TECHNICAL EVALUATION REPORT

Modular Wetland System Stormwater Treatment System Performance Monitoring

Prepared for
Modular Wetland Systems, Inc.

Prepared by
Herrera Environmental Consultants, Inc.

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Some pages in this document have been purposely skipped or blank pages inserted so that this document will copy correctly when duplexed.

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Prepared for
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EXECUTIVE SUMMARY

Modular Wetland System - Linear filtration system (MWS-Linear) is a water quality treatment system consisting of a pre-treatment chamber, a media cartridge pre-filter, a wetland biofiltration chamber, and an outlet control device. The system is housed in a precast concrete vault and can be designed in numerous configurations including piped, curb or grated inlet structures.

Installation of the monitored MWS-Linear system at the Albina Maintenance Facility in Portland, Oregon.

From April 2012 through May 2013, Herrera Environmental Consultants, Inc. (Herrera) conducted hydrologic and water quality monitoring of a MWS-Linear for Modular Wetland Systems, Inc. at one approved test installation in Portland, Oregon. Herrera conducted this monitoring to obtain performance data to support the issuance of a General Use Level Designation (GULD) for the MWS-Linear by the Washington Department of Ecology (Ecology). Monitoring was performed in accordance with procedures described in *Guidance for Evaluating Emerging Stormwater Treatment Technologies; Technology Assessment Protocol – Ecology (TAPE)* (Ecology 2011).

This technical evaluation report (TER) was prepared by Herrera to demonstrate satisfactory performance of the MWS-Linear in meeting the minimum requirements as specified by Ecology (2011) for basic treatment, phosphorus treatment, and enhanced treatment.

Sampling Procedures

To evaluate the stormwater treatment performance of the MWS-Linear based on Ecology's TAPE guidelines, a test system was installed at the Portland Bureau of Environmental Services Albina Maintenance Facility in Portland, Oregon (Figure 1). This system is identified herein as the Albina Modular Wetland System (AMWS). Automated monitoring equipment was installed to continuously measure influent, effluent, and bypass flow volumes. Automated equipment was used to collect flow-weighted composite samples of the system's influent and effluent during 28 separate storm events in the monitoring period. The collected flow-weighted composite samples were analyzed for the following water quality parameters:

- Total suspended solids (TSS)
- Particle size distribution (PSD) (influent only)

- Total and dissolved copper
- Total and dissolved zinc
- Total phosphorus (TP)
- Soluble reactive phosphorus (SRP)
- Hardness
- pH

These data were subsequently analyzed in the following ways:

- Computation of pollutant removal efficiencies with bootstrap confidence intervals
- Statistical comparisons of influent and effluent concentrations
- Correlation analysis to examine the influence of treated flow rate on system performance

These results were then compared to TAPE minimum requirement goals for basic, phosphorus, and enhanced treatment.

Hydrologic Performance

The water quality treatment goal for the test system was to capture and treat 91 percent of the average annual runoff volume. Monitoring data showed that stormwater bypassed the AMWS test system during 49 out of 81 monitored events during the 14-month monitoring period. The system was able to treat 75 percent of the total volume that entered the system over this period. Consequently, the goal of treating 91 percent of the volume from the site was not achieved. This was most likely due to the high level of fine clay content of the runoff resulting in clogging of the media cartridge pre-filter located in the pre-treatment chamber (see *Maintenance Schedule*). In addition, analysis of the flow data at the end of the project indicated that the system was undersized for the basin. On average, a 1.54-inch storm (6-month storm for the region) produced a 102.6 gallons per minute peak discharge. The system was only sized to treat 41 gallons per minute.

During the monitoring period, it appeared that the wetland chamber's biofiltration media did not experience a substantial decrease in flow capacity indicating that the pre-treatment prevented the wetland media from clogging. There was a negative trend over time for treated flow rate during bypass due to accumulation of fine sediment on the pre-filter media. On average, the pre-filters required changing every 2 to 3 months. This frequency of maintenance was due, in large part, to the high clay content of the runoff from the Albina site. Under more typical stormwater loading conditions, it is anticipated that the pre-filter media will last 6 to 24 months before the media is required to be removed and replaced. Furthermore, since no flow decrease was observed in the WetlandMedia, it is anticipated that the wetland chamber will not require maintenance for several years. It should also be noted that with the inclusion of additional pre-filter cartridges the maintenance interval would likely have been extended. The required number of pre-filters should be determined on a site specific basis.

Water Quality Performance

Basic Treatment

The basic treatment goal in the TAPE guidelines is 80 percent removal of total suspended solids for influent concentrations ranging from 100 to 200 milligrams per liter (mg/L). For concentrations less than 100 mg/L, facilities must achieve an effluent goal of 20 mg/L pursuant to TAPE guidelines.

Total suspended solids removal rates ranged from 61 to 98 percent, with a mean value of 84.9 percent. The upper 95 percent confidence interval about the mean effluent concentration was 12.8 mg/L. The TAPE effluent goal is 20 mg/L or less, therefore the Basic water treatment criteria were met. Analyses of flow and water quality data indicated the treatment goal for total suspended solids removal was met up to and through the design flow rate of 41 gallons per minute (gpm) (equivalent of 1 gpm/ft^2 of media loading rate) for the MWS-Linear and even exceeded treatment goals at 50 gpm (1.21 gpm/ft^2).

Phosphorus Treatment

The phosphorus treatment goal in the TAPE guidelines is 50 percent removal of total phosphorus for influent concentrations ranging from 0.1 to 0.5 mg/L.

A bootstrap estimate of the lower 95 percent confidence limit (LCL95) of the mean total phosphorus reduction was 61.7 percent. Consequently, it can be concluded that the mean percent removal was significantly greater than the 50 percent goal specified in the TAPE guidelines. The system also exhibited removal rates greater than 50 percent up to and through the design flow rate of 41 gpm and even exceeded treatment goals at 50 gpm (1.21 gpm/ft^2).

Enhanced Treatment

The dissolved zinc treatment goal in the TAPE guidelines is 60 percent removal for influent concentrations ranging from 0.02 to 0.3 mg/L. The dissolved copper treatment goal is 30 percent removal for influent concentrations ranging from 0.005 to 0.02 mg/L. The lower 95 percent confidence limit of the mean percent removal was 60.5 and 32.5 percent for dissolved zinc and dissolved copper, respectively. These data indicate that the TAPE removal criteria were met for both dissolved zinc and dissolved copper. Treatment above the TAPE criteria of 60 percent removal was evident in the dissolved zinc results from treated flow rates up to and including the design flow rate of 41 gpm. Dissolved copper treatment was only evident up to 28 gpm; however, if lab data from 2007 are added to the data set, the flow rate at which 30 percent dissolved copper reduction can be achieved increases to the design flow rate of 41 gpm (1 gpm/ft^2 of media).

INTRODUCTION

The Modular Wetland Systems - Linear (MWS-Linear) is a structural stormwater treatment system developed by Modular Wetland Systems, Inc. The MWS-Linear utilizes a multi-stage treatment processes, including a pre-treatment chamber that houses a settling basin and a media cartridge pre-filters that are designed to remove coarse to fine sediment and hydrocarbons from entering the subsequent wetland chamber. The wetland chamber media provides chemical and biological filtration and secondary physical filtration. This system is housed in a modular precast concrete structure that can be designed in many inlet configurations. The MWS-Linear provides water quality treatment of captured flows through the processes of separation, sedimentation, filtration, adsorption, absorption, sequestration, volatilization, ion exchange, biological remediation, and uptake.

The Washington State Department of Ecology (Ecology) has established specific use level designations for emerging stormwater treatment technologies like the MWS-Linear in accordance with guidelines that are identified by Ecology (2011) in *Technical Guidance for Evaluating Emerging Stormwater Treatment Technologies: Technology Assessment Protocol - Ecology (TAPE)*.

There are three use level designations: pilot, conditional, and general. Pilot and conditional use level designations allow limited application of emerging stormwater treatment technologies in western Washington to facilitate field testing. If the testing shows that the treatment technology meets minimum treatment goals as identified in the TAPE, Ecology may issue a general use level designation (GULD) for the treatment technology, permitting its widespread use in Washington.

TAPE guidelines indicate that 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.

This document is the TER for the MWS-Linear, and was prepared by Herrera -to demonstrate satisfactory performance of the MWS-Linear in meeting treatment goals specified by Ecology (2011) for basic treatment, total phosphorus and enhanced treatment. It specifically presents data from a test MWS-Linear installed at the Portland Maintenance Bureau Albina Maintenance Facility (Figure 1). This monitoring was performed over a 14-month period, from April 14, 2012, through May 31, 2013.

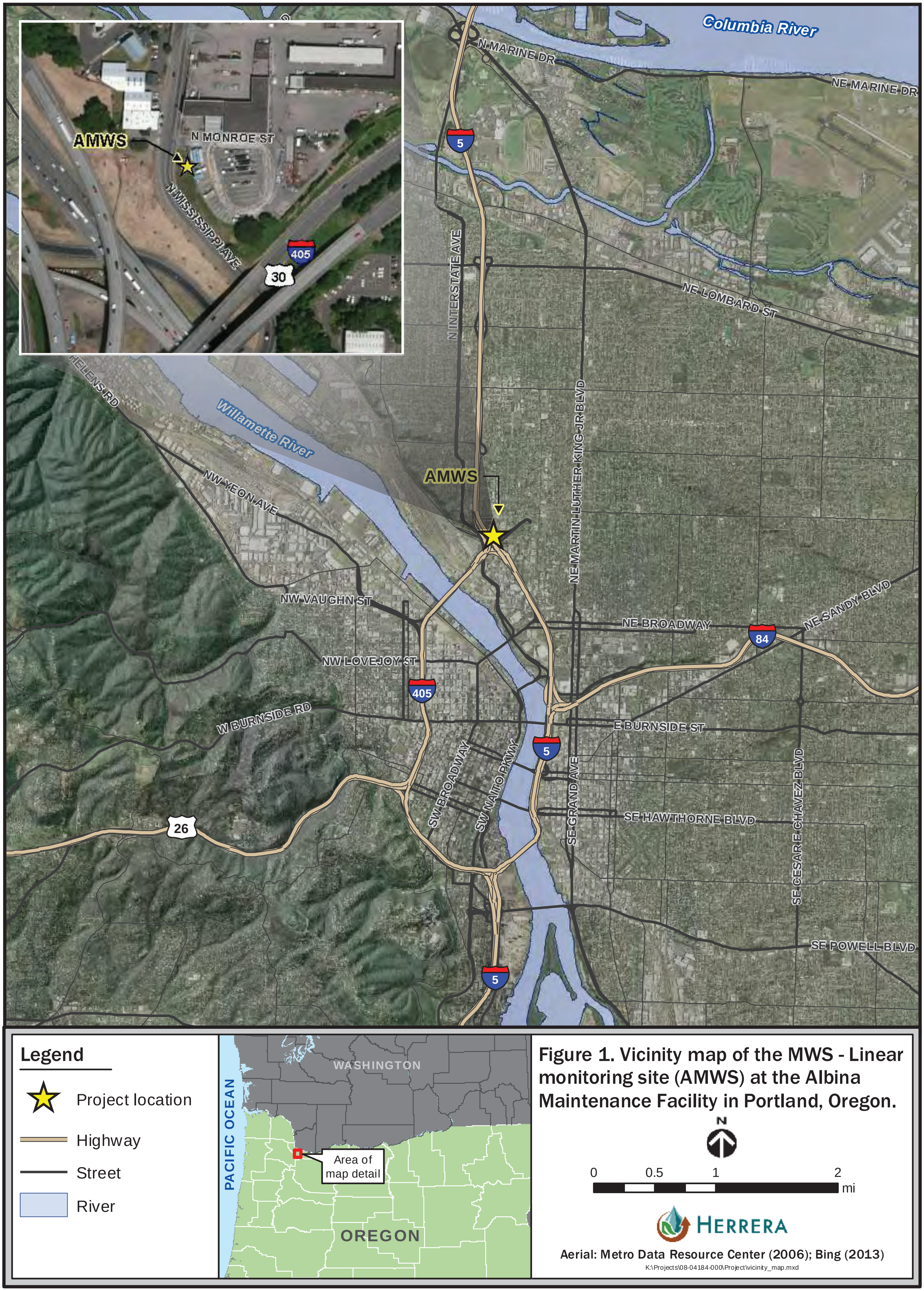

Figure 1. Vicinity map of the MWS - Linear monitoring site (AMWS) at the Albina Maintenance Facility in Portland, Oregon.

Aerial: Metro Data Resource Center (2006); Bing (2013)

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TECHNOLOGY DESCRIPTION

The MWS-Linear stormwater filtration system provides water quality treatment of captured flows through several physical, biological, and chemical unit processes. This section describes the system's physical components, treatment processes and removal mechanisms, sizing methods, expected treatment capabilities, expected design life, and required maintenance procedures.

System Overview

The MWS-Linear can be used in a variety of configurations, including curb, grate, and vault-type (piped) designs (Figures 2, 3, and 4). New construction and stormwater retrofit projects can utilize the modular design of the MWS-Linear in place of standard catch basin structures, rain gardens, bioretention cells, media filters, or other treatment devices. A variety of inlet, bypass, and wetland chamber designs are available for the MWS-Linear and can be easily be adapted for different stormwater drainage system designs and needs. However, the hydraulics within the system itself and the treatment processes are the same for each of these configurations.

Stormwater runoff enters the MWS-Linear via pipe, curb, or grate opening. For the MWS-Linear with a grate or curb-type opening, a catch basin filter insert facilitates the removal of gross solids and floatable trash prior to the stormwater entering the pre-treatment chamber. For the MWS-Linear with pipe openings (such as the study unit presented herein), stormwater enters the pre-treatment chamber directly. The pre-treatment chamber is specifically designed to settle out trash and litter, gross solids, and suspended sediment. Stormwater is then treated by the media cartridge pre-filters, which removes several pollutants, fine TSS, and hydrocarbons to protect the wetland chamber from clogging. After the stormwater moves through the media cartridge pre-filter, it enters the wetland chamber, which acts as a biofilter and is the main treatment component of the system. The MWS-Linear processes stormwater horizontally through the biofiltration media contained within the wetland chamber. Within this wetland chamber, a combination of physical, chemical, and biological mechanisms remove additional particulate and soluble pollutants. Treated runoff leaving the wetland chamber is controlled by a downstream orifice or flow control structure in the discharge chamber and leaves the system via the discharge chamber piping. The hydraulic conductivity of the biofiltration media contained within that wetland chamber is higher than the set orifice rate. In this manner the biofiltration media has a built-in hydraulic safety factor to ensure sustained treatment flow rates.

Physical Components

The MWS-Linear consists of a series of treatment components, beginning with a catch basin filter insert (for grate and curb-type configurations), a pre-treatment chamber, the BioMediaGREEN pre-filter, and finishing with a wetland chamber and discharge chamber. The

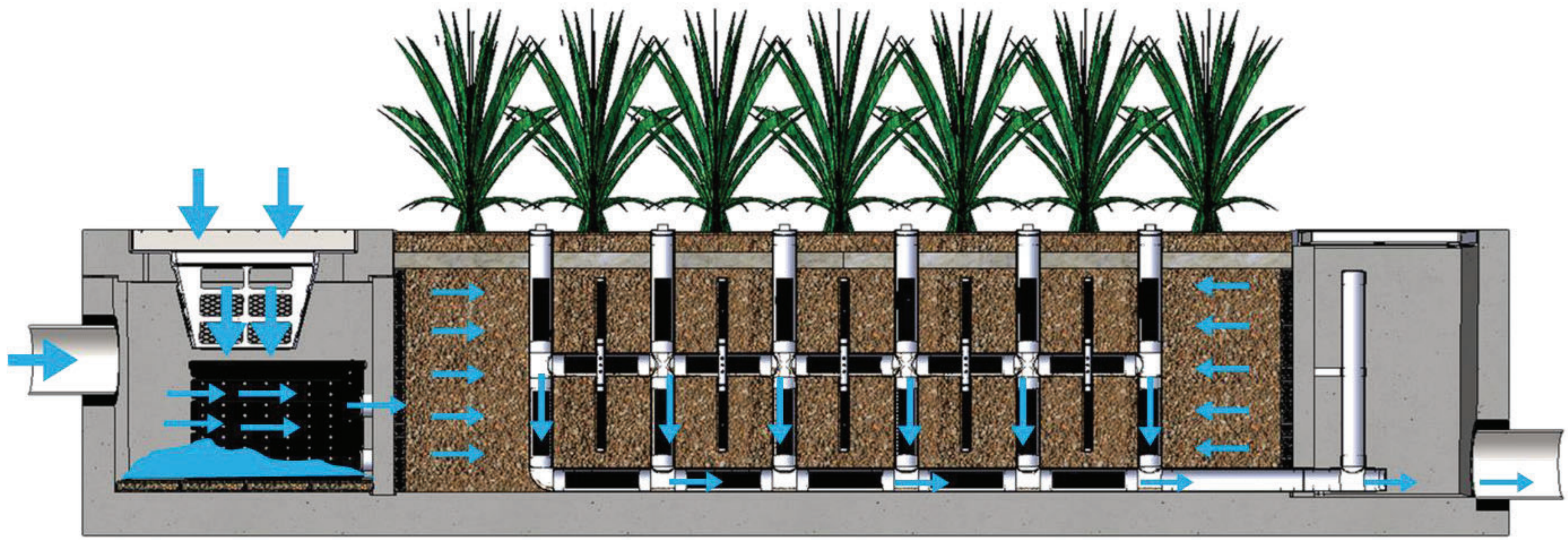

Figure 2. Cross-section of Typical Offline MWS-Linear System with Piped and Grated Inlet Flow.

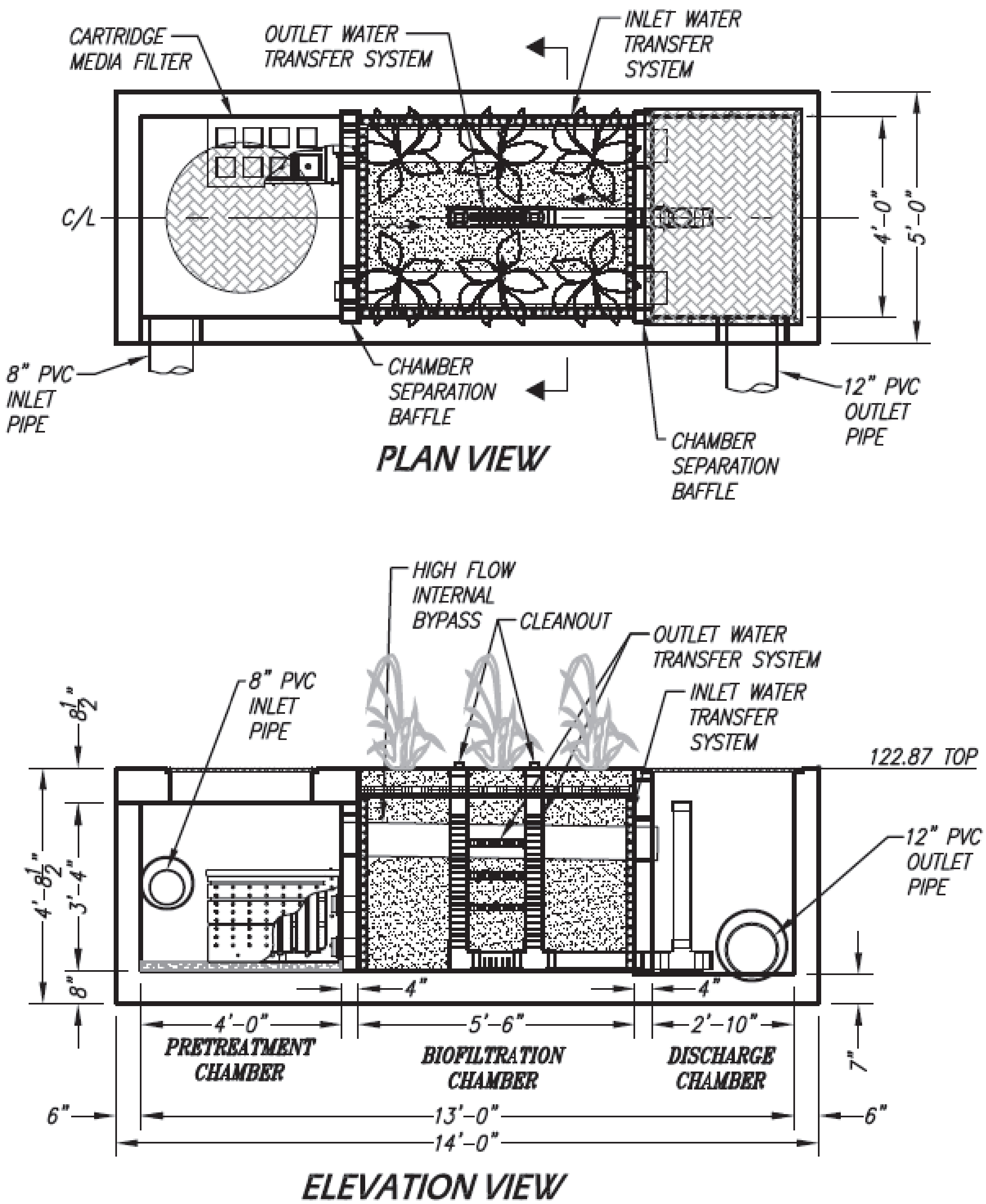

Figure 3. Design Details of Half Size MWS-Linear system with Piped Inlet Flow.

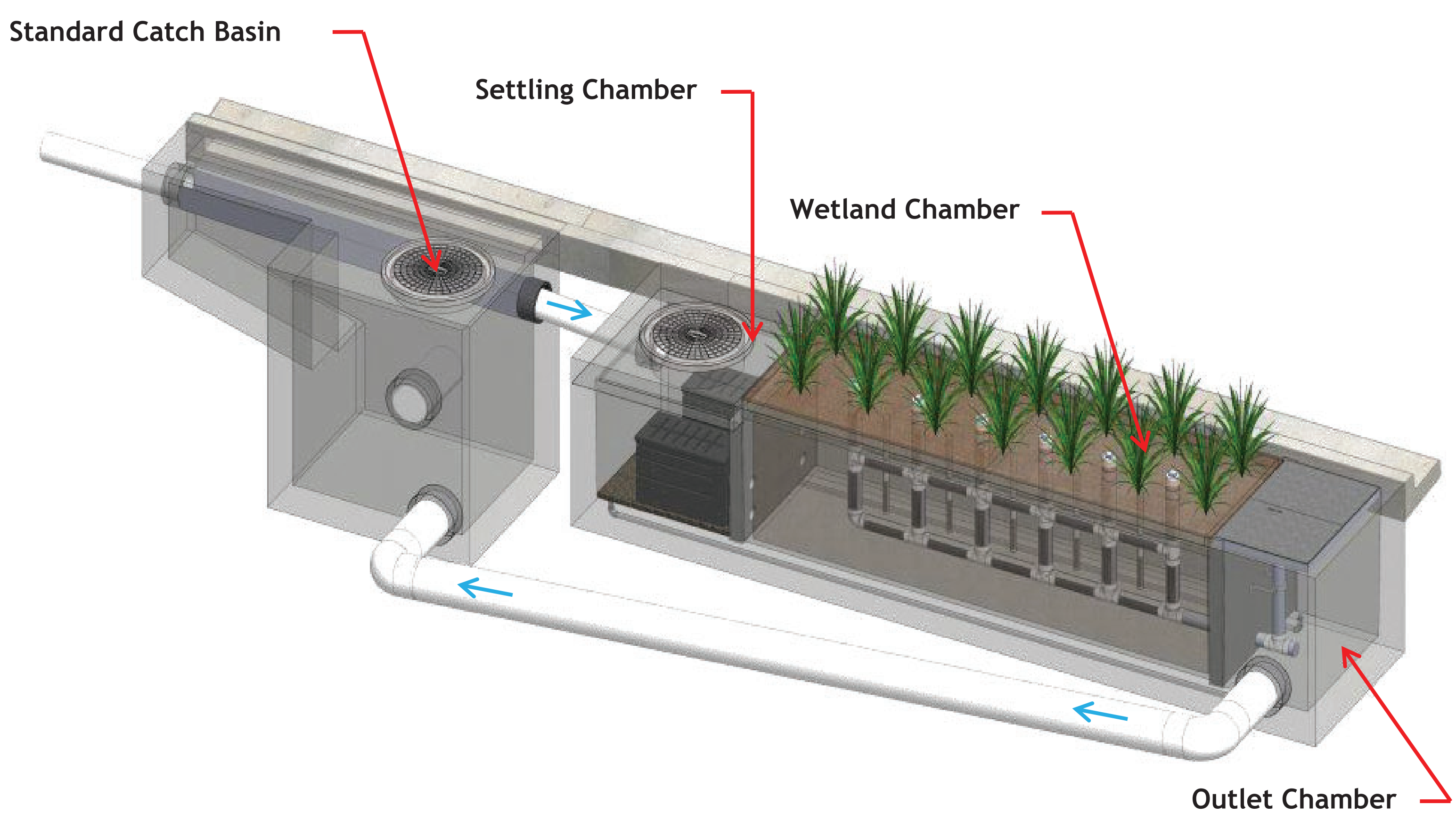

Figure 4. Perspective Rendering of Example MWS-Linear System with Piped Inflow and Upstream Structure.

discharge chamber collects flow from the wetland chamber and internal bypass pipes and routes stormwater to the outlet pipe.

The BioMediaGREEN can easily be removed and replaced from the media cartridge pre-filters to maintain the treatment performance within an acceptable range; the catch basin filter insert, pre-treatment chamber, and media cartridge pre-filter improve the wetland chamber performance by minimizing the pollutant loading on the biofiltration media. The primary components of the MWS-Linear are described below.

Structure

The MWS-Linear is a modular, precast concrete structure. Each MWS-Linear concrete structure is available in numerous lengths and widths to accommodate flow or volume requirements. There are several alternative configurations and the MWS-Linear can be adapted to a variety of site conditions. Each complete unit weighs approximately 9,000 to 70,000 pounds and requires a boom crane for installation.

Runoff can enter the system via built-in grate or curb inlet or enter directly into the pre-treatment chamber via pipe. The system has been designed to accommodate different depths without changing biofiltration media thickness or stormwater detention time. The system's horizontal flow biofilter and inlet configurations also allow it to be utilized in volume-based configurations downstream of storage BMPs, such as detention basins, ponds, or underground facilities.

The MWS-Linear is constructed with non-corrosive materials. All internal piping is SD35 or SD40 PVC. Catch basin filter insert components, including mounting hardware, fasteners, support brackets, filtration material, and support frame are constructed of non-corrosive materials (316 stainless steel and UV protected/marine grade fiberglass). Fasteners are stainless steel and the primary filter mesh is stainless steel welded screens. Media cartridge pre-filters are constructed of high strength HDPE. Mounts are constructed of stainless steel. BioMediaGREEN is a sorptive rock substrate and is inert and non-corrosive. The drain down filter cover is constructed of high strength HDPE and the hinge and mount are constructed of stainless steel.

Inlet

The MWS-Linear is available with a built-in grate or curb opening and/or can accept runoff via pipe. In the grate or curb type configuration, a catch basin filter is mounted directly under the opening to intercept trash and debris as well as coarse or large sediment. The size and shape of the catch basin filter varies from model to model. The catch basin filter utilizes progressively finer screen sizes to facilitate removal and maintain flow rates. It also possesses built-in internal openings for bypassing higher flows.

Pre-Treatment Chamber

The pre-treatment chamber is located below the inlet. The settling area within this chamber has been specifically designed to provide secondary pre-treatment of stormwater to settle large and coarse suspended solids.

Media Cartridge Pre-Filter

The media cartridge pre-filter is designed to house BioMediaGREEN but can use other various types of filter media. BioMediaGREEN is a proprietary engineered filter media made of a unique combination of inert, naturally occurring minerals. The BioMediaGREEN is designed as lightweight porous blocks, which are then cut into 1- by 1-centimeter cubes, and are packed into eight (8) separate cells around a center drain tube in each filter cartridges (Figure 5). This natural product is non-combustible, stable, biodegradable, and inert, having no known adverse effects on the environment.

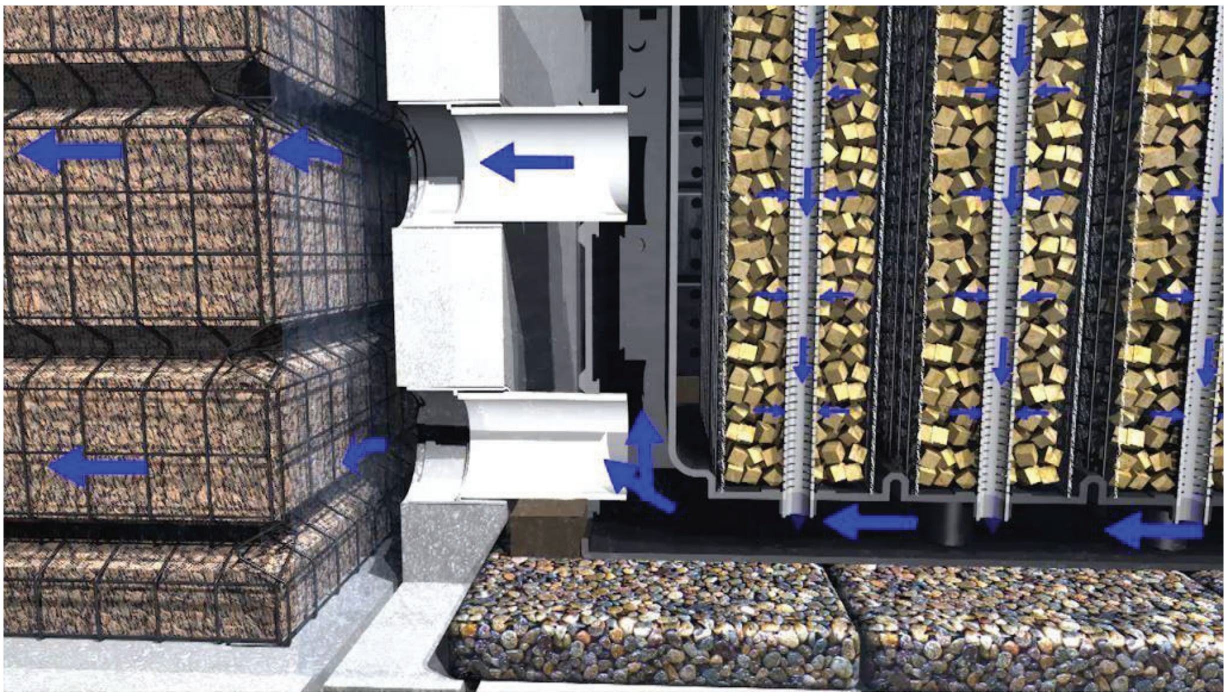

Figure 5. Rendering of Media Cartridge Pre-filters (Right) and Water Routing into the Wetland Chamber (Left).

The highly porous nature of BioMediaGREEN allows stormwater to easily flow around and through the cubes. The hydraulic conductivity of BioMediaGREEN is rated at 595 inches per hour, but stormwater also flows around each cube, so the actual hydraulic conductivity of the cartridges is much higher than the stated flow above.

BioMediaGREEN cubes also contain a high surface area to volume ratio, which promotes elevated levels of physical, chemical, and biological processes to treat stormwater. BioMediaGREEN filter cubes are designed to capture high levels of soluble and insoluble pollutants and hydrocarbons, including oils and grease, gasoline, diesel, polycyclic aromatic hydrocarbons (PAHs), and other organic chemicals. BioMediaGREEN cubes have the physical ability to block and filter trash, litter, vegetative matter, sediment, total suspended solids (TSS), total and dissolved metals, nutrients, and bacteria.

Maintenance of the media cartridge pre-filter is simple, and only requires access to the pre-treatment chamber (cartridges do not need to be removed for maintenance). To maintain, the lid of the cartridge is removed, the used BioMediaGREEN cubes are removed from each cell within the cartridge, the cartridge housing cleaned, new BioMediaGREEN cubes added, and the cartridge lid replaced. BioMediaGREEN cubes are light green in color when new, and turn a darker color as pollutants and sediment are absorbed onto its surface from untreated stormwater. Maintenance crews can easily determine if the filter cubes need replacement by virtue of this color change. The BioMediaGREEN cubes can typically be disposed of in an ordinary landfill (local regulations may apply).

The number and size of media cartridge pre-filters is customizable and can range from one to dozens depending on the treatment flow rate and influent solids loading. Recommendations for pre-filter configurations are provided in the *Sizing Methodology* section.

Stormwater Conveyance into Wetland Chamber and High Flow Bypass

After stormwater has passed through the pre-treatment chamber's settling area and media cartridge pre-filter, it is transferred out of the cartridge into a series of 4-inch diameter PVC SD35 manifolds (Figure 5) that lead to the wetland chamber's peripheral void area (known as the inlet water transfer system and described in the next section).

The MWS-Linear is available with one or more high flow bypass pipes near the top of the pre-treatment chamber for internal bypass. External bypass configurations are also available. All bypass configurations are used to convey stormwater around the wetland chamber and to the discharge chamber or downstream tie-in points. High flow bypass occurs when the MWS-Linear's flow capacity is exceeded. Alternative bypass configurations are also available for smaller and larger MWS-Linear models that include a built-in internal bypass weir wall. Since the wetland chamber is separated from the pre-treatment and discharge chamber, internal bypass has no effect on performance. Therefore, the wetland chamber only experiences the orifice controlled water quality flow rate, as determined during MWS-Linear sizing for each specific contributing drainage area.

Wetland Chamber

The wetland chamber is the primary stage of water treatment for the MWS-Linear. The system employs an innovative peripheral (perimeter) 2" void area on all four sides of the biofiltration media that extends to at least the height of the wetland chamber's operating hydraulic gradient level (HGL). This is known as the inlet water transfer system. Incoming stormwater surrounds the biofiltration media bed within the void space and migrates towards a series of vertically extended underdrain or collection piping located in the center of the cell. This is known as the outlet water transfer system. As such, it operates similar in fashion to a radial cartridge filter. The horizontal flow path through the media from an outside perimeter maximizes the available surface area and thus, treatment flow capacity. Because flow through the media is horizontal, the media thickness from influent point to effluent point remains constant, regardless of the height of the wetland chamber. Therefore, shallow or deeper systems can be specified without compromising treatment efficiencies associated with downward flow systems such as rain garden, bioretention systems and the like – all of which require the removal of media to accommodate shallow requirements.

The wetland chamber is filled with an engineered organic-free sorptive biofiltration media called WetlandMedia. The WetlandMedia is designed to maximize physical, chemical, and biological treatment processes along with supporting live vegetation. The WetlandMedia also includes a layer of plant propagation media above the active treatment zone to help with establishing vegetation. For example, the MWS-Linear Model #MWS-L-4-21 has a wetland chamber that is 4 feet wide by 13.8 feet long and has a physical chamber height of 4 feet. The overall O.D. dimensions of this model including the concrete vault, pre-treatment, and discharge chamber is 5 by 22 by 4.8 feet. The active media surface area of the wetland chamber for this model is 117 square feet at standard height. Radial subsurface flow through the WetlandMedia provides a combination of physical, chemical, and biological filtration processes for treatment of stormwater before it enters the discharge chamber. As interstitial voids in the media begin to slowly accrete suspended solids from the stormwater, the media becomes more carbon and nutrient rich. This results in more vigorous plant growth and increased micro-biological processing of the stormwater. The ecosystem that develops around the roots of the plants (or rhizosphere) is a complex combination of oxygen rich bacteria, fungi, and carbonaceous plant material. Biological growth and oxygen rich organisms mobilize, metabolize, and decompose influent pollutants and contribute to the overall treatment performance of the MWS-Linear.

After stormwater passes through the WetlandMedia it enters a series of perforated, 4-inch diameter, SD35 PVC outflow chamber transfer pipes, located along the chamber's central axis (Figure 3). The vertically extending perforated under drain pipes join to a common solid horizontal pipe manifold along the bottom of the wetland chamber. This pipe collects sub-surface flow from the wetland chamber and conveys the treated stormwater to the discharge chamber through an orifice that regulates treatment flow and loading rates through the wetland chamber.

Wetland Chamber Vegetation

A wide variety of upland or wetland plant species can be planted on the surface of the wetland chamber. Vegetation can be selected based on aesthetics, local climatic conditions, traffic safety, and maintenance considerations. However, adequate time (months) is necessary to allow for the plant roots and eco-biological organisms to colonize and to be well established within the wetland chamber. Table 1 provides a recommended plant palette for installations in the Pacific Northwest. For installations outside this area, the manufacturer will recommend other appropriate plants.

Vegetation was initially planted in mid-July of 2011, only 8 months prior to testing. The MWS-Linear had a physical height of 4 feet, yet due to the height limitation of the external bypass weir, the WetlandMedia was saturated to a depth of only 2.3 feet. The distance from the top of the unit, in which the vegetation is planted, and the active WetlandMedia was 1.6 feet. Based upon the observations of plant growth rate and root establishments rates for the variety of the plants utilized, it was determined that the roots did not reach the active treatment zone during at least the first years of testing from April 2012 to April 2013. Consequently, it can concluded that the systems physical, chemical, and biological treatment of the stormwater was primarily a function of the WetlandMedia and the microbes and beneficial bacterial that live within in it and less as function of the vegetation's root systems.

Table 1. Recommended Plant List for MWS Units Installed in the Pacific Northwest.

Scientific Name	Common Name
Grasses and Sedges	
Bromus carinatus	California brome grass
Bromus sitchensis	Alaska brome
Bromus vulgaris	California brome grass
Carex exicata	Blister sedge
Carex stipata	Awlfruit sedge
Elymus glaucus	Blue wildrye
Festuca californica	California fescue
Festuca occidentalis	Western fescue
Hordeum brachyantherum	Meadow barley
Forbes (Flowering Plants)	
Aquilegia formosa	Red columbine
Aster suspicatus	Douglas' aster
Camassia leichtlinii	Leichtlin's camas
Clarkia amoena	Farewell to spring
Delphinium leucophaeum	Pale larkspur
Epilobium angustifolium	Fireweed
Huechera micrantha	Smallflowered alumroot
Iris tenax	Oregon iris
Mimulus guttatus	Yellow monkey-flower
Sisyrinchium idahoense	Blue-eyed grass

Discharge Chamber

The discharge chamber collects treated stormwater from the outlet water transfer system as well as stormwater from high flow bypass pipes or weirs. The outlet water transfer system connects to the discharge chamber via a 4-inch PVC pipe to an orifice or flow control structure housed in the discharge chamber (Figure 3). The orifice is set to discharge stormwater at a calculated treatment flow rate equal to and not exceeding the design wetland loading rate given the media surface area for any size or height system. For example, the orifice insures the system is operating at 100 in/hr or 1.03 gpm at peak capacity and never at a higher flow rate to ensure optimal performance. The flow through the orifice is also much less than the hydraulic conductivity of the media itself and therefore providing a built-in safety factor against potential clogging over several years or operation. Flows collected in the discharge chamber are routed to a discharge pipe.

Treatment Mechanisms

The MWS-Linear provides water quality treatment of captured flows through physical, chemical, and biologic unit processes. Runoff treatment is achieved through screening, sedimentation, filtration, absorption, adsorption, sequestration, sorption, biological remediation, and uptake.

Screening

For MWS-Linear grate-type systems, the catch basin insert located at the inlet intercepts the majority of floatable and gross solids, trash and litter, and coarse sediment before entering the pre-treatment chamber. The catch basin insert filter is designed with multiple levels of various screen sizes to remove pollutants.

Sedimentation

The MWS-Linear contains a pre-treatment chamber below the inlet, and has been designed to promote gravity or hydrodynamic settling of entrained particles. Settling of large particles in the pre-treatment chamber improves the system's performance as well as extends the life of the media cartridge pre-filter. The amount of sedimentation is a function of particle density, size, water density and viscosity, internal turbulence, and residence time.

Filtration

Particulates are physically removed from suspension as they contact the BioMediaGREEN contained within in media cartridge pre-filter(s). Pollutant removal rates achieved through the cartridges alone are a function of the stormwater composition, flow, and pre-treatment effectiveness. Filtration is also the primary physical unit process or mechanism in the wetland chamber. The 3- to 5-millimeter WetlandMedia in the wetland chamber creates a non-linear and torturous flow path which enhances contact between the stormwater and the various filtration media.

Adsorption

Unlike filtration, where physical processes control removal of sediment from suspension, adsorption relies on opposing surface charges of the BioMediaGREEN filter media and wetland chamber media and dissolved constituents to remove pollutants from stormwater. The BioMediaGREEN filter media is designed with a high surface area so that the binding sites are not exhausted through its expected life cycle. In addition, both the WetlandMedia and the BioMediaGREEN possess a high cation exchange capacity that promotes the effective removal of positively charged dissolved pollutants (including transition and heavy metal ions) from the incoming stormwater.

Biological Remediation

Bacterial growth, supported by the root system in the wetland chamber, performs a number of treatment processes. These vary as a function of moisture, temperature, pH, salinity, and pollutant concentrations. Biologically available forms of nitrogen, phosphorus, and carbon are actively taken into the cells of vegetation and bacteria, and used for metabolic processes (i.e., energy production and growth). Nitrogen and phosphorus and many heavy metals common to stormwater are actively taken up as micronutrients that are vital for a number of cell functions, growth, and energy production. These biological processes remove metabolites from the media during and between storm events, making the media available to capture more nutrients from subsequent storm events.

Aerobic and anaerobic soil organisms in the wetland chamber break down, decompose, sequester, and volatilize a wide array of organic compounds into less toxic forms or completely break them down into carbon dioxide and water (Means and Hinchee 1994). Bacteria can also cause metals to precipitate out as salts, bind them within organic material, and accumulate metals in nodules within the cells. Finally, plant growth may metabolize many pollutants, sequester them or rendering them less toxic (Reeves and Baker 2000).

Site Requirements

Necessary Soil Characteristics

Specific underlying soil characteristics are not required for the MWS-Linear, since it is a self-contained, watertight system and is fully enclosed. However, the manufacturer does require that the MWS-Linear system be installed on a level bed of gravel 6 inches in depth (see Installation Manual). The system can be installed with open holes in the bottom of the discharge chamber to transfer treated stormwater to soils below to maximize infiltration if desired.

Hydraulic Grade Requirements

The MWS-Linear is completely passive and requires a minimum of 4.13 feet fall from the top of the unit to pipe invert outlet for standard models. Taller and shorter units are available for areas with limited fall conditions. For piped flows, water entering the system can come in with as little as 6 inches of flow between inflow pipe and outflow pipe. At the same time, the internal the internal or external bypass must be at an elevation equal to the operating hydraulic gradient level (HGL) of the system. Bypass can be either internal or external depending on the site specific configuration. Surface bypass occurs with curb or grate type configurations where a secondary basin in installed just downstream of the MWS-Linear to intercept all flows above its treatment capacity. For pipe flows, an internal or external bypass pipe(s) or weir can be used at the proper elevation. This amount of fall ensures that the maximum wetland surface area is utilized in the MWS-Linear for maximum performance. The MWS-Linear can also accept runoff from upstream storage basins in a volume based configuration.

Depth to Groundwater Limitations

Since it is fully enclosed, the MWS-Linear does not have depth to groundwater limitations. For each installation, the manufacturer assess groundwater depth and calculates buoyancy assuming dry filtration media to assure that the system will be negatively buoyant.

Utility Requirements

The MWS-Linear system is a passive system that requires no power, and has a free-draining outfall to an appropriate water conveyance or storage system (e.g., wet pond, storm sewer, or underground infiltration).

Intended Application

The MWS-Linear is intended to be used for stormwater filtration in applications ranging from industrial and commercial to high and low density residential settings. Depending on the land use, maintenance frequency may have to be adjusted accordingly. For instance, the pre-treatment chamber including the media cartridge pre-filter will likely have to be more frequently maintained when treating high ADT roadway versus residential street runoff.

Pretreatment Requirements

There are no pretreatment requirements for the MWS-Linear since the system includes a built-in multi-stage pre-treatment system. However, in applications where heavy sediment loading is anticipated from upstream basins connected to the MWS-Linear via pipe the use of catch basin filters or standard sumped catch basins can be helpful.

Current Installations

As of August 2013, there are 143 MWS-Linear installations nationwide. Appendix A provides the location, land use, and size of each of these installations. There is currently one MWS-Linear installed in the Pacific Northwest, with more than a dozen set for installation by the end of 2014.

Sizing Methodology

Laboratory testing of the MWS-Linear indicates high levels of pollutant removal performance at a loading rate of 100 inches an hour or 1.03 gallons per minute per square foot (gpm/sq ft) of surface area of the WetlandMedia inside the wetland chamber. The MWS-Linear offers adjustable pre-filter sizing based on influent solids loading. For moderate total suspended solids runoff concentrations of between 10 and 50 mg/L (typical of residential basins and moderate use parking lots), the pre-filter is sized at 3 gpm/sq ft of surface area. For total suspended solids loading greater than 50 mg/L (typical of commercial/industrial basins or high use parking lots), the pre-filter is sized at 2.1 gpm/sq ft of surface area. It is recommended that periodic monitoring during the first year of installation be conducted in order to determine the correct pre-filter configuration.

The MWS-Linear is available in over nine standard models, each model containing different size wetland chambers and pre-filter configurations. Since the MWS-Linear is a horizontal flow biofilter, its operation is similar to a radial cartridge. Influent stormwater fills the void area around the biofiltration bed (WetlandMedia) bed in the wetland chamber up to a specific operating level or height. The surface area of the biofiltration bed is calculated by adding all perimeter lengths by the operating height of the biofiltration bed. An orifice or flow control structure is housed downstream of the wetland chamber in the discharge chamber. The size of the orifice is calculated based upon a target-loading rate of 1.03 gpm/sq ft of surface area, with the maximum loading rate not to exceed the maximum flow rate for the three media cartridge pre-filters. The maximum water level before bypass is set to meet the required or desired operating level of the wetland chamber. The WetlandMedia has a hydraulic conductivity of greater than 12.75 gpm/sq (or 1,275 in/hr). This provides a safety factor of over 12 based on its orifice controlled design rate of 1.03 gpm/sq ft. The pre-filter media (BioMediaGREEN cubes) has a hydraulic conductivity of 5.95 gpm/sq ft (or 595 in/hr). This provides a safety factor of at least two based upon its design loading rate of between 2.1 and 3 gpm/sq ft.

For preliminary sizing purposes, a sizing table was developed that provides maximum contributing areas for each of the standard sizes of MWS-Linear for both western (Table 2) and eastern Washington (Table 3). In addition, the recommended number of pre-filter cartridges based on loading from the basin is provided in each table. The following sections describe the modeling used to generate the tables.

Western Washington

MWS-Linear systems designed for use in western Washington are sized using the Western Washington Hydrology Model, Version 2012 (WWHM2012), or another continuous hydrologic model approved by Ecology, to treat a minimum 91 percent of the annual stormwater volume. The remaining 9 percent of the annual stormwater volume bypasses the treatment system through either an external bypass pipe or internal weir wall. The design calculations for each size MWS-Linear system are determined at an approved hydraulic loading rate of1.03 gpm/sq ft.

For preliminary flow-based sizing purposes, a sizing table was developed that provides maximum contributing areas for each of the standard sizes of MWS-Linear systems (Table 2). The table provides design flow rates for MWS-Linear systems with external bypasses, the design flow rates will be reduced by 29 and 18 percent for systems with internal piped or internal weir bypasses, respectively. The sizing table was generated based on a developed ("mitigated") basin that consists of a flat parking area located in a region represented by the SeaTac rain gage with a precipitation-scaling factor of 1.0. The sizing table is to be used for planning level use only. The design engineer must use a continuous model with the site-specific drainage area and precipitation to confirm that the unit will treat the required volume. As part of the design process Modular Wetland System's engineering department reviews the water quality requirements and confirms the MWS-Linear is sized correctly and according to the approved loading rate and projects treatment flow.

Eastern Washington

MWS-Linear systems designed for use in Eastern Washington are sized to treat the 6-month, 3-hour storm. For preliminary sizing purposes, a sizing table was developed that provides maximum contributing areas for each of the standard sizes of MWS-Linear systems in Region 3 - Spokane (Table 3). The table provides design flow rates for MWS-Linear systems with external bypasses, the design flow rates will be reduced by 29 and 18 percent for systems with internal piped or internal weir bypasses, respectively. The sizing table is to be used for planning level use only. The design engineer must use an approved single event model with the site-specific drainage area and precipitation to confirm that the unit will treat the required volume.

Expected Treatment Capabilities

The MWS-Linear is designed to remove gross solids, suspended solids, heavy metals, petroleum hydrocarbons, bacteria, and nutrients from stormwater. A combination of field and laboratory tests have been conducted on the MWS-Linear and the media cartridge pre-filter BioMediaGREEN. Specifically, in 2007 a scaled-down laboratory test was conducted to assess the performance of the MWS-Linear system; the same year, a separate laboratory test was

Table 2. MWS-Linear Sizing Table for Western Washington.

Available MWS Box Sizes (feet)	Total Wetland Media Surface Area (sf)	Water Quality Design Flow Rate Target (cfs)	Maximum Contributing Drainage Area (acres)	15-minute Offline Water Quality Flow Rate (cfs)	15-minute Offline Water Quality Flow Rate (gpm)	# of Pre-filter Cartridges: Moderate Influent Loading	# of Pre-filter Cartridges: High Influent Loading
4 x 4	22.8	0.052	0.567	0.052	23.3	3	4
3 x 6	34.2	0.078	0.850	0.078	35.0	4	6
4 x 8	50.3	0.115	1.253	0.115	51.6	6	8
4 x 13	62.6	0.144	1.569	0.144	64.6	7	10
4 x 15	76.2	0.175	1.907	0.175	78.5	8	12
4 x 17	89.8	0.206	2.245	0.206	92.5	10	14
4 x 19	103.4	0.237	2.582	0.237	106.4	11	16
4 x 21	117	0.268	2.920	0.268	120.3	13	18
8 x 12	151	0.346	3.770	0.346	155.3	16	23
8 x 16	201.3	0.462	5.033	0.462	207.4	21	30

Notes:

1. Sizing table intended for planning level use. The design engineer must use WWHM2012 or approved equivalent and the site location mapping to calculate the appropriate facility size for each installation in western Washington.
2. Sizing table meets the offline 15-minute water quality flow rate as specified in the Stormwater Management Manual for Western Washington (Ecology 2012).
3. Sizing table based on WWHM2012 parking/flat basin (100 percent impervious) and SeaTac rain gage with precipitation factor of 1.0.
4. Sizing based upon standard height unit with external bypass and an active wetland media height of 3.4 feet. Internal piped bypass will reduce the design flow rate by 29 percent while internal weir bypass (available on the 4x4, 4x8, 8x12, and 8x16 models) will reduce the design flow rate by 18 percent.
5. Pre-filter sizing is adjustable based on influent loading. Moderate loading can be expected from residential areas and moderate use parking lots, heavy loading can be expected from commercial/industrial areas and high use parking lots.

Table 3. MWS-Linear Sizing for Eastern Washington

Available MWS Box Sizes (feet)	Total Wetland Media Surface Area (sf)	Water Quality Design Flow Rate Target (cfs)	Maximum Contributing Drainage Area (acres)	6-month, 3-hour Flow Rate (cfs)	6-month, 3-hour Flow Rate (gpm)	# of Pre-filter Cartridges: Moderate Influent Loading	# of Pre-filter Cartridges: High Influent Loading
4 x 4	22.8	0.052	0.091	0.052	23.3	3	4
3 x 6	34.2	0.078	0.147	0.078	35.0	4	6
4 x 8	50.3	0.115	0.228	0.115	51.6	6	8
4 x 13	62.6	0.144	0.290	0.144	64.6	7	10
4 x 15	76.2	0.175	0.358	0.175	78.5	8	12
4 x 17	89.8	0.206	0.425	0.206	92.5	10	14
4 x 19	103.4	0.237	0.492	0.237	106.4	11	16
4 x 21	117	0.268	0.559	0.268	120.3	13	18
8 x 12	151	0.346	0.728	0.346	155.3	16	23
8 x 16	201.3	0.462	0.979	0.462	207.4	21	30

Notes:

1. Sizing table intended for planning level use. The design engineer must use an accepted single event model to calculate the appropriate facility size for each installation in eastern Washington.
2. Sizing table treats the 6-month, 3-hour storm as specified in the Stormwater Management Manual for Eastern Washington (Ecology 2004).
3. Sizing table based on a 100 percent impervious basin (CN = 98) and Region 3 – Spokane precipitation.
4. Sizing based upon standard height unit with external bypass and an active wetland media height of 3.4 feet. Internal piped bypass will reduce the design flow rate by 29 percent while internal weir bypass (available on the 4x4, 4x8, 8x12, and 8x16 models) will reduce the design flow rate by 18 percent.
5. Pre-filter sizing is adjustable based on influent loading. Moderate loading can be expected from residential areas and moderate use parking lots, heavy loading can be expected from commercial/industrial areas and high use parking lots.

conducted to assess the performance of the BioMediaGREEN alone. Subsequent to these tests, a full-scale field test of the MWS-Linear system was conducted in California to evaluate removal of several stormwater pollutants of concern, including total suspended solids, phosphorus, and total and dissolved metals. The results from these experiments indicated that the combination of the media cartridge pre-filter containing BioMediaGREEN and MWS-Linear WetlandMedia removed greater than 80 percent total suspended solids, 70 percent dissolved copper, 88 percent dissolved zinc, and 70 percent total phosphorus. Additional information about previous studies of the MWS-Linear and BioMediaGREEN can be found in the Conditional Use Level Designation (Herrera 2011a) for the MWS-Linear, which was filed with the Washington State Department of Ecology in May 2011.

Estimated Design Life

The non-consumable structural components of the MWS-Linear system are designed to last 25 years or more before needing maintenance or replacement of internal components. The concrete structure of the system has a user life of over 50 years. The manufacturer recommends that, on average, the pre-treatment chamber be maintained every 6 to 12 months. The manufacturer also recommends that the pre-filter media be replaced every 6 to 24 months depending on loading conditions and number of pre-filters installed. If pollutant loading is abnormally high, however (e.g., due to roadway sanding, construction runoff, or when installed at Industrial sites), the maintenance requirements of the pre-treatment chamber and media cartridge pre-filter will increase. In addition, if the system is inadvertently undersized for the basin it is expected that more frequent replacement of the pre-filter media will be required. Maintenance on the wetland chamber is not expected for many years, as the media cartridge pre-filter will prevent sediments and hydrocarbons from entering and clogging the WetlandMedia. Due to the high variation of loading conditions from site to site, it is recommended that first year inspections are done to assess the loading condition of the site on the MWS-Linear. Based upon this first year of observation, a site-specific maintenance frequency and pre-filter configuration can be established.

Installation

The MWS-Linear is a precast watertight concrete structure. The internal components are pre-assembled prior to delivery to the installation site. The system is delivered on a flatbed truck. The installer or contractor will need to provide a crane capable of off-loading the unit and placing it into the ground. Prior to delivery, the appropriate excavation should be completed, and the bottom 6 inches backfilled and leveled using the appropriate and recommended material compacted to 95 percent of maximum density.

Prior to installation, all inlets are blocked and wetland chamber covered to prevent construction sediment contamination from the site. Backfilling should be performed in a careful manner, bringing the appropriate fill material up in 6-inch lifts on all sides. Precast sections shall be set in a manner that will result in a watertight joint. In all instances, installation of the MWS-Linear shall conform to ASTM specification C891 *Standard Practice for Installation of Underground Precast Utility Structures*, unless directed otherwise in contract documents.

Operation and Maintenance Requirements

Every installed MWS-Linear unit is to be maintained by the Supplier, or a Supplier approved contractor for at least the first year. The cost of this service varies among outside service providers. The MWS-Linear is a multi-stage self-contained treatment train for stormwater treatment. Each stage is designed and intended to protect subsequent stages from clogging. Stages include screening, separation, cartridge media filtration, and biofiltration. The biofiltration stage can contain various types of vegetation or plantings. Annual inspection is required to evaluate plant health and trim excess vegetation. The maintenance procedures are described below.

1. **Clean Catch Basin Filter –** On systems with surface inlet flow, screening is provided by a catch basin filter. The filter will contain coarse sediment, trash, and other floatables. Sediment capacity is reached at 2 cubic feet for the curb style inlet and 4 cubic feet for the drop or grated inlet configuration (varies with smaller and larger models). The filter removes gross solids, including litter, and sediment greater than 200 microns. The cleaning procedure is easily done by hand or with a small industrial vacuum device. This filter is located directly under the manhole cover or grate for easy access.

2. **Clean Pre-Treatment Chamber –** separation occurs in the pre-treatment chamber's settling area located directly under the curb or grated inlet. This chamber has a capacity of approximately 21 cubic feet for trash, debris, and sediments for most model sizes (varies with smaller and larger models). The chamber targets total suspended solids and particulate metals and nutrients. Cleaning the settling area can be performed with a standard vacuum truck or hand held industrial shop vacuum. This chamber is located directly under the manhole or grate access cover for easy access into the chamber.

3. **Replace Pre-Filter Cartridge Media (BioMediaGREEN™) –** Initial filtration is provided by a horizontal flow cartridge filter utilizing BioMediaGREEN media. Media life depends on local sediment loading conditions and can easily be replaced and disposed of without any equipment. The BioMediaGREEN media is held within the media cartridge pre-filters that are housed in the pre-treatment chamber. Entry into the pre-treatment chamber is required to replace the BioMediaGREEN media. The lid of the media cartridge pre-filter is removed by loosening two bolts. Once removed maintenance personnel have unimpeded access to each media cage housing the BioMediaGREEN which can be quickly removed by hand or with a vacuum truck. Once old BioMediaGREEN is removed new material, provided is pre-weighed bags, is dropped into the media cage housings. Once completed, the cartridge lid is replaced and bolts tightened on the lid of the media cartridge pre-filter.

4. **Replace Drain Down Filter Media (BioMediaGREEN™) –** An optional drain down filter (not included in the test unit), similar in function to the media cartridge pre-filter is located in the discharge chamber. This filter allows any standing water from the pre-treatment chamber to drain from under the pervious pavers through the small filtration cartridge located in the discharge chamber. The drain down device addresses

any vector issues, by eliminating all standing water within the MWS-Linear. Replacement of media can be performed by hand.

5. **Trim Vegetation -** The MWS-Linear utilizes multiple plants in the wetland chamber to enhance pollutant removal. The vegetation will need to be maintained (trimmed) as needed and is done as part of regular site landscaping or system maintenance. Modular Wetland Systems, Inc. recommends that the plantings are never given any fertilizer to promote plant growth or health.

6. **Evaluate Flow Hydraulic Conductivity -** The system's flow characteristics can be assessed from the discharge chamber. This inspection for adequate flow capacity should be done during a rain event. By inspecting and viewing the discharge chamber, the flow out of the system can be easily observed or measure. If flow out of the orifice is too low, it could indicate media cartridge pre-filter fouling and maintenance may need to be provided to the BioMediaGREEN as described above.

7. **WetlandMedia Maintenance -** biofiltration is provided by an advanced horizontal flow vegetated wetland chamber. This biofilter contains a mix of sorptive media, known as WetlandMedia, which is designed to supports abundant plant and biological life. The life of this media can be up to 20 years when properly maintained. The peripheral void area surrounding the perimeter of the WetlandMedia can be accessed to remove any surface clogging. The vertical risers in the middle of the WetlandMedia can also be accessed and water injected to backwash the WetlandMedia. These features allow the wetland chamber to be fully maintained to ensure the WetlandMedia will not need to be replaced for many years. If full flow capacity cannot be restored by these steps, the WetlandMedia can be replaced.

8. **WetlandMedia Replacement -** Removal of spent WetlandMedia can be done with a shovel nose of any vacuum truck. Replacement of the WetlandMedia, although not anticipated for 20 years, is done by adding new WetlandMedia from a number of vendor supplied supersacs and added to fill the wetland chamber to recommended levels.

Reliability

The MWS-Linear is a robust water quality system designed to withstand a variety of conditions in the field. The media cartridge pre-filter containing BioMediaGREEN is designed to capture sediment and hydrocarbons and subsequently clog before the WetlandMedia in the biofiltration or wetland chamber. Once the pre-filter clogs, flow capacity decreases and the influent flows are routed around the wetland chamber through the external or internal bypass mechanism until the unit is maintained. The likelihood of this occurring is also significantly reduced by the design of the bypass. If an MWS-Linear begins to clog, it will go into bypass before flushing built up pollutants from the media(s) as bypass occurs around these mechanisms and not through their chambers. The pre-treatment chamber can also be fitted with an optional drain down system to prevent any standing water conditions in the chamber between storm events. This can be used in areas where vector control may be an issue. The current flow capacity of the MWS-Linear can easily be monitored by observing flow into the discharge chamber. Various instrumentation can be used to verify the flow rate through the system. If the system is operating at less than 100 percent, treatment flow capacity maintenance procedures can be pre-formed in the pre-treatment chamber.

Modular Wetlands Systems, Inc. warranties that the materials used to manufacture its products will be able to withstand and remain durable to environmental conditions for a period of 5 years from the date of purchase. All other proprietary stormwater systems on the market today only offer a 1-year limited warranty.

Other Benefits and Challenges

Unlike many precast stormwater treatment devices, the MWS-Linear has a vegetative component that can add aesthetics to any streetscape. The plants in the wetland chamber perform an important filtration function while also adding an aesthetically pleasing element to what may otherwise be a barren urban context. Though the aesthetic aspects of the technology are in no way assessed herein, they are mentioned here as an element that may be of interest to municipalities serving the many landscape interests of their citizens.

Sampling Procedures

This section describes the sampling procedures that were used to evaluate the performance of the MWS-Linear. It begins with a general overview of the monitoring design and describes the specific goals Ecology has established for the types of treatment that are being sought under the GULD. Separate sections then describe in more detail the site location, test system, monitoring schedule, and the specific procedures used to obtain the hydrologic and water quality data, respectively. Analytical methods, quality assurance and control measures, data management procedures, and data analysis procedures are also discussed.

Monitoring Design

To facilitate performance monitoring pursuant to the TAPE procedures, a 4- by 13-foot (ID) MWS-Linear unit (Model # MWS-L-4-13) was installed for testing purposes at the Portland Bureau of Maintenance Albina Maintenance Facility, which is located at North Mississippi and North Monroe Street in Portland, Oregon (Figure 1). This system is identified herein as the Albina Modular Wetland System (AMWS).

Automated equipment was installed in conjunction with the AMWS system to facilitate continuous monitoring of influent, effluent, and bypass flow volumes over a 14-month period extending from April 14, 2012, through May 31, 2013. In association with this hydrologic monitoring, automated samplers were also employed to collect flow-weighted composite samples of the influent and effluent during discrete storm events for subsequent water quality analyses.

Using the data obtained from the AMWS monitoring, removal efficiencies and effluent concentrations were characterized for targeted monitoring parameters. These data were subsequently compared to goals identified in the TAPE to support the issuance of a GULD for the MWS-Linear.

These treatment goals are described below for the three types of treatment that are under consideration for inclusion in the GULD:

1. **Basic Treatment** – 80 percent removal of total suspended solids 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 total suspended solids.
2. **Phosphorus Treatment** – 50 percent removal of total phosphorus for influent concentrations ranging from 0.1 to 0.5 mg/L
3. **Dissolved Metals Treatment** – 30 percent removal of dissolved copper when influent concentrations range from 0.005 to 0.02 mg/L and 60 percent removal of dissolved zinc when influent concentrations range from 0.02 to 0.3 mg/L

Site Location

The AMWS system was installed at the Portland Bureau of Maintenance Albina Maintenance Facility, which is located at North Mississippi Avenue and North Monroe Street in Portland, Oregon (Figure 1). The Facility includes a parking lot for trucks and heavy equipment as well as outdoor storage of stockpiles of rock and dirt debris and miscellaneous snow removal equipment. Stormwater from the parking area for trucks and heavy equipment on the south side of the facility is collected in a series of catch basins along the western edge of the lot. Stormwater was conveyed from this system to Portland's municipal drainage system. The AMWS system received stormwater runoff from this parking area, and the treated effluent from the system was then discharged into the existing municipal drainage system before discharging via outfall to the Willamette River.

The drainage area for this parking lot and storage areas is approximately 0.45 acres (see site map in Figure 6 for delineation), and generally slopes from the east to the west with a grade of approximately 5.0 percent. The installation location for the MWS-Linear system within this drainage basin is designated "AMWS" in Figure 6.

Monitoring Schedule

Hydrologic and water quality monitoring were conducted at the AMWS test system over a 14-month period April 14, 2012, through March 31, 2013. During this monitoring period, 28 separate storm events were successfully sampled.

Test System Description

The AMWS test unit consists of a 4- by 13-foot ID vault with an 18.4-foot perimeter biofiltration bed (WetlandMedia), and had a piped inflow configuration (Figure 3). The Modular Wetland System Linear was constructed with an 8-inch smooth-walled PVC inlet pipe that enters the northeast wall of the pre-treatment chamber. Water exits the system through a 12-inch smooth-walled PVC outlet pipe located on the northeast wall of the discharge chamber.

In order to simplify monitoring, the AMWS was installed with an upstream external bypass weir (Figures 6 and 7). This configuration made it possible to segregate treated and bypassed flows for quantity and quality monitoring. The bypass weir was adjustable in order to maintain a specified driving head in the AMWS. The weir was adjusted to route the design flow rate of 41 gpm to the system before bypass occurred. The internal bypass piping was capped to prevent internal bypass flows from affecting estimates of treated effluent flow rates and chemistry.

Test System Sizing

The WWHM2012 was used to estimate water quality design flow rates for the 0.45-acre study basin. The WWHM2012 model was run for a moderate sloped basin (5 to 15 percent) and with a 15-minute time step. The resultant model run indicated that the water quality design flow

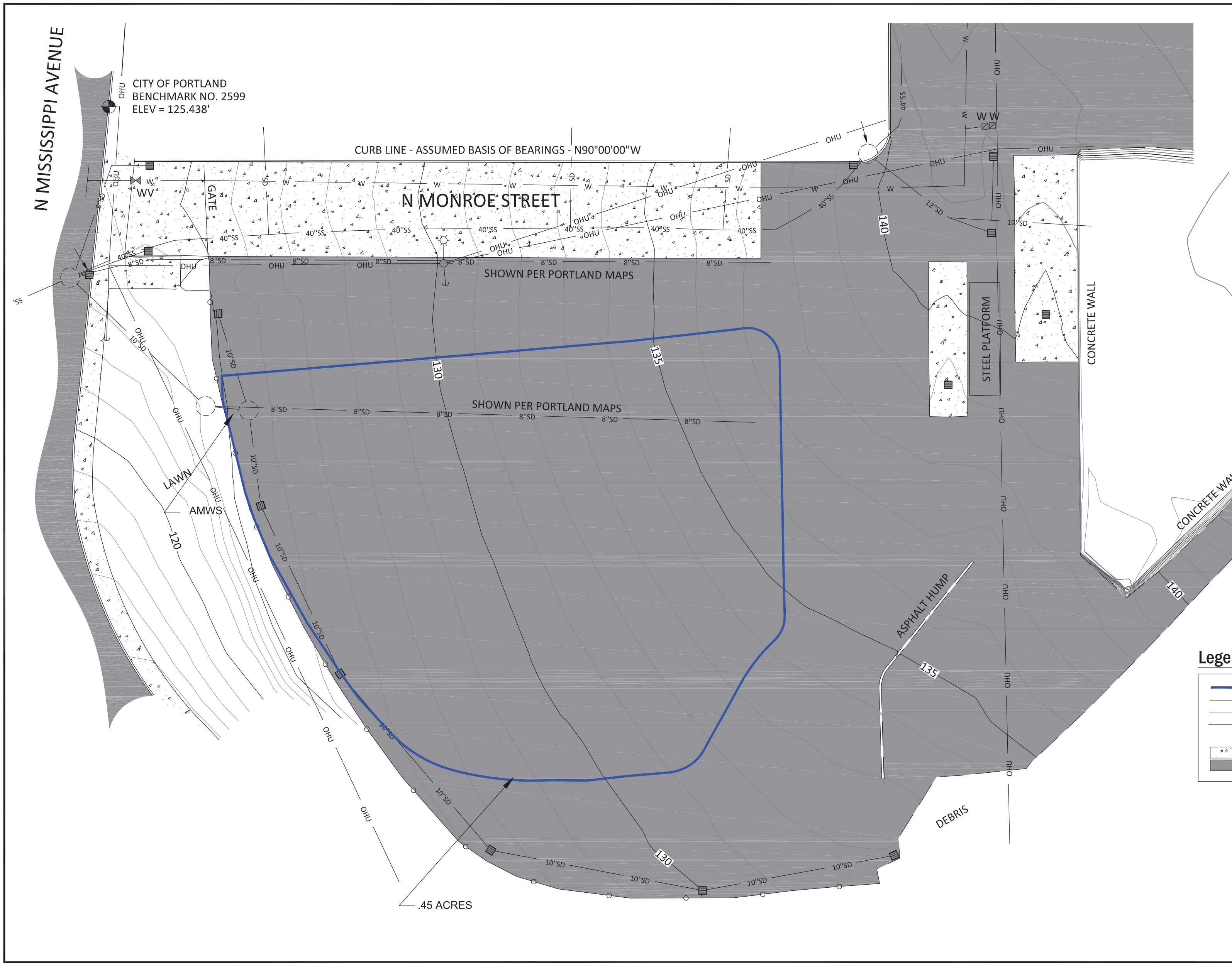

Figure 6.
Site map of the MWS - Monitoring site (AMWS) at the Albina Maintenance Facility in Portland, Oregon.

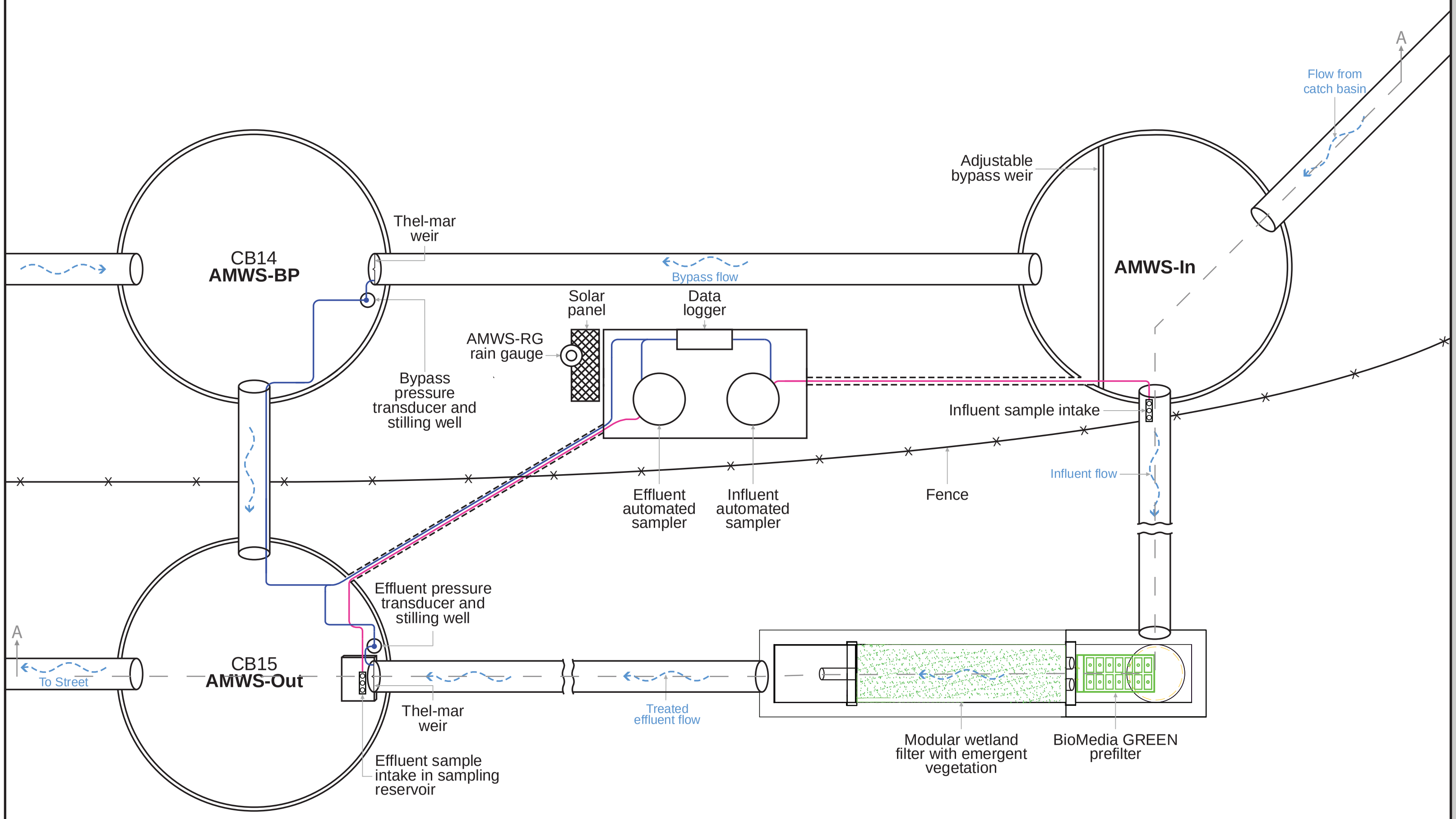

Figure 7.
Plan view diagram of the MWS monitoring site (AMWS).

Legend
- Pressure transducer and cable
- Sampling and pH line cable
- Direction of flow
- 3" conduit

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Not to scale

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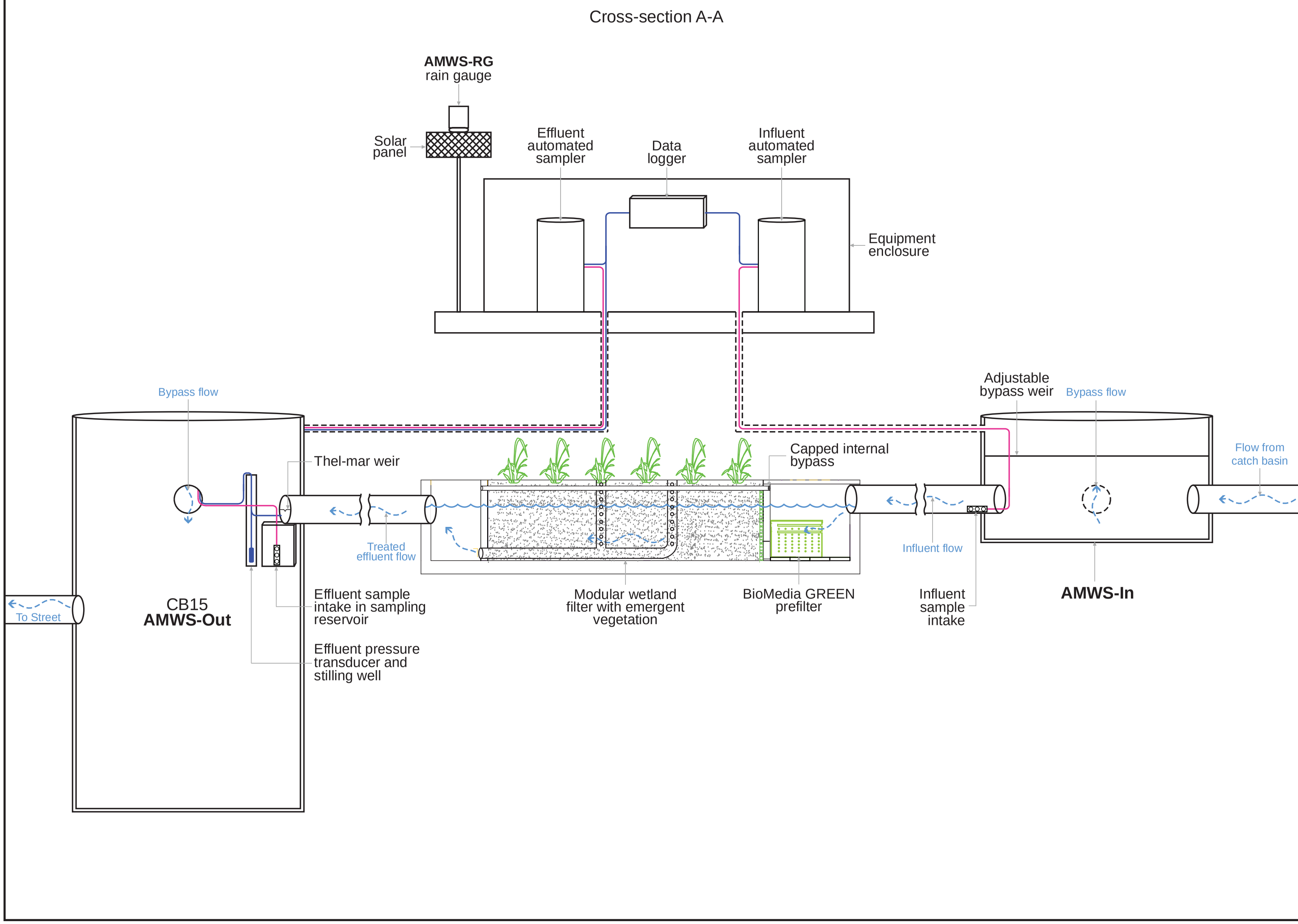

Figure 8.
Cross-section of the MWS monitoring site (AMWS).

Legend
- Pressure transducer and cable
- Sampling and pH line cable
- Direction of flow
- 3" conduit

Note: CB14 and associated bypass flow monitoring station not depicted in cross-section. See Figure 6.

Not to scale

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rate for the basin was 0.0676 cubic feet per second. However, preliminary flow monitoring indicated that a 1.5-inch storm generated a flow rate of 0.23 cubic feet per second (103 gallons per minute). This was an indication that additional flow was entering the basin. The basin is complex due to potential upslope contributions and the absence of a curb along the base of the basin. Due to the complexity of the drainage, it was exceedingly difficult to estimate the basin size for accurate WWHM3 modeling; consequently, the system was sized assuming a 0.45-acre drainage area. As mentioned above, this resulted in a design flow rate for the test system of 0.091 cfs (41 gpm). Subsequent analysis of the flow data after completion of the project indicated that, on average, a 1.54-inch storm produced a flow rate of 95 gpm. Based on hydrologic modeling, the 1.54-inch storm for the study region is equivalent to the 6-month storm. Standard sizing techniques dictate that in order to treat 91 percent of the annual runoff the system must be able to treat 100 percent of the 6-month storm. This is an indication that, even though the basin area was assumed larger than the mapped basin during the sizing calculations, the system was undersized for the basin.

Maintenance Schedule

Maintenance of the MWS-Linear consists of vactoring and power washing the pre-treatment chamber and replacing the BioMediaGREEN in the media cartridge pre-filters. The frequency of these maintenance activities is a function of solids loading from the site. The Albina Maintenance Facility was a challenging environment for stormwater filtration due to the high degree of fine sediment loading in the runoff (likely sourced from the debris piles in the yard and from mud and sediment from high levels of vehicle traffic in and out of the maintenance yard). The excessive fines fraction (Figure 9) blinded the BioMediaGREEN in the media cartridge pre-filter more quickly relative to what would be expected from suspended solids with a more typical particle size distribution (PSD) found in streets, parking lots and other land uses where installation of these systems generally occur. This site demonstrated a “worst case scenario” type condition that is in general found on dirty and unmaintained industrial sites. To adapt to this condition, various configurations of the BioMediaGREEN were tried to decrease maintenance frequency requirements on this site. These steps are described in this section.

Initially, standard solid BioMediaGREEN blocks were installed in the media filter pre-cartridge located in the pre-treatment chamber on April 12, 2012. After noting that the filter was blinding quicker than anticipated based on initial sediment load estimates (Figure 9), it was replaced on May 2, 2012 with a modified BioMediaGREEN with ribs to increase the filter surface area (Figure 9). These modified blocks were in place through a dry period during which one sample was collected, but again flow rates through the media diminished too rapidly and the BioMediaGREEN media was replaced again on August 8, 2012. To set a baseline, an perlite media (Figure 9) was installed for 2 months during which time two samples were collected. On October 26, 2012, a cubed BioMediaGREEN was installed (Figure 9), this media provided similar resistance to surface occlusion (blinding) as the perlite but with a more reactive surface. The cubed BioMediaGREEN lasted until January 27, 2013 (3 months), during which 13 samples were collected. It is anticipated that the cubed BioMediaGREEN would last 6 to 24 months depending on stormwater loading conditions. Per the current TAPE protocol, maintenance interval will be determined on a site-by-site basis after issuance of a GULD. In addition, the manufacturer now recommends using additional pre-filter cartridges for sites with high solids loading (see Tables 2 and 3). Analysis of the potential effect of the various pre-filters on the final data set is presented below in the *Water Quality Results* section.

During the entire duration of the field testing the flow rate through the wetland chamber and its WetlandMedia was unaffected. The last few storms during May of 2013 had some of the highest recorded treatment flow rates proving that the pre-treatment chamber and its pre-settling and pre-filters prevented the migration of fine sediments and hydrocarbons from reaching the wetland chamber and affecting its flow rate capacity directly. Based upon these findings it is estimated that maintenance on the wetland chamber will not be required for several years.

Hydrologic Monitoring Procedures

Generalized schematics of the equipment that was installed in association with the AMWS test system are provided in Figures 6 and 7. The equipment installation was completed on April 22, 2011. Continuous hydrologic monitoring was performed in conjunction with the AMWS test system at four separate monitoring stations: AMWS-BP, AMWS-OUT, AMWS-RG, and AMWS-IN (Figures 6 and 7). AMWS-BP was a bypass flow monitoring station, AMWS-OUT was an effluent flow monitoring station located at the outlet that was used to characterize influent flows since there are no water losses through the system, and AMWS-RG was a precipitation monitoring station. AMWS-IN was only used for sample collection and no hydrologic monitoring was conducted at the station. These hydrologic monitoring stations are discussed in separate subsections below, followed by a summary of the maintenance procedures performed on the monitoring equipment. These monitoring procedures are also described in greater detail within the quality assurance project plan (QAPP) that were prepared for this study (Herrera 2011b) (Appendix B).

Hydrologic monitoring instruments at each of the stations discussed below were all interfaced with a Campbell Scientific CR1000 datalogger, which served to record data, run simple algorithms based on those data, and control the automated sampling equipment. The datalogger was programmed to scan every 10 seconds and record average readings on a 5-minute time step. The datalogger was interfaced with an Airlink Raven XTV digital cellular modem (Appendix B). This communication system was configured to automatically download data on a 5-minute basis and send text message alarms to field technicians and project managers. Power to the system was supplied using a 12-volt sealed, rechargeable battery that was charged using an 80-watt solar panel installed at the site.

The datalogger, battery, digital cell phone link, and automated samplers were housed in a Knaack box model 69 enclosure (Appendix B). Conduit was installed to convey pressure transducer cabling and autosampler suction lines from the base of the enclosure to each station.

Bypass Flow Monitoring (AMWS-BP)

In order to simplify monitoring, the AMWS was installed with an upstream external bypass (Figures 6 and 7). This configuration made it possible to segregate treated and bypassed flows for quantity and quality monitoring. The upstream bypass weir was adjustable in order to

Highly turbid inflow

BioMediaGREEN blocks coated with fines

Ribbed BioMediaGREEN blocks coated with fines

Installation of temporary perlite prefilter with new cartridge design

Cubed BioMediaGREEN ready for installation

High sediment loading in drainage basin

Figure 9. Photos of Sediment Loading and Pre-filters Used at the AMWS Monitoring Site.

maintain required driving head in the MWS-Linear. The weir was adjusted to route the design flow rate of 0.091 cfs (41 gpm) to the system before bypass occurred. The internal bypass piping was capped to prevent internal bypass flows from affecting estimates of treated effluent flow rates and chemistry. Engineering design plans for the AMWS system are provided in Appendix C.

Water that passed over the diversion weir was routed through a 10-inch pipe to CB-14 (Figure 7). A 10-inch Thel-Mar weir was installed at the end of this pipe and a hole was drilled through the face of the weir for connecting a section of reinforced 3/8-inch ID polyethylene tubing. The other end of the tubing was connected to a stilling well that was constructed from 3-inch diameter PVC pipe. An Instrumentation Northwest PS9805 submersible pressure transducer (0 to 2.5 psi) was installed in the stilling well to measure water levels behind the Thel-Mar weir. The pressure transducer was interfaced with the Campbell Scientific CR1000 datalogger described above. When bypass occurred, the datalogger converted bypass weir water level readings to estimates of discharge based on standard hydraulic equations (Walkowiak 2006).

Influent/Effluent Flow Monitoring Station (AMWS-OUT)

To facilitate continuous monitoring of influent and effluent flow rates, a monitoring station, designated AMWS-OUT, was established at the end of the 12-inch outlet pipe (Figures 6 and 7). It was assumed that, given the small size and associated low water residence time for the AMWS, the effluent flow would be essentially equivalent to influent. A 12-inch Thel-Mar was installed at the end of the outlet pipe in CB15 and a hole was drilled through the face of the weir for connecting a section of reinforced 3/8-inch ID polyethylene tubing. The other end of the tubing was connected to a stilling well that was constructed from 3-inch diameter PVC pipe. An Instrumentation Northwest PS9805 submersible pressure transducer (0 to 2.5 psi) was installed in the stilling well to measure water levels behind the Thel-Mar weir.

The AMWS-OUT pressure transducer was interfaced with the same Campbell Scientific CR1000 datalogger described above. The datalogger converted water level readings in the stilling well (which were equivalent water levels behind the Thel-Mar weir) to estimates of discharge based on standard hydraulic equations (Walkowiak 2006).

Precipitation Monitoring Station (AMWS-RG)

In addition to the two pressure transducer stations, a third hydrologic monitoring station, designated AMWS-RG, was installed adjacent to the equipment enclosure (Figures 6 and 7) to facilitate continuous monitoring of precipitation depths. The station was equipped with a Hydrological Services TB4-L60 rain gauge (Appendix B) that was mounted on an 8-foot steel pole and interfaced with the same Campbell Scientific CR1000 datalogger described above.

Monitoring Equipment Maintenance and Calibration

Maintenance and calibration of the rain gauge and flow monitoring equipment was conducted on a routine basis during pre- and post-storm checks. Instrument maintenance and calibration activities were documented on standardized field forms. Rain gauge and level calibration data can be found in the hydrologic data quality assurance memorandum in Appendix D. In addition, on February 14, 2013, a dynamic flow test was conducted using known flow rates from a nearby fire hydrant. The hydrant flows were used to calibrate the Thel-Mar weir equations at AMWS-OUT and AMWS-BP. Results from the dynamic flow testing are presented in Appendix D. The adjusted rating curves which resulted from this testing were applied to the entire dataset prior to final analysis.

Water Quality Monitoring Procedures

To evaluate the water quality treatment performance of the AMWS test system, water quality sampling was conducted at the influent (AMWS-IN) and effluent (AMWS-OUT) stations (Figures 6 and 7) during 28 discrete storm events over the period from April 2012 through May 2013. A general description of the procedures used for this monitoring is provided herein. A more detailed description of these procedures can also be obtained from the QAPP that was prepared for this study (Herrera 2011b). To facilitate water quality sampling for this study, Isco 6712 portable automated samplers were installed in association with the AMWS-IN and AMWS-OUT stations. The intake strainer for the automated sampler at the AMWS-IN station was positioned in the outlet pipe of the bypass structure (Figures 6 and 7); the intake strainer for the automated sampler at the AMWS-OUT station was located in a sampling tray located below the invert of the outlet pipe in CB15. 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. The sampler suction lines consisted of Teflon tubing with a 3/8-inch inner diameter.

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 period of at least 6 hours after the event with less than 0.04 inches of precipitation

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 20-liter 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 based on data from the rain gauge installed at the site. During the storm event sampling, the datalogger was programmed to enable the sampling routine in response to a predefined increase in water level (stage) at AMWS-OUT. The automated samplers were then programmed to collect 220-milliliter sample aliquots at preset flow increments. 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**
- Sampling was targeted to capture **at least 75 percent** of the hydrograph
- Due to sample holding time considerations, the maximum duration of automated sample collection was **36 hours**.

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. If the sample was determined to be acceptable, the carboy was immediately capped, removed from the automated sampler, and kept below 6ºC 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)
- Particle size distribution (PSD)
- Total phosphorus (TP)
- Orthophosphorus
- Total and dissolved copper
- Total and dissolved zinc
- pH
- Hardness

Additional parameters were measured, but this report only addresses those parameters that are pertinent to the basic, phosphorus, and enhanced treatment GULD.

Sediment Monitoring Procedures

In addition to water sampling, TAPE guidance calls for the assessment of sediment accumulation and sediment particle size distribution within the monitored treatment technology. However, under normal operating conditions, sediment will settle in the pre-treatment chamber of MWS-Linear system and the media cartridge pre-filter. Each pool of sediment will have a different volume and particle size distribution. To assess the particle size distribution and sediment volume within the each of these areas would be exceedingly difficult. This process would also likely be prohibitively expensive and, due to the difficulty of differentiating between media and accumulated sediment, would result in an inaccurate assessment of accumulated sediment volume and particle size distribution. Due to these considerations, field technicians only recorded sediment depth within the pre-treatment chamber. Particle size distribution of these accumulated sediments was not conducted because it would not provide an assessment of total system treatment; rather, it would only provide an assessment of the setting unit-process aspect of the pre-treatment.

Analytical Methods

Analytical methods for this project are summarized in Table 4. Test America in Portland, Oregon, was the initial laboratory used for this project. However, due to performance issues with the lab that did not affect data quality, ALS, Inc. in Kelso, Washington, was used for the final 17 collected composite samples. Both laboratories are certified by Ecology, and participate 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. Chemoptix Laboratories in West Linn, Oregon was initially used for PSD analysis; when the lab switch occurred, PSD was analyzed at Analytical Resources, Inc. in Tukwila, Washington.

Quality Assurance and Control Measures

Field and laboratory quality control procedures used for the MWS-Linear 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 sampler tubing was cleaned before the collection of each aliquot using an automated double rinse cycle. In addition, deionized water was back flushed through the sample tubing before each monitored event. Field blanks were collected on November 10, 2011, prior to the first sampled storm event at both monitoring locations. A second set of field blanks was collected on March 1, 2012, after a few storm events had been sampled. The 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 approximately 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 were present. The resultant data from these samples was

Table 4. Methods and Detection Limits for Water Quality Analyses.

Parameter	Analytical Method	Method Number [a]	Field Sample Container	Pre-Filtration Holding Time	Total Holding Time [b]	Field Preservation	Laboratory Preservation	Reporting Limit/ Resolution	Units
Total suspended solids	Gravimetric [c]	SM 2540D	20 L HDPE bottle	7 days	7 days	Maintain ≤ 6°C	Maintain ≤ 4°C	1.0	mg/L
Total phosphorus	Automated ascorbic acid	EPA 365.3		NA	28 days		Maintain ≤ 4°C, H_2SO_4 to pH < 2	0.002	mg/L
Orthophosphorus	Automated ascorbic acid	EPA 365.3		24 hours [d]	48 hours		Maintain ≤ 4°C, H_2SO_4 to pH < 2	0.001	mg P/L
Hardness	Titration	SM 2340B		28 days	28 days		Maintain ≤ 4°C, HNO3 to pH < 2	0.1	mg/L as $CaCO_3$
pH	Potentiometric	SM 4500-H^+		24 hours [d]	24 hours		Maintain ≤ 4°C	0.01	std. units
Particle Size Distribution	Sieve and filter	TAPE App. F		7 days	7 days		Maintain ≤ 4°C	NA	microns
Copper, dissolved	ICP-MS	EPA 200.8		18 hours [d]	6 months		Maintain ≤4°C, HNO_3 to pH < 2 after filtration [g]	0.002	mg/L
Copper, total				NA			Maintain ≤ 4°C, HNO_3 to pH < 2	0.002	
Zinc, dissolved	ICP-MS	EPA 200.8		18 hours [d]	6 months		Maintain ≤ 4°C, HNO_3 to pH < 2 after filtration [g]	0.01	mg/L
Zinc, total				NA			Maintain ≤ 4°C, HNO_3 to pH < 2	0.01	

[a] SM method numbers are from APHA et al. (1998); EPA method numbers are from US 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 US EPA guidance (US EPA 1983, 1984) or referenced in APHA et al. (1992) for equivalent method.

[c] A G4 glass fiber filter will be used for the total suspended solids filtration.

[d] EPA requires filtering for orthophosphorus and dissolved metals and measurement of pH within 15 minutes of the collection of the last aliquot. This goal is exceedingly difficult to meet when conducting flow-weighted sampling. A more practical proxy goal for this study is 24 hours.

C = Celsius.

mg/L = milligrams per liter.

HDPE = High-Density Polyethylene

NA = not applicable.

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 D.

Laboratory Quality Control

Accuracy of the laboratory analyses was verified with blank analyses, duplicate analyses, laboratory control spikes, and matrix spikes in accordance with the analytical methods employed. Test America, Inc. and ALS, 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 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.

Test America, Inc. and ALS, 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.

Data Management Quality Control

An independent review was performed to ensure that the data were entered into the database without error. Specifically, all of the sample values in the database were crosschecked 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 Analysis Procedures

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
- Bypass flow duration
- Effluent flow duration
- Bypass peak discharge rate
- Effluent peak discharge rate
- Bypass discharge volume
- Effluent discharge volume

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. Bypass frequency data was also used to assess when BioMediaGREEN media required replacement.

Water Quality Data Analysis Procedures

Data analyses were performed to evaluate the water quality treatment performance of the test system. The specific procedures that were used in these analyses are as follows:

- Statistical comparison of influent and effluent concentrations
- Calculation of pollutant removal efficiency using bootstrap analysis
- Calculation of pollutant removal efficiency as a function of flow

Each of these procedures is described in more detail in the following subsections.

Statistical Comparisons of Influent and Effluent Concentrations

Pollutant concentrations were compared for paired influent and effluent across all storm events using a 1-tailed Wilcoxon signed-rank test (Helsel and Hirsch 2002). Using 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. A 1-tailed test was used to evaluate the specific hypothesis that effluent pollutant concentrations were significantly lower than those in the influent were. In all cases, the statistical significance was evaluated at an alpha level (α) of 0.05.

Calculation of the Pollutant Removal Efficiency using Bootstrap Analysis

The removal (in percent) in pollutant concentration during each individual storm (ΔC) was calculated as:

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

Where: C_{in} = Flow-weighted influent pollutant concentration
C_{eff} = Flow-weighted effluent pollutant concentration

After the percent removal for each qualifying event was calculated, the mean percent removal values and 95 percent confidence interval about the mean were estimated using a bootstrapping approach (Davison and Hinkley 1997). Bootstrapping offers a distribution-free method for estimates of confidence intervals of a measure of central tendency. 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.

To perform the bootstrapping analysis, the percent removal values for each valid event were sampled randomly with replacement until a new synthetic percent removal dataset of equivalent size was generated. The median percent removal was then calculated on the synthetic dataset and the process was repeated. Repetition generates a distribution of possible values for the mean. Quantiles of this distribution are confidence intervals of the statistic. For example, in the analysis the mean was replicated 10,001 times; after sorting the replications, the 250th and 9,750th elements constituted the 95 percent confidence interval of the median, while the reported mean was the 5,000th ranked value.

The results from this test were used to determine if the mean percent removal was significantly different from percent removal thresholds presented in TAPE (e.g., 80 percent total suspended solids removal).

Calculation of Pollutant Removal Efficiency as a Function of Flow

To determine pollutant removal performance as a function of flow rate the sampled flow rate must first be calculated. Specifically, for composite samples the instantaneous flow rates associated with each aliquot were averaged over the sampled event to generate an average sampled flow rate. This value was then compared with the percent pollutant removal for the event. This process was repeated for each sampled event, the results were plotted on a percent removal versus sampled flow rate graph, and a regression analysis conducted to determine if system performance varied as a function of influent flow rate.

DATA SUMMARIES AND ANALYSIS

This section summarizes data collected during the 2012-2013 monitoring period. The presentation of these data is organized under separate subsections for the hydrologic and water quality monitoring results, respectively. A memorandum discussing the quality of the hydrologic data is presented in Appendix D, while Appendix E presents a quality assessment of the water quality data.

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. Appendix D 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 MWS-Linear, an analysis was performed on rainfall data collected at the National Weather Service (NWS) rain gauge at Portland Airport (PDX) to determine if rainfall totals from the monitoring period (i.e., April 1, 2012, through May 31, 2013) were anomalous. The NWS rain gauge is located at Portland International Airport, approximately 4.9 miles northeast of the AMWS rain gauge. The analysis specifically involved a comparison of rainfall totals measured at the PDX rain gauge over the monitoring period to averaged totals for the same gauge from the past 73 years. These data are summarized in Table 5 along with data from the rain gauge associated with the AMWS monitoring site.

Results from this analysis showed the average annual rainfall total at the Portland Airport rain gauge from 1940 through 2013 was 42.9 inches. In comparison, the rainfall total at the same rain gauge over the monitoring period was 41.3 inches. This value is within the normal range of rainfall (i.e., 25th to 75th percentile) for the Portland Airport rain gauge based on the 73-year rainfall record; thus, the rainfall total during the monitoring year is generally representative of rainfall during an average year.

Table 5 also indicates that precipitation measured at the Albina Maintenance Facility Bureau of Environmental Services gauge were similar to rainfall measurements at PDX during the monitoring period. However, rain data collected with the project rain gauge at AMWS-RG were approximately 17 percent greater than at the Albina Maintenance Facility Bureau of Environmental Services or PDX gauge. This discrepancy is discussed further in the hydrologic quality assurance assessment (Appendix D).

Table 5. Monthly and Annual Precipitation Totals (in inches) for 2012-2013 at the MWS-Linear Monitoring Site, Compared to Historical Totals at Portland Airport.

Month	AMWS Rainfall Data (2012-2013) [a]	Portland Albina Maintenance Facility BES Gauge Rainfall Data (2012-2013) [b]	Portland Airport NWS Station PDX Rainfall Data (2012-2013)	Portland Airport NWS Station PDX Rainfall Data (1940-2013) [c]
April	4.09	3.18	3.25	2.73
May	3.83	3.11	3.37	2.47
June	3.45	2.98	4.10	1.70
July	0.39	0.29	0.21	0.65
August	0.00	0.01	0.00	0.67
September	0.02	0.01	0.04	1.47
October	6.41	5.61	6.14	3.00
November	9.35	8.32	8.23	5.63
December	9.6	8.54	7.56	9.63
January	3.09	2.83	3.49	4.88
February	3.22	1.48	1.26	3.66
March	2.19	2.09	1.46	3.68
April	2.67	2.38	2.19	2.73
May	5.19	4.21	4.57	3.35
Total	53.5	45.04	45.87	46.25

AMWS: Albina Modular Wetland System

BES: Bureau of Environmental Services

[a] Source: AMWS RG precipitation monitoring station for the AWMS

[b] Source: Portland Bureau of Environmental Services

[c] Source: Portland Airport rain gauge (http://www.wrh.noaa.gov/pqr/pdxclimate/index.php). Based on average monthly and annual precipitation totals measured over the period from 1940 to 2013.

Water Budget

The water budget for the AMWS test system was analyzed to determine bypass frequency and volume (Table 6). WWHM modeling indicated that with the estimated basin area of 0.45 acres, the water quality design flow rate is 0.091 cfs or 41 gpm.

Separate analyses of hydrologic data were performed to meet the following objectives:

- Determine whether treatment goals for the test system were met based on the volume treated and bypassed
- Determine whether bypass frequency and volume varied as a function of storm rainfall depth, storm rainfall intensity, influent flow volume, and sampling date
- Determine site specific maintenance frequency by examining bypass over the course of the study

The data used in these analyses are presented in their entirety in Appendix F.

Table 6. Summary Statistics for Storms That Produced Bypass Flow at the AMWS Test System from April 1, 2012, Through May 31, 2013.						
Storm Start Date & Time	**Storm Depth (inches)**	**Peak Storm Intensity (in/hr)**	**Total Volume (gpm)**	**Bypass Volume (gallons)**	**% of Total Volume Bypassed**	**Peak Treated Flow Rate during Bypass (gpm)**
New Pre-Filter Installed 4/12/2012 (Solid BioMediaGREEN)						
4/17/2012 21:20	0.31	0.03	1168	407	26	24.1
4/19/2012 8:30	0.68	0.02	1499	991	40	12.0
4/29/2012 22:50	0.33	0.01	1786	112	6	19.5
5/1/2012 13:10	0.15	0.03	902	98	10	13.4
New Pre-Filter Installed 5/2/2012 (Ribbed BioMediaGREEN)						
5/4/2012 5:10	0.41	0.08	2133	4179	66	45.3
5/22/2012 8:35	0.37	0.03	3689	497	12	38.5
5/24/2012 19:10	0.15	0.03	1330	165	11	29.6
5/25/2012 19:35	0.21	0.02	1249	254	17	26.7
6/4/2012 20:20	0.63	0.04	2836	1885	40	8.7
6/7/2012 3:10	0.52	0.02	1802	1286	42	5.7
6/8/2012 7:10	0.57	0.1	839	2806	77	3.9
6/22/2012 18:40	0.5	0.04	1428	281	16	10.1
6/24/2012 3:45	0.23	0.02	388	188	33	2.4
New Pre-Filter Installed 8/28/2012 (Perlite)						
10/14/2012 19:15	0.65	0.05	6309	190	3	41.8
10/15/2012 12:30	0.58	0.06	5210	2370	31	41.8
10/19/2012 13:00	0.39	0.08	3286	33	1	40.6
New Pre-Filter Installed 10/26/2012 (Cubed BioMediaGREEN)						
10/27/2012 6:50	0.61	0.03	4834	272	5	46.7
10/28/2012 6:15	1.04	0.03	10302	399	4	48.0
10/29/2012 22:45	0.65	0.05	5786	572	9	48.0
11/11/2012 13:20	1.41	0.02	12362	84	1	42.3
11/17/2012 3:05	0.72	0.04	5820	267	4	40.6
11/18/2012 16:10	2.27	0.08	24874	8491	25	37.0
11/20/2012 3:50	0.58	0.1	5170	2710	34	30.0
11/20/2012 19:25	0.28	0.02	2251	789	26	26.1
11/21/2012 9:15	0.19	0.03	1519	154	9	23.4
11/23/2012 8:25	1.61	0.03	16628	6982	30	23.4
11/29/2012 6:15	0.57	0.03	4597	762	14	20.6
11/30/2012 17:35	0.7	0.04	5181	6085	54	21.0
12/1/2012 14:10	0.86	0.03	8123	2694	25	16.3
12/3/2012 22:30	0.51	0.03	2937	5052	63	12.0
12/4/2012 9:45	0.82	0.05	8116	2437	23	42.9
12/11/2012 11:20	0.33	0.02	3119	918	23	30.9
12/15/2012 9:10	0.38	0.03	2600	490	16	24.3
12/16/2012 3:15	1.37	0.03	11554	4597	28	23.9
12/19/2012 2:10	1.85	0.03	20266	8113	29	21.0
12/23/2012 5:15	0.44	0.01	4298	61	1	17.8
12/25/2012 3:10	1.13	0.02	10044	2620	21	17.0
1/6/2013 19:50	0.56	0.02	4812	226	4	25.7
1/24/2013 17:50	0.5	0.02	3096	51	2	25.0
New Pre-Filter Installed 1/27/2013 (Cubed BioMediaGREEN)						
2/22/2013 9:30	0.67	0.03	9208	1442	14	38.6
3/19/2013 15:35	1.03	0.04	11259	3555	24	31.8
4/5/2013 14:20	0.63	0.09	4349	2182	33	32.3
4/6/2013 16:45	0.71	0.02	6524	131	2	18.2
4/10/2013 8:50	0.15	0.05	1468	157	10	26.1
New Pre-Filter Installed 5/6/2013 (Cubed BioMediaGREEN)						
5/16/2013 12:15	0.17	0.08	1422	440	24	47.6
5/21/2013 11:15	0.43	0.06	3522	543	13	45.6
5/22/2013 5:40	2.78	0.05	22799	24475	52	31.8
5/27/2013 2:20	0.76	0.1	8473	1213	13	21.9
5/28/2013 17:45	0.55	0.03	4260	3058	42	19.0

gpm: gallons per minute

Performance in Relation to Design Treatment Goal

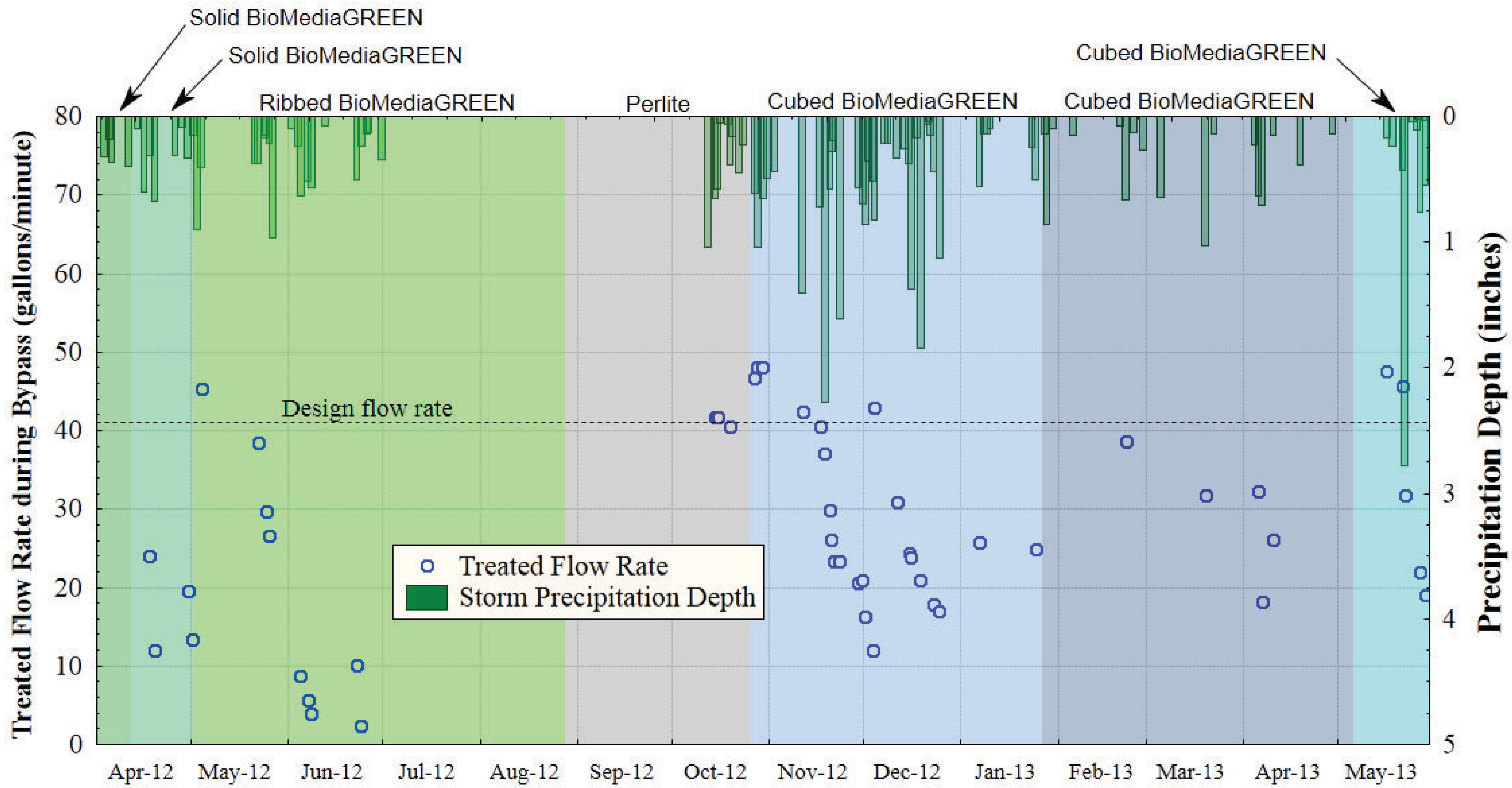
The water quality treatment goal for the AMWS test system was to capture and treat 91 percent of the average annual runoff volume. Precipitation and flow data measured during storms that produced bypass flow are presented in Table 6. These data indicate that the AMWS test system bypassed during 49 out of 81 qualifying storm events that occurred from April 1, 2012, through May 31, 2013. The system was able to treat 75 percent of the total 14-month volume. Consequently, the goal of treating 91 percent of the volume from the site was not achieved. This was due to the high clay content loading to the AMWS of the runoff clogging the media cartridge pre-filter in the Pre-treatment Chamber (see *Maintenance Schedule* section above) and the fact that the system was undersized by a factor of 2.3 (see *Test System Sizing* section). Analysis of the rainfall and flow data at the end of the project indicated that, on average, the 1.54-inch storm (the 6-month event for the region) produced a peak storm discharge of 95 gallons per minute. If the system was sized correctly (i.e., to treat 100 percent of the 6-month storm), then the design flow rate should have been equivalent to approximately 95 gpm, instead it was sized to 41 gpm (undersized by a factor of 2.3). The maintenance frequency is discussed in more detail below.

Treated Flow Rate during Bypass

In order to investigate system performance over the course of the study period, peak treated flow rate during bypass was assessed as a function of time. During bypass, 2.3 feet of the WetlandMedia is activated, so the peak treated flow rate during bypass should be at or above the water quality design flow rate. If this flow rate consistently falls below the design flow rate, it is likely that the pre-filter media is clogging. Figure 10 presents a plot of treated bypass flow rate through the course of the 14-month study. As is apparent, the treated flow rate decreases between each pre-filter change. In the three periods during which the cubed BioMediaGREEN was installed, the time it took for the treated flow rate to drop to 50 percent of the design flow rate ranged from 1 month to 3 months. These data indicate that for an undersized system with a pre-filter sized at 3.0 gpm/sq ft located at an industrial site with fine TSS loading, such as that observed at the Albina Maintenance Facility testing site, a maintenance interval of 2 to 3 months would be appropriate. If the MWS-Linear system is granted TAPE approval, site-specific maintenance intervals and pre-filter configurations will be determined for each installation. Under more typical loading conditions and with proper unit sizing and pre-filter configuration, the manufacturer expects the maintenance interval to be between 6 and 24 months due to the high variation of loading from site to site. With each replacement of BioMediaGREEN in the pre-filters the MWS-Linear once again was able to operate near the original peak treatment flow rate of 41 gpm indicating that the wetland chamber and its WetlandMedia was protected from clogging by the pre-filters and orifice control. Considering that minimal clogging was observed in the wetland chamber it can be anticipated the WetlandMedia will not need to be maintained for several years.

Water Quality Data

This section summarizes water quality data collected during the monitoring period at the AMWS, including a comparison of data compiled over this period with guidelines identified by Ecology (2011) for assessing data acceptability. Monitoring results for each parameter are summarized and discussed in separate sections. Field forms completed by staff during



Storms with no bypass were excluded from the graph

Figure 10. Temporal Plot of Peak Treated Flow Rate during Bypass and Storm Precipitation Depth.

each sampling visit are presented in Appendix G. Individual Storm Reports showing sample collection times in relation to influent and effluent hydrographs are presented in Appendix H for all sampled storm events. In addition, laboratory reports for each sampled event are presented in Appendix I.

Comparison of Data to TAPE Guidelines

Ecology (2011)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. In this section, only the data that are being submitted as valid for TAPE certification are presented. Water quality and hydrologic data from all events, including those that did not meet the TAPE criteria, are presented in Appendix F.

Storm Event Guidelines

During the April 14, 2012, through May 31, 2013 monitoring period, 28 storm events were sampled to characterize the water quality treatment performance of the AMWS Filter test system. 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 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 7 for each of the 28 sampled storm events. These data show the guideline for minimum precipitation depth (0.15 inch) was met during all storm events except the April 29, 2013, event. Because it was determined that the precipitation gauge may have been overestimating rainfall by 17 percent, two additional storms may have not met the minimum storm depth requirement of 0.15 inches: the April 10, 2013, and the May 16, 2013, event (Table 7). All three of these events had precipitation intensities that exceeded 0.03 inches/hour, so they were included in the final data set and analyzed herein. The minimum, median, and maximum precipitation depths across all 28 sampled storm events were 0.14, 0.51, and 2.27 inches, respectively. The guideline for minimum antecedent dry period (6 hours) was met for all 28 of the events. The storm duration criteria (1 hour) was also met for all 28 storm events except the April 19, 2013, event which was a short intense event lasting 0.3 hours. The April 19, 2013, event was included in the final analysis because it met other storm and sampling requirements. Antecedent dry periods during the sampled storm events ranged from 9.5 to 416.8 hours, with a median value of 33.3 hours. Storm durations ranged from 0.3 to 35.2 hours, with a median value of 10.0 hours (Table 7).

Table 7. Comparison of Precipitation Data from Sampled Storm Events at the AMWS Test System to Storm Event Guidelines in the TAPE.

Storm Start Date & Time	Storm Precipitation Depth (in)	Storm Antecedent Dry Period (hours)	Storm Precipitation Duration (hours)	Average Storm Intensity (inches/hour) [b]
4/15/2012 22:45	0.60	51.4	10.1	0.06
4/17/2012 21:20	0.31	36.8	9.2	0.034
4/19/2012 8:30	0.68	28.6	9.3	0.073
4/25/2012 20:50	0.31	13	9.8	0.032
5/2/2012 21:50	0.90	29.8	15.4	0.058
5/21/2012 4:45	0.38	16.8	13.4	0.028
10/14/2012 19:15	0.65	45.9	6.7	0.097
10/15/2012 12:30	0.58	10.9	8.5	0.068
10/28/2012 6:15	1.04	10	23.3	0.045
10/29/2012 22:45	0.65	18.8	17.2	0.038
10/31/2012 5:25	0.49	16.1	33.3	0.015
11/23/2012 8:25	1.61	44.5	17.8	0.091
11/29/2012 6:15	0.57	20	31.2	0.018
12/2/2012 14:10	0.35	9.5	25.8	0.014
12/3/2012 22:30	0.51	13	4.3	0.118
12/11/2012 11:20	0.33	44.5	7.4	0.044
12/19/2012 2:10	1.85	17.4	35.2	0.052
1/23/2013 12:15	0.25	214.1	4.7	0.054
1/24/2013 17:50	0.50	25.7	16.8	0.03
2/22/2013 9:30 [a]	0.67	41.6	6.4	0.104
3/19/2013 15:35 [a]	1.03	71.7	16	0.064
4/4/2013 8:00	0.22	305.2	7.5	0.029
4/6/2013 16:45	0.71	10.5	30.8	0.023
4/10/2013 8:50	*0.15*	63.5	3.2	0.047
4/18/2013 20:45	0.39	69.9	10.9	0.036
4/29/2013 3:15	**0.14**	236.4	**0.3**	0.420
5/16/2013 12:15 [a]	*0.17*	416.8	4.8	0.036
5/21/2013 11:15 [a]	0.43	67	6.3	0.068
Minimum	0.14	9.5	0.3	0.014
Median	0.51	33.3	9.95	0.046
Maximum	2.27	416.8	35.2	0.420

Values in **bold** do not meet storm event guidelines recommended in the TAPE (Ecology 2011).

Values in *italics* indicate the events which may not meet the TAPE guidelines for precipitation depth because the project precipitation gauge may not have been properly calibrated.

[a] All sampled events were flow-weighted composite sampled except these events, which consisted of samples collected above a high flow rate threshold.

[b] Majority of events exceeded the 0.03 in/hr rainfall intensity criteria

The minimum average storm intensity of 0.03 inches per hour was achieved for 80 percent of the sampled storm events (Table 7). The TAPE storm event guidelines recommend this threshold for at least half of the sampled storms; consequently this criterion was also met.

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 (Ecology 2011):

- A minimum of 10 aliquots were collected for each event.
- Sampling was targeted to capture at least 75 percent of the hydrograph.
- Due to sample holding time considerations, the maximum duration of automated sample collection at all stations was 36 hours.

The guideline for minimum number of sample aliquots (10) was met for all of the sampled storm events (see Table 8). It should be noted that 4 of the 28 sampled events were peak flow sample events, not flow weighted composites. The TAPE (2011) indicates that samples must represent a wide range of treated flows; in order to get samples representative of the highest treated flow rates discrete peak flow sampling is required.

The criterion for minimum portion of storm volume covered by sampling (75 percent) was met for all but one of the sampled flow-weighted storm events (see Table 8). The December 19, 2012, event had 71 percent sampling coverage. This was deemed close enough to 75 percent and the sample was included for analysis.

Table 8. Comparison of Flow-weighted Composite Data from Sampled Storm Events at the AMWS Test System to Criteria in the TAPE.

Storm Start Date & Time	Influent and Effluent Sample Aliquots (#)	Influent and Effluent Storm Coverage (%)	Influent and Effluent Sampling Duration
4/15/2012 22:45	18	92.3	8.6
4/17/2012 21:20	31	97.9	8
4/19/2012 8:30	32	95.1	6.8
4/25/2012 20:50	50	98	5.4
5/2/2012 21:50	75	81.4	10.4
5/21/2012 4:45	53	96.7	9.7
10/14/2012 19:15	35	96.5	6.5
10/15/2012 12:30	39	98	5.9
10/28/2012 6:15	74	94.9	16.1
10/29/2012 22:45	31	95.3	14.7
10/31/2012 5:25	33	94.4	23.9
11/23/2012 8:25	80	77.3	12.9
11/29/2012 6:15	63	98.4	24.1
12/2/2012 14:10	24	77.5	19.2
12/3/2012 22:30	10	83.4	3.8
12/11/2012 11:20	69	97.3	4.2
12/19/2012 2:10	80	**71**	23.7
1/23/2013 12:15	32	99.2	6.1
1/24/2013 17:50	20	88.7	12.8
2/22/2013 9:30 [a]	20	NA	0.4
3/19/2013 15:35 [a]	55	NA	0.8
4/4/2013 8:00	12	89.4	5.3
4/6/2013 16:45	36	96.8	27.8
4/10/2013 8:50	41	95.6	5.3
4/18/2013 20:45	56	96.6	7.3
4/29/2013 3:15	24	91.2	3.3
5/16/2013 12:15 [a]	20	NA	0.4
5/21/2013 11:15 [a]	12	NA	0.2
Minimum	10	71	0.2
Median	35	95.2	7.3
Maximum	80	99.2	27.8

Values in **bold** do not meet storm event guidelines recommended in the TAPE (Ecology 2011)

NA = not applicable

[a] All sampled events were flow-weighted composite sampled except these events, which consisted of samples collected above a high flow rate threshold

PERFORMANCE EVALUATION

This section evaluates water quality data based on treatment goals addressed in this TER.

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.

Two separate laboratories were used for PSD analysis. For the first 18 events, Chemoptix, Inc. was used, while Analytical Resources, Inc. was used for the last 10 events. The laboratories where switched due to inadequate service from the first laboratory and the fact that they could not bin the PSD data in the desired format. The separate PSD results obtained from the Chemoptix, Inc. and Analytical Resources, Inc. are shown in Figures 11 and 12, respectively.

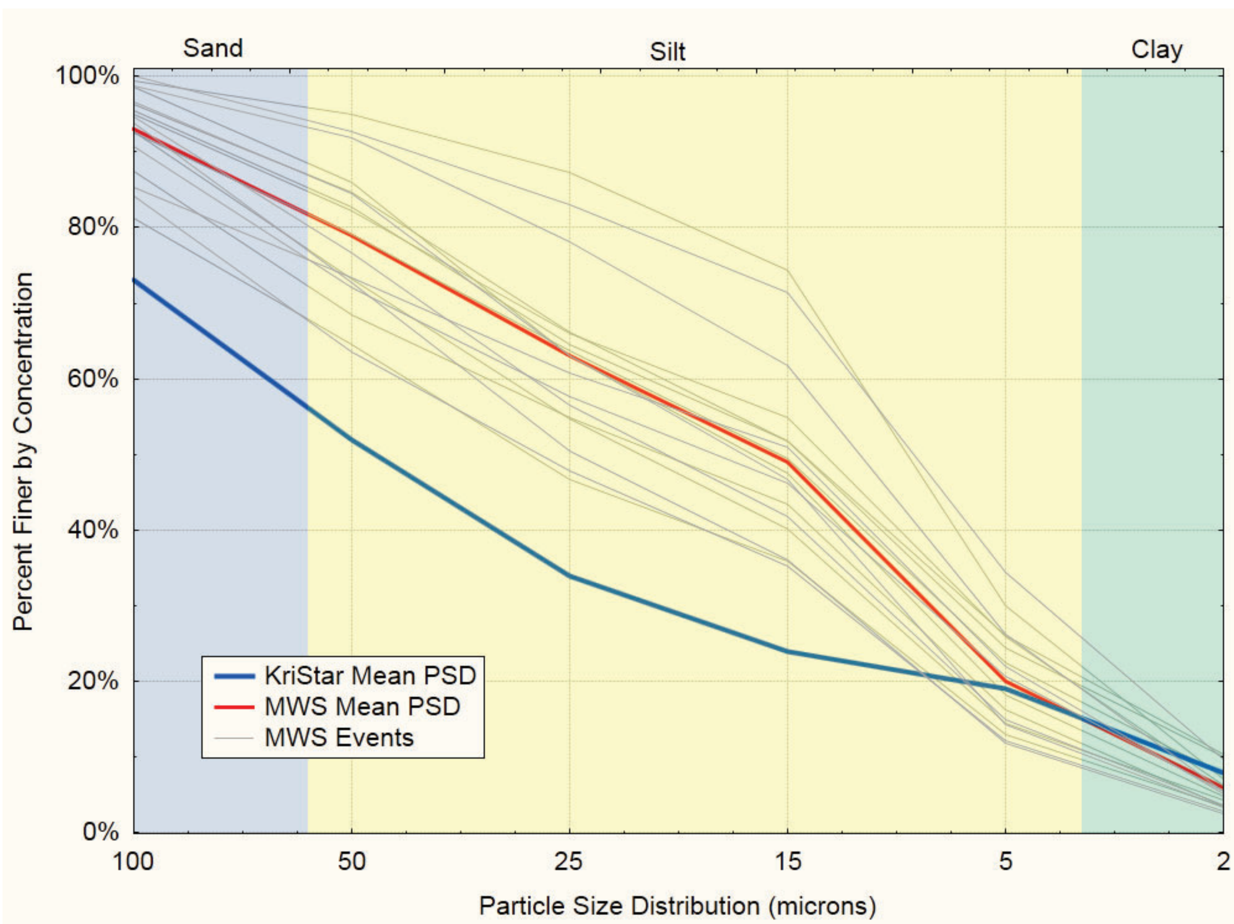


Figure 11. Influent PSD Results from Chemoptix (First 18 Samples).

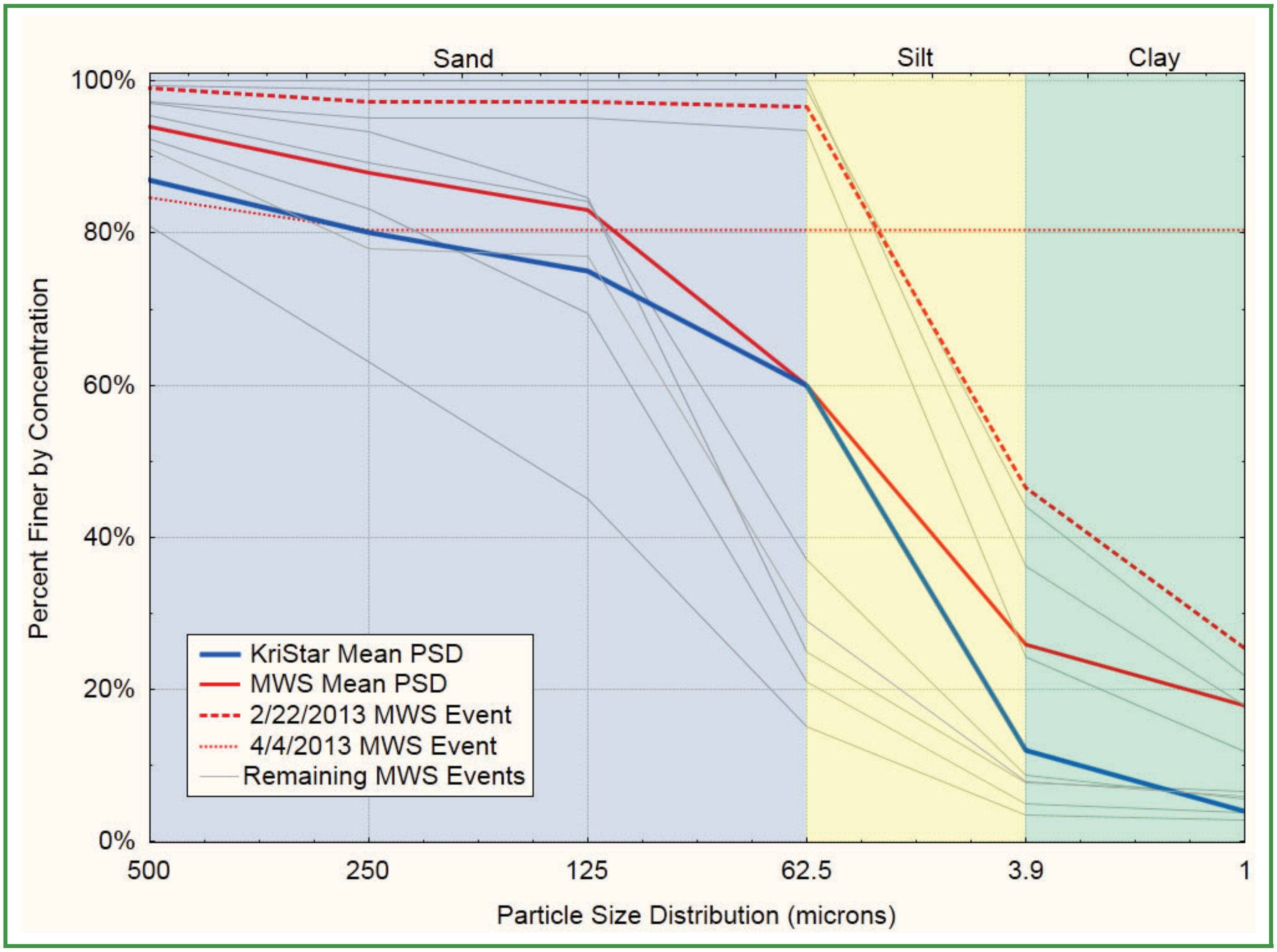


Figure 12. Influent PSD Results from Analytical Resources, Inc. (Last 10 Samples).

In Figure 11, it is apparent that the suspended solids in the stormwater are mostly comprised of silt sized particles. As was indicated in the *Maintenance Schedule* section above, the stormwater at the AMWS test site was unusually turbid. In order to quantify this, the mean PSD from a previous TAPE monitoring project (KriStar Perk Filter) was plotted with the AMWS data in Figure 11. As is apparent from Figure 11, there is 25 percent more silt at the AMWS site and an equivalent amount of clay when compared to the Kristar PSD. A somewhat similar pattern was observed with the PSD results from Analytical Resources, Inc. (Figure 12). Figure 12 shows there is, on average, equivalent silt content between AWMS and the KriStar data and 14 percent more clay at the AMWS site. In both cases, the data clearly show that significantly more fine sediment (either silt or clay) was being exported from the AMWS site than was from the KriStar site.

This comparison helps explains why the pre-filters were clogging at the AMWS site (see *Maintenance Schedule* and *Treated Flow Rate during Bypass* sections above). Figure 12 also highlights two events that produced PSD results that are considered outliers. The PSD results from the April 4, 2013, event indicated that 80 percent of the suspended solids were finer than clay (colloidal). This was deemed a spurious result and the PSD results were not used in calculating the mean PSD for the site; however, the chemistry results for the same sample appeared typical so they were included in the final analyses. Also noted on Figure 12 is the

PSD result from February 22, 2013. This sample exhibited the highest clay content (47 percent) of any of the accepted samples and was characterized by only 61 percent TSS removal (see *Basic Treatment* section below).

Basic Treatment

The basic treatment goal listed in the TAPE guidelines indicate that the bootstrapped 95 percent lower confidence interval (LCL95) of the mean total suspended solids (TSS) removal must be greater than or equal to 80 percent for influent concentrations ranging from 100 to 200 mg/L. For influent TSS concentrations less than or equal to 100 mg/L but greater than 20 mg/L, the upper 95 percent confidence interval (UCL95) of the mean effluent concentration must be less than or equal to 20 mg/L. There is no specified criterion for influent TSS concentrations less than 20 mg/L; consequently, those sample pairs (influent and effluent) cannot be used for assessment of TSS removal performance. For influent concentration that exceed 200 mg/L, the treatment goal is an LCL95 of greater than an 80 percent reduction. Additionally, it must be shown that a statistically significant difference between influent and effluent concentrations exists. Finally, pollutant removals that meet the TAPE goals must be shown for sample pairs across a range of treated flow rates up to and including the design flow rate. This section describes the sampling results in relation to these criteria based on data from 24 events where influent concentrations were greater than 20 mg/L.

Before any performance analyses were conducted, the dataset was analyzed in relation to the different pre-filters configurations that were installed during monitoring. Due to issues associated with the high clay content of the runoff, the pre-filter design had to be altered during the course of the monitoring project. This resulted in samples being collected with four different types of pre-filters: BioMediaGREEN blocks, ribbed BioMediaGREEN blocks, perlite, and finally BioMediaGREEN cubes. The manufacturer plans to use cubed BioMediaGREEN for all future MWS-Linear installations; consequently, a statistical test was run to indicate if the cubed BioMediaGREEN performed differently than the other pre-filters types. Specifically, a Mann-Whitney U-test was run on the 16 TSS percent removal results collected with the cubed BioMediaGREEN versus the 8 collected with the other pre-filter configurations. The test indicated that there was no significant difference between the datasets ($p = 0.110$). Consequently, the data collected under all pre-filter configurations were combined for use in the following analyses.

A one-tailed Wilcoxon signed-rank test performed on the total suspended solids data with influent concentrations ≥20 mg/L ($n = 24$) indicated there was a statistically significant ($p < 0.001$) decrease in effluent total suspended solids concentrations compared to influent total suspended solids concentrations. Consequently, this aspect of the Basic Treatment criteria for TAPE was met.

The majority of the samples collected at AMWS had influent concentrations below 100 mg/L (Table 9). Of the 28 sampled events, 18 had influent concentrations between 20 and 100 mg/L. The UCL95 mean concentration for these 18 samples was 12.8 mg/L, which is below the 20 mg/L threshold and consequently these samples also show the Basic Treatment criteria for TAPE was met.

Seven of the sampled events were characterized by influent concentrations greater than 100 mg/L, with three events exceeding 200 mg/L (Table 9). The mean TSS removal for these events was 84.9 percent (above the 80 percent reduction criteria). While the mean TSS removal for the events with influent from 100 to 200 mg/L and >200 mg/L, was 90.8 and 77 percent, respectively (Table 9). An LCL95 mean removal was not calculable for these samples, since at least 10 samples are required for a bootstrap analysis. However, these samples were used in the assessment of removal efficiency at various treatment flow rates.

Because flow-weighted composite sampling consists of combined samples collected across a wide range of flow rates through the entire storm hydrograph, the resultant average sampled treated flow rate for a given composite sample will almost always be below the design flow rate. In order to see how the system performed at higher flow rates discrete "peak flow" samples had to be collected (see Table 9). A potential ramification of having most of the samples collected below the design flow rate is that the average percent removal result will be biased high. This is based on the assumption that treatment will be more efficient at lower flow rates through the filter. Figure 13 displays percent removal as a function of treated flow rate. As can be seen from this figure, there is no trend indicating that lower treated flow rates produced higher percent removal results. Consequently, we posit that the sampling design is not biased and is sufficient to determine treatment performance across a range of flow rates.

To determine with what flow rates the TSS removals were associated, the flow rate at the point when each aliquot was collected was calculated. These flow rates were then averaged for each sampled event. As shown in Table 9, these results indicate the mean sampled treated flow rate was 17.3 gpm. As described in the *Test System Sizing* section above, the design flow rate for the system is 41 gpm. Figure 13 displays percent removal versus average treated flow rate for all of the 24 qualifying TSS sample pairs. For reference, the open blue dots on the figure are sample pairs with influent less than 100 mg/L while the solid red dots are sample pairs with influent TSS from 100 – 200 mg/L, and the black squares represent sample pairs with influent TSS > 200 mg/L. The TAPE (Ecology 2011) indicates that a regression analysis should be conducted to determine the treatment efficiency varies as function of treated flow rate. The results of the regression analysis indicated there is no significant relationship between treatment efficiency and treated flow rate ($p = 0.822$).

Visual examinations of the relationship between treatment efficiency and treated flow rate in Figure 13 highlight the anomalous results from the February 22, 2013, event. As indicated in the *Particle Size Distribution* section above, the influent sample for this event was characterized by 47 percent suspended clay, 21 percent more clay than the average for the site. This may explain why the TSS removal for this sample pair was so low. If this data point is removed, it is clear that the TSS removal is above 80 percent up to and through the design flow rate of 41 gpm. In addition, it appears as if the system is capable of removing TSS at flow rates up to 50 gpm.

Taken together, the above analyses indicate that the Basic Treatment criteria were met based on the data collected at the AMWS test site.

Table 9. Total Suspended Solids Concentrations and Removal Efficiency Estimates for Valid Sampling Events at the AMWS Test System.

Storm Start Date & Time	Influent Conc. (mg/L)	Qualifier	Effluent Conc. (mg/L)	Qualifier	Effluent Conc. (in = 20-100) (mg/L)	% Removal (in = 100-200)	% Removal (in >200)	Sampled Flow Rate (gpm) [b]	Max Treated Flow Rate (gpm)	Bypass?
4/15/2012 22:45	**26**		**2.8**		**2.8**			7	16.5	
4/17/2012 21:20	**100**		**2.3**		**2.3**	**98**		13	24.1	✓
4/19/2012 8:30	**46**		**4.8**		**4.8**			6	12.0	✓
4/25/2012 20:50	**20**		**3.2**		**3.2**			10	24.1	
5/2/2012 21:50	**32**		**3**		**3**			15	35.8	
5/21/2012 4:45	**70**		**12**		**12**			22	33.3	
10/14/2012 19:15	**26**		**7.4**		**7.4**			28	41.8	✓
10/15/2012 12:30	**67**		**17**		**17**			28	41.8	✓
10/28/2012 6:15	**22**		**4.1**		**4.1**			28	48.0	✓
10/29/2012 22:45	**57**		**12**		**12**			23	48.0	✓
10/31/2012 5:25	**30**		**11**		**11**			6	12.7	
11/23/2012 8:25	6.5		1.7					19	23.4	✓
11/29/2012 6:15	**34.2**		**16**		**16**			10	21.0	✓
12/2/2012 14:10	6.7		2.6					5	10.2	
12/3/2012 22:30	**22.8**		**5.7**		**5.7**			11	12.0	✓
12/11/2012 11:20	6.7		5					19	30.9	✓
12/19/2012 2:10	**48.7**		**5.5**		**5.5**			17	21.0	✓
1/23/2013 12:15	**42**		**26.7**		**26.7**			6	10.2	
1/24/2013 17:50	**41.2**		**14.3**		**14.3**			8	25.0	✓
2/22/2013 9:30 [a]	**339**		**132**				**61**	40	38.6	✓
3/19/2013 15:35 [a]	**209**		**47**				**78**	28	31.8	✓
4/4/2013 8:00	**145**	**J**	**19**			**87**		3	5.5	
4/6/2013 16:45	12		2.1					11	18.2	✓
4/10/2013 8:50	**153**		**17**			**89**		13	26.1	✓
4/18/2013 20:45	**20.6**		**2.6**		**2.6**			9	14.3	
4/29/2013 3:15	**186**		**21**			**89**		20	37.0	
5/16/2013 12:15 [a]	**251**		**20.8**				**92**	50	47.6	✓
5/21/2013 11:15 [a]	**79**		**20.5**		**20.5**			28	45.6	✓
n	28		28		18	4	3	28	28	
UCL95 Mean [c]					12.3					
Mean	75.0		15.7		9.5	90.8	77.0	17.3	27.0	
LCL95 Mean [d]										

[a] All sampled events were flow-weighted composite sampled except these events, which consisted of samples collected above a high flow rate threshold (per TAPE requirements).

[b] Sampled flow rate is calculated by averaging the instantaneous flow rate associated with each aliquot in the composite sample.

[c] Bootstrapped estimate of the upper 95% confidence limit of the mean. Only calculated for effluent concentration with influent between 20 and 100 mg/L per the TAPE (Ecology 2011).

[d] Bootstrapped estimate of the lower 95% confidence limit of the mean. Only calculated for percent removal when influent ≥100 mg/L per the TAPE (Ecology 2011). Not calculated for this data set because n value was too low for bootstrap procedure.

Bold values met influent screening criteria and were used in performance analyses.

J = estimated value based on water quality data (Appendix E)

gpm = gallons/minute

mg/L = milligram/liter

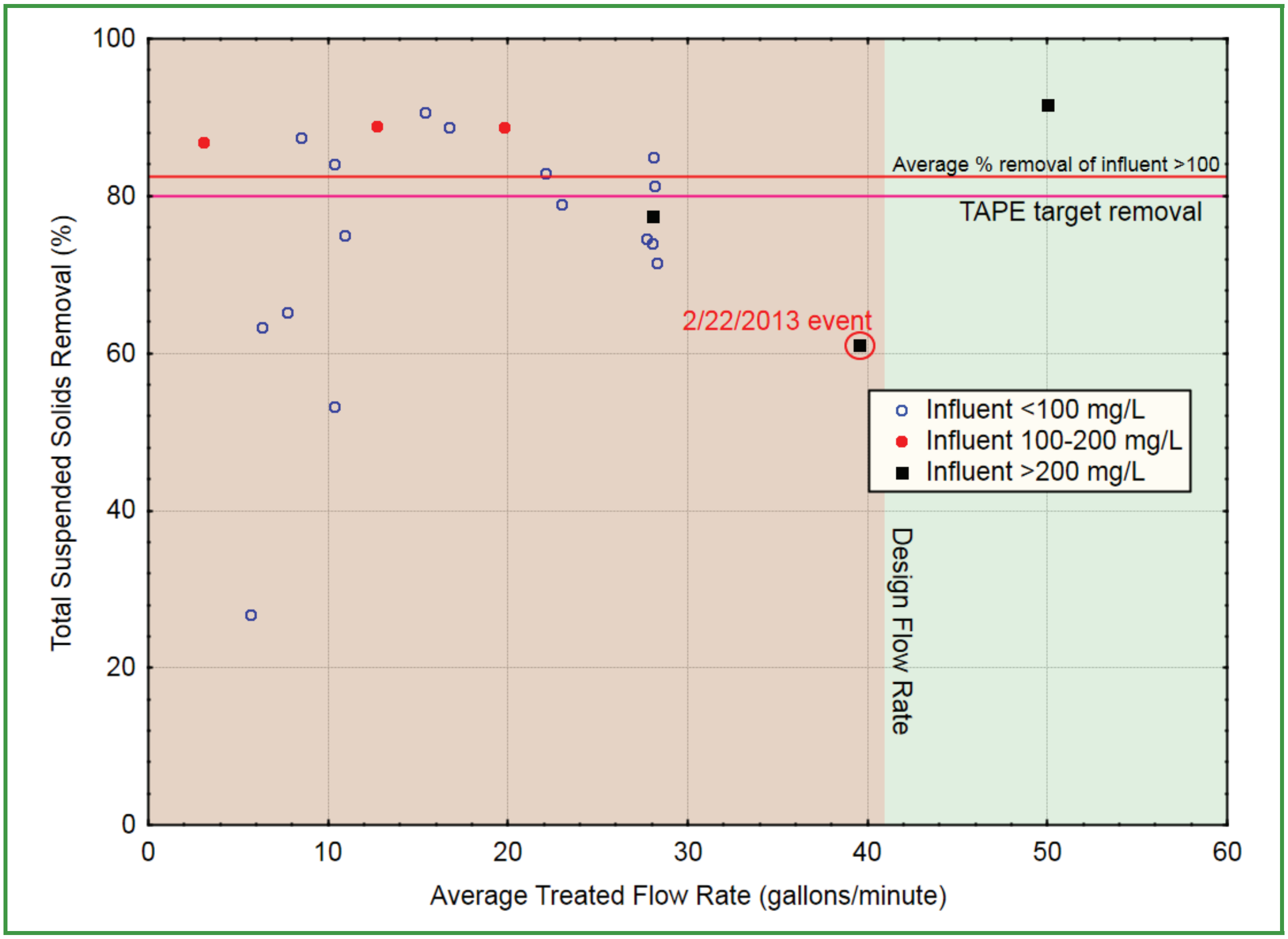


Figure 13. TSS Removal (%) as a Function of Average Treated Flow Rate.

Phosphorus Treatment

The phosphorus treatment goal listed in the TAPE guidelines indicates that the LCL95 of the mean removal must be greater than or equal to 50 percent for influent total phosphorus (TP) concentrations ranging from 0.1 to 0.5 mg/L. In addition, it must be shown that a statistically significant difference between influent and effluent concentrations exists. Finally, pollutant removals that meet the TAPE goals must be shown for sample pairs across a range of treated flow rates up to and including the design flow rate. This section describes the sampling results in relation to this criterion based on data from 17 events where influent concentrations were within the specified target range.

Before any performance analyses were conducted, the dataset was analyzed in relation to the pre-filters that were installed during monitoring. Specifically, a Mann-Whitney U-test was run on the 10 qualifying TP percent removal results collected with the cubed BioMediaGREEN versus the 7 collected with the other pre-filter configurations. The test indicated that there was no significant difference between the datasets ($p = 0.482$). Consequently, the data collected under all prefilter configurations were combined for use in the following analyses.

It should also be noted that one of the data points used in the analyses presented herein is an orthophosphorus result instead of a TP result. A high flow rate sample was collected on

May 16, 2013, but the sample was mistakenly not analyzed for TP. Orthophosphorus was used in lieu of TP for this event, which is a conservative approach as orthophosphorus is more difficult to treat and remove than is TP. This substitution was approved by Ecology in a meeting held on June 5, 2013.

A one-tailed Wilcoxon signed-rank test performed on the TP data with influent concentrations from 0.1 to 0.5 mg/L ($n = 19$) indicated there was a statistically significant ($p < 0.001$) decrease in effluent TP concentrations compared to influent concentrations. Consequently, this aspect of the Phosphorus Treatment criteria for TAPE was met.

The LCL95 mean percent reduction for the 17 qualifying TP sample pairs was 57.6 percent (Table 10), which is above the goal of ≥50 percent; consequently, these samples also show the Phosphorus Treatment criteria for TAPE was met.

To determine with what flow rates the TP removals were associated, the flow rate at the point when each aliquot was collected was calculated. These flow rates were then averaged for each sampled event. As shown in Table 10, these results indicate the mean sampled treated flow rate was 17.3 gpm. As described in the *Test System Sizing* section above, the design flow rate for the system is 41 gpm. Figure 14 displays percent removal versus average treated flow rate for all of the 17 qualifying TP sample pairs. Figure 14 indicates the high flow rate orthophosphorus result as well as all of the qualifying TP results. As is apparent, only one result fell below the 50 percent reduction threshold. It should be noted that in Figure 14, it is apparent that there is no trend indicating that there is increased TP removal at lower treated flow rates. Consequently, the LCL95 mean removal of 57.6 percent is not biased by the fact that the majority of the samples were collected below the design flow rate.

The results of the regression analysis on the percent removal versus flow rate data indicated there is no significant linear relationship between these variables ($p = 0.834$). A visual assessment of the data in Figure 14 also indicates treatment efficiency greater than 50 percent is evident up to and through the design flow rate; therefore, it can be safely assumed that the system can reduce TP by greater than 50 percent at the design flow rate of 41 gpm. In addition, it appears as if the system can effectively remove phosphorus at flow rates up to 50 gpm (Figure 14).

Taken together, the above analyses indicate that the Phosphorus Treatment criteria were met based on the data collected at the AMWS test site.

Enhanced Treatment

The TAPE enhanced treatment criteria indicate that the LCL95 of the mean dissolved zinc removal must be greater than 60 percent for influent concentrations ranging from 0.02 to 0.3 mg/L. In addition, the LCL95 of the mean dissolved copper removal must be greater than 30 percent for influent concentrations ranging from 0.005 to 0.02 mg/L. In addition, it must be shown that a statistically significant difference between influent and effluent concentrations exists. Finally, pollutant removals that meet the TAPE goals must be shown for sample pairs across a range of treated flow rates up to and including the design flow rate. Separate subsections below describe the sampling results in relation to these criteria based

Table 10. Total Phosphorus Concentrations and Removal Efficiency Estimates for Valid Sampling Events at the AMWS Test System.

Storm Start Date & Time	Influent Conc. (mg/L)	Qualifier	Effluent Conc. (mg/L)	Qualifier	% Removal (in= 0.1-0.5) [b]	Sampled Flow Rate (gpm) c	Max Treated Flow Rate (gpm)	Bypass?
4/15/2012 22:45	0.092		0.026		72	7	16.5	
4/17/2012 21:20	0.14	J	0.02	U	86	13	24.1	✓
4/19/2012 8:30	0.087	J	0.1	U		6	12.0	✓
4/25/2012 20:50	0.15		0.062		59	10	24.1	
5/2/2012 21:50	0.090		0.038		58	15	35.8	
5/21/2012 4:45	0.18		0.062		66	22	33.3	
10/14/2012 19:15	0.18		0.079		56	28	41.8	✓
10/15/2012 12:30	0.098		0.01		90	28	41.8	✓
10/28/2012 6:15	0.066		0.039			28	48.0	✓
10/29/2012 22:45	0.13		0.041		68	23	48.0	✓
10/31/2012 5:25	0.1		0.039		61	6	12.7	
11/23/2012 8:25	0.026		0.1	U		19	23.4	✓
11/29/2012 6:15	0.093		0.036		61	10	21.0	✓
12/2/2012 14:10	0.027		0.01			5	10.2	
12/3/2012 22:30	0.075		0.023			11	12.0	✓
12/11/2012 11:20	0.257		0.054		79	19	30.9	✓
12/19/2012 2:10	0.073		0.025			17	21.0	✓
1/23/2013 12:15	0.103		0.083		19	6	10.2	
1/24/2013 17:50	0.098		0.039		60	8	25.0	✓
2/22/2013 9:30 [a]	0.56		0.26			40	38.6	✓
3/19/2013 15:35 [a]	0.398		0.13		67	28	31.8	✓
4/4/2013 8:00	2.15	J	0.4			3	5.5	
4/6/2013 16:45	0.165		0.041		75	11	18.2	✓
4/10/2013 8:50						13	26.1	✓
4/18/2013 20:45						9	14.3	
4/29/2013 3:15						20	37.0	
5/16/2013 12:15 [a]	0.114 f		0.05 f		56 f	50	47.6	✓
5/21/2013 11:15 [a]	0.212		0.1		53	28	45.6	✓
n	25		25		17	28	28	
UCL95 Mean [d]								
Mean	0.231		0.076		63.9	17.3	27.0	
LCL95 Mean [e]					57.6			

[a] All sampled events were flow-weighted composite sampled except these events, which consisted of samples collected above a high flow rate threshold.
[b] Percent removal is only calculated for sample pairs with influent 0.1 – 0.5 mg/L.
[c] Sampled flow rate is calculated by averaging the instantaneous flow rate associated with each aliquot in the composite sample.
[d] Bootstrapped estimate of the upper 95% confidence limit of the mean. Only calculated for TSS effluent concentrations (not applicable for TP).
[e] Bootstrapped estimate of the lower 95% confidence limit of the mean. Used to compare to the TAPE TP criteria of at least 50 percent removal.
[f] Orthophosphorus results used in lieu of TP results for this event (due to missing TP data).
Bold values met influent screening criteria and were used in performance analyses
J = estimated value based on water quality data (Appendix E)
U = result at or below the reporting limit
gpm = gallons/minute
mg/L = milligram/liter

on data from 11 and 14 events where influent concentrations were within the specified ranges for dissolved zinc and copper, respectively.

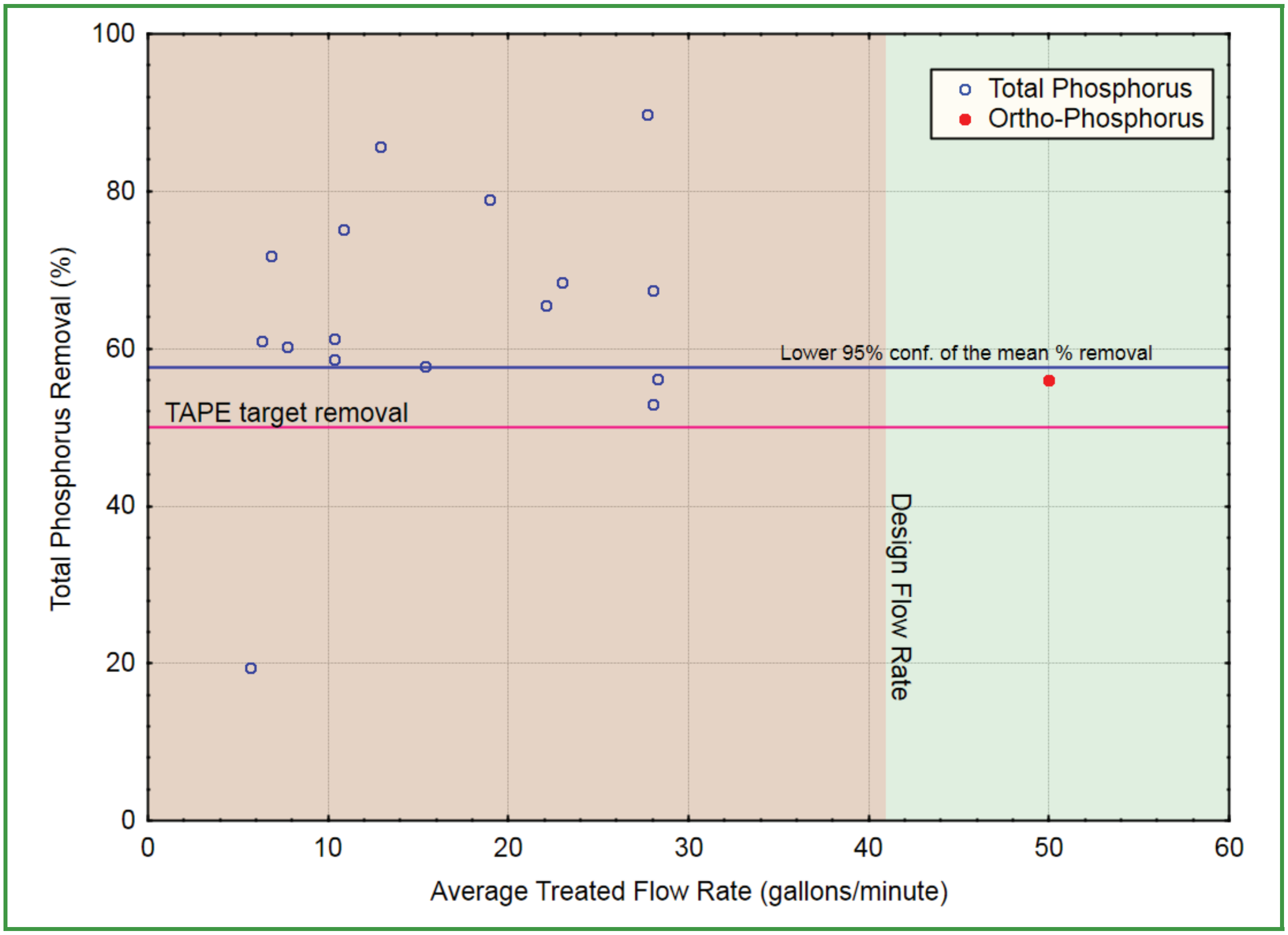


Figure 14. TP Removal (%) as a Function of Average Treated Flow Rate.

Dissolved Zinc Treatment

Before any performance analyses were conducted, the dissolved zinc dataset was analyzed in relation to the pre-filters, which were installed during monitoring. Specifically, a Mann-Whitney U-test was run on the 11 qualifying dissolved zinc percent removal results collected with the cubed BioMediaGREEN versus the 7 collected with the other pre-filter configurations. The test indicated that there was a significant difference between the datasets ($p = 0.004$). Consequently, only the data collected when the cubed BioMediaGREEN was installed were used in the final assessment. This results in a dataset with only 11 qualifying events. The TAPE indicates that 12 events are required. However, based on conversations with Douglas Howie of Ecology (June 5, 2013) and due to the challenging site conditions, 11 events was deemed adequate for this TER.

A one-tailed Wilcoxon signed-rank test performed on the dissolved zinc data with influent concentrations from 0.02 to 0.3 mg/L ($n = 11$) indicated there was a statistically significant ($p < 0.001$) decrease in effluent dissolved zinc concentrations compared to influent concentrations. Consequently, this aspect of the Enhanced Treatment criteria for TAPE was met.

The LCL95 mean percent reduction for the 11 qualifying dissolved zinc sample pairs was 60.5 percent (Table 11), which is above the goal of ≥60 percent; consequently, these samples also show the Enhanced Treatment criteria for TAPE was met.

To determine what flow rates were associated with the dissolved zinc removals, the flow rate was calculated at the point when each aliquot was collected. These flow rates were averaged for each sampled event. As shown in Table 11, these results indicate the mean sampled treated flow rate was 17.3 gpm. As described in the *Test System Sizing* section above, the design flow rate for the system is 41 gpm. Figure 15 displays percent removal versus average treated flow rate for all of the 11 qualifying dissolved zinc sample pairs (closed red dots). Figure 15 indicates the results from when the other pre-filters were installed (open blue circles) for reference purposes only. As is apparent, only three results from when the cubed BioMediaGREEN was installed fell below the 50 percent reduction threshold. These three results occurred at lower sampled flow rates. Closer to and through the design flow rate, the percent reduction results exceed 60 percent. The results of the regression analysis on the percent removal versus flow rate data also indicated there is no significant relationship between these variables ($p = 0.707$). Therefore, it can be safely assumed that the system can reduce dissolved zinc by greater than 60 percent at the design flow rate of 41 gpm. It should be noted that in Figure 15 it is apparent that there is no trend indicating that there is increased dissolved zinc removal at lower treated flow rates. Consequently, the LCL95 mean removal of 60.5 percent is not biased by the fact that the majority of the samples were collected below the design flow rate.

Taken together, the above analyses indicate that the Enhanced treatment criterion for dissolved zinc in TAPE was met based on the data collected at the AMWS test site.

Dissolved Copper Treatment

Before any performance analyses were conducted, the dissolved copper dataset was analyzed in relation to the pre-filters, which were installed during monitoring. Specifically, a Mann-Whitney U-test was run on the nine qualifying dissolved copper percent removal results collected with the cubed BioMediaGREEN versus the five collected with the other pre-filter configurations. The test indicated that there was no significant difference between the datasets ($p = 0.797$). Consequently, the data collected under all pre-filter configurations were combined for use in the following analyses.

A one-tailed Wilcoxon signed-rank test performed on the dissolved copper data with influent concentrations from 0.005 to 0.02 mg/L ($n = 14$) indicated there was a statistically significant ($p < 0.001$) decrease in effluent dissolved copper concentrations compared to influent concentrations. Consequently, this aspect of the Enhanced Treatment criteria for dissolved copper in TAPE was met.

The LCL95 mean percent reduction for the 14 qualifying dissolved copper sample pairs was 32.5 percent (Table 12), which is above the goal of ≥30 percent; consequently, these samples also show the Enhanced Treatment criterion for dissolved copper in TAPE was met.

Table 11. Dissolved Zinc Concentrations and Removal Efficiency Estimates for Valid Sampling Events at the AMWS Test System.

Storm Start Date & Time	Influent Conc. (mg/L)	Qualifier	Effluent Conc. (mg/L)	Qualifier	% Removal (in= 0.02-0.3) [b]	Sampled Flow Rate (gpm) [d]	Max Treated Flow Rate (gpm)	Bypass?
4/15/2012 22:45	**0.029**		**0.02**		**31 (NA)**	7	16.5	
4/17/2012 21:20	**0.020**		**0.011**		**45 (NA)**	13	24.1	✓
4/19/2012 8:30	0.011		0.01	U		6	12.0	✓
4/25/2012 20:50	**0.060**		**0.056**		**7 (NA)**	10	24.1	
5/2/2012 21:50	**0.022**		**0.012**		**45 (NA)**	15	35.8	
5/21/2012 4:45	**0.06**		**0.033**		**45 (NA)**	22	33.3	
10/14/2012 19:15	**0.031**		**0.012**		**61 (NA)**	28	41.8	✓
10/15/2012 12:30	**0.022**		**0.011**		**50 (NA)**	28	41.8	✓
10/28/2012 6:15	0.015		0.0046			28	48.0	✓
10/29/2012 22:45	**0.020**		**0.0074**		**63**	23	48.0	✓
10/31/2012 5:25	0.015		0.0068			6	12.7	
11/23/2012 8:25	0.0107		0.0034			19	23.4	✓
11/29/2012 6:15	0.0108		0.0099			10	21.0	✓
12/2/2012 14:10	0.0148		0.006			5	10.2	
12/3/2012 22:30	0.013		0.0109			11	12.0	✓
12/11/2012 11:20	**0.045**		**0.0133**		**70**	19	30.9	✓
12/19/2012 2:10	**0.0314**		**0.0072**		**77**	17	21.0	✓
1/23/2013 12:15	0.0156		0.0076			6	10.2	
1/24/2013 17:50	**0.0198**		**0.0069**		**65**	8	25.0	✓
2/22/2013 9:30 [a]	0.0022		0.0060			40	38.6	✓
3/19/2013 15:35 [a]	0.0104		0.0122			28	31.8	✓
4/4/2013 8:00	**0.352** [c]		**0.1940**		**45**[c]	3	5.5	
4/6/2013 16:45	**0.0338**		**0.0156**		**54**	11	18.2	✓
4/10/2013 8:50	**0.152**		**0.0652**		**57**	13	26.1	✓
4/18/2013 20:45	**0.299**		**0.0312**		**90**	9	14.3	
4/29/2013 3:15	**0.315** [c]		**0.0610**		**81**[c]	20	37.0	
5/16/2013 12:15 [a]	**0.0715**		**0.0238**		**67**	50	47.6	✓
5/21/2013 11:15 [a]	**0.0349**		**0.0136**		**61**	28	45.6	✓
n	28		28		11	28	28	
UCL95 Mean [e]								
Mean	0.0620		0.0240		66.4	17.3	27.0	
LCL95 Mean [f]					60.5			

[a] All sampled events were flow-weighted composite sampled except these events, which consisted of samples collected above a high flow rate threshold.
[b] Percent removal is only calculated for sample pairs with influent 0.02 – 0.3 mg/L. For exception see footnote c.
[c] Influent exceeded 0.3 mg/L but after discussions with Ecology on 6/5/2013, it was determined that these samples could be included for analysis.
[c] Sampled flow rate is calculated by averaging the instantaneous flow rate associated with each aliquot in the composite sample.
[d] Bootstrapped estimate of the upper 95% confidence limit of the mean. Only calculated for TSS effluent concentrations (not applicable to dissolved zinc).
[e] Bootstrapped estimate of the lower 95% confidence limit of the mean. Used to compare to the TAPE dissolved zinc criteria of at least 60 percent removal.
Bold values met influent screening criteria and were used in performance analyses
NA = not applicable. Percent removal results are associated with pre-filters which performed statistically worse than the cubed BioMediaGREEN. These results were not used in the final analysis.
U = result at or below the reporting limit
gpm = gallons/minute
mg/L = milligram/liter

Table 12. Dissolved Copper Concentrations and Removal Efficiency Estimates for Valid Sampling Events at the AMWS Test System.

Storm Start Date & Time	Influent Conc. (mg/L)	Qualifier	Effluent Conc. (mg/L)	Qualifier	% Removal (in= 0.005-0.02) [b]	Sampled Flow Rate (gpm) [d]	Max Treated Flow Rate (gpm)	Bypass?
4/15/2012 22:45	**0.0053**		**0.0027**		**49**	7	16.5	
4/17/2012 21:20	0.0026		0.002	U		13	24.1	✓
4/19/2012 8:30	0.0021		0.002	U		6	12.0	✓
4/25/2012 20:50	**0.011**		**0.0073**		**34**	10	24.1	
5/2/2012 21:50	0.0025		0.0021			15	35.8	
5/21/2012 4:45	**0.0066**		**0.0038**		**42**	22	33.3	
10/14/2012 19:15	**0.0057**		**0.0043**		**25**	28	41.8	✓
10/15/2012 12:30	**0.0049**		**0.0034**		**31**	28	41.8	✓
10/28/2012 6:15	0.0018		0.0016			28	48.0	✓
10/29/2012 22:45	0.0028		0.0021			23	48.0	✓
10/31/2012 5:25	0.0018		0.0011			6	12.7	
11/23/2012 8:25	0.0012		0.0016			19	23.4	✓
11/29/2012 6:15	0.0027		0.0019			10	21.0	✓
12/2/2012 14:10	0.0032		0.0046			5	10.2	
12/3/2012 22:30	0.0024		0.0028			11	12.0	✓
12/11/2012 11:20	**0.0051**		**0.0024**		**53**	19	30.9	✓
12/19/2012 2:10	0.001		0.0009			17	21.0	✓
1/23/2013 12:15	0.0041	J	0.0035			6	10.2	
1/24/2013 17:50	**0.0117**		**0.0053**		**54**	8	25.0	✓
2/22/2013 9:30 [a]	0.0025		0.0024			40	38.6	✓
3/19/2013 15:35 [a]	0.0026		0.0022			28	31.8	✓
4/4/2013 8:00	**0.034** [c]	**J**	**0.0275**		**19** [c]	3	5.5	
4/6/2013 16:45	**0.0144**		**0.0086**		**40**	11	18.2	✓
4/10/2013 8:50	**0.0205** [c]		**0.0090**		**56** [c]	13	26.1	✓
4/18/2013 20:45	**0.0225** [c]		**0.0090**		**60** [c]	9	14.3	
4/29/2013 3:15	**0.0471** [c]		**0.0354**		**25** [c]	20	37.0	
5/16/2013 12:15 [a]	**0.012**		**0.0093**		**23**	50	47.6	✓
5/21/2013 11:15 [a]	**0.0076**		**0.0056**		**26**	28	45.6	✓
n	28		28		14			
UCL95 Mean [e]								
Mean	0.0049		0.0059		38.4			
LCL95 Mean [f]					32.5			

[a] All sampled events were flow-weighted composite sampled except these events that consisted of samples collected above a high flow rate threshold.
[b] Percent removal is only calculated for sample pairs with influent 0.005 – 0.02 mg/L. For exception see footnote c.
[c] Influent exceeded 0.02 mg/L but after discussions with Ecology on 6/5/2013, it was determined that these samples could be included for analysis.
[d] Sampled flow rate is calculated by averaging the instantaneous flow rate associated with each aliquot in the composite sample.
[e] Bootstrapped estimate of the upper 95% confidence limit of the mean. Only calculated for TSS effluent concentrations.
[f] Bootstrapped estimate of the lower 95% confidence limit of the mean. Used to compare to the TAPE dissolved copper criteria of at least 30 percent removal.
Bold values met influent screening criteria and were used in performance analyses
J = estimated value based on water quality data (Appendix E)
U = result at or below the reporting limit
gpm = gallons/minute
mg/L = milligram/liter

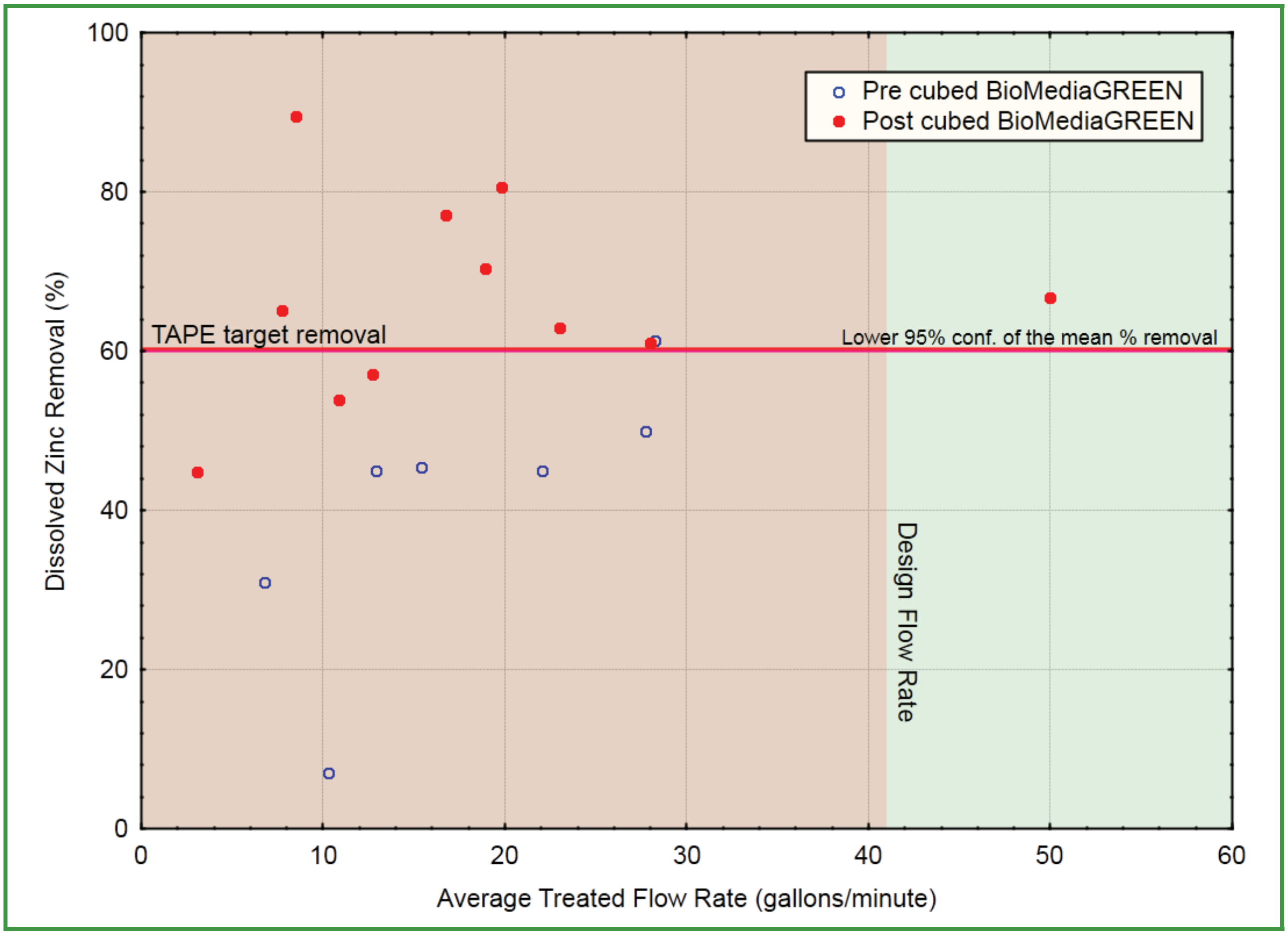


Figure 15. Dissolved Zinc Removal (%) as a Function of Average Treated Flow Rate.

To determine with flow rates were associated with dissolved copper removals, the flow rate at the point when each aliquot was collected was calculated. These flow rates were then averaged for each sampled event. As shown in Table 12, these results indicate the mean sampled treated flow rate was 17.3 gpm. As described in the *Test System Sizing* section above, the design flow rate for the system is 41 gpm. Figure 16 displays percent removal versus average treated flow rate for all of the 14 qualifying dissolved copper sample pairs (open blue circles). In addition, a data point from lab data collected in 2007 is included as a high flow rate reference point (red closed dot). The lab study data are summarized in the CULD application for the Modular Wetland System (Herrera 2011a). The TAPE indicates that lab data can be used to augment field data when determining performance at different flow rates. It should be noted that in Figure 16 it is apparent that there is no trend indicating that there is increased dissolved copper removal at lower treated flow rates. Consequently, the LCL95 mean removal of 32.5 percent is not biased by the fact that the majority of the samples were collected below the design flow rate.

The results of the regression analysis on the percent removal versus flow rate data indicated there is no significant relationship between these variables (p = 0.079); a visual assessment of the data in Figure 16 also show treatment above the TAPE target of 30 percent removal is evident until approximately 28 gpm. However, when the lab data point is included in the assessment, it is evident that the system (under less adverse conditions) can treat at a much higher efficiency at the design flow rate of 41 gpm. Given this, and considering the challenging site conditions at the Albina Maintenance Facility, we propose that Ecology grant dissolved copper removal certification at 41 gpm.

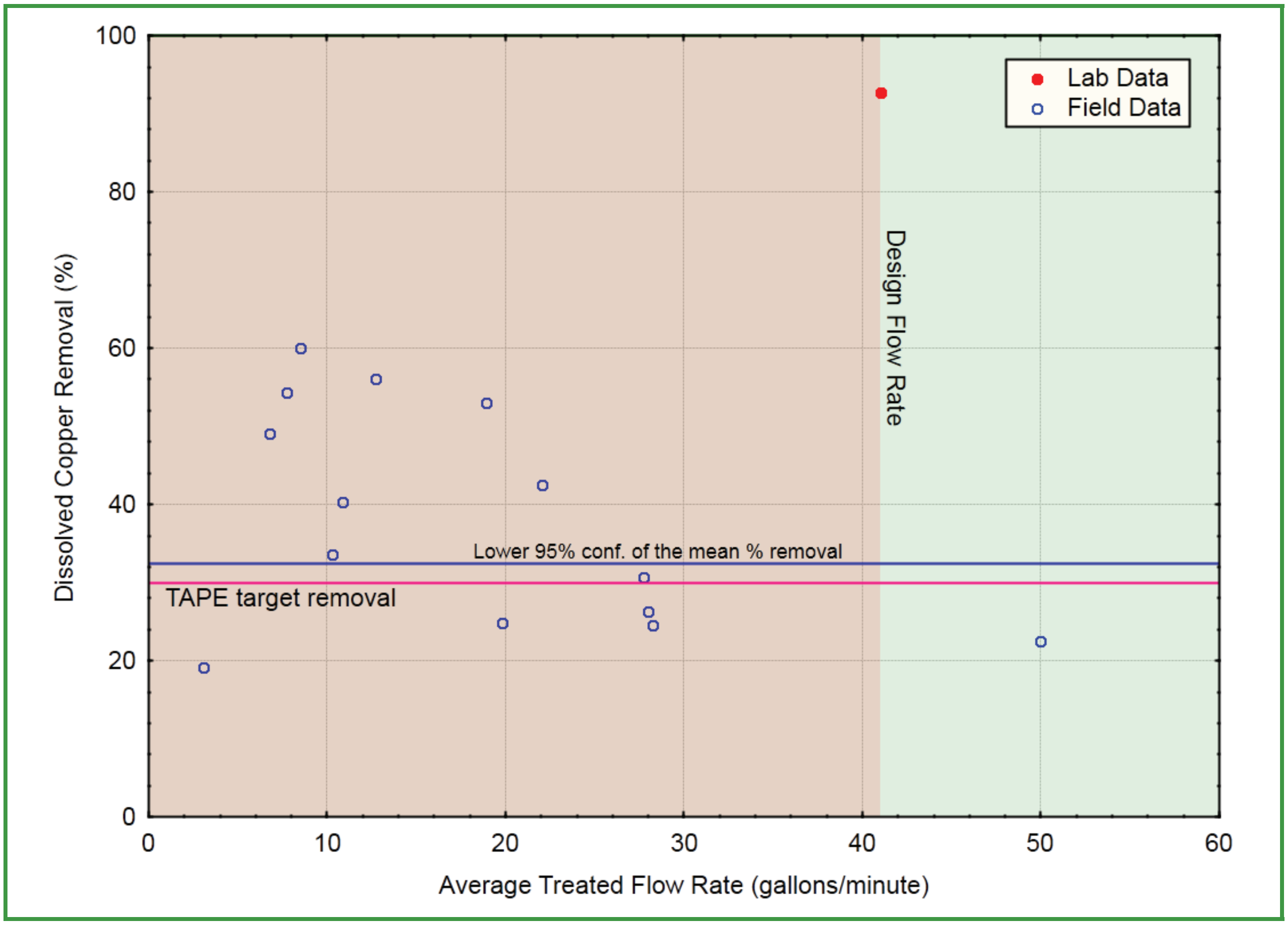


Figure 16. Dissolved Copper Removal (%) as a Function of Average Treated Flow Rate.

Taken together, the above analyses indicate that the Enhanced Treatment criteria for dissolved copper in TAPE was met. The flow rate at which dissolved copper is approved needs to be investigated further, but we propose approving dissolved copper at a flow rate of 41 gpm based on the lab data that indicates high removal at 41 gpm flow rate.

Other Parameters

The TAPE (Ecology 2011) indicates that in addition to required parameters mentioned above, screening parameters should be analyzed. The screening parameters consist of hardness, pH, and orthophosphate. The results for these parameters are presented in Table 13. The AMWS system had a negligible effect on hardness and pH. The average hardness concentrations were 37.6 and 40.6 mg $CaCO_3$/L at the inlet and outlet, respectively. The average pH concentrations were 7.6 and 7.5 at the inlet and outlet, respectively. TAPE guidelines indicate that the test system should not increase of decrease pH by more than one unit for any given event or export concentration less than 4 or greater than 9. The pH data presented in Table 13 indicate that these conditions were met for each sampled event.

Table 13. Summary Results for Screening Parameters.

Storm Start Date & Time	Influent Hardness (mg $CaCO_3$ /L)	QA	Effluent Hardness (mg $CaCO_3$ /L)	QA	Influent pH (std. units)	QA	Effluent pH (std. units)	QA	Influent ortho-P (std. units)	QA	Effluent ortho-P (std. units)	QA
4/15/2012 22:45	31		43		7.53		6.17		0.01		0.01	U
4/17/2012 21:20	37		51		7.54		7.51		0.01	U	0.01	U
4/19/2012 8:30	26		33		7.46		7.41		0.01	U	0.01	U
4/25/2012 20:50	39		48		7.51		7.54		0.069		0.024	
5/2/2012 21:50	26		31		7.4		7.29		0.016		0.01	U
5/21/2012 4:45	37		44		7.48		7.45		0.047		0.013	
10/14/2012 19:15	30		48		7.13		6.82		0.073		0.05	U
10/15/2012 12:30	35		42		7.3		7.2		0.059		0.08	
10/28/2012 6:15	29		31		7.57		7.45		0.05	H	0.05	UH
10/29/2012 22:45	35		35		7.41		7.36		0.05	U	0.05	U
10/31/2012 5:25	45		46		7.52		7.56		0.05	U	0.05	U
11/23/2012 8:25					7.29	J	7.41	J				
11/29/2012 6:15	33.2		30.4		7.74		7.32		0.05	U	0.05	U
12/2/2012 14:10	29.2		30		7.15		7.19		0.05	U	0.05	U
12/3/2012 22:30									0.05	U	0.05	U
12/11/2012 11:20	27.2		29.6		7.88	J	7.92	J	0.05	U	0.05	U
12/19/2012 2:10	19.6		25.2		7.86		7.71		0.05	U	0.05	U
1/23/2013 12:15	40		41.2		8.06		7.72		0.05	U	0.05	U
1/24/2013 17:50	38		34.8		7.71		7.81		0.05	U	0.05	U
2/22/2013 9:30 [a]	62.8		50.8		8.84		8.14		0.05	U	0.05	U
3/19/2013 15:35 [a]	36.8		39.2		7.86		7.77		0.05	U	0.05	U

Table 13 (continued). Summary Results for Screening Parameters.

Storm Start Date & Time	Influent Hardness (mg $CaCO_3$ /L)	QA	Effluent Hardness (mg $CaCO_3$ /L)	QA	Influent pH (std. units)	QA	Effluent pH (std. units)	QA	Influent ortho-P (std. units)	QA	Effluent ortho-P (std. units)	QA
4/4/2013 8:00	76		58.8		7.09	J	7.69	J	0.96		0.199	
4/6/2013 16:45	36		38.4		7.67		6.96		0.123		0.05	U
4/10/2013 8:50	43.2		41.6		7.83		8.13		0.426		0.05	U
4/18/2013 20:45	48		47.2		7.66		7.69		0.06		0.05	U
4/29/2013 3:15	42.4		47.6		7.33		7.52		0.156		0.05	U
5/16/2013 12:15 [a]	47.2		53.2		7.32		7.41		0.114		0.05	U
5/21/2013 11:15 [a]	28.4		34.4		7.65	J	7.57	J	0.062		0.05	U
Minimum	19.6		25.2		7.09		6.17		0.01	U	0.01	U
Mean	37.6		40.6		7.6		7.5		0.093		0.031	
Maximum	76		58.8		8.84		8.14		0.960		0.199	

[a] All sampled events were flow-weighted composite sampled except these events, which consisted of samples collected above a high flow rate threshold.

Ortho-P = Orthophosphorus

J = estimated value based on water quality data (Appendix E)

QA = quality assurance

The orthophosphorus data indicated that the AMWS system reduced orthophosphorus by 67 percent, on average. When compared with other treatment systems (Herrera 2006, 2009, 2010, 2011c), the AMWS exhibited a substantially higher orthophosphorus removal rate.

CONCLUSIONS

To obtain performance data to support the issuance of a GULD for the Modular Wetland System - Linear stormwater filtration system, Herrera conducted hydrologic and water quality monitoring at a test system in Portland, Oregon from April 14, 2012, to May 31, 2013. During this monitoring period, 28 separate storm events were sampled.

Of the 28 sampled events, 24 qualified for total suspended solids analysis. The data were segregated into sample pairs with influent concentration greater than and less than 100 mg/L. The UCL95 mean effluent concentration for the data with influent less than 100 mg/L was 12.8 mg/L, below the 20 mg/L threshold. In addition, the system exhibited TSS removal greater than 80 percent at flow rates up to and including the design flow rate of 41 gpm. Based on these results we recommend the system be granted Basic Treatment certification at 50 gpm (equivalent to 1.21 gpm/ft^2 of media).

Nineteen of the 28 sampled events qualified for total phosphorus analysis. The LCL95 mean percent removal was 61.7, well above the TAPE goal of 50 percent. Treatment above 50 percent was evident at flow rates up to and including the design flow rate of 41 gpm. Based on these results we recommend the system be granted Phosphorus Treatment certification at 50 gpm (equivalent to 1.21 gpm/ft^2 of media).

Eleven of the 28 sampled events qualified for assessment for dissolved zinc removal. The LCL95 mean removal was 60.5 percent while the TAPE goal is greater than 60 percent removal. Treatment above 60 percent was evident at flow rates up to and including the design flow rate of 41 gpm. Consequently, the MWS-Linear met the Enhanced Treatment criterion specified for dissolved zinc in TAPE at the design flow rate.

Fourteen of the 28 sampled events qualified for assessment for dissolved copper removal. The LCL95 mean removal was 32.5 percent while the TAPE goal is greater than 30 percent removal. Treatment above 30 percent was evident at flow rates up to 28 gpm. When lab data are used to augment the dataset, the results indicate the MWS-Linear met the Enhanced Treatment criterion specified for dissolved copper in TAPE at flow rates up to and including the design flow rate of 41 gpm.

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