Verification of a Method for Sizing All Proprietary Single Chamber Treatment Devices with Settling as a Unit Process

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Abstract

Methods for sizing single chamber tanks to remove different amounts of total suspended solids (TSS) have been available for some time. One method found in the literature uses the concept of upflow velocity \( v \) or the critical settling velocity of a particle in a tank to determine what size particles will be removed in the tank. The critical settling velocity depends on the relationship between discharge rate from the tank \( Q \) and the surface area of the tank \( A \) as described in the equation \( v = Q/A \). One of the urban runoff models using this relationship to determine the efficiency of settling devices is the Source Loading and Management Model (WinSLAMM).

The purpose of this paper is to verify the upflow velocity concept as it is used in WinSLAMM. The model is tested with the results from monitoring the effectiveness of two proprietary stormwater treatment practices – the Stormceptor and Vortechs System. Both of these practices rely on settling as the mechanism for removing solids from the flow stream. The model is tested using the site specific characteristics, such as rainfall, dimensions of each practice, and the average particle size distributions.

The reductions of TSS estimated by the model closely matched the measured sum of the loads values (SOL). The TSS measured SOL value for the Stormceptor and the Vortechs is 5 and 19 percent respectively, while the model predicted values of 12 and 19 percent. The model results do not match the efficiencies of the individual storms as well as a group of storms. Information is not provided to the model on the variation in particle size distribution between storms, the variability in influent concentrations, and the identity of storms with re-suspension of trapped sediments. Results of this verification effort indicate the upflow velocity method should provide a reasonable estimate of the long-term TSS reductions expected for single chamber proprietary treatment practice that use settling as the primary unit process.

Introduction

Wisconsin cities must achieve a 40 percent reduction in annual stormwater load of total suspended solids (TSS) by year 2013. In new developments the requirement is a 80 percent reduction in TSS compared to no controls. Many cities are considering proprietary treatment devices to achieve the performance standards, especially the 40 percent reduction. Most of the devices being offered to the cities use settling as the primary means of removing the TSS. People working for the cities have the challenge of not only finding the best price for a product, but insuring the product will achieve the performance standards.
In most cases the cities rely upon the manufacture’s claims for the expected level of TSS reduction. This approach has opened the possibility the bidding process will be more a function of trying to keep the bid low than making the device big enough to achieve the TSS reduction goal. There is no doubt it will be more fair to the manufacturers and the people working for the cities if there is an approach agreed upon for sizing the proprietary treatment devices. One approach is to have an approval process that might include some monitoring. This approach would validate the sizing method used by each manufacturer. Some states, like the state of Washington, already have an approval process for proprietary treatment devices. Although it is appropriate many of the existing approval processes include some type of monitoring, the monitoring can be expensive for the manufacturer and it might take a number of years to complete the process for all the products. Another approach is to select a generic sizing approach for all the products with a similar unit process, such as settling.

The purpose of this paper is to verify one method that could be used to size all single chamber proprietary treatment devices that have settling as a unit process. Any generic method will not be perfect. But the intent is to describe the settling process with enough accuracy to be within 10 percent of the actual TSS reduction. Sensitivity of the calculations to factors causing variability in the trap efficiency, such as the amount of scour and short-circuiting, will certainly contribute to the uncertainty in the method. Uncertainty created by these types of variables, however, should be much less than the uncertainty that now exists when the cities and the manufacturers attempt to agree on the benefits of each device.

The method verified in this paper is the concept called ‘upflow’ velocity. The concept of upflow velocity (v) or the critical settling velocity of a particle in a tank depends on the relationship between the discharge rate (Q) from the tank and the surface area (A) of the tank in the equation v = Q/A. This method has been successfully applied to the design of wet detention ponds. WinSLAMM is one of the models using the upflow concept to design settling systems like wet detention ponds (Pitt and Voorhees, 2002).

Monitoring results from testing the TSS reduction achieved by the Stormceptor and the Vortechs will be used to verify the estimates of efficiency calculated with WinSLAMM. Both of these devices have most of TSS trapped in a single chamber and they depend on settling as the primary unit process. Measured rainfall data, particle size distributions, actual product dimensions are used for all the model runs.

**Monitoring Results from Testing the Vortech and Stormceptor**

The U.S. Geological Survey (USGS) tested the pollutant reduction effectiveness of the Vortech and the Stormceptor. Both devices are proprietary and they are designed to remove settleable pollutants and floating debris from stormwater runoff. The Vortech Stormwater Treatment System is owned by Vortechs, Inc. with headquarters in Scarborough Maine. The Stormceptor stormwater treatment device is owned by Stormceptor Corporation headquartered in Canada. A report is available describing the results of testing the Stormceptor (Waschbusch, 1999). Monitoring of the Vortech was
completed in late 2004 and a final USGS report will be available at the end of 2005. Results from the Vortech project will also be published in 2005 by the National Sanitation Foundation as a final Environmental Technology Verification (ETV) report and posted on the ETV web site.

**Site Description**

In May, 1996, a Stormceptor model STC 6-000 was installed underground at a maintenance yard in Madison, Wisconsin. The storm sewer system connected to the Stormceptor drains 4.3 acres of paved surface and rooftop. The maintenance yard is used for yard-waste drop-off; fueling, storage, and cleaning of city utility and maintenance vehicles; and storage of sand and salt for road application.

A Vortechs Model 1000 Stormwater Treatment System was installed underground on a municipal parking beneath an elevated Milwaukee freeway (I-794) in 2001. The Vortechs Systems receives runoff from 0.25 acres of the westbound highway surface of I-794. There is no other landuse in the drainage area. Runoff from the elevated deck reaches the Vortechs via downspouts mounted to the deck and pilings. The elevation drop is about 15 feet.

**Product Dimensions**

The diameter of the Stormceptor treatment chamber is 10 feet. The average depth of the sump below the outlet is 13.5 feet. The inlet and outlet pipes to the chamber are 0.83 feet in diameter. The surface area of the chamber is 78.5 square feet. Distance from the bottom of the sump to the surface of the pavement is 17.5 feet. The system will bypass flows at 1.1 cubic feet per second. Diagrams of the Stormceptor and the site are in the final report (Waschbusch, 1999).

The surface area of the grit chamber in the Vortechs System is 7.1 square feet and the diameter is 3 feet. The diameter of the outlet pipe is 0.33 feet. The average depth of the grit chamber below the outlet pipe is 3 feet. The maximum treatment capacity is 1.6 cubic feet per second. The depth from the bottom of the sump to the overflow weir is 4.3 feet. There is no bypass for the Vortechs System. More information about the site and the description of the device is in the test plan for the Vortech (NSF International, 2002).

**Monitoring Protocol**

A continuous recording gauging station was used to monitor flow, precipitation, and water quality at the Stormceptor site. Flow-composite samples were collected at the inlet and outlet to the Stormceptor and time composite samples were collected in the bypass water. Flow-composite samples were collected with refrigerated automatic point samplers. All the samples were analyzed for TSS. Continuous precipitation data were collected with a tipping bucket rain gage. The amount of sediment trapped in the treatment chamber was determined after completion of all the sampling.
The Vortechs System was tested using the ETV verification protocol (U.S. EPA, 2002). The verification protocol establishes the requirements and guidelines for testing the performance of stormwater treatment technologies under the Wet Weather Flow Technologies of the ETV program. A continuous recording gauging station was installed just upstream and downstream from the device. Flow meters continuously recorded flow in the pipes and precipitation was measured with a tipping bucket rain gauge. Flow-composite samples were collected in a refrigerated automatic point sampler. All the samples were analyzed for TSS. Sediment remaining in the device was sampled for total weight and particle size distribution after all the sampling was completed. The sampling approach used for the Stormceptor has most of the features of the ETV protocol.

**Measured Sum of the Loads for TSS**

The sum of the loads (SOL) calculation provides a measure of the efficiency of a stormwater treatment technology. SOL calculations determine the mass pollutant load (concentration times volume) for each constituent. Because the volume is included, the SOL calculation weights each storm. Storms with the largest runoff volume tend to have larger influence on the efficiency determined for a technology. This gives more importance to the storms with highest impact on the environment.

The following equation is used to calculate the SOL:

$$\text{SOL} = 100 \times (1 - \frac{\text{SOL}_{\text{effluent}}}{\text{SOL}_{\text{influent}}})$$

A total of 45 flow-composite samples were collected from the inlet and outlet to the Stormceptor between August 1996 and April 1997. Twenty five of the samples were collected during periods of snowmelt. Only the first fifteen rainfall runoff events are used to calculate the SOL for TSS. The snowmelts are not included because they are not part of the ETV protocol and SLAMM does not calculate snowmelt runoff. Seven of the fifteen runoff events had high enough flows to have some bypass episodes during the event. The amount of TSS in the bypass water is added to the TSS load at the outlet to produce the total TSS leaving the Stormceptor. A total of 939 pounds of TSS was measured at the inlet for the fifteen storms and the amount of sediment measured leaving the device was 895 pounds. The SOL for the fifteen storms is 5 percent. If the bypass water is not added to the outlet TSS load, the SOL value would be 8 percent.

Eighteen runoff events from the Vortechs site are used to determine the SOL. These samples were collected between April 2003 and August 2004. For the inlet the total TSS load is 63 pounds and the outlet load is 51 pounds. The SOL for the eighteen runoff events is 19 percent.
Particle Size Distribution

Both the Stormceptor and the Vortech site have particle size distribution data available at the influent side for several events. The average particle size distribution appears in Figure 1. For particles larger than about 28 microns the shape of the curves is quite different. The curve for the Stormceptor site drops much more rapidly than the Vortech site. The percentage of the particles in the sand size fraction (greater than 63 microns) for the Vortech site is 18 percent and only 3 percent for the Stormceptor.

The difference in the curves might help explain some of the difference in the SOL values for the sites. Under ideal settling conditions, such as the lack of scour and short-circuiting, the SOL value for each site corresponds to all particles greater than a certain size on the curve. The SOL of 5 percent for the Stormceptor site appears to be associated with particles greater than 55 microns (Table 1). About the same particle size for the Vortech site achieves a 20 percent SOL value. The Vortech would only have to control the 410 micron size particle to achieve an SOL of 5 percent. Both devices might be controlling about the same size particles, but the differences in the particle size distributions curves produces different SOL values.

![Particle-size data used in WINSLAMM](image)

Figure 1. Influent Particle Size Distributions for the Stormceptor and Vortech Monitoring Sites.
Table 1. Particle Size Associated with Different Levels of TSS Reduction Under Ideal Settling Conditions.

<table>
<thead>
<tr>
<th>Percent Control (Percent greater than on Fig. 1)</th>
<th>Particle Size, Microns</th>
<th>Stormceptor</th>
<th>Vortechs System</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>15</td>
<td>10</td>
<td></td>
</tr>
<tr>
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<td>10</td>
<td>45</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>55</td>
<td>410</td>
<td></td>
</tr>
</tbody>
</table>

SOL Estimates Using WinSLAMM

WinSLAMM was selected for this verification effort because it calculates particulate deposition in wet ponds and catch basins using the upflow velocity method (Linsley and Franzini, 1964; Pitt, 2002, Pitt and Voorhees, 2003; Pitt, 2004). This method has been verified with data from monitoring the efficiency of wet detention ponds (Pitt and Voorhees, 2003). If the settling process in a single chamber proprietary technology is similar to what happens in a wet detention pond, the calculations performed by WinSLAMM should provide a reasonable way to predict the effectiveness of these relatively small devices.

The upflow velocity is defined as the pond outfall rate divided by the pond surface area \(v = Q/A\). For an ideal sedimentation pond, any particle that has a settling velocity greater than this upflow velocity will be retained in the pond. Only increasing the surface area, or decreasing the pond outflow rate, will increase pond settling efficiency. To use the detention pond or catch basin routine in WinSLAMM, the user must define the particle size distribution for the influent water. WinSLAMM uses the particle size distribution to calculate the particle settling rates from Stoke and Newton settling equations. WinSLAMM calculates the critical particle sizes retained in each calculation interval during the runoff event and sums the mass of particles trapped for each event. All of the influent and effluent loads for the individual events are then added to produce the SOL for the pond.

Matching Measured Influent TSS Loads and Water Volumes

Before verifying the upflow velocity calculation in WinSLAMM, it is important to determine if the influent water volumes and TSS loads estimated by the model are reasonably close to the measured values. Accurate influent flows are important because they impact the effluent discharge rate, \(Q\), in the upflow velocity equation and the influent TSS loads are used to determine the mass of sediment in each particle size. Past evaluations of WinSLAMM have shown it is capable of doing a good job of estimating
water volumes and pollutant discharges for different source areas, such as parking lots, and land uses, such as medium density residential (Bannerman, 2003).

WinSLAMM closely matched the water volumes and TSS loads for the fifteen runoff events at the Stormceptor site and the eighteen events at the Vortech site. WinSLAMM slightly overestimates the volumes and loads at the Vortech site and slightly underestimates the measured numbers at the Stormceptor site (Table 2). Just as importantly, the model provides a reasonable match to the values observed for the individual events (Figures 2, 3, 4 and 5).

Table 2. Measured and Estimated Influent Water Volumes and TSS Loads for the Stormceptor and Vortech Site.

<table>
<thead>
<tr>
<th></th>
<th>Stormceptor</th>
<th>Vortech System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Estimated</td>
</tr>
<tr>
<td>Water Volume, cubic feet</td>
<td>85,600</td>
<td>73,893</td>
</tr>
<tr>
<td>TSS Load, lbs.</td>
<td>939</td>
<td>814</td>
</tr>
</tbody>
</table>

Figure 2. Observed versus estimated influent water volumes for the Vortechs site.

Figure 3. Observed versus estimated influent TTS loads for the Vortechs Site.
Comparing WinSLAMM and Measured SOL Values

Sum of the loads estimates were determined with WinSLAMM using the catch basin option. The calculations in the catch basin option are very similar to those used for the detention pond option, but the things like the scale of the dimensions in the catch basin option are more suitable for single chamber devices. Also, a flow splitter can be applied to the catch basin calculations. Some of the SOL calculations were repeated with the detention pond option and the answers were the same.

Files with the measured rainfall data, average particle size distributions, and site characteristics, such as acres of paved storage area, were created for input to the model. Calculations of the SOL were made for the actual dimensions of each device. The TSS sum of the load calculated for the Stormceptor is 12 percent. This is calculated from an influent load for the fifteen runoff events of 814 pounds and an effluent load of 716 pounds. The influent TSS load calculated for the Vortechs System is 68 pounds and the effluent load is 55 pounds. The calculated SOL for Vortech is 19 percent.

The SOL for the Vortechs System is 24 percent if two other chambers in the device are included in the surface area, $A$. The area for the grit chamber at the front end of the device is 7.1 square feet and the total area with the two additional chambers is 17.6 square feet. Most of the deposited material in the Vortechs System is found in the 3 foot diameter grit chamber, so the area of that chamber is used to calculate the SOL. Only about 10 percent of all the sediment deposited in the device is found in the two small chambers following the grit chamber. Adding those two chambers only increased the SOL by 5 percent.

Both of the SOL values are within 10 percent of the measured values. This result is close enough to be of real use to cities and manufactures trying to determine the proper sizing of the single chamber proprietary treatment devices. Using the upflow velocity method to calculate the SOL of a treatment device should insure the final design will have a reasonable chance of achieving the TSS reduction goals. For example, WinSLAMM could be used to approximate surface area needed to reduce the TSS load by 40 percent at each of the verification sites. The Vortechs System grit chamber would have to be about

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**Figure 4.** Observed versus estimated influent water volumes for the Stormceptor

**Figure 5.** Observed versus estimated influent TSS loads for the Stormceptor.
160 square feet instead of 7.1 square feet and the surface area of the Stormceptor chamber would have to be 500 square feet instead of 78.5 square feet.

The biggest challenge to a person using the upflow velocity concept to size a treatment device might be selecting a particle size distribution that is appropriate for a site. Two other particle size distributions were applied to the Stormceptor and Vortechs sites to evaluate their impact on the SOL. Both of the distributions are derived from the National Urban Runoff Program (NURP) (Burton, 2002). One curve is called the high NURP and the other is called the average NURP. The median particle size for high NURP is 70 microns and the median size for the average NURP is 10 microns. The Stormceptor SOL values for TSS are 58 percent for high NURP and 17 percent for average NURP. The SOL values for the Vortech are about the same with the high NURP at 63 percent and the average NURP at 20 percent. Both of the devices would perform dramatically better for a site with the high NURP as the particle size distribution. The average NURP is close enough to the measured distributions to have little effect on the SOL for the sites.

WinSLAMM Percent Reduction Values for Individual Events

If it is ever necessary to improve how well WinSLAMM matches the measured SOL values, the calibration process should focus on the efficiencies estimated for each runoff event. As with all efforts to simulate the variability in storm flows and pollutant concentrations, the calibration process will attempt to find a balance between the number of efficiencies the model overestimates and underestimates. Although the match will not be perfect for individual storms, the off-set between the under and over estimates should produce a reasonable SOL value when estimated for a large number of storms.

WinSLAMM underestimated and overestimated the percent TSS reduction for individual events for both sites (Figures 6 and 7). A similar number of storms are under and over estimated at the Vortech site. Almost all of the overestimated values for this site occurred for the highest peak flows or peak flows over about 0.3 cubic feet per second. The negative loading rates observed at these higher peak flows might be a result of scour, which is not accounted for in Win SLAMM until the depth of the deposited sediment is within one foot of the outlet. The model underestimated the reductions for most of the lower peak flows. An equal number of storms are also under and over estimated at the Stormceptor site. Unlike the Vortech site the overestimated values occur more equally at low and high peak flows. It is expected WinSLAMM would overestimate reduction values when the peak flows exceed the bypass flows of 1.1 cubic feet per second.

For about one half the storms at the Stormceptor site the estimates are only about 10 percent higher or lower than the measured values, while good agreement is observed for about one third of the storms at the Vortech site. Good agreement occurred at low and high peak flows for both sites. It appears the reason the estimated SOL values are reasonable is because the over and under estimates must off-set each other and many of the estimated efficiencies are already close to the measured values.
However, the large difference observed between many of the estimated and measured percent reductions does raise the concern about the ability WinSLAMM to calculate a reasonable SOL for every site. This is especially true at the Vortech site for peak flows between 0.023 and 0.138 cubic feet per second (Figure 7). Measured percent reductions range from 5 to 69 percent, while the estimated values cover a relatively narrow range of 14 to 24 percent. The range in values is much more similar for the Stormceptor site with a measured range of 2 to 55 percent and an estimated range of 5 to 41 percent. This observation at the Stormceptor sits ignores an outlier of 84 percent reduction for the measured values. Another important difference between the measured and estimated TSS percent reductions is the estimated values are never negative.

There are a number of factors that could cause the larger differences observed in estimated and measured values on Figures 6 and 7. The types of factors affecting the WinSLAMM estimates are the choice of particle size distribution, potential for short circuiting, and the scour of deposited material. At the same time it must be remembered the difficulty in obtaining a representative TSS sample from a storm sewer pipe might lead to errors in the measured percent reductions. There is no way of checking the monitored data, but some discussion about the factors affecting WinSLAMM is possible.

![Vortech Removal efficiency of suspended solids as a function of peak discharge](image)

Figure 6. Measured and estimated percent TTS reductions for individual runoff events at the Vortechs System site.
Particle size distributions will vary with each runoff event. Particle size data collected at a storm sewer in Madison, Wisconsin exhibited a wide range in distributions over 45 runoff events (Greb and Bannerman, 1997). The percent of particles in the sand size fraction (greater than 62 microns) ranged from 0 to 51 percent. WinSLAMM estimates would be improved if the correct particle size distribution is available for every event. It is not practical to restrict the sizing of treatment devices to sites with particle size distributions available for a wide range of runoff conditions. Instead an effort must be made to provide average particle size distributions for different types of source areas and land uses. Until more particle size data is available, the Wisconsin Department of Natural Resources is suggesting the average NURP distribution be used to size all stormwater treatment practices that use settling as the unit process.

Short-circuiting allows some large particles to be discharged that theoretically would be completely trapped in a pond. A short-circuiting factor is included in WinDETPOND which contains the same upflow velocity calculations as WinSLAMM (Pitt and Voorhees, 2003). The short-circuiting effects in the model are based on particle trapping equations presented by Fair and Geyer (1954). A pond is considered to have poor performance if the short-circuiting factor is between 1 and 2. WinDETPOND was used to test the sensitivity of the Stormceptor and Vortech to a wide range of short-circuiting factors. Very little change was observed for the SOL values.
It is possible the devices are very efficient at capturing the larger particles the short-circuiting factor effects. The average critical settling velocity for both devices is around 50 microns, so they retain most of the sand size particles. Also, the number of particles greater than sand size is very small at the Stormceptor and Vortech sites. Even a 20 percent reduction in the trap efficiency of these particles would have a small effect in the final SOL. A short-circuiting factor should be added to the WinSLAMM calculation.

A minimum pool depth of about 3 feet is recommended to decrease scour of previously settled material in a wet detention pond. A permanent pool depth of 3 feet in the Vortech and a depth of about 13 feet for the Stormceptor should provide some protection from scour. At both sites the amount of deposited material did not significantly reduce the depth of the permanent pool. Scour did appear to be a problem for the Stormceptor, if scour is indicated by the effluent concentration being larger than the influent concentration. This does not rule out scour, but the large depth of the permanent pool and a design that bypasses all the larger flows surely reduced the possibility of scour occurring. The negative values on Figure 7 are due to the bypass flows.

Effluent concentrations were higher than influent concentrations for 4 runoff events at the Vortech site. Scour is the most likely cause of the negative TSS reductions. Unlike the Stormceptor, the Vortech accepts all the higher flows and the permanent pool is relatively shallow. All of the negative reductions occurred during the storms with the highest peak flows and the rains with the highest intensity. Scour appears to occur for storms with peak flows between 0.35 and 2.45 cubic feet per second. Scour is obviously going to be a factor in the calculation of SOL for some proprietary treatment devices. A scour calculation that is sensitive to water depth and velocity should be added to WinSLAMM.

**Conclusions**

The upflow velocity calculations as used in WinSLAMM provide a reasonable way to approximate the SOL values for single chamber proprietary treatment devices that use settling as the primary unit process. The SOL values estimated with WinSLAMM for the Stormceptor and Vortechs System sites closely matched the measured values. Estimates with the model would improve if more site specific particle size distribution data were available. Particle size data is needed for both source areas, such as parking lots, and land uses, such as shopping centers. Additional modifications to the model will insure the SOL values will be sensitive to variations in the design of the treatment devices. WinSLAMM should be improved to include calculations for quantifying the occurrence of short-circuiting and scour.

**References**


Greb, S. and Bannerman, R; 1997; Influence of particle size on wet pond effectiveness; Water Environment Research, Volume 69, Number 6


Pitt, R; 2004, Module 5: Stormwater Quality and Treatment An Introduction to the Source Loading and Management Model (WinSLAMM).
