User Guide of HydroInternational's Up-Flo® Filter in WinSLAMM

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Introduction and Summary

The Up-Flo™ stormwater filter technology was initially developed under the US EPA's SBIR program by researchers at The University of Alabama under the leadership of Dr. Robert Pitt with Richard Field as the EPA project officer and Dr. Ramjee Raghavan from US Infrastructure as project manager and the SBIR contractor. SBIR Phase 1 included laboratory and pilot-scale tests, SBIR Phase 2 added full-scale field tests, including preparation of the framework of how this technology could be incorporated into WinSLAMM, and to prepare the upflo filter for commercialization. Hydro International has been responsible for its further development and commercialization after the SBIR Phase 2 activities. The results of testing and evaluations leading ultimately to the development and commercialization of the Up-Flo Filter are fully documented as part of the SBIR Phase 1 and Phase II research activities which were funded by the US EPA (Pitt, R. and Khambhammettu, U., 2006. "Field

Verification Tests of the UpFlo™ Filter". Small Business Innovative Research, Phase 2 Report. *U.S. Environmental Protection Agency*, Edison, NJ. 275 pages. http://unix.eng.ua.edu/~rpitt/Publications/StormwaterTreatability/Up-Flo%20EPA%20report%20Pitt%20and%20Uday%202006.pdf and other presentations and papers available at: http://unix.eng.ua.edu/~rpitt/Publications/StormwaterTreatability/Up-Flo%20EPA%20report%20Pitt%20and%20Uday%202006.pdf)

Work began on incorporating the Upflo Filter into WinSLAMM in 2011. On March 26, 2016, WinSLAMM version 10.2.1, which included the Upflo Filter, was released. Minor modifications or bug fixes were included in some subsequent releases.

Field performance verification tests under actual storms were monitored using Hydro International's full-scale Up-Flo® filter by researchers from the Department of Civil, Construction, and Environmental Engineering at the University of Alabama from July 2010 to March 2013. The tests were conducted at the Riverwalk parking lot near Bama Belle in Tuscaloosa, Alabama. The Up-Flo® filter was installed by personnel from the City of Tuscaloosa in early 2009. The filter was a standard six module unit containing the standard CPZ Mix™ with the addition of 5% iron fillings (for the last series of full-scale tests; the first series of full-scale tests did not contain the iron). The first series of full-scale tests were conducted by Dr. Noboru Togawa as part of his dissertation research (*Development and Testing of Protocols for Evaluating Emerging Technologies for the Treatment of Stormwater*, 2011, available at: http://unix.eng.ua.edu/~rpitt/Publications/11_Theses_and_Dissertations/UpFlo_Filter_Dissertation_Noboru_Togawa_Final.pdf) while the final set of full-scale tests were conducted by Yezhao Cai as part of his thesis research (Full-Scale Up-Flo® Stormwater Filter Field Performance Verification Tests, June 2013, available at: http://unix.eng.ua.edu/~rpitt/Publications/11_Theses_and_Dissertations/Cai_thesis.pdf. These two extensive reports contain much information concerning the testing protocols and detailed data analyses and should be examined for further information. A summary report incorporating much of the information from these research reports is at: http://unix.eng.ua.edu/~rpitt/Publications/5_Stormwater_Treatment/Treatment_trains_and_sizing_controls/Upflow_Filter/UpFlo%20Filter%20Final%20Performance%20Report.pdf

A number of different tests were conducted with the full-scale Up-Flo® filter, starting with preliminary controlled quality assurance/quality control tests including:

- Hydraulic flow tests (using pumped river water) to calibrate the flow monitoring equipment and to test the filter behavior of installed filter media bags under different simulated influent flow loadings.
- Ground silica (Sil-Co-Sil) and fine sand mixture performance tests under pumped water tests to measure performance of the Up-Flo® filter under different flows, particle sizes, and sediment concentration conditions.

After these preliminary controlled QA/QC field tests, continuous hydraulic and water quality performance monitoring was conducted during actual storm events. Earlier laboratory and pilot-scale tests were also conducted during the development of the Up-Flo® filter. Reviews and summaries of these early tests are included in the above referenced dissertation and thesis.

The water quality performance evaluation focused on the pollutant removal capability of the Up-Flo® filter over a wide range of particle sizes, influent pollutant concentrations, and rain conditions. The performance data for the same narrow particle size ranges obtained under actual rainfall conditions were compared to the controlled QA/QC tests that used mixed ground silica and fine sands having known specific gravity and concentrations. In addition, sump sediments were also sampled and analyzed at the end of the monitoring period for mass balance calculations, and for adjustments of automatic sampler performance data for the large particle sizes.

Field performance testing of the full-scale Up-Flo® Filter during actual storms was initially conducted by Togawa (2011) who examined 20 storm events during his dissertation research during an approximate one-year period. An additional 30 storm events were sampled and monitored at the same test site with the same test methodology as part of Cai's thesis (2013). Overall, a total of 50 events have been evaluated to describe the performance of the Up-Flo® Filter under a wide range of rainfall and runoff conditions, resulting in increased confidence of the performance observations.

Tables 1 and 2 show the overall water quality performance of the full-scale Up-Flo® Filter for these sampled storm events monitored at the Bama Belle test site. All solids constituents, including each particle size range, had significant reductions with Wilcoxon Signed Rank p-values of <0.001 and high levels of flow-weighted reductions for TSS and SSC. Average effluent TSS and SSC concentrations were 22 and 26 mg/L, respectively. Table 1 shows the overall accumulative sum-of-loads performance associated with 41 sampled events for each particle size. These data are shown for 41 events as several influent samples were influenced by local erosion areas that adversely affected the influent sediment measurements, resulting in very large concentrations. These events were therefore eliminated from this performance summary. The total influent measured particulate loading for these 41 events was 478 pounds (217 kg), while 93 pounds (42 kg) was the measured effluent particulate mass. The percentage solids captured for each specific particle range generally increased as the particle sizes increased, as expected, and the overall removal rate for the total particulates loading was about 80%, which was within the design goal of solids removal performance of the full-scale Up-Flo® filter.

Table 1. Accumulative Mass of Influent and Effluent Total Particulates by Particle Size Range for 41 Sampled Storms

Particle Size Range (um)	Influent Total Mass (With Sump*) (lbs)	Effluent Total Mass (lbs)	Percent Reduction
0.45 - 3	1.75	1.13	35.6
3 - 12	58.79	11.41	80.6
12 - 30	85.24	26.03	69.5
30 - 60	52.35	16.29	68.0
60 - 120	43.04	11.01	74.4
120 - 250	52.94	1.97	96.3
250 - 1180	120.54*	19.49	83.8

> 1180	63.28*	6.14	90.3
Total:	478*	93	80.4

* Without the sump mass corrections for the large particle sizes. The overall calculated performance for all 50 events was much larger (>95% for SSC) due to likely biases in the influent autosampler from nearby erosion sources.

The removals for all nutrients also have significant reductions due to relatively large numbers of paired observations having detectible concentrations. The flow-weighted calculated levels of treatment for the nutrients were low to moderate, ranging from about 22% for dissolved phosphorus to about 34% for total nitrogen. The flow-weighted levels of control were all high for those heavy metal constituents having sufficient data, ranging from 62 to 72% for total copper, to greater than 85% for total chromium. The overall treatability for total and dissolved Cd, dissolved Cu, dissolved Pb and dissolved Zn were not significant due to numerous non-detected influent concentration values, resulting in few paired data sets. The flow-weighted removals for *E. Coli* (46%) and Enterococci (56%) were also significant (p<0.001).

Table 2. Summary of Water Quality Performance for 50 Sampled Storms

Constituent	Influent Average Conc., mg/L (COV)	Effluent Average Conc., mg/L (COV)	Flow-weighted (sum of loads) Percent Reduction	Wilcoxon Signed Rank P-value (Significant or Not)	MDL
Turbidity	26.8 (0.91)	10.0 (0.81)	58.4%	<0.001 (S)	0 NTU
TDS	76 (0.68)	54 (0.52)	31.8%	<0.001 (S)	1 mg/L
Total N as N	1.9 (0.74)	1.2 (0.63)	34.4%	<0.001 (S)	0.1 mg/L
Dissolved N as N	1.2 (0.69)	0.7 (0.63)	33.9%	<0.001 (S)	0.1 mg/L
Nitrate as N	0.48 (1.03)	0.34 (0.79 to 0.80)	27.9% to 28.0%	<0.001 (S)	0.02 mg/L
Total P as P	1.01 (0.56)	0.80 (0.62)	24.1%	<0.001 (S)	0.02 mg/L
Dissolved P as P	0.61 (0.67)	0.48 (0.70 to 0.71)	21.5% to 21.6%	<0.001 (S)	0.02 mg/L
Total Cd	0.048 (1.06)	0.005 (0.00)	91.9% to 100%	0.125 (N)	0.005 mg/L
Dissolved Cd	0.038 (0.89)	0.005 (0.00)	87.6% to 100%	0.250 (N)	0.005 mg/L
Total Cr	0.027 (1.06)	0.005 (0.00)	85.5% to 100%	<0.001 (S)	0.005 mg/L
Dissolved Cr	BDL (NA)	BDL (NA)	NA	NA	0.005 mg/L
Total Cu	0.033 (1.68)	0.013 (1.06)	62.6% to 72.9%	0.016 (S)	0.005 mg/L
Dissolved Cu	0.025 (1.04)	0.016 (0.94)	33.6% to 53.7%	0.125 (N)	0.005 mg/L
Total Pb	0.015 (0.98)	0.006 (0.42)	57.6% to 86.8%	0.002 (S)	0.005 mg/L
Dissolved Pb	0.006 (NA)	0.005 (NA)	16.7%	0.750 (N)	0.005 mg/L
Total Zn	0.087 (2.30)	0.022 (0.66)	71.7% to 74.5%	<0.001 (S)	0.005 mg/L
Dissolved Zn	0.058 (2.94)	0.009 (0.65)	82.3% to 85.2%	0.340 (N)	0.005 mg/L
E. Coli	6,064 (1.88)	3,432 (2.13)	46.1%	<0.001 (S)	<1
Enterococci	6,027 (1.08)	2,734 (1.79)	55.8%	<0.001 (S)	<1

Monitoring Location

The test site for the full-scale field monitoring was at the Bama Belle parking area adjacent to the Black Warrior River in Tuscaloosa, Alabama. The tested full-scale (6 modules) Up-Flo® Filter was installed in a city-owned catchbasin on January 8, 2009. Figure 1 and Table 3 show an aerial photograph and the surface cover details of the test site. Figure 2 includes some photographs taken at the test site. The total contributing drainage area is about 0.9 acres, and includes asphalt paved parking, concrete sidewalks, asphalt roadways, a small building, and landscaped park areas. The impervious area, mainly consisting of asphalt pavement, was about 68% of the total drainage area. The Up-Flo® Filter receives and treats the runoff from these areas, and discharges the treated flow directly to the Black Warrior River through a 30 feet long pipe from the filter.

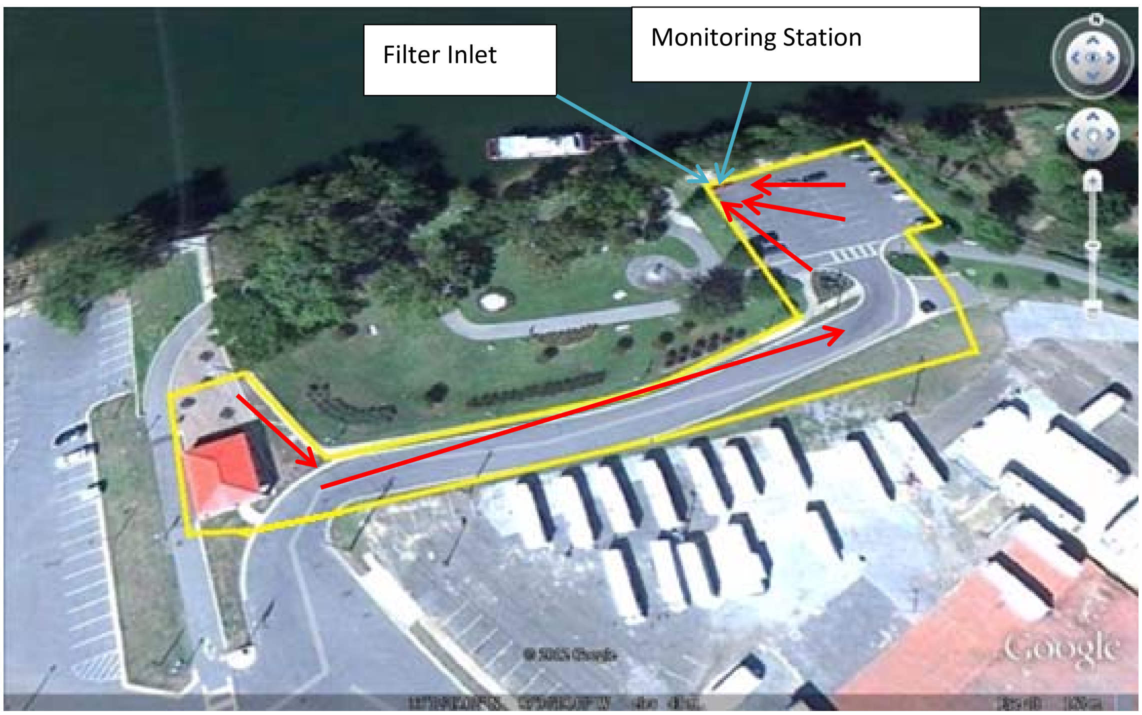


Figure 1: Aerial View of Bama Belle Test Site

Table 3: Flow Contributing Area at Bama Belle Test Site

Land Cover	Area (ft^2)	Area (acres)	Percentage of Drainage Area (%)
Landscaped park area	12,400	0.29	32
Asphalt parking	11,800	0.27	31
Asphalt entrance road	10,990	0.25	28
Concrete sidewalks	2,100	0.05	5.4
Small roof area	1,300	0.03	3.4
Total drainage area	38,610	0.89	100
Total impervious area	26,190	0.60	68
Total pervious area	12,400	0.29	32


Runoff enters filter inlet through roadside gutter and pavement sheetflow


Asphalt pavement with oil and grease stains


Only one building at the site with small roof area


Slight slope along the parking lot entrance road directs the runoff into the parking area and filter


Landscaped area with concrete walkway surrounding the parking area


Drainage area has a large fraction of impervious asphalt pavement

Eroding soils beside the roadway near the filter inlet due to fire ant activity

Fire ant hills besides the filter inlet increased the sediment load into the filter during some storms due to erosion

Figure 2: Bama Belle Test Site Photographs

The full-scale Up-Flo® Filter was installed within a commonly-sized 4-ft diameter catchbasin manhole at the Bama Belle test site. It incorporates a combination of treatment technologies including gravitational separation of settleable gross sediments, coarse screening of floatable materials, and upflow filtration through a treatment media mixture incorporating physical filtration along with ion exchange and sorption. Overall, much finer stormwater particulates can be removed compared to sedimentation processes alone at the design treatment flow rates. Each Up-Flo® Filter system can have up to seven filter modules in the 4 ft catchbasin manhole; the actual number is selected depending on the expected runoff rates needing to be treated. Each filter module has a design hydraulic treatment flow rate of about 25 gallons per minute (GPM). Large areas can contain several systems having many modules located in treatment vaults.

Figures 3 is a schematic of the Up-Flo® Filter showing the major components of a typical six-module configuration, while Figure 4 is the cross-section of the filter module (shown as blue color in Figure 3) which contains the two CPZ™ filter media bags (a combination of activated carbon, spganum peat moss, and manganese coated zeolite), distribution metalla materials, and a restraining lid with a conveyance slot designed as the main outlet weir for the treated flow. During the last year of the full-scale tests, the media also contained 5% iron fillings.

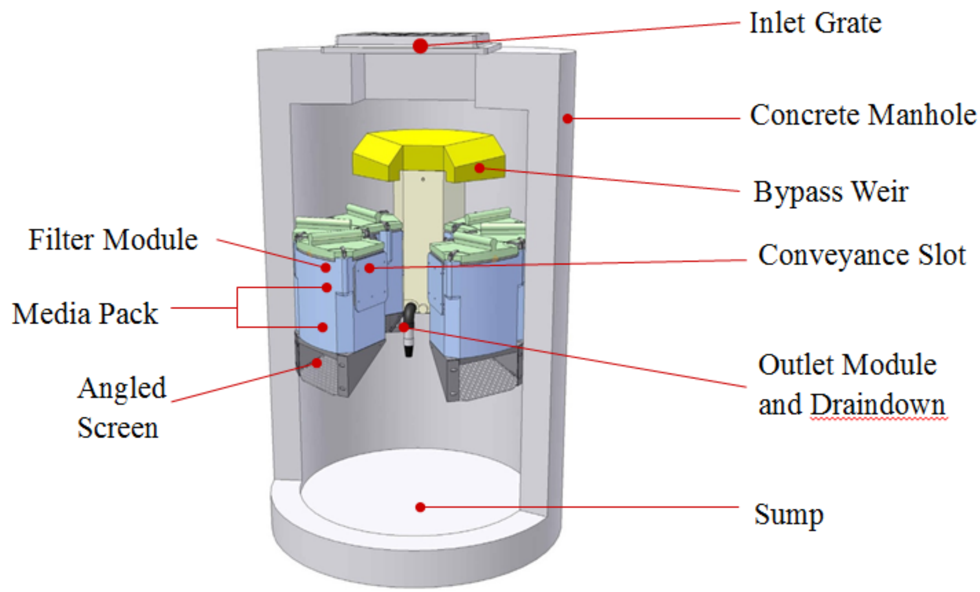


Figure 3: Up-Flo® Filter

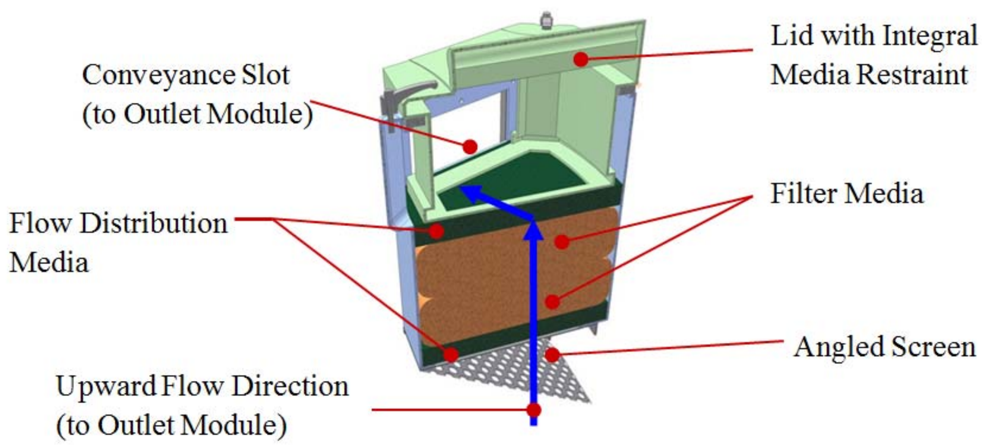


Figure 4: Filter Module Component

During a storm event, the stormwater enters the filter chamber and the sump water stage rises. Larger particles settle to the bottom of the sump and the gross debris and floatables are separated by the angled screens that are below the upflow filter modules. The flow continues to rise and flows through the screens to the filter module. This rising water column in the sump provides a driving head and differential pressure between sump and filter module so that the upward flow can go through the restrained, but partially expanded, filter media in a controlled manner. Runoff treatment with high flow rates is accomplished by controlled fluidization of the filter media in the media bags so that fine particulates are captured throughout the depth of the media bags and at the media filter surface. During peak rainfall periods, the flow may exceed the treatment capacity, with the excess bypass flow discharges to the outlet directly from the siphon-activated bypass, while the filter module still keeps treating flows at its rated capacity, and the large sediment is captured in the sump due to gravitational settling. Excess bypassed flows are therefore partially treated by the sump and also by the siphon floatable control. Following a storm event, the elevated water column drains down slowly through the depth of the filter media bags through the draindown outlet. During this draining period, a slight backwashing effect occurs with some of the captured particulates washed from the media filter bags and into the sump. The elevated sump water continues to drain to the standing water level below the level of the media through the draindown port, thereby allowing the media to drain completely and remain aerated between rains. At the same time, the screened trash and debris on the angled screens are also released by the downward flow of the water which are then retained in the sump.

Monitoring Methodology

The performance monitoring of the Up-Flo® Filter consisted of hydrologic, water quality, and sediment monitoring, in accordance with the TARP and NJDEP demonstration protocols. ISCO 4250 area-velocity flow meters with depth sensors were used to continuously monitor the hydrological conditions at both the inlet and outlet locations of the Up-Flo® Filter, and ISCO 6712 automatic water samplers were used to collect flow-weighted composite samples at the influent and effluent locations. In addition, sediment monitoring was conducted using a liquid-filled, load-cell USGS scour sensor placed on the bottom of the sump for continuously monitoring deposition and scour conditions during storm events (periodic manual sediment depth measurements were also made for verification). Sediment in the sump was also collected at the end of the monitoring period for particle size distribution (PSD), nutrients, metals, and percent volatile solids analyses.

Hydrologic monitoring of the Up-Flo® Filter included effluent discharge rate, rain depth and intensity, water stage of the filter sump, bypass frequency, duration and volume of runoff flows, and draindown performance after events. Both ISCO 4250 area-velocity sensors were verified during the controlled hydraulic flow tests and were used to continuously monitor the water stage in the influent sump and the flow rate in the effluent pipe.

The data loggers for the flow meters, rain gage, and water samplers, were set up before each targeted storm event. The rain depth and intensity were also monitored continuously by the ISCO 674 tipping bucket rain gage installed on the top of the monitoring station. A totalizing rain gage was also located beside the ISCO rain gage for rain depth verification. However, the rainfall data from these rain gages is not expected to accurately represent the rainfall information since there are some tall trees closer to the monitoring station than desired (about half of the tree height in distance). The tipping bucket rain gage's main function was as a trigger for the automatic samplers, not accurate depth measurements. The rain depth information obtained is secondary while the actual flow conditions are important and were used in evaluating performance. The selection of events to monitor was based on reliable local weather prediction information, such as contained at: http://www.weather.com/weather/hourbyhour/graph/Tuscaloosa+AL+USAL0542:1:US.

During the water quality monitoring, the ISCO 674 tipping bucket rain gage was used as a sampler trigger while the area-velocity sensor in the effluent pipe was used for the sampling pacing and for hydraulic performance analyses of the Up-Flo® Filter. At the beginning of each event, both automatic samplers were initiated when the rain gage registered 0.02 inches (2 tips) of rainfall within 30 minutes. The samplers then obtained subsamples simultaneously from the influent and effluent of the Up-Flo® Filter based on the programmed sampling pace, which was proportional to the monitored effluent flow rates. The water samples were obtained from the sampler intakes that were placed in small secured plastic trays where the runoff cascaded directly onto the sampler intakes, reducing problems associated with stratified flows. However, due to the demonstrated deficiency of autosamplers for collecting bedload material (inconsistent and poor sampler efficiency for particles larger than about 250 µm), the sump information was used during the mass balance evaluations to identify periods of sampler errors for the large particles. Figure 5 shows the pre-storm field setup and cleaned plastic trays at the influent and effluent locations. Both YSI 6600 water quality sondes were secured in the plastic sampling trays at the inlet and outlet of the Up-Flo® Filter for continuous water quality monitoring (mainly for turbidity). After the samples were retrieved and brought to the UA laboratory for initial processing and shipping, the plastic tray at the inlet was emptied into the filter sump for the overall mass balance through the monitoring period.

Figure 5: Pre-Storm Field Setup and Cleaned Plastic Trays of Influent and Effluent

Sediment monitoring is an important part of the mass balance calculations. Two kinds of sediment monitoring were conducted as described below. Before the monitoring period, the filter sump was cleaned and a liquid-filled (degassed water), USGS load-cell scour sensor from Rickly Hydrological Company was placed on the bottom of the filter sump. The scour sensor continuously monitored the sump sediment accumulation rate (sediment depth and mass) over the monitoring period, and continuously detected any sump sediment scouring during storm events. Manual sediment depth measurements were also taken after each storm event to evaluate the use of this unique monitoring tool. Figure 6 is the time series of the sediment accumulation during the last year of the monitoring showing both the results of the load cell and the manual monitoring. The scour sensor was not able to detect accumulations until the sediment depth was at least several inches, but is shown to accurately follow the fewer manual depth measurements after that initial lag period. There were no obvious periods of significant scour of sediment in the sump. At the end of the monitoring period, sediment grab samples were also collected and analyzed as they were after the first series of tests.

The sediments were air dried, weighed, sieved, and analyzed for several size ranges for heavy metals (Cd, Cr, Cu, Pb and Zn), specific gravity, nutrients, sulfur compounds (total sulfide, total sulfate and total sulfite), nutrients (total phosphorus and total nitrogen), chemical oxygen demand (COD), percent volatile solids, and particle size distributions (PSD). The filter media bags and flow distribution material were also dried and weighed to estimate the accumulation of solids within the media to complete the mass balance calculations.

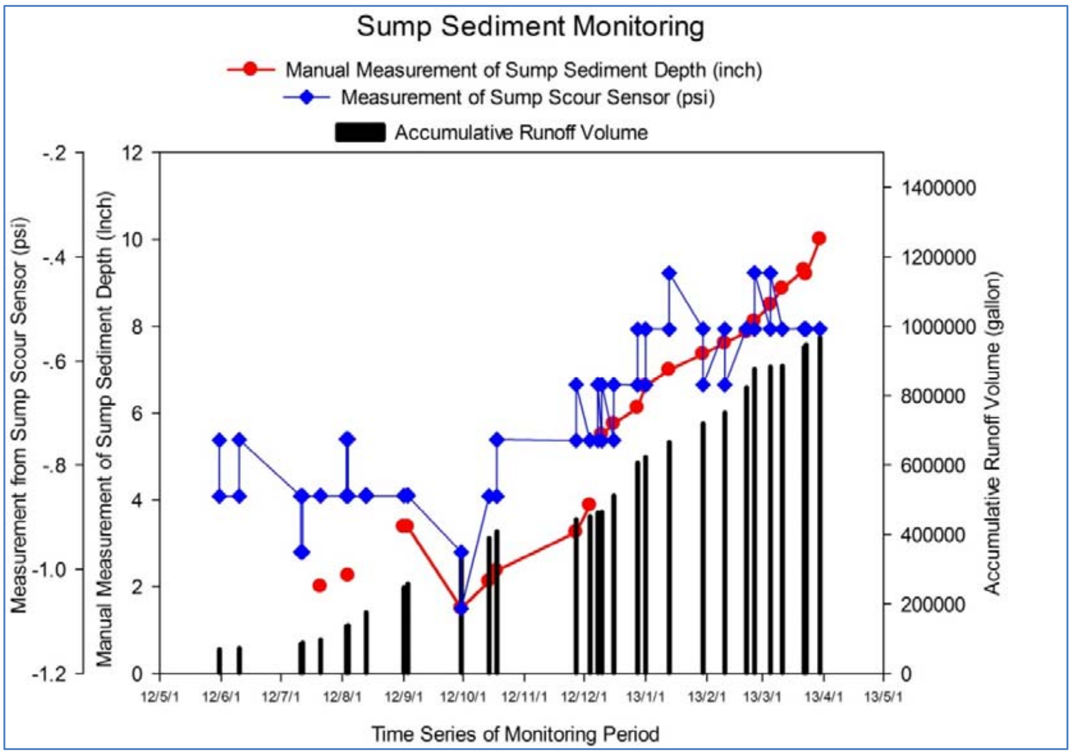


Figure 6: Sump Sediment Depths during One-Year Monitoring Period

Figure 7 is a time series plot of the treatment flow rates observed (the maximum flows associated when the sump water stage dropped back down to the level of the bypass weir). This was assumed to be the level associated with the maximum operational treatment flowrate of the Up-Flo® Filter. The flow rate when the sump elevation was dropping was used instead of rising because the sump stage increases were very unsteady and greatly fluctuated as the influent flow rates varied during runoff events. Dropping sump levels on the recession limb of the hydrographs resulted in steadier flow rates and better represented the stage and flow conditions when bypassing occurred. The blue line in the plot verifies the water stage corresponding to the bypass rate, which is shown as the pink line. High treatment flow rates (with large variations) occurred at the beginning of the study period. These early maximum treatment flows ranged from about 100 to 250 GPM for the 6 module system. The treatment flow rates dropped dramatically after about nine months in the middle of January 2013, at around the 20th sampled event after about 34 inches rainfall and 650,000 gallons of runoff were treated by the Up-Flo® Filter. These reduced flow rates were about 50 GPM for the 6 module system and were quite stable during the last several months of the monitoring period. The system monitoring ended at the end of March 2013; it is therefore unknown when complete clogging and

100% bypassing would have occurred in the absence of any site maintenance. At the end of the project monitoring period, the old media bags were removed and replaced with new bags.

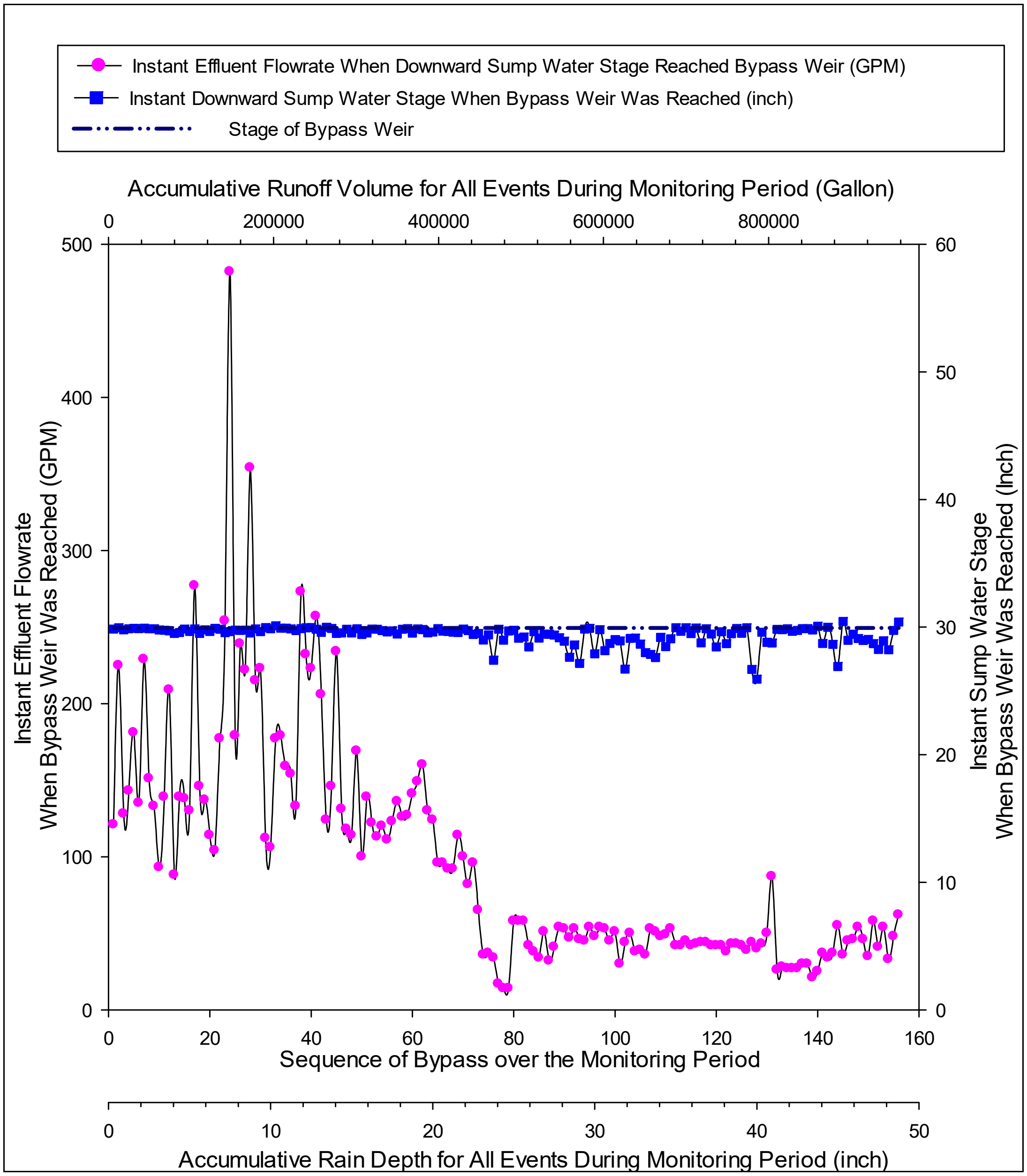


Figure 7: Time Series Relationship of Effluent Flowrate and Sump Water Stage at Bypass Weir

Solids Performance Comparison during Actual Storm Monitoring and Controlled Sediment Tests

Controlled sediment tests were conducted during the first phase of the actual storm monitoring in order to quantify the solids removal performance under known steady flow rates and particle concentrations. Similar to the hydraulic flow tests, the controlled sediment test influent water was pumped from the adjacent Black Warrior River into a large plastic drum that has flow control outlets to regulate the influent flow rate to the Up-Flo® Filter. Excess water from the pumping was allowed to overflow the drum and drain back into the river away from the Up-Flo® Filter inlet. Flows were calculated by timing how long it took to fill a container having a known volume. Figure 8 illustrates these tests.

Different influent flow rates were tested along with different solids concentrations by manually feeding test particulates into the flow entering the Up-Flo® Filter under steady flow hydraulic conditions. The solids mixture was made using ground silica along with fine and coarse sand in the following proportions: fine sand: coarse sand: Sil-Co-Sil 106: Sil-Co-Sil 250 at 5: 17: 70: 8 mass ratios. This resulted in particle sizes ranging from 20 to 2,000 µm which were tested at approximately 50 mg/L, 100 mg/L, 250 mg/L, and 500 mg/L concentrations. The river water also contributed small portions of fine particles to the mixture. The test mixtures were not intended to coincide with typical particle size distributions of stormwater, but to represent sufficient amounts of the different particle size categories for individual size analyses using combined sieving/Coulter Counter analyses to allow performance calculations for narrow particle size ranges. The following discussion compares the solids performance test results during the controlled and the actual storm period monitoring to indicate performance by size range. The controlled particle control tests also enabled us to examine performance over a wider range of particle size concentrations than were available during the actual storm conditions.

River water is pumped into the plastic flow splitter barrel (high flow test)

River water is pumped into the plastic flow splitter barrel (low flow test)

Pumped river water is discharged from splitter barrel to the 11 gallon plastic tray to manually measure the flow entering the Up-Flo® Filter

Sediment mixture is added to the flow entering the Up-Flo® Filter

Samples are taken from the effluent box after the Up-Flo® Filter

Sample splitting using churn splitter

Figure 8. Controlled Sediment Capture Test

Figure 9 shows the regression plot for both test series combined. The overall SSC performance under actual storms was shown to be greater than those under controlled sediment tests. This is likely due to the controlled solids tests having a greater fraction of smaller particles (from the river water), which are much difficult to be retained by the filter media. These differences are eliminated in the following plots when particle categories are examined separately. These SSC plots were therefore not used in the final performance evaluations because of the differences in the psds of the two series of tests, as the narrow ranges of particle sizes were of greatest interest.

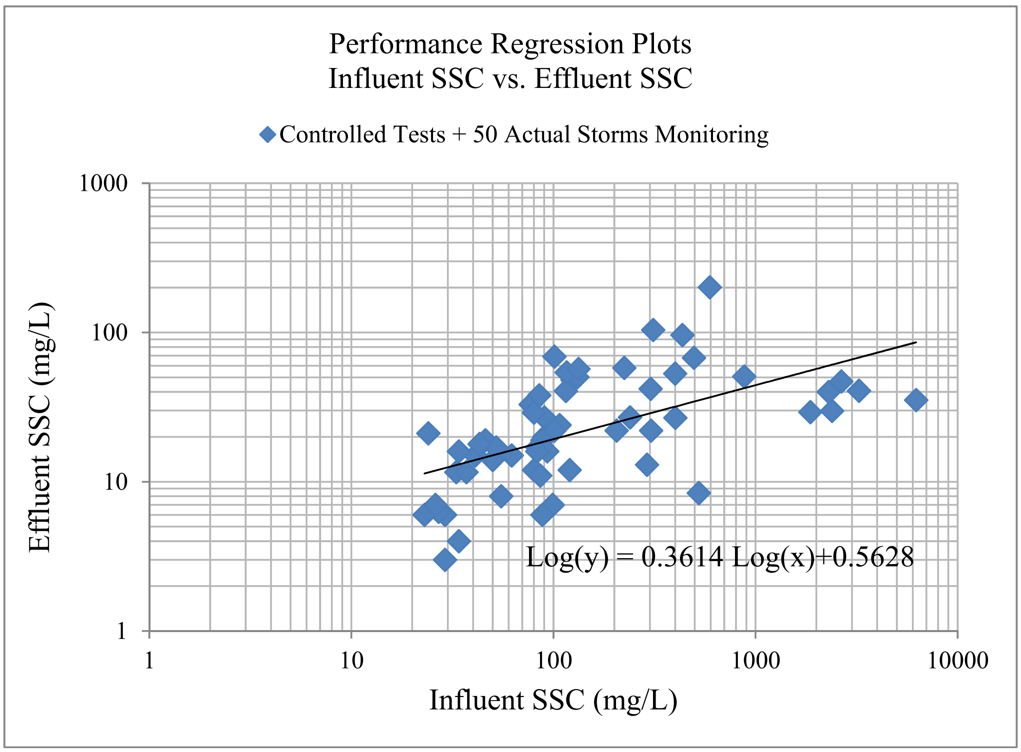


Figure 9: Performance Regression for SSC for Combined Data

Figure 10 combines the two test phases into one regression. While the influent concentrations during the actual monitored storms were always lower than during the controlled tests (due to the large amount of fine particles in the river water), the slopes of the both regression equations are similar and intersect, indicating that the full-scale filter is capable of similarly retaining these very small particles under a wide range of influent concentration and flow conditions.

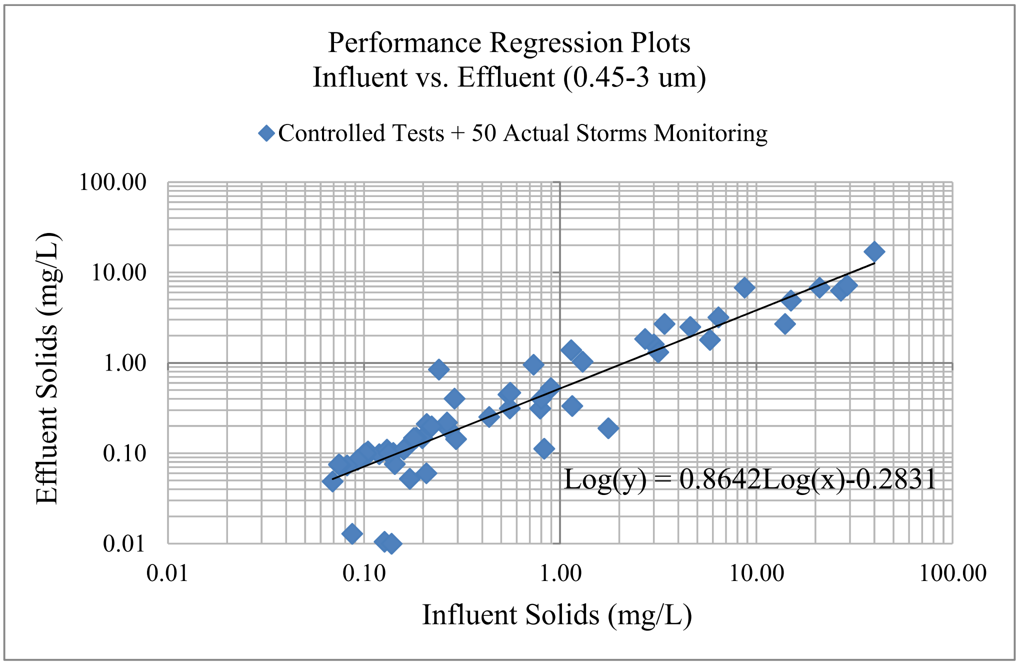


Figure 10. Combined Performance Regression for 0.45-3 µm Solids

Figure 11 shows a similar combined performance regression plot for 3 to 12 µm particles for the controlled sediment tests and during the actual storm monitoring. A large range of influent solids concentrations were included in this particle size range for both controlled sediment tests and actual storm monitoring, from about 1 mg/L to 100 mg/L, with the controlled test concentrations being on the higher end of the range. The controlled tests resulted in higher effluent concentrations than the actual storms tests for this particle size range, but there was substantial overlap of the data.

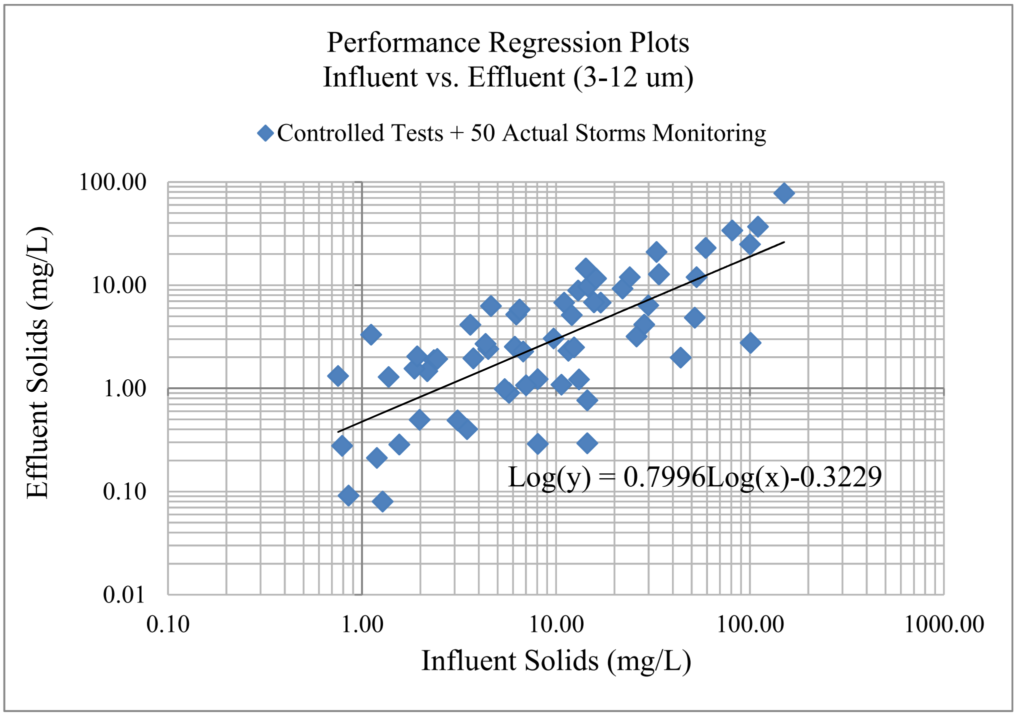


Figure 11: Combined Performance Regression for 3-12 µm Solids

Figure 12 shows the performance regression plot for 12 to 30 µm particles showing the two test categories combined. Both sets of data had wide ranges of influent solids concentrations with much overlap, with the controlled tests being slightly on the upper range of influent concentrations again.

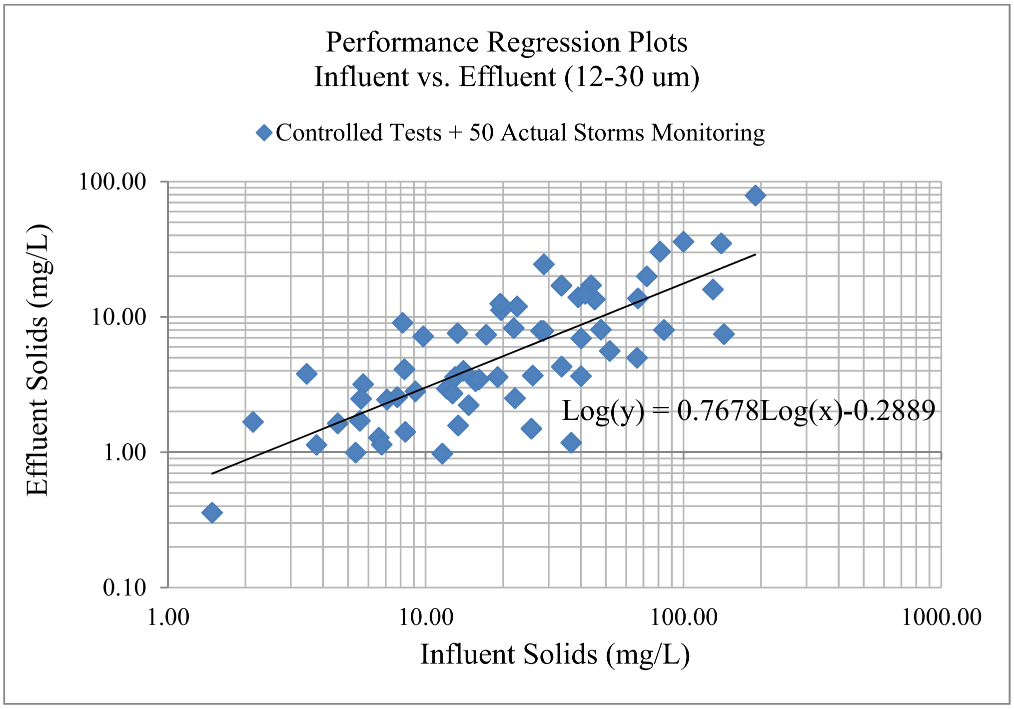


Figure 12: Combined Performance Regression for 12-30 µm Solids

Figure 13 shows the performance plot for the 30-60 µm solid particle size range, indicating substantial overlapping data for both test series.

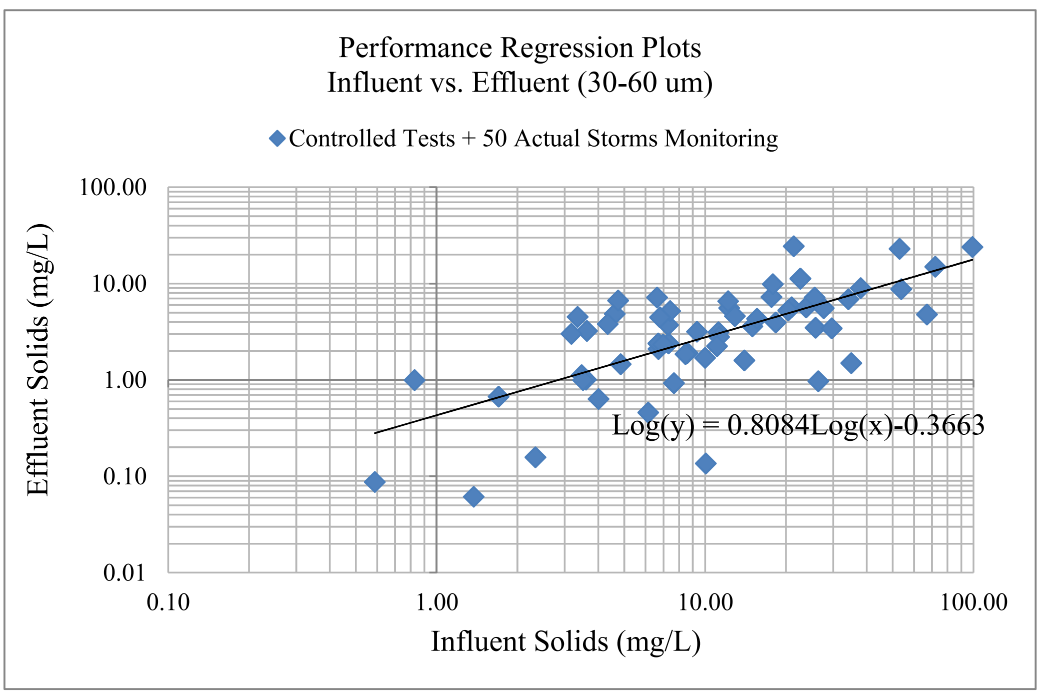


Figure 13: Combined Performance Regression for 30-60 µm Solids

Figure 14 shows the similar performance plot for the particulates in the 60-120 µm particle size range, also indicating substantial overlapping of the data.

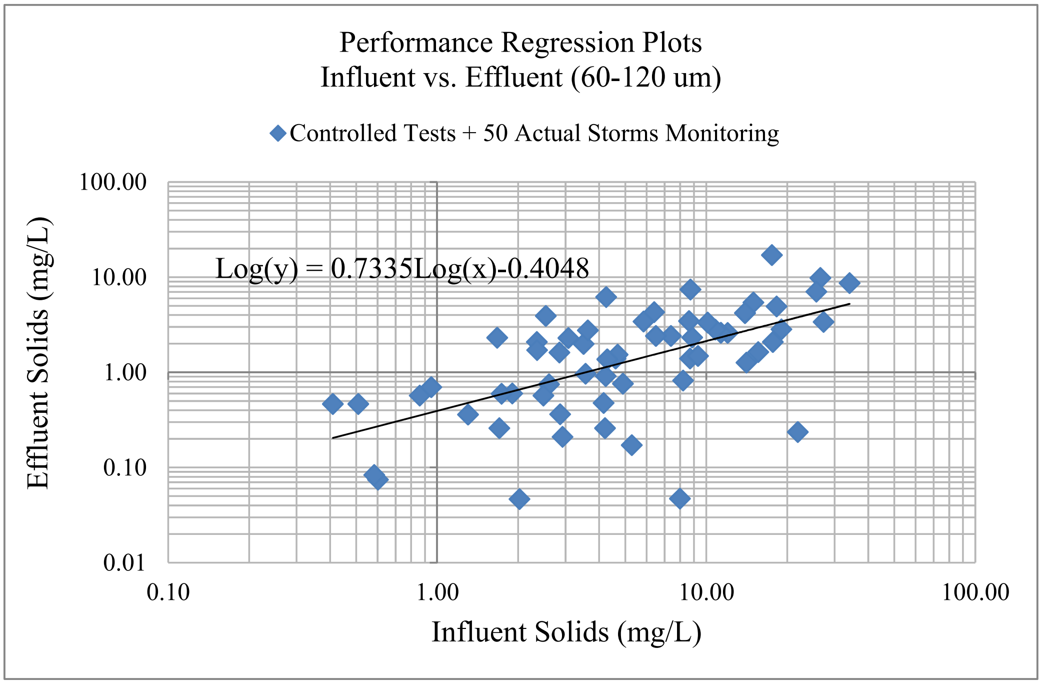


Figure 14: Combined Performance Regression for 60-120 µm Solids

There is no suitable regression for either set of data for the 120 – 250 µm particle range, as shown in Figure 15. The influent concentration ranges substantially overlapped both test series. The effluent concentrations are random and very low (<0.5 mg/L) compared to the influent concentrations. Therefore the performance of this particle size range is described by the average and coefficient of variation (COV) (the ratio of the standard deviation to the average) of the effluent quality. The removals were significant for both categories of testing separately and combined.

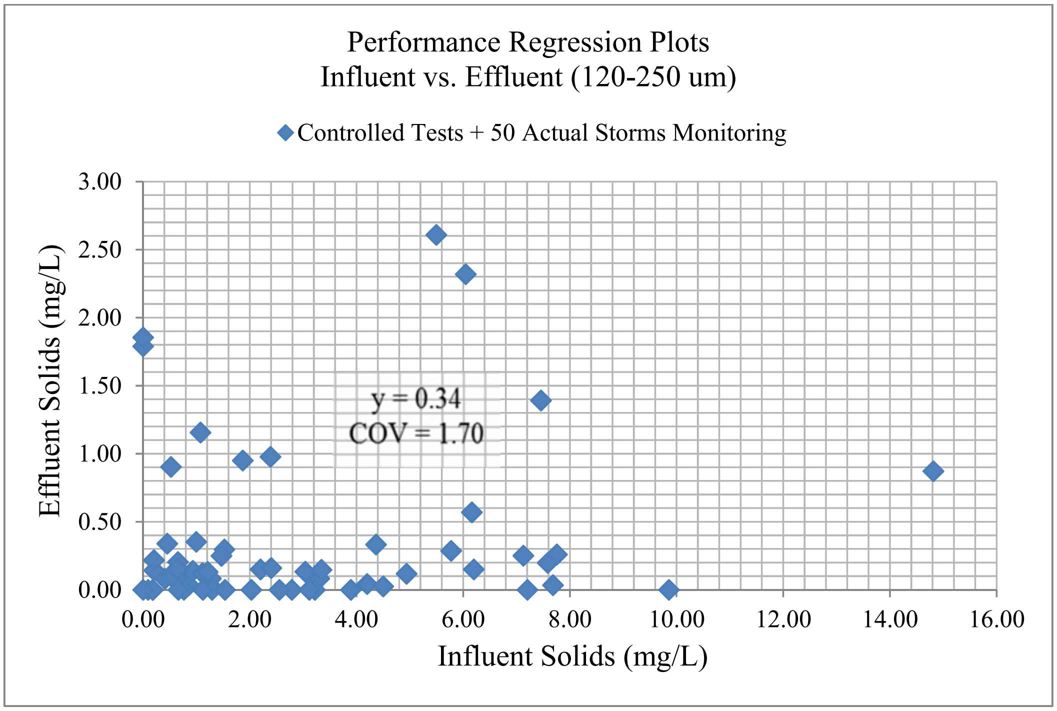


Figure 15: Combined Performance Regression for 120-250 µm Solids

Figure 16 show the performance plot for the 250 – 1180 µm particle size range. Effluent concentrations in this size range for all of the controlled tests were not detected, while there were some large particles in the effluent in this particle range during the actual storms tests. This is likely due to the difference in the specific gravities of the particles in the two sample sets. During the controlled tests, the ground silica with a 2.65 specific gravity were used, while these particles during the actual storms had much lower specific gravities and therefore had reduced settling capabilities. Some of the low influent concentration tests were associated with effluent concentrations that were greater than the influent concentrations, possibly indicating some scour in this size range, or just more uncertainty in the analyses for these sizes at the low concentrations observed. Therefore, the combined regression only considers the performance during actual storm monitoring.

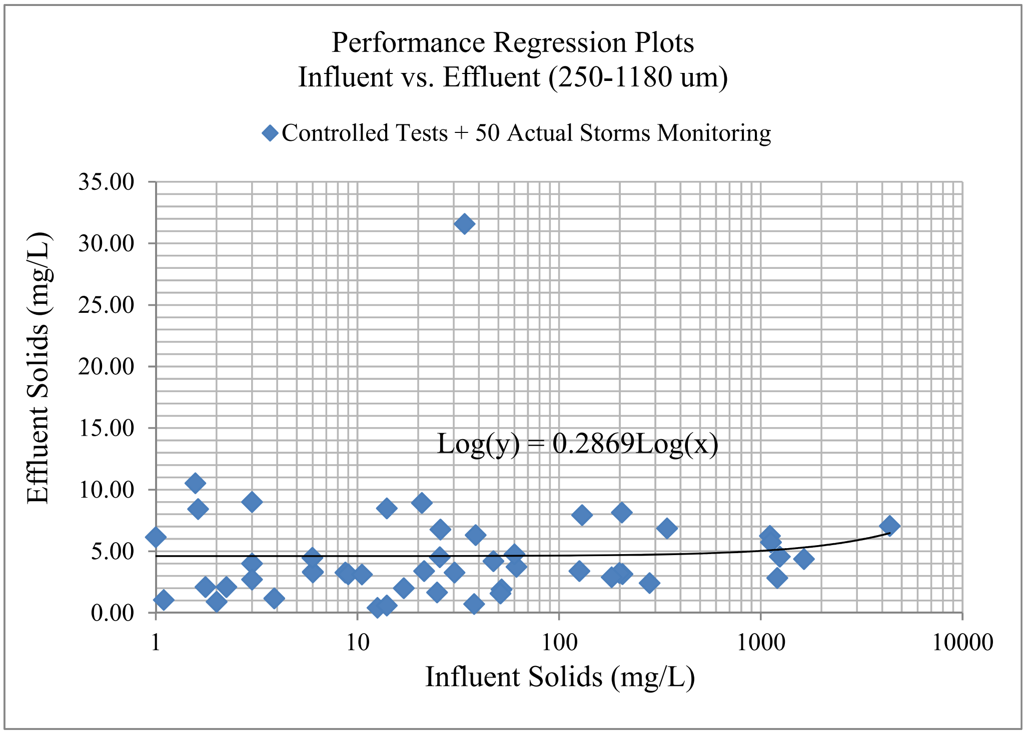


Figure 16: Combined Performance Regression for 250-1180 µm Solids

There were no detected effluent concentrations for the largest particle size category (>1,180 µm) during either the controlled or actual storm monitoring periods. Therefore, no performance comparison plots or regressions for this size range were prepared (effluent = 0 mg/L under all conditions regardless of the influent solids concentrations).

In summary, the performances of the controlled and actual storm tests were very similar. It was originally thought that the specific gravity of the ground silica and sand components during the controlled tests (being about 2.65) would result in significantly better removals compared to the same particle ranges during the actual storm tests, when the specific gravities were much lower (1.5 to 2.5). Apparently, the UpFlo® filter is less sensitive to these specific gravity differences than originally thought, and as would be evident for sedimentation type controls. Two differences were noted during these tests. The influent solids concentrations for the smallest particle size range during the controlled tests were larger than those observed during the actual storm monitoring likely due to a greater amount of fine suspended matter in the river water that was used during these controlled tests. However, the performance relationships during the two test series for this size were similar when combined. Also, the performance of the 250 to 1,180 µm particle size range during the actual rains apparently were somewhat affected by automatic sampler inconsistencies in this larger size range or light-weight organic material, resulting in decreased performance compared to the controlled tests. The mass balance evaluations and sump analyses described later were also used to examine the performance in this larger particle size range.

As noted, the PSDs for the controlled tests were not intended to be similar to stormwater, but were designed to provide sufficient particulate mass in each of the size ranges for the targeted analyses and comparison with those in actual storms. These performance equations for each separate size range were used in WinSLAMM to predict the performance of the UpFlo® filter under a wide range of psd and concentration conditions.

Sum-of-Loads and Mass Balance Evaluations

Large subsamples of the filter sump sediment were collected for drying and further analyses at the end of the monitoring period to compare with the calculated particulate removals during the monitoring period from the automatic samplers. Automatic water samplers have decreased sampler efficiency for large (>250 um) particles, but can also bias the results of large particles if the intakes are located near the bottom of a flow path where bedload accumulates. This mass balance monitoring is therefore another QA/QC check of the monitoring data.

Sump sediment analyses included particle size distribution (PSD), percent volatile solids, specific gravity, bulk density, and selected constituents for separate particle size ranges. The evaluation focused on an overall solids mass balance calculation for the calibration of the performance data from the auto samplers. The sediment analyses effort also included continuous monitoring of sump sediment accumulations by periodically manually measuring the sediment depth, and automatically recording using a liquid-filled (degassed water) USGS load-cell scour sensor (from Rickly Hydrological Company) placed on the bottom of the sump. The filter media bags were also carefully removed when the sump sediment was sampled and replaced with new media bags. The used media bags were also dried and weighed to estimate the accumulation of solids captured within the media bags.

About 10 inches of sediment was measured in the sump at the end of the monitoring period (on April 2nd, 2013). During the monitoring period, about 980,000 gallons of runoff had been treated by the UpFlo® filter system. In order to keep sediment accumulations well away from the bottom of the filter media bags and coarse screening, the maximum sediment depth before cleanout needs to be less than 2 ft deep. This depth of sediment may therefore accumulate in about 2.5 years of operation for the rain and runoff conditions encountered at the test site (about 60 inches of rainfall a year, or 150 inches of rain before the sump would require cleaning).

Four large subsamples were obtained from the sump for analyses at the end of the monitoring period. The particle size distribution plots for these sump sediment samples are shown on Figure 17. The plots shows that the median particle size in the sump was about 390 µm, and about 10% of the captured mass retained in the sump was less than 80 µm. The sediment coefficient of uniformity was 6.7 (the ratio of the 60th percentile diameter to the 10th percentile diameter). Very few particles smaller than 50 µm are observed in catchbasin sumps, as the highly turbulent flow conditions during storms mostly hinders the settling of fine materials.

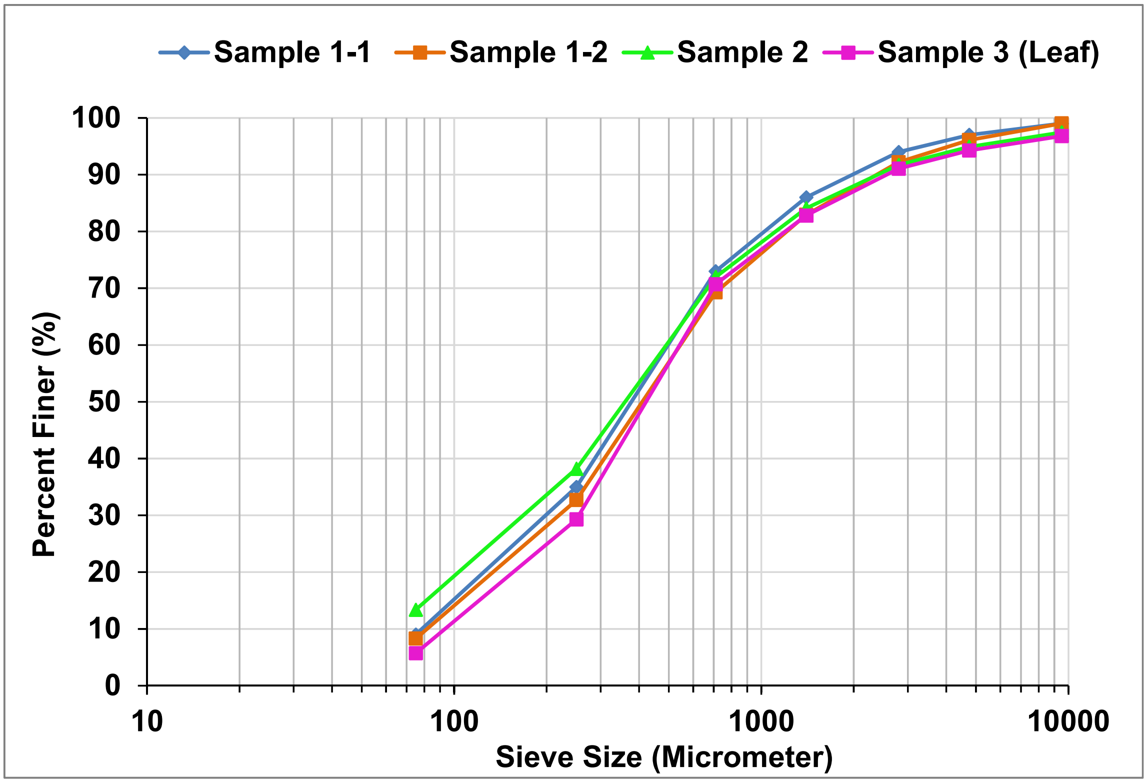


Figure 17: Particle Size Distributions of Four Sump Subsamples.

Table 4 shows that the average dry bulk density of the sampled sediment was about 0.6 g/cc. This bulk density value is low compared to those for typical urban street dirt and sump sediments (usually about 1 g/cc). The Bama Belle monitoring site has nearby trees, and leaves were about 3.5% by mass of the sediment (but comprised a large volume fraction). Table 5 shows that the specific gravities of the sediment (always larger than the bulk density as the specific gravities are corrected by the void volume) increased as the particle size ranges decreased, indicating increasing amounts of mineral soils with decreasing size and larger amounts of lighter organic material for the larger particles.

Table 4: Solids Characteristics of Sump Sediment Samples (average of four large subsamples)

Average Dry Bulk Density (g/cc)	d_{10} (µm)	d_{50} (µm)	d_{60} (µm)	Coefficient of Uniformity (C_u)*
0.6	80	390	525	6.7

* d_{60}/d_{10}

Table 5: Solids Characteristics of Sump Sediment Samples

Sieve size range (um)	Specific Gravity (g/cc)	Total Solids Portion Size Range (%)	Volatile Solids of Particles in Size Range (%)
Leaves	2.28	1.85	93.2
Sticks	0.84	2.00	81.2
>2800	0.66	7.29	70.9
1400 - 2800	1.15	8.90	57.8
710-1400	1.43	13.08	42.7
355-710	2.56	18.31	26.1
180-355	2.76	20.32	19.4
75-180	2.97	17.32	20.6
45-75	3.30	5.10	25.7
<45 (Pan)	3.46	5.83	26.0

Tables 6 and 7 show the results of chemical analyses (mostly heavy metals and nutrients) for each particle size of the sediment samples. The composite samples were prepared after drying and sieving the large bulk subsamples. Lead, copper, and zinc show the typical pattern of having increasing concentrations in the smaller particle sizes. Cadmium was only detected barely above the detection limits and showed no obvious pattern, while chromium had the highest concentrations in the mid to large particle sizes. The large organic material (leaves and sticks) had the lowest concentrations of the heavy metals, including the large mineral fraction (general). The nutrients were more evenly distributed by particle size, with total nitrogen apparently higher in the leaf fraction, and the COD having a larger peak concentration with the larger sieved material.

Table 6. Heavy Metal Content of Sump Sediments

Sieve size range (µm)	Cd (mg/kg)	Cr (mg/kg)	Pb (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
Leaves	1.6	7	5.8	28	90
Sticks	<0.5	3	2.7	12	62
>2800	1	12	8.8	20	131
1400 - 2800	1.5	130	16	25	233
710-1400	1.4	104	20.6	26	213
250-710	0.5	55	14.7	13	127
75-250	0.9	39	28	47	209
<75 (Pan)	1.5	71	45.9	53	344
DL	0.5	2	0.5	2	2

Table 7. Nutrient and Other Analyses of Sump Sediments

Sieve size range (µm)	COD (mg/kg)	Total Nitrogen (mg/kg)	Total Phosphorus (mg/kg)	Total Sulfate* (mg/kg)
Leaves	3,500	8,170	213	2,120
Sticks	2,230	5,490	78	1,630
>2800	11,800	5,750	436	2,620
1400 - 2800	3,100	6,430	128	1,370
710-1400	1,350	7,200	65	1,300
250-710	750	1,330	374	860
75-250	1,980	2,740	164	2,040
<75 (Pan)	3,350	4,540	53	4,380
DL	50	50	10	10

*total sulfide and total sulfite were all BDL (DL = 50 and 100 mg/kg respectively)

About 10.5 ft^3 (corresponding to about 400 lbs) of sediment was calculated to be in the sump after the one-year monitoring period based on the known geometry of the filter sump, the calculated dry bulk density of the sediment (0.6 g/cc), and the measured sump sediment depth (10 inch). About 150 lbs of this total mass in the sump were assumed to be associated with the 25 selected sampled storms during the second monitoring period, based on the ratio of the runoff depth for the monitored storms and runoff for all storms during the period. Only 25 of the 30 total events were used in this sum of loads calculation as five sampled events were excluded due to unusually high mass loads of particles from the influent auto sampler for some size ranges which led to a large bias in the mass balance. About 20 lbs of material was also captured in the filter media bags and flow distribution material during the one year period (calculated by the weight increase between the initial weighing and final weighing at the end of the study period after the media bags and flow distribution material were dried and weighed), with about 7.7 lbs of captured material in the filter modules associated with the 25 sampled storms.

A total of about 170 lbs of solids was estimated to be retained in the whole filter system (filter media and sump bottom) associated with the 25 monitored storms during the one year period. This total mass was prorated into each particle size range of each selected sampled event based on the sump sediment PSD. The sump mass indicated only about half of the total measured particulate removals as measured by the automatic samplers (assuming a bulk density of 0.6 g/cc). With a typical bulk density closer to 1 g/cc, the mass balance would be quite close. As a conservative approach, the automatic sampler data was used for the particles <250 µm, while the prorated sump mass (likely low) was used for the larger particles (acknowledging the autosamplers have inconsistent performance for the larger particles). Similar mass balance calculations were also conducted to a set of 16 sampled storms from first full-scale monitoring phases (which were associated 191 pounds of sump sediment). Not all of the initial 20 full-scale monitoring events had complete data sets, so four were removed from these analyses. Therefore, a total of 41 sampled storm events were included in the final sum-of-loads evaluation to verify the solids removal performance for a wide range of monitoring conditions.

Table 8 shows the overall accumulative sum-of-loads performance associated with the 41 sampled events for each particle size. The total influent measured particulates for these 41 events were 478 pounds (217 kg), while 93 pounds (42 kg) was the measured effluent particulate mass, for a measured accumulation close to the observed 400 lbs found in the sump. The solids captured for each specific particle range increased as the particle sizes increased, as expected, and the overall removal rate for the total particulates loading was about 80%, which was within the design goal of solids removal performance of the full-scale Up-Flo® filter.

Table 8: Accumulative Mass of Influent and Effluent Total Particulates by Particle Size Range

Particle Size Range (um)	Influent Total Mass (With Sump*) (lbs)	Effluent Total Mass (lbs)	Percent Reduction
0.45 - 3	1.75	1.13	35.6
3 - 12	58.79	11.41	80.6
12 - 30	85.24	26.03	69.5
30 - 60	52.35	16.29	68.0
60 - 120	43.04	11.01	74.4
120 - 250	52.94	1.97	96.3
250 - 1180	120.54*	19.49	83.8
> 1180	63.28*	6.14	90.3
Total:	478*	93	80.4

* Without the sump mass corrections for the large particle sizes. The overall calculated performance would be much larger due to likely biases in the influent autosampler

Table 9 shows the summary information for the regression and ANOVA analyses for each particle size range for the sum-of-load evaluations for the mass removals (in lbs). These regression equations are different from the previous regressions that were based on influent and effluent concentrations (mg/L). All of these regression calculations were based on $\log_{10}$ transformed data, except for the particle size 120-250 µm and >1180 µm due to the large fraction of non-detectable effluent concentrations. These regressions and ANOVA summaries demonstrate that all of the particle size ranges had statistically significant reductions, as the p-values based on Wilcoxon Signed Rank hypothesis test were all less than or equal to 0.005. Some of the R^2 values are low, corresponding to effluent concentrations that varied little.

Table 9: Summary of SOL Regression Performance of Particle Size Ranges (41 eligible events); influent and effluent values are loads (lbs)

Particle Size (um)	Regression Equation	Adjusted R Square	P-value of X Variable	P-value of Intercept	Significance Factor of Equation	P-value of Influent Equals to Effluent
0.45 to 3	Log(y) = 1.0979Log(x)	0.95	<0.0001	NA	<0.0001	<0.001
3 to 12	Log(y) = 0.7228Log(x)-0.6503	0.46	<0.0001	<0.0001	<0.0001	0.001
12 to 30	Log(y) = 0.9318Log(x)-0.5856	0.67	<0.0001	<0.0001	<0.0001	<0.001
30 to 60	Log(y) = 1.0153Log(x)-0.6203	0.59	<0.0001	<0.0001	<0.0001	<0.001
60 to 120	Log(y) = 0.9936Log(x)-0.7933	0.43	<0.0001	<0.0001	<0.0001	<0.001
120 to 250	y = 0.048 (COV = 2.42)	NA	NA	NA	NA	<0.001
250 to 1180	Log(y) = 0.4626Log(x)-0.6972	0.17	0.0048	<0.0001	0.0048	<0.001
>1180	y = 0.1523x	0.27	0.0042	NA	0.0044	<0.001
Total (SSC)	Log(y) = 0.9273Log(x)-0.7165	0.59	<0.0001	<0.0001	<0.0001	<0.001

Figures 18 and 19 show the particle size distributions for the accumulative particulate solids percentage and mass distributions for these 41 sampled storm events, incorporating the prorated portion of the sump sediment for the large particles. The accumulative percentage plot indicates that the overall median particle size of the influent was about 60 µm, while the median particle size for the effluent was about 20 µm.

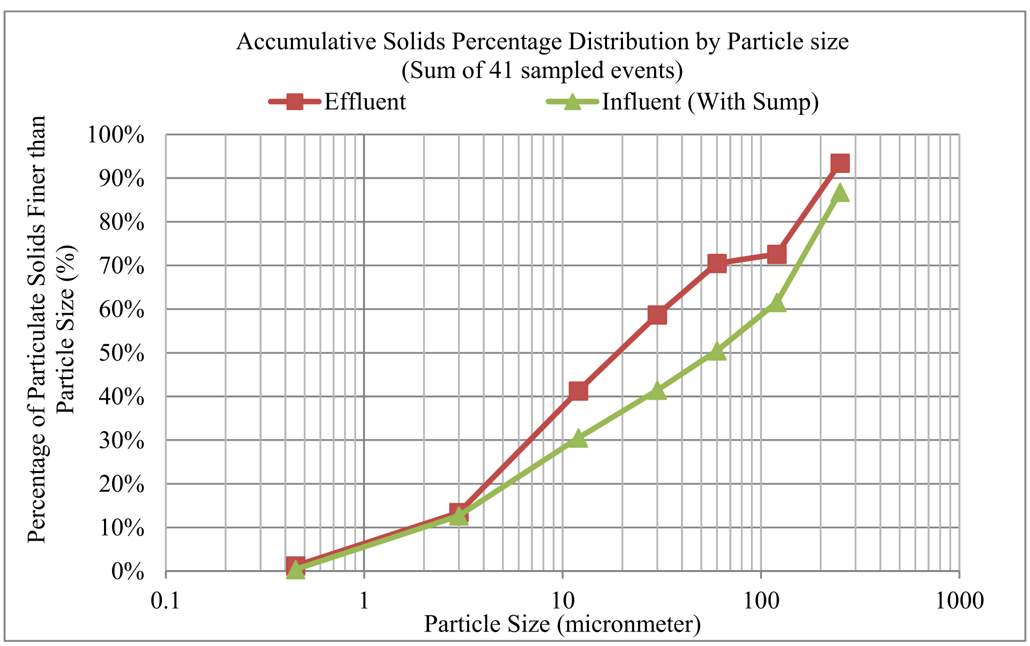


Figure 18: Accumulative Solids Percentage Distribution by Particle Size with Sump Sediment (41 Sampled Events)

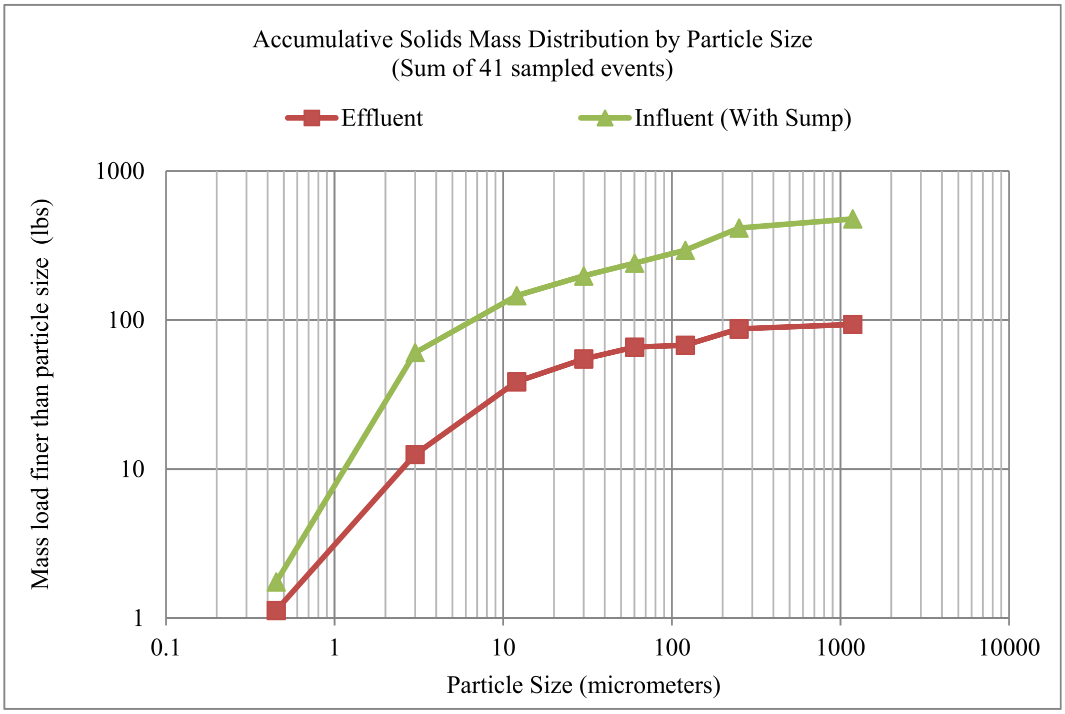
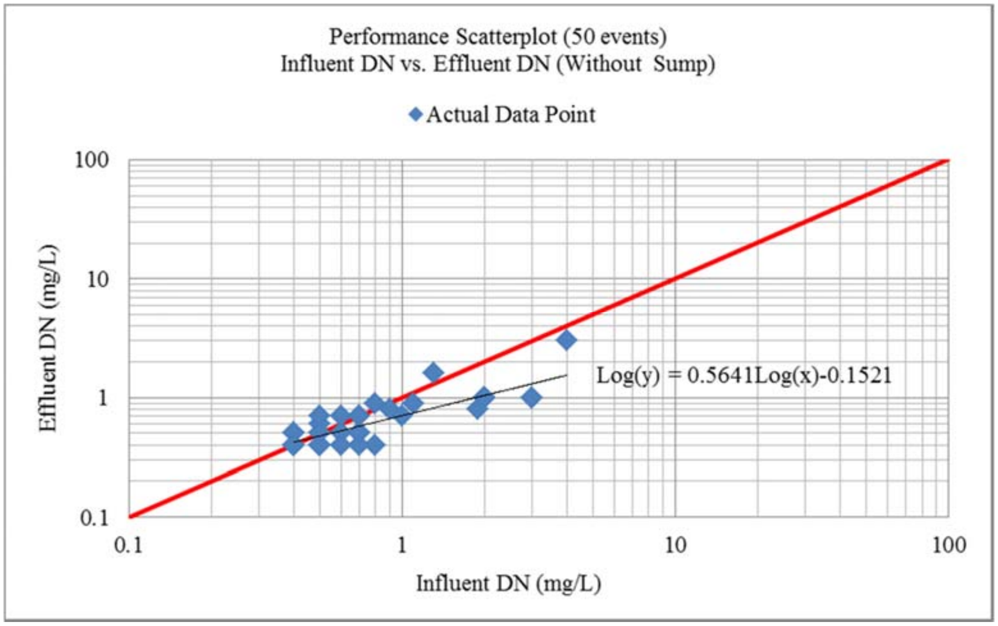


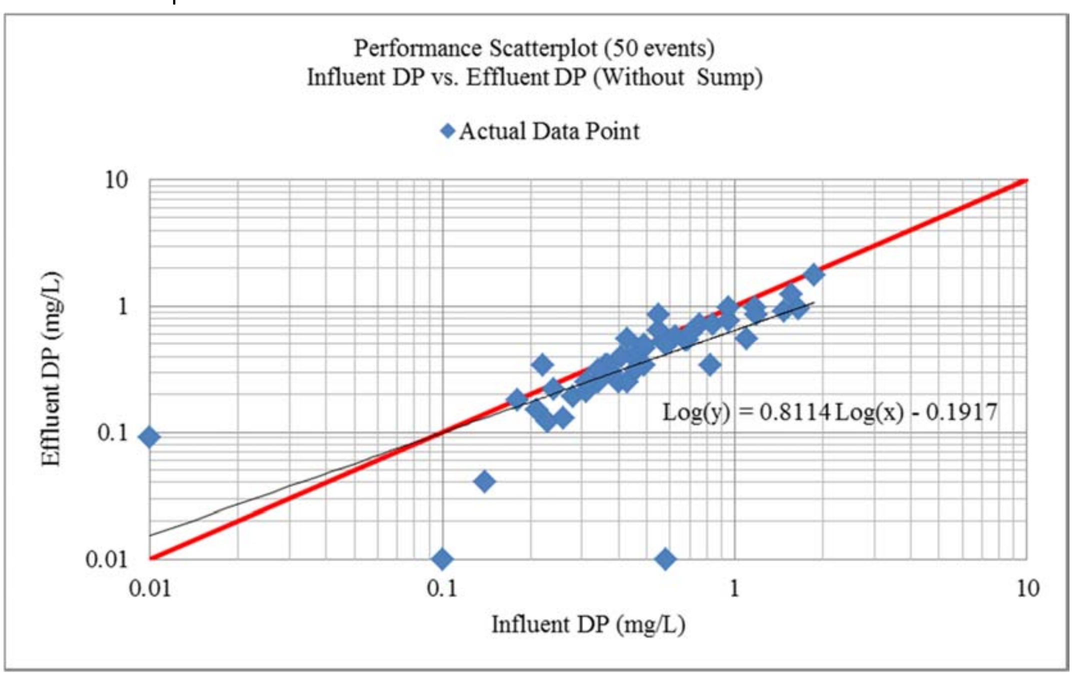
Figure 19: Accumulative Solids Mass Distribution by Particle Size with Sump Sediment (41 Sampled Events)

Filterable Nitrogen, Filterable Phosphorus, and Bacteria Removals in UpFlow Filter (statistically significant removals)

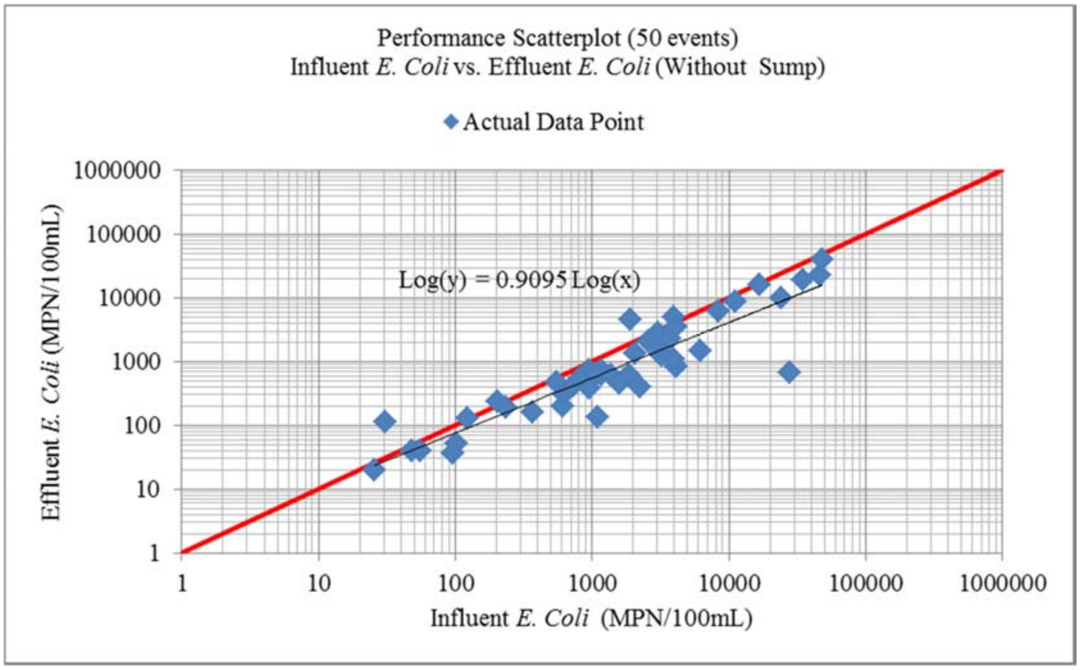
Dissolved Nitrogen:



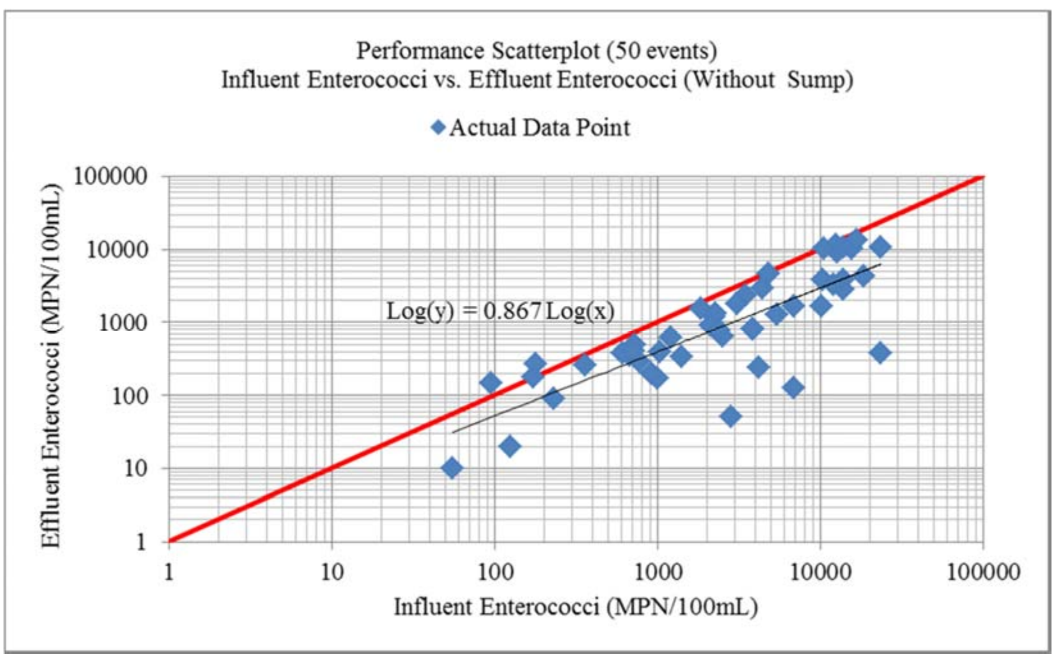
Dissolved Phosphorus:



E. Coli:

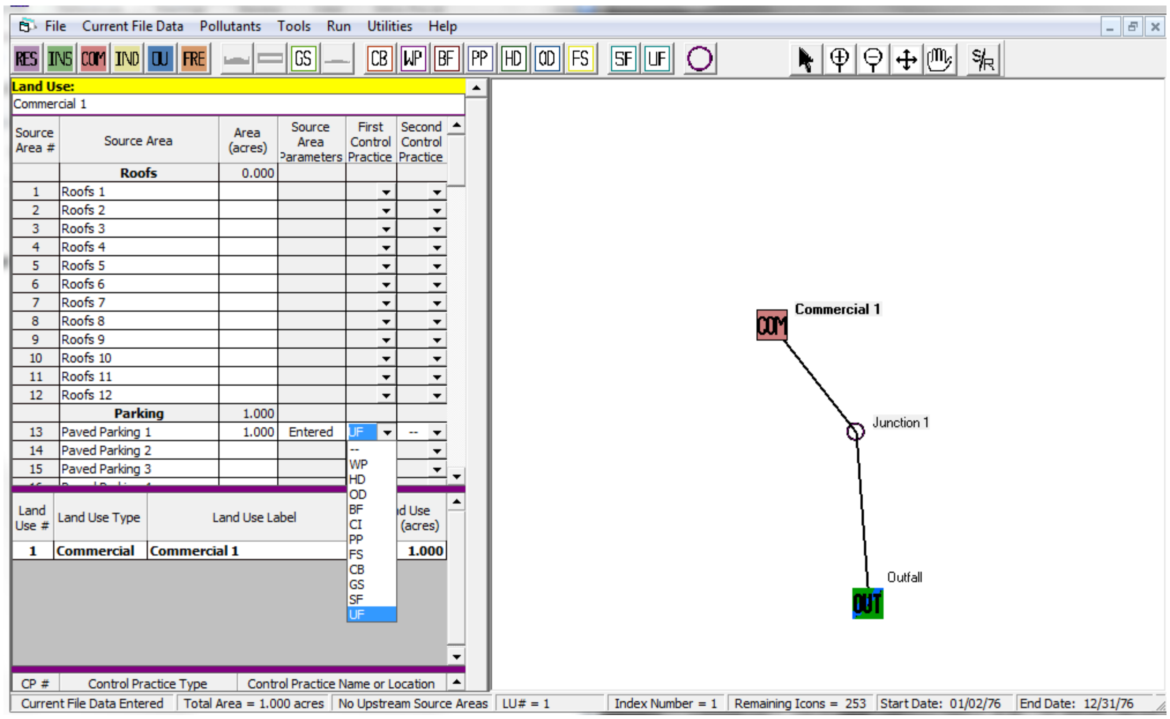


Enterococci:

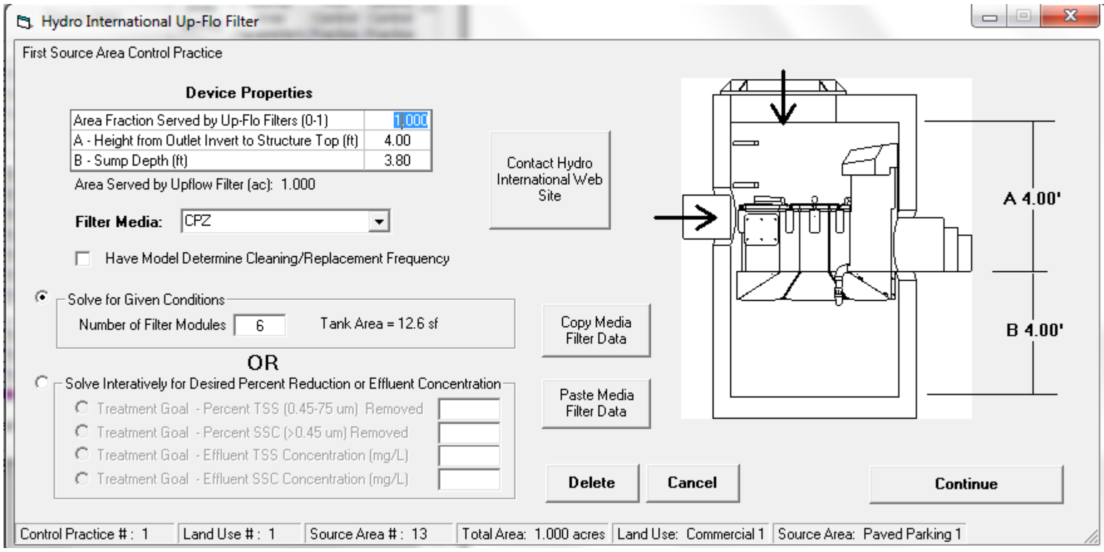


User Guide for UpFlo Filter Evaluations in WinSLAMM

The UpFlo filter can be used at either a source area (as shown below for a paved parking area dropdown menu) or as a system control as indicated by the UF symbol on the top row.



The UpFlo Filter device screen is simple, as much of the manufacture's information concerning dimensions and media selections are incorporated as menu items. The only dimensions needed are the height from the outlet invert to the structure top (noted as "A" on the screen) and the sump depth (noted as "B" on the screen). The fraction of the area directed to the device can also be changed (1, or 100% is shown as the default value, but it can be reduced). Any water from the source area not treated is diverted around the device and blended with the treated effluent. The characteristics of the runoff (volumes, flow rates, quality, particle size distribution) being treated are determined by the model for each rain based on the source area characteristics (paved parking, street, roof, driveway, etc.) and land use.



The media in the UpFlow Filter is also selected, from the most common CPZ (carbon, peat and zeolite), CPS (the northern mixture using sand instead of the zeolite to prevent metal ion exchange with deicing salts), filter sand, or perlite. Contact HydroInternational for availability of specific media for the site conditions.

In addition, WinSLAMM can evaluate the performance of the UpFlo Filter in two ways: selecting a given condition for a specific number of filter modules (after entering the value, the model shows the corresponding footprint area in square feet), or the model can solve for the number of cartridges (and footprint area) for a desired effluent goal (TSS or SSC, mg/L or % reduction). In some cases, the goal cannot be achieved, as indicated by reviewing the "control practices" tab. Column 24 in the summary shows the number of cartridges (either specified or solved). Columns 55 and 56 should also be noted if the desired level of control was not achieved.

Land Uses | Junctions | **Control Practices** | Outfall | Output Summary

Runoff Volume | Part. Solids Yield (lbs) | Part. Solids Conc. (mg/L) | **Summary Table**

Data File: C:\WinSLAMM Files\E
Rain File: AL Birmingham 76.RAN
Date: 07-30-15 Time: 16:30:05
Site Description:

Col. #:	2	4	5	6	7	8	9	10	11	12	13	14
Control Practice No.	Control Practice Type	Total Inflow Volume (cf)	Total Outflow Volume (cf)	Percent Volume Reduction	Total Influent Load (lbs)	Total Effluent Load (lbs)	Percent Load Reduction	Flow Weighted Influent Conc (mg/L)	Flow Weighted Effluent Conc (mg/L)	Percent Conc. Reduction	Influent Median Part. Size (microns)	Effluent Median Part. Size (microns)
1	Upflo Filter	159942	159799	0.08941	1298	248.4	80.86	130.0	24.90	80.845	55.00	6.40

Junctions | **Control Practices** | Outfall | Output Summ

Part. Solids Yield (lbs) | Part. Solids Conc. (mg/L) | **Summary Table**

15	18	24	40	41	42	43	44	45	46	47
Notes	Maximum Stage (ft)	Number of Cartridges	Number of Tank Overflows (Count)	Number of Tank Height Exceedance	Bypass Volume (cf)	Bypass Conc. (mg/L)	Bypass Mass (lbs)	Overflow Volume (cf)	Overflow Conc. (mg/L)	Overflow Mass (lbs)
	6.63	6	#> 6.63' = 40	#> 9.8' = 0	0	0.00	0.00	41921	65.51	171.44

Junctions | **Control Practices** | Outfall | Output Summary

Part. Solids Yield (lbs) | Part. Solids Conc. (mg/L) | **Summary Table**

47	48	49	50	51	52	53	54	55	56	61
Overflow Mass (lbs)	Cartridge Flow Volume (cf)	Cartridge Effluent Conc. (mg/L)	Cartridge Effluent Mass (lbs)	Final Sump Sediment Depth (ft)	Average Cleaning Frequency (yrs)	Cartridge Particulate Removal Efficiency-%	Residence Time in Media (hrs)	Max. Filter Number	Max. Filter Treatment Goal mg/L or %	Runoff Producing Events/ Ttl. Rains
171.44	117878	10.46	76.98	0.84	Not Cleaned	30	0.038	0	0.00	112/112

Control Practices Summary Sheets for UpFlo Filter.

Performance Functions of UpFlo Filter in WinSLAMM under Various Conditions

The Hydro International UpFlo filter can be evaluated in WinSLAMM using many different options and routines, as described above. When designing the input screens, great care was taken to simplify the input requirements for the user by coding in standard dimensions and only showing available choices. The stormwater treatment performance of the UpFlo Filter is affected by many different factors, including drainage area/rainfall characteristics and particle size distributions of the particulate solids, along with the fraction of the pollutants in filterable forms. The following is a brief summary showing how these factors can affect the performance of the UpFlo Filter under a range of conditions: five year analyses for one acre paved parking areas in Seattle, Madison, Cincinnati, and Atlanta, with four different particle size distributions: NURP psd, SSC psd, TSS, and Sil-Co-Sil 10. The UpFlow Filter system reduces particulate solids through both sedimentation in the sump and by filtering in the cartridges themselves. The NURP particle size distribution has few large particles so more cartridges are needed to attain an 80% particulate solids reduction. The TSS, SSC, and SCS 106 size distributions have similar 80th percentile values so the number of cartridges do no vary much for these three size distributions (which vary greatly for the smaller particle sizes). In addition, locations having more intense rains (as reflected by Atlanta) require more cartridges for the same level of control compared to areas having relatively mile rain intensities (as reflected by Seattle in this example). The cleaning frequency of the chambers (and concurrent media replacement) ranged from about every 6 months to every 2 years (based on the accumulation of material in the sump). The residence time in the media filters was about 4 or 5 minutes for these conditions.

Seattle, WA (1995 thru 1999; 41.7 in/yr annual rainfall) with CPZ media

Particle Size Distribution (91 mg/L influent past. solids)	# of cartridges needed for 80% particulate solids reduction (per acre of paved parking)	cleaning frequency (yrs)	residence time in media (minutes)
NURP	5	0.6	4.7
TSS	2	0.3	4.7
SSC	3	0.6	4.7
SCS 106	2	0.5	4.7

Madison, WI (1995 thru 1999 rains: 24.4 in/yr annual rainfall, w/o winter) with CPZ media

Particle Size Distribution (195 mg/L influent part. solids)	# of cartridges needed for 80% particulate solids reduction (per acre of paved parking)	cleaning frequency (yrs)	residence time in media (minutes)
NURP	9	0.9	4.5
TSS	6	0.6	4.4
SSC	6	0.9	4.4
SCS 106	5	0.7	4.3

Cincinnati, OH (Covington KY 1995 thru 1999 rains: 41.8 in/yr annual rainfall) with CPZ media

Particle Size Distribution (118 mg/L influent part. solids)	# of cartridges needed for 80% particulate solids reduction (per acre of paved parking)	cleaning frequency (yrs)	residence time in media (minutes)
NURP	8	0.7	3.8
TSS	4	0.5	3.8
SSC	4	0.6	3.8
SCS 106	4	0.5	3.8

Atlanta, GA (1995 thru 1999; 46.7in/yr annual rainfall) with CPZ media

Particle Size Distribution (53 mg/L influent part. Solids)	# of cartridges needed for 80% particulate solids reduction (per acre of paved parking)	cleaning frequency (yrs)	residence time in media (minutes)
NURP	14	2.3	2.5
TSS	8	2.2	2.3
SSC	8	2.2	2.3
SCS 106	8	1.9	1.3