Product Evaluation

Silt loam TSS removal efficiency of a stormwater BMP:

Coarse/fine perlite StormFilter cartridge at 28 L/min (7.5 gpm)

ABSTRACT: This experiment assesses the ability of a Stormwater Management StormFilter® (StormFilter) cartridge configured with coarse/fine perlite to remove total suspended solids (TSS) with a silt loam texture (15% sand, 65% silt, 20% clay) at a filtration rate of 28 L/min (7.5 gpm) (100% design, per cartridge, operating rate for this configuration). Under controlled conditions, 21 runoff simulations were performed using influent TSS event mean concentrations (EMCs) between non-detect and 247 mg/L. A strong relationship between influent and effluent TSS EMC was observed, challenging the hypothesis of a true relationship between influent TSS EMC and TSS removal efficiency as documented in the literature. Additionally, an exploration of the significance of the precision associated with current TSS analytical methods was done, revealing the limited usefulness of discrete TSS removal efficiency calculations. Based upon these observations, the mean TSS (silt loam) removal efficiency for this StormFilter cartridge configuration was determined using regression statistics and found to be 71% (with 95% confidence, 68% lower limit and 75% upper limit) over the range of influent EMCs tested. Optical particle size observations indicated noticeable removal of silt-sized particles (2 to 50 um as per USDA definitions). Additionally, it was discovered that the sample-splitting technique recommended by EPA method 160.2 for TSS analysis is incompatible with TSS bearing a significant sand fraction.

Introduction

The dynamics of particle transport within a fluid flow is a function of many variables, the most important of which are flow velocity, particle size, and particle density. Just as these variables control the transport of particles, they also control the retention of particles within any given system. An additional variable, apparently specific to the particle removal efficiency of stormwater Best Management Practices (BMPs), is influent concentration (Allan et al., 1997; APWA, 1999; Bell et al., 1995; SMI, 2001; Lenhart, 1998; Portland BES, 2000; Law et al., 1998; SMI, 2000; Urbonas, 1999). Ultimately, it is these variables that will dictate the ability of stormwater BMPs to remove suspended solids from stormwater runoff.

Stormwater BMPs are often chosen through direct comparison of reported total suspended solids (TSS) removal efficiencies. However, these values are rarely accompanied by data identifying flow velocity, particle size, particle density, and influent TSS concentration. Without addressing these variables, true comparison of TSS removal efficiency data resulting from different systems is impossible. For example, a system encountering large, high-density, sand-type solids would operate more efficiently than the same system encountering small, low-density, organic solids. The purpose of this experiment is to generate TSS removal efficiency data, in accordance with existing protocols, that is accompanied by the previously mentioned variables so as to provide the means for more accurate system comparison and performance prediction. This experiment assesses the ability of the Stormwater Management StormFilter® system (StormFilter) to remove TSS with a particle size distribution (PSD) characteristic of a silt loam material.

The StormFilter system is typically comprised of a vault that houses rechargeable, media-filled, filter cartridges (StormFilter cartridges). Stormwater from storm drains is percolated through these media-filled cartridges, which trap and remove pollutants such as solids, dissolved metals, nutrients, and hydrocarbons. During the filtering process, the StormFilter system also removes surface scums and floating oil and grease. Once filtered through the media, the treated stormwater is directed to a collection pipe or discharged to an open channel drainage way.

The StormFilter cartridge configuration chosen for this experiment was the coarse/fine perlite StormFilter cartridge operating at 28 L/min (7.5 gpm). Twenty-one, cartridge-scale tests were conducted in the laboratory environment using simulated stormwater with TSS influent event mean concentrations (EMCs) ranging between non-detect (ND) and 247 mg/L. Composite samples representing true TSS EMC values were used to characterize the influent and effluent and ultimately used to estimate mean TSS removal efficiency. One corresponding pair of influent and effluent TSS samples was taken for particle size assessment using optical methods.

Apparatus

Test Apparatus

The typical precast StormFilter system is composed of three bays: the inlet bay, the filtration bay, and the outlet bay. Stormwater first enters the inlet bay of the StormFilter vault through the inlet pipe. Stormwater in the inlet bay is then directed through the flow spreader, which traps some floatables, oils, and surface scum, and over the energy dissipator into the filtration bay where treatment will take place. Once in the filtration bay, the stormwater begins to pond and percolate horizontally through the media contained in the StormFilter cartridges. After passing through the media, the treated water in each cartridge collects in the cartridge's center tube from where it is directed into the outlet bay by an under-drain manifold. The treated water in the outlet bay is then discharged through the single outlet pipe to a collection pipe or to an open channel drainage way.

The test apparatus used for this experiment simulates the filtration bay component of a full-scale StormFilter system, including the energy dissipator. Since the design of full-scale StormFilter systems varies, and since the operation of a full-scale system in the laboratory environment would require very large volumes of water, the use of the most common components among all of the possible designs, the StormFilter cartridge and the associated volume of filtration bay area, were selected so as to provide a very conservative estimate of StormFilter performance.

Unlike chemical removal testing, suspended solids removal testing is challenging due to the relatively large, dense, insoluble nature of the contaminant. Care must be taken to maintain the suspension of solids within the influent and effluent reservoirs, maintain the suspension of solids within the conveyance system, avoid the fouling of flow metering devices, avoid the destruction of individual solids by the pumping system, and avoid the destruction of the pumping system by the solids.

The apparatus used for this experiment was carefully designed to meet these challenges. Figure 1 demonstrates the layout of the test apparatus. Influent and effluent storage was provided by individual 950-L (250 gallon), conical bottom, polyethylene tanks (Chem-Tainer). The conical bottom design ensured full drainage of the tanks, in addition to the movement of all solids out of the tanks. Suspension of solids within the tanks was maintained by individual, 1/2-hp, electric, propeller mixers (J.L Wingert, B-3-TE-PRP/316). The propeller design maximized the vertical circulation of solids within the tank and ensured the homogeneity of the mixture. Peristaltic-type pumps (Vanton, 19 L/min (5 gpm) Flex-i-liner) were used to recirculate water through the underlying manifolds of both tanks during sampling so as to eliminate any possibility of sediment accumulation in the manifolds.

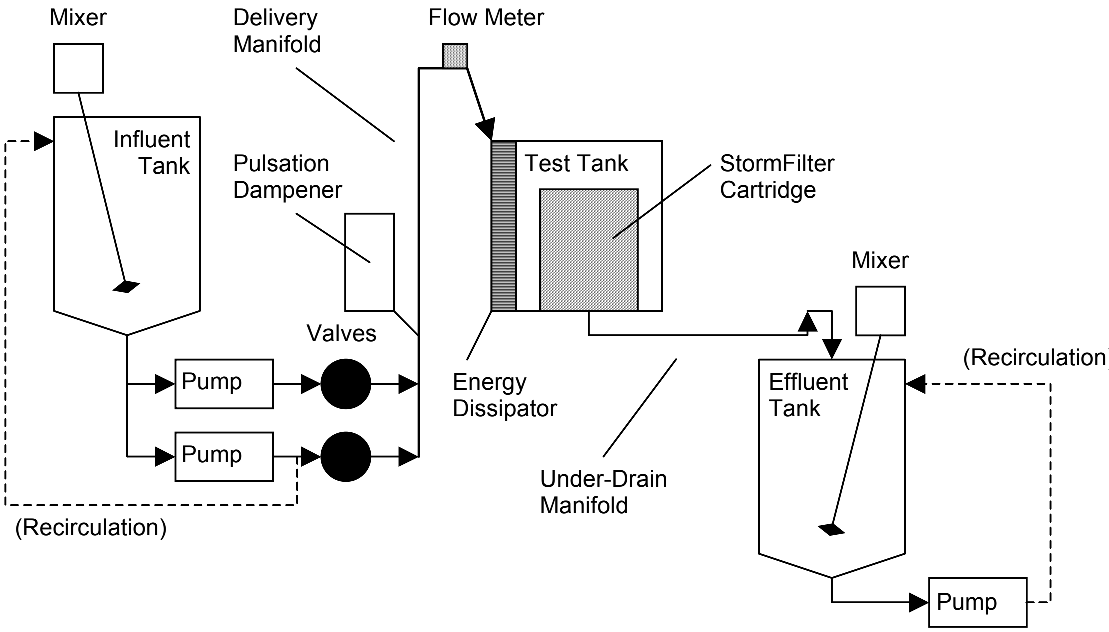

Figure 1. Schematic diagram of the test apparatus. Arrows indicate flow pathways. Dashed arrows indicate recirculation pathways employed during influent and effluent sampling.

Influent was carried from the influent tank by two peristaltic-type pumps (Vanton, 38 L/min (10 gpm) and 19 L/min Flex-i-liner) plumbed into a common PVC intake manifold below the influent tank and discharged into a common delivery manifold of 25 mm (1 in) PVC pipe. The peristaltic pumps specified for use in this experiment were selected because of their ability to handle solids to 1 mm without breaking down the solids themselves. Also, despite the associated head loss, 25 mm diameter pipe was selected to ensure high flow velocities to maintain the suspension of solids during transfer. The pulsating flow generated by the pumps also helped to eliminate settling within the piping.

Discharge from the delivery manifold into the 56 cm x 56 cm x 62 cm (22 in x 22 in x 24.5 in) (LxWxH) polypropylene StormFilter cartridge test tank was by free discharge into the tank-mounted energy dissipator, which consisted of a vertical length of 76 mm (3 in) PVC pipe with an open bottom and multiple 3 mm (1/8 in) wide horizontal slots along its entire length. The energy dissipator was used to minimize the re-suspension of settled material within the test tank by restricting turbulence to the region within the dissipator. Discharge from the StormFilter cartridge test tank into the effluent tank was through direct discharge from the under-drain manifold component of the test tank over the top of the effluent tank.

Flow into the StormFilter cartridge test tank was controlled by individual ball valves placed between each pump and the delivery manifold, and flow was monitored with a paddle-wheel type electronic flow meter (GF Signet, Rotor-X Low Flow) coupled with a flow transmitter with totalizer (GF Signet, Processpro). A pulsation dampener, consisting of a constant air pocket constructed out of a capped length of 76 mm PVC pipe, was fitted to the delivery manifold to dampen the pulsating flow generated by the peristaltic-type pumps. An empty 1-L polypropylene sample bottle was floated in the influent tank to prevent cavitation of the mixer by blocking the intake of air by potential vortices.

Media

The media chosen for this experiment was a combination of coarse and fine perlite. Perlite is a naturally occurring volcanic mineral product and is a common raw material obtainable from a variety of suppliers. The grade of perlite specified by Stormwater360 for use with the StormFilter cartridge was selected for its superior physical characteristics. Lightweight, chemically inert, coarse, and granular, it is an effective physical filtration media.

When used in combination, fine and coarse perlite are added to the StormFilter cartridge as individual, vertically-oriented, cylindrical layers. In this configuration, the outer layer is coarse and 76 mm (3 in) thick, and the inner layer is fine and 102 mm (4 in) thick.

Prior to testing, the coarse/fine perlite StormFilter cartridge was flushed so as to remove the residual dust within the media left over from the cartridge production process, as well as to allow the media to approach a typical, wet operating condition. Individual, ~800-L, tap water flushes were performed according to the operation segment of the procedure section. Flushing was ceased after four flushes, at which point the effluent TSS EMC stabilized at 5 mg/L from an initial value of 13 mg/L.

Contaminant

For the purpose of this experiment, TSS is defined according to EPA method 160.2 with the additional constraint of a maximum particle size of 1000 um. This definition of TSS is in accordance with APWA (1999) and Portland BES (2001) protocols for the laboratory testing of stormwater treatment technologies.

In the interest of generating a conservative result, synthetic or refined silica-based materials were not used for testing due to their high density and uniform sphericity. Instead, actual soil was used, thus providing the range of particle sizes, shapes, and densities of a material that might actually erode or otherwise become entrained by stormwater runoff.

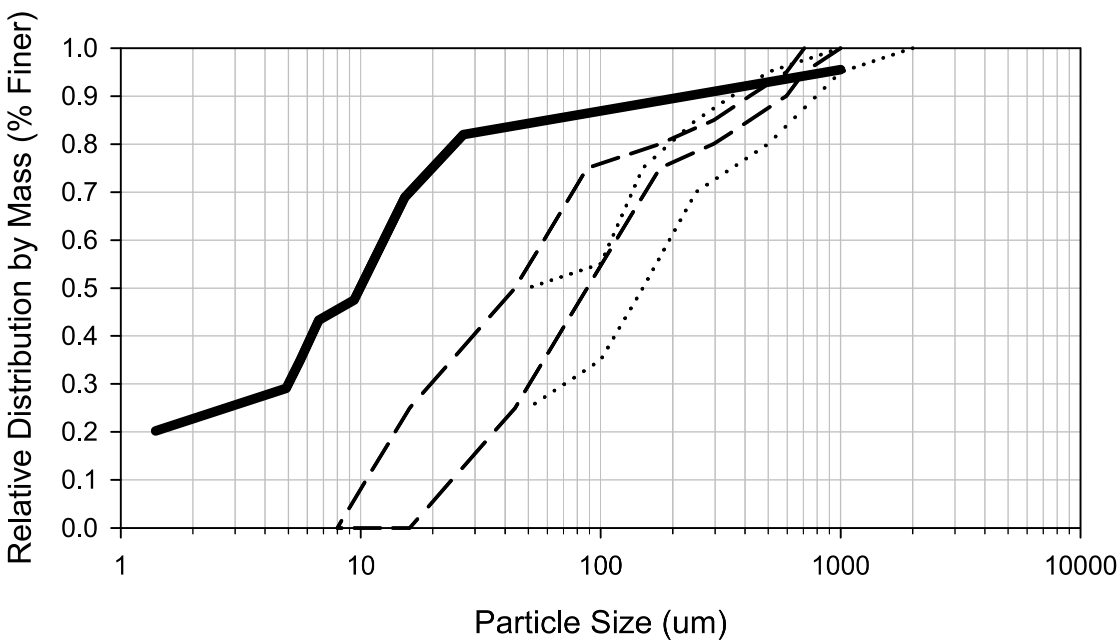

Figure 2. Particle size distribution (shown as solid line) for bulk soil sample "OSU Silt Loam GPS W.P. #10" used for testing. Sand/silt/clay fractions according to USDA definitions are approximately 15%, 65%, and 20%, indicating that the texture corresponds to a silt loam material. Dashed and dotted lines indicate particle size distribution range recommended by Portland BES (2001) and APWA (1999), respectively, for materials used for laboratory evaluation of TSS removal efficiency.

The suspended solids used in the experiment were supplied through the addition of a silt loam soil to the influent. The soil was collected in collaboration with J. H. Huddleson, Soil Specialist with Oregon State University, and originated in the Willamette Valley, OR. A bulk sample, "OSU Silt Loam GPS W.P. #10," was collected in the field and prepared for use by air-drying followed by de-aggregation. De-aggregation was accomplished by tumbling the dried sample in a clean cement mixer in the presence of several sections of 51 mm (2 in) diameter PVC cylinder.

Following preparation of the bulk sample, particle size analysis was performed internally using hydrometer and sieve techniques (Gee and Bauder, 1986), revealing the particle size distribution shown in Figure 2. This particle size distribution is much finer than that recommended by APWA (1999) and Portland BES (2001) for laboratory performance testing. The approximate 15% sand, 65% silt, and 20% clay content (hereafter presented as a 15:65:20) confirmed the silt loam textural classification derived in the field.

Despite the de-aggregation process employed during the preparation of the bulk sample, solids were given the opportunity to hydrate prior to experimentation so as to further promote the decomposition of fine aggregate particles. Based upon an 800-L influent volume, target TSS EMCs were determined for each planned contaminated simulation and associated masses of contaminant were placed in 1-L HDPE bottles of tap water--one bottle of concentrate per planned contaminated simulation. Target TSS EMCs between 0 and 300 mg/L and the order in which they were to be used were randomly selected using random number techniques so as to provide a good range of influent TSS EMCs and performance conditions. These concentrates were then left out at room temperature for a day and periodically shaken to encourage the dissolution of any aggregates. Following this initial equilibration period, the concentrates were refrigerated until needed.

During addition to the influent reservoir, each concentrate solution was passed through a 1000 um sieve to ensure the utilization of TSS <1000 um in size. Material captured on the sieve screen was agitated and washed repeatedly in the influent to ensure the breakup of any remaining aggregates. Since the fraction of particles >1000 um present in the 15:65:20 silt loam (~5% by mass) were not passed through the system, the actual PSD of the TSS in the influent was slightly finer than that reported in Figure 2; however, the PSD was not adjusted so as to further add an element of conservatism to the overall result.

Procedure

Operation

The operational procedure consisted of performing multiple runoff simulations, tests, or runs using the same StormFilter cartridge test tank and apparatus described in the Test Apparatus section above. Runs proceeded as follows.

The influent tank was filled with ~800-L of tap water, and the predetermined contaminant concentrate was added to the influent tank. The influent tank was then mixed thoroughly with the mechanical mixer while influent was re-circulated through the lowest port in the underlying manifold and allowed to equilibrate for 5 to 10 minutes before sampling.

Following influent sample collection, re-circulation was stopped and the influent was pumped into the test tank energy dissipator via the delivery manifold. Flow rate was controlled through periodic adjustment of the influent flow valves so as to maintain a constant flow rate reading of 28 L/min $\pm$ 1.9 L/min (7.5 gpm $\pm$ 0.5 gpm). Mixing and re-circulation of the effluent reservoir was started towards the end of a run to allow effluent equilibration prior to sample collection.

The influent pumps were operated until as much of the influent had been pumped from the influent reservoir and underlying manifold as was possible, at which point the influent pumps were shut down and the StormFilter cartridge test tank was allowed to drain. Once the float valve within the StormFilter cartridge closed, effluent was sampled and the total run volume reported by the totalizer was recorded.

Table 1. Summary of influent and effluent TSS EMCs and removal results for a coarse/fine perlite StormFilter cartridge test unit operating at 28 L/min for TSS with a silt loam texture (15% sand, 65% silt, 20% clay by mass), in order of increasing influent TSS EMC. Bracketed values indicate internally derived results and associated calculations. Darkened cells indicate data that were discarded due to the incompatibility of the EPA method 160.2 sample-splitting technique with sand-bearing TSS samples based upon both internal observations and the recommendations of Gray et al. (2000). Non-darkened cells indicate data collected using the "whole sample" variation of EPA method 160.2. Non-detect (ND) values include associated practical quantitation limit value in parenthesis. Duplicate samples are presented as replicate runs followed by duplicate sample number.

Influent TSS EMC (mg/L)	Effluent TSS EMC (mg/L)	Run	Run Volume (L)	Discrete TSS Removal Efficiency
ND (1)	5	21	826	-400%
3 [5]	4 [5]	1	829	-33% [0%]
6 [10]	5 [5]	2	838	17% [50%]
26	12	13.2	830	54%
27	12	13.1	830	56%
30	12	17	838	60%
53	16	7	822	70%
57	24	6.1	827	65%
59	24	6.2	826	60%
62	22	18	826	64%
68	27	20.2	824	58%
75	27	20.1	824	59%
76 [103]	29 [29]	3.1	825	65% [72%]
80 [109]	28 [31]	3.2	826	70% [72%]
82	29	12	836	62%
99	30	9	836	65%
103	46	4	820	68%
133	42	14	825	75%
143	36	10	824	69%
155	48	15	818	71%
157	46	8.2	826	55%
159	67	5	818	76%
187	45	8.1	824	66%
206	71	16	823	69%
222	68	19	819	58%
247	80	11	810	68%

Sampling

Composite samples of entire influent and effluent volumes were collected for both TSS and particle size analysis; five of the 21 events were sampled in duplicate to increase the overall accuracy of the experiment. All sample pairs were subject to TSS analysis and one pair was subject to particle size analysis. Sample handling was performed in accordance with standard handling techniques; all samples were promptly refrigerated following collection, shipped in ice-packed coolers to the appropriate laboratories for analysis within seven days, and accompanied by chain-of-custody documentation. Severn Trent Services (Tacoma, WA) was employed to provide TSS analysis according to EPA method 160.2, and Chemoptix Microanalysis (West Linn, OR) was used to perform the particle size analysis according to ASTM method F312-97, an optical technique.

Samples were collected in 1-L HDPE, wide-mouthed bottles using a 0.5-L PE, 1.2-m ladle to extract individual sample volumes using a sweeping motion across and through the center of the reservoir. Care was taken to transfer all solids from the ladle. The sampling ladle was subject to a high-pressure wash between uses.

Results

TSS EMC results for each run are shown in Table 1. A very good distribution of influent TSS EMCs was obtained, and a direct relationship between influent and effluent TSS EMC was observed. Calculation of discrete efficiencies, efficiencies based upon individual pairs of associated influent and effluent TSS EMCs, revealed a wide variety of results that generally increased with increasing influent TSS EMC.

Runs 1 through 3 were subject to internal TSS analysis in addition to that performed by the laboratory. Differences between internal and laboratory TSS analyses seemed to be limited to the influent samples, where internal results appeared to be consistently higher than those obtained from the laboratory.

The particle size data shown in Table 2 indicate that removal of particles as small as 25 um was observed. Due to the limitations of the analytical technique (as discussed on p. 14), particle counts in the particle size range above 200 um were not available. No clear relationship between particle size and particle removal efficiency by count is observable.

Table 2. Summary of categorized influent and effluent particle observations for a coarse/fine perlite StormFilter cartridge test unit operating at 28 L/min for TSS with a silt loam texture (15% sand, 65% silt, 20% clay by mass). Results represent Run 10 of the experiment, which was randomly selected for particle size analysis. Removal of particles as small as 25 um in size was observed. Analysis was performed using ASTM method F312-97.

Particle Size Range (um)	Categorized Particle Count per mL		Removal Efficiency (%)
	Influent	Effluent	
1 to 2	5640	5880	(-)
2 to 5	29900	40670	(-)
5 to 15	23500	31620	(-)
15 to 25	5260	5250	<1
25 to 50	2500	1800	28
50 to 100	420	200	52
100 to 200	40	30	25

Using the TSS EMC and associated run volume data shown in Table 1, influent and effluent TSS loads can be compared to determine that 1.58 kg of the 2.28 kg of 15:65:20 silt loam introduced into the system was retained by the StormFilter cartridge test tank. The TSS load captured outside of the StormFilter cartridge, but within the StormFilter cartridge test tank, was manually extracted from the StormFilter cartridge test tank, dried, and determined to be 0.63 kg. Comparison of these values reveals that 60% of the cumulative TSS load retained by the system was removed by the filtration media, with the remaining 40% settling outside the StormFilter cartridge due to the flow rate control provided by the cartridge.

Discussion

Variance among TSS analytical methods

The difficulty of working with TSS was a major challenge throughout the experiment. Although great care was taken in the design of the experimental procedure and apparatus so as to minimize the effects of settling outside of the cartridge test tank, little control over the analysis of the influent and effluent TSS samples was available due to the use of a third-party for sample analysis. Thus, in addition to the third-party analysis of the single and duplicate TSS samples, analysis of additional replicate TSS samples was performed internally according to APHA et al. (1995) so as to provide an early indication of system performance before official results could be obtained from the analytical laboratory (results included in Table 1). Comparison of these values to those reported by the analytical laboratory indicated that the analytical laboratory was consistently underestimating influent TSS concentration, resulting in discrete TSS removal efficiency calculations that were 10 to 15 percentage points lower than anticipated based upon internally measured influent TSS concentrations. However, little or no difference was observed between effluent TSS concentrations measured internally and by the laboratory.

Investigation of the interpretation of EPA method 160.2 employed by the laboratory revealed that the original 1-L composite TSS samples were split by carefully pouring 500 mL from the original sample bottle into a graduated cylinder after shaking. This corresponds with the EPA's internal documentation regarding EPA method 160.2 (USEPA, 1999). Based upon this finding, it was hypothesized that a representative proportion of sand-sized particles was not being transferred from the original sample to the sub-sample due to rapid settling within the original sample container despite the shaking step. Since a commercially available solution of diatomaceous earth (very fine material with low density) is used by some analytical laboratories for the quality control of EPA method 160.2 (ERA, 1999), the incompatibility of this particular sample-splitting technique with sand-bearing samples may not have been previously detected. This would also explain the lack of a discrepancy between the effluent samples analyzed internally and by the laboratory, since these samples contained much finer solids than those in the influent samples.

Investigation of the existing literature further supports this hypothesis. Gray et. al. (2000) discusses the comparison of two methods for the determination of the concentration of suspended solids: ASTM method D3977-97 and APHA et al. (1995) method (Standard Method) 2540D. EPA method 160.2 is essentially a variation of APHA et al. (1995) method 2540D that employs pouring after shaking, rather than pipetting during mixing, to split the sample. The essential difference between the ASTM, APHA et al. (1995), and EPA methods is that the ASTM method utilizes the entire sample volume, or whole sample, whereas the APHA et al. (1995) and EPA methods utilize sample-splitting techniques. Using statistical methods, Gray et al. (2000) determined that data resulting from these two types of methods--methods that <u>do</u> and <u>do not</u> employ sample splitting--could not be justifiably compared, especially when samples contained a substantial portion of sand-sized particles.

Influent samples for runs 1 through 6, including the flush runs, were analyzed using the standard sample-splitting protocol outlined in EPA method 160.2. Subsequent samples were analyzed using a modification of EPA method 160.2 that eliminated sample-splitting by using the whole sample. As shown in Table 1, this produced two sets of noticeably different results. Thus based upon the conclusions of Gray et al. (2000), as well as the observations associated with samples 1 through 3 discussed above, the samples associated with runs 1 through 6 were not used for performance evaluation due to the known variance contributed by the presence and absence of a sample-splitting step during analysis.

Statistical estimation of mean TSS removal efficiency

With the data set defined, linear regression statistics similar to those suggested by Martin (1988) and URS et al. (1999) were used to estimate the mean TSS removal efficiency demonstrated by the system. Linear regression statistics were used for the following reasons: 1) each run differed only in terms of the influent TSS EMC and all other important variables were kept relatively constant; 2) a very strong dependence of effluent TSS EMC on influent TSS EMC was observed; and 3) a very good distribution of influent TSS EMCs was obtained. Instead of using calculated TSS load values as suggested by Martin (1988), regressions were performed on EMC values alone so as to avoid the propagation of any error associated with the volume data. Also, the y-intercept of the regression was not constrained to the origin as suggested by Martin (1988). This addressed the concerns of URS et al. (1999) and allowed the estimation of the mean irreducible effluent TSS concentration (CWF, 1996).

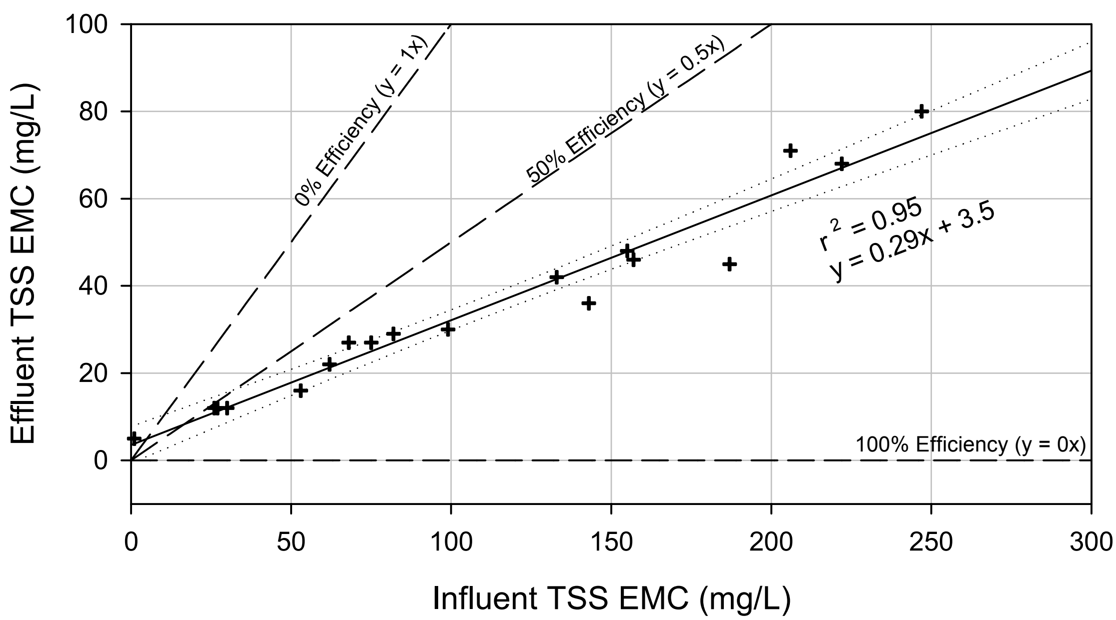

Figure 3. Plot of influent TSS EMC and corresponding effluent TSS EMC observations for a coarse/fine perlite StormFilter cartridge test unit operating at 28 L/min for TSS with a silt loam texture (15% sand, 65% silt, 20% clay by mass). The regression coefficient yields the mean TSS removal inefficiency, 29%. Subtracting this value from 1 yields the mean TSS removal efficiency, 71%. Dotted lines represent upper and lower 95% confidence intervals for the regression. 0, 50, and 100% efficiency lines, with ideal irreducible effluent TSS concentrations of zero, have been provided for comparison.

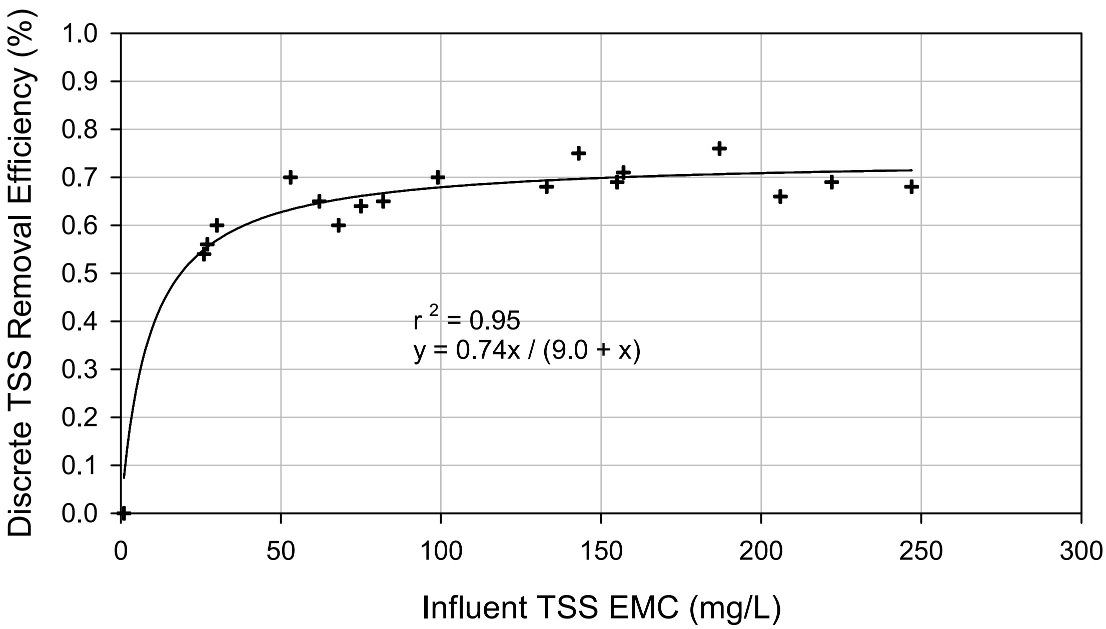

Figure 4. Plot of discrete TSS removal efficiency vs. influent TSS EMC for a coarse/fine perlite StormFilter cartridge test unit operating at 28 L/min for TSS with a silt loam texture (15% sand, 65% silt, 20% clay by mass). The very strong coefficient of determination of 0.95 for the parabolic regression suggests a very strong relationship between discrete TSS removal efficiency and influent TSS EMC, especially for influent TSS EMC values below 50 mg/L. Such a conclusion is supported by the existing literature. However, the tendency of the slope of this regression to approach zero, as well as the very strong, consistent relationship between influent TSS EMC and effluent TSS EMC observed in Figure 3 implies that the true existence of a relationship between discrete TSS removal efficiency and influent TSS EMC is questionable.

As shown in Figure 3, the coefficient of determination (r^2) of 0.95 associated with the linear regression indicates a very strong dependence of effluent TSS EMC on influent TSS EMC. Thus removal efficiency, the relationship between influent and effluent TSS EMCs, can be said to be independent of influent TSS EMC, and the regression coefficient (the slope of the linear regression) can be interpreted as the mean TSS removal inefficiency demonstrated by the system for any given influent TSS EMC. Subtracting the regression coefficient from 1 yields the mean TSS removal efficiency demonstrated by the system for any given influent TSS EMC, which in this case is 71% with 95% upper and lower confidence limits of 75% and 68%, respectively. The mean irreducible effluent TSS EMC, observed as the y-intercept of the linear regression, is ~4 mg/L with 95% upper and lower confidence limits of ~10 mg/L and <1 mg/L, respectively.

Limitations of discrete TSS removal efficiency calculations

Within the literature it has been custom to display individual storm/test results in a “removal efficiency vs. influent concentration” format (Figure 4) so as to allow the visualization of a relationship between influent concentration and removal efficiency. This approach is used by Portland BES (2001) and APWA (1999) for comparison with a “line of comparative performance” to compare the performance of structural BMPs to that of wet ponds, swales, and sand filters. Previous interpretations of the data presented in this format have resulted in the hypothesis that a direct relationship exists between influent concentration and mean removal efficiency (Allan et al., 1997; APWA, 1999; Bell et al., 1995; SMI, 2001; Lenhart, 1998; Portland BES, 2000; Law et al., 1998; SMI, 2000; Urbonas, 1999), especially for influent TSS EMCs below 100 mg/L. However, the strength of the relationship observed between influent TSS EMC and effluent TSS EMC in this study, as well as the tendency of the slope of the efficiency vs. influent concentration relationship to approach zero (Figure 4), challenges this hypothesis.

Upon studying the limitations of the current TSS analysis methodology with respect to practical quantitation limits (PQLs) (also known as detection limits) and standard error, it becomes clear that the hypothetical relationship between influent TSS EMC and discrete TSS removal efficiency (Allan et al., 1997; APWA, 1999; Bell et al., 1995; SMI, 2001; Lenhart, 1998; Portland BES, 2000; Law et al., 1998; SMI, 2000; Urbonas, 1999) is possibly nothing more than an artifact. Figure 5 demonstrates the absolute maximum, observable, discrete removal efficiency trend for any given flow-through solids removal device subject to TSS analysis with a PQL of 1, 2, or 4 mg/L, when the PQL is used for calculation purposes in lieu of a non-detect (ND) value. Apparently, the true removal efficiency below a concentration of roughly 100 mg/L is masked by the insufficient resolution provided by the analytical technique. These hyperbolic curves are similar to that observed in Figure 4, though the curves converge on a discrete removal efficiency of 100% rather than ~70%. The consideration of even the smallest degree of error associated with the experiment further obscures the true removal efficiency at these lower influent concentrations. This is supported by the convergence of the efficiency curves shown in Figure 5, as well as by APWA (1999). The cumulative result is the low probability of observing the true TSS removal efficiency of the system using discrete TSS removal efficiency calculations.

Discrete removal efficiencies should be understood to be apparent results as opposed to actual or true results. While an apparent result still has meaning, its use obscures the observation of the true relationships governing the system. Discrete efficiencies should also be understood to be estimates of performance rather than representative of a mean result associated with a particular influent concentration.

The use of regression statistics avoids such complications by explicitly defining the best relationship between the “raw” influent and effluent data. This way, each discrete influent/effluent pair is weighed in proportion to other influent/effluent pairs in the estimation of statistics such as the mean, standard deviation, and confidence limits. This would explain the high coefficient of determination associated with the linear regression despite the limitations associated with discrete TSS removal efficiencies as previously discussed. Overall, the use of linear regression to estimate mean TSS removal efficiency highlights the value of statistics in properly evaluating system performance.

It is for these reasons that the mean TSS removal efficiency of the experiment has been estimated in such a way that does not require the calculation of the discrete TSS removal efficiency associated with each storm/run event. While both accurate and informative, the use of linear regression to characterize efficiency requires the discretion of the investigator to recognize that influent TSS EMCs below roughly 50 mg/L alone cannot be used to characterize system performance due to the pronounced effect of a small degree of error on values of this magnitude. Similarly, it must be understood that discrete removal efficiencies associated with influent TSS EMCs less than roughly 100 mg/L will not reflect the removal efficiency estimated using regression statistics.

It is also possible that the relationships between discrete TSS removal efficiency and influent TSS EMC observed by Allan et al. (1997), APWA (1999), Bell et al. (1995), Portland BES (2000), Randall (1983), and Urbonas (1999) are exclusive of the StormFilter system. This would indicate that unlike the wetland, wet pond, swale, and horizontal-bed sand/compost filter systems covered by these studies, StormFilter technology actually operates with a constant TSS removal efficiency irrespective of influent TSS EMC. Alternately, the control over all variables except influent TSS EMC provided by this experiment may have resulted in the elucidation of the true relationship between influent and effluent TSS EMC, something that is not obtainable when comparing multiple data points resulting from multiple systems or for a single system with multiple variables, especially those associated with varying storm size, as is the case with the aforementioned studies.

Estimation of particle size removal efficiency

The data facilitate the generation of particle size removal efficiency estimates such as those shown in Table 2. Previous evaluation of similar data by Stormwater360 (2001) indicated a linear relationship between particle size removal efficiency by categorical particle count and increasing particle size category. This previous observation makes intuitive sense since it is theoretically easier to filter or settle out a large particle than a smaller particle, assuming uniform particle characteristics. Unfortunately, the particle size removal efficiency data from this experiment do not demonstrate the same trend, possibly providing an indication of the error associated with ASTM method F312-97.

Another limitation affecting the quantitative estimation of the particle size removal efficiency of the system is that Table 2 represents a discrete data set. Thus the results suffer from the same limitations inherent to discrete TSS removal efficiencies based upon concentration as previously discussed. Nevertheless, the discrete particle size removal efficiencies by categorical particle count have been presented since only one pair of influent and effluent analyses were performed.

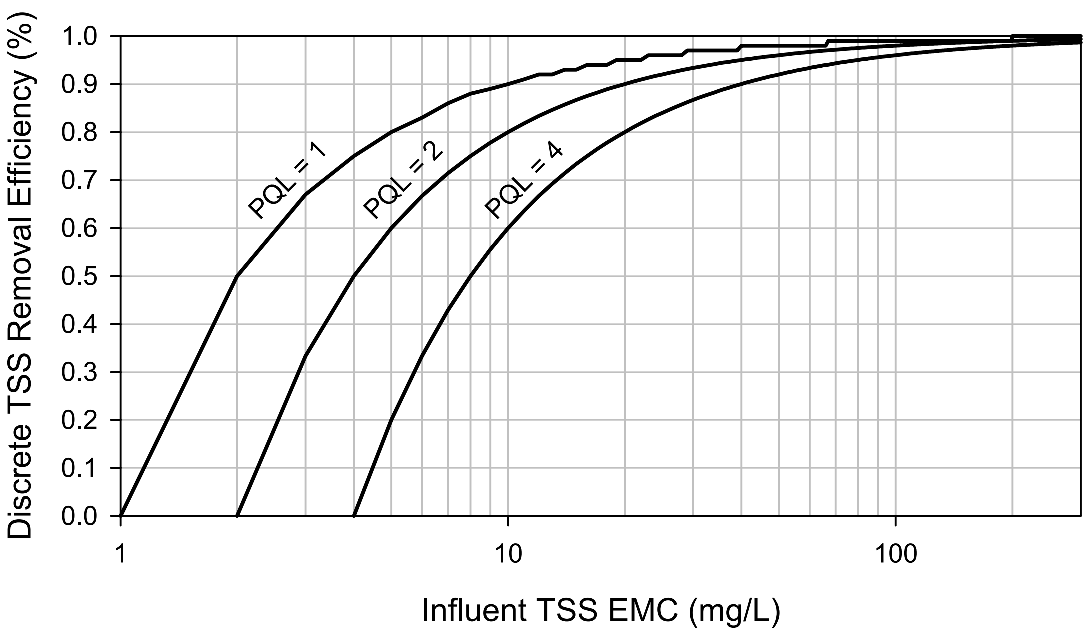

Figure 5. Maximum observable removal efficiency for a theoretical solids removal device performing at 100% removal efficiency that is subject to performance evaluation using an analysis with a detection limit of 1, 2, and 4 mg/L, assuming zero error. Curves were generated by calculating discrete TSS removal efficiencies for all possible influent TSS EMCs using a constant probable quantitation limit (PQL) of 1, 2, and 4 mg/L for effluent TSS EMCs. The area above each curve is impossible to observe. Thus, true performance is impossible to observe until well after an influent concentration of 100 mg/L when the effects of the low resolution of the PQL become insignificant relative to the influent TSS EMC values. The consideration of a small degree of error increases the degree of scatter below each curve.

Thus, while Table 2 clearly allows the observation of particle size removal trends as well as the minimum particle size range removed by the system under evaluation, it would be more conservative to interpret the data qualitatively and perhaps state that the system demonstrated the ability to remove a significant portion of the silt mass entering the system.

Limitations of optical particle size analytical technique

The purpose of using ASTM method F312-97, an optical particle size characterization technique, was to provide some insight into the ability of the system to remove silt, defined as particles measuring between 2 and 50 um according to the USDA classification system. The benefit of ASTM method F312-97 is that it produces an indication of the efficiency of the system to remove particles in the <50 um range using a very small sample volume.

Due to the use of a very small sub-sample, there is a limitation as to the extent to which the resulting data can be used since this decreases the likelihood that the sample is representative of the body of water from which it originated. The observation that the system was more efficient in the removal of particles in the 50 to 100 um range than in the 100 to 200 um range, defies basic logic. A similar experiment by Stormwater360 (2001) used the same analysis with samples from a nearly identical StormFilter system and observed a direct relationship between particle size removal efficiency by count and increasing particle size. The difference between these observations further illustrates the limited accuracy associated with ASTM method F312-97.

Regardless, more data is necessary to properly assess the abilities of ASTM method F312-97, and future experiments involving the method should utilize more than one sample in order to increase accuracy.

Conclusion

The experiment yielded a wealth of information beyond the performance of a stormwater BMP. Further insight into the relationship between removal efficiency and influent TSS EMC was obtained, variance between TSS analytical techniques was discovered, and meaning of discrete TSS removal efficiencies was explored. In summary:

1. Effluent TSS EMC was shown to have a strong dependence upon influent TSS EMC;
2. A coarse/fine perlite StormFilter cartridge test unit operating at 28 L/min for TSS with a silt loam texture (15% sand, 65% silt, 20% clay by mass) provides a mean TSS removal efficiency of 71% with 95% confidence limits of 68 and 75%;
3. Variance exists within EPA Method 160.2 depending on whether a sample is split or whether the whole sample is used;
4. Discrete TSS removal efficiencies provide an apparent, not true, indication of performance due to the significance of error on discrete TSS removal efficiency calculations involving concentrations less than ~100 mg/L;
5. A coarse/fine perlite StormFilter cartridge test unit operating at 28 L/min for TSS with a silt loam texture (15% sand, 65% silt, 20% clay by mass) is capable of removing TSS down to 25 um.

Some of these conclusions have important implications for the selection of analytical techniques to be used for future experiments.

The measurement of influent and effluent TSS EMCs for 14 (14 usable out of 21 total) simulated runoff events covering a wide range of influent TSS EMCs revealed a very strong relationship between these two variables. This finding, coupled with the limitations associated with discrete TSS removal efficiency calculations, reveals that the largely accepted relationship between influent concentration and removal efficiency is possibly nothing more than an artifact, representing an apparent, rather than true, relationship. The use of a linear regression to estimate the mean TSS removal efficiency of the experimental system minimizes the propagation of the error associated with discrete TSS removal efficiencies.

A mean TSS removal efficiency estimate of 71% can be used to define the ability of a coarse/fine perlite StormFilter Cartridge operating at 28 L/min to remove a 15:65:20 silt loam. This estimate is very conservative, not only for the reasons stated earlier in the apparatus and procedures sections, but also because of the constant flow rate used during testing. The 28 L/min filtration rate represents the 100% design filtration rate specified per cartridge for the treatment of a design storm event. In an actual StormFilter system, an appropriate number of cartridges would be used such that each cartridge would be treating 28 L/min during the peak of the design storm event. Thus during most storm events, as well as during the head and tail end of the design storm event, the filtration rate per cartridge would be less than 28 L/min, with a higher mean TSS removal efficiency resulting from the lower filtration rate (see SMI (2002) for details regarding full-scale system hydraulics).

It should be kept in mind that the mean TSS removal efficiency estimate ultimately only holds true for the system under evaluation. The addition or absence of settling, the presence of dead storage, and the location and design of the sampling ports within a similar system can have significant implications on overall system performance such that results observed for similar systems might differ from those observed in this experiment. This will be most pronounced in systems that are “volume-based” or located downstream of a detention system.

Since the acceptance of stormwater BMPs is usually based upon TSS removal efficiency data, the detection of variance within EPA method 160.2 for TSS analysis due to sample splitting is quite troubling. The elimination of the sample-splitting step and the use of the whole sample seem to adequately eliminate any possible error on account of a sample-splitting step. Use of the whole sample allows the sample container to be rinsed with de-ionized water so as to ensure the full transfer of solids from the sample container. This “whole sample” variation is recommended for all future EPA method 160.2 TSS analyses applied to stormwater and corresponds with the conclusions of Gray et al. (2000).

It is encouraged that the comparison of the system in this study with other systems of a similar nature be done through the comparison of influent/effluent TSS EMC regression coefficients. Comparison of the linear regression methodology to arithmetic averaging techniques using discrete efficiencies is offered by FHWA (2000), Martin (1988), and URS et al. (1999) and indicates noticeable differences between both methods of mean removal efficiency estimation. This experiment indicates that the use of linear regression to characterize performance will yield an estimate of mean removal efficiency that is less affected by error than that derived through arithmetic averaging of discrete removal efficiencies.

The system in this study demonstrated the ability to remove silt-sized particles (2 to 50 um). However, one variable that is still in question is the density of the TSS materials encountered by the system. Naturally, according to Stokes law, the density of these particles will influence the degree to which they are removed within the system. A silt loam consisting of low-density, organic material will be more difficult to remove than a silt loam consisting of higher density mineral material. Further investigation into the influence of material density with regard to removal by filtration is necessary.

Since the classification of the material used in the experiment is based upon the composition and density assumptions inherent to the hydrometer method for particle size analysis (Gee and Bauder, 1986), a new method for determining the particle size distribution of both bulk sediment samples and small water samples should be found that does not require such assumptions. Unfortunately, the optical particle size analysis technique used for this experiment, ASTM method F312-97, appears to only be appropriate for qualitative interpretation. Besides the low accuracy associated with the technique for the purpose of evaluating TSS removal, it cannot be used practically for the analysis of particles larger than

100 um. New methods for particle size analysis using small sample volumes, such as ASTM method D3977-97 C proposed by Gray et al. (2000), should be explored.

Stormwater360, Stormwater Management Inc, and Vortechnics Inc. are now CONTECH Stormwater Solutions Inc.

References

Allan, C., Forsythe, R., & Diemer, J. (1997). Piedmont N.C. wet detention basins: Performance factors, sediment behavior, and seepage losses. Raleigh, North Carolina: North Carolina State University Water Resources Research Institute.

American Public Health Association (APHA), American Water Works Association, & Water Environment Federation. (1995). 2540 D: Total suspended solids dried at 103 - 105°C. In A. D. Eaton, L. S. Clesceri, and A. E. Greenberg (Eds.), Standard Methods for the Examination of Water and Wastewater, (19th Edition). Washington, D. C.: American Public Health Association.

American Public Works Association (APWA). (1999). Protocol for the acceptance of unapproved stormwater treatment technologies for use in the Puget Sound watershed. Washington: APWA Washington Chapter, Stormwater Managers Committee. Retrieved January 3, 2002, from the Municipal Research and Services Center of Washington website: http://www.mrsc.org/environment/water/water-s/apwa/protocol.htm

Bell, W., Stokes, L., Gavan, L. J., & Nguyen, T. (1995). Assessment of the pollutant removal efficiencies of Delaware sand filter BMPs. Alexandria, Virginia: City of Alexandria, Department of Transportation and Environmental Services.

Center for Watershed Protection (CWP). (1996). Irreducible pollutant concentrations discharged from stormwater practices. Watershed Protection Techniques, 2(2), 369-372. Retrieved January 3, 2002, from the Stormwater Manager's Resource Center website: http://www.stormwatercenter.net/Practice/65-Irreducible%20Pollutant%20Concentrations.pdf

Environmental Resource Associates (ERA). (1999). Material Safety Data Sheet: WasteWatR™ Hardness, InterLaB WatR™ Pollution Hardness, Hardness Titration-Solution. Arvada, Colorado: Environmental Resource Associates.

Federal Highway Administration (FHWA). (2000). Stormwater best management practices in an ultra-urban setting: Selection and monitoring (Publication No. FHWA-EP-00-002). Washington, D. C.: United States Department of Transportation, Office of Natural Environment.

Gee, G. W., & Bauder, J. W. (1986). Particle size analysis. In A. Klute (Ed.), Methods of soil analysis: Part 1--physical and mineralogical methods (2nd ed.) (pp. 383-411). Madison, Wisconsin: American Society of Agronomy, Soil Science Society of America.

Gray, J. R., Glysson, G. D., Turcios, L. M., & Schwarz, G. E. (2000). Comparability of suspended-sediment concentration and total suspended solids data (Water Resources Investigations Report 00-4191). Reston, Virginia: United States Geological Survey.

Law, N. L., & Band, L. E. (1998). Performance of Urban Stormwater Best Management Practices. Retrieved February 1, 2002, from University of North Carolina website: http://www.unc.edu/depts/geog/them/projects/BMP.html

Lenhart, J. H. (1998, June). Percent removal: Is it an accurate performance measure? WaterWorld. Retrieved January 7, 2002, from WaterWorld website:
http://ww.pennnet.com/Articles/Article_Display.cfm?Section=Archives&Subsection=Display&ARTICLE_ID=75215

Martin, E. H. (1988). Effectiveness of an urban runoff detention pond--wetlands system. Journal of Environmental Engineering, 114(4), 810-827.

Portland Bureau of Environmental Services (Portland BES). (2001). Vendor submission guidance for evaluating stormwater treatment technologies. Portland, Oregon: City of Portland, Bureau of Environmental Services.

Stormwater360. (2001). Sandy loam TSS removal efficiency of a stormwater BMP: Coarse perlite StormFilter cartridge at 57 L/min (15 gpm) (Report No. PD-01-002.0). Portland, Oregon: Author.

Stormwater Management Inc. (SMI). (2000). Total suspended solids removal using StormFilter technology. (Report No. PD-00-001.0). Portland, Oregon: Author.

Stormwater Management Inc (SMI). (2001). Performance of XFCSF Media used in Conjunction with Stormwater Management StormFilter® Technology for Cu, Zn, and TSS Removal (Report No. PD-01-003.0). Portland, Oregon: Author.

Stormwater Management Inc. (SMI). (2002). Product design manual, v. 3.0. Portland, Oregon: Author.

United States Environmental Protection Agency (USEPA), Region 5 Central Regional Laboratory. (1999). Standard operating procedure for the analysis of residue, non-filterable (suspended solids), water, method 160.2 NS (gravimetric, 103 - 105°C). Retrieved January 4, 2002, from United States Environmental Protection Agency website:
http://www.epa.gov/rmdcrl/sop/sopdoc/AIG018.pdf

Urbonas, B. (1999). Assessment of stormwater best management practice effectiveness. In J. P. Heaney, R. Pitt, and R. Field (Eds.), Innovative urban wet-weather flow management systems. Retrieved January 2, 2002, from United States Environmental Protection Agency website:
http://www.epa.gov/ednnrmrl/publish/book/epa-600-r-99-029/

URS (URS), Urban Drainage and Flood District, & Urban Water Resources Research Council of ASCE. (1999). Determining urban stormwater best management practice (BMP) removal efficiencies. Task 3.1--Technical Memorandum. Retrieved January 2, 2002, from American Society of Civil Engineers website:
http://www.asce.org/pdf/task3_1.pdf

Revision Summary

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Document rebranded.

PE-B012
Document number changed; document rebranded; no substantial changes.

PD-01-001.1
Updated paper format; updated SMI references and in-text citations.

PD-01-001.0
Original.