Assessment of Hydrodynamic Separators for Storm-Water Treatment

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Abstract: Hydrodynamic separators are proprietary underground devices designed to remove floatable debris (e.g., leaves, trash, oil) and to remove suspended solids from storm-water runoff by sedimentation. They are designed for storm-water treatment in urban areas to meet tight space constraints. Limited data on the suspended solids removal performance of installed devices are available, and existing data are questionable because of the problems associated with assessment by monitoring. The objectives of our research are to: (1) investigate the feasibility and practicality of field testing to assess the performance of hydrodynamic separators as underground storm-water treatment devices; (2) evaluate the effects of sediment size and storm-water discharge on the performance of six devices from different manufacturers; and (3) develop a universal approach for predicting the performance of a device for any given application. In the field tests, a controlled and reproducible synthetic storm event containing sediment of a well defined size distribution and concentration was fed to a precleaned device. The captured sediment was then removed, dried, sieved, and weighed. To assess the performance of the devices, suspended sediment removal efficiency was related to a Péclet number, which accounts for two major processes that control performance: (1) settling of particles; and (2) turbulent diffusion or mixing of particles. After analyzing the data, all devices showed similar behavior, therefore, a three-parameter performance function was proposed for all devices. Performance functions were developed from the result of the field tests and parallel testing of two other full-scale devices in the laboratory. The performance functions can be used to determine the efficiency of the tested devices and to improve the selection and sizing of hydrodynamic separators and the assessment of their overall performance after installation.

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Introduction

As a result of the 1987 Amendments to the Clean Water Act, storm-water pollution prevention programs will be implemented at facilities owned and/or operated by the state, cities, towns, counties, flood control and watershed districts, or similar entities. In order to implement such programs, information is needed on the pollutant removal performance of storm-water best management practices (BMPs), such as detention ponds, bioretention systems, and underground devices. Underground devices are attractive for removing leaves, trash, and suspended solids from storm-water runoff in dense urban areas because they have a small footprint. These devices are usually divided into three groups: hydrodynamic separators, underground settling devices, and filters. Settling devices and hydrodynamic separators are primarily used for removing floatables and coarser and heavier suspended sediments from storm-water runoff. Hydrodynamic separators are designed to utilize the resulting hydraulic conditions in the sumps for separating suspended sediments from the rest of the flow. Hydrodynamic separators can function as standalone treatment systems or as a pretreatment to other devices such as ponds and infiltration basins to reduce maintenance costs. In hydrodynamic separators, water either enters a sump tangentially thus creating a swirl, e.g., CDS, Environment21 [Fig. 1(a)], Vortech Systems, ecoStorm, or water plunges into a sump, e.g., Stormceptor [Fig. 1(b)] and BaySaver. Hydrodynamic separators may be single sump devices, e.g., ecoStorm and Stormceptor [Fig. 1(b)] or multiple sump devices, e.g., Vortech Systems, CDS, BaySaver, and Environment21 [Fig. 1(a)].

A number of field monitoring studies have previously been undertaken to quantify the pollutant removal performance of hydrodynamic separators (Fassman 2006; Roseen et al. 2005; ETV 2005a,b; Bonestroo, Rosene, Anderlik and Associates, Inc. 2002, and 2003; Yu and Stopinksi 2001; England 2001; Strynchuk et al. 2000; and Waschbusch 1999). It is difficult to compare the results from these studies because different experimental approaches and evaluation criteria were used. Comparison is further complicated by the diversity of existing proprietary hydrodynamic separators and the watersheds they are installed in. In addition, field moni-

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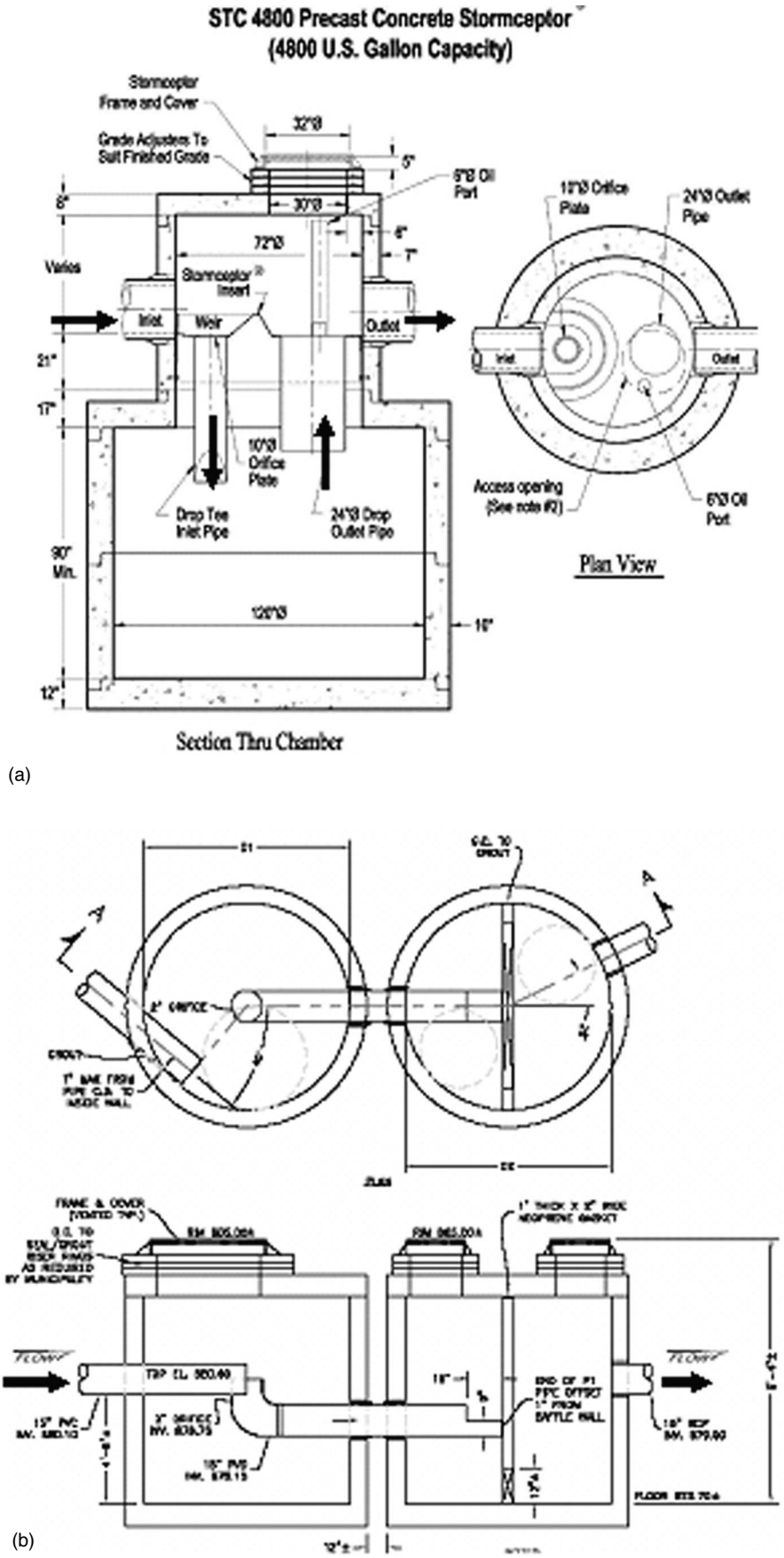

Fig. 1. (a) General plan and section of Stormceptor STC4800 (arrows show direction of flow under low flow conditions, i.e., before bypass becomes operational); (b) plan and section of V2B1 Model 4

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toring relies on sampling, which is problematic for coarse and heavy suspended solids like sand (Andoh and Saul 2003; Roesner et al. 2007).

In this paper we will: (1) investigate the viability of "controlled field testing" of hydrodynamic separators as an alternative to "field monitoring," eliminating the need for automatic sampling; (2) evaluate the suspended sediment removal capability of six hydrodynamic separators when subjected to field or laboratory testing with a range of sediment sizes and discharges; and (3) develop similarity criteria for predicting the performance of a given device based on a dimensionless parameter. The main product of a field testing effort is a "performance function" for each type of device in which removal efficiency is expressed as a function of a dimensionless number that accounts for the two major processes that control performance: (1) advection or settling of particles; and (2) turbulent diffusion or particles suspension. This performance function can serve as a tool to predict the removal performance for a wide range of influent discharge, particle size and density, and influent temperature (i.e., fluid viscosity).

Methods and Materials

Site Selection

Prospective testing sites where proprietary hydrodynamic separators had been installed in the Minneapolis/St. Paul metropolitan area were identified, screened, and evaluated for field testing potential based on a variety of characteristics: (1) safety; (2) parking and storage of equipment; (3) proximity to a fire hydrant as water source; (4) maximum treatment flow rate of the device (i.e., must be less than the total maximum discharge from nearby hydrants); and (5) access to treatment chamber sumps for thorough cleanout activities. The proper level measurement required the absence of tailwater effects and hydraulic jumps over a suitable distance upstream of a flow measurement weir, so that the approach flow to the weir was subcritical and free from surface waves.

The following treatment systems were ultimately selected and tested in the field: the V2B1 Model 4 by Environment21, the Vortechs Model 2000 by Stormwater360, the Stormceptor STC4800 by Imbrium Systems, and the CDS PMSU20_15 by CDS Technologies. Full-scale laboratory studies were also performed on the BaySaver Model 1k by BaySaver Technology, Inc. (Carlson et al. 2006), and Model 3 ecoStorm by Royal Environmental Systems (Mohseni and Fyten 2007).

Testing Material

A silica sand mixture was prepared and used to simulate suspended sediments transported by storm-water runoff (Wilson et al. 2007). Sand was sieved to create three discrete fractions with median sizes of 107 μm (ranging from 89 to 125 μm), 303 μm (ranging from 251 to 355 μm), and 545 μm (ranging from 500 to 589 μm). The three sand-sized fractions were then combined to create a composite sample for testing by mixing equal parts by weight of each. In addition, a few experiments were performed with silt-sized particles. These samples were comprised of a commercially available silica gradation with a median particle diameter of approximately 45 μm, a d_{90} of 150 μm, and a d_{10} of 2 μm.

Field and Laboratory Testing

Prior to the commencement of testing activities, each site was prepared as follows: (1) for real-time flow rate measurement, a pre-calibrated circular weir and pressure transducer were installed in the storm drain system near the treatment device. Circular weirs were used to minimize the backwater effects on the systems (Gulliver and Anderson 2008). The measured water depths were stored in a data logger and used to calculate flow rate based on conduit geometry. (2) The treatment manhole(s) were dewatered and solids were removed with the assistance of vacuum trucks provided in each case by the city in which the research was being conducted. (3) A piping system was customized for the delivery of fire hydrant water as influent test water. (4) Inflatable plugs were used when necessary to seal off alternative flow paths that could lead to additions or losses of storm water, sediment, or both. Additionally, leaking sumps were repaired at three of the four sites to ensure proper hydraulics and system operation.

After each site and device were prepared for assessment, testing progressed as follows:

1. The desired discharge through the system was established using a gate valve on the hydrant and the real time water flow rate measurement system described above. The data logger recorded 60 s average levels and provided an updated readout every second.
2. The sand test mixture was added continuously to the influent hydrant water using a precalibrated sediment feeder to achieve a relatively constant concentration of 200 mg/L. The total load varied between 10 and 15 kg depending on the expected retention of the sediment.
3. The water temperature, mass of sediments delivered, and test duration were recorded.
4. Following a 15–20 min period to allow the sand particles to settle, the device was dewatered with sump pumps, and retained sediments were removed from each manhole separately with a wet/dry vacuum.
5. The collected sediment was oven-dried, sieved into the original size fractions, and weighed.

The fractional removal of each sediment size fraction was computed by dividing the mass of sand in that size fraction retained by the treatment device by the known quantity of sand in that size fraction delivered to the device. Each test produced three data points because three discrete sand size ranges were used. Each device was tested under four discharge conditions in triplicate, between 15 and 100% of the maximum treatment rate, for a total of 12 tests. Under ideal test conditions, the removal efficiency of each device would thus be described by 36 data points.

After conducting several tests, it was determined that some suspended sediment loading scenarios were difficult to simulate. For low discharges, larger sand grains may settle to the bottom of the inlet pipe and not enter the treatment device. To minimize this problem, one or more of the following approaches were used: (1) increasing the minimum discharge; (2) eliminating the largest sand size fraction; and (3) moving the sediment delivery point closer to the inlet of the device.

In many underground treatment devices, pollutants are removed by the settling chamber as well as the floatables trap. Sand retained in each chamber during testing was collected and inventoried separately.

Scaling of Removal Efficiency

Dhamotharan et al. (1981) found that two dimensionless numbers are appropriate and sufficient to explain sediment deposition rates in reservoirs, a Péclet number

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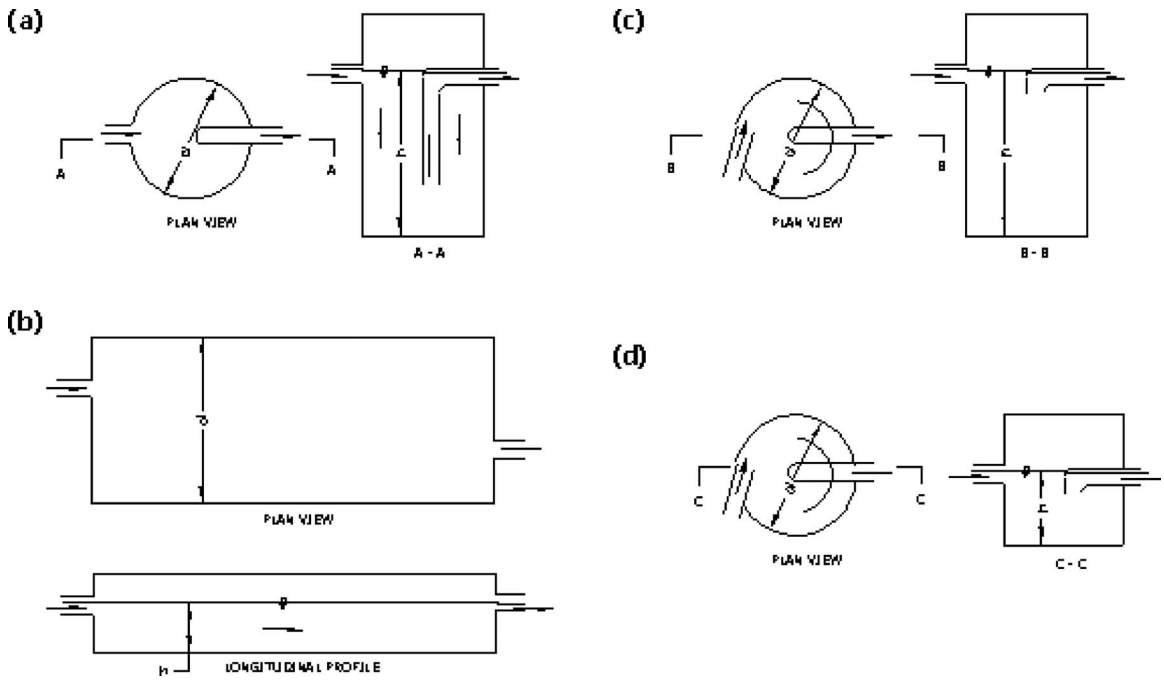

Fig. 2. General flow conditions in hydrodynamic separators and settling devices: (a) water plunges vertically into sump; (b) water plunges horizontally into shallow, long tank; (c) water enters tangentially and swirls in deep sump; and (d) water enters tangentially and swirls in shallow sump

$$\mathsf{P} = \frac{V_s h}{D_t} \tag{1}$$

where V_s=particle settling velocity; h=settling depth; and D_t =turbulent diffusion coefficient; and a dimensionless time T

$$T = \frac{V_s t}{h} \tag{2}$$

where t=time. Péclet number is defined as the ratio of convection to diffusion: in this case the convective, settling process is opposed by turbulent diffusion in the system tending to keep solids in suspension. When the diameter is the shortest dimension of the flow, $D_t \sim Ud$, where U=flow velocity; d=device diameter; and by continuity $D_t \sim Qd/A$. In many hydrodynamic separators, flow enters the chamber from above [Fig. 2(a)] and turbulence is stronger where plunging occurs. Therefore, if A is taken as the horizontal projection of the chamber (the cross-sectional area of mixing) which is proportional to d^2, then $D_t \sim Qd/d^2 = Q/d$. The Péclet number for the storm-water treatment device therefore becomes

$$\mathsf{P} = \frac{V_s hd}{Q} \tag{3}$$

If the smallest dimension of the device is its height, or settling distance, as is the case for detention ponds and underground settling devices [Fig. 2(b)], then inflow is relatively horizontal and thus A becomes the vertical cross section of the pond, hd. Therefore $D_t \sim Qh/hd = Q/d$ and $\mathsf{P} = V_s hd/Q$. In both cases, one obtains the same equation for the Péclet number.

In the hydrodynamic separators where water enters tangentially, turbulence is dependent upon the aspect ratio of the sump (Poncet et al. 2008). The shortest dimension will influence turbulent diffusion. If the diameter is the shortest dimension [Fig. 2(c)], P is described by Eq. (3). If water depth is the shortest dimension [Fig. 2(d)], then

$$\mathsf{P} = \frac{V_s d^2}{Q} \tag{4}$$

When time is replaced with residence time, the dimensionless time introduced by Dhamotharan et al. (1981) becomes the Hazen number, which is the ratio of settling velocity to overflow rate (Bloodgood et al. 1956) Using the parameters that are normally available for hydrodynamic separators

$$T = \mathrm{Ha} \cong \frac{V_s d^2}{Q} \tag{5}$$

where Ha=Hazen number. For Fig. 2(d), there is no difference between the Hazen number and the Péclet number. In this application, the only difference between Eqs. (3) and (5) is that two length scales are used in the Péclet number. We use the term Péclet number, however, because it emphasizes the importance of turbulent diffusion to the separation process at intermediate values of P or Ha. Both the Péclet number and the Hazen number can be rearranged to show the contribution of the residence time ($\mathsf{P} = V_s . T_r/(4d/\pi)$). However, as is shown in the "Results" section of this paper, residence time alone cannot explain the deposition of sediments in hydrodynamic separators or settling devices.

Settling velocity was assumed to follow Eq. (5) proposed by Cheng (1997)

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$$V_s = \frac{\nu}{D}\left(\sqrt{25 + 1.2\left(D\left(\frac{g\frac{\rho_s - \rho}{\rho}}{\nu^2}\right)^{1/3}\right)^2} - 5\right)^{1.5} \quad (6)$$

where ν=kinematic viscosity of the fluid; D=particle diameter; g=gravitational constant; ρ_s=particle density; and ρ=fluid density. In a study comparing multiple soil particle settling formulae versus measured settling data Fentie et al. (2004) showed that Eq. (6) outperformed other settling models. Eq. (6) is an explicit relationship for settling of natural sand particles derived from the particle Reynolds number (R) and a dimensionless particle parameter. It is applicable to a wide range of R, from the Stokes flow to turbulent regimes, and becomes Stokes law (Stokes 1851) at small particle diameters.

Results

Data Collected

Performance functions were developed for six hydrodynamic separators. Two devices were tested in the laboratory and four devices were tested in the field. Because the ecoStorm and Stormceptor units are single manhole treatment systems, only one performance function was generated for each device. For the remaining two-chamber devices, performance functions were generated for the settling chamber (termed "primary") and for the combination of the settling and floatables-trap chambers (termed "total"). The dimensions from the settling chamber, h and d, were used in the Péclet number for both the settling chamber and total removal data sets. Including sediments retained in the floatables trap may yield overestimations of the removal capability of a device because the floatables-trapping manholes use underflow baffle walls that may lead to resuspension of settled solids, especially at higher discharges.

Data Analysis

Because tests were conducted in triplicate for each discharge, a normalized range (range/mean) was calculated in order to assess the repeatability of each experiment. The normalized ranges of removal efficiencies varied from 0.6 to 15.6%, with a mean of 5.8%. This variation is small, compared to the accuracy typical of field measurements on storm-water treatment facilities (Weiss et al. 2007). Much of the variability can be attributed to slightly different experimental conditions during replicate tests. In some cases, discharges differed by as much as 13%, and in others there were small but unavoidable differences in water temperature (up to 2.5°C), which influence viscosity, and thus particle settling velocity. Changes in discharge or temperature produce different Péclet numbers and different removal performance. In this study changes in water temperature and flow rate were recorded and incorporated in computing the Péclet number of each particle size tested during each test.

Each treatment device has its own "signature" removal efficiency versus Péclet number performance function (Figs. 3–9). This performance function depends, of course, on the design of each device, i.e., the hydraulic conditions in the sump(s). Nevertheless, the performance functions for all six devices tested have several common features: the sediment removal efficiencies for the six devices approached 0% at low Péclet numbers and approached 100% at high Péclet numbers. For a given device with

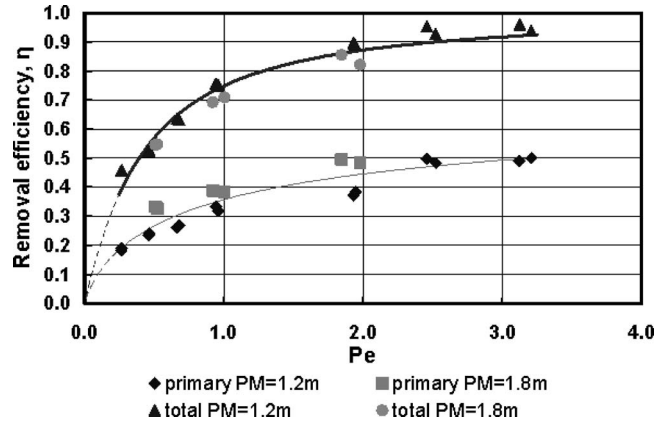

Fig. 3. Removal efficiency versus P for BaySaver Model 1k in Cartesian coordinates (after Carlson et al. 2006)

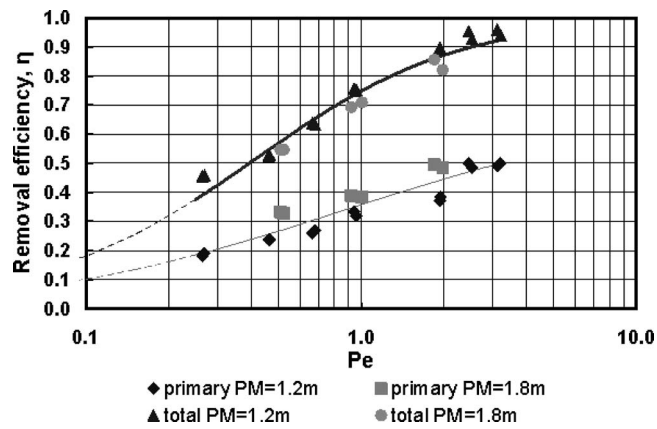

Fig. 4. Removal efficiency versus P for BaySaver Model 1k in semi-log coordinates (after Carlson et al. 2006)

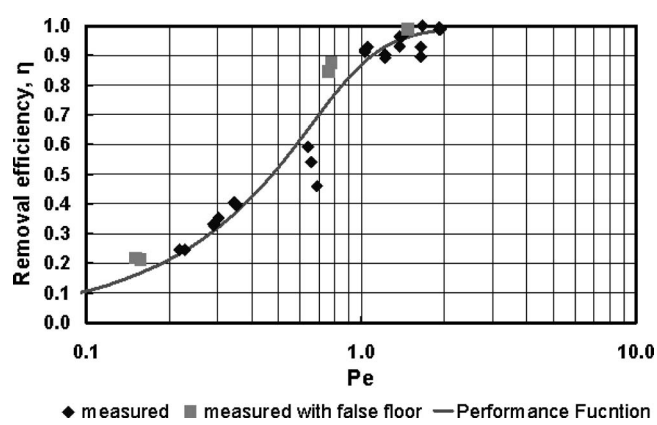

Fig. 5. Removal efficiency of Model 3 ecoStorm versus P (from Mohseni and Fyten 2007)

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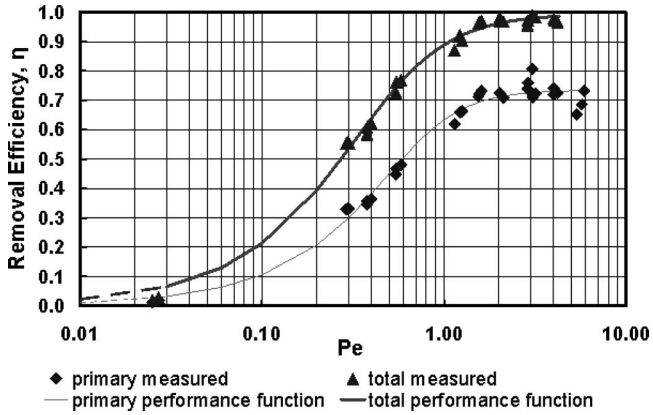

Fig. 6. Removal efficiency versus P for V2B1 Model 4, reflecting removal by: (1) solely settling chamber; (2) total removal by combination of settling chamber and floatables trap (Ha=1.22 P)

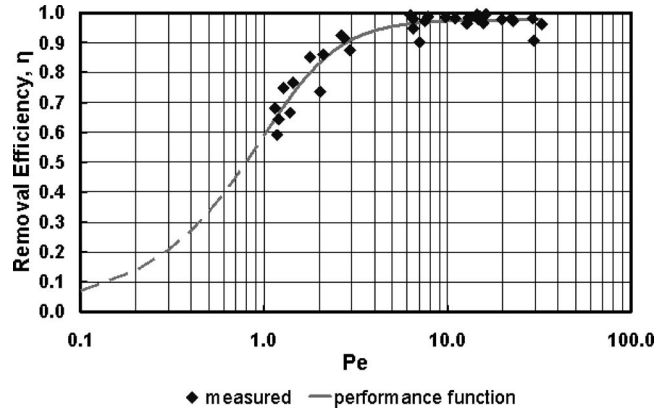

Fig. 8. Removal efficiency versus P for Stormceptor STC4800 (Ha =0.876 P)

fixed length scales h and d, a low Péclet number can result from either a low settling velocity, V_s, or from a high discharge, Q; therefore, detention time by itself cannot be used to explain the removal efficiency of these devices. Not surprisingly, all devices removed sediment more successfully at higher Péclet numbers.

Data Fitting

A three parameter, exponential function of Péclet number given in Eq. (7) was fit to the solids removal results obtained for each device.

$$\eta = \left(\frac{1}{R^b} + \frac{1}{(a\mathrm{P})^b}\right)^{-(1/b)} \tag{7}$$

where η=removal efficiency; R=removal efficiency as P approaches infinity; a=initial slope of the curve at P=0, the exponent b=measure of the curvature in the function at P=R/a, i.e., as b increases, η approaches the intersection of two asymptotes ($\eta=a\mathrm{P}$ and $\eta=R$) at P=R/a, and the Péclet number P =independent dimensionless variable. The parameter R was limited to positive values less than or equal to unity because theoretically removal efficiency cannot exceed 100%. As $b\rightarrow\infty$, the value of η becomes the lesser of the two asymptotic values, i.e., at values of P less than R/a, $\eta=a\mathrm{P}$, and at values of P greater than R/a, $\eta=R$. This particular function [Eq. (7)] for removal efficiency was chosen because it captures the concavity of the trend, it tends toward zero as the Péclet number approaches zero and it tends toward R as the Péclet number approaches infinity. A nonlinear regression analysis was performed on each dataset to determine the best fit values for each of the three parameters (Table 1).

The Nash–Sutcliffe coefficient (NSC) was calculated and tabulated (Table 1) for each dataset as a measure of the fit between Eq. (7) and the dataset, relative to the variance of the dataset around its mean value. The NSC is computed as follows:

$$\mathrm{NSC} = 1 - \frac{\Sigma(\eta_{\mathrm{meas}\ i} - \eta_i)^2}{\Sigma(\bar{\eta}_{\mathrm{meas}} - \eta_{\mathrm{meas}\ i})^2} \tag{8}$$

where $\eta_{\mathrm{meas}\ i}$=measured removal efficiency; η_i=fitted value from Eq. (7); and $\bar{\eta}_{\mathrm{meas}}$=mean measured removal efficiency for the dataset.

The root-mean-square error (RMSE) defined by Eq. (9) was also tabulated for each dataset as another measure of the goodness of fit of Eq. (7) to each data set

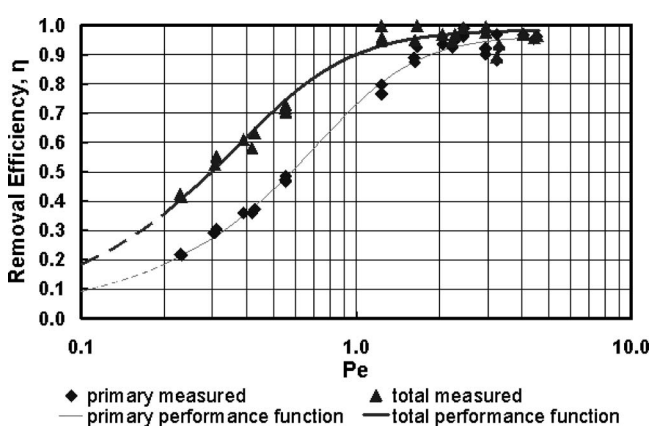

Fig. 7. Removal efficiency versus P for Vortechs Model 2000, reflecting removal by: (1) solely settling chamber; (2) total removal by combination of settling chamber and floatables trap (Ha=0.977 P)

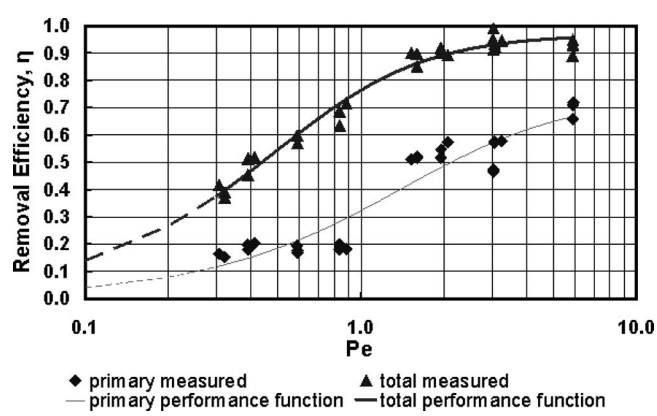

Fig. 9. Removal efficiency versus P for CDS PMSU20_15, reflecting removal by: (1) solely settling chamber; (2) total removal by combination of settling chamber and floatables trap (Ha=0.434 P)

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Table 1. Summary of Fitted Performance Function Parameters and Corresponding Statistical Measures

		Fitted parameters			Statistical measures	
Device and function	Related figure	a	b	R	NSC	RMSE (%)
BaySaver primary	3,4	1.77	0.62	0.74	0.87	4.1
BaySaver total	3,4	2.02	1.22	1.0	0.99	3.8
ecoStorm	5	1.07	4.15	0.99	0.96	6.6
V2B1 primary	6	1.06	2.36	0.74	0.98	3.1
V2B1 total	6	2.20	1.85	0.99	0.99	2.1
Vortechs primary	7	0.92	2.71	0.97	0.99	2.7
Vortechs total	7	1.86	2.32	0.99	0.98	3.2
Stormceptor	8	0.70	2.28	0.98	0.91	3.6
CDS primary	9	0.41	1.48	0.75	0.89	6.9
CDS total	9	1.42	1.75	0.97	0.97	3.5

$$\mathrm{RMSE} = \sqrt{\frac{\Sigma(\eta_{\mathrm{meas}\ i} - \eta_i)^2}{m - p}} \tag{9}$$

In Eq. (9), m=number of observations; and $p(=3)$=number of parameters in the fitted function [Eq. (7)]. Thus, RMSE =average deviation of the data points from the fitted function. The NSC values in Table 1 are all greater than 0.87, and the RMSE values are all less than 7%. Thus, Eq. (7) fit the removal efficiency results well.

Performance of Individual Treatment Devices

The performance functions for the BaySaver model 1k are the results of testing at St. Anthony Falls Laboratory in 2005 and early 2006 (Figs. 3 and 4). Discharges tested were approximately 25, 50, 75, and 100% of the maximum treatment rate. One deviation from the field test method is that the BaySaver device was tested with a narrowly graded particle size distribution (F95), ranging from 50 to 300 μm, with a median particle diameter of approximately 120 μm. Some context for the interpretation of the parameter a and the exponent b is provided in Fig. 3. A broader view of overall performance is provided in Fig. 4 by plotting removal efficiency versus the log of Péclet number. In current installations, silts and clays are typically below a P of 0.1, where little removal occurs.

The fitted parameters for each of the performance functions, along with associated statistical measures describing the goodness of fit of each function, are provided in Table 1. Both the primary and total removal efficiency functions of the BaySaver device have a large initial slope (a), but a relatively slow transition (small value of b) to the R value at large P. At a P of 1, the removal efficiencies for the primary chamber and total device were 36 and 75%, respectively. The maximum removal approached 74% (primary) and 100% (total).

A modified version of this device was also tested, and the results are also shown in Figs. 3 and 4. For the second test, the size of the settling chamber manhole was increased from 1.22 m (4 ft) to 1.83 m (6 ft). The removal efficiencies from both tests fit a single function (Figs. 3 and 4) indicating that the Péclet number is a reasonable scaling parameter. The NSC of the fit was computed to be 0.99 (Table 1). Using the Hazen number instead of the Péclet number, the NSC of the best fit was computed to be 0.98.

The data and performance function for the Model 3 ecoStorm, tested at St. Anthony Falls Laboratory in the summer and fall of 2006, are shown in Fig. 5. The ecoStorm was tested under a wide range of discharges spanning from 15 to 160% of the maximum treatment rate. The ecoStorm contained only one settling chamber. The relatively low value of a is countered by a large value of b. Thus, at a P of 1, the removal efficiency is greater than 85%. The maximum removal approached 99%. The device height was modified to 80% of the original height using a temporary false floor to assess the scalability of the performance function (Mohseni and Fyten 2007). The results with the modified chamber dimensions are included in Fig. 5. The NSC of the fit was computed to be 0.96 (Table 1). Using the Hazen number instead of the Péclet number, the NSC of the best fit was computed to be 0.97.

The data and performance functions for the field-tested Environment21 V2B1 Model 4 are shown in Fig. 6. This device was installed in the summer of 2005. Discharges tested were approximately 0.017 m^3/s (0.6 cfs), 0.021 m^3/s (0.75 cfs), 0.030 m^3/s (1.05 cfs), and 0.040 m^3/s (1.4 cfs), which corresponded to 43, 53, 75, and 100% of the maximum treatment rate, respectively. The results are consistent with the expectation of better removal at higher Péclet number. If the results are extrapolated to low Péclet numbers, one would expect that the V2B1 would not be effective at removing finer particles such as silt and clay. This hypothesis was verified with two tests conducted with silt-sized particles, with a median particle diameter of approximately 45 μm. Tests with this particle size produced a Péclet number of 0.03, and a low removal efficiency. Total removal efficiencies approached 98% for large Péclet numbers, but only 74% for the primary settling chamber. At a P of 1, the removal efficiencies for the primary chamber and total device were 64 and 89%, respectively.

The data and performance functions for the field tested Vortechs Model 2000, installed in the fall of 2005, are shown in Fig. 7. Discharges tested were approximately 0.013 m^3/s (0.45 cfs), 0.017 m^3/s (0.6 cfs), 0.023 m^3/s (0.8 cfs), and 0.031 m^3/s (1.1 cfs), which corresponded to 41, 55, 73, and 100% of the maximum treatment rate, respectively. The value of b was relatively high, so the device had a rapid transition to the maximum removal efficiencies of 97% (primary) and 99% (total). At a P of 1, the removal efficiencies were 73% (primary) and 90% (total).

The data and performance function for the field-tested Stormceptor STC4800, installed in 1999 and retrofit in the summer of 2006, are shown in Fig. 8. Discharges processed by the Stormceptor were 0.021 m^3/s (0.75 cfs), 0.030 m^3/s (1.05 cfs), 0.042 m^3/s (1.5 cfs), and 0.051 m^3/s (1.8 cfs), which corresponded to 42, 58, 83, and 100% of the maximum treatment rate,

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respectively. This device has a relatively low value of a, but high values of b and R. Thus the removal efficiency of 60% at a P of 1 rapidly transitioned toward 98% at higher P. Some obvious differences exist between this plot and the others. The Péclet numbers generated during testing are larger, owing to the fact that each of the two length scales, h and d, are approximately double that of any other devices tested, resulting in a maximum Péclet number for the Stormceptor approximately four times larger than that for other devices.

Finally, data and performance functions for the field-tested CDS PMSU 20_15, installed in the spring of 2006, are shown in Fig. 9. Discharges processed by the CDS were 0.011 m^3/s (0.4 cfs), 0.014 m^3/s (0.5 cfs), 0.017 m^3/s (0.6 cfs), and 0.022 m^3/s (0.77 cfs), which corresponded to 52, 65, 78, and 100% of the maximum treatment rate, respectively. Bypassing of the internal weir did not occur until the discharge reached 0.022 m^3/s (0.77 cfs), but according to technicians at CDS Technologies, the unit was designed for a maximum treatment rate of 0.020 m^3/s (0.7 cfs). Thus, the tests at 0.022 m^3/s (0.77 cfs) represent an evaluation of discharge that is greater than the design treatment rate. At a P of 1, the fitted removal efficiency was 32% (primary) and 77% (total). The general trend of increasing removal efficiency by the primary (settling) chamber with an increasing Péclet number is observed, however, there is no obvious plateau in the primary chamber at Péclet numbers greater than about 2, while there is a plateau for the total performance of the device. The flow patterns inside the primary chamber of CDS are essentially the same as those observed in Environment21 and Vortechs 2000, and only the outflow is different. Therefore, it is very likely that by conducting a few more tests at lower flow rates and with larger particles, one could observe the plateau exhibited in other devices. The maximum removal approached 76% (primary) and 97% (total).

Discussion

The results of this research indicate that controlled field testing of hydrodynamic separators is a viable alternative to field monitoring. Field testing presents some site selection constraints that need to be overcome, as outlined in the "Site Selection" section. Similar to monitoring, controlled field testing requires working around the inconveniences of an in situ system, such as baseflow in the system, leaking chambers, challenging hydraulics, etc. Nevertheless, field testing offers potentially significant savings in time and cost to obtain information on treatment efficiencies of hydrodynamic separators. Most importantly, the advantages offered by controlled field testing in terms of accuracy and repeatability of suspended sediment removal capability cannot be understated.

The main finding of this study is that removal efficiency of a given hydrodynamic separator can be explained using a Péclet number, which accounts for particle settling and turbulent diffusion. The removal efficiency versus Péclet number relationship was maintained after changing the length scales of two of the devices tested. Dhamotharan et al. (1981) showed that in reservoirs, deposition becomes independent of the Péclet number when the dimensionless time is less than 0.2 or larger than 5. The residence time of hydrodynamic devices is very short, therefore, it was decided to compute the dimensionless time at $t=T_r$, i.e., the Hazen number. The Hazen number varied from 0.15 to 5.3 for all devices except for a number of tests done on Stormceptor and a couple of tests done on Environment21. For Stormceptor (Fig. 8), those tests resulted in very large Péclet numbers which are on the plateau of the performance function. For Environment21, those two tests were conducted using the silica sand with a median size of 45 μm, which resulted in a Hazen number less than 0.1 and very small Péclet numbers where the device removed little suspended sediment from storm water. Therefore, the results of this study are in agreement with the findings of Dhamotharan et al. (1981) and the performance of the devices tested indicate that the Péclet number is a suitable dimensionless number describing the behavior of these devices.

Many of the devices tested approach a plateau in removal efficiency at Péclet numbers of about 3, where further increases in the size of the device have a reduced impact on performance. Based on the performance functions fitted to the measurements the total removal efficiency is greater than 90% when Péclet number is larger than 3 for all devices tested. Thus, a P value of 3 may be a cost-effective target for sizing hydrodynamic separators. The removal efficiency of the primary settling chamber, however, is more variable among devices.

It should also be noted that the reported total removal efficiencies for some devices include removal by the floatables trap. Sediments captured by the floatables trap may be subject to scour at discharges above the design maximum treatment rate, with subsequent release of the resuspended sediments to downstream receiving waters.

The six devices tested effectively removed sand >250 μm and removed 30–70% of very fine sand (89–125 μm) from the runoff. Nevertheless, the field tests and the performance functions indicate that, as designed and sized, the devices will not remove much silt or clay. The nondimensional representation of the performance functions with Péclet number indicates that the product of h and d would need to be increased by one order of magnitude to remove an appreciable amount of silt from storm-water runoff over an equivalent range of treatment flow rate (Q). Finally, it may be inappropriate to make direct comparisons of the performance of individual devices tested in this work because the devices were designed and installed at different times and may represent different generations of underground sedimentation devices in this continually evolving field.

Application of Results

A performance function can be used as a tool to: (1) predict the expected suspended sediment removal of an existing underground device; or (2) select the size of a new underground device installation. The simplest approach for either case is to select a target particle size in the storm-water runoff, which fixes V_s. The more complete alternative is to use a particle size distribution, which results in a range of V_s values. Then, to predict the removal performance of a given device, the maximum discharge for the device is input as Q. Finally, the Péclet number is computed using V_s, Q, and the device dimensions and the removal efficiency is obtained from the device performance function. To determine device size for a new installation, a target particle size or particle size distribution (PSD) in the storm-water runoff must be selected. Then, the maximum discharge, Q, can be estimated from a design storm hydrograph for the watershed under consideration. Alternatively, the entire range of discharges for the design storm hydrograph can be applied assuming a fixed particle size or PSD. Finally, a suitable model size of the device, i.e., its length scales, h and d, can be determined from the Péclet number corresponding to the desired removal efficiency. The resulting design using the

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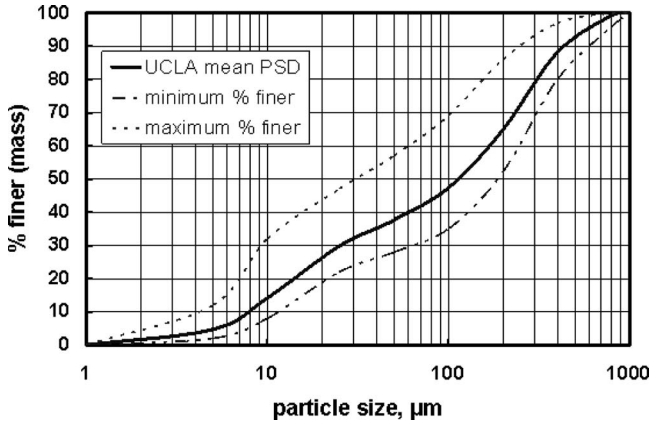

Fig. 10. Particle size distribution in storm-water runoff from urban freeway watershed, along with range of gradations measured in six runoff events (Li et al. 2005)

maximum discharge is conservative in that the lower discharges during storm events will result in greater P values and hence, greater removal efficiencies.

An example illustrating the use of the performance functions for predicting the suspended solids removal efficiency of a given device is provided below. In this example, the d_{50}, of a sample PSD obtained from urban roadway runoff (Li et al. 2005) was selected as the target particle size. The d_{50} from the PSD (Fig. 10) is approximately 120 μm, which produces a settling velocity of 0.008 m/s (0.027 ft/s), using Eq. (6) for water at 20°C and particle density $(\rho_p)=2.65$ g/cm^3. At a discharge of 0.051 m^3/s (1.8 cfs) from the watershed and the device dimensions $h=3.4$ m (11.2 ft) and $d=3.7$ m (12 ft), the computed P is 1.97. Using the performance function in Fig. 8, the predicted removal efficiency of the 120 μm particles is approximately 84%. When the entire particle size distribution in Fig. 10 is routed through the performance function in Fig. 8 at a constant concentration and a constant discharge of 0.051 m^3/s, the total removal efficiency is 57%.

Conclusions and Recommendations

Controlled field tests, conducted similar to those described herein, are a practical, robust, and accurate means of determining suspended sediment removal efficiency of hydrodynamic separators and a viable alternative to field monitoring. The main advantages of the field testing approach in comparison to monitoring are decreased time and improved accuracy.

A Péclet number, $\mathsf{P}=V_s hd/Q$ that combines two length scales (h and d), the particle settling velocity (V_s), and the influent discharge (Q), was developed and shown to be a useful parameter for fitting the sediment removal efficiency results for each storm-water treatment device. The resulting relationship between sediment removal efficiency and Péclet number is called a "performance function." Performance functions have been successfully established from the data collected for four devices in field tests, and two devices in laboratory tests.

The suspended sediment removal efficiencies for the six devices approached 0% for low Péclet numbers and approached 100% for high Péclet numbers. Based on the performance functions, the total removal efficiency of all devices tested is greater than 90% when the Péclet number is larger than 3. The removal efficiency of the primary settling chamber is more variable among devices. Tests on the scour that would occur at discharges above the maximum treatment rate have not been undertaken.

The Péclet number-based performance function is not only useful for predicting the performance of an underground device over a range of storm magnitude, sediment size, and sediment density but also it might be useful as a tool for sizing a new installation of that device. The field testing approach and the testing results described herein should be useful tools for consultants, manufacturers, local governments, and state agencies in selecting, sizing, and evaluating storm-water treatment technologies to protect water resources.

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Notation

The following symbols are used in this paper:

A = cross-sectional mixing area in primary settling chamber;
a = measure of initial slope of fitted function at $\mathsf{P}=0$;
b = measure of curvature in fitted function at proximity of intersection of asymptotes;
D = particle diameter;
D_t = turbulent diffusion coefficient;
d = diameter of primary settling chamber;
g = gravity constant;
h = settling depth of primary settling chamber;
m = number of observations in dataset;
P = Péclet number, independent dimensionless variable in performance function;
p = number of parameters in fitted function;
Q = discharge;

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R = asymptotic removal as P approaches infinity;
T_r = residence time;
t = time;
U = flow velocity;
V_s = particle settling velocity;
η = removal efficiency;
η_i = fitted removal data point for given P;
$\bar{\eta}_{\text{meas}}$ = mean measured removal of dataset;
$\eta_{\text{meas } i}$ = measured removal data point for given P
ν = kinematic viscosity;
ρ = fluid density; and
ρ_s = particle density.

References

Andoh, R. Y. G., and Saul, A. J. (2003). "The use of hydrodynamic vortex separators and screening systems to improve water quality." *Water Sci. Technol.*, 47(4), 175–183.

Bloodgood, D. E., Boegly, W. J., and Smith, C. E. (1956). "Sedimentation studies." *Proc. Am. Soc. Civil Engrg.*, 82(SA5), 90–93.

Bonestroo, Rosene, Anderlik and Associates, Inc. (2002). *Walker Avenue V2B1 performance*, Roseville, Minn.

Bonestroo, Rosene, Anderlik and Associates, Inc. (2003). *Walker Avenue V2B1 2001–2002 performance assessment*, Roseville, Minn.

Carlson, L., Mohseni, O., Stefan, H., and Lueker, M. (2006). "Performance evaluation of the BaySaver stormwater separation system." *St Anthony Falls Laboratory Project Rep. No. 472*, Univ. of Minnesota, Minneapolis.

Cheng, N. S. (1997). "A simplified settling velocity formula for sediment particle." *J. Hydraul. Eng.*, 123(2), 149–152.

Dhamotharan, S., Gulliver, J. S., and Stefan, H. G. (1981). "Unsteady one-dimensional settling of suspended sediment." *Water Resour. Res.*, 17(4), 1125–1132.

England, G. (2001). "Success stories of Brevard County, Florida stormwater utility." *J. Water Resour. Plann. Manage.*, 127(3), 180–185.

Environmental Technology Verification (ETV). (2005a). *ETV Rep.: BaySaver Separation System, Model 10k*, NSF International, Ann Arbor, Mich.

Environmental Technology Verification (ETV). (2005b). *ETV Rep.: Vortechs System, Model 1000*, NSF International, Ann Arbor, Mich.

Fassman, E. A. (2006). "Improving effectiveness and evaluation techniques of stormwater best management practices." *J. Environ. Sci. Health Part A (Special Issue)*, A41(7), 1247–1256.

Fentie, B., Yu, B., and Rose., C. W. (2004). "Comparison of seven particle settling velocity formulae for erosion modeling." *Proc., 13th Int. Soil Conservation Organisation Conference*, ISCO, Brisbane, Australia, 1–3.

Gulliver, J. S., and Anderson, J. L. (2008). *Assessment of stormwater best management practices*, Water Resources Center, Univ. of Minnesota, Minneapolis, ⟨http://wrc.umn.edu/outreach/stormwater/bmpassessment/assessmentmanual/pdfs/asbmpcover.pdf⟩.

Li, Y., Lau, S.-N., Kayhanian, M., and Stenstrom, M. K. (2005). "Particle size distribution in highway runoff." *J. Environ. Eng.*, 131(9), 1267–1276.

Mohseni, O., and Fyten, A. (2007). "Performance assessment of ecoStorm™ for removing suspended sediments from stormwater." *St Anthony Falls Laboratory Project Rep. No. 495A*, Univ. of Minnesota, Minneapolis.

Poncet, S., Shiestel, R., and Monchaux, R. (2008). "Turbulence modeling of von Karman flows: Viscous and inertial stirring." *Int. J. Heat Fluid Flow*, 29, 62–74.

Roesner, L. A., Pruden, A., and Kidner, E. M. (2007). *Improved Protocol for Classification and Analysis of Stormwater-Borne Solids, Water Environment Research Foundation (WERF) Rep. 04-SW-4*.

Roseen, R. M., Ballestero, T. P., Houle, J. J., and Avelleneda, P. (2005). "Normalized technology verification of structural BMPs, low impact development (LID) designs, and manufactured BMPs." *Proc., Watershed Management Symposium*, ASCE, Reston, Va., 135–146.

Stokes, G. G. (1851). "On the effect of the internal friction of fluids on the motion of pendulums." *Trans. Cambridge Philos. Soc.*, 9, 6–106.

Strynchuk, J., Royal, J., and England, G. (2000). *Continuous deflective separation (CDS) unit for sediment control in Brevard County, Florida*, Brevard County Surface Water Improvement, Viera, Fla., *Proc., U.S. EPA National Conf. on Tools for Urban water Resources Management and Protection*, Chicago.

Waschbusch, R. J. (1999). "Evaluation of the effectiveness of an urban stormwater treatment unit in Madison, Wisconsin, 1996-97." *U.S.G.S. Water-Resources Investigations Rep. No. 99-4195*, Middleton, Wis.

Weiss, P., Gulliver, J. S., Erickson, A. J. (2007). "Cost and pollutant removal of storm-water treatment practices." *J. Water Resour. Plann. Manage.*, 133(3), 218–229.

Wilson, M., Gulliver, J. S., Mohseni, O., and Hozalski, R. M. (2007). "Performance assessment of underground stormwater treatment devices." *St Anthony Falls Laboratory Project Rep. No. 494*, Univ. of Minnesota, Minneapolis.

Yu, S. L., and Stopinski, M. D. (2001). "Testing of ultra-urban stormwater best management practices." *VTRC 01-R7*, Virginia Transportation Research Council, Charlottesville, Va.

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