Title
Evaluating hydrodynamic separators

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EVALUATING HYDRODYNAMIC SEPARATORS

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Abstract: With the advent of both federal and state storm water management regulations, state and municipal highway departments must consider a broad array of Best Management Practices (BMPs) for meeting storm water treatment objectives for both new road construction and roadway-improvement projects. In recent years, a number of manufacturers have entered the marketplace with a variety of proprietary devices for treating storm water. One of the most common types of devices is the hydrodynamic separator (also referred to as innovative water-quality inlet, particle separator, or swirl concentrator). Evaluating these technologies for application in the highway setting requires consideration of a number of factors relative to these devices' treatment performance, inspection and maintenance requirements, and installation and operating costs.

The Massachusetts Highway Department (MassHighway), under a cooperative agreement with the U.S. Geological Survey, recently conducted a detailed field study of water-quality inlets (WQIs) located on the Southeast Expressway in Boston. That study provided valuable lessons regarding storm water sampling protocols and data analyses used to evaluate hydrodynamic separators. (These products generally consist of refinements in the design of the standard WQI.) This paper discusses the lessons learned and offers recommendations for evaluating the performance of proprietary designs within this class of BMP.

A variety of findings came out of the Southeast Expressway (SEE) Study that should be considered when evaluating "hydrodynamic separators." The study evaluated two separate WQIs, each of which received storm water discharges from deep-sump (four-foot) catch basins. It was found that the one continuously monitored deep-sump catch basin had an annual suspended sediment removal efficiency (SSRE) of 39%, whereas the annual average SSRE for two WQIs was 32% (based on the remaining load after flow through the catch basins).

Captured sediments were comprised predominantly of sand-sized particles. Residence time was the primary factor controlling the SSRE. To a lesser degree, antecedent conditions and volume of rain also affected the SSRE. Other findings were that metals and nutrients tend to concentrate on particles smaller than sand and that sediment resuspension occurred in both the catch basin and the WQIs.

In addition to the limited suspended sediment removal efficiency of the WQIs, the SEE Study found that the WQIs were ineffective at removing soluble pollutants, fine particles, floatable solids (debris and litter), and oils and grease. Prior to installing hydrodynamic separators, the operators of drainage systems and environmental regulators should obtain scientifically supportable data on the field performance of hydrodynamic separators. Based on the findings and experience obtained over the course of the SEE Study, MassHighway recommends the following key elements for validating the field performance of hydrodynamic separators:

- Collect field data that is both representative of the range of rainfall events and that is applicable to the conditions (e.g., ambient particle-size distributions) under which the BMP likely will be installed;
- When sampling, differentiate between the effects of "supernatant displacement" and active-particle removal by the separator (i.e., "hydrostatic" versus "hydrodynamic" separation). This requires flow-proportional sampling throughout each storm event;
- Account for antecedent conditions, bypass flows, and resuspension when calculating the SSRE;
- Sample a sufficient number of storms not only to obtain statistically significant data, but to include the full range of operating conditions to which the device will be subject;
- Analyze treatment performance by "Summation of Loads," which is the preferable method for accuracy and quality control;
- Sample storms sequentially, to allow for a mass-balance calculation;
- Include measurements of particle-size distribution in the sampling and analysis program to assess the removal efficiency of Total Suspended Solids (or, preferably, Suspended Sediment Concentration), as well as that of other contaminants associated with various particle-size fractions.

Hydrodynamic separators should also be evaluated relative to other potential limitations. For example, if these underground structures function to contain fuel spills, then they have the potential to create an explosion hazard. In addition, according to the literature, hydrodynamic separators also may create conditions suitable for breeding mosquitoes and bacteria or conditions that result in liberating nutrients and metals from captured sediments.

Based on its evaluation of WQIs and on the literature MassHighway has reviewed to date, further scientifically sound evaluation is necessary to demonstrate the effectiveness of hydrodynamic separators as primary-treatment devices. Although MassHighway has documented the limitations of the WQIs used along the Southeast Expressway (e.g., low overall removal of suspended sediment, particularly fine particles), hydrodynamic separators may be appropriate for pre-treatment and retrofit applications where sand is the target contaminant and where the operator has adequate maintenance capabilities.

Abbreviations

BMP: Best Management Practice

DOT: Department of Transportation

EMC: Event Mean Concentration

EPA: Environmental Protection Agency
PSD: Particle-Size Distribution
SEE: Southeast Expressway
SSC: Suspended Sediment Concentration
SSRE: Suspended Sediment Removal Efficiency
TSS: Total Suspended Solids
USGS: U. S. Geological Survey
WQI: Water-Quality Inlet

Introduction

The focus of this paper will be on a specific category of storm water Best Management Practices (BMPs) known as hydrodynamic separators (also known as innovative water-quality inlets, particle separators, or swirl concentrators). Hydrodynamic separators are flow-through structures with a separation unit to remove sediments and other pollutants. The separation of sediments depends primarily on settling and may be enhanced by the swirling action of flowing water and/or by modifying the flow path with a system of baffles. A number of devices accumulate and store settled solids in a manner designed to minimize resuspension of previously captured particulates.

In recent years, hydrodynamic separators have become increasingly common. MassHighway has considered this class of BMP for application in a number of settings and has had experience in the application and evaluation of these and similar devices. Based on this experience, MassHighway has identified a number of issues that should be considered by drainage-system operators and environmental regulators when assessing the performance of these devices and ultimately choosing the most cost-effective BMP (including both structural and non-structural methods) for treating storm water.

BMP Performance Evaluation

USGS-MassHighway study: evaluation of BMPs along the Southeast Expressway
During 1999-2000, MassHighway conducted a field study with the U.S. Geological Survey (USGS) to evaluate the treatment effectiveness of a deep-sump catch basin and two conventional water-quality inlets (WQIs) located along the Southeast Expressway (I-93) in Boston. The objectives of the Southeast Expressway (SEE) Study were to characterize the concentrations and loads of suspended sediment during a multitude of sequential storm events and to define the suspended sediment removal efficiency of two 1,500 gallon WQIs and one deep-sump catch basin (Smith 2002).

Water-quality analyses included metals, nutrients, organics, bacteria, and suspended sediment along with particle size. Two WQIs were sampled, using automated samplers to capture storm water events continuously—one for 10 months and the other for 14 months—for a total of 133 storms. A mass balance was computed based on measurements of the material captured (i.e., the measured inlet loading plus the mass of material captured equaled the measured outlet loading). Removal efficiencies were estimated using the “summation of loads” method.

Figure 1 presents a schematic diagram of the drainage BMPs evaluated by the SEE Study. As is typical of hydrodynamic separators, each had a bypass weir in order to minimize high velocities and the resuspension of sediment from within the device.

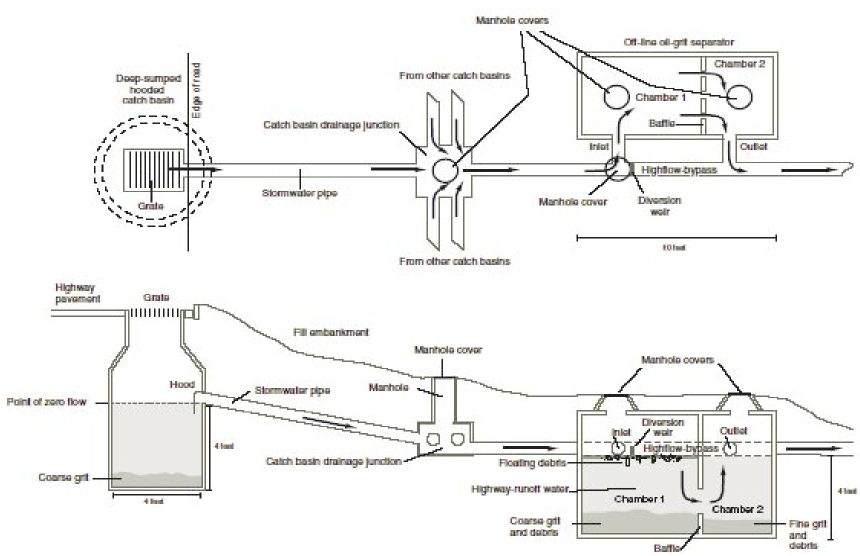

Figure 1. Schematic section of a deep-sump hooded catch basin and a 1,500-gallon off-line water-quality inlet.

Summary of Findings

1. The suspended sediment removal efficiency (SSRE) of the deep-sump hooded catch basin was found to be 39% over a 14-month period. The WQIs achieved a SSRE of 35 and 28%, for an average of 32%. However, if the removal efficiency of the catch basin is factored into this BMP "treatment train," then the SSRE of the WQIs averaged only 18% of the influent's *total* suspended sediment load.
2. WQIs and the deep-sump hooded catch basin captured predominantly sand-sized particles (i.e., greater than 0.062 mm). This finding has been attributed to the short residence times within the WQIs (fine particles have long settling times). The average retention times for the 1,500 gallon WQIs ranged from one hour to less than a minute. Therefore, residence time was the primary factor controlling suspended sediment removal efficiency.
3. Other factors affecting SSRE included: antecedent conditions (i.e., length of time between storms, which in turn affects particle settling time), rainfall intensity (i.e., if high, then large particles became dislodged and entered the runoff flows), and the volume of rainfall. The SEE Study found that for small events (< 0.2 inches of rain, where the total rainfall volume was less than 1,500 gallons) and also when there had been no rain for at least five days, that the WQIs removed more than 80% suspended sediment. When the antecedent dry period was only two days, then less than 40% of suspended sediment was removed. These observations again demonstrate the importance of residence time between storms.
4. Sediment resuspension occurred in both the catch basin and the WQIs, which reduced their sediment-removal effectiveness. Sediment capture also was reduced when high flows bypassed the WQIs. Resuspension and bypass flows each accounted for a similar level of total sediment loading: approximately 2 to 3%.
5. Metals and nutrients tend to concentrate on particles smaller than sand (<0.062 mm), in part due to their greater surface area (per unit weight). The WQIs were found to remove only 5 to 15% of most metals and nutrients from the influent.
6. The WQIs also were ineffective at removing dissolved pollutants, particle sizes finer than sand, floatable solids, and oils and grease (as well as total petroleum hydrocarbons).

BMP evaluation by manufacturers

BMP manufacturers offer a variety of supporting documentation regarding the treatment effectiveness of their devices. However, inconsistent sampling methods, lack of associated design information, and different reporting protocols make comparisons between devices difficult (Federal Highway Administration 2001). For example, individual studies often include the analysis of different constituents and do not use the same methods for data collection and analysis, and do not report equivalent information on BMP design and flow characteristics. This results in a range of BMP "efficiencies" reported in manufacturers' literature. In addition, the effectiveness of a hydrodynamic separator is oftentimes based on a low number of select storms or on limited sampling within each storm event. Thus, the available data for the various hydrodynamic separators do not appear to allow for comparison between other similar devices or other types of BMPs.

The SEE Study provided valuable experience in sampling and analysis methodology for a device that has a limited residence time. The following discussion highlights several sampling and analysis protocols that should be applied to future field-performance studies of other hydrodynamic separators in order to provide valid and comparable scientific basis for evaluating these devices' pollutant removal performance.

Storm Water Data—Quality Control and Analysis

Representative storms

The monitoring requirements of the National Pollutant Discharge Elimination System (for industrial activities) identify key characteristics that result in a "representative storm." According to these requirements, the total precipitation and duration of a "representative storm" should be within 50% of the average event for a given location, produce equal to or greater than 0.1 inches of precipitation, and have an antecedent dry period (i.e., less than 0.1 inches precipitation) of at least 72 hours (GeoSyntec et al. 2002). This sets up a worst-case scenario, where the runoff has a relatively high concentration of pollutants that have built up during the antecedent dry period. Unfortunately this sampling criterion can lead to bias in calculating the removal efficiency of storm water BMPs (as described further below, Displacement versus Treatment).

For BMP monitoring purposes, strict adherence to these criteria is not necessary and likely not desirable because there is no truly "representative storm." It is preferred that monitoring be performed under a wide variety of conditions and storms such that the storm water data represents the annual range of rainfall events (GeoSyntec et al. 2002). Different site conditions, such as seasonality, temperature, ambient particle sizes, runoff rates, precipitation volumes, durations, and intensities, all contribute to "make each storm a unique event" (Church et al. 1999). Therefore, all these variations should be considered when determining the period over which the monitoring program will be run, and are key to interpreting BMP monitoring data and predicting effectiveness (Muthukrishnan et al. 2004).

WQIs are particularly sensitive to variations in influent water quantity and quality, due to their small volumes and the relatively short retention times during flow events. Therefore, when evaluating any hydrodynamic separator, the sampling program should include an extended and continuous period of study covering the full range of events that would affect the unit's operation. For example, it was found during the SEE Study that about 90% of the sediment loading was carried in 10% of the storm events. Figure 2 illustrates the inlet and outlet sediment loads and how the SSREs varied from storm to storm, and were sometimes below zero when effluent loads exceeded influent loads (representing sediment resuspension, further discussed below).

In addition, any BMP monitoring programs also should provide a description of the statistical error and confidence of its findings. Obtaining statistically valid results requires a sufficient number of storms sampled to draw valid conclusions at high levels of confidence (Muthukrishnan et al. 2004). As described above, the SEE Study monitored a total of 133 storms—74 and 59, respectively, at two separate sites. Nonetheless, the USGS corroborated that a relatively high statistical confidence could be derived from just 15 to 20 sequential and continuously monitored storms. For example, by calculating the SSRE of 20 storms, a BMP monitoring program could predict (with 89% confidence) that the SSRE of the BMP will be lower than the minimum SSRE (of the 20 events) less than 10% of the time for all future storm events. For 15 and 10 storms, the confidence drops to 79% and 65%, respectively. Still, although sampling 15-20 sequential storms allows for a mass-balance computation, it may not be adequate for deriving contaminant loading estimates and average BMP performance on an annual basis because of the variability in hydrologic factors in the Northeast U.S.

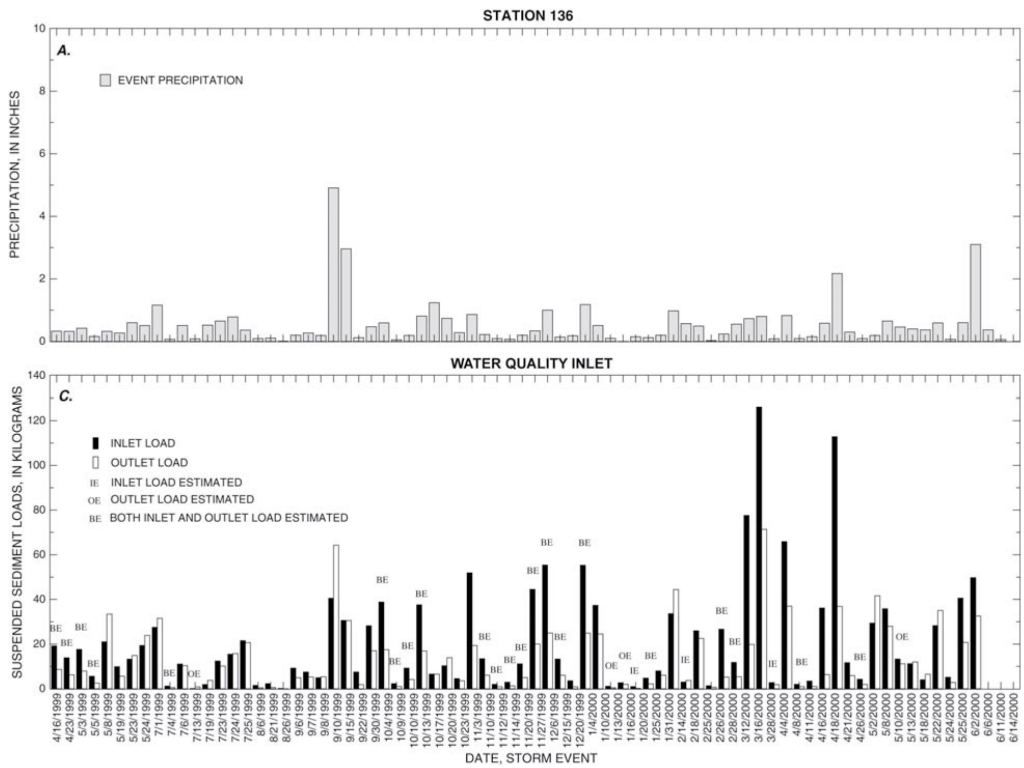

Figure 2. Precipitation and suspended sediment loading for long-term sampling period at a WQI.

Sampling frequency
The SEE Study measured the concentrations of various contaminants in the influent and effluent flows, which were observed to vary widely during the events sampled. If influent and effluent water quality were sampled only once at random during a storm (i.e., grab sample), or even at a preset time interval following the onset of a storm, the variations in water quality over the course of the storms could not have been measured. This would have been a significant source of error in calculating sediment loading, and therefore the treatment performance of the WQIs.

In addition, the SEE Study employed automatic sampling equipment to collect flow-proportional samples over the entire duration of each storm. The samples were analyzed to accurately calculate sediment loading and capture throughout the storm. This sampling methodology should always be used to evaluate hydrodynamic separators so as to account for all the variability in storm water quality and treatment performance.

Applicability of BMP performance to other sites
Site conditions can vary significantly from one location to another, which can affect storm water treatment performance by BMPs. Geographic variables such as climate, geology, hydrology, land use, and local water quality make each site unique (Berg 2002). Therefore, field studies should take place in settings that are representative of those where the respective BMP will most likely be used. This will increase the likelihood that the performance results will be authentically transferable to similar sites.

Examples of particular test sites of interest include a DPW maintenance yard with outdoor storage of sand, a well-maintained parking lot, a road with an eroding edge of pavement, a high-volume expressway, and a local service road. Note, however, how each of these sites may have varying types and volumes of sediment loading and other pollutants and that the treatment-evaluation results for a device at one type of site may not be readily transferable to another type of site (at least not without careful study design).

BMP performance historically has been evaluated in the context of a particular device being a stand-alone system. This probably does not reflect actual applications, however, because storm water BMPs almost always are used in conjunction with various upstream controls, most typically catch basins. According to the SEE Study, it was found that the upstream catch basins captured the bulk of the drainage area's coarse sediments. Specifically, if the WQIs were used as stand-alone BMPs, they would have captured up to 57% of total suspended sediment load. However, since the upstream catch basins captured 39%, the WQIs captured only 18% of the total annual sediment load. Therefore, to make findings comparable, all BMP evaluation studies should be designed in a way to correctly account for how the BMP performs when pre-treatment occurs upstream (e.g., through the use of catch basins). If the effects of pre-treatment are not incorporated into the BMP findings, then the calculations for total removal efficiencies will be incorrect.

Another variable that affects the comparability of BMP studies is the size of the area that drains to, and the flow rates that pass through, the BMP (particularly hydrodynamic separators). A smaller drainage area implies smaller storm flows, greater average device-residence times, and a likely reduction in rates of resuspension. All of these effects could result in a higher treatment efficiency for the hydrodynamic separator. The field study of a particular BMP should therefore be designed to reflect the drainage areas, flow rates, volumes, and other conditions that characterize the full range of circumstances anticipated for actual future application of the device.

Bypass flows and resuspension

Early discussions of storm water treatment theorized that if a storm water BMP is designed to treat the first 0.5 inch or inch of rainfall, then the majority of pollutants will be captured. Under this scenario, runoff volume in excess of this "first-flush volume" might be allowed to bypass the BMP untreated, under the assumption that the water is relatively clean (Berg 2002). However, for certain pollutants, such as nitrate, ortho-phosphate, bacteria, and sediment, the first-flush theory is weak or absent altogether (Schueler 1994). One major criticism of the first-flush theory is that it overlooks the effects of rainfall intensity. High-velocity flows resulting from high-intensity rainfall events are capable of transporting larger sediment particles and debris that is not often mobilized by more frequent, but less intense, storm events (Berg 2002).

Regardless, bypasses (such as a control weir within the drainage structure located just upstream of the BMP) are often considered necessary to diminish high flows that would otherwise move through storm water BMPs, especially hydrodynamic separators, and resuspend captured material. Bypasses can have a measurable effect on the ability of a BMP to remove constituents and, if set too low, may reduce the overall capture efficiency of the system as a whole. On the other hand, providing insufficient high-flow bypass risks the potential for resuspension of captured sediments and associated pollutants from within a separator. Minimizing resuspension is important because of the propensity of finer particles, which are associated with relatively higher concentrations of contaminants, to become resuspended selectively.

During the SEE Study, resuspension was observed within the WQIs during storm events with high flows and/or rainfall intensities (as depicted in figure 2 above). As illustrated in table 1, the amount of sediment resuspended from the WQIs was about 8% of that captured (2 to 3% of the total sediment loading at the drainage-outfall pipe). Coincidentally, the sediment load that bypassed the WQIs represented about 2 to 3% of the total loading.

Table 1. Conditions and frequency of resuspension and bypass

Description	Station 136 WQI	Station 739 WQI
Range of flows when resuspension was observed	0.46 to 0.97 cfs	0.41 to 2.81 cfs
Range of maximum 5-minute rain intensities during these storms	0.04 to 0.23 in	0.04 to 0.18 in
Number of events exceeding resuspending flows and intensities	33 (of 74)	22 (of 59)
Percentage of captured SSC resuspended	8%	8%
Percentage of total SSC load resuspended	2.8%	2.2%
Percentage of total SSC load bypassed	3%	2%

Disregarding bypass flows when evaluating BMP performance will result in misleading conclusions (Muthukrishnan et al. 2004). Comprehensive inflow and outflow measurements should be used in calculating the mass balance of contaminant loading, which includes the loading in bypass flows. This mass-balance calculation will provide the most accurate estimation of the BMP's overall efficiency.

Displacement versus treatment
As discussed above, the volume of storm water passing through the separator is a critical parameter in estimating the performance of hydrodynamic separators and differentiating between active contaminant removal and hydrostatic settling prior to the storm. For this reason, evaluations should avoid the use of random sampling or single-event sampling at a fixed time period of the storm. Flow-proportional sampling should be conducted over the full duration of each event (as well as over a full range of events) to account for the wide variability of influent and effluent water quality.

This potential source of bias was observed in the SEE Study when the WQI influent and effluent were sampled at the initial onset of a storm event. After the suspended sediment in the WQI had settled over the course of several days, the incoming turbid storm water pushed the clarified water out. The resulting effluent was cleaner than the influent because of "displacement" and not because of the dynamic removal of sediment within the WQI. In fact, in almost every case, as samples were taken later into the storms, there was much less difference in the suspended sediment concentrations between the influent and effluent samples.

In addition, assessing the performance of hydrodynamic separators based solely on very small rainfall events can lead to erroneous findings because of the "displacement" phenomenon. When a storm's volume (to the device) is less than device volume, the monitored effluent will reflect the storm water that had been stored from the previous event, rather than from the event under study. This would not represent the "flow through" operating characteristics of the device and could bias the estimate of overall performance. This bias can be overcome by monitoring a full range of storm events over an extended period and by taking flow-proportional samples throughout each event.

Laboratory partitioning error—SSC versus TSS
There currently is debate over the most appropriate analytical method for measuring the concentration of solids in storm water samples. The Total Suspended Solids (TSS) analysis requires extracting an aliquot from the original sample, which is then analyzed to determine the sediment concentration, whereas the Suspended Sediment Concentration (SSC) method uses the entire sample for the analysis. Although TSS has been widely used as a parameter in water-quality analyses (dating back to the 1970s and 1980s in the wastewater-treatment industry), the SSC method ensures that all material present in the sample is represented in the results.

In a study by the USGS, it was determined that in samples containing 25% or more of sand-sized particles, the TSS method consistently under-reported sediment concentrations when compared to the corresponding SSC samples. Because of its high settling velocity, sand-sized material is often under-represented in the aliquot drawn for the TSS analysis (Gray et al. 2000). Thus a new measurement of sediments, SSC, was developed and is now a standard water-quality analysis for the USGS (GeoSyntec et al. 2002). This method has been proven to measure sediment loads more accurately, and therefore BMP removal efficiencies (Berg 2002).

Since the SSC test is biased toward heavier particle sizes, TSS will provide a much more conservative measure of BMP performance. Therefore, it can be assumed that the average SSRE of 32% would have been even lower if the SEE Study had measured for TSS rather than SSC.

BMP efficiency computation
A number of different methods can be used to estimate the efficiency of BMPs. The most common method is the Efficiency Ratio method (GeoSyntec et al. 2002). The SEE Study used the summation of loads method, which was determined to be more appropriate for the evaluation of sediment removal efficiency of the WQIs. Based on the findings of this study, MassHighway recommends that this approach be used for evaluating the performance of other hydrodynamic separators.

Efficiency Ratio Method
The "efficiency ratio" is an estimate of the average event mean concentration (EMC) of pollutants over a given time period. EMCs are determined from flow-weighted composite samples in the field or derived from discrete samples. The method weights EMCs from all storms equally, regardless of the volume of the storm or the concentration of the parameter under study. The method is most useful where loads are directly proportional to storm volume.

Summation of Loads Method
The "summation of loads" method estimates efficiency based on the ratio of the sum of all influent loads to the sum of all effluent loads. The method assumes that the removal of material over the entire period of analysis is most relevant. The method also assumes that monitoring data are sufficient to represent the actual entire volume of loads into and out of the BMP under study for a long enough period to account for temporary storage and export of the study parameter.

In the SEE Study, where there was an extensive data set (based on 133 storm events), the summation of loads method was used because it accounted for the wide variation of concentrations over the course of storm events and among storm events, as well as the temporary storage and export of sediment from the WQIs. Further, the difference between inlet and outlet loads were directly estimated from this method (i.e., a mass balance could be determined) and compared with field measurements of sediment accumulation in the WQIs. This provided an ideal method for corroborating the test results.

By sampling every sequential storm throughout the SEE Study and then measuring total mass of sediment captured within the WQIs at the end of the study, a critical element of quality assurance was added to the data. This technique clearly showed the limitations of the WQIs in capturing sediment particles smaller than 62 μm and also was used to develop an accurate annual SSRE for these devices.

It also was found that the overall treatment efficiency of a BMP is a more meaningful measure than the average efficiency. The Massachusetts Department of Environmental Protection's Storm Water Management Policy requires that storm water management systems remove 80% of TSS on an average annual basis. Given this requirement and based on the experience from this study, the most appropriate measure of BMP effectiveness for long-term sediment removal is the summation of TSS (i.e., SSC) loads, provided that the storms sampled are generally representative of Massachusetts' typical storm distribution.

Particle-size distribution

The SEE Study indicated that residence time was a key factor in the sediment removal efficiency of the WQI. This conclusion was expected, given that the device depends on settling as its primary treatment process. Since the performance of a hydrodynamic separator is particularly sensitive to particle size and specific gravity and given the short residence time of most storm flows within such a device, any suspended sediment removal claim should include the particle sizes associated with the stated removal rates. Washington's guidance for evaluating innovative storm water BMPs provides a good example of the method for qualifying sediment removal rates (Washington State Department of Ecology 2004).

When BMPs are evaluated under laboratory conditions to determine their suspended sediment removal rates, the use of an appropriate particle-size distribution (PSD) representative of storm water becomes a pivotal component of the study. But without a standardized definition for PSD in "typical urban runoff," the TSS removal rate claims made by various manufacturers may not be comparable to one another. Particle-size determinations are especially important when testing the effectiveness of hydrodynamic separators because the larger the average particle size used for evaluation, the higher the treatment efficiency.

To address this issue, it is recommended that all BMP evaluations address removal rates by particle size, and that the particle-size fractions should comprise a standardized distribution established by the U.S. Environmental Protection Agency (Driscoll et al. 1986). The EPA report, based on an analysis of the National Urban Runoff Program data, presents a typical settling-velocity distribution for sediment found in urban runoff. Converting the settling-velocity distribution to particle sizes (using Stoke's Law and assuming a specific gravity of 2.65) shows that 90% of sediment particles in storm water are smaller than 69 ?m and only 20% of particles are larger than 40 μm (the size of very fine sand).

Since larger particle sizes settle more quickly than smaller ones (i.e., greater settling velocities), they are easier to remove from storm water. Therefore, the sediment removal performance of a BMP is highly dependent on the PSD. For example, several performance studies of hydrodynamic separators have been conducted in the upper Midwest and Northeast where deicing sand is commonly used. The sand, washed off during spring and summer storms, skewed the PSD to larger sizes not commonly found in the storm water that occurs in other parts of the country. Consequently, a lower level of efficiency may be observed if the same BMP is installed in areas where deicing sand is used less or not at all (California Stormwater Quality Association 2003).

The importance of the PSD in storm water was demonstrated in the SEE Study, where particle sizes in the sand range generally were not mobilized under low-flow conditions, but were under high flows. Hence, the WQIs were often most effective during the larger storms because there were more sand-sized particles in the storm water flows to remove.

It was estimated that throughout the SSE Study, more than half of the total sediment loads contained in the storm water fell below the 50-μm particle size range. Hence, it is unlikely that the WQIs could achieve 80% TSS removal when they are virtually incapable of capturing particles less than 50 μm in size. In addition, since pollutants have a higher affinity for absorption to finer sediment due to the fine particles' large surface area per unit volume (Horowitz and Elrick 1987), WQIs are presumed to also have low removal efficiencies for pollutants.

Other performance factors of concern

This paper has addressed the evaluation of WQIs in particular and future assessment of hydrodynamic separators primarily with respect to treatment removal effectiveness of suspended sediment. However, there are a number of other performance factors that must eventually be addressed to document the effectiveness of this class of storm water BMP. Some (but not all) of these factors were considered in the SEE Study, but all warrant further analysis by future research. These factors include:

1. Removal of dissolved pollutants and fine particles

   Little information is available for hydrodynamic separators treating pollutants other than suspended solids. As was found in the SEE Study, pollutants such as nutrients and metals, which adhere to fine particulates, as well as dissolved solids, were not significantly removed by the WQI device. Moreover, heavy storms may cause mixing and subsequent resuspension of any captured fine particles. More information is needed on hydrodynamic separators' ability to remove both fine particles and dissolved pollutants.

2. Removal of oil and grease

   Oil and grease in storm water typically are in the range of 5-10 mg/l. There is no comparative data that these units are capable of trapping oil and grease. The Utah Department of Transportation (DOT) does not recommend that hydrodynamic separators be used for treating and/or reducing oil and grease concentrations in typical urban storm water runoff for two reasons: by the time the oil reaches the device, it will have adhered to sediment and/or will have emulsified in the runoff, making it too difficult to separate. Further, oil and grease exist in very low concentrations in storm water, making it very difficult for these devices to treat them to even lower levels. Nonetheless, the Utah DOT will consider these systems for capturing oil and grease in high-loading areas ("hot spots") (Nichols et al. 2005).

   Silverman and Stenstrom (1989) also acknowledge the relative ineffectiveness of hydrodynamic separators in capturing oil and grease. They cite that 40% to 60% of oil and grease associated with urban runoff are in a dissolved or colloidal state. Thus, baffled BMPs that are designed to separate free-floating oil and grease may not provide effective treatment for this pollutant.

3. Removal of floatable solids

   During the course of the SEE Study, it was found that floatable debris was readily discharged from the WQIs. These devices might be more effective at floatable-solids removal if cleaned regularly (e.g., monthly), before the floatables become neutral-buoyant and flush out of the WQI. General performance of hydrodynamic separators for floatable-solids removal appears to require further study.

4. Containment of hazardous spills

   Spill containment should be considered carefully in coordination with local fire department personnel (and/or other "first spill response" entity) before installing a hydrodynamic separator. For example, trapping a large quantity of spilled gasoline in an underground structure may constitute a safety hazard that could outweigh the apparent benefits of "containment." MassHighway is not aware of studies that have addressed this concern.

5. Incubation of bacteria

   With a nutrient-rich medium, relatively stable temperatures, and a lack of UV light, hydrodynamic separators may breed bacteria. It is documented that storm-drain sediments can function as a reservoir of Fecal Coliform and Fecal Streptococci bacteria under warm conditions. This implies that displacement of collected storm water may release bacteria into the receiving water bodies (Marino and Gannon 1991). MassHighway is not aware of any studies that specifically address the potential for bacterial growth and export associated with this class of BMP.

6. Potential breeding habitat for mosquitoes

   An issue associated with storm water management that is receiving more and more attention is the potential public-health risk created by the use of certain BMPs. If not designed and managed properly, they can provide habitat conditions suitable for the propagation of mosquitoes. This is an issue of prime concern because of the existing and widespread presence of endemic vector-borne diseases (e.g., West Nile virus, eastern equine encephalitis). Statistically, as vector populations increase, so does the risk of disease transmission (Metzger 2003, Metzger et al. 2002).

   In 1998, the California Department of Health Service's Vector-Borne Disease Section, in cooperation with the California Department of Transportation, conducted a two-year study of vector production associated with the 37 operational storm water BMP structures in southern California. The study found that a variety of vector species, particularly mosquitoes, utilize the habitats created by storm water BMP structures throughout the U.S. With easy access, no predators, and constant water levels, mosquitoes can easily propagate within hydrodynamic separators.

7. Liberation of metals and nutrients

   Due to the relatively quiescent conditions inside the separators, there is little oxygen exchange and the material captured within the sump of the device can develop conditions with low dissolved oxygen (DO). During periods of low DO concentrations, metals and nutrients adsorbed to sediments can become desorbed and dissolve into solution (Breault and Granato 2000, Rushton 1998). This means that storms accompanying this process would displace the captured storm water containing these dissolved nutrients and metal ions. Further analysis of this class of BMPs is warranted to characterize their effects on the release of metals and nutrients from captured sediments into the water column.

8. Operation and maintenance considerations

   Regular maintenance is critical to the proper function of storm water BMPS. Hydrodynamic separators pose particular requirements for maintenance. Without regular clean-outs the devices may be prone to the following: accumulated sediment reducing available treatment volume, sediment resuspension during high-flow storm events, and accumulated floating material becoming entrained into the water and ultimately discharged during subsequent storm flows.

   In the SEE Study, MassHighway found that inspection and maintenance of the WQI is much more difficult than with open systems (e.g., detention basins, drainage swales) or even catch basins. Routine inspection and the determination of sediment accumulation were constrained by the limited access and physical size and configuration of the device.

   Physically cleaning the WQI also was difficult and required using personnel to access the device under "confined-space protocol" to ensure effective cleaning of the device. Cleaning and disposal costs are anticipated to be much higher for this type of device than for "open" BMPs.

   The assessment of any particular hydrodynamic separator should include an evaluation of the procedures, cleaning frequencies, and associated costs, as well as the treatment effectiveness, in order to determine if their use is warranted in a particular setting.

Figure 3. Vacuum truck employed during the cleaning operation of a water-quality inlet along the Southeast Expressway in Boston (left) and a maintenance worker pushing sediments to a vacuum hose while exercising "confined-space entry" protocol (right).

Conclusions and Recommendations

The field evaluation of the treatment performance of hydrodynamic separators requires careful planning and appropriate study methodology to secure representative storm water data. Without such data, the results from these studies will lack scientific credibility and/or statistical confidence. Scientifically valid data is essential for the selection and design of BMP technologies and for assessing whether these technologies are capable of meeting regulatory requirements. This paper has presented some primary factors that should be incorporated into the design of a scientifically valid BMP test study.

Based on the findings and experience gained during the Southeast Expressway Study, MassHighway recommends the following for validating the field performance of hydrodynamic separators:

- Collect field data that is both representative of the range of rainfall events and that is applicable to the conditions (e.g., ambient particle-size distributions) under which the separator likely will be installed;
- Sample a sufficient number of storms to obtain statistically significant data and cover the full range of operating conditions to which the device is subject;
- Sample storms sequentially, with complete data acquisition to allow for a mass-balance calculation;
- When sampling, use flow-proportional sampling throughout the duration of each storm event to determine the active-particle removal by the separator (i.e., "hydrostatic" vs. "hydrodynamic" separation) and not bias the results because of "supernatant displacement;"
- Account for antecedent conditions, bypass flows, and resuspension when calculating the SSRE;
- Analyze treatment performance by "Summation of Loads" to characterize long-term overall effectiveness; and
- Include measurements of particle-size distribution in the sampling and analysis program to assess the removal efficiency of TSS (or preferably SSC) as well as that of other contaminants associated with various particle-size fractions.

In light of MassHighway's evaluation of WQIs and on the literature discussed herein, further evaluation—using scientifically sound methods that generate data with high statistical confidence—is necessary to demonstrate the effectiveness of hydrodynamic separators as primary-treatment devices. Although MassHighway has documented the limitations of the WQIs used along the Southeast Expressway (e.g., low overall removal of suspended sediment, particularly fine particles), hydrodynamic separators may be appropriate for pre-treatment and retrofit applications where sand is the target contaminant and where the operator has adequate maintenance capabilities.

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