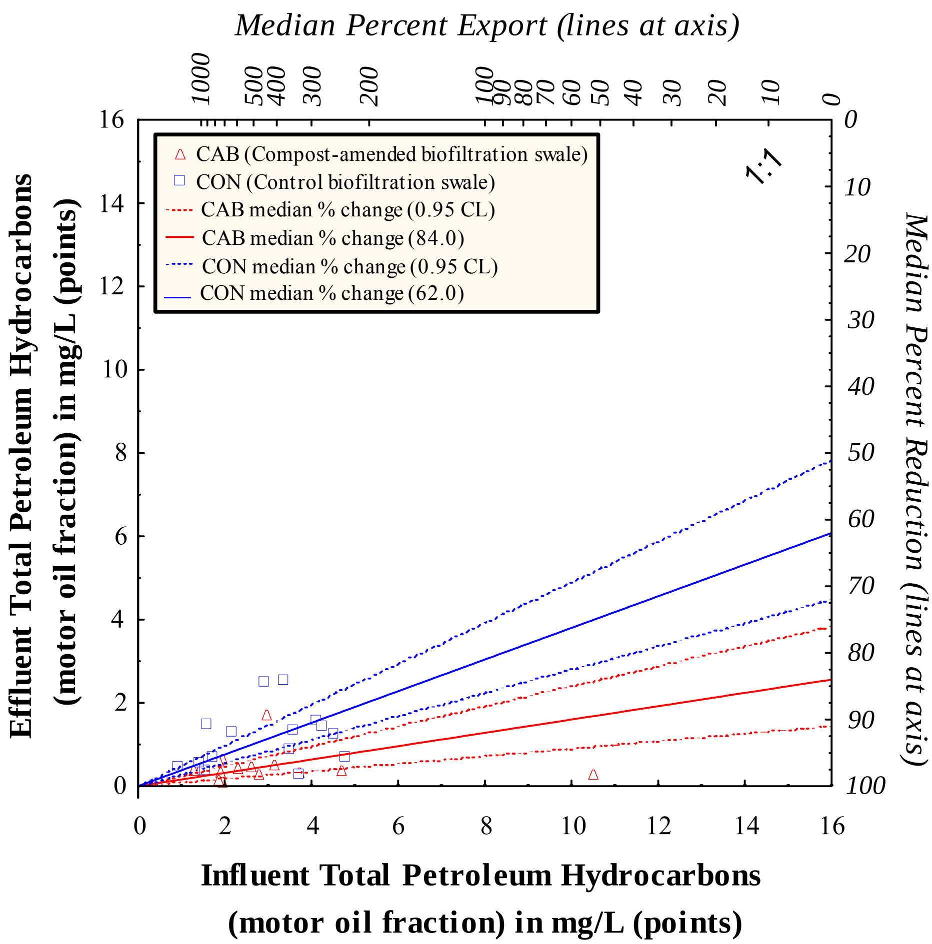

Figure 7. Total petroleum hydrocarbon (motor oil fraction) data collected at the SR 518 monitoring site during the 2009-2010 monitoring year.

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-2) was performed on the TPH data from the compost-amended and control biofiltration swales. The results indicated that TPH effluent concentrations were significantly lower ($p = 0.0003$) than TPH influent concentrations for both biofiltration swales.

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-3) was also used to compare the effluent TPH concentrations and removal efficiencies between the compost-amended and control biofiltration swales. The results indicated there was a statistically significant ($p = 0.0004$) decrease in effluent TPH concentrations in the compost-amended biofiltration swale compared to the control biofiltration swale, corresponding to a median difference of 0.87 mg/L. There was also a statistically significant ($p = 0.0009$) increase in TPH removal efficiency in the compost-amended biofiltration swale compared to the control biofiltration swale, corresponding to a median difference of 22 percent.

A Kendall's tau correlation analysis was performed to determine if treatment performance of the biofiltration swales varied in relation to different storm event characteristics. Influent and effluent TPH concentrations and TPH removal efficiency estimates from the compost-amended biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G; Tables G-4, G-5, and G-6).

TPH removal efficiency estimates from the control biofiltration swale showed a significant positive correlation with average precipitation intensity ($\tau = 0.383$, $p = 0.047$) (Appendix G, Table G-9 and Figure G-17). Influent and effluent TPH concentrations from the control biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Tables G-7 and G-8).

Total Zinc

Based on the metals data obtained from the 16 storm events sampled at the compost-amended biofiltration swale, influent total zinc concentrations ranged from 0.076 to 0.287 mg/L, with a median value of 0.149 mg/L (Table 14, Figure 8). Across the same storm events, effluent total zinc concentrations ranged from 0.006 to 0.016 mg/L, with a median value of 0.012 mg/L. Across all sampled storm events at the compost-amended biofiltration swale, total zinc removal efficiency estimates ranged from 86 to 95 percent, with a median value of 92 percent (Table 14).

Influent total zinc concentration from the 16 sampled storm events at the control biofiltration swale ranged from 0.071 to 0.254 mg/L, with a median value of 0.148 mg/L (Table 14, Figure 8). Effluent total zinc concentrations for the control biofiltration swale ranged from 0.018 to 0.159 mg/L, with a median value of 0.050 mg/L. Across all sampled storm events at the control biofiltration swale, total zinc removal efficiency estimates ranged from 37 to 84 percent, with a median value of 66 percent (Table 14).

The results from a one-tailed Wilcoxon signed-rank test (Appendix G, Table G-2) applied to the data for both biofiltration swales indicated that effluent total zinc concentrations were significantly lower than influent concentrations ($p = 0.0002$). Across all pairs of influent and effluent samples, the median difference (i.e., influent minus effluent) in total zinc concentrations at the compost-amended biofiltration swale was 0.136 mg/L compared to a median difference of 0.097 mg/L in the control biofiltration swale.

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-3) was also used to compare the effluent total zinc concentrations and removal efficiencies between the compost-amended and control biofiltration swales. The results indicated there was a statistically significant ($p = 0.0003$) decrease in effluent total zinc concentrations in the compost-amended biofiltration swale compared to the control biofiltration swale, corresponding to a median difference of 0.039 mg/L. There was also a statistically significant ($p = 0.0003$) increase in total zinc removal efficiency in the compost-amended biofiltration swale compared to the control biofiltration swale, corresponding to a median difference of 26 percent.

Table 14. Total zinc concentrations and removal efficiency estimates for individual sampling events at the SR 518 biofiltration swales.

	Compost-Amended Biofiltration (CAB) Swale			Control (CON) Biofiltration Swale		
Event No.	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal
2	ND	ND	ND	0.122	0.026	79
3	0.287	0.015	95	0.190	0.030	84
4	0.206	0.016	92	0.140	0.023	84
6	0.089	0.006	93	0.081	0.028	65
7	0.094	0.011	88	0.088	0.018	80
8	0.078	0.006	92	0.071	0.031	56
11	0.182	0.012	93	0.170	0.102	40
12	0.218	0.016	93	0.254	0.159	37
13	0.148	0.013	91	0.138	0.055	60
14	0.104	0.010	90	0.108	0.036	67
15	0.161	0.008	95	0.179	0.063	65
16	0.178	0.015	92	0.185	0.061	67
17	0.084	0.010	88	0.171	0.065	62
18	0.076	0.011	86	ND	ND	ND
19	0.125	0.010	92	0.149	0.050	66
21	0.177	0.013	93	0.191	0.064	66
22	0.150	0.013	91	0.147	0.050	66
Mean	0.147	0.012	92	0.149	0.054	65
Median	0.149	0.012	92	0.148	0.050	66
Minimum	0.076	0.006	86	0.071	0.018	37
Maximum	0.287	0.016	95	0.254	0.159	84

Note: Grab samples were the only samples collected for Storms 1, 5, 9, 10, 20, and 23.
ND: no data was collected for this storm event
mg/L: milligrams/liter

A Kendall's tau correlation analysis was performed to determine if treatment performance of the biofiltration swales varied in relation to different storm event characteristics. Effluent total zinc concentrations in the compost-amended biofiltration swale showed a significant positive correlation with peak precipitation intensity ($\tau = 0.369$, $p = 0.046$) (Appendix G, Table G-5 and Figure G-18). Influent total zinc concentrations and removal efficiency estimates from the compost-amended biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Tables G-4 and G-6).

Influent and effluent total zinc concentrations in the control biofiltration swale showed a significant negative correlation with antecedent dry period ($\tau = -0.477$, $p = 0.010$ and $\tau = -0.403$, $p = 0.029$, respectively) (Appendix G; Tables G-7 and G-8, Figures G-19 and G-20). Effluent total zinc concentrations in the control biofiltration swale also showed a significant positive correlation with sample date ($\tau = 0.410$, $p = 0.027$) (Appendix G, Table G-7). Total zinc removal efficiency estimates from the control biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Table G-9 and Figure G-21).

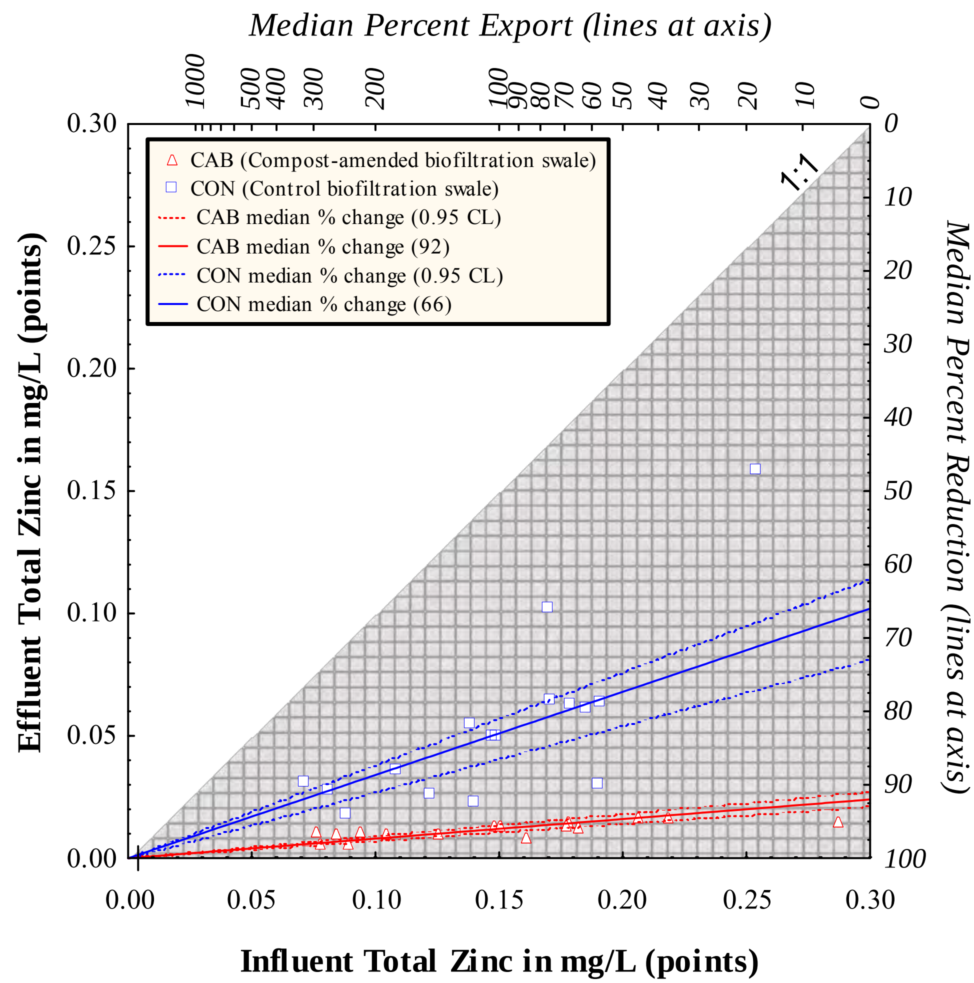

Figure 8. Total zinc data collected at the SR 518 monitoring site during the 2009-2010 monitoring year.

Total Copper

Based the metals data obtained from 16 storm events sampled at the compost-amended biofiltration swale, influent total copper concentrations ranged from 0.0092 to 0.068 mg/L, with a median value of 0.029 mg/L (Table 15, Figure 9). Across the same storm events, effluent total copper concentrations ranged from 0.0039 to 0.0094 mg/L, with a median value of 0.0058 mg/L. Across all sampled storm events at the compost-amended biofiltration swale, total copper removal efficiency estimates ranged from 57 to 87 percent, with a median value of 79 percent (Table 15).

Table 15. Total copper concentrations and removal efficiency estimates for individual sampling events at the SR 518 biofiltration swales.

	Compost-Amended Biofiltration (CAB) Swale			Control (CON) Biofiltration Swale		
Event No.	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal
2	ND	ND	ND	0.0250	0.0119	52
3	0.0683	0.0094	86	0.0461	0.0152	67
4	0.0518	0.0070	86	0.0343	0.0112	67
6	0.0184	0.0051	72	0.0185	0.0095	49
7	0.0217	0.0072	67	0.0226	0.0076	66
8	0.0092	0.0039	58	0.0135	0.0078	42
11	0.0408	0.0065	84	0.0443	0.0110	75
12	0.0371	0.0047	87	0.0435	0.0148	66
13	0.0263	0.0058	78	0.0270	0.0088	67
14	0.0222	0.0057	74	0.0239	0.0078	67
15	0.0330	0.0044	87	0.0411	0.0111	73
16	0.0328	0.0065	80	0.0365	0.0123	66
17	0.0133	0.0045	66	0.0293	0.0093	68
18	0.0135	0.0058	57	ND	ND	ND
19	0.0219	0.0058	74	0.0318	0.0095	70
21	0.0441	0.0078	82	0.0487	0.0169	65
22	0.0314	0.0057	82	0.0312	0.0109	65
Mean	0.030	0.0060	76	0.032	0.011	64
Median	0.029	0.0058	79	0.032	0.011	67
Minimum	0.0092	0.0039	57	0.014	0.0076	42
Maximum	0.068	0.0094	87	0.049	0.017	75

Note: Grab samples were the only samples collected for Storms 1, 5, 9, 10, 20, and 23.
ND: no data was collected for this storm event
mg/L: milligram/liter

Influent total copper concentrations from 16 sampled storm events at the control biofiltration swale ranged from 0.014 to 0.049 mg/L, with a median value of 0.032 mg/L (Table 15, Figure 9). Effluent total copper concentrations for the control biofiltration swale ranged from 0.0076 to 0.017 mg/L, with a median value of 0.011 mg/L. Across all sampled storm events at the control biofiltration swale, total copper removal efficiency estimates ranged from 42 to 75 percent, with a median value of 67 percent (Table 15).

The results from a one-tailed Wilcoxon signed-rank test (Appendix G, Table G-2) applied to the data for both biofiltration swales indicated that effluent total copper concentrations were significantly lower than influent concentrations ($p = 0.0002$). Across all pairs of influent and effluent samples, the median difference (i.e., influent minus effluent) in total copper concentrations at the compost-amended biofiltration swale was 0.0231 mg/L.

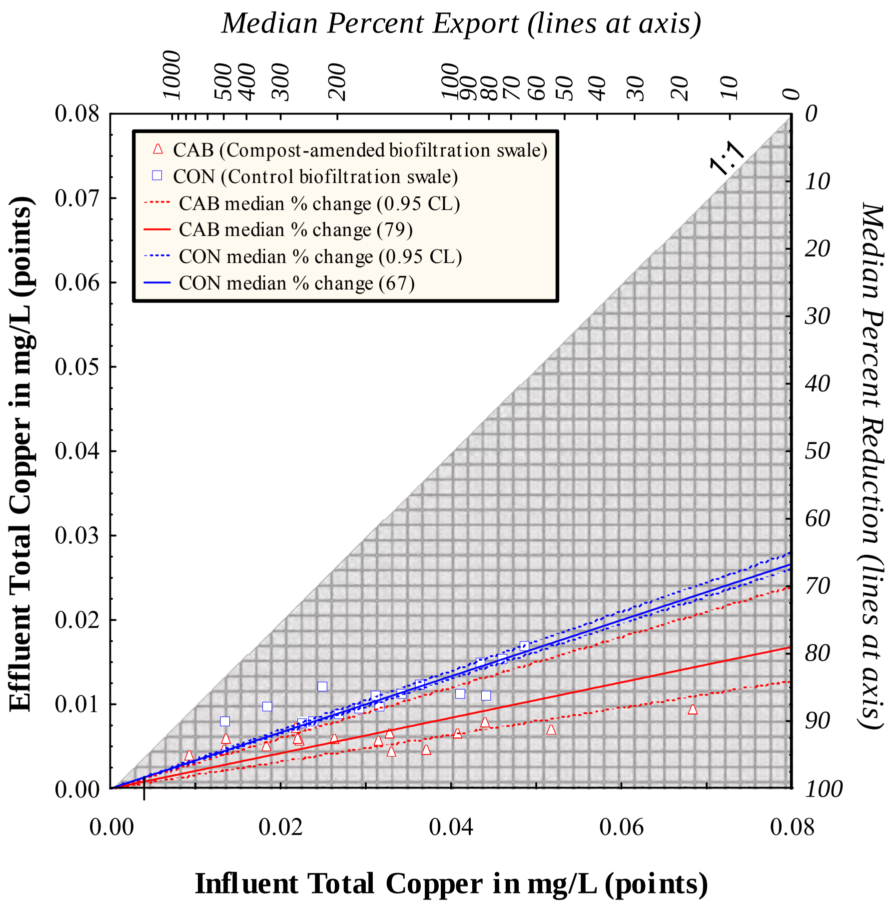

Figure 9. Total copper data collected at the SR 518 monitoring site during the 2009-2010 monitoring year.

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-3) was also used to compare the effluent total copper concentrations and removal efficiencies between the compost-amended and control biofiltration swales. The results indicated there was a statistically significant ($p = 0.0003$) decrease in effluent total copper concentrations in the compost-amended biofiltration swale compared to the control biofiltration swale, corresponding to a median difference of 0.0052 mg/L. There was also a statistically significant ($p = 0.0005$) increase in total copper removal efficiency in the compost-amended biofiltration swale compared to the control biofiltration swale, corresponding to a median difference of 12 percent.

A Kendall's tau correlation analysis was performed to determine if treatment performance of the biofiltration swales varied in relation to different storm event characteristics. Effluent total copper concentrations in the compost-amended biofiltration swale showed a significant positive correlation with average precipitation intensity ($\tau = 0.386$, $p = 0.037$) and peak precipitation intensity ($\tau = 0.537$, $p = 0.004$) (Appendix G; Table G-5, Figures G-22 and G-23). Influent total copper concentrations and total copper removal efficiency estimates from the compost-amended biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Tables G-4 and G-6).

Influent and effluent total copper concentrations in the control biofiltration swale showed a significant negative correlation with antecedent dry period ($\tau = -0.577$, $p = 0.002$ and $\tau = -0.414$, $p = 0.025$, respectively) (Appendix G; Tables G-7 and G-8, Figures G-24 and G-25). Total copper removal efficiency estimates from the control biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Table G-9).

Total Phosphorus

Based on the data obtained from 16 storm events sampled at the compost-amended biofiltration swale, influent TP concentrations ranged from 0.036 to 0.310 mg/L, with a median value of 0.127 mg/L (Table 16, Figure 10). Across the same storm events, effluent TP concentrations ranged from 0.212 to 0.973 mg/L, with a median value of 0.378 mg/L. Across all sampled storm events at the compost-amended biofiltration swale, TP removal efficiency estimates ranged from -51 to -1433 percent, with a median value of -201 percent (Table 16). These results indicate that phosphorus export occurred during all sampled storm events from the compost-amended biofiltration swale.

Influent TP concentrations at the control biofiltration swale ranged from 0.048 to 0.270 mg/L, with a median value of 0.142 mg/L based on the data obtained from 16 sampled storm events (Table 16, Figure 10). Across the same storm events, effluent TP concentrations ranged from 0.032 to 0.228 mg/L, with a median value of 0.063 mg/L. Across all sampled storm events at the control biofiltration swale, TP removal efficiency estimates ranged from -84 to 81 percent, with a median value of 57 percent (Table 16). These results indicate that phosphorus export occurred from the control biofiltration swale during three storm events, but in general, the phosphorus export was much lower from the traditional biofiltration swale compared to the compost- amended biofiltration swale. Phosphorus removal actually occurred during a majority of the storm events at the control biofiltration swale.

Although the phosphorus treatment goal is not evaluated in this TER due to the phosphorus export from the compost-amended biofiltration swale, it is important to note that the phosphorus treatment goal is based on an influent TP concentration ranging from 0.1 to 0.5 mg/L. Six samples collected at CAB In and three samples collected at CON In had influent TP concentrations less than 0.1 mg/L. Five of the six samples from the compost-amended biofiltration swale with influent TP concentrations less than 0.1 mg/L resulted in the largest phosphorus export values (ranging from -409 to -1,433 percent TP removal). The irreducible TP concentration reported in Schueler (1996) was 0.15 to 0.20 mg/L.

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-2) was performed on the TP data from the biofiltration swales. The results confirmed that there was a statistically significant ($p = 0.0018$) decrease in effluent TP concentrations compared to influent TP concentrations from the control biofiltration swale; however, there was no statistically significant decrease ($p = 1.0$) in influent TP concentrations compared to effluent TP concentrations at the compost-amended biofiltration swale.

Table 16. Total phosphorus concentrations and removal efficiency estimates for individual sampling events at the SR 518 biofiltration swales.

	Compost-Amended Biofiltration (CAB) Swale			Control (CON) Biofiltration Swale		
Event No.	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal
2	ND	ND	ND	0.124	0.228	-84
3	0.310	0.973	-214	0.151	0.120	21
4	0.270	0.823	-205	0.205	0.090	56
6	0.064	0.786	-1128	0.081	0.084	-3.7
7	0.076	0.387	-409	0.066	0.064	3.0
8	0.036	0.552	-1433	0.048	0.062	-29
11	0.141	0.341	-142	0.129	0.050	61
12	0.142	0.300	-111	0.172	0.073	58
13	0.103	0.297	-188	0.101	0.046	54
14	0.099	0.212	-114	0.115	0.032	72
15	0.138	0.331	-140	0.137	0.055	60
16	0.138	0.332	-141	0.146	0.066	55
17	0.078	0.416	-433	0.212	0.052	75
18	0.081	0.557	-588	ND	ND	ND
19	0.116	0.368	-217	0.167	0.048	71
21	0.170	0.506 J	-198	0.243	0.064	74
22	0.235	0.355	-51	0.270	0.051	81
Mean	0.137	0.471	-357	0.148	0.076	39
Median	0.127	0.378	-201	0.142	0.063	57
Minimum	0.036	0.212	-1433	0.048	0.032	-84
Maximum	0.310	0.973	-51	0.270	0.228	81

Note: Grab samples were the only samples collected for Storms 1, 5, 9, 10, 20, and 23.
ND: no data was collected for this storm event
mg/L: milligram/liter
J: estimated values based on the data quality assurance review (see Appendix D)

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-3) was also used to compare the effluent TP concentrations and removal efficiencies between the compost-amended and control biofiltration swales. The results indicated that the compost-amended biofiltration swale was exporting TP compared to the control biofiltration swale. The increase in effluent TP concentrations in the compost-amended biofiltration swale compared to the control biofiltration swale corresponded to a median difference of -0.315 mg/L. The decrease in TP removal efficiency between the two biofiltration swales corresponded to a median difference of -258 percent.

A Kendall's tau correlation analysis was performed to determine if treatment performance of the biofiltration swales varied in relation to different storm event characteristics. Influent TP concentrations in the compost-amended biofiltration swale showed a significant negative correlation with antecedent dry period (τ = -0.454, p = 0.014) (Appendix G, Table G-4 and Figure G-26). Effluent TP concentrations and TP removal efficiency estimates from the compost-amended biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Tables G-5 and G-6).

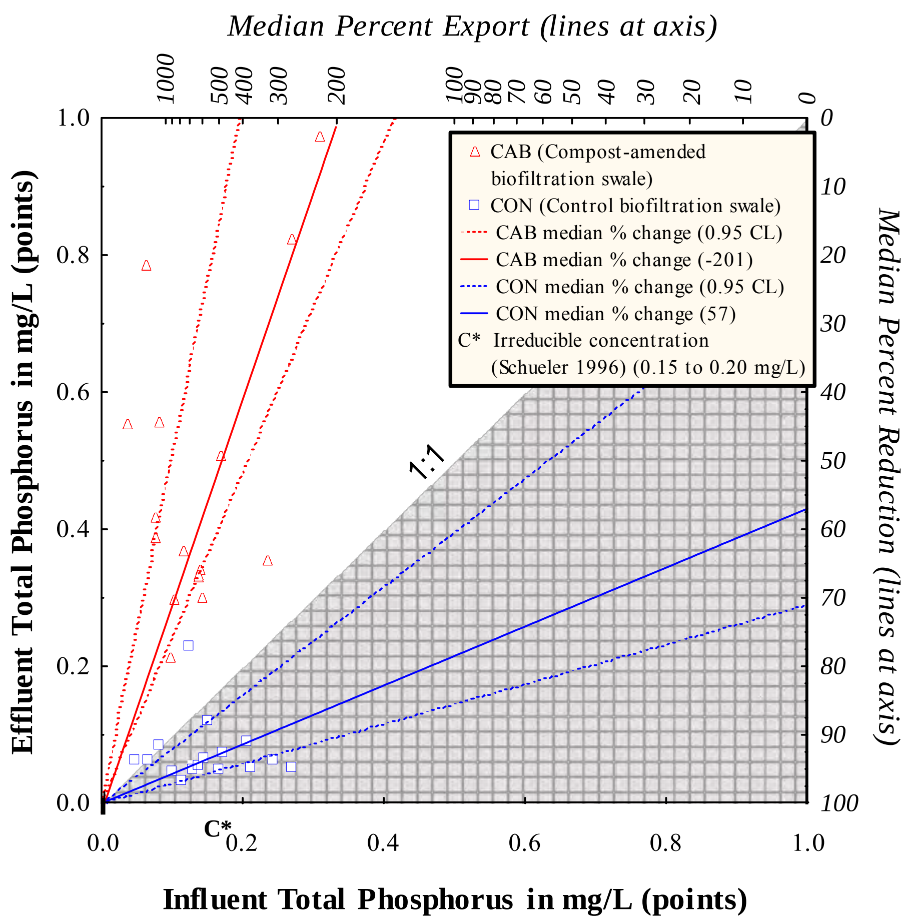

Figure 10. Total phosphorus data collected at the SR 518 monitoring site during the 2009-2010 monitoring year.

Influent TP concentrations and TP removal efficiencies from the control biofiltration swale showed a significant negative correlation with antecedent dry period (τ = -0.427, p = 0.021 and τ = -0.460, p = 0.013, respectively) (Appendix G; Tables G-7 and G-9, Figures G-27 and G-28). Influent TP concentrations and TP removal efficiencies from the control biofiltration swale also showed a significant positive correlation with sample date (τ = 0.433, p = 0.019 and τ = 0.633, p = 0.001, respectively) while effluent TP concentrations showed a significant negative correlation with sample date (τ = -0.527, p = 0.004) (Appendix G, Tables G-7 through G-9 and Figures G-29 through G-31).

Soluble Reactive Phosphorus

Based on the data obtained from 16 storm events sampled at the compost-amended biofiltration swale, influent SRP concentrations ranged from 0.002 to 0.023 mg/L, with a median value of 0.006 mg/L (Table 17, Figure 11). Across the same storm events, effluent SRP concentrations ranged from 0.178 to 0.860 mg/L, with a median value of 0.290 mg/L. Across all sampled storm events at the compost-amended biofiltration swale, SRP removal efficiency estimates ranged from -11,700 to -2938 percent, with a median value of -6595 percent (Table 17). Similar to TP, these results indicate that SRP export occurred during all sampled storm events from the compost-amended biofiltration swale. A majority of the phosphorus export also occurred in the form of SRP.

Table 17. Soluble reactive phosphorus concentrations and removal efficiency estimates for individual sampling events at the SR 518 biofiltration swales.

	Compost-Amended Biofiltration (CAB) Swale			Control (CON) Biofiltration Swale		
Event No.	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal
2	ND	ND	ND	0.066	0.132	-100
3	0.023	0.860	-3639	0.021	0.045	-114
4	0.012 J	0.732 J	-6000	0.012 J	0.026 J	-117
6	0.008 J	0.676 J	-8350	0.008 J	0.022 J	-175
7	0.005	0.312	-6140	0.007	0.022	-214
8	0.005	0.479	-9480	0.009	0.024	-167
11	0.007	0.257	-3571	0.006	0.009	-50
12	0.002	0.223	-11050	0.006	0.006	0.0
13	0.002	0.228	-11300	0.003	0.007	-133
14	0.003	0.178	-5833	0.003	0.005	-67
15	0.008	0.243	-2938	0.003	0.005	-67
16	0.007	0.233	-3229	0.015	0.015	0.0
17	0.003	0.308	-10167	0.004	0.005	-25
18	0.006	0.429	-7050	ND	ND	ND
19	0.003	0.272	-8967	0.005	0.004	20
21	0.006	0.344	-5633	0.010	0.006	40
22	0.002	0.236	-11700	0.003	0.003	0.0
Mean	0.006	0.376	-7190	0.011	0.022	-73
Median	0.006	0.290	-6595	0.007	0.008	-67
Minimum	0.002	0.178	-11700	0.003	0.003	-214
Maximum	0.023	0.860	-2938	0.066	0.132	40

Note: Grab samples were the only samples collected for Storms 1, 5, 9, 10, 20, and 23.

ND: no data was collected for this storm event

mg/L: milligram/liter

J: estimated values based on the data quality assurance review (see Appendix D)

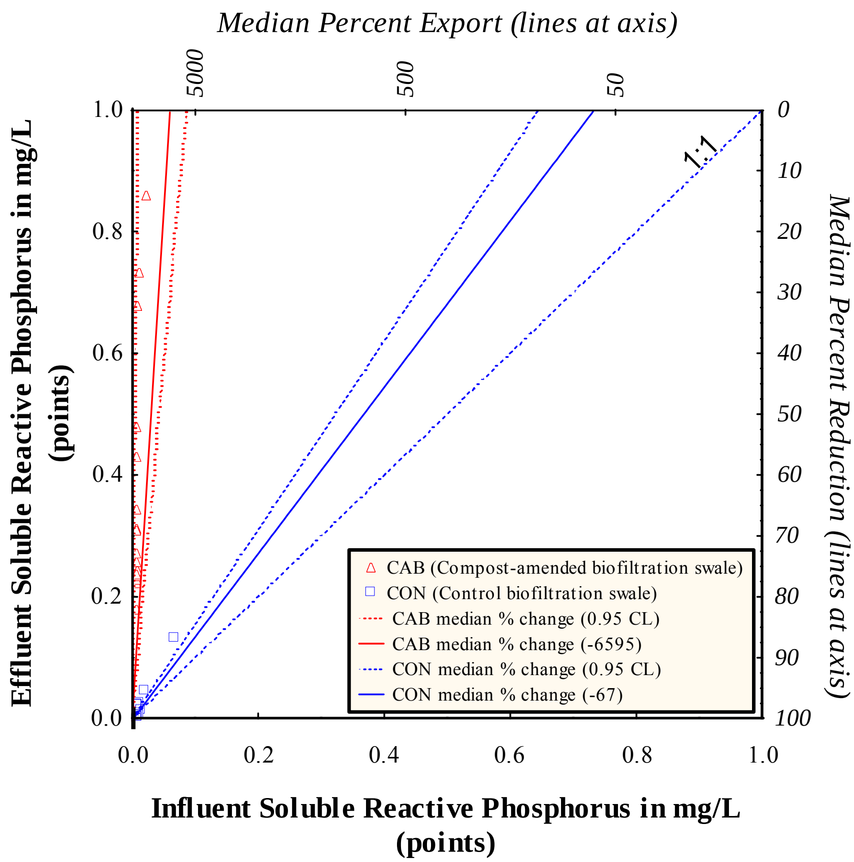

Figure 11. Soluble reactive phosphorus data collected at the SR 518 monitoring site during the 2009-2010 monitoring year.

Influent SRP concentrations at the control biofiltration swale ranged from 0.003 to 0.066 mg/L, with a median value of 0.007 mg/L based on the data obtained from 16 sampled storm events (Table 17). Effluent SRP concentrations at the control biofiltration swale ranged from 0.003 to 0.132 mg/L, with a median value of 0.008 mg/L. Across all sampled storm events at the control biofiltration swale, SRP removal efficiency estimates ranged from -214 to 40 percent, with a median value of -67 percent (Table 17). Although TP removal occurred during a majority of the storm events from the control biofiltration swale, SRP export occurred during most of the storm events. Three storm events had zero removal (i.e., the same SRP concentration was measured in the influent and effluent), and two storm events towards the end of the monitoring season (Storms 19 and 21) demonstrated SRP removal.

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-2) was performed on the SRP data from the biofiltration swales. The results indicated there was no statistically significant decrease ($p = 1.0$) in influent SRP concentrations compared to effluent SRP concentrations.

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-3) was also used to compare the effluent SRP concentrations and removal efficiencies between the compost-amended and control biofiltration swales. The results indicated that the compost-amended biofiltration swale was exporting SRP compared to the control biofiltration swale. The increase in effluent SRP concentrations in the compost-amended biofiltration swale compared to the control biofiltration swale corresponded to a median difference of 0.282 mg/L. The decrease in SRP removal efficiency between the two biofiltration swales corresponded to a median difference of -6528 percent.

A Kendall's tau correlation analysis was performed to determine if treatment performance of the biofiltration swales varied in relation to different storm event characteristics. Influent SRP concentrations in the compost-amended biofiltration swale showed a significant negative correlation with sample date ($\tau = -0.400$, $p = 0.031$) (Appendix G, Table G-4 and Figure G-32). Effluent SRP concentrations and SRP removal efficiency estimates from the compost-amended biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Tables G-5 and G-6).

Influent and effluent SRP concentrations from the control biofiltration swale showed a significant negative correlation with sample date ($\tau = -0.489$, $p = 0.008$ and $\tau = -0.775$, $p < 0.0001$, respectively) while SRP removal efficiencies showed a significant positive correlation with sample date ($\tau = 0.542$, $p = 0.003$) (Appendix G, Tables G-7 through G-9 and Figures G-33 through G-35). SRP removal efficiencies from the control biofiltration swale also showed a significant negative correlation with antecedent dry period ($\tau = -0.434$, $p = 0.019$) (Appendix G, Table G-9 and Figure G-36).

Hardness

Based on the data obtained from 16 storm events sampled at the compost-amended biofiltration swale, influent hardness values ranged from 2.54 to 27.6 milligrams of calcium carbonate per liter (mg $CaCO_3$/L), with a median value of 5.57 mg $CaCO_3$/L (Table 18). Across the same storm events, effluent hardness values ranged from 8.79 to 75.8 mg $CaCO_3$/L, with a median value of 14.4 mg $CaCO_3$/L.

Influent hardness values for the control biofiltration swale obtained from 16 sampled storm events ranged from 3.32 to 29.7 mg $CaCO_3$/L, with a median value of 5.38 mg $CaCO_3$/L (Table 18). Across the same storm events, effluent hardness values ranged from 4.50 to 39.5 mg $CaCO_3$/L, with a median value of 7.53 mg $CaCO_3$/L.

Based on the results from a two-tailed Wilcoxon signed-rank test, effluent hardness concentrations from the compost-amended and control biofiltration swales were significantly higher ($p = 0.0004$ and 0.0007, respectively) than influent hardness concentrations (see Appendix G, Table G-2). Across all pairs of influent and effluent samples, the median difference (i.e., effluent minus influent) in hardness concentrations for the compost-amended biofiltration swale was 8.12 mg $CaCO_3$/L. In comparison, the median difference (i.e., effluent minus influent) in the hardness concentrations for the control biofiltration swale was 1.47 mg $CaCO_3$/L.

A two-tailed Wilcoxon signed-rank test (Appendix G, Table G-3) was also used to compare the effluent hardness concentrations between the compost-amended and control biofiltration swales. The results indicated that the effluent hardness concentrations in the compost-amended biofiltration swale were significantly higher ($p = 0.0076$) than the control biofiltration swale. The increase in effluent hardness concentrations in the compost-amended biofiltration swale compared to the control biofiltration swale corresponded to a median difference of 6.83 mg $CaCO_3$/L.

Table 18. Hardness values for individual sampling events at the SR 518 biofiltration swales.

	Compost-Amended Biofiltration (CAB) Swale		Control (CON) Biofiltration Swale	
Event No.	Influent Concentration (mg $CaCO_3$/L)	Effluent Concentration (mg $CaCO_3$/L)	Influent Concentration (mg $CaCO_3$/L)	Effluent Concentration (mg $CaCO_3$/L)
2	ND	ND	7.62	9.58
3	5.86	16.0	5.28	7.23
4	6.06	15.0	4.69	8.01
6	4.10	18.8	4.50	7.04
7	2.54	8.79	3.32	4.50
8	3.91	16.8	5.47	6.45
11	7.04	12.7	8.01	23.5
12	27.6	75.8	29.7	39.5
13	5.47	11.9	6.25	8.40
14	5.86	9.38	4.89	5.47
15	7.82	15.6	8.79	9.38
16	5.67	13.5	6.84	8.60
17	8.99	15.8	7.43	7.82
18	5.28	16.4	ND	ND
19	4.10	12.5	4.89	6.06
21	3.71	13.7	5.28	5.28
22	3.91	10.9	4.89	5.08
Mean	6.75	17.7	7.37	10.1
Median	5.57	14.4	5.38	7.53
Minimum	2.54	8.79	3.32	4.50
Maximum	27.6	75.8	29.7	39.5

Note: Grab samples were the only samples collected for Storms 1, 5, 9, 10, 20, and 23.
ND: no data was collected for this storm event
mg $CaCO_3$/L: milligrams of calcium carbonate per liter

A Kendall's tau correlation analysis was performed to determine if hardness concentrations measured in the biofiltration swales varied in relation to different storm event characteristics. Effluent hardness concentrations in the compost-amended biofiltration swale showed a significant negative correlation with precipitation depth ($\tau = -0.517$, $p = 0.005$), average precipitation intensity ($\tau = -0.454$, $p = 0.014$), and peak precipitation intensity ($\tau = -0.587$, $p = 0.002$) (Appendix G, Table G-5 and Figures G-37 through G-39). Influent hardness concentrations from the compost-amended biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Table G-4).

Influent hardness concentrations from the control biofiltration swale showed a significant negative correlation with precipitation depth (τ = -0.417, p = 0.024) (Appendix G, Table G-7 and Figure G-40). Effluent hardness concentrations from the control biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Table G-8).

pH

Based on the data obtained from 16 storm events sampled at the compost-amended biofiltration swale, influent pH values ranged from 5.87 to 6.81, with a median value of 6.26 (Table 19). Across the same storm events, effluent pH values ranged from 5.81 to 7.27, with a median value of 6.59. Influent pH values for the control biofiltration swale obtained from 16 sampled storm events ranged from 5.88 to 6.78, with a median value of 6.25 (Table 19). Across the same storm events, effluent pH values ranged from 5.90 to 6.88, with a median value of 6.26.

Table 19. pH values for individual sampling events at the SR 518 biofiltration swales.

	Compost-Amended Biofiltration (CAB) Swale		Control (CON) Biofiltration Swale	
Event No.	**Influent Concentration (std. units)**	**Effluent Concentration (std. units)**	**Influent Concentration (std. units)**	**Effluent Concentration (std. units)**
2	ND	ND	6.11	6.47
3	5.92	6.39	5.88	5.96
4	6.49	6.89	6.41	6.45
6	6.54	7.13	6.58	6.67
7	6.21	6.74	6.27	6.43
8	6.81	7.27	6.66	6.88
11	6.37	6.59	6.56	6.55
12	6.77	6.82	6.76	6.68
13	5.87	6.35	6.00	6.17
14	6.11	6.44	6.22	6.35
15	6.42	6.83	6.78	6.00
16	6.47	6.40	6.51	5.90
17	6.23	5.81	5.96	5.94
18	6.28	6.58	ND	ND
19	6.10	6.65	6.06	6.17
21	5.97	6.40	6.11	6.14
22	6.03	6.15	5.96	6.11
Mean	6.29	6.59	6.30	6.30
Median	6.26	6.59	6.25	6.26
Minimum	5.87	5.81	5.88	5.90
Maximum	6.81	7.27	6.78	6.88

Note: Grab samples were the only samples collected for Storms 1, 5, 9, 10, 20, and 23.

ND: no data was collected for this storm event

Effluent pH levels for the compost-amended biofiltration swales were significantly higher ($p = 0.0032$) than influent pH levels, based on the results from a two-tailed Wilcoxon signed-rank test (see Appendix G, Table G-2). There was no significant difference between influent and effluent pH levels in the control biofiltration swale. Across all pairs of influent and effluent samples, the median difference (i.e., effluent minus influent) in pH levels for the compost-amended biofiltration swale was 0.405. In comparison, the median difference (i.e., effluent minus influent) in the pH levels for the control biofiltration swale was 0.085.

A two-tailed Wilcoxon signed-rank test (Appendix G, Table G-3) was also used to compare the effluent pH levels between the compost-amended and control biofiltration swales. The results indicated that the effluent pH in compost-amended biofiltration swale was significantly higher ($p = 0.0229$) than the control biofiltration swale. The increase in effluent pH levels in the compost-amended biofiltration swale compared to the control biofiltration swale corresponded to a median difference of 0.325.

A Kendall's tau correlation analysis was performed to determine if pH levels measured in the biofiltration swales varied in relation to different storm event characteristics. Influent and effluent pH levels from the compost-amended biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Tables G-4 and G-5).

Effluent pH levels from the control biofiltration swale showed a significant negative correlation with sample date ($\tau = -0.377$, $p = 0.042$) (Appendix G, Table G-8 and Figure G-41). Influent pH levels from the control biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Table G-7).

Particle Size Distribution

The TAPE guidelines state that Pacific Northwest stormwater typically contains mostly silt-sized particles; thus, PSD results should be provided to indicate whether the stormwater runoff analyzed is consistent with particle sizes typically found in urban runoff in this region. Size breaks for the analysis of the PSD samples were set based on the Wentworth scale (Wentworth 1922) and are summarized in Table 20.

Table 20. Summary of particle size distributions measured at the SR 518 biofiltration swales during the 2009-2010 monitoring year.

Particle Size Definition	Particle Size Range (microns)	Proportion of Particle Size in Size Range (%)			
		CAB In	CAB Out	CON In	CON Out
Coarse sand	> 500	5%	7%	4%	3%
Medium sand	250 - 500	3%	10%	4%	6%
Fine sand	125 - 250	2%	0%	0%	1%
Very fine sand	62.5 - 125	1%	0%	5%	2%
Silt	3.9 - 62.5	46%	12%	59%	29%
Clay	1.0 - 3.9	25%	25%	17%	24%
Colloid	< 1.0	18%	46%	11%	35%

Influent PSD data from the compost-amended biofiltration swale showed that an average of 89 percent of the sample could be classified as silt particles and smaller with specifically 46 percent of this average classified as silt (Table 20, Figure 12). Although slightly less than 50 percent of the influent data at the compost-amended biofiltration swale is present in the silt range, an additional 43 percent is primarily fine particles in the clay and colloid range; thus this dataset meets the TAPE guidelines of mostly silt-sized particles. Effluent PSD data from the compost-amended biofiltration swale showed that an average of 83 percent of the sample could be classified as silt particles and smaller, but only an average of 12 percent could be classified as silt (Table 20, Figure 13). The largest median removal rates at the compost-amended biofiltration swale occurred in the medium sand, fine sand, very fine sand, and silt fractions (100 percent for all four size fractions) (Table 21).

Table 21. Median percent removal for particle size distributions measured at the SR 518 biofiltration swales during the 2009-2010 monitoring year.

Particle Size Definition	Particle Size Range (microns)	Median Percent Removal	
		CAB	CON
Coarse sand	> 500	76%	93%
Medium sand	250 - 500	100%	90%
Fine sand	125 - 250	100%	100%
Very fine sand	62.5 - 125	100%	100%
Silt	3.9 - 62.5	100%	96%
Clay	1.0 - 3.9	87%	57%
Colloid	< 1.0	61%	29%

Influent PSD data from the control biofiltration swale showed that an average of 87 percent of the sample could be classified as silt particles and smaller with 59 percent of this average composed of silt particles (Table 20, Figure 14). Greater than 50 percent of the influent data at the control biofiltration swale is present in the silt range, thus this dataset meets the TAPE guidelines of mostly silt-sized particles. Effluent PSD data from the control biofiltration swale showed that an average of 88 percent of the sample could be classified as silt particles and smaller, but only an average of 29 percent could be classified as silt (Table 20, Figure 15). The largest median removal rates at the control biofiltration swale occurred in the fine sand and very fine sand fractions (100 percent for both size fractions) (Table 21). Medium sand and silt removal rates at the control biofiltration swale were slightly lower at 90 percent and 96 percent, respectively.

Total Kjeldahl Nitrogen

Although, nitrogen concentrations are not required to be monitored under the TAPE protocol (Ecology 2008), this study evaluated TKN and nitrate + nitrite to get a better idea of the concentrations found in stormwater and if they were treatable using biofiltration swales. High levels of nitrogen can be a concern in marine systems, such as Puget Sound.

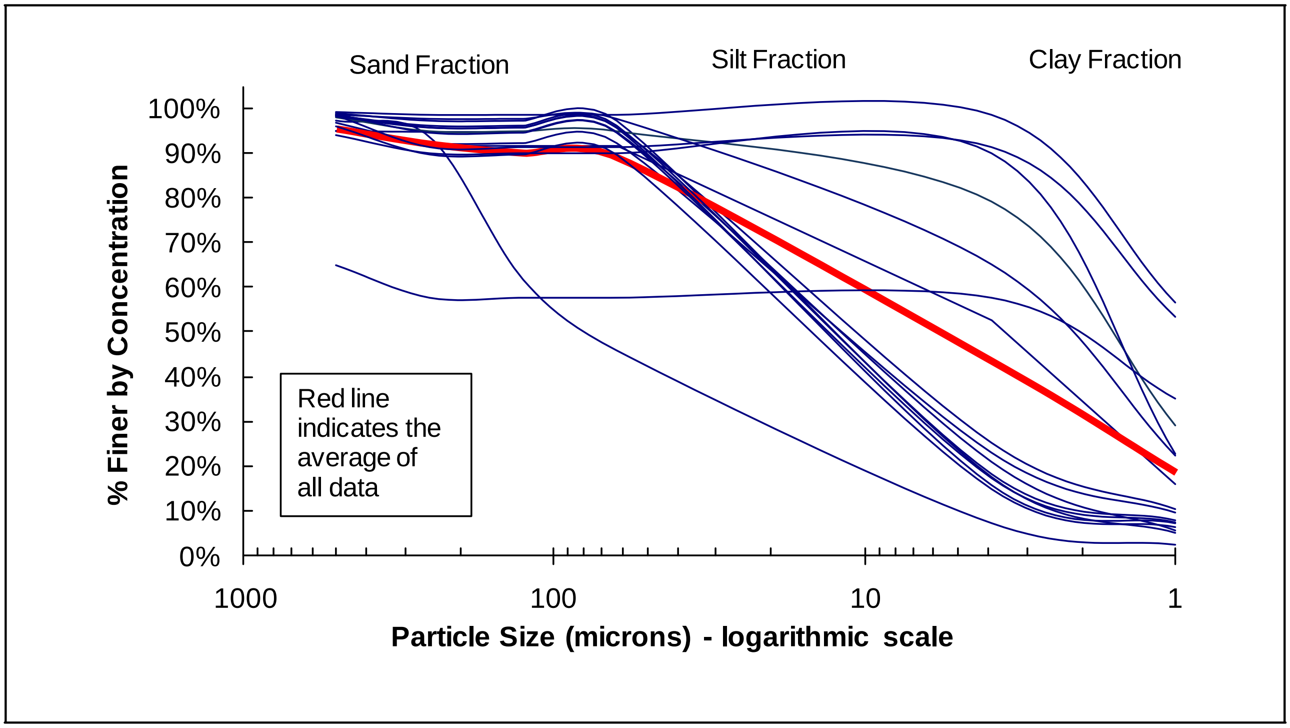

Figure 12. Particle size distribution data collected from the compost-amended biofiltration swale influent during the 2009-2010 monitoring year.

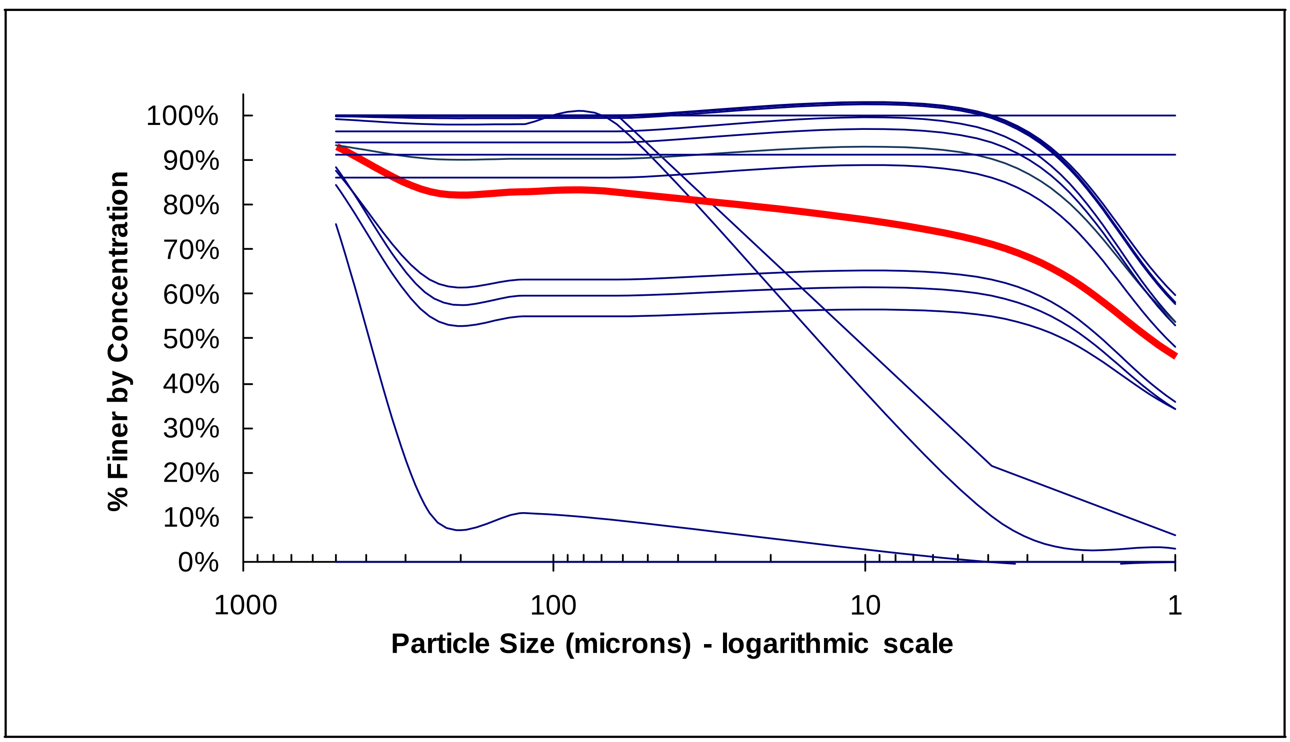

Figure 13. Particle size distribution data collected from the compost-amended biofiltration swale effluent during the 2009-2010 monitoring year.

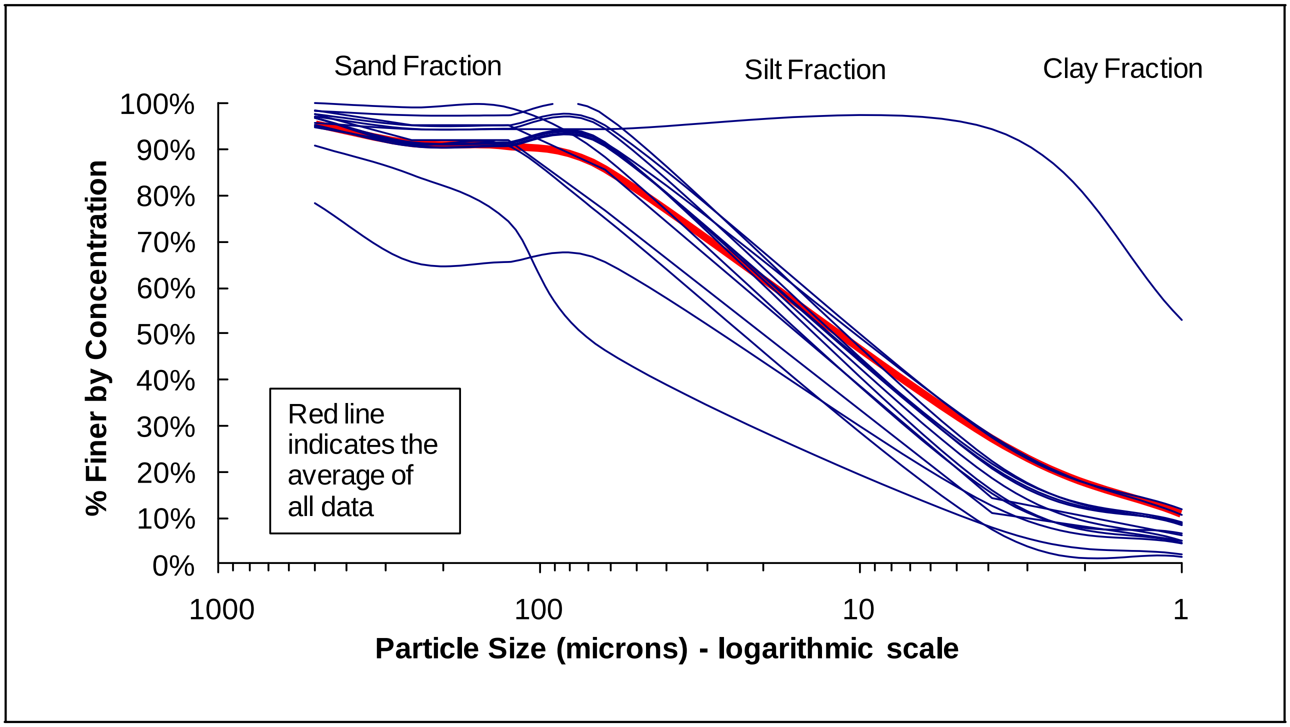

Figure 14. Particle size distribution data collected from the control biofiltration swale influent during the 2009-2010 monitoring year.

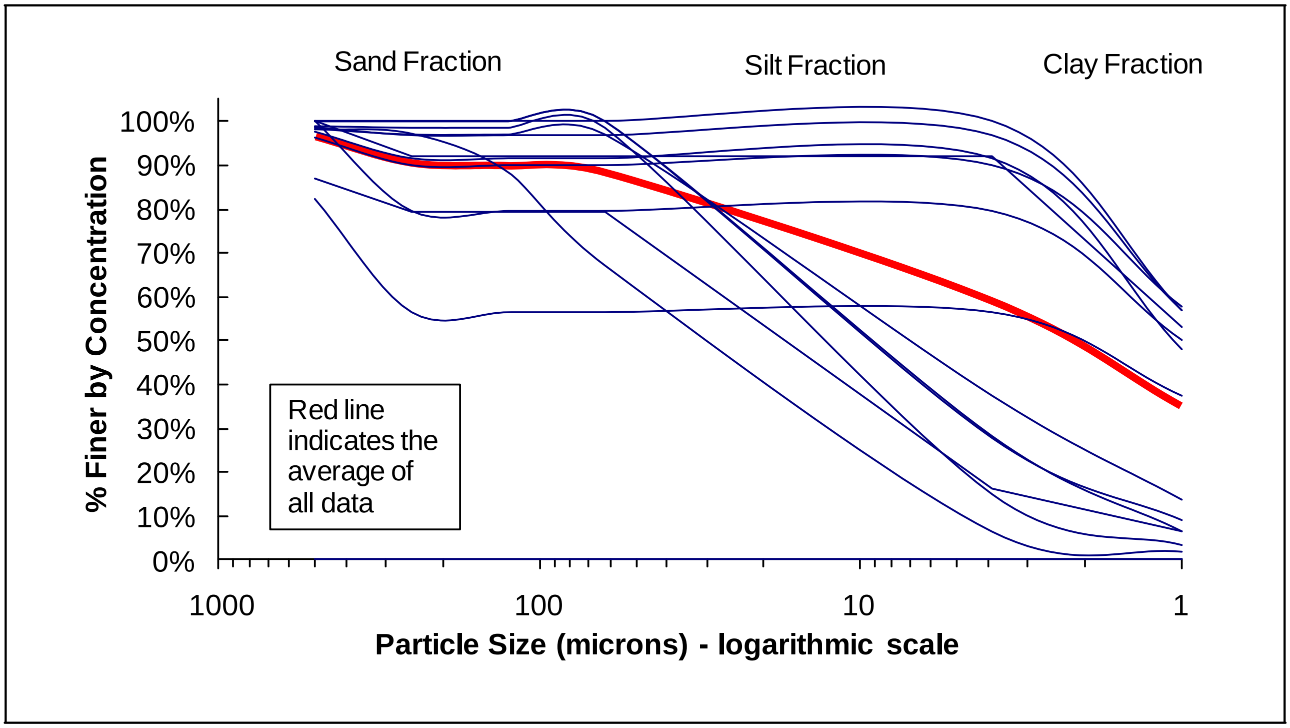

Figure 15. Particle size distribution data collected from the control biofiltration swale effluent during the 2009-2010 monitoring year.

Based on the data obtained from 16 storm events sampled at the compost-amended biofiltration swale, influent TKN concentrations ranged from 0.379 to 1.89 mg/L, with a median value of 0.890 mg/L (Table 22, Figure 16). Across the same storm events, effluent TKN concentrations ranged from 0.249 to 1.23 mg/L, with a median value of 0.528 mg/L. Across all sampled storm events at the compost-amended biofiltration swale, TKN removal efficiency estimates ranged from 3.1 to 64 percent, with a median value of 38 percent (Table 22).

Table 22. Total Kjeldahl nitrogen concentrations and removal efficiency estimates for individual sampling events at the SR 518 biofiltration swales.

	Compost-Amended Biofiltration (CAB) Swale			Control (CON) Biofiltration Swale		
Event No.	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal
2	ND	ND	ND	1.09	1.26	-16
3	1.73	1.23	29	1.51	0.923	39
4	0.957	0.358	63	0.54	0.224	59
6	1.02	0.988	3.1	1.05	0.707	33
7	0.695	0.576	17	0.662	0.495	25
8	0.905	0.666	26	1.10	0.783	29
11	0.828	0.478	42	0.905	0.76	16
12	1.89	0.733	61	1.87	1.50	20
13	0.786	0.480	39	0.912	0.666	27
14	0.379	0.249	34	0.475	0.315	34
15	0.981	0.352	64	1.03	0.513	50
16	1.64	0.952	42	1.83	1.84	-0.5
17	0.552	0.350	37	0.799	0.271	66
18	0.816	0.678	17	ND	ND	ND
19	0.743	0.432	42	0.885	0.386	56
21	1.05	0.841	20	1.06	0.623	41
22	0.874	0.450	49	0.816	0.452	45
Mean	0.990	0.613	37	1.03	0.751	33
Median	0.890	0.528	38	0.971	0.645	33
Minimum	0.379	0.249	3.1	0.475	0.224	-16
Maximum	1.89	1.23	64	1.87	1.84	66

Note: Grab samples were the only samples collected for Storms 1, 5, 9, 10, 20, and 23.
ND: no data was collected for this storm event
mg/L: milligrams/liter

Influent TKN concentrations from 16 sampled storm events at the control biofiltration swale ranged from 0.475 to 1.87 mg/L, with a median value of 0.971 mg/L (Table 22, Figure 16). Effluent TKN concentrations for the control biofiltration swale ranged from 0.224 to 1.84 mg/L, with a median value of 0.645 mg/L. Across all sampled storm events at the control biofiltration swale, TKN removal efficiency estimates ranged from -16 to 66 percent, with a median value of 33 percent (Table 22).

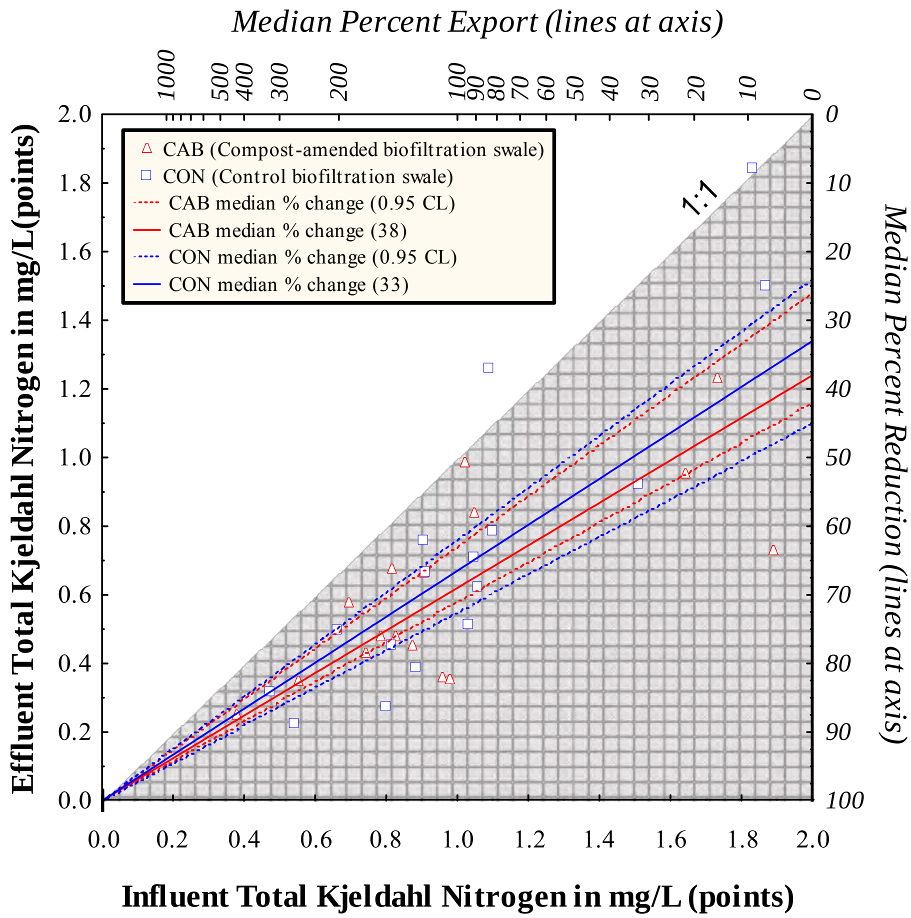

Figure 16. Total Kjeldahl nitrogen data collected at the SR 518 monitoring site during the 2009-2010 monitoring year.

The results from a one-tailed Wilcoxon signed-rank test (Appendix G, Table G-2) indicated that effluent TKN concentrations were significantly lower than influent TKN concentrations for both the compost-amended biofiltration swale ($p = 0.0002$) and the control biofiltration swale ($p = 0.0007$). Across all pairs of influent and effluent samples, the median difference (i.e., influent minus effluent) in TKN concentrations at the compost-amended biofiltration swale was 0.309 mg/L. A similar median difference (i.e., influent minus effluent) of 0.330 mg/L TKN was measured at the control biofiltration swale.

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-3) was also used to compare the effluent TKN concentrations and removal efficiencies between the compost-amended and control biofiltration swales. The results indicated that there was no significant difference between TKN effluent concentrations and removal efficiencies between the compost-amended and control biofiltration swales. The median difference in effluent TKN concentrations between the two biofiltration swales was 0.117 mg/L. The median difference in TKN removal efficiency between the two biofiltration swales was 4.6 percent.

A Kendall's tau correlation analysis was performed to determine if treatment performance of the biofiltration swales varied in relation to different storm event characteristics. There was no significant correlation between the influent and effluent TKN concentrations or the TKN removal efficiencies with the storm event characteristics or sampling date at either the compost-amended or control biofiltration swale (Appendix G; Tables G-4 through G-9).

Nitrate + Nitrite Nitrogen

Based the data obtained from 16 storm events sampled at the compost-amended biofiltration swale, influent nitrate + nitrite concentrations ranged from 0.095 to 0.457 mg/L, with a median value of 0.181 mg/L (Table 23, Figure 17). Across the same storm events, effluent nitrate + nitrite concentrations ranged from 0.132 to 1.23 mg/L, with a median value of 0.431 mg/L. Across all sampled storm events at the compost-amended biofiltration swale, nitrate + nitrite removal efficiency estimates ranged from -523 to 50 percent, with a median value of -254 percent (Table 23). Nitrate + nitrite export occurred from the compost-amended biofiltration swale for a majority of the storm events.

Influent nitrate + nitrite concentrations from 16 sampled storm events at the control biofiltration swale ranged from 0.104 to 0.484 mg/L, with a median value of 0.261 mg/L (Table 23, Figure 17). Effluent nitrate + nitrite concentrations for the control biofiltration swale ranged from 0.097 to 0.489 mg/L, with a median value of 0.218 mg/L. Across all sampled storm events at the control biofiltration swale, nitrate + nitrite removal efficiency estimates ranged from -129 to 47 percent, with a median value of 6.1 percent (Table 23). Nitrate + nitrite export occurred from the control biofiltration swale for 6 out of the 16 sampled storm events.

The results from a one-tailed Wilcoxon signed-rank test (Appendix G, Table G-2) indicated that influent nitrate + nitrite concentrations were not significantly lower than effluent nitrate + nitrite concentrations for the compost-amended biofiltration swale ($p = 1.0$) or the control biofiltration swale ($p = 0.2040$). Across all pairs of influent and effluent samples, the median increase in nitrate + nitrite concentrations in the compost-amended biofiltration swale was 0.323 mg/L compared to the control biofiltration swale which had a median decrease of 0.0095 mg/L.

A one-tailed Wilcoxon signed-rank test (Appendix G, Table G-3) was also used to compare the effluent nitrate + nitrite concentrations and removal efficiencies between the compost-amended and control biofiltration swales. The results indicated that the compost-amended biofiltration swale was exporting nitrate + nitrite compared to the control biofiltration swale. The increase in effluent nitrate + nitrite concentrations in the compost-amended biofiltration swale compared to the control biofiltration swale corresponded to a median difference of 0.214 mg/L. The decrease in nitrate + nitrite removal efficiency between the two biofiltration swales corresponded to a median difference of -260 percent.

A Kendall's tau correlation analysis was performed to determine if treatment performance of the biofiltration swales varied in relation to different storm event characteristics. Influent nitrate + nitrite concentrations and nitrate + nitrite removal efficiency in the compost-amended biofiltration swale showed a significant negative correlation with sample date ($\tau = -0.460$, $p = 0.013$ and $\tau = -0.633$, $p = 0.001$, respectively) (Appendix G; Tables G-4 and G-6, Figures G-42 and G-43) while effluent nitrate + nitrite concentrations showed a significant positive correlation with sample date ($\tau = 0.417$, $p = 0.024$) (Appendix G, Table G-5 and Figure G-44). Effluent nitrate + nitrite concentrations from the compost-amended biofiltration swale also showed a significant negative correlation with peak precipitation intensity ($\tau = -0.449$, $p = 0.015$) (Appendix G, Table G-5 and Figure G-45).

Table 23. Nitrate + nitrite nitrogen concentrations and removal efficiency estimates for individual sampling events at the SR 518 biofiltration swales.

	Compost-Amended Biofiltration (CAB) Swale			Control (CON) Biofiltration Swale		
Event No.	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal
2	ND	ND	ND	0.484	0.485	-0.21
3	0.304	0.204	33	0.306	0.248	19
4	0.378 J	0.190 J	50	0.336 J	0.178 J	47
6	0.248 J	0.236 J	4.8	0.252 J	0.264 J	-4.8
7	0.095	0.132	-39	0.160	0.097	39
8	0.223 J	0.261	-17	0.258	0.205	21
11	0.118	0.411	-248	0.147	0.337	-129
12	0.227	1.23	-442	0.276	0.489	-77
13	0.457	0.415	9.2	0.356	0.230	35
14	0.163	0.373	-129	0.150	0.142	5.3
15	0.188	0.847	-351	0.478 J	0.269	44
16	0.174	0.845	-386	0.264	0.305	-16
17	0.230	0.827	-260	0.265	0.182	31
18	0.134	0.746	-457	ND	ND	ND
19	0.110	0.475	-332	0.128	0.137	-7.0
21	0.107	0.667	-523	0.161	0.150	6.8
22	0.095	0.447	-371	0.104	0.138 J	-33
Mean	0.203	0.519	-216	0.258	0.248	-1.1
Median	0.181	0.431	-254	0.261	0.218	6.1
Minimum	0.095	0.132	-523	0.104	0.097	-129
Maximum	0.457	1.23	50	0.484	0.489	47

Note: Grab samples were the only samples collected for Storms 1, 5, 9, 10, 20, and 23.

ND: no data was collected for this storm event

mg/L: milligrams/liter

J: estimated values based on the data quality assurance review (see Appendix D)

Effluent nitrate + nitrite concentrations from the control biofiltration swale showed a significant negative correlation with precipitation depth ($\tau = -0.410$, $p = 0.027$) (Appendix G, Table G-8 and Figure G-46). Influent nitrate + nitrite concentrations and nitrate + nitrite removal efficiency from the control biofiltration swale were not correlated with any of the storm event characteristics or sampling date (Appendix G, Tables G-7 and G-9).

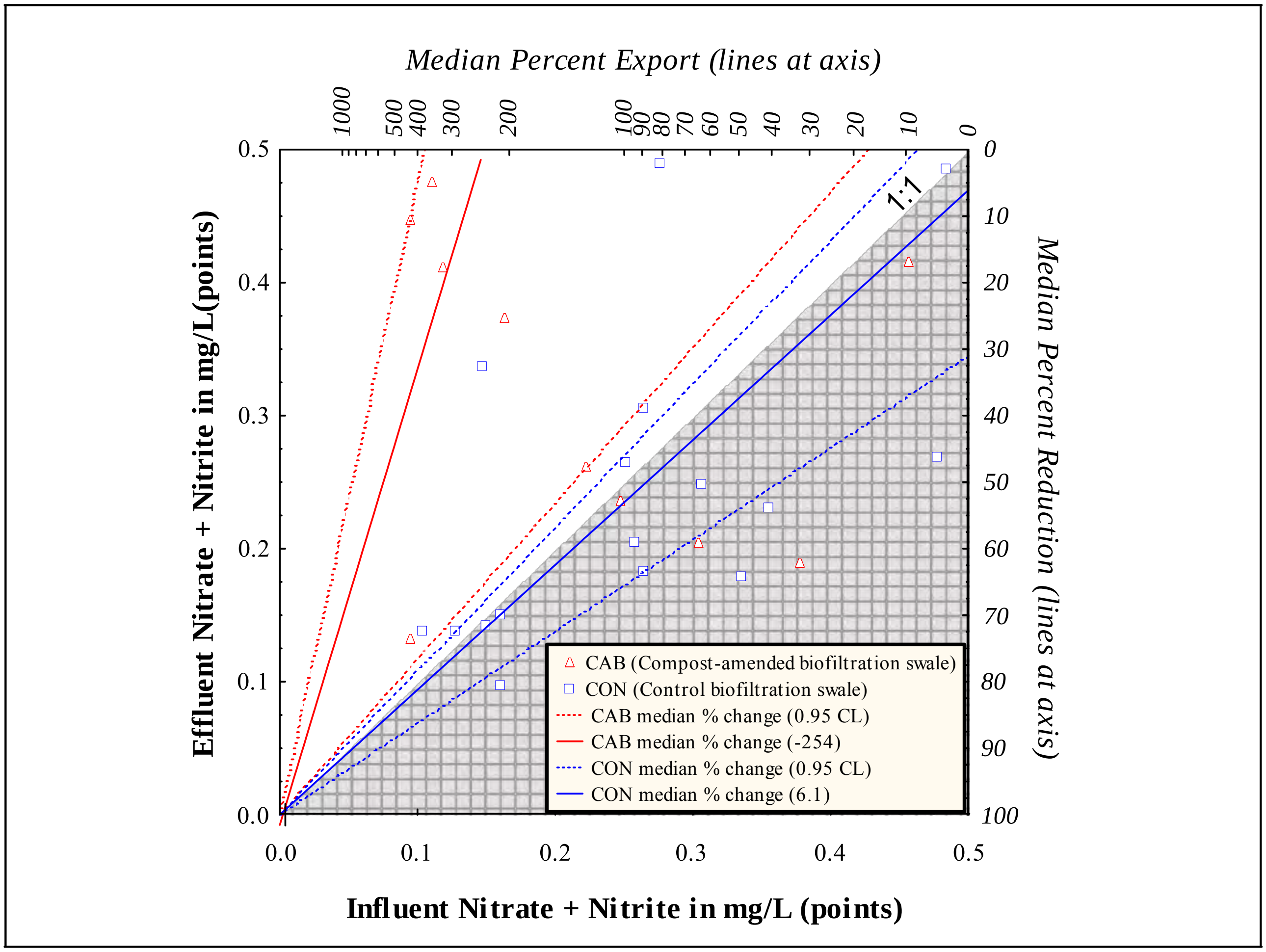

Figure 17. Nitrate + nitrite nitrogen data collected at the SR 518 monitoring site during the 2009-2010 monitoring year.

Evaluation of Performance Goals

This section evaluates water quality data for each treatment goal addressed in this TER, verifying performance claims for each treatment goal and providing possible explanations (when necessary) for when a particular goal was not completely met.

Basic Treatment

TAPE guidelines specify a basic treatment goal of 80 percent TSS removal for influent concentrations ranging from 100 to 200 mg/L. For influent TSS concentrations greater than 200 mg/L, a higher treatment goal may be appropriate. For influent TSS concentrations less than 100 mg/L, the facilities should achieve an effluent goal of 20 mg/L. There is no specified goal for influent TSS concentrations less than 20 mg/L. Based on discussions with Ecology about data requirements, only samples with influent TSS concentrations of 20 mg/L or greater are acceptable for evaluating performance in meeting TAPE basic treatment goals.

TAPE guidelines require a minimum of 12 sampling events. A total of 15 valid samples were collected at the compost-amended biofiltration swale during the 2009-2010 monitoring period (one sample was less than the minimum influent concentration of 20 mg/L). Eight of the 15 valid samples at the compost-amended biofiltration swale were in the 20 to 99 mg/L influent TSS range, and the remaining 7 samples were in the 100 to 200 mg/L range (Table 24). Since the sampled storm events were divided evenly between the two influent ranges, both performance goals were evaluated.

As shown in Table 25, the mean effluent TSS concentration from this subset of data was 5.2 mg/L, and the upper 95 percent confidence limit for the mean was 6.0 mg/L. Because the upper confidence limit is lower than the effluent goal of 20 mg/L, it can be concluded that the compost-amended biofiltration swale met the basic treatment goal with a confidence level of 95 percent. The mean TSS percent removal from this subset of data was 93 percent, and the lower 95 percent confidence limit for the mean was 91 percent. Because the lower confidence limit is higher than the 80 percent removal goal, it also can be concluded that the compost-amended biofiltration swale met the basic treatment goal with a confidence level of 95 percent.

In order to evaluate pollutant removal performance as a function of flow rate, a regression analysis was performed on the TSS percent removal and effluent TSS concentration data from the compost-amended biofiltration swale. No significant relationship was found between the aliquot-weighted average flow rate and TSS percent removal, thus it can be assumed that there is no relationship between flow and TSS percent removal over the range of flow rates monitored during this study (0.010 to 0.078 cfs) (Appendix L, Figure L-1). There was a significant positive relationship ($p = 0.0468$) between the aliquot-weighted average flow rate and effluent TSS concentrations; however, the maximum TSS effluent concentration measured at the compost-amended biofiltration swale was 7.5 mg/L, so all of the samples were well below the 20 mg/L effluent goal over the range of flow rates monitored during this study (Appendix L, Figure L-2).

Table 24. Total suspended solids concentrations and removal efficiency estimates for valid sampling events at the compost-amended biofiltration swale.

	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Percent Removal
Events with influent TSS concentrations from > 20 to 99 mg/L			
6	24	2.3	90
17	31	4.5	85
18	46	7.3	84
7	51	5.0	90
13	64	5.8	91
19	79	4.8	94
16	89	5.8	93
12	93	2.7	97
Events with influent TSS concentrations 100 to 200 mg/L			
11	102	6.5	94
21	105	5.0	95
14	107	4.8	96
15	107	2.5	98
3	141	7.5	95
22	146	5.7	96
4	159	7.5	95
Mean	90	5.2	93
Median	93	5.0	94
Minimum	24	2.3	84
Maximum	159	7.5	98

mg/L: milligrams/liter

Table 25. Total suspended solids summary statistics for the compost-amended biofiltration swale sampling events with influent TSS concentrations of 20 mg/L or greater.

All Data	Influent (mg/L)	Effluent (mg/L)	Percent Removal
COV	0.46	0.33	0.043
Bootstrapped Lower CI Mean	70	4.3	91
Bootstrapped Mean	90	5.2	93
Bootstrapped Upper CI Mean	110	6.0	95

mg/L: milligrams per liter

COV: coefficient of variance

CI: confidence interval

Enhanced Treatment

TAPE guidelines indicate that data collected for an "enhanced" BMP should demonstrate significantly higher removal rates for dissolved metals than basic treatment facilities. The performance goal for enhanced treatment assumes that the facility treats stormwater with dissolved zinc influent concentrations ranging from 0.02 to 0.3 mg/L, and dissolved copper influent concentrations ranging from 0.003 to 0.02 mg/L. The influent dissolved zinc and dissolved copper concentrations from all 16 storm events sampled at the compost-amended biofiltration swale fell within acceptable TAPE ranges; thus all data presented in Tables 11 and 12 will be used to evaluate the enhanced treatment goal.

To evaluate the performance goal for enhanced treatment, the dissolved zinc and dissolved copper data obtained from the compost-amended biofiltration swale were compared to basic treatment facility performance data obtained from the ISBMPD (ASCE 2009). Pollutant removal efficiency estimates for ISBMPD data were calculated based on paired dissolved zinc data from 475 individual storm events, and dissolved copper data from 409 individual storm events that fell within the acceptable range for this study (e.g., 0.02 to 0.3 mg/L for dissolved zinc and 0.0029 to 0.02 mg/L for dissolved copper). These data were obtained from monitoring conducted on the following types of basic treatment facilities:

- Biofiltration systems (e.g., grass strips and grass swales)
- Media filters (e.g., sand filters, peat mixed with sand, StormFilter)
- Retention ponds (e.g., surface wet ponds with a permanent pool)
- Retention underground vaults or pipes (e.g., surface tanks with impervious liners)

Influent and effluent dissolved zinc and dissolved copper concentrations measured in these basic treatment facilities during each sampled storm event are provided in Appendix I (Tables I-1 and I-2) with associated removal efficiency estimates (calculated based on concentration). As described in *Sampling Procedures* above, the TAPE goal for enhanced treatment was evaluated based on one-tailed Mann-Whitney U tests comparing the removal efficiency for dissolved zinc and copper in the compost-amended biofiltration swale to the removal efficiency calculated for each type of basic treatment facility.

Based on these data, the compost-amended biofiltration swale had significantly higher removal rates for dissolved zinc than all seven BMP types in the ISBMPD (Table 26, Figure 18). The compost-amended biofiltration swale also performed significantly better than the control biofiltration swale (which is classified as a basic treatment facility) in removing dissolved zinc.

The performance of the compost-amended biofiltration swale was also compared to the WSDOT Ecology Embankment and the Filterra Bioretention System, which both have a GULD for enhanced treatment. Comparisons showed the compost-amended biofiltration swale performed significantly better than both of these BMPs in removing dissolved zinc (Table 26): the mean dissolved zinc removal for the compost-amended biofiltration swale was 82 percent, compared to a mean of 75.4 percent for the WSDOT Ecology Embankment, and a mean of 58 percent for the Filterra Bioretention System.

Table 26. Dissolved zinc basic treatment percent removal data from the ISBMPD and approved enhanced treatment facilities compared to this study.

BMP Type	n	Number of Facilities	Minimum Percent Removal	Mean Percent Removal	Maximum Percent Removal	p-value [a]
Basic Treatment Facilities (International Stormwater Best Management Practice Database)						
Biofilter – Grass Strip	170	26	-319%	55%	93%	< **0.0001**
Biofilter – Grass Swale	86	13	-100%	37%	83%	< **0.0001**
Filter – Other Media	3	1	0%	10%	17%	**0.0036**
Filter – Peat Mixed With Sand	16	2	28%	71%	97%	**0.0298**
Filter – Sand	82	8	-69%	64%	99%	**0.0350**
Retention Pond (Wet) – Surface Pond With a Permanent Pool	85	8	-858%	22%	133%	< **0.0001**
Retention Underground Vault or Pipes (Wet)	33	2	-550%	-10%	85%	< **0.0001**
Total	475	60	-858%	43%	133%	
WSDOT Monitoring Study (2009-2010)						
Compost-Amended Biofiltration Swale (CAB)	16	1	69%	82%	91%	NA
Control Biofiltration Swale (CON)	16	1	-71%	21%	72%	< **0.0001**
Enhanced Treatment Facilities (General Use Level Designation from Ecology)						
WSDOT Ecology Embankment	24	1	34.4%	75.4%	91.9%	**0.0756**
Filterra Bioretention System	23	2	42%	58%	94%	< **0.0001**

[a] Values in **bold** indicate that the alternate hypothesis is valid at a significance level of 0.10 (i.e., CAB removal > Basic or Enhanced treatment removal).

The compost-amended biofiltration swale also had significantly higher removal rates of dissolved copper for two of the six BMP types (grass swales and sand filters) in the ISBMPD (Table 27, Figure 19). No significant difference was found between dissolved copper removal in the compost-amended biofiltration swale and the other four BMP types: grass strips, filters with peat mixed with sand, retention ponds, and retention vaults.

The WSDOT Ecology Embankment and the Filterra Bioretention System also performed significantly better than the compost-amended biofiltration swale in removing dissolved copper (Table 27). The mean dissolved copper removal for the compost-amended biofiltration swale was 22 percent, compared to a mean of 41.0 percent for the WSDOT Ecology Embankment and a mean of 46 percent for the Filterra Bioretention System. However, dissolved copper removal for the compost-amended biofiltration swale was likely underestimated during this study due to low dissolved copper concentrations at the SR 518 site. As shown in Table 11, the compost-amended biofiltration swale exhibited fairly high dissolved copper removal during the two storms with the highest influent dissolved copper concentrations (46 percent for Storm 3 and 74 percent for Storm 12). In contrast, the dissolved copper “export” occurred during the storms with the lowest influent dissolved copper concentrations (-44 percent for Storm 7, -2.4 percent

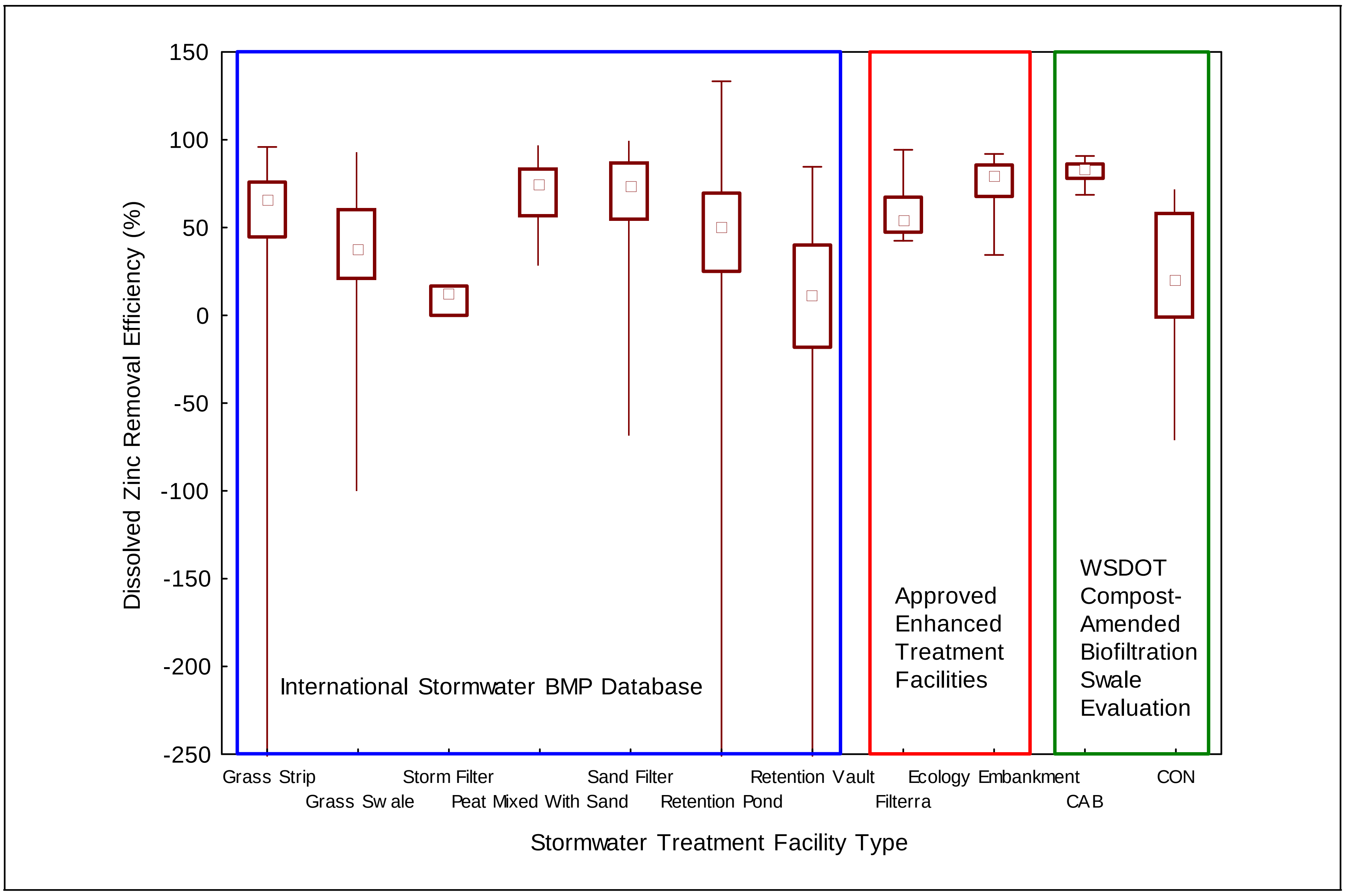

Figure 18. Comparison of dissolved zinc removal efficiency estimates from the ISBMPD and approved enhanced treatment facilities compared to this study.

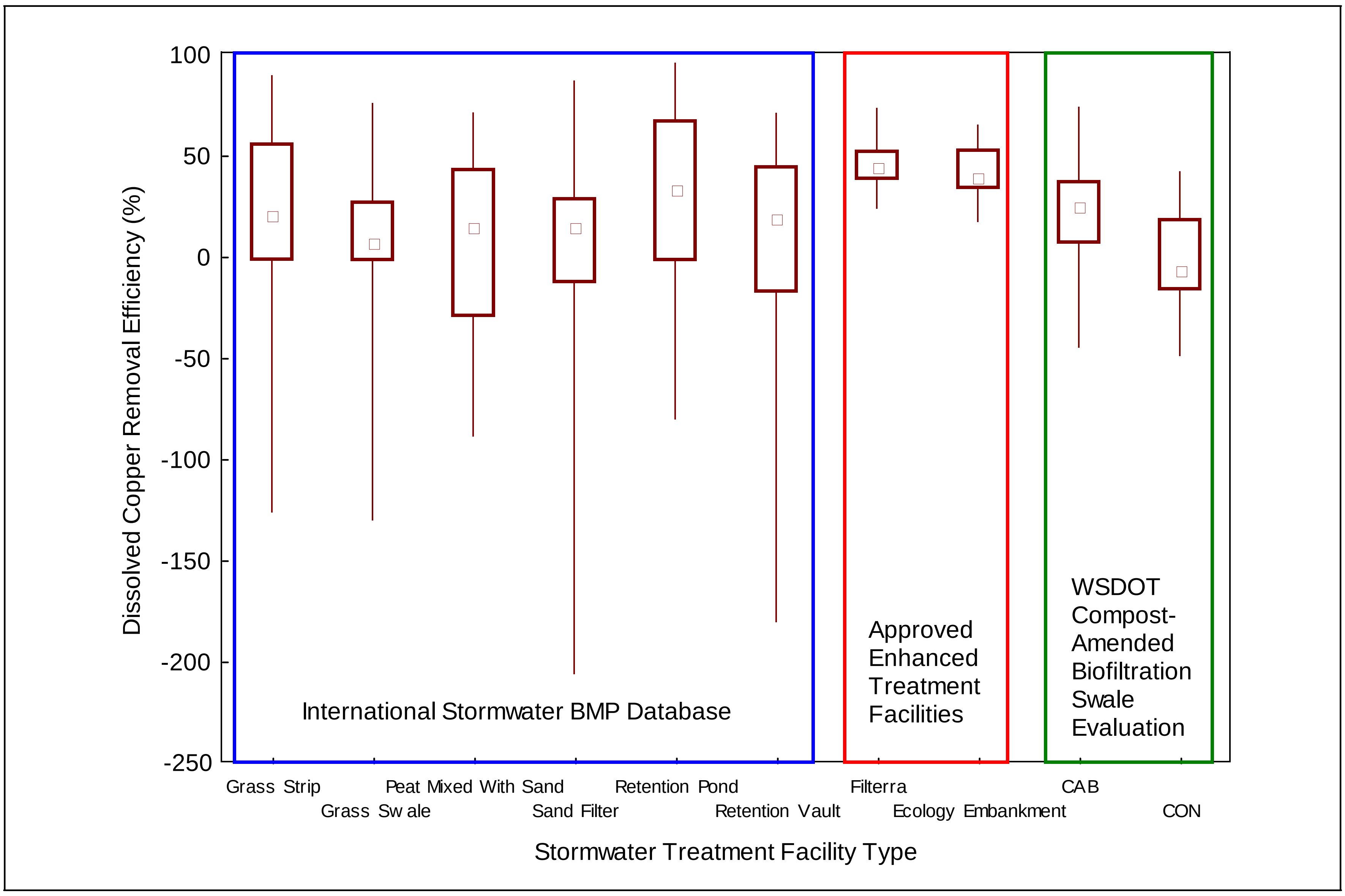

Figure 19. Comparison of dissolved copper removal efficiency estimates from the ISBMPD and approved enhanced treatment facilities compared to this study.

for Storm 19, and -13 percent for Storm 22). If the storm events with dissolved copper influent concentrations less than 0.006 mg/L are removed from the valid dataset, the new mean dissolved copper removal is 38 percent, comparable to the results from the WSDOT Ecology Embankment and Filterra Bioretention System studies. If an additional dissolved copper influent data point (i.e., 0.0054 mg/L) is added to bring the total number of samples up to 10, the bootstrapping approach can be used to analyze the data. Based on the results of this analysis, the lower 95 percent confidence limit for the mean was 29 percent. The same analysis performed on the control biofiltration swale data results in a mean of 11 percent and a lower 95 percent confidence limit for the mean of -3.0 percent (with an influent dissolved copper data point of 0.0059 mg/L added for a total of 10 samples).

Table 27. Dissolved copper basic treatment percent removal data from the ISBMPD and approved enhanced treatment facilities compared to this study.

BMP Type	n	Number of Facilities	Minimum Percent Removal	Mean Percent Removal	Maximum Percent Removal	p-value [a]
Basic Treatment Facilities (International Stormwater Best Management Practice Database)						
Biofilter – Grass Strip	151	25	-126%	23%	90%	0.4924
Biofilter – Grass Swale	86	15	-130%	11%	76%	**0.0452**
Filter – Peat Mixed With Sand	9	2	-88%	3.6%	72%	0.2667
Filter – Sand	78	8	-206%	5.6%	88%	**0.0548**
Retention Pond (Wet) – Surface Pond With a Permanent Pool	56	5	-80%	29%	96%	0.2343
Retention Underground Vault or Pipes (Wet)	29	2	-180%	7.5%	71%	0.2170
Total	409	57	-206%	17%	96%	
WSDOT Monitoring Study (2009-2010)						
Compost-Amended Biofiltration Swale (CAB)	16	1	-44%	22%	74%	NA
Control Biofiltration Swale (CON)	16	1	-49%	0.74%	43%	**0.0131**
Enhanced Treatment Facilities (General Use Level Designation from Ecology)						
WSDOT Ecology Embankment	10	1	17.6%	41.0%	65.5%	*1.0*
Filterra Bioretention System	23	2	24%	46%	74%	*1.0*

[a] Values in **bold** indicate that the alternate hypothesis is valid at a significance level of 0.10 (i.e., CAB removal > Basic or Enhanced treatment removal).

[b] Values in *italics* indicate that the null hypothesis is valid at a significance level of 0.10 (i.e., CAB removal ≤ Basic or Enhanced treatment removal).

To evaluate how irreducible dissolved copper concentrations may have influenced the results of this study, the ISBMPD was screened to look at influent dissolved copper concentrations less than 0.006 mg/L. In the dataset used for this analysis (Appendix I), there were 131 paired samples in the 0.0029 to < 0.006 mg/L range. The mean dissolved copper removal for this dataset was only 7.5 percent. The influent dissolved copper from the WSDOT Ecology Embankment evaluation was also examined; however, the lowest dissolved copper influent concentration in that study was 0.0075 mg/L, thus the same issues with irreducible dissolved copper concentrations were not encountered in that study.

Because dissolved copper treatment performance during this study was highly influenced by the low influent dissolved copper concentrations at this particular monitoring site, it is proposed that performance goals for dissolved zinc and copper also be evaluated based on the paired design with the control biofiltration swale serving as the basic treatment facility. Both swales received similar dissolved zinc (median of 0.051 mg/L for both swales) and dissolved copper (median of 0.0060 and 0.0064 mg/L for the compost-amended and control biofiltration swales, respectively) influent concentrations. Despite the same median influent dissolved zinc concentration for both swales, the compost-amended biofiltration swale results demonstrated a significantly higher removal efficiency (corresponding to a median improvement of 64 percent between the two swales) (Appendix G, Table G-3). Based on these results, and the comparison to dissolved zinc removal efficiency estimates from other basic and enhanced treatment facilities presented in Table 26, the compost-amended biofiltration swale does provide a level of treatment for dissolved zinc that can be considered better than basic.

Although the case for dissolved copper is slightly weaker, the comparison between the control and compost-amended biofiltration swales also demonstrated that the compost-amended biofiltration swale demonstrated a significantly higher removal efficiency (corresponding to a median improvement of 31 percent between the two swales) (Appendix G, Table G-3). The compost-amended biofiltration swale also performed significantly better than grass swales and sand filters in the ISBMPD. These results also indicate the compost-amended biofiltration swale does provide a level of treatment for dissolved copper that can be considered better than basic and a GULD should be issued for enhanced treatment.

In order to evaluate pollutant removal performance as a function of flow rate, a regression analysis was performed on the dissolved copper and dissolved zinc percent removal data from the compost-amended biofiltration swale. No significant relationship was found between the aliquot-weighted average flow rate and dissolved zinc percent removal, thus it can be assumed that there is no relationship between flow and dissolved zinc percent removal over the range of flow rates monitored during this study (0.010 to 0.078 cfs) (Appendix L, Figure L-3). There was a significant positive relationship ($p = 0.0256$) between the aliquot-weighted average flow rate and dissolved copper percent removal; however, dissolved copper percent removal is strongly related to influent dissolved copper concentration ($p = 0.0013$) (Appendix L, Figures L-4 and L-5, respectively). This suggests that dissolved copper is source-limited such that the influent dissolved copper concentration decreases (i.e., becomes more dilute) as the flow rate increases. Thus, the apparent relationship between flow rate and dissolved copper percent removal is confounded by this other explanatory variable. When influent dissolved copper concentrations less than 0.006 mg/L are removed from the dataset, the regression relationship between aliquot-weighted average flow rate and dissolved copper concentration is no longer significant (Appendix L, Figure L-6).

Oil Treatment

TAPE guidelines indicate an oil treatment goal of no ongoing or recurring visible sheen, a daily average TPH concentration of no greater than 10 mg/L, and a maximum of 15 mg/L for a discrete grab sample. Although only one influent sample collected in this study was higher than the minimum influent concentration of 10 mg/L, all results are presented here, since they represent typical concentrations found in highway runoff.

Based on TPH data obtained from 15 storm events sampled at the compost-amended biofiltration swale, influent TPH concentrations ranged from 1.28 to 10.5 mg/L, with a mean value of 3.00 mg/L (Table 13). For the same storm events, effluent TPH concentrations ranged from 0.11 to 1.72 mg/L, with a mean value of 0.47 mg/L. For all sampled storm events at the compost-amended biofiltration swale, TPH removal efficiency estimates ranged from 42 to 97 percent, with a mean value of 81 percent (Table 13).

As shown in Table 28, the upper 95 percent confidence limit for the mean effluent TPH concentration measured in the compost-amended biofiltration swale was 0.69 mg/L and the lower 95 percent confidence limit for the mean TPH percent removal was 73 percent. Visible oil sheen was not observed in any of the effluent samples (Table 29). Despite lower TPH influent concentrations than those specified in the oil treatment performance goals, the data presented in this TER shows that the compost-amended biofiltration swale is capable of providing significant treatment for the TPH concentrations found in typical highway runoff.

Table 28. Total petroleum hydrocarbon summary statistics for the compost-amended biofiltration swale.

All Data	Influent (mg/L)	Effluent (mg/L)	Percent Removal
COV	0.75	0.81	0.18
Bootstrapped Lower CI Mean	2.10	0.31	73
Bootstrapped Mean	3.00	0.47	81
Bootstrapped Upper CI Mean	4.20	0.69	88

mg/L: milligrams per liter
COV: coefficient of variance
CI: confidence interval

In order to evaluate pollutant removal performance as a function of flow rate, a regression analysis was performed on the TPH percent removal and effluent TPH concentration data from the compost-amended biofiltration swale. One outlier (Storm 5) had to be removed from the dataset since it imparted undue influence on the regression relationship due to the high flow rate (0.278 cfs) measured at the time that the sample was collected. The remainder of the instantaneous flow rates measured when the grab samples were collected ranged from 0 to 0.076 cfs. A log transformation was also performed on the data since the variance of the dependent variable was not constant across the range of values for the independent variable. After these data adjustments were made, the regression model was deemed to be valid. No significant relationship was found between the instantaneous flow rate and TPH percent removal or effluent TPH concentration, thus it can be assumed that there is no relationship between flow and TPH pollutant removal performance over the range of flow rates monitored during this study (0 to 0.076 cfs) (Appendix L, Figures L-7 and L-8).

Table 29. Visible sheen observations and TPH concentrations at the compost-amended biofiltration swale.

Event No.	Compost-Amended Biofiltration (CAB) Swale Inlet Observation	Compost-Amended Biofiltration (CAB) Swale Outlet Observation	Influent Concentration (mg/L)	Effluent Concentration (mg/L)
1	Not reported	Not reported	2.96	1.72
2	No visible sheen	No visible sheen	2.80	0.30
3	Visible sheen	No visible sheen	NA	NA
4	Visible sheen	No visible sheen	1.94	0.11
5	Visible sheen	No visible sheen	2.29	0.42
6	No visible sheen	No visible sheen	1.90	0.31
7	Visible sheen	No visible sheen	3.74	0.34
8	Visible sheen	No visible sheen	NA	NA
9	Visible sheen	No visible sheen	1.97	0.66
10	Visible sheen	No visible sheen	3.14	0.51
11	Visible sheen	No visible sheen	NA	NA
12	Visible sheen	No visible sheen	4.70	0.38
13	Visible sheen	No visible sheen	1.44	0.35
14	Visible sheen	No visible sheen	1.28	0.39
15	Visible sheen	No visible sheen	2.62	0.44
16	Visible sheen	No visible sheen	NA	NA
17	Visible sheen	No visible sheen	NA	NA
18	Visible sheen	No visible sheen	NA	NA
19	Visible sheen	No visible sheen	1.86	0.15
20	Visible sheen	No visible sheen	1.88	0.62
21	Not reported	Not reported	NA	NA
22	Visible sheen	No visible sheen	NA	NA
23	Visible sheen	No visible sheen	10.5	0.29

Note: Grab samples were not collected for Storms 3, 8, 11, 16, 17, 18, 21, and 22.

mg/L: milligrams/liter

Conclusions

Currently, WSDOT has very limited options for meeting end-of-pipe enhanced treatment for stormwater runoff. Constructed wetlands, the primary available stormwater technology, require a large area and ongoing maintenance, both of which are expensive in urban areas. Biofiltration swales require much less area and can easily fit in medians or right-of-way; however, they are currently approved for basic treatment, not for enhanced treatment.

This report presents performance data collected to support the issuance of a GULD for the compost-amended biofiltration swale. Hydrologic and water quality monitoring was conducted in a standard biofiltration swale (control) and a compost-amended biofiltration swale from May 2009 through June 2010. During this monitoring period, a total of 23 separate storm events were sampled, resulting in a total of 15 grab samples and 16 composite samples from each swale (15 of which were paired events with successful sampling at both the compost-amended and control biofiltration swales). The major conclusions for this monitoring are summarized below:

- The compost-amended biofiltration swale achieved superior treatment performance to the control biofiltration swale for all of the following parameters: TSS, dissolved and total zinc, dissolved and total copper, and TPH.
- The compost-amended biofiltration swale generally exported TP whereas the control biofiltration swale did not. Both the compost-amended biofiltration swale and control biofiltration swale exported SRP; however, SRP export from the compost-amended biofiltration swale was much higher.
- Based on the upper confidence limit for the mean TSS concentration in effluent samples (6.0 mg/L), and lower confidence limit for the mean TSS percent removal (91 percent), the compost-amended biofiltration swale met the basic treatment goal specified in TAPE with required statistical confidence.
- There was no significant relationship between flow rate and TSS removal, dissolved zinc removal, TPH removal, or effluent TPH concentration, demonstrating that the measured pollutant removal performance can be applied to the range of flow rates monitored during this study (0.010 to 0.078 cfs).
- There was a significant positive relationship between the aliquot-weighted average flow rate and effluent TSS concentrations; however, the maximum TSS effluent concentration measured at the compost-amended biofiltration swale was well below the 20 mg/L effluent goal over the range of flow rates monitored during this study.

- The compost-amended biofiltration swale provided superior treatment performance for dissolved zinc and copper relative to the control biofiltration swale and a number of other basic treatment BMPs. This provides a strong argument that the compost-amended biofiltration swale should be issued a GULD for enhanced treatment through the TAPE process.

- There was a significant relationship between the aliquot-weighted average flow rate and dissolved copper removal; however, dissolved copper percent removal is strongly related to the influent dissolved copper concentration. As the flow rate increases, the influent dissolved copper concentration decreases (i.e., becomes more dilute at higher flow rates). When influent dissolved copper concentrations less than 0.006 mg/L are removed from the dataset, the regression relationship is no longer significant.

- Despite lower TPH influent concentrations than those specified in the oil treatment performance goals for TAPE, data shows that the compost-amended biofiltration swale is capable of providing significant treatment for TPH concentrations found in typical highway runoff.

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