Hydroworks Hydroguard Laboratory Testing and Sizing Implications

Introduction

Laboratory and field testing results are typically not evaluated with respect to the sizing methodology used for stormwater technologies. This has led to a discontinuity between the laboratory and field testing results for stormwater technologies and the sizing of the stormwater technologies for use on actual projects.

The sizing of a stormwater technology is based on performance calculations (theoretical or field/laboratory), local hydrology, and the desired pollutant for removal. In the design of hydrodynamic separators the pollutant typically chosen is total suspended solids (TSS) and the typical design criteria is 80% annual TSS removal. In order to demonstrate an annual TSS removal rate some type of continuous analysis (continuous simulation model, annual rainfall intensity analysis) must be used in conjunction with an assumed particle size distribution for TSS. The particle size(s) used to define TSS has the greatest impact on the size of technology required to achieve the required level of TSS removal.

Laboratory testing protocols for hydrodynamic separators and filters require testing with particle distributions where 40%-55% of the particles are smaller than 30 µm and 25% of the particles are smaller than 10 µm (NJDEP, Sil-Co-Sil 106). These particle size distributions are typically finer than those used for sizing on actual projects. Particle size distributions from literature/ field studies are used for sizing and these distributions tend to be coarser than those tested under laboratory conditions.

In the majority of design applications the particle size distribution of TSS to be captured is not provided as a design parameter. It is generally left up to the vendor to select a TSS particle size distribution for design purposes and this has led to inequitable comparisons on individual projects.

There are numerous assumptions inherent in annual TSS removal calculations that affect the TSS removal results. For example, the hydraulic response of TSS can be changed in a computer model that will affect the distribution of pollution with flow rate and annual pollutant removal results (i.e. if washoff parameters are used that washoff all of the TSS during low flow conditions a smaller separator will be required since high flows need not be treated).

Several agencies have adopted the use of a water quality flow rate that must be treated in addition to an annual TSS removal rate to reduce the potential for inequitable comparisons based on annual TSS removal alone. Similar to TSS removal, however, flow rate alone is an inaccurate parameter to dictate TSS removal. Flow rate does not take into account the relationship between TSS removal and flow rate for a stormwater technology, nor the relationship between stormwater pollution and flow rate.

Independent laboratory testing provides a relationship of TSS removal with flow rate. This relationship provides an opportunity to calibrate computer sizing models that are used for sizing.

It is important to calibrate theoretical continuous simulation computer models to ensure that the sizing of technologies accurately reflects the projected annual TSS removal results.

Hydroworks uses the EPA Storm Water Management Model (SWMM) model to determine stormwater separator sizing on individual projects. Although laboratory performance equations can be input to the model to determine separator sizing, this sizing is only applicable if the particle size distribution to be used for sizing matches the distribution used in the laboratory testing. As discussed previously, however, the particle size distribution used for sizing varies on a project by project basis. Therefore, a basis for calibrating the sizing model that is flexible enough to predict the change in performance with different particle size distributions is desirable.

Methodology

Two methodologies were used in this analysis to calibrate the Hydroworks sizing model to independent laboratory results to provide a strategy to design projects with different particle size distributions based on laboratory performance.

1. Adjustment of TSS particle specific gravity
2. Use of the Peclet number

The Hydroworks (SWMM) sizing model was used to simulate the exact flow rates that were independently tested at Alden Labs in 2008 for a full scale HG6. The sizing model can be simulated at a single rainfall intensity to determine the TSS removal performance at a single flow rate. Rainfall intensities were chosen for a 1 acre impervious area to match the flow rates that were tested in the laboratory. The NJDEP particle size distribution as measured at Alden labs (Table 1) was input as the TSS particle size distribution and the pipe diameter and inlet pipe slope that was tested at Alden labs was input as pipe parameters in the sizing model.

Table 1. NJDEP Particle Size Distribution (PSD)	
% Finer (Cumulative)	Particle Size (µm)
5	2
10	3
15	5
20	8
25	11
30	15
35	21
40	30
45	40
50	70
60	150
70	190
80	230
90	350
95	510
100	800

The TSS removal results for a HG6 as predicted by the Hydroworks (SWMM) model and the independent laboratory results (Alden, 2008) are shown on Figure 1 for a standard non-organic specific gravity of 2.65. Figure 1 demonstrates that the use of Stoke's law in the Hydroworks Sizing Model will underestimate the TSS removal performance measured at the Alden Research Laboratory.

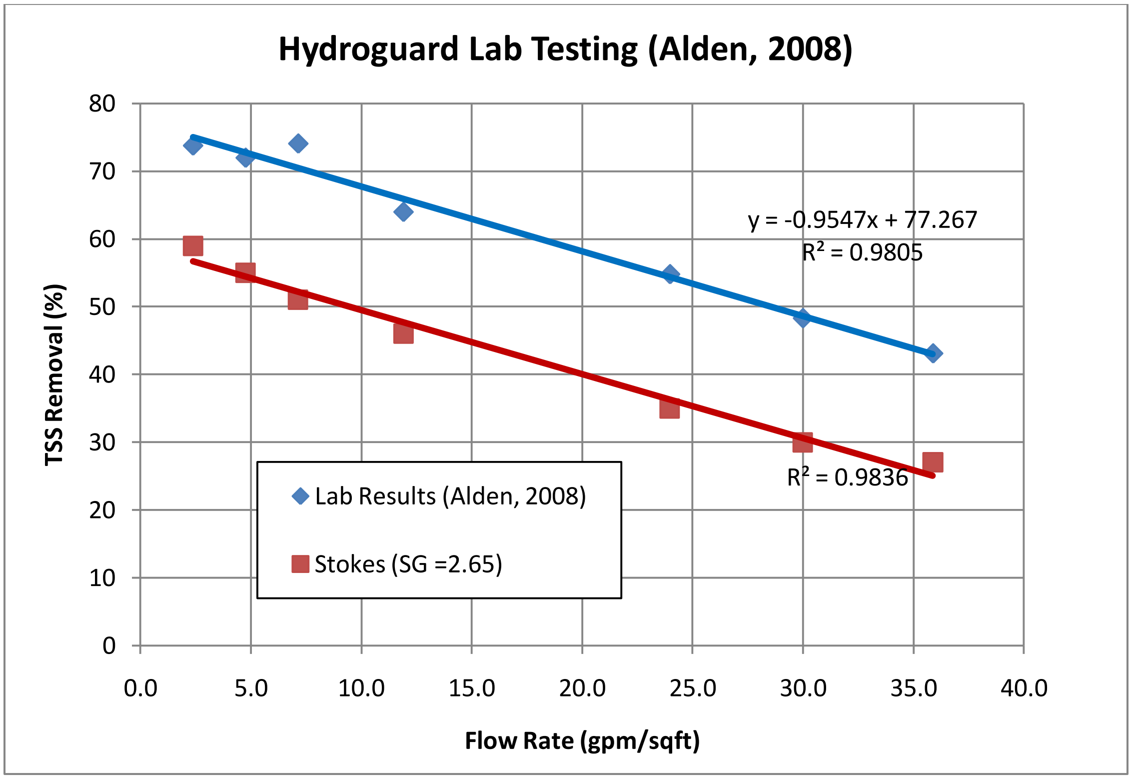

Figure 1. Independent Laboratory Testing vs. Hydroworks Sizing Model (Stokes)

Calibration of Specific Gravities

Specific gravities were adjusted for each particle size to determine adjusted values to calibrate the theoretical SWMM-based sizing model TSS removal results with the measured TSS removal results from the independent laboratory testing. The measured laboratory TSS removal results were matched to the Hydroworks sizing model results by increasing the specific gravity of particles less than 100 um from 2.65 to 20 and increasing the specific gravity of particles greater than 100 um from 2.65 to 6 (Figure 2). The TSS removal results from the sizing model match the measured laboratory TSS removal results with a correlation coefficient of 0.97 (r^2 = 0.95) when the changes to specific gravities are implemented.

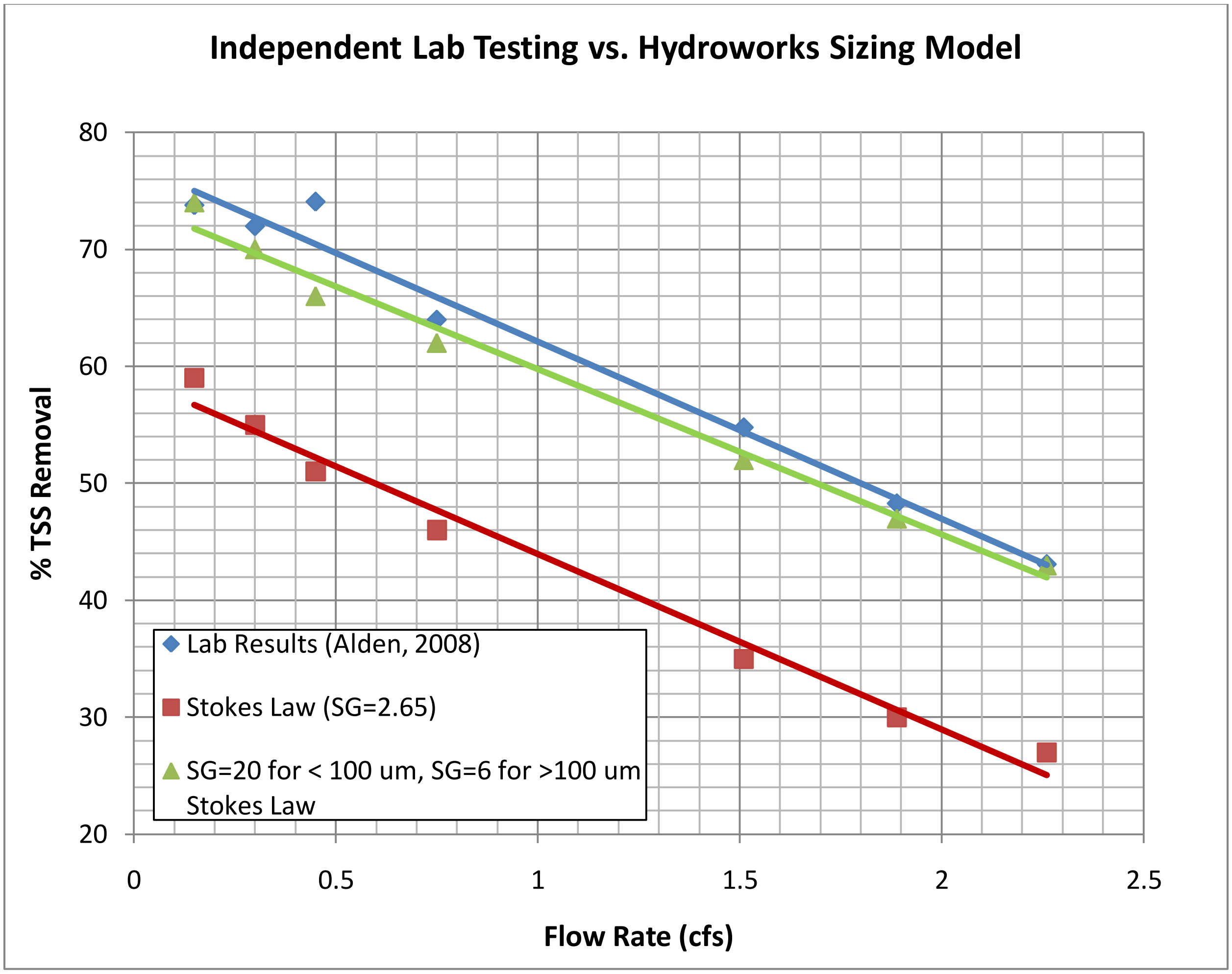

Figure 2. Independent Lab Testing Compared to the Hydroworks Sizing Model

Peclet Number

The Peclet number has been used as a dimensionless scaling number for sediment deposition in lakes (Dhamotharan, et. Al. 1981). Others have suggested its use for scaling of TSS removal results for hydrodynamic separators (Dhanak, 2008, Gulliver, Guo and Wu, 2008). The Peclet number is the ratio of convection (convective settling) to diffusion (turbulence keeping particles in suspension). The Peclet number (Equation 1) varies with the size of separator, particle size of TSS, and flow rate.

$$Pe = Vs\ h\ d\ /Q \qquad \text{Equation 1}$$

Where Pe = Peclet number
Vs = settling velocity
h = depth of separator sump
d = separator diameter
Q = flow rate

A particle will be removed in the separator if the Peclet number is equal to, or greater than, the Peclet number calculated for removal of that particle based on the independent laboratory results. The TSS removal value at each flow rate during the independent laboratory testing provides an indication of the smallest particle removed at each flow rate based on the influent particle size distribution (Table 1). The Peclet number was calculated for the smallest particle removed at each flow rate to generate a relationship between Peclet number and particle size removed in the Hydroguard.

The Peclet number is based on the settling velocity of the TSS particle. Settling velocities were calculated using Cheng (1997) instead of Stoke's law (Equation 2) since previous research (Cheng, 1997) has indicated that it provides better correlation with sedimentation rates measured in the field.

$$Vs = \nu/d_p\ [(25+1.2(d_1)^2)^{0.5} -5]^{1.5} \qquad \text{Equation 2}$$

$$d_1 = d_p\ [(g\ (\rho_s-\rho)/\ \rho)/\nu^2\ ]^{0.33}$$

Where Vs = settling velocity
ν = kinematic viscosity of water
d_p = particle diameter
ρ_s = particle density
ρ = water density

Cheng settling velocities provide values smaller than Stoke's law for particles smaller than 120 µm and settling velocities larger than Stoke's law for particles greater than 120 µm.

Figure 4 indicates that the relationship between TSS removal performance and flow rate is linear for the flow rates tested in the laboratory (blue line r^2 = 0.98). The linear regression equation from Figure 4 (Equation 3) was used to determine TSS removal results at various flow rates. Table 1 was used with the resulting TSS removal results to determine the smallest particle size removed at each flow rate.

TSS Removal = -15.155 Q + 77.267 Equation 3

Where Q = flow rate in ft^3/s

Table 2 provides a range of Peclet Numbers corresponding to TSS removals calculated using Equation 3 based on the independent laboratory results.

Table 2. Peclet Number for TSS Particle Size Removed

Flow Rate (cfs)	TSS Removal (%)	Particle Removed (µm)	Peclet Number
0.48	70	18	0.053
1.14	60	35	0.085
1.47	55	55	0.163
1.80	50	110	0.532
2.46	40	170	0.928
3.12	30	210	1.114
3.78	20	290	1.745
4.44	10	430	3.231
4.77	5	655	6.797

Equation 3 was used to determine TSS removal in Table 2 instead of the actual testing results since the lowest TSS removal rate measured during the independent laboratory testing was 43% which corresponds to a removed particle size of 151 µm. Equation 3 was used to allow the construction of a relationship between Peclet Number and settled particle size for particles between 150 µm and 655 µm.

Figure 3 shows the relationship between Peclet Number and Particle Size removed.

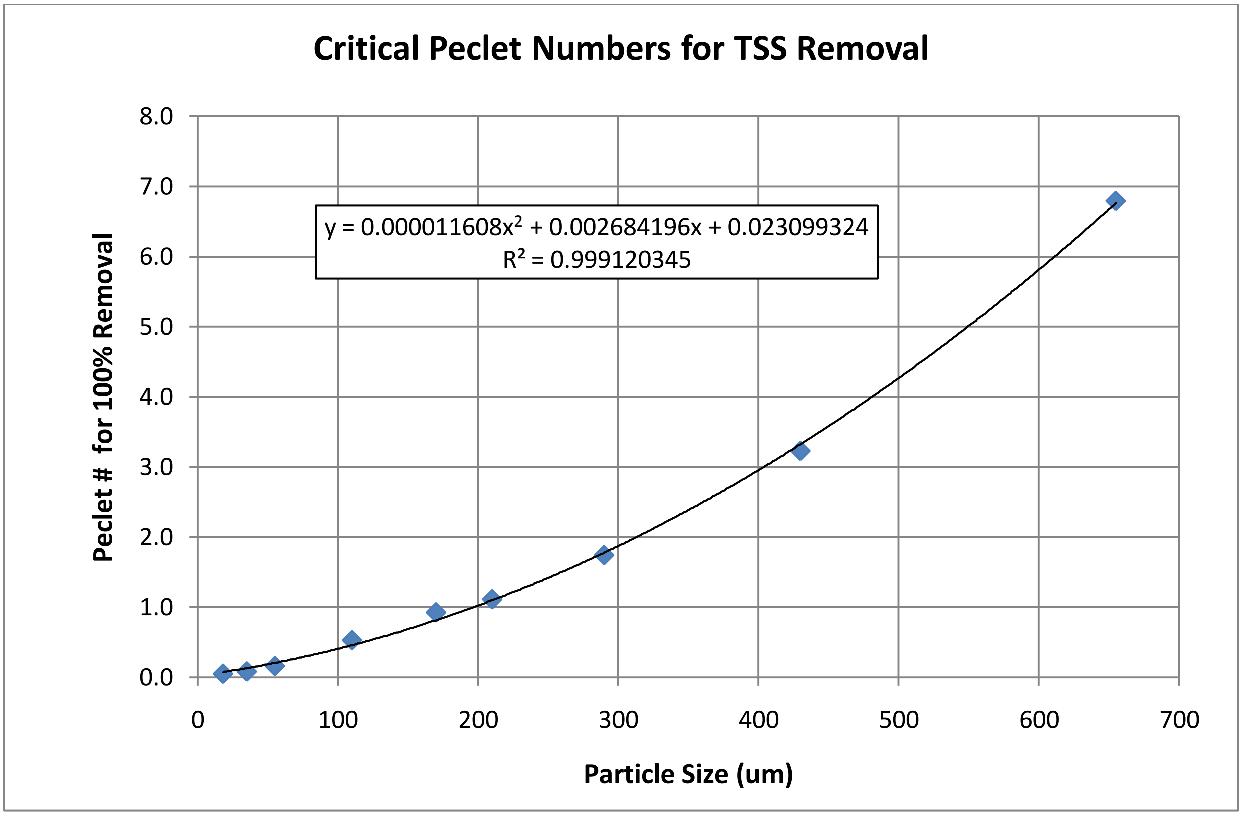

Figure 3. Critical Peclet Numbers for Particle Removal

Figure 3 indicates that a critical Peclet Number associated with the removal of a specific particle size can be calculated using equation 4 ($r^2 = 0.99$).

Critical Peclet Number = $0.0000116\, d^2 + 0.002684\, d + 0.023$ Equation 4

Where d= Particle Diameter (µm)

And Critical Peclet Number ≥ 0.050

If the Peclet number calculated for any size of Hydroguard, for any particle size, at any flow rate is larger than the Critical Peclet Number for that size of particle it will be removed (i.e. Peclet number lies above the curve in Figure 3). If the Peclet number is less than the Critical Peclet Number the particle will pass through the separator (i.e. Peclet number lies below the curve in Figure 3).

Table 3 provides the relationship between Peclet number and TSS removal rate based on the actual independent laboratory testing results.

Table 3. Peclet Number for TSS Particle Size Removed			
Flow Rate (cfs)	TSS Removal (%)	Particle Removed (µm)	Peclet Number
0.15	73.8	14	0.106
0.30	72.0	16	0.068
0.45	74.1	14	0.034
0.75	64.0	27	0.079
1.51	54.8	57	0.172
1.89	48.3	120	0.605
2.26	43.1	151	0.801

Table 3 shows that the Peclet numbers are inconsistent at the lower flow rates due to the fluctuations in TSS removal results at the low flow rates. The results indicate that the smallest particle able to be effectively removed by the separator tested (Hydroguard HG6) during flow periods is 15 µm. Indeed the removal of particles smaller than 15 µm by hydrodynamic separators during flow through periods is not considered realistic due to the potential for these small particles to stay suspended in the water column. Accordingly the fluctuation in TSS removal rates with fine particles is expected at low flow rates due to experimental error and fluctuations in settling velocity for very fine particles. In order to properly account for this phenomenon, a minimum Critical Peclet number of 0.050 was established for any particle to be removed during flow conditions in the separator regardless of flow rate, separator size, and particle size diameter.

Equation 4 was used in the settling model to determine a critical Peclet Number for each particle size simulated in the model. For each size of separator and flow rate at any given timestep the Peclet number was calculated for each particle size and compared to the critical Peclet number for that particle size. If the Peclet number calculated at the particular timestep exceeded the critical Peclet number the TSS associated with that particle size for that timestep was considered removed (settled). This calculation occurs for each timestep/flow rate and each particle size such that an overall TSS removal result for the simulation period can be determined.

Figure 4 shows the results from the sizing model simulated for constant flow rates to replicate the independent laboratory tests. The calculations of TSS removal using the Peclet Number methodology match the laboratory results (using Table 1 for the particle size distribution) with a correlation coefficient of 0.96 ($r^2 = 0.91$).

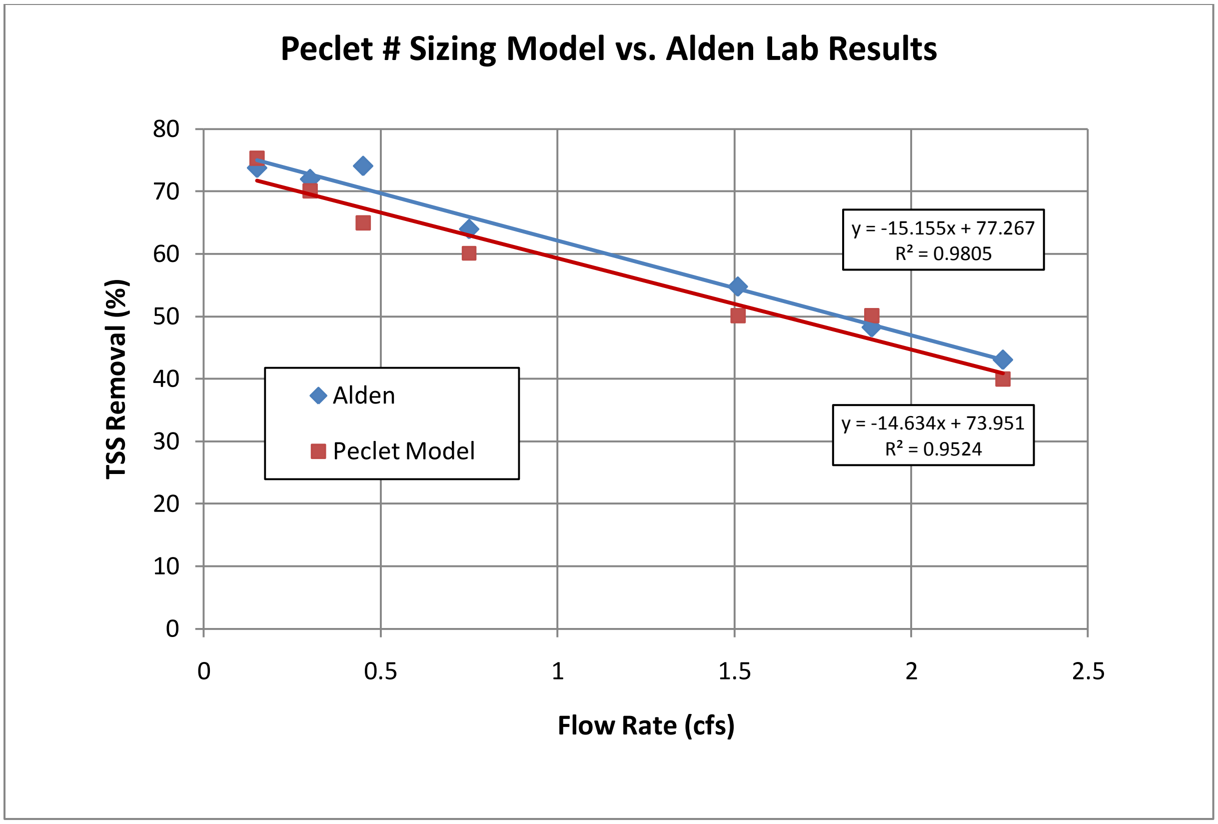

Figure 4. Peclet Number Sizing Compared to Independent Laboratory Results

Discussion

Two methods (adjustment of specific gravities and the use of Peclet numbers) were established to calibrate the Hydroworks sizing model based on independent laboratory testing TSS removal results.

Both methods provide results with high correlation coefficients to the measured laboratory performance data. The Peclet number methodology has the advantage of incorporating scaling parameters for the size of separator (settling depth, flow dimension) which make it more applicable to predicting TSS removal for different sizes of separators. In addition, the Peclet number provides a better representation of the changing relationship of particle removal (settling velocity) with influent separator flow rate. Accordingly the Peclet methodology is considered preferable for these reasons.

Although the relationship between Peclet number and particle size removal will be different for each storm water quality device, the methodology outlined in this paper could be applied to any system that has this type of data to allow the prediction of long term TSS removal results based on laboratory performance for any given particle size distribution, separator size, and local hydrology.