WHITE PAPER

Filterra® Bioretention Systems: Technical Basis for High Flow Rate Treatment and Evaluation of Stormwater Quality Performance

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Abstract

Media flow rate is one of many variables that influence the performance of bioretention systems. While conventional thinking is that bioretention systems with lower media flow rates provide better pollutant removal, a review of scientific principles and monitoring data suggests otherwise. Based on a review of scientific principles, the Filterra® Bioretention Stormwater Treatment System is expected to be capable of achieving pollutant removal efficiencies and system longevity on par with conventional slow flow rate bioretention systems. A review of monitoring data demonstrates that Filterra® systems are capable of achieving higher pollutant removal efficiency ratios and lower effluent concentrations, on average, compared to similar categories of non-proprietary stormwater treatment best managements practices (BMPs). In addition, Filterra® systems showed statistically significant removals for a broader range of pollutants than similar classes of non-proprietary BMPs. Finally, hydraulic performance data demonstrate sustained high media flowrates in Filterra® systems over a variety of ages. Overall, this paper finds that incorporation of a specialized media that can efficiently treat stormwater at a high flow rate while supporting biological processes within a relatively small footprint makes the Filterra® Bioretention System an effective tool based on low impact development (LID) principles.

1. Executive Summary

Conventional thinking is that slow flow rate bioretention media works better than high flow rate bioretention media to remove pollutants from stormwater; however, an understanding of the pollutant removal mechanisms of bioretention systems and analysis of water quality data collected from high flow rate systems demonstrates that this is not the case. In addition, the common use of high flow rate media and natural high flow systems for both water and wastewater treatment provides long standing empirical evidence of the effectiveness of these types of systems.

The dominant unit treatment processes provided by bioretention systems occur predominantly during storm events and consist of inert and reactive filtration. A review of the scientific principles behind these mechanisms suggests that high flow rate bioretention media would not necessarily achieve significantly lower removal of particulate-bound and dissolved constituents than low flow rate media. Processes occurring between storm events are also critical for the retention of captured pollutants and the preservation or regeneration of hydraulic capacity and the function of the dominant treatment mechanisms. Inter-storm processes, including microbially-mediated transformations, biological uptake and sequestration, volatilization, bacterial inactivation processes, soil processes, and routine maintenance, do not vary significantly between high flow rate and slow flow rate bioretention systems. The Filterra® Bioretention System (Filterra® system) is designed to promote the within-storm and inter-storm treatment processes characteristic of bioretention systems through the incorporation of mulch, specialized media, and biologically active components. Based on a review of scientific principles, the Filterra® system is expected to be capable of achieving pollutant removal efficiencies and system longevity on par with conventional slow flow rate bioretention systems.

Third-party analyses of the Filterra® system have demonstrated sustained high media flow rates and treatment performance. Laboratory scale testing results support media filtration rates of greater than 100 inches per hour. Results from field scale testing of hydraulic function of systems of a variety of ages support the current design flow rate recommendation of 100 to 140 inches per hour. Field scale testing of treatment performance has demonstrated variable, but generally high and sustained performance. Results from five field studies were fairly consistent for total suspended solids (TSS) with efficiency ratios ranging from 83 to 88 percent. The efficiency ratio for total phosphorus had a much wider range from 9 to 70 percent, across five studies; the low end of this range was due to low total phosphorus concentrations and high fractions of soluble reactive phosphorus measured during one study. Total Kjeldahl nitrogen (TKN) had an efficiency ratio of 40 percent in one study. The efficiency ratio for total copper ranged from 33 to 77 percent in three studies, while dissolved copper had an efficiency ratio of 48 percent in one study. The efficiency ratio for total zinc removal ranged from 48 to 79 percent in three studies, while dissolved zinc had an efficiency ratio of 55 percent in one study. The oil and grease efficiency ratio was lower than expected (59 percent) due to low influent concentrations near the detection limit in one study; however, the total petroleum hydrocarbon (TPH) efficiency ratio was 96 percent in a different study.

Effluent concentrations achieved in the full-scale studies were generally equal to or lower than median effluent concentrations for the biofilter and media filter classes of best management practices (BMPs) reported in the International Stormwater BMP Database. In addition, Filterra® systems showed statistically significant removals for a broader range of pollutants than were shown for the biofilter and media filter categories in the International Stormwater BMP Database.

In summary, the Filterra® Bioretention System incorporates a specialized media that can treat stormwater at a high flow rate to provide pollutant removal capabilities using a relatively small footprint compared to slow flow rate bioretention systems. These design characteristics make the Filterra® system a well-suited BMP, designed based on low impact development (LID) principles, for a wide variety of conditions, allowing pollutant loads to be addressed close to their source even on space-constrained sites where the use of traditional slow flow rate systems would be problematic or infeasible. The Filterra® system also supports inter-storm processes that work to preserve and restore treatment capacity and hydraulic function. These processes are believed to help preserve the longevity of the system and reduce the need for major maintenance and media replacement.

2. Introduction

Conventional thinking is that slow flow rate bioretention media works better than high flow rate bioretention media to remove pollutants from stormwater; however, an understanding of the pollutant removal mechanisms of bioretention systems and analysis of water quality data collected from high flow rate systems demonstrates that this is not necessarily the case. This paper discusses the pollutant removal mechanisms and presents the technical basis to demonstrate the effectiveness of high flow rate media used in the Filterra® Bioretention Stormwater Treatment System (Filterra® system) developed by Americast, Inc.

Similar to rain gardens and planter boxes, the Filterra® system design is based on bioretention and LID principles. Bioretention technologies operate similarly to media filters (e.g., sand or organic/sand filters) in terms of particulate removal and sorption of reactive constituents. Additional unit treatment processes inherent to bioretention designs include microbially-mediated transformations, biological uptake, evapotranspiration, and other processes associated with the vegetation and root structure. A key difference between bioretention systems and biologically inactive media filtration systems is the contribution of these biological processes to the retention and sequestration of captured pollutants and preservation and regeneration of hydraulic function and pollutant removal capacity; therefore, bioretention systems can be considered a sustainable design.

Bioretention technology design ranges from conventional bioretention media facilities (with large unit storage volumes and a relatively slow filtration rate) to specialized media facilities (with small unit storage volumes and a high filtration rate). Filterra® systems lie near the latter end of this continuum by treating stormwater near its source, filtering stormwater at a high rate, allowing for a small footprint, and providing a standardized, easily installed and maintained design. Specialized media in the Filterra® system is designed to optimize both a high flow rate and the treatment capacity of the system. Inter-storm processes help to maintain these higher flow rates and partially regenerate the pollutant removal capacity of the media. High flow rate media and natural high flow systems are commonly used in both water and wastewater treatment (Crites and Tchobanoglous 1998).

Section 3 of this white paper discusses treatment processes inherent to bioretention systems, with a specific discussion of how media flow rates are expected to affect system performance. The unit treatment mechanisms provided by Filterra® systems are discussed in Section 4.1, and a summary of laboratory and field-scale evaluations of Filterra® system performance are provided in Sections 4.2, and 4.3, respectively. Results from flow rate longevity studies and recommendations for system maintenance are provided in Section 4.4.

3. Review of Unit Treatment Processes Provided by Bioretention Systems

3.1 The Unit Treatment Process Approach

The unit treatment process approach to stormwater BMP selection and design is a widely accepted approach that explicitly considers the characteristics of the pollutants of concern to identify effective removal mechanisms that target those pollutants. The stormwater treatment system is then designed to include components that provide the identified removal mechanisms. This approach has been recommended in stormwater guidance documents published by respected national research organizations (WERF 2005; NCHRP 2006) and is recognized as a robust approach for BMP selection and design.

Bioretention systems provide numerous removal mechanisms to address a variety of stormwater pollutants. For the purposes of this white paper, the key unit treatment processes provided by bioretention areas are classified as *within-storm treatment processes* and *inter-storm treatment processes*:

> ***Within-storm treatment processes*** act on stormwater as it fills the bioretention system, flows through the system, and is drawn down after the event. Most bioretention systems are designed to:
>
> 1. Process a significant volume of water during an event
> 2. Draw down the remaining volume relatively quickly following an event
> 3. Retain little water between events
>
> Therefore, within-storm processes are considered the most important for the removal of pollutants from stormwater; the bulk of load reductions occur as stormwater is briefly retained on the vegetated surface and then passed through the underlying porous media to the bioretention system underdrains or to the underlying native soils.

> ***Inter-storm treatment processes*** act on water and pollutants remaining in the bioretention system (i.e., within soil pore spaces) for days, weeks, or months between storm events. Inter-storm treatment processes do not provide a significant direct contribution to pollutant removal due to the relatively small volume of water retained within media pore spaces after an event, but are critical for the retention of captured pollutants and the preservation or regeneration of within-storm treatment mechanisms. For example, mechanisms like microbially-mediated transformations and biological uptake can stabilize pollutants and regenerate sorption sites.

Bioretention systems provide the following key pollutant removal mechanisms:

Within-storm Treatment Processes

- Inert Filtration (including surface sedimentation)
- Reactive Filtration

Inter-storm Treatment Processes

- Microbially-mediated Transformations
- Biological Uptake and Sequestration
- Volatilization
- Bacterial Inactivation Processes
- Soil Processes
- Routine Maintenance

In addition to the efficiency of a BMP in removing of pollutants from treated water, the overall effectiveness of a BMP in reducing pollutant loads is a function of the percentage of the long term stormwater runoff volume that the BMP captures and treats (i.e., the capture efficiency), and percentage of this volume that is lost to infiltration and evapotranspiration and is not discharged (i.e., volume reduction). Capture efficiency is dependent on runoff patterns, the storage volume of the BMP, the rate at which water is processed during a storm event, and the rate at which the stored water is drawn down after an event. Bioretention systems with higher media flow rates can achieve relatively high capture efficiency in smaller footprints, while bioretention systems with slower flow rates generally require more storage volume and a larger footprint to achieve the same capture efficiency. Volume reduction is a function of the surface area of the BMP, the infiltration rate of underlying soils, depth to groundwater, the moisture retention capacity of the media, and the evapotranspiration rates during the periods between storm events. For bioretention systems without an impermeable liner, volume loss to infiltration can be an important mechanism for removal of pollutant loads; volume losses to evapotranspiration tend to be relatively minor for both lined and unlined bioretention systems.

3.2 Within-storm Treatment Processes

As mentioned above, within-storm treatment processes for bioretention systems primarily include those that are associated with surface detention and filtration. For the purpose of discussion, removal mechanisms are divided into two types of filtration:

1. ***Inert filtration:*** filtration components that remove particulate-bound pollutants through physical processes (e.g., straining); sedimentation at the surface of a filter bed is considered to be a component of inert filtration
2. ***Reactive filtration:*** filtration components that remove dissolved and colloidal pollutants through chemical or biological processes

The following sections describe these processes as they apply to conventional and high flow rate bioretention systems.

3.2.1 Inert Filtration

Inert filtration involves six distinct mechanisms (Metcalf and Eddy 2003):

1. ***Straining*** – surficial straining or chance contact within the filter
2. ***Sedimentation*** – particles settle on the filtering medium within the filter
3. ***Impaction*** – heavy particles cannot follow the flow streamlines
4. ***Interception*** – particles following streamlines are removed upon contact with media surfaces
5. ***Adhesion*** – particles become attached to surfaces as they pass by
6. ***Flocculation*** – large particles overtake small particles and join them to form larger particles

Inert filtration is the dominant treatment mechanism for particulate-bound pollutants in bioretention systems where removal is primarily accomplished by sedimentation and retention of particles near the surface via surface straining, cake filtration, and shallow depth filtration. Surface straining is the retention of particles larger than the pore size at the surface of the media bed. Cake filtration occurs after particles have accumulated on the surface and this “cake” layer begins to control the filtration process. Depth filtration retains small particles that are unable to follow the convoluted paths through the media, where removal is primarily caused by electrostatic attraction of particles to media, and micro-settling when laminar zones around the media particles are formed.

Vegetation and mulch at the surface of bioretention systems also play an important role in inert filtration processes by helping to promote localized settling and inhibiting the re-suspension of settled pollutants. The roots and stems of plants also help keep soils open for infiltration, effectively counteracting clogging mechanisms associated with filtration.

For poorly-graded media beds (i.e., uniformly-graded sand), the ability of inert filtration to retain a specific particle size is primarily a function of filter media particle size and bed depth. As a general rule, when the median particle size of the influent is greater than one-tenth the median particle size of the media, surface filtration (also known as cake filtration) will dominate (Sansalone and Teng 2004; Teng and Sansalone 2004). Depth filtration also occurs for smaller particles, but as influent particles become very small relative to the median particle size of the media, mechanical filtration is no longer effective and sorption processes tend to dominate.

The depth of the media bed becomes a critical design factor when depth filtration and sorption processes dominate. However, depths greater than 24 inches are typically not needed to achieve high sediment removal in granular media filters (Crites and Tchabanoglous 1998). Further, the top layer of the soil column represents the biologically active zone in which much of the microbial, animal, and plant activity takes place.

Table 1 summarizes the dominant filtration mechanism by median diameter of the media ($D50_{media}$) and median diameter of the influent particles ($D50_{influent}$).

Table 1. Dominant filtration mechanism based on media and influent particle size.

Condition	Dominant Removal Mechanisms for Particles
D50media / D50influent < 10	Surface filtration (cake filtration)
10 < D50media / D50 influent < 20	Depth filtration of particulates
D50media / D50 influent > 20	Physical sorption of colloidal particulates

Source: Sansalone and Teng (2004)

$D50_{media}$ is the median diameter of the media (by mass).

$D50_{influent}$ is the median diameter of the influent particles (by mass).

Based on the classical model of a uniformly-graded media bed filter developed by O'Melia and Ali (1978), permeability is inversely proportional to the square of the specific surface area of the filter (internal surface area per bed volume). Because the internal surface area decreases as the media particle size increases, larger media particle sizes are required to increase the treatment flow rate. As shown by the relationships presented in Table 1, an increase in media particle size would tend to result in less removal by cake filtration, and more removal by depth filtration for a given stormwater particle size distribution. Thus, an increase in media particle size requires an increase in bed depth to achieve equivalent particle removal performance (Yao 1971). However, Johnson et al. (2003) found that particle removal within various media filters did not increase as contact times increased beyond about 3 minutes.

While the classical model is useful in understanding filtration concepts, bioretention systems may behave differently. Bioretention media beds are not commonly designed to utilize the full depth of filtration. Media bed depth is typically selected to provide sufficient contact time for reactive filtration processes rather than to provide greater depth for inert bed filtration. Li and Davis (2008) found that TSS particles typically will not penetrate beyond the first 2 to 8 inches (5 to 20 centimeters) of bioretention media. By comparison, bioretention filter beds are commonly designed to be 18 to 36 inches deep. Therefore, an increase in the particle size distribution of bioretention media (and infiltration rate) may not result in a significant reduction in performance; instead, it may promote a greater utilization of the filter bed depth while achieving similar overall performance.

For well-graded media beds (i.e., beds with a well-distributed range of particle sizes), the median grain size is a poor proxy for the average pore size, and smaller particles may be retained through cake and depth filtration mechanisms. Compared to sand filter media, bioretention media typically contains a more heterogeneous mix of granular materials and organic materials, which would limit the depth of particle penetration to a smaller depth than predicted by the classical model based on median particle diameter.

The combination of these factors suggests that high flow rate bioretention media would not necessarily achieve significantly lower particle removal than low flow rate media. This is supported by Filterra® performance monitoring data as introduced and discussed later in this paper.

3.2.2 Reactive Filtration

Beyond the mechanisms provided by inert filtration, reactive filtration involves three primary mechanisms (Metcalf and Eddy 2003):

1. ***Chemical adsorption*** – bonding and chemical interaction
2. ***Physical adsorption*** – electrostatic forces, electrokinetic forces, and van der Waals forces
3. ***Biological growth*** – growth of biological film; can be significant in continuously-fed filters, but is uncommon in well-drained filters that are allowed to dry between events

While inert filtration is the dominant removal mechanism for solids and particulate-bound pollutants in bioretention systems, reactive filtration can play a major role in the removal of dissolved constituents and very fine particles. In well drained systems (i.e., bioretention systems), biological (biofilm) growth is limited. Therefore, reactive filtration generally includes chemical and physical sorption processes—specifically precipitation, ion exchange, and adsorption.

Precipitation primarily occurs when carbonates are released by the media and combined by constituents in solution to form solid precipitates that are subsequently filtered by the media matrix. Ion exchange involves the replacement of a charged media particle (e.g., Mn^{2+}, Fe^{2+}, Ca^{2+}) with a charged particle in solution (e.g., Cu^{2+}, Zn^{2+}). Adsorption primarily involves the incorporation of constituents onto the surface of media particles by bonding, chemical interactions, and to a lesser extent, molecular dipole attractions (i.e., van der Waals forces). The cation exchange capacity (CEC) of a reactive medium defines the bulk quantity of positively-charged ions that can be exchanged or adsorbed. Materials such as granulated activated carbon (GAC), zeolite, rhyolite, clays, diatomaceous earth, and organic matter all can have high CECs.

When analyzing pollutant affinity and reaction kinetics, two primary media characteristics are of interest:

1. ***Equilibrium capacity*** – how much pollutant the media can retain
2. ***Reaction rate*** – how fast the media can retain the pollutant

Equilibrium capacity is defined by sorption isotherms that can be used to predict the amount of pollutant removed at a known concentration for a fixed mass of media at a constant temperature and pH. While various researchers have reported coefficients for their fitted isotherm models, isotherms are not readily transferrable since they are specific to the media, solids gradation, and water chemistry used in their development (WERF 2005). The reaction rates for the various mechanisms also depend on the pollutant type, stormwater characteristics, water (e.g., pH, temperature, etc.), and media characteristics. For example, phosphorus can generally be removed in reactive filters through a combination of sorption and precipitation, depending on pH, with reaction rates of minutes to several hours (WERF 2005).

Various materials used in media filters have a wide range of capacities and reaction rates to accumulate and retain dissolved pollutants. Materials can be specifically selected and engineered to have more reactive surfaces and a higher density of sorption sites. Based on extensive testing of various media types, Johnson et al. (2003) found that a peat-sand mix, zeolite, compost, and iron oxide-coated sand generally showed the best overall performance at removing dissolved metals from stormwater. Literature suggests that contact times of several hours may be needed for conventional materials found in bioretention media such as silica sand, loam soil, and compost (e.g., Wanielista and Chang 2008; Sun and Davis 2007), but only a few minutes may be needed for highly reactive media such as magnesium oxide-coated sand (e.g., Liu et al. 2004). Johnson et al. (2003) found that increasing contact times beyond the scale of several minutes does not to significantly improve treatment efficiency.

An optimized point can therefore be identified where the ability to treat a higher fraction of the stormwater runoff volume is balanced with the ability to provide longer residence times. With consideration of observed diminishing returns in treatment efficiency beyond the scale of several minutes of residence time, the optimal design for space constrained locations likely lies in a system with high media flow rate, specialized media, and relatively small footprint per unit volume of water captured.

3.3 Inter-storm Treatment Processes

For well-drained bioretention systems, the inter-event volume stored equals the water content associated with the field capacity of the porous media. The treatment processes that act upon this inter-event volume include microbially-mediated transformations, biological uptake and storage, and volatilization. These processes are considered critical to retaining pollutants that have been removed by within-storm processes and regenerating the capacity of reactive filtration processes.

Other important processes that occur between events include evaporation, surface drying/ cracking, plant activity (e.g., root growth/penetration, vegetative stabilization), and animal activity (e.g., earthworm, insect, etc.), considered collectively as soil processes. These processes are believed to be important to preserve the hydraulic function of bioretention media. Routine maintenance is also considered to be an important inter-storm pollutant removal process.

3.3.1 Microbially-Mediated Transformations

Microbially-mediated transformations include the metabolic activity of bacteria, algae and fungi that promotes degradation of organic pollutants and oxidation or reduction of inorganic pollutants (WERF 2005). Metabolic activity is primarily associated with the natural biochemical cycles of carbon, nitrogen, phosphorus, and sulfur (Crites and Tchabanoglous 1998). However, xenobiotic metabolism (i.e., biotransformation of chemicals foreign to an organism) can play a significant role in the transformation, stabilization, and detoxification of heavy metals and organic chemicals.

Stormwater bioretention systems are variably-saturated and include root zone biomass that can create pockets of aerobic and anaerobic conditions that promote diverse microbial activity. For example, an aerobic environment is generally needed for nitrification (ammonia → nitrite → nitrate) and an anaerobic environment is needed for denitrification (nitrate → nitrogen gas). If this process is completed within a bioretention system, nitrogen can be removed. However, anaerobic conditions are often not prevalent enough to cause large nitrate reductions. Clark and Pitt (2009) evaluated the retention of pollutants for a variety of media types and found that dissolved metals adsorbed to media are likely to be retained by most media types under both aerobic and anaerobic conditions, but phosphorus release may occur during anaerobic conditions, especially if the media contains highly organic compost.

Microorganisms within the root zone of plants can alter the pH and redox potential within the soil, which can degrade organic chemicals, cause metals to precipitate, or convert various pollutants into a form that can be accumulated or adsorbed by plants and microbes (McCutcheon and Schnoor 2003). These microbially-mediated transformations have the ability to regenerate the sorption capacity of filtration media between storms.

3.3.2 Biological Uptake and Sequestration

Biological uptake and sequestration as a pollutant removal mechanism refers to the removal of organic and inorganic constituents from stormwater by plants and microorganisms through nutrient uptake and bioaccumulation. Biological uptake results in the conversion of nutrients in stormwater into living tissue, while bioaccumulation results in the sequestering of pollutants into organisms regardless of what is immediately needed (WERF 2005). Organisms may assimilate macronutrients such as phosphorus for metabolism and growth, in addition to micronutrients (i.e., some trace metals), and nonessential constituents (i.e., other trace metals). Phosphorus uptake by plants and microbes may improve the capacity of the soil to adsorb other constituents. Some plants sequester metals in the root zone, and expel matter that can foster metals precipitation. Uptake of metals depends on bioavailability; some chemical forms are more reactive and readily assimilated by biological matrices than others.

Uptake as a within-storm removal process may not be significant in high flow rate BMPs due to the time needed for such processes; however, biological uptake is believed to help regenerate media function between storms by freeing sorption sites and providing more permanent pollutant retention mechanisms within biomass in the media.

3.3.3 Volatilization

Volatilization is the process of liquids and solids vaporizing and escaping to the atmosphere. Compounds that readily evaporate at normal pressures and temperatures are considered volatile compounds. While these compounds are not frequently detected in urban runoff, volatile organic compounds (VOCs) or semi-volatile organic compounds (SVOCs) are sometimes present, including various petroleum hydrocarbons (e.g., BTEX[1] and PAHs[2]), gasoline oxygenates (e.g., MTBE[3]), herbicides, and pesticides. VOCs can also be formed during some microbial and phytochemical redox transformations of other pollutants in urban runoff. Volatile compounds are usually highly soluble in water and can easily pass through bioretention systems if they are not volatilized between storm events.

3.3.4 Bacterial Inactivation Processes

The term “inactivation” with respect to bacteria is analogous to sequestration of non-living pollutants. Bacteria are removed from stormwater by the within-storm processes; particulate-bound bacteria are predominantly addressed by physical filtration while free-floating bacteria are predominantly addressed by reactive components of filtration (sorption). Once removed, other processes may work to inactivate the bacteria so that they do not multiply or wash out in subsequent events.

While limited study has been conducted, it is believed that inactivation processes of bacteria in bioretention systems may include predation by other microorganisms (Ruby 2008), solar irradiation of material retained on the surface of the media, and development of conditions inhospitable for growth, including drying of media between storm events (Hunt and Lord 2010). It is believed that the media goes through a maturation process where it develops a complex microbiological ecosystem that enhances predation of bacteria (Ruby 2008). Studies have found that long term removal efficiencies of over 90 percent can be achieved by bioretention systems (Ruby 2008; Hunt and Lord 2006), indicating that slow media flow rates do not necessarily result in higher initial removal and inactivation (Ruby 2008).

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[1] Benzene, toluene, ethylbenzene, and xylenes
[2] Polycyclic aromatic hydrocarbon
[3] Methyl tert-butyl ether

3.3.5 Soil Processes

Soil processes means evapotranspiration, surface weathering, plant activity (e.g., root growth and penetration, vegetative stabilization), animal activity (e.g., earthworms, insects), and other processes (e.g., fungal activity).

- ***Evapotranspiration*** is the combined effects of evaporation and transpiration in reducing the volume of water in a vegetated area during a specific period of time. The volume of water in the root zone of soils is taken up by roots and then transpired through the leaves of the plant. The suction pressure exerted by evapotranspiration may have the effect of loosening soil that may have been compacted by hydraulic impact (i.e., the downward forces of incoming stormwater) during an event. Drying of the media can exert environmental stress on pathogenic bacteria that are retained in the media via desiccation, contributing to inactivation of these constituents (Crites and Tchobanoglous 1998).

- ***Weathering*** (i.e., drying or cracking) is caused by evaporation, media expansion and contraction, and other physical processes and that can break up accumulated surface sediment and cause internal adjustments to the structure of the media matrix. Unlike mineral sands; peats, zeolites, and loams have high internal porosity and therefore, can exhibit more dramatic expansion and contraction during hydration and dehydration processes. Li and Davis (2008) state that compared to rigid sand filter media, bioretention media is relatively plastic, allowing for media shape adjustments to incorporate captured particles and improve the infiltration capacity during the dry period.

- ***Plant activity*** in the media layer can be important for preserving and regenerating hydraulic function, stabilizing accumulated sediment, and preserving/increasing levels of organic matter in the soil. In addition, the movement of plant stalks due to wind and bird activity can break up surface crusts thereby maintaining or increasing infiltration rates. Plant roots contract and expand depending on water availability which helps to develop preferential flow pathways. Plant roots also increase aeration and void space by breaking up the media for water and oxygen to permeate. Root growth aids in the development of healthy and biologically-active soil structures and can increase infiltration rates over time due to the creation of macropores in the media (Facility for Advancing Water Biofiltration in Australia 2008; PGC-DER 2009).

- ***Animal activity*** in the soil layer can be important for maintaining or increasing porosity, preserving hydraulic function over the long term, preserving or increasing the organic content of the soil, and stimulating microbial activity (Nogaro et al. 2006; Nogaro et al. 2007; Derouard 1997). Worms aid in the development of natural soil structure over time, which can increase infiltration rates. Worms create cavities and worm castings can help with soil aggregation as well as pollutant removal.

- ***Other processes***, such as those performed by fungi, also may play a critical role in maintaining aggregate stability within the media. For example, fungi contain individual fungal filaments known as hyphae, which together form mycelia and aid in soil structure stabilization. Fungi also excrete microbial slime that aids in aggregation. In addition, mycorrhizae fungi located on and within the plant root system aid in water and pollutant uptake.

3.3.6 Routine Maintenance as a Pollutant Removal Mechanism

Particulate "break-through" in bioretention systems may occur if fine particles migrate through the media bed. In addition, reductions in hydraulic capacity may result from an increase in the percentage of fine particles in the media bed, resulting in greater frequency of bypass of the system. Finally, dissolved constituent break-through is possible due to short-circuiting or depletion of adsorption sites. Maintenance activities, in addition to inter-storm processes, can promote effective long-term inert and reactive filtration. The removal of accumulated sediment at the surface of the system and removal and replacement of the surface mulch layer may have the following effects:

- Reduces the potential for migration of particles from the surface cake layer into the media bed
- Permanently removes the dissolved constituents adsorbed to accumulated sediment and mulch
- Refreshes the adsorption capacity of the entire bed through the addition of new mulch

The accumulation of fines in the filter media theoretically improves the ability of the media to remove pollutants; however, these fines also tend to decrease the media filtration rate over time which can reduce the capture efficiency of the BMP. The effect of reduction in media flow rate on the capture efficiency achieved by a Filterra® system is shown for an example location in Figure 1. As this figure illustrates, the influence of reduction in media flow rate on capture efficiency is relatively minor; a reduction in media flow rate of 50 percent from 140 to 70 inches/hour results in an expected decline in capture efficiency of less than 10 percent. This is explained by the fact that smaller, more frequent storms contribute the majority of average annual runoff volume. Relationships will vary based on precipitation patterns of an area, but the general nonlinear trend is expected to be consistent across a wide range of climates.

3.4 Summary of Unit Treatment Processes

Table 2 summarizes unit treatment processes provided by bioretention systems and the pollutant or conditions that they are intended to address or support.

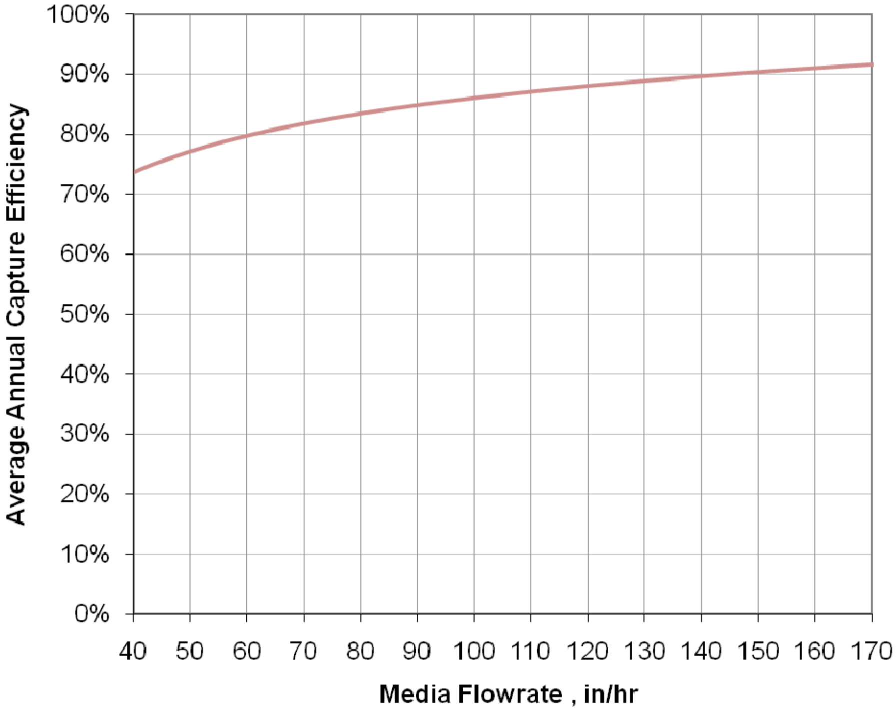

Figure 1. Effect of media flow rate on capture efficiency in Fairfax County, Virginia (adapted from Geosyntec 2008a, 6’× 6’ Filterra®, 0.23-acre tributary area).

Table 2. Summary of unit treatment processes and pollutant removal.

Unit Removal Processes Potentially Provided by Bioretention Systems	Pollutant Removal							Other Performance Factors	
	Particulates and Particulate-bound	Dissolved Metals	Dissolved Nitrogen	Dissolved Phosphorus	Bacteria	Oil and Grease	VOCs and SVOCs	Hydraulic Capture Efficiency	Volume Reduction
Inert Filtration	◆	○	○	○	◆	◆	○	NA	NA
Reactive Filtration	○	◆	M	◆	◆	○	M	NA	NA
Microbially-mediated Transformations	S	S	S	S	○	S	○	NA	NA
Biological Uptake and Storage	○	S	S	S	S	S	○	NA	NA
Volatilization	○	○	S	○	○	○	M	NA	NA
Bacterial Inactivation Processes	○	○	○	○	S	○	S	NA	NA
Soil Processes	S	S	S	S	S	S	S	S	S
Routine Maintenance	◆	S	S	S	S	S	S	S	NA

◆ Primary removal mechanism in bioretention systems
M Generally limited removal mechanism in bioretention systems unless specific design attributes are included
S Supporting process in well-drained bioretention systems
○ Process with no contribution or unknown contribution to pollutant removal

NA: not applicable; VOCs: volatile organic compounds; SVOCs: semi-volatile organic compounds

4. Filterra® Bioretention Stormwater Treatment System

4.1 System Components and Unit Treatment Processes

The Filterra® system is housed in a precast concrete curb inlet structure with a tree frame and grate cast in the top slab, and includes engineered filter media topped with mulch that supports a tree or other type of plant (Figure 2). The following sections describe the three key pollutant removal components of the Filterra® system: mulch, engineered filter media, and vegetation and other system biota.

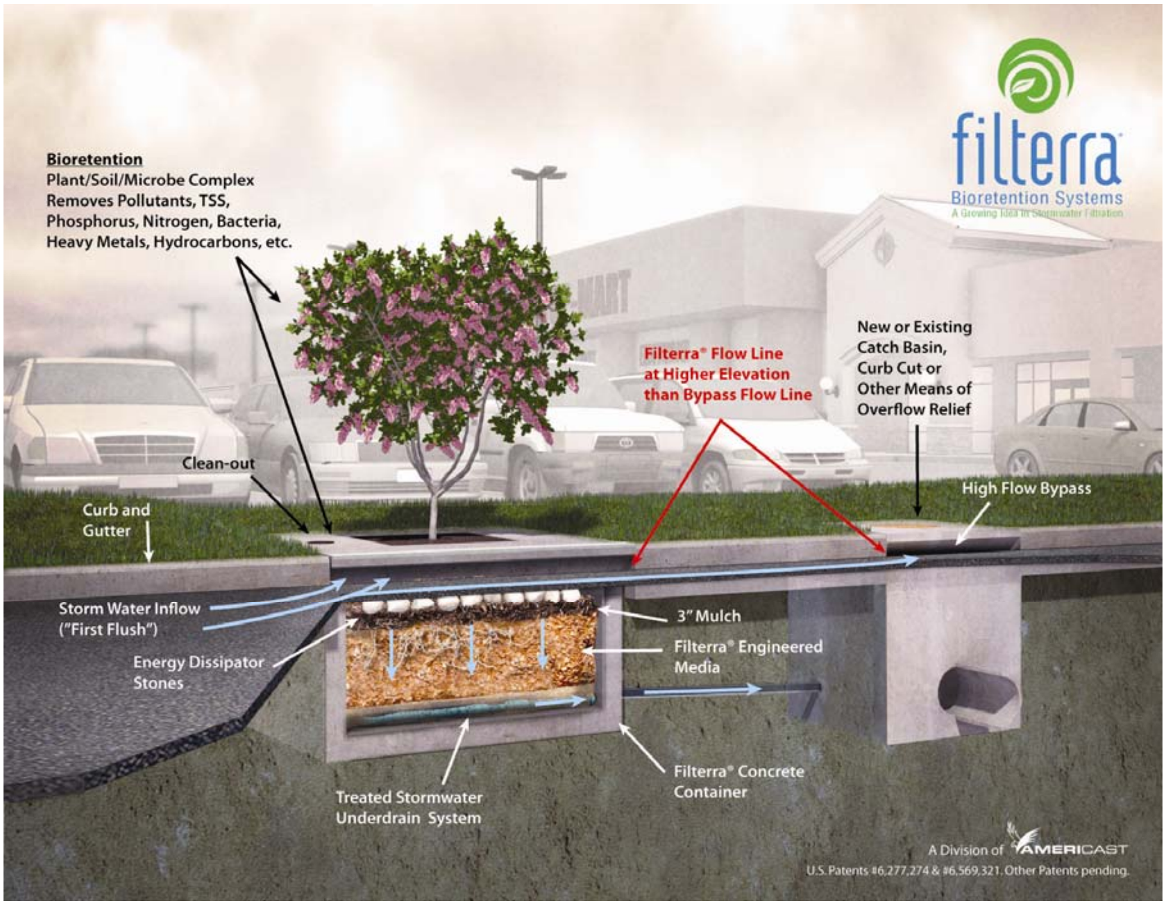

Figure 2. Typical Filterra® system design.

4.1.1 Mulch

The Filterra® system includes a 3-inch layer of shredded wooden mulch. The mulch provides pretreatment and protection of the engineered filter media, and is expected to perform the following within-storm unit treatment processes:

- Inert filtration
- Reactive filtration

To promote filtration, the Filterra® system is typically designed with approximately 6 inches of freeboard above the top of the mulch to the gutter elevation at the curb face. This ponding area provides surface storage for a portion of the water quality treatment volume and promotes settling of fine particles present in the stormwater on the surface of the mulch (CWP 1996). The mulch layer filters out large particles (gross and suspended solids) present in the stormwater that might otherwise prematurely clog the media. Because the mulch is heterogeneous, it captures relatively small particles without limiting the hydraulics of the system. The amount of inert filtration that occurs in the mulch layer is a function of particle density, size, and water density.

Mulch also supports reactive filtration processes. Due to the high CEC present in organic matter contained in the mulch layer, the mulch adsorbs dissolved pollutants, such as heavy metals. Mulch also provides a constant supply of organic material to the media from mulch fines to sustain the CEC of the media for removal of dissolved constituents.

The mulch layer also helps to retain moisture in the Filterra® system, which supports vegetation growth, decomposition of organic matter, and microbial communities (CWP 1996). This moisture retention may lead to a lower frequency of irrigation requirements for system maintenance. Semi-annual removal and replacement of the mulch layer allows for removal of pollutants that have been absorbed by the mulch, as well as trash, debris, and silt that have accumulated on top of the mulch layer.

4.1.2 Media

The mulch layer is underlain by 1.5 to 3.5 feet of engineered filter media, consisting of a specified gradation of washed aggregate and organic material homogeneously blended under strict quality controlled conditions. The engineered filter media is tested for hydraulic functionality, fertility, and particle size distribution to ensure uniform performance. At a design infiltration rate of 100 to 140 inches/hour, a media bed depth of 2.0 feet, and a porosity of 40 percent, the steady state residence time in the media layer would be approximately 4 to 6 minutes. While initial flows entering a dry system may begin to discharge somewhat more quickly than steady state as a result of initial wetting processes, the calculated steady state residence time (4 to 6 minutes) is expected to be provided for the great majority of volume during each storm event and is therefore considered to be characteristic of Filterra® system operation. The media is expected to perform the following within-storm unit treatment processes:

- Inert filtration
- Reactive filtration

Using data from studies conducted by the University of Virginia (2001), the filter media was optimized to operate under high flow rates while maintaining pollutant removal performance. The engineered filter media contains hydrophilic adsorbents such as aluminosilicates (sand) and hydrophobic adsorbents such as carbonaceous/organic matter, which have been included to promote the partitioning of pollutants to the soil particles. The combination of hydrophilic and hydrophobic adsorbents is designed to capture a wide range of pollutants through physical adsorption (e.g., electrostatic forces). The amount of adsorption that occurs is a function of the available surface area and the polarity of the constituents passing through the Filterra® system. As discussed in the previous section, media specifically designed for rapid reactive filtration can achieve significant removal on the order of several minutes (consistent with the 4- to 6-minute characteristic residences time calculated for the Filterra® system).

The media is also expected to perform the following inter-storm unit treatment processes:

- Microbially-mediated transformations
- Biological uptake and storage
- Volatilization

The engineered filter media is designed with a high percentage of organic material for uptake of nutrients and other pollutants. Organic material is added for initial organic complexing (i.e., cation exchange) with pollutants and to help promote biological growth. The mulch, rhizosphere degradation, and runoff continuously add organics to the media to replace the amount lost to microbiological processes.

Bacterial growth, supported by the root system and organic soil content, also contributes to pollutant removal and are a function of moisture, temperature, pH, salinity, pollutant concentrations (particularly toxins), and available oxygen. In addition, volatilization may also occur if VOCs (i.e., gasoline) are captured in the filter media.

Finally, the wetting and drying of the media during and after storm events expand and contract organics in the system, which help in the creation of preferential flow pathways (Americast, Inc. 2009a).

4.1.3 Vegetation and Other System Biota

The Filterra® system includes a vegetation component selected based on aesthetics, local climatic conditions, traffic safety (i.e., limiting the height or breadth of the vegetation), and maintenance considerations (i.e., may restrict deciduous vegetation).

The selected vegetation may include flowers, grasses, a shrub, or a tree, and is expected to perform the following inter-storm unit treatment processes:

- Microbially-mediated transformations
- Biological uptake and storage
- Soil processes

As discussed previously, microorganisms present in the root zone of the vegetation in the Filterra® system can assist with adsorption of pollutants into the media layer and regeneration of the sorption capacity of the media between storm events. Bacterial growth on the root system can bind with particulate organic matter and heavy metals. Growth of vegetation in the Filterra®

system also requires macronutrients (i.e., nitrogen and phosphorus) and micronutrients (i.e., metals) found in stormwater runoff for metabolic processes (i.e., energy production and growth).

As the biomass (i.e., plant and microbes) of the Filterra® system grows, it is assumed that the system's capacity to capture and process more pollutants increases (Ruby and Appleton 2010). This increase in biomass not only increases infiltration rates but also the surface area of the roots, allowing for increased pollutant adsorption and creation of additional pore space in the media layer. Filterra® systems have also been observed to contain fungi and worms which help with media stabilization, aggregation, and development of the media structure over time, maintaining the flow rate capacity of the system.

4.2 Results Documenting High Flow Rate Treatment from Bench-scale Testing

Third-party bench-scale testing efforts have been conducted to evaluate achievable treatment flow rates and particle removal performance of the media in the Filterra® system. Summaries of these independent studies are provided below.

4.2.1 Media Flow Rates in Bench-scale Testing

Column tests were completed by GeoTesting Express (2005) to support Technology Assessment Protocol-Ecology (TAPE) monitoring in Washington State. The specific goal of these column tests was to evaluate flow rates in heavily- and lightly-compacted media. Measured infiltration rates were approximately 50 inches/hour for heavily-compacted media, and 300 inches/hour for lightly-compacted media. Under normal operating conditions and maintenance schedules, the Filterra® system media is expected to perform between these extremes. The concrete top slab covering the Filterra® system is also designed to protect the media from vehicular and foot traffic which would prevent heavy compaction of the media from occurring and would maintain the high flow rate capacity of the system.

4.2.2 Bench-scale Testing of TSS Removal

Two bench-scale analyses were conducted to evaluate removal of TSS by Filterra® system media.

Geosyntec Consultants (2006) conducted a column study to analyze the TSS treatment performance of the Filterra® system media. A manufactured silica product (Sil-Co-Sil 106) with a size distribution consisting of 80 percent of the particle mass less than 50 microns (µm) was selected to simulate expected influent TSS from an urban setting. A total of 15 treatment simulations were conducted, with influent TSS concentrations ranging from 8.3 to 260 milligrams per liter (mg/L) and hydraulic loading rates of 50 to 55 inches/hour. The effluent TSS concentrations were consistently less than 20 mg/L for all simulations and the median effluent TSS concentration was 7.8 mg/L. The TSS removal ranged from 70 to 95 percent with a median removal of 90.7 percent[4].

Americast, Inc. conducted a second column study in 2009 to investigate how hydraulic loading affects the TSS treatment performance of the Filterra® system media. Sil-Co-Sil 106 was used to represent the particle size distribution typical of TSS in urban runoff. Thirty events were simulated with flow rates ranging from 25 to 150 inches/hour and influent TSS concentrations ranging from 42 to 252 mg/L. The effluent TSS concentration ranged from 0.8 to 42.8 with a median of 5.1 mg/L. The TSS removal ranged from 25 to 99.5 percent with a median removal of 96.7 percent. Mehta and Williamson (2009) conducted a third-party review of this study. No statistically significant correlation was found between hydraulic loading and effluent concentration (Mehta and Williamson 2009). Similarly, no significant correlations between influent and effluent TSS concentrations were found. Figure 3 compares the effluent TSS concentrations to flow rates and influent TSS concentrations. Note the very low coefficient of determination (R^2) and the statistically insignificant p-value (>0.05) for both regression lines.

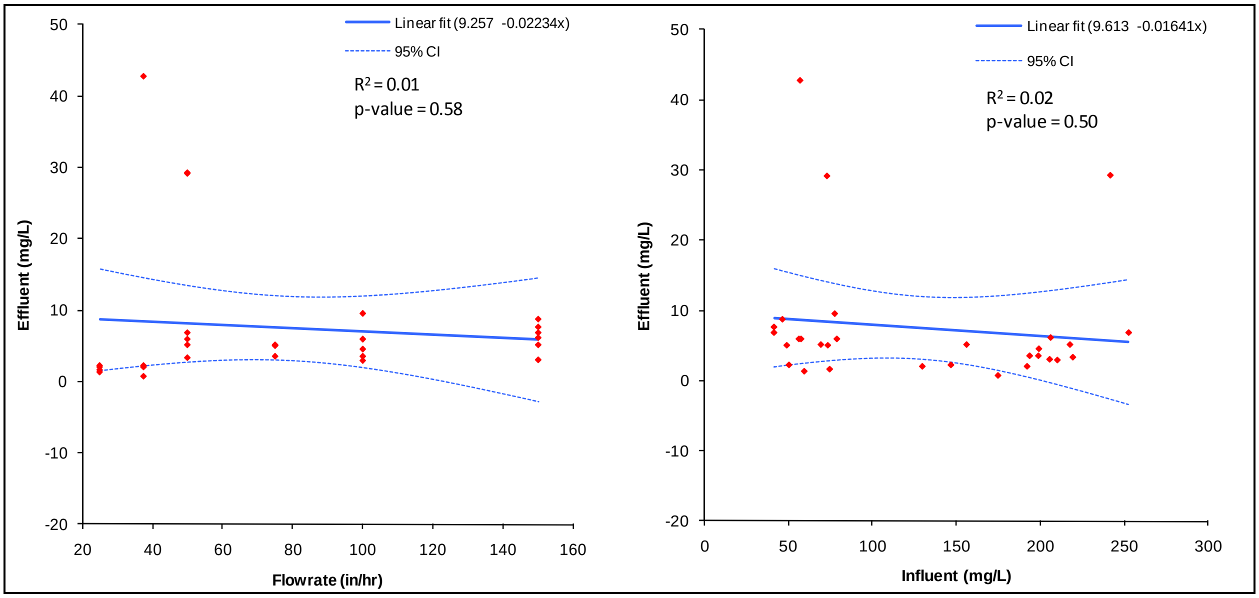

Figure 3. Effluent TSS concentration compared to flow rate and influent TSS concentration.

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[4] In general, the concept of a percent reduction should be applied with caution as a sole means of quantifying stormwater treatment performance, particularly because this estimator is inherently biased towards “dirtier” sites, (i.e., those with relatively high influent levels) (Strecker et al. [2001]). When influent levels are low, it becomes increasingly difficult to achieve a dramatic percent reduction; furthermore, variability inherent to the analysis methods, sampling procedures and other factors unrelated to actual treatment performance have an exaggerated influence on the result when influent is very close to effluent. Where used, percent reductions should be reported with observed influent and effluent concentrations.

4.2.3 Applicability of Bench-scale Testing to Field Performance

The controlled lab experiments indicate that media flow rates greater than 100 inches/hour and significant removal of small particles are possible using Filterra® system media. Both studies described previously were performed using a rigorous testing protocol designed to mimic typical stormwater characteristics and media placement in the field. Compared to field studies, laboratory studies allow for control of environmental conditions, flow rates, influent concentrations, and particle size distributions. Controlled experiments reduce the number of variables that may influence performance, providing higher confidence in the collected data and eliminating the site specificity of the study. For these reasons, the results of the laboratory studies can be more generally applicable than field study results at a particular location.

Because stormwater characteristics vary significantly from site to site, the results of laboratory studies are not a reliable predictor of performance for a specific site during a specific storm event. However, these studies can inform estimates of average performance under average stormwater conditions, and provide cross-validation of results obtained during field-scale testing.

4.3 Results Documenting High Flow Rate Treatment from Full-scale Testing

4.3.1 Evaluation of Hydrologic Performance

Maximum capacity flow rate tests performed on 10 different Filterra® systems of varying age (recently activated to 3 years) and varying maintenance periods (recently maintained to 2 years without maintenance) demonstrated that the saturated hydraulic conductivity (K_{sat}) of Filterra® media ranged from 86 inches per hour to 205 inches per hour, with a 95th percent confidence interval on the median of 129 to 197 inches per hour. Tests included two systems with greater than or equal to 4.5 inches of sediment accumulation. While the results from the sediment-laden systems were not found to be true statistical outliers, the range of observed K_{sat} without these studies was 152 to 205 inches per hour. From these tests, a design media flow rate of 140 inches per hour was recommended, based on the lower 95th percent confidence limit of all data points (including sediment-laden system), adjusted to account for driving head on the system under normal operation (Geosyntec 2008b). Different wetting periods were also tested during these flow rate studies, looking at both constant and periodic wetting. These studies showed that Filterra® systems that received a periodic introduction of runoff (i.e., similar to that of a typical storm event) achieved the highest flow rate. In general, the media is well drained under normal operating conditions.

Core samples collected from 11 Filterra® systems of different ages (6 to 18 months) with no maintenance showed that there was not a significant change in the particle size distribution of the media and the amount of silts and clays up to 18 months after installation (Brim 2007). Four core samples were collected from each Filterra® system and the particle size distribution in the top 10 centimeters of the media was evaluated. All of the evaluated systems contained a percentage of fine particles that matched the Filterra® system media specification, demonstrating that significant media degradation had not occurred. (However, the younger systems had relatively higher accumulations of fine particles than the older systems due to a difference in drainage area size and stormwater runoff quality.) These findings reinforce the important role that the mulch plays in capturing relatively small particles without limiting the hydraulic capacity of the system.

4.3.2 Evaluation of Water Quality Treatment Performance

This section presents water quality treatment performance data collected from the following Filterra® installations:

- One Filterra® system installation in Falls Church, Virginia (Technology Acceptance Reciprocity Partnership [TARP] study and TARP addendum)
- Three Filterra® system installations in Maryland and Virginia (performance over time study)
- Two Filterra® system installations at the Port of Tacoma in Tacoma, Washington (TAPE study)
- One Filterra® system installation in Bellingham, Washington (Bellingham study)

The TARP study was conducted from October 2004 through November 2005 to obtain approval for basic treatment in California, Massachusetts, Maryland, New Jersey, Pennsylvania, and Virginia (Yu and Stanford 2006). The TARP addendum study using simulated storm events was conducted in December 2006 and January 2007 to supplement the TSS and total phosphorus data presented in the TARP (ATR Associates 2009). The performance over time study was conducted from January 2008 through February 2010 on three Filterra® systems installed in restaurant, oil service station, and gas station parking lots (Americast, Inc. 2009b). The Filterra® systems monitored for the performance over time study ranged in age from 2 years (restaurant parking lot) to 5 years (gas station parking lot). The TAPE study was conducted from May 2008 through May 2009 at two sites at the Port of Tacoma (POT1 and POT2 test systems) to obtain a General Use Level Designation (GULD) basic, enhanced (dissolved metals), and oil treatment from the Washington Department of Ecology (Ecology) (Herrera 2009). The Bellingham study was conducted from March 2009 through April 2010 to test the phosphorus removal performance of the Filterra® system (M. Ruby, personal communication, June 8, 2010).

The pollutant removal performance of these systems was evaluated based on flow-weighted composite samples and discrete grab samples that were collected from influent and effluent of each system during storm events. Automated samplers were used to collect flow-weighted composite samples of the influent and effluent during discrete storm events for the TARP, TAPE, and Bellingham studies. Flow-weighted composite samples were manually collected during the TARP addendum study. Discrete grab samples were also collected for the TAPE study for TPH analysis. All samples collected for the performance over time study were discrete grab samples.

The pollutant removal performance was quantified based on efficiency ratios that were calculated for each parameter using the following equation:

$$EF = 1 - \frac{C_{Effuent}}{C_{Infleunt}}$$

where:

EF = efficiency ratio

C_{effluent} = mean or median effluent concentration

C_{influent} = mean or median influent concentration

The efficiency ratio is a commonly used method for calculating pollutant removal performance (Geosyntec et al. 2002; CWP 2008). It was calculated based on event mean concentrations (EMC) from the flow-weighted composite samples that were collected for the TARP and TAPE studies, and concentrations from discrete samples that were collected for the performance over time study. In each case, the efficiency ratios were computed based on the mean influent and effluent concentrations if the associated data were found to potentially arise from a normal distribution (i.e., the null hypothesis that the data come from a normal distribution could not be rejected at an alpha significance level of 0.05 using a Shapiro-Wilk test). If the data had a non-normal distribution, a natural logarithmic transformation was applied to the influent and effluent concentrations. The transformed data were then analyzed to determine if they have a normal distribution. If this proved to be the case, the mean and standard deviation of the log transformed data were used to calculate arithmetic estimates of the means in their original units and used to calculate the efficiency ratios. If the log transformed data of either the influent or effluent did not have a normal distribution, the efficiency ratios were calculated based on the median influent and effluent concentrations.

Results from all five studies were fairly consistent for TSS with efficiency ratios ranging from 83.3 percent (ATR Associates 2009) to 88.3 percent (Americast, Inc. 2009b) (Table 3). The efficiency ratio for total phosphorus had a much wider range from 8.5 percent (Herrera 2009) to 69.5 percent (ATR Associates 2009) due to low total phosphorus concentrations and high soluble reactive phosphorus fractions measured during the TAPE study. Follow-up field testing in two more typical urban applications for phosphorus monitoring under TAPE is pending. TKN was only measured during the TARP study and had a removal efficiency of 39.5 percent (Yu and Stanford 2006). The efficiency ratio for total copper ranged from 33.2 percent (Yu and Stanford 2006) to 76.9 percent (Americast, Inc. 2009b), while dissolved copper was only monitored during the TAPE study and had an efficiency ratio of 48.0 percent. The efficiency ratio for total zinc removal ranged from 48.1 percent (Yu and Stanford 2006) to 78.7 percent (Americast, Inc. 2009b), while dissolved zinc had an efficiency ratio of 54.9 percent during the TAPE study. The oil and grease efficiency ratio measured during the performance over time study was lower than expected (58.6 percent) due to low influent concentrations near the detection limit; however, the TPH efficiency ratio calculated for the TAPE study was 96.1 percent (Herrera 2009).

Table 3. Pollutant removal performance of the Filterra® system.

Pollutant	n	Median Influent (mg/L)[a]	Median Effluent (mg/L)[a]	Mean Influent (mg/L)[a]	Mean Effluent (mg/L)[a]	Effluent < Influent?	Efficiency Ratio	Reference
Total Suspended Solids	11	20	2.5 U	28.8	5.2	Yes[b]	87.5%[d]	TARP
	7	63.4	11.6	66.3	11.1	Yes[c]	83.3%[e]	TARP Addendum
	34	38.0	4.1	71.0[f]	8.3[f]	Yes[c]	88.3%[f]	Perf. Over Time
	18	36.3	4.8	68.9	7.4	Yes[b]	86.9%[d]	Bellingham[g]
	10	27.5	4.2	28.8	4.3	Yes[c]	85.2%[e]	TAPE[g]
Total Phosphorus	14	0.14	0.076	0.23	0.090	Yes[c]	59.7%[f]	TARP
	6	0.52	0.16	0.59	0.18	Yes[c]	69.5%[f]	TARP Addendum
	41	0.29	0.16	1.15	0.49	Yes[b]	44.8%[d]	Perf. Over Time
	15	0.12	0.054	0.16	0.065	Yes[b]	56.5%[d]	Bellingham[h]
	12	0.15	0.14	0.19[f]	0.17[f]	No[c]	8.5%[f]	TAPE[h,i]
Total Kjeldahl Nitrogen	6	1.90	1.15	2.22	1.27	Yes[b]	39.5%[d]	TARP
Total Copper	8	0.012	0.01 U	0.015	0.01 U	No[c]	33.2%[f]	TARP
	30	0.061	0.014	0.083	0.029	Yes[b]	76.9%[d]	Perf. Over Time
	29	0.0081	0.0034	0.0082	0.0037	Yes[b]	58.0%[d]	TAPE
Dissolved Copper	23	0.0056	0.0033	0.0070[f]	0.0036[f]	Yes[c]	48.0%[f]	TAPE[j]
Total Zinc	16	0.039	0.02 U	0.070	0.023	Yes[b]	48.1%[d]	TARP
	30	0.355	0.08	88.7	18.1	Yes[b]	78.7%[d]	Perf. Over Time
	29	0.384	0.102	0.516	0.230	Yes[b]	73.4%[d]	TAPE
Dissolved Zinc	23	0.194	0.082	0.267[f]	0.120[f]	Yes[c]	54.9%[f]	TAPE[k]
Oil & Grease	20	7.0	2.9	26.8	4.2	Yes[b]	58.6%[d]	Perf. Over Time[l]
TPH	12	43.4	1.2	55.7[f]	2.2[f]	Yes[c]	96.1%[f]	TAPE[m]

mg/L: milligrams per liter

U: at or below detection limit

TARP: Technology Acceptance Reciprocity Partnership study conducted in Falls Church, Virginia (Yu and Stanford 2006)

TARP Addendum: Technical Report Addendum Additional Field Testing and Statistical Analysis conducted in Falls Church, Virginia (ATR Associates 2009)

Perf. Over Time: Performance Over Time study conducted in Maryland and Virginia (Americast 2009b)

Bellingham: study conducted in Bellingham, Washington, not all data summarized meets storm coverage criteria and post-storm dry period data required by TAPE (M. Ruby, personal communication, June 8, 2010)

TAPE: Technology Assessment Protocol – Ecology study conducted in Tacoma, Washington (Herrera 2009)

[a] Non-detect values (U) assigned a value of one-half the detection limit in calculations.

[b] Based on a Wilcoxon signed-rank test (1-tailed) test with a significance level at $p<0.05$.

[c] Based on a paired t-test with a significance level at $p<0.05$.

[d] Based on median influent and effluent concentrations.

[e] Based on mean influent and effluent concentrations.

[f] Based on arithmetic estimate of the mean computed from log-transformed influent and effluent concentrations.

[g] TSS data in the influent range accepted by Ecology (20 mg/L and greater).

[h] TP data in the influent range accepted by Ecology (0.1 to 0.5 mg/L).

[i] Low TP removal due to anomalous phosphorus data collected at the Port of Tacoma included very low TP influent concentrations and a high fraction of soluble reactive phosphorus.

[j] Dissolved copper data in the influent range accepted by Ecology (0.0029 to 0.02 mg/L).

[k] Dissolved zinc data in the influent range accepted by Ecology (0.02 to 0.6 mg/L).

[l] Low oil and grease removal due to low influent concentrations near the detection limit (5.0 mg/L).

[m] TPH data in the influent range accepted by Ecology (10 mg/L and greater).

Table 4 compares effluent concentrations for the Filterra® system from the five studies identified above to typical effluent concentrations for biofilters and media filters; two categories of BMPs reported in the International Stormwater BMP Database that generally provide similar unit treatment processes to Filterra® systems. Performance summaries for the biofilter and media filter classes of BMPs were derived from studies of the International Stormwater BMP Database (Geosyntec and WWE 2008a, 2008b). For reference, Table 4 also presents influent concentrations that were measured during the sampling of each system. These data generally show that effluent concentrations for the Filterra® system are equivalent or slightly lower than those from the other two BMP types. All the systems were able to achieve significant reductions in influent concentrations for the following parameters: TSS, total zinc, dissolved zinc and total copper, and dissolved copper. Biofilters and Filterra® systems were also able to achieve significant reductions in influent dissolved zinc concentrations. Finally, media filters and Filterra® systems were able achieve significant reductions in influent total phosphorus concentrations.

4.3.3 Evaluation of Hydraulic Loading Rate

To evaluate Filterra® system performance as a function of hydraulic loading, the following three types of hydraulic loading rates were calculated from data collected during the TAPE study:

1. ***Average hydraulic loading rate:*** average flow rate across entire sampled storm event
2. ***Peak hydraulic loading rate:*** maximum flow rate across entire sampled storm event
3. ***Average instantaneous hydraulic loading rate:*** average of flow rates measured during collection of individual aliquots for flow-weighted composite samples

All three types of hydraulic loading rates were calculated for each of the 22 sampled storm events sampled for TSS during the TAPE study (POT1 test system). Based on these calculations, the average hydraulic loading rate from storm events sampled for TSS ranged from 5 to 36 inches/hour, the peak hydraulic loading rates ranged from 14 to 133 inches/hour, and the average instantaneous hydraulic loading rates ranged from 8.6 to 53 inches per hour. Because composite samples are flow-weighted, the samples tend to be weighted towards system performance under higher hydraulic loading; therefore, the majority of the runoff volume in the sampled storms occurred during periods of high flow.

The average and peak hydraulic loading rates were also calculated for each of the 23 sampled storm events sampled for dissolved metals during the TAPE study (POT1 and POT2 test systems). Based on these calculations, the average hydraulic loading rate from storm events sampled for dissolved metals ranged from 5 to 55 inches/hour, the peak hydraulic loading rates ranged from 14 to 133 inches/hour, and the average instantaneous hydraulic loading rate ranged from 8.6 to 81 inches per hour.

Table 4. Typical influent and effluent concentrations in the International Stormwater Best Management Practice Database and for the Filterra® system.

Pollutant	Units	Biofilter			Media Filter			Filterra® System		
		Influent Range	Effluent Range	Effluent < Influent? [a]	Influent Range	Effluent Range	Effluent < Influent? [a]	Influent Range	Effluent Range	Effluent < Influent? [b]
Total Suspended Solids	mg/L	41-63	15-33	Yes	27-60	9.7-22	Yes	31-41	3.5-5.0	Yes
Total Phosphorus	mg/L	0.22-0.28	0.26-0.41	No	0.15-0.26	0.11-0.16	Yes	0.16-0.25	0.08-0.14	Yes
Total Copper	µg/L	25-39	7.7-14	Yes	11-18	8.2-12	Yes	9.3-26	4.3-10	Yes
Dissolved Copper	µg/L	10-18	5.7-12	Yes	4.6-11	7.3-11	No	4.5-7.0	2.6-3.9	Yes
Total Zinc	µg/L	128-225	28-52	Yes	52-132	17-59	Yes	158-290	41-80	Yes
Dissolved Zinc	µg/L	33-79	19-32	Yes	38-101	29-74	Yes	177-322	75-110	Yes

mg/L: milligrams per liter

µg/L: micrograms per liter

Influent and effluent ranges are calculated based on the 95 percent confidence intervals about the median for the ISBMPD (Geosyntec and WWE 2008a) and five Filterra® field studies (Yu and Stanford 2006; ATR Associates 2009; Americast, Inc. 2009b; Herrera 2009; M. Ruby personal communication, June 8, 2010).

[a] Based on a non-parametric analysis of the difference in median values of site averages (Geosyntec and WWE 2008b).

[b] Based on a Wilcoxon signed-rank (1-tailed) test with a significance level at $p<0.05$.

To evaluate potential influences on system performance, correlation analyses were performed on the TSS, dissolved copper, and dissolved zinc data from the TAPE study to determine if effluent concentrations varied in relation to any of the following variables: influent concentration, average hydraulic loading, average instantaneous hydraulic loading, and peak hydraulic loading. Computed correlation coefficients (Spearman's rho) from these analyses are presented in Table 5 while graphical representations of these relationships are shown in Figure 4 using matrix scatter plots. These results indicate that effluent concentrations for all three parameters show a significant positive correlation with influent concentrations; in other words, effluent concentrations decreased when influent concentrations decreased. When the various measures of hydraulic loading are examined, the results indicate that dissolved copper shows a negative correlation with both average instantaneous hydraulic loading, and peak hydraulic loading. In addition, dissolved zinc shows a negative correlation with peak hydraulic loading.

Table 5. Correlation between influent concentration, effluent concentration, and hydraulic loading at the Port of Tacoma in Tacoma, Washington.

Pollutant	Correlation Parameter	Influent Concentration	Average Hydraulic Loading	Average Instantaneous Hydraulic Loading	Peak Hydraulic Loading
Total Suspended Solids	Spearman's rho	0.49	-0.15	0.11	0.15
	95% Confidence Interval	0.09 to 0.76	-0.54 to 0.29	-0.33 to 0.51	-0.29 to 0.54
	p-value	**0.020**	0.493	0.636	0.514
Dissolved Copper	Spearman's rho	0.91	-0.32	-0.43	-0.45
	95% Confidence Interval	0.8 to 0.96	-0.65 to 0.1	-0.71 to -0.02	-0.73 to -0.04
	p-value	**0.000**	0.134	**0.042**	**0.032**
Dissolved Zinc	Spearman's rho	0.51	-0.23	-0.28	-0.50
	95% Confidence Interval	0.06 to 0.79	-0.63 to 0.26	-0.66 to 0.21	-0.78 to -0.04
	p-value	**0.030**	0.351	0.253	**0.034**

Bolded values are significant at $p < 0.05$ at the 95% confidence level.

While these results would seem to indicate that effluent concentrations are decreasing as hydraulic loading increases, it is more likely that other confounding factors are influencing these relationships. Specifically, influent concentrations of both dissolved copper and zinc may be decreasing as hydraulic loading increases due to dilution. Therefore, the primary influence in these relationships is likely influent concentration and not hydraulic loading; as noted above, the correlations analyses show that effluent concentrations for these parameters decrease when influent concentrations decrease.

Correlations analyses were also performed to determine if percent removal for the parameters identified above varied in relations to average hydraulic loading, average instantaneous hydraulic loading, and peak hydraulic loading. Computed correlation coefficients from these analyses are presented in Table 6 while graphical representations of these relationships are shown in Figure 5 using matrix scatter plots. These results show there was generally no correlation between the various measures of hydraulic loading and percent removal with one exception: percent removal for dissolved copper was negatively correlated with average hydraulic loading rate. Again, the primary influence in this relationship is likely influent concentration and not hydraulic loading. Specifically, as average hydraulic loading rate increases, influent concentrations decrease and become more difficult to treat.

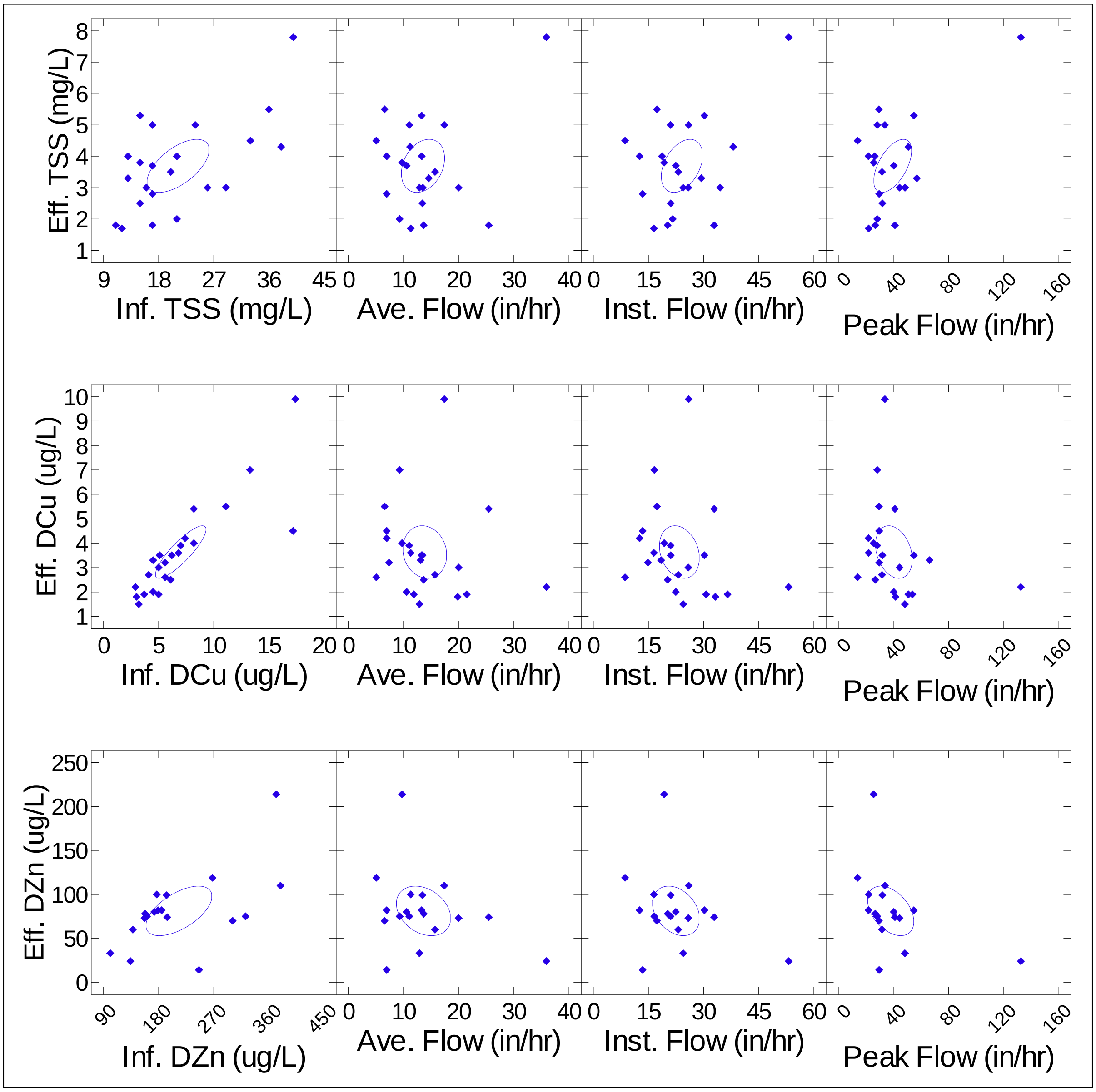

Figure 4. Matrix scatter plots showing relationships between effluent concentration and the following variables: influent concentration, average hydraulic loading, average instantaneous hydraulic loading, and peak hydraulic loading.

Table 6. Correlation between percent removal and hydraulic loading at the Port of Tacoma in Tacoma, Washington.

Pollutant	Correlation Parameter	Average Hydraulic Loading	Average Instantaneous Hydraulic Loading	Peak Hydraulic Loading
Total Suspended Solids	Spearman's rho	-0.17	-0.05	-0.10
	95% Confidence Interval	-0.55 to 0.27	-0.46 to 0.38	-0.5 to 0.33
	p-value	0.450	0.832	0.645
Dissolved Copper	Spearman's rho	-0.47	-0.29	-0.36
	95% Confidence Interval	-0.74 to -0.08	-0.63 to 0.13	-0.67 to 0.06
	p-value	**0.022**	0.173	0.090
Dissolved Zinc	Spearman's rho	-0.04	0.13	0.34
	95% Confidence Interval	-0.49 to 0.44	-0.36 to 0.56	-0.15 to 0.7
	p-value	0.887	0.616	0.168

Bolded values are significant at $p < 0.05$ at the 95% confidence level.
in/hr: inches per hour
mg/L: milligrams per liter

4.4 Maintenance

The major challenge to the longevity of the Filterra® system is sediment buildup on the surface of the Filterra® system, which could restrict free flow of runoff, trash and debris into the system. As long as routine maintenance is performed, the Filterra® system will theoretically last indefinitely, since it essentially sequesters and recycles nutrients, metals, and organics in the biomass (i.e., plant and microbes). The only major maintenance required would be replacement of the plant if it should die. As long as the plant is thriving, the Filterra® system should function as designed.

Americast, Inc. recommends a semiannual maintenance schedule for installations on the east coast and an annual maintenance schedule for installations on the west coast. However, in industrial areas with heavy petroleum loading, the frequency of maintenance may need to be increased to maintain the flow rate of the mulch layer that protects the filtration media. For other land use applications where petroleum loadings are expected to be lower, progressive accumulation of petroleum that leads to reduction in hydraulic capacity and more frequent bypasses of the treatment system is not expected to be a significant issue.

As mentioned previously, maximum capacity flow rate tests performed on 10 different Filterra® systems demonstrated that the influent flow rate was maintained at or above the design flow rate (100 to 140 inches/hour) for systems of varying age (recently activated to 3 years) and varying maintenance periods (recently maintained to 2 years without maintenance) (Geosyntec 2008b).

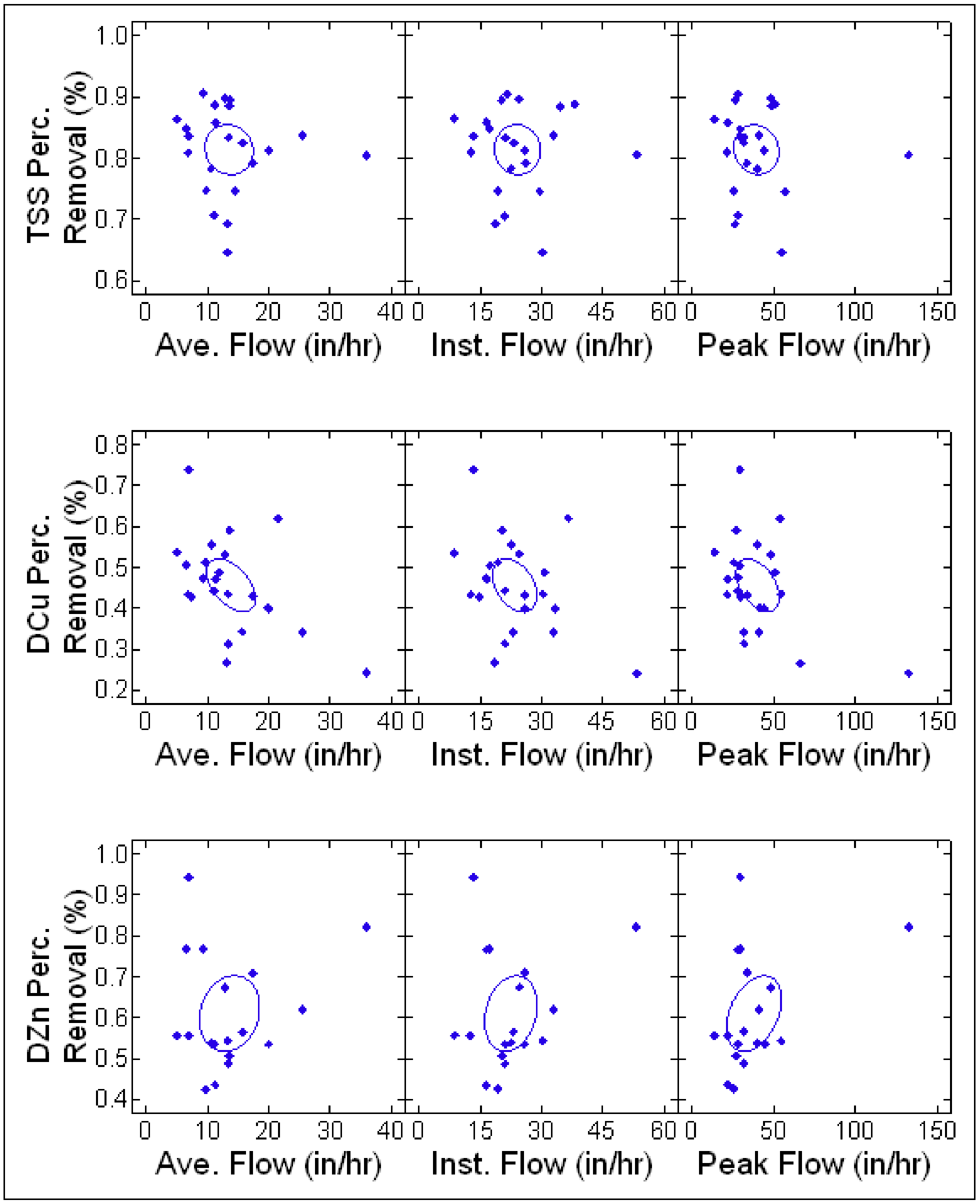

Figure 5. Matrix scatter plots showing relationships between percent removal and the following variables: average hydraulic loading, average instantaneous hydraulic loading, and peak hydraulic loading.

5. Conclusion

The Filterra® system design is based on bioretention technology and involves similar unit treatment processes. The mulch and the media layer perform inert and reactive filtration processes during storm events. The media layer also is expected to perform microbially-mediated transformations, biological uptake and sequestration, bacterial inactivation processes, and volatilization between storm events. In addition to microbially-mediated transformations and biological uptake and sequestration, soil processes such as evapotranspiration, surface weathering, plant activity, and animal activity occur in and around the vegetation component and its root system. These inter-storm processes support the retention of captured pollutants and the preservation and regeneration of hydraulic function and pollutant removal capacity.

Filterra® systems filter stormwater at a high rate, allowing for a small footprint and providing a standardized, easily installed and maintained design. Field flow rate tests performed on Filterra® systems of varying age and varying maintenance periods resulted in a recommended design flow rate of 140 inches per hour. Bench-scale experiments indicated that media flow rates greater than 100 inches/hour and significant removal of small particles is possible using Filterra® system media. Five full-scale studies evaluating water quality treatment performance also found:

- TSS efficiency ratio of 83 to 88 percent; median TSS effluent concentration of less than 2.5 to 11.6 mg/L
- Total phosphorus efficiency ratio of 9 to 70 percent; median TP effluent concentration of 0.054 to 0.16 mg/L
- TKN efficiency ratio of 40 percent; median TKN effluent concentration of 1.15 mg/L Total copper efficiency ratio of 33 to 77 percent; median total copper effluent concentration of 0.0034 to 0.014 mg/L
- Dissolved copper efficiency ratio of 48 percent; median dissolved copper effluent concentration of 0.0033 mg/L
- Total zinc efficiency ratio of 48 to 78 percent; median total zinc effluent concentration of less than 0.02 to 0.102 mg/L
- Dissolved zinc efficiency ratio of 55 percent; median dissolved zinc effluent concentration of 0.082 mg/L
- Oil and grease efficiency ratio of 59 percent; median oil and grease effluent concentration of 2.9 mg/L
- TPH efficiency ratio of 96 percent; median TPH effluent concentration of 1.2 mg/L

Effluent concentrations achieved in the full-scale studies were generally equal to or lower than median effluent concentrations for the biofilter and media filter classes of BMPs reported in the International Stormwater BMP Database. In addition, Filterra® systems showed statistically significant removals for a broader range of pollutants than were shown for the biofilter and media filter categories in the International Stormwater BMP Database.

Correlation analyses performed on effluent concentrations and computed percent removals for TSS, dissolved copper, and dissolved zinc showed that system performance varied with influent concentration; however, these same analyses indicated that there is likely not a direct relationship between system performance and hydraulic loading rate.

The semiannual maintenance schedule recommended by Americast, Inc. for east coast installations and annual maintenance schedule for west coast installations appears to be sufficient, based on results from maximum capacity flow rate tests demonstrating that the media flow rate was maintained at or above 100 to 140 inches/hour for Filterra® systems of varying age and varying maintenance periods. In industrial areas with heavy petroleum loading, the maintenance frequency for the Filterra® system may need to be increased to maintain the flow rate of the mulch layer protecting the filtration media.

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