Product Evaluation

*Influence of analytical method, data summarization method, and particle size on total suspended solids (TSS) removal efficiency

ABSTRACT: Analytical method, data summarization method, and particle size have been found to have a noticeable degree of influence on the final outcome of the total suspended solids (TSS) removal efficiency summarization of stormwater best management practices. Based upon the data from three source studies, each of these variables were isolated, evaluated, and found to demonstrate the potential to influence the summary of TSS removal efficiency by a minimum of 9 to 10 percent. Compounding of these differences resulting from combinations of these variables could lead to a considerable range of possible results. It was found that a consistent analytical method, data summarization method, and particle size must be applied to systems under review in order to produce accurate, comparable data. Moreover, these variables must be consistent among data sets in order to allow meaningful comparison.

Introduction

Stormwater best management practices (BMPs) are often evaluated through comparison of their ability to remove total suspended solids (TSS). Based upon field or laboratory experiments, performance is often converted into a single removal efficiency value by means of a variety of mathematical methods. The resulting values are often regarded as definitive, comparable values that can be used to both select acceptable BMPs as well as predict BMP performance in a specific situation. When such decisions are made with the intention of protecting the environment and meeting regulatory requirements, truly comparable, precise data is of the utmost importance. Unfortunately, due to the large number of site-specific, design-specific, and weather-controlled variables, the single values listed in the existing literature defining BMP performance are not of sufficient detail and quality to warrant direct, precise comparison. While ultimate system performance must necessarily be defined in the field, the theory applied to field system evaluation can easily be tested in the laboratory environment.

For non-structural BMP designers and structural BMP manufacturers, incomparable data has the potential to make BMP design difficult in terms of developing new designs and products and determining whether they provide a different level of treatment than existing designs. Fortunately, much design work can be performed in a controlled, laboratory environment where variables can be isolated and tested on an individual basis. Thus, proper laboratory experimentation has the potential to produce TSS removal performance summary data that is truly comparable for the purposes of design comparison and improvement.

Unfortunately, even laboratory experimentation with TSS is complicated by several factors. Firstly, TSS is a very poorly defined contaminant. Unlike chemical contaminants that have a specific chemical identity, definitions of TSS vary from jurisdiction to jurisdiction. The understandable explanation for this is the heterogeneity of TSS on a site-by-site basis. However, since TSS analysis does not provide an indication of particle size, a clear variable with regard to the removal of particulate matter from a waste-stream, TSS analytical results are of questionable comparative value unless specific details are known.

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A set of three source studies have been used in an attempt to quantify the potential impact of such specific details on the performance assessment of stormwater BMPs. As a result, a new variable was realized, a hypothetical variable was challenged, and the influence of two theoretical variables on BMP TSS removal performance were verified and quantified. These variables are TSS analytical method, influent TSS concentration, method for data summarization, and TSS particle size, respectively. Aside from influent TSS concentration, each variable was found to have a noticeable influence on the formulation of a single numerical outcome defining system performance.

The source studies used for this investigation are Stormwater360 (2002a), SMI (2002a), and Stormwater360 (2002b). Each study concerned the evaluation of the TSS removal performance of The Stormwater Management StormFilter® (StormFilter), a filtration-based stormwater BMP (SMI, 2002b), under controlled conditions. The data resulting from these studies was used in the place of field data due to the difficulty in defining the influence of several field-specific variables, such as sampling technique and rainfall intensity, the influence of which have yet to be explored.

Comparability of the Source Studies

Test Apparatus

The experiments encompassed by the three source studies were conducted using the cartridge-scale test apparatus operated by Stormwater360. This system assesses the TSS removal performance of an individual StormFilter cartridge and the associated housing. Using conical bottom tanks, mixers, peristaltic pumps, and carefully designed plumbing, the test apparatus is designed with TSS testing in mind and assures the transport of influent TSS through the apparatus.

Three slightly different configurations of the same apparatus were used for the three source studies. The core apparatus used is described in detail by Stormwater360 (2002b). For the SMI (2002a) experiment, baffles were added to the influent reservoir to enhance vertical mixing. For the Stormwater360 (2002a) experiment, baffles were added to the effluent reservoir for the same purpose. Implementation of these modifications appears to have improved the precision of the data, which is evident by chronological review of the source studies. Additionally, the Stormwater360 (2002b) source study used a simulated storm volume of 800-L, while other two source studies used a simulated storm volume of 400-L.

Operation of the test apparatus was consistent among the source studies. A storm simulation consisted of pumping influent of a defined quality through the test apparatus at a constant flow rate. Specific details regarding the operation of the test apparatus can be found in Stormwater360 (2002b).

BMP configuration

The source studies utilized the coarse/fine perlite StormFilter cartridge configuration. Specific details regarding the media associated with this configuration can be found in Stormwater360 (2002b). The flow rate at which the cartridge was operated was also consistent among the source studies at 28 L/min ± 1.9 L/min (7.5 gpm ± 0.5 gpm), the 100% design (maximum), per-cartridge flow rate recommended for this StormFilter configuration.

Contaminant Sources

To test the influence of the particle size, two specific materials were used by the source studies to simulate TSS. For the Stormwater360 (2002b) and SMI (2002a) experiments, a specific, natural soil material was used and will be referred to as "OSU Silt Loam #10". It was collected from a research soil pit used by Oregon State University and located in the Willamette Valley, OR. For the Stormwater360 (2002a) experiment, a commercial, synthetically graded, crushed sand material was used and will be referred to as "SIL-CO-SIL 106". The SIL-CO-SIL 106 is manufactured by the US Silica Company, Berkeley Springs, WV.

Particle size distributions for the test materials and the guidance documents are shown in Figure 1. OSU Silt Loam is substantially finer than the SIL-CO-SIL 106 and consists of 15% sand, 65% silt, and 20% clay. The SIL-CO-SIL 106 consists of 20% sand, 75% silt, and 5% clay. Both materials were finer than the particle size ranges suggested by APWA (1999) and Portland BES (2001) guidance documents for the laboratory testing of stormwater BMPs, thus their use to simulate TSS was justified.

Both materials were integrated into the experiments in a similar manner. Specific details can be found in the respective documents.

Sampling

Given the controlled nature of the source studies, entire influent and effluent volumes could be stored and sampled in a representative manner. Thus, composite sampling, producing true event mean concentrations (EMCs), was used by the source studies. Specific sampling and sample handling procedures were very similar among the source studies. The only difference among the source studies is that SMI (2002a) and Calvert Stormwater360 (2002a) employed the use of a churn splitter for sample collection while Stormwater360 (2002b) used a composite-grab technique to produce individual samples. Specific details regarding sampling can be found in the respective documents.

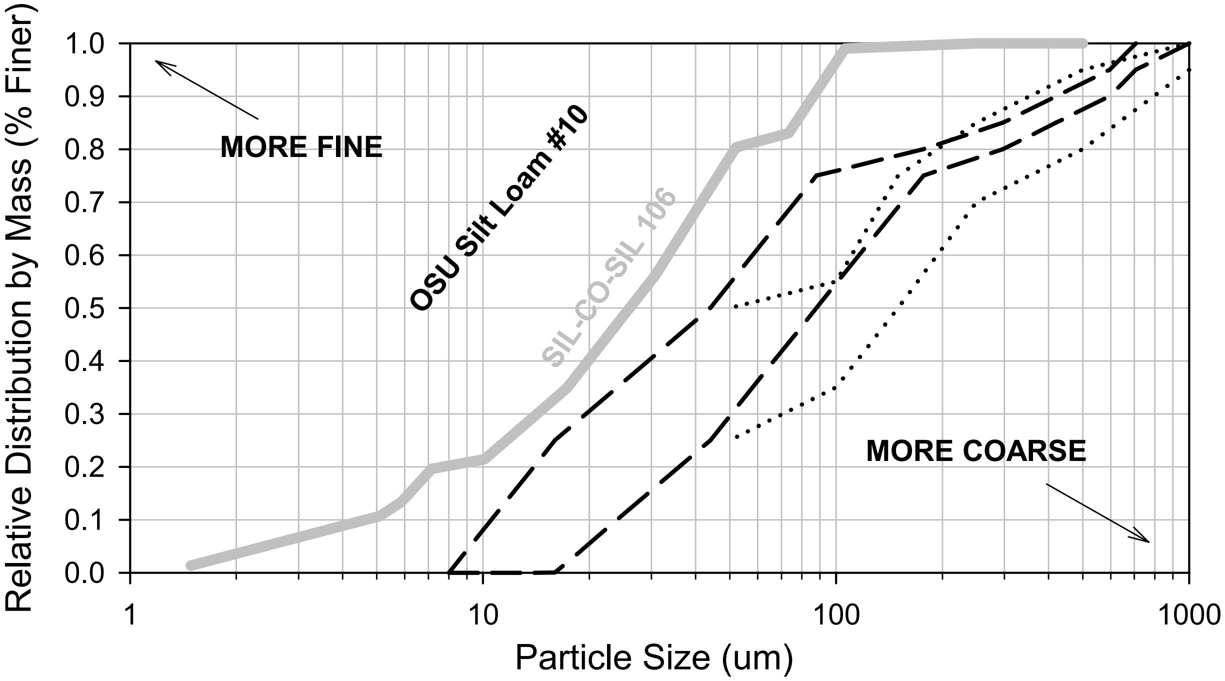


Figure 1. Particle size distributions for the materials used for TSS production as well as ranges suggested by various guidance documents. Dashed and dotted lines indicate acceptable particle size distribution ranges suggested by Portland BES (2001) and APWA (1999).

Influence of Analytical Methods

TSS analysis of the initial samples associated with the Stormwater360 (2002b) study were performed externally according to EPA Method 160.2 (USEPA, 1999) and internally according to Standard Method (SM) 2540D (APHA, 1995). Discrepancies between the internally and externally derived results initiated a review of the details associated with the two analytical methods. Table 1 shows the analytical results associated with simulated storm 3 (Run 3) of the source study according to the two analytical methods.

The importance of the discrepancy lies in the fact that the discrete removal efficiency--meaning the performance associated with a single event--resulting from the EPA 160.2 analysis yields 63% while that resulting from SM 2540D yields 72%. This is a difference of 9 percentage points assuming zero analytical and experimental error. Thus, data sets developed using different TSS analytical methods may promote the generation of misleading conclusions upon comparison.

EPA 160.2 and SM 2540D are practically identical methods. The only substantial difference between the two methods is the manner in which sub-samples are collected. EPA 160.2 specifies that the sample be shaken by hand followed by extraction of a sub-sample via pouring (USEPA, 1999). SM 2540D involves extraction of a sub-sample using a volumetric pipette while the sample container is being stirred on a magnetic stirring plate (APHA, 1995). It was hypothesized by Stormwater360 (2002b) that EPA 160.2 promoted settling during the pour-off step, therby explaining the considerably lower TSS EMC relative to that resulting from extraction during mixing.

Based upon this finding, the remaining analyses associated with the Stormwater360 (2002b) source study were analyzed using a “whole-volume” variation of 160.2 wherein the entire sample volume is filtered and sample-splitting, along with the associated bias, is completely eliminated. Results associated with the standard EPA 160.2 analysis were discarded. This method was subsequently adopted for the SMI (2002a) and Stormwater360 (2002a) studies. Thus all of the TSS samples associated with these source studies were analyzed using the same method.

A review of the existing literature reveals similar comparisons of TSS analytical methods by other researchers. Gray et al. (2000) and Bent et al. (2001) discuss a similar difference between an ASTM analytical method, ASTM D3977-97 “B”, and EPA 160.2 and SM 2540D. While ASTM D3977-97 “B” produces a suspended sediment concentration (SSC) result as opposed to total suspended solids (TSS), the difference between this and the other methods appears to be due to differences with regard to sample splitting. Functionally, all three methodologies are the same except for the fact that ASTM D3977-97 “B” explicitly requires the use of the whole sample volume (ASTM, 1997), while the other two methods allow it.

Table 1. Averaged results (primary and duplicate) for Run 3 of Stormwater360 (2002b) source study using two different TSS analytical methods. Note that a substantial discrepancy only exists between the influent samples, which in turn has a substantial effect on discrete TSS removal efficiency.

Analytical Method	Average Influent TSS EMC (mg/L)	Average Effluent TSS EMC (mg/L)	Discrete TSS Removal Efficiency (%)
SM 2540D	106	30	72
EPA 160.2 (standard)	78	29	63
difference	28	1	9

The methods also differ in that ASTM D3977-97 “B” is not widely used by analytical laboratories, therefore making third-party analysis of data using this method sometimes impossible. Since the only substantial functional difference between ASTM D3977-97 “B” and the other two methodologies involves the use of the whole sample volume, and since EPA 160.2 is the most widely used method, the decision by Stormwater360 (2002b), SMI (2002a), and Stormwater360 (2002a) to use a “whole-sample” variation of 160.2 is supported by the findings of Gray et al. (2000) and Bent et al. (2001). Furthermore, Calvert SMI (2002a) determined the difference between the “whole-sample” variation of EPA 160.2 and ASTM D3977-97 “B” to be statistically insignificant.

Influence of Data Summarization Method

Data associated with the SMI (2002a) source study were used to explore the influence of data summarization method on TSS removal performance summarization. In this study, the effects of two different fine perlite products on the performance of the same experimental system were evaluated. The SMI (2002a) study incorporated the data from the Stormwater360 (2002b) study into a single data set describing the ability of a coarse/fine StormFilter cartridge to remove OSU Silt Loam #10 at a flow rate of 28 L/min after finding the functional difference between the two products to be statistically insignificant. This data set is shown in Table 2 and provides both a large number of data points as well as a broad range of influent TSS concentrations for this aspect of the investigation.

In an attempt to simplify and standardize the BMP review process, regulatory agencies have included acceptable methods for data summarization in their guidance documents. Unfortunately, the provision of multiple formulas by multiple agencies provides for the possibility of the production of incomparable performance summarizations, barring any influence of analytical method. Thus, a visual exploration of the data was performed in order to select the most appropriate method for performance summarization.

It has been customary in the literature to calculate the discrete removal efficiency associated with individual storm results (Table 2) and plot this against influent TSS concentration (or EMC). The result is a curve that has been used to support the hypothesis that BMP performance increases as influent TSS concentration increases. Stormwater360 (2002b), however, suggests that this hypothesis is incorrect.

Figure 2 supports the conclusion by Stormwater360 (2002b) that the hypothetical, functional relationship observed between discrete TSS removal efficiency and influent TSS concentration is false, and that the true relationship between these variables, at least for the system associated with the source studies, is constant. The plot of effluent TSS EMC vs. influent TSS EMC produces a clear linear relationship, indicating that effluent quality is proportionate to influent quality regardless of influent quality.

As discussed by Stormwater360 (2002b), the apparent relationship between discrete TSS removal efficiency and influent TSS EMC is an artifact of the low precision of the analytical methods as well as the larger influence of error on low values. This manifests itself into a gradual convergence of the apparent relationship between discrete TSS removal efficiency and influent TSS EMC upon a constant removal efficiency as influent TSS EMC increases and the significance of precision constraints and error decreases. As an extreme example, if influent TSS EMC is 4 mg/L using an analytical technique with a probable quantitation limit (PQL) of 2 mg/L, the possible outcomes for the effluent are 4, 3, and 2 mg/L, which translates into possible discrete removal efficiencies of either 0%, 25%, or 50%. Thus if the system associated with the example was known to operate with a consistent 75% removal efficiency, it would be impossible to observe the true efficiency due to the low precision of the analytical technique.

Table 2. Summary of data from the SMI (2002a) source study in order of increasing influent TSS EMC. Non-detect (ND) values include associated practical quantitation limit value in parenthesis for calculation purposes.

Influent TSS EMC (mg/L)	Effluent TSS EMC (mg/L)	Volume (L)	Discrete TSS Removal Efficiency (%)
ND (1)	5	826	-400
15	10	820	33
16	11	820	31
20	12	819	40
26	12	830	54
27	12	830	56
30	12	838	60
53	16	822	70
62	22	827	65
68	27	826	60
75	27	826	64
82	29	825	65
83	27	821	67
99	30	826	70
133	42	820	68
143	36	825	75
155	48	824	69
157	46	818	71
168	51	814	70
175	52	814	70
186	53	820	72
187	45	818	76
206	71	824	66
222	68	823	69
247	80	810	68
255	84	814	67
322	98	816	70

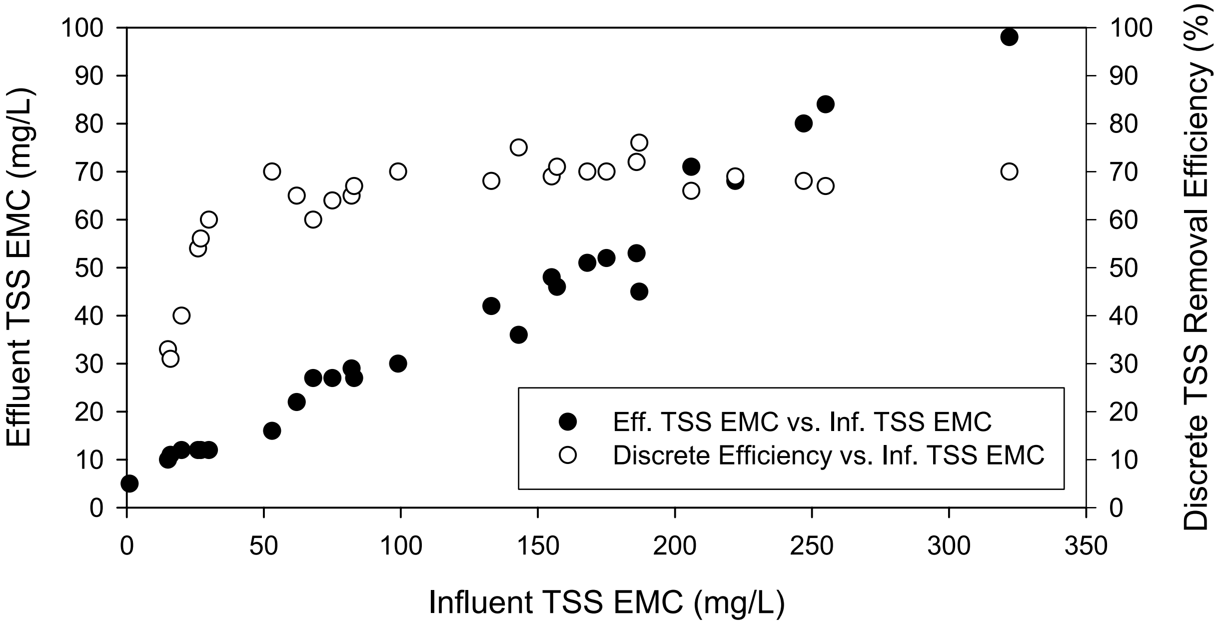


Figure 2. Dual y-axis plot of discrete TSS removal efficiency and effluent TSS EMC versus influent TSS EMC. Both plots display the same data but indicate different relationships. The data point corresponding to the discrete removal efficiency of -400% is not in view for the Discrete TSS Removal Efficiency vs. Influent TSS EMC plot.

The realization that TSS removal efficiency is independent of influent TSS EMC is of fundamental importance. Firstly, influent TSS EMC can now be discounted as a variable, which simplifies data comparison and experimentation. Secondly, it allows the refinement of the performance summary by necessitating the use of a summarization method that is not prone to the negative bias induced by the data corresponding to low concentrations.

With this in mind, available guidance documents were referred to in order to evaluate the influence of data summarization method selection on the outcome of stormwater BMP TSS removal efficiency performance evaluation. The Portland BES (2001), APWA (1999), FHWA (2000), and URS et al. (1999) guidance documents each contain multiple methods, as shown in Table 3. The data from the SMI (2002a) source study, shown in Table 2, was summarized using each method and the resulting outcomes are presented in Table 3. Some overlap among documents was evident; however, different terminology was often used to describe similar methods as well as the definition of the result.

All of the methods encompassed by the four regulatory documents were reviewed and categorized, resulting in the five basic method types shown in Table 3: methods using individual storm data (Discrete Storm), methods using data from multiple storms (Multiple Storm), methods involving comparison of individual storm data to a reference curve (Comparative), methods involving the log-transformation of the data from multiple storms (Transformed Multiple Storm), and Regression methods. Except for the Regression methods in the existing guidance literature, the user has the option of inputting data in the form of EMC values or load values (the product of EMC and associated volume). For the Regression method, only load data is currently suggested. An option specific to the Regression method is the constraint of the y-intercept to the origin, a detail that will be discussed in depth.

Two of the available five method types, Discrete Storm and Comparative, were not feasible for summarizing system performance for the purpose of comparison. During the influence of analytical method investigation, Discrete Storm methods were shown to result in discrete efficiencies that are prone to negative bias. Perhaps with this in mind, but not explicitly stated, the guidance documents do not suggest how to process the results of Discrete Storm methods for the purpose of producing a single, comparable value. Despite the lack of a prescribed formula for this purpose, many users simply calculate an arithmetic mean, which is very sensitive to bias and thus produces a very negatively biased result that consistently underestimates performance, especially when the data set includes low-concentration influent data.

Comparative methods, though very useful and appropriate for the analysis of field data, are also prone to bias. This approach is more prone to bias as the number of low-concentration data points is increased since performance objectives are currently more lenient at low influent concentrations and exceedingly stringent at high influent concentrations. Additionally, Comparative methods involve standards (lines of comparative performance) that can differ from jurisdiction to jurisdiction and also evolve over time (APWA, 1999), severely complicating the effort to produce clear, comparable results. Moreover, Comparative methods using standards founded upon the hypothesis that removal efficiency increases as influent concentration increases are potentially flawed since this relationship appears to be illusionary, as demonstrated in Figure 2.

Table 3. Summary of methods suggested for the purpose of TSS removal performance summarization by several guidance documents. Notice the degree of overlap among documents, as well as the range of possible outcomes.

Reference	Reference-specific Method ID	Outcome (Summarized TSS Removal Efficiency (%))	Method Type
APWA (1999)	#1	---	Discrete Storm
	#2	68	Multiple Storm
	#3	61	Transformed Multiple Storm
	Line of Comparative Performance	---	Comparative
URS et al. (1999)	3.1	68	Multiple Storm
		61	Transformed Multiple Storm
	3.2	68	Multiple Storm
	3.3	69	Regression
		71	Regression
	3.4	68	Multiple Storm
	3.5	---	Discrete Storm
		68	Multiple Storm
Portland BES (2001)	#1	---	Discrete Storm
	#2	68	Multiple Storm
	#3	61	Transformed Multiple Storm
	#4	---	Discrete Storm
	Line of Comparative Performance	---	Comparative
FHWA (2000)	EMC	68	Multiple Storm
	ROL	69	Regression
	SOL	68	Multiple Storm

Of the five possible method types, three lend themselves to the creation of comparable performance summaries. These three method types result in six possible outcomes due to the option of using EMC or load data. Using the Multiple Storm method, the data used for this study produce a 68% removal efficiency. Since the experiment was conducted under controlled conditions, the use of EMC or load data does not affect the outcome. The Transformed Multiple Storm method yields 61% removal efficiency. Again, the outcome is not affected by the use of either EMC or load data. Choice concerning the treatment of the y-intercept associated with the Regression method, however, produces two different results. Constraint of the y-intercept to zero yields 69%, while allowing the y-intercept to assume its natural position yields 71%.

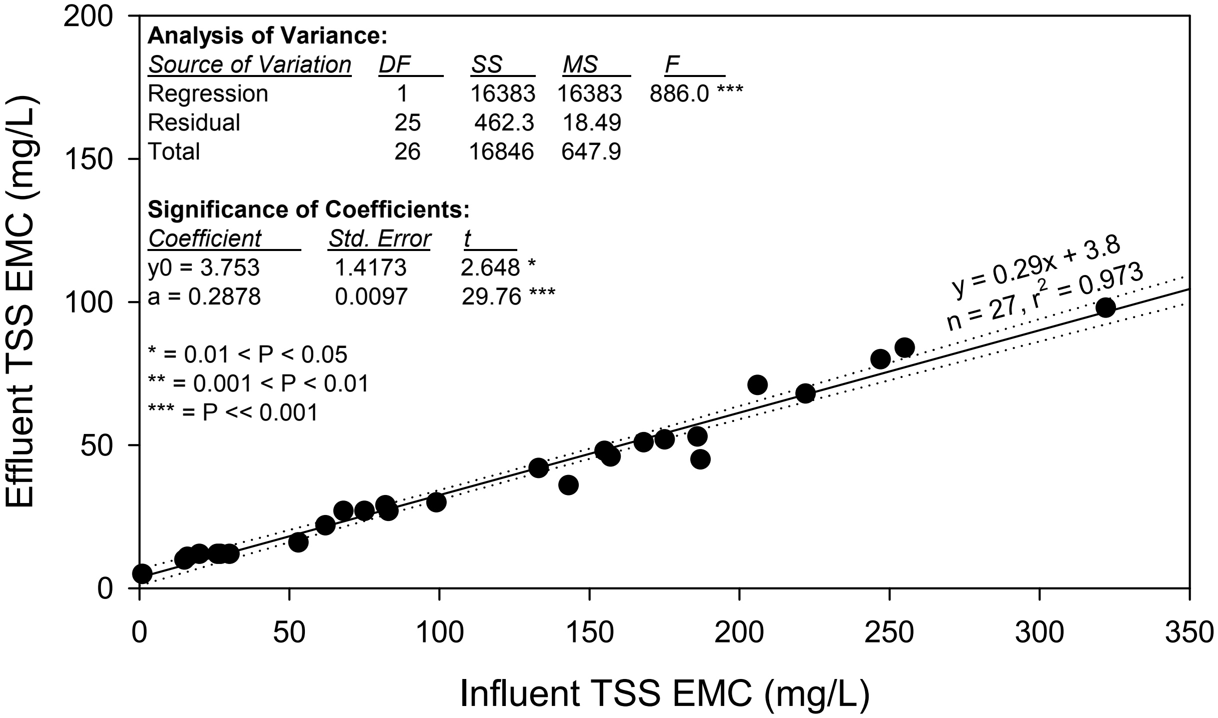
Aside from the more favorable results, the selection of the Regression method for performance summarization is logical. Considering the excellent linear relationship demonstrated by the influent and effluent TSS EMC data demonstrated in Figure 2, it is very easy to understand how the relationship between the two variables is truly constant. Perhaps most importantly, given a good distribution of values, the Regression method would seem to be insensitive to bias. While the guidance literature suggests the use of load data, the use of EMC data would provide an even more accurate result since any error associated with the volume or flow data would not be incorporated into the result, which is of particular concern when load values are calculated and used for performance summarization.

Proper manipulation of the y-intercept has the potential to yield a valuable piece of information that is not a product of any of the other formula types. Allowing the y-intercept to take its natural place yields the irreducible effluent concentration discussed by CWP (1996), which is the effluent TSS concentration that could be expected if pure water was run through the system. Martin (1988) suggests that the y-intercept be constrained to the origin, presumably based upon the assumption that pure influent produces pure effluent. Based upon the frequent observation of negative discrete TSS removal efficiencies in the literature, this assumption does not seem to be warranted. URS et al. (1999) also question this assumption, but suggest it be used with field data due to the excessive scatter and poor distribution associated with this data. Since the data used for this study were neither scattered nor poorly distributed (as should be expected for laboratory data), constraint of the y-intercept to the origin was not warranted.

Though not specifically recommended in the guidance literature, regression using EMC values produced the same result as using load values. This is most likely due to the precise nature of the source studies. With the goal of producing both precise and accurate comparable data for the purpose of product development in mind, the Regression method using EMC values was used for the analysis of the data used for this study. Figure 3 presents the data, the associated regression, and statistics indicating the significance of the regression and regression coefficients.

Thus, among the three applicable data summarization method types that could be applied to the data, a difference of up to 10 percentage points was observed. As discussed earlier, this difference is of paramount importance in an environment where BMP technologies are designed, compared with a high degree of precision, and selected with specific quantitative goals in mind. As with analytical methods, unless data sets are analyzed using the same data summarization method, they will be incomparable, and the use of additional statistical methods for comparison and analysis may be fruitless.

With this in mind, all of the data accompanying the source studies was summarized using the a Regression of EMC, $y_0 \neq 0$ method in order to produce the most comparable results. It is suggested that this method be used for future controlled experiments.



Analysis of Variance:

Source of Variation	DF	SS	MS	F
Regression	1	16383	16383	886.0 ***
Residual	25	462.3	18.49	
Total	26	16846	647.9	

Significance of Coefficients:

Coefficient	Std. Error	t
y0 = 3.753	1.4173	2.648 *
a = 0.2878	0.0097	29.76 ***

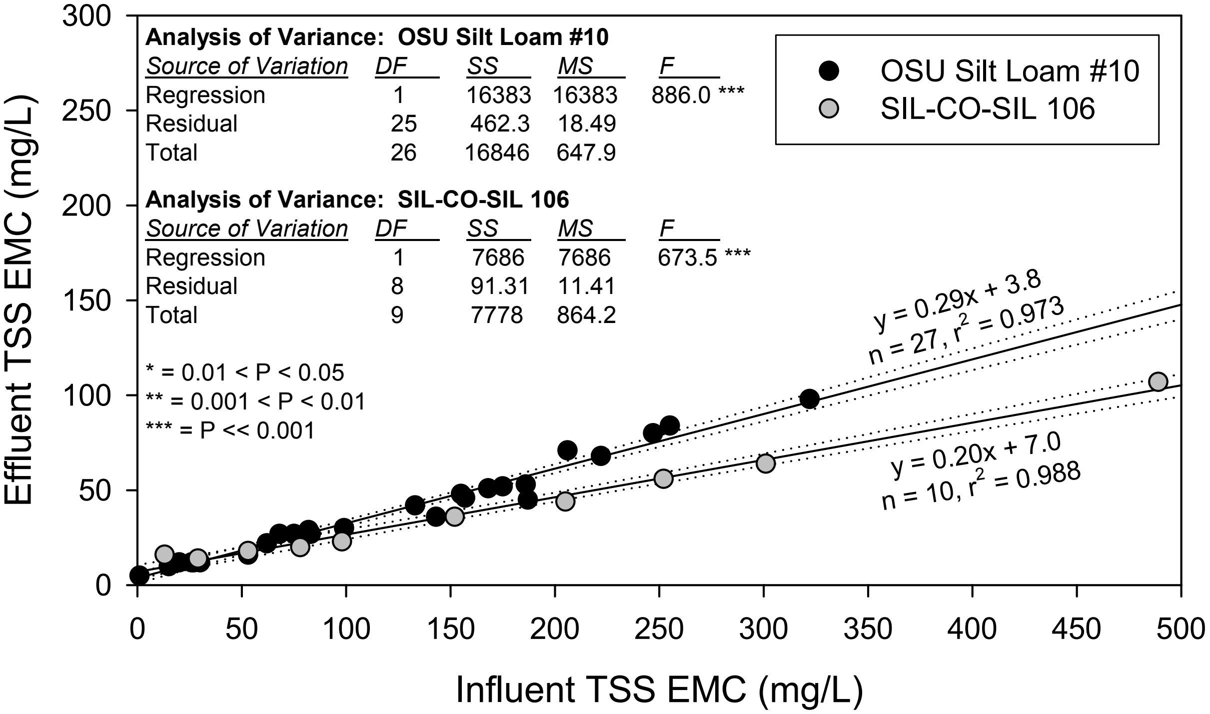
* = 0.01 < P < 0.05
** = 0.001 < P < 0.01
*** = P << 0.001

Figure 3. Regression of EMC, y0 ≠ 0, used for the summarization of the data used for this study. The inverse of the slope of the regression (solid line) yields the mean removal efficiency demonstrated by the system, 71%. The dotted lines about the regression are the upper and lower confidence intervals for the regression (P=0.05: L_c=70%, L_2=73%). ANOVA indicates a significant (P<0.001) linear relationship.

Influence of Particle Size

The influence of particle size can be explored through the comparison of the SMI (2002a) and the Stormwater360 (2002a) studies, wherein the same system was subject to testing using both the OSU Silt Loam #10 and SIL-CO-SIL 106 materials. Since both source studies utilized the same experimental apparatus, the "whole-sample" variation of EPA 160.2 for sample analysis, and the Regression of EMC, $y_0 \neq 0$ method for performance summarization, their comparability is solid. Furthermore, since regression statistics were used to summarize both experiments, the difference, if any, between the two results can be assessed through comparison of the regressions and the regression statistics.

Figure 4 displays the results of both source studies and indicates the presence of two distinct and statistically significant (P<0.001) regressions. The confidence intervals of the regression slope coefficients can be used to determine whether the performance indicated by the two regressions is statistically different. Though the confidence intervals overlap at influent TSS EMC concentrations below roughly 100 mg/L, this is to be expected given the similar y-intercepts. For the OSU Silt Loam #10 the regression slope coefficient confidence intervals (P=0.05) are 70% and 73%. For the SIL-CO-SIL 106 the regression slope coefficient confidence intervals (P=0.05) are 79% and 82% (Stormwater360, 2002a). Since these confidence intervals do not overlap, it could be said that the removal performance indicated by these two regressions are statistically different.



Analysis of Variance: OSU Silt Loam #10

Source of Variation	DF	SS	MS	F
Regression	1	16383	16383	886.0 ***
Residual	25	462.3	18.49	
Total	26	16846	647.9	

Analysis of Variance: SIL-CO-SIL 106

Source of Variation	DF	SS	MS	F
Regression	1	7686	7686	673.5 ***
Residual	8	91.31	11.41	
Total	9	7778	864.2	

Figure 4. Comparison of the performance of the coarse/fine perlite StormFilter cartridge operating at 28 L/min using both the OSU Silt Loam #10 and the SIL-CO-SIL 106 materials. Both regressions are significant at the P<0.001 level, and the difference between the two trends is indicated by the substantial lack of overlap by the respective 95% confidence intervals.

The mean difference between the summarized TSS removal efficiency of the same experimental system using the two different TSS materials is 9 percentage points. Since these TSS materials by no means bracket the possible range of materials that are present in stormwater, it is safe to assume that the potential influence of the particle size variable is much larger. Thus fundamental environmental variables, such as particle size, have the potential to influence performance such that data sets are incomparable unless this variable, as well as the other two covered by this study, is know to be constant among the data sets in question.

Conclusions

Using the data from three similar studies, it has been demonstrated that analytical method, data summarization method, and particle size hinder the accurate summarization of the TSS removal efficiency of a stormwater BMP. While these variables by no means encompass all of the possible variables affecting performance summarization, they do represent three of the most fundamental variables affecting the performance evaluation of stormwater BMPs. Based upon these findings, recommendations concerning the future production of comparable data can be made:

1. Either the “whole-sample” variation of EPA 160.2 or ASTM 3977-97 should be consistently used for TSS analysis to ensure both the comparability and accuracy of performance data;

2. When care is taken to control specific variables, regression analysis is an accurate, unbiased method for the evaluation and comparison of experimental data sets covering a range of influent concentrations;
3. Influent TSS concentration has been shown to be a questionable variable with regard to performance evaluation and may be an artifact of the susceptibility of lower concentration TSS data to negative bias;
4. A standardized TSS material (preferably from a specific source) should be used for the laboratory evaluation of BMP designs.

Integration of these recommendations into future BMP evaluation experiments performed in controlled environments should ensure the production of accurate, comparable data. Reports resulting from such work should still explicitly specify how each source of influence was addressed in order to ensure the proper use of the resulting data by the scientific community.

This study has shown that attention must be paid to the procedural aspects of data sets undergoing comparison. While the variables underlying the data gathered from the field evaluation of stormwater BMPs are almost impossible to grasp, such data must be used with caution, especially if it is to be used for comparative purposes. It must be realized that analytical results cannot be taken at face value, but instead must be regarded in light of the details surrounding their creation. Considering that the precise summarization of TSS removal efficiency has been shown to be challenging under even controlled conditions, perhaps additional parameters besides TSS removal efficiency should be taken into consideration in order to qualitatively compare the performance of systems evaluated under largely uncontrollable field conditions.

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

References

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.: Author.

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. Available online:
http://www.mrsc.org/environment/water/water-s/apwa/protocol.htm

American Society for Testing and Materials (ASTM). (1997). Standard test methods for determining sediment concentration in water samples (ASTM Designation: D 3977-97). West Conshohocken, Pennsylvania: Author.

Bent, G. C., Gray, J. R., Smith, K. P., & Glysson, G. D. (2001). A synopsis of technical issues for monitoring sediment in highway and urban runoff (Open-File Report 00-497). Denver, Colorado: United States Geological Survey. Available online:
http://ma.water.usgs.gov/fhwa/products/ofr00497.pdf

Center for Watershed Protection (CWP). (1996). Irreducible pollutant concentrations discharged from stormwater practices. Watershed Protection Techniques, 2(2), 369-372. Available online:
http://www.stormwatercenter.net/Practice/65-Irreducible%20Pollutant%20Concentrations.pdf

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.

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. Available online: http://water.usgs.gov/osw/pubs/WRIR00-4191.pdf

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. Available online:
http://www.cleanrivers-pdx.org/pdf/appendix_b.pdf

Stormwater360 (2002a). Evaluation of the Stormwater Management StormFilter® cartridge for the removal of SIL-CO-SIL 106, a synthetically graded sand material: Coarse/fine perlite StormFilter cartridge at 28 L/min (7.5 gpm) (Report No. PD-02-003.1). Portland, Oregon: Author.

Stormwater360. (2002b). Silt loam TSS removal efficiency of a stormwater BMP: Coarse/fine perlite StormFilter cartridge at 28 L/min (7.5 gpm) (Report No. PD-01-001.0). Portland, Oregon: Author.

Stormwater Management Inc (SMI). (2002a). Evaluation of a new fine perlite media product for silt loam TSS removal and comparison with existing product: Coarse/fine perlite StormFilter cartridge at 28 L/min (7.5 gpm) (Report No. RD-02-004.0). Portland, Oregon: Author.

Stormwater Management, Inc. (SMI). (2002b). Product design manual, v. 3.0. Portland, Oregon: Author. Available online:
http://www.stormwatermgt.com/products/onlinedesman.shtml

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). Available online: http://www.epa.gov/rmdcrl/sop/sopdoc/AIG018.pdf

URS Greiner Woodward Clyde (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. Available online: http://www.asce.org/pdf/task3_1.pdf

Revision Summary

PE-C063
Document Rebranded.

PE-C062
Document number changed; document rebranded; no substantial changes.

PD-02-006.1
Stormwater360 (2002a) data set corrected; regression statistics added to Figures 3 and 4; statistical discussions were clarified; SMI references were reformatted. The impact of this revision on the conclusions is negligible.

PD-02-006.0
Original.