Upflow Filtration for the Treatment of Stormwater at Critical Source Areas

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XX.1 Abstract

One approach to the treatment of urban runoff is to treat the runoff from critical source areas before it mixes with runoff from less pollutant areas. Some of the general features of critical source areas appear to be large paved areas, heavy vehicular traffic, and/or exposed heavy equipment, materials or products. The control of runoff from relatively small critical source areas (such as loading docks, fueling areas, small maintenance yards, etc.) may be the most cost effective approach for the treatment/reduction of stormwater toxicants. However, in order for a treatment device to be usable, it must be inexpensive, both to purchase and to maintain, and be effective.

Upflow filtration of stormwater was tested during both controlled tests, and under actual rainfall conditions, during SBIR1 (Small Business Innovative Research) and SBIR2 research funded by the US EPA. This paper summarizes the work presented by Pitt, *et al.* (2005), Khambhammettu (2006), and Pitt, *et al.* (2006) reporting on this research. Upflow filtration was originally developed to overcome some of the problems associated with conventional filtration. The most serious problem is that downflow filters clog relatively quickly, reducing the treatment flow rate potential and total treatment capacity, potentially causing large amounts of the stormwater to bypass the treatment units. Clogging does not occur as fast with upflow

filtration. One reason is that the heavier particles are drawn away from the filtration interface due to gravity and fall into the sump which is an integral part of the upflow filter design. Figures 1 and 2 are schematics of the prototype UpFlo[TM] filter that was evaluated at Tuscaloosa, AL, as part of the SBIR2 tests. Figure 3 is a drawing of the full-scale commercial UpFlo[TM] filter that is undergoing EPA ETV (Environmental Technology Verification) testing at Penn State – Harrisburg.
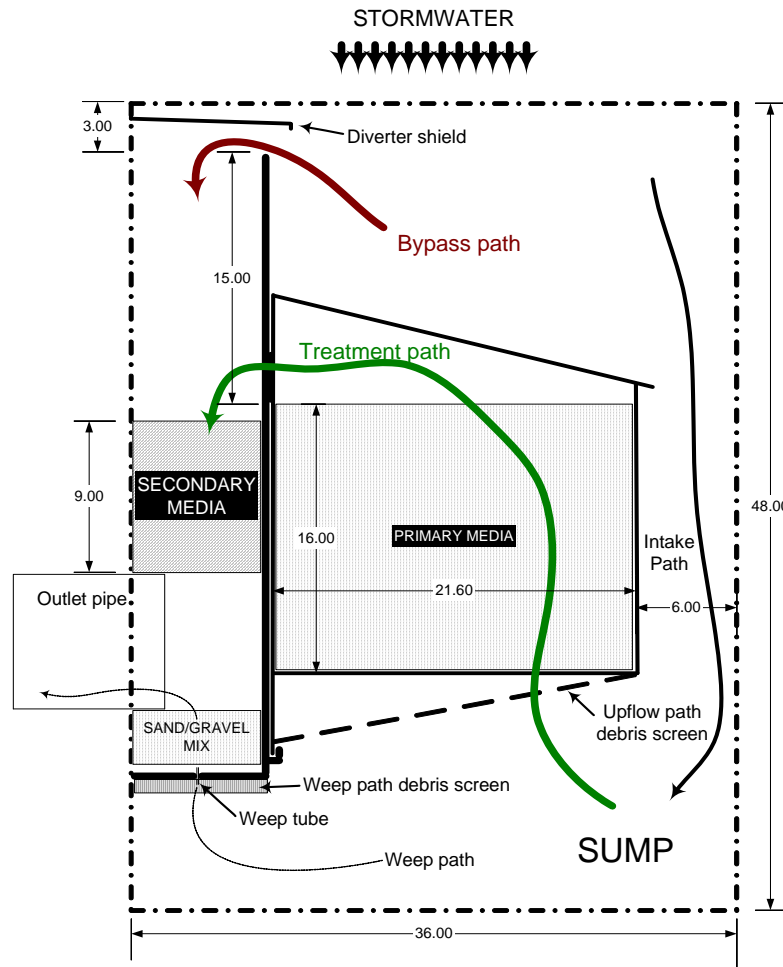
Figure 1. Side view of UpFlo[TM] filter.

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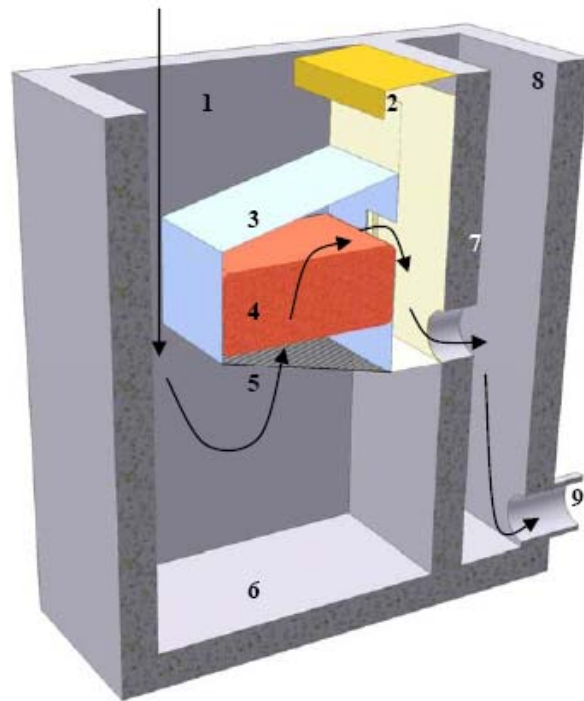so vertical dimension
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Figure 2. Schematic of Up-Flo™ Filter prototype
(Hydro International, Ltd.).

1. Filtration chamber
2. Bypass with floatables
   baffle
3. Media housing
4. Filtration media
5. Angled screen
6. Sump
7. Baffle wall
8. Effluent chamber
9. Outlet pipe
10. Weep tubes (not shown)

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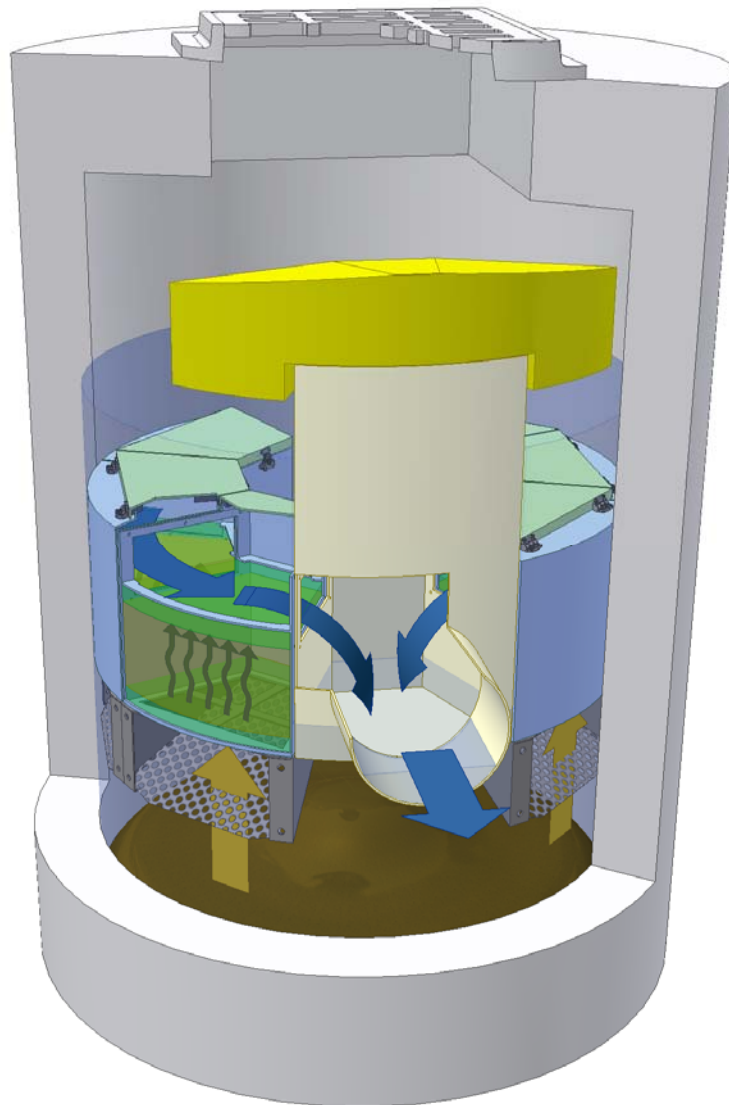so vertical dimension
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Figure 3. UpFlo™ filter drawing during normal filtering operation (Hydro International, Ltd.).

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XX.2 Introduction

Numerous manufacturers have developed proprietary devices to treat stormwater runoff. These devices have been designed to treat one or more of the common stormwater pollutants – solids, metals, oil and grease, nutrients and bacteria. Few have been designed to treat a broad range of pollutants in a single device. In addition, many of these devices provide inconsistent performance from one installation to another. Treatment of runoff from critical source areas requires a device with robust removal ability.

The performance of the prototype Upflo^{TM} filter has been tested under controlled flow and actual storm events with the following objectives

- To determine how the head loss and associated treatment rate change during upflow filtration.
- To evaluate the effect of decreasing/increasing the filter flow rate on the treatment efficiency.
- To predict the performance of the upflow filtration for various pollutants.

XX.3 Controlled Flow Tests

The maximum flow capacities for different media were determined using measured flows. The controlled particle trapping tests were then conducted at high, medium and low flow rates (full flow, ½, and ¼ of the maximum flow rates) with varied influent sediment concentrations (500 mg/L, 250 mg/L, 100 mg/L and 50 mg/L). Flow tests were conducted in the field with the cooperation of the Tuscaloosa Water Department by using a fire hose connected to a fire hydrant adjacent to the test site. The flows were measured using their calibrated meter, and also checked at the test rates by timing the filling of large containers. Maximum flow rates of about 30 GPM (1700 m/day) were obtained during the tests, for a filter area of about 1.5 ft^2 (0.14 m^2). Figure 4 shows how the flows varied for different hydraulic heads over the mixed media.

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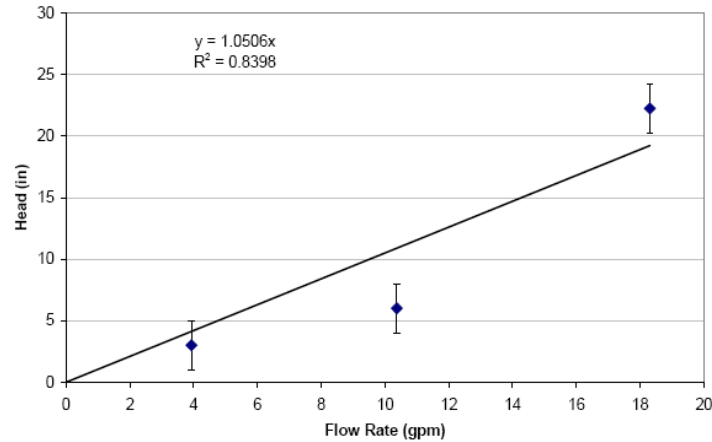so vertical dimension
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Figure 4. Flow characteristics for tested media.

The sediment in the stormwater stimulant was based on the following mixture: Sil-Co-Sil 250, Sil-Co-Sil 106 (both from the U.S. Silica Co.), coarse sand, and fine sand. The mixture was made by using equal weight fractions of each of the four components. The test sediment particle size ranged from 0.45 µm to 2,000 µm. More of the larger particles were included in the test mixture than expected in normal stormwater in order to be more confident of the expected very high removal rates for these large particles (the concentrations and removal rates were determined for eight separate particle size ranges, not just for the complete sample).

A total of 21 separate controlled experiments were conducted, resulting in the collection of 84 samples, including the blank samples for each experiment. Total solids, suspended solids, total dissolved solids (by difference), and particle size distribution (PSD) analyses were carried out for each sample and its duplicate (duplicates were made from time composites in the field using a churn splitter). Therefore, the total number of samples analyzed during the controlled tests numbered 168. Before conducting the analyses, each of the 168 samples were split into 10 equal volumes of 100 mL each using a Decaport/USGS cone splitter for the separate analyses.

Figures 5 and 6 are example data plots for the controlled tests. Figure 5 shows the particle size distribution plots for the influent test mixture, and the measured effluent particle size distributions. Very few particles larger than 30 µm were found in the effluent. Also, influent concentration and flow rate

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had little effect on the effluent particle size distributions. Beckmann Coulter Counter was used in analyzing the particle size distributions.
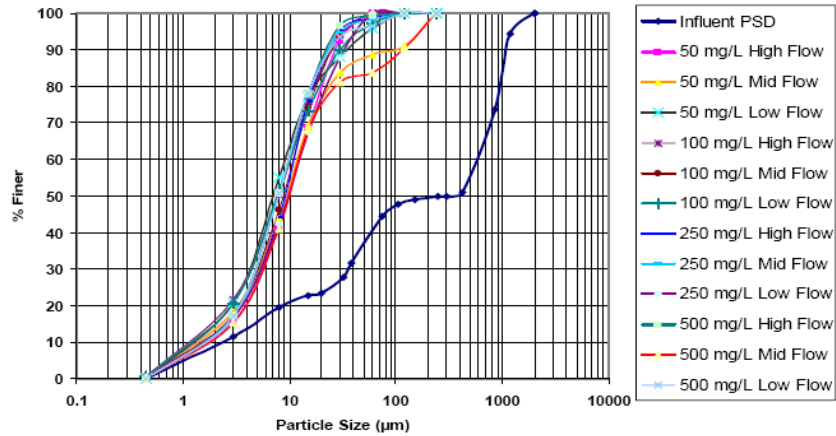
Figure 5. Performance plot of particle size distribution for mixed media

Figure 6 indicates some very small improved levels of performance for lower flows at each concentration tested. The effluent concentrations were also about the same, but the lowest effluent concentrations were associated with the lowest concentration, lowest flow tests.
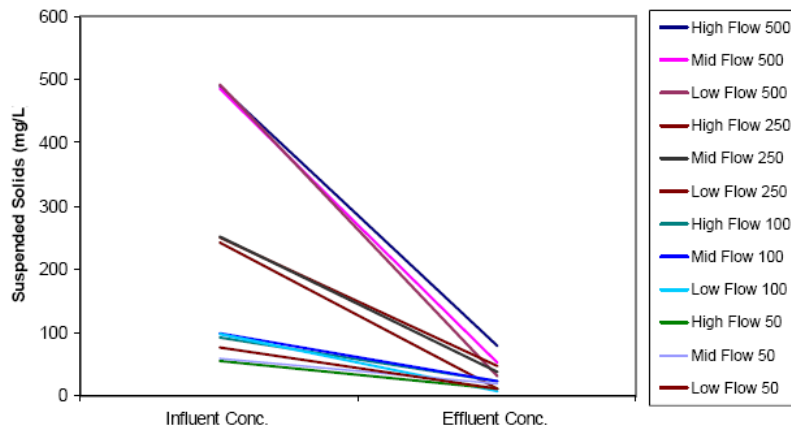
Figure 6. Performance plot for mixed media for suspended solids at influent concentrations of 500 mg/L, 250 mg/L, 100 mg/L and 50 mg/L.

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Overall suspended solids removal efficiencies of 85 to 90% were observed for all of the controlled tests. As shown on Table 1, the larger particles were removed most effectively, as expected. The removals of the 0.45 to 30 µm particles were about 50%, while the removals of particles larger than 30 µm were 95 to 100%. The 0.45 to 30 µm particle sizes indicated some irreducible concentration effects, below which no further removals were observed.

Table 1. High Flow Rate (20 gpm/ft^2) Controlled Test Results

Size Range (µm)	Effluent quality (y = effluent concentration; x = influent concentration, both in mg/L of particulate solids in designated size range)	Approx. irreducible concentration in size range (mg/L)
0.0 to 0.45 (TDS)	y = x	na
0.45 to 3	y = 0.6057x + 1.2409	2.0
3 to 12	y = 0.6371x + 0.5216	1.4
12 to 30	y = 0.6279x + 1.5312	4.1
30 to 60	y = 0.0414x	0
60 to 120	y = 0.0154x	0
120 to 240	y = 0	0
>240	y = 0	0

XX.4 Evaluations during Actual Storms

From March through December, 2005, a total 24 pairs of inlet and outlet samples were collected during 10 different storm events, from the 31 storms that occurred. The Tuscaloosa, AL, city hall test site was about 0.9 acres in area, comprised of a steep aluminum roof, a concrete parking deck, and an asphalt parking deck, plus some small areas of older flat commercial roofs.

Sampling was conducted using two ISCO 6712 automatic samplers. The flow rates were determined using two ISCO 4250 area-velocity meters which also measured the stage both in the influent sump (the catchbasin sump) and in the effluent pipe. The rainfall intensity and amount were measured using a standard tipping bucket rain gauge. A small totalizing rain gauge was also used as a cross check. YSI 6600 water quality sondes were used to measure real time water quality data (temperature, dissolved oxygen, pH, ORP, turbidity, conductivity, and water depth) of the influent and the effluent flows at 1 minute intervals during storm flows and at 5 minute intervals during interevent periods. Once the appropriate samples were selected for analyses, the samples were divided using a Dekaport/USGS cone splitter (Rickly Hydrological Company). Every storm evaluated had a hyetograph (rainfall pattern) and hydrograph (runoff pattern) prepared with

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the treatment flow capacity marked for that particular event. An example is shown in Figure 7. A minimum sample volume of 400 mL was required to conduct the analyses. All the constituents were measured for both corresponding influent and effluent samples. The samples were evaluated for TS, SS, Escherichia coli, total coliforms, nitrates, total phosphorus, Chemical Oxygen Demand, heavy metals (focusing on copper, lead, and zinc), and particle size distributions.
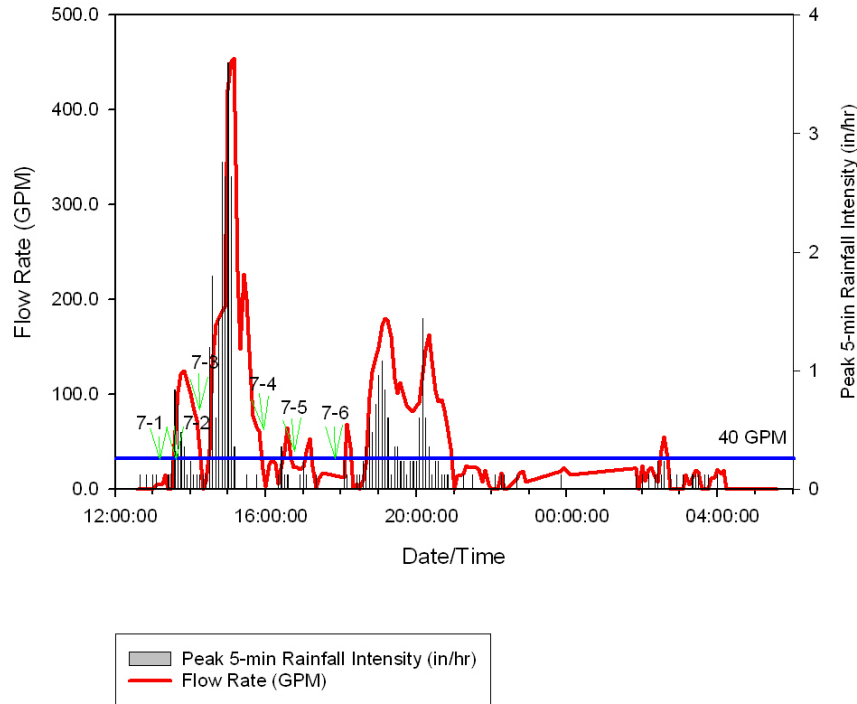

Figure 7. Hydrograph and Hyetograph for Hurricane Katrina, August 29, 2005.

The 10-month monitoring period started off unusually dry in the late winter to early summer months. However, the mid summer was notable for severe thunderstorms having peak rain intensities (5-min) of up to 4 inches

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per hour. The late summer was also notable for several hurricanes, including Hurricane Katrina on August 29, 2005 (Figure 7) that delivered about 3 inches of rain over a 15 hour period, having peak rain intensities as high as 1 in/hr in the Tuscaloosa area.

During the monitoring period, the treatment flow rates in the prototype UpFlo[TM] filter were observed to decrease with time, as expected. Figure 8 shows the decreasing flow rate with rain depth. The flow rate through the filter was always greater than the specified 25 gpm treatment flow rate during the 10 month period. It is estimated that the 25 gpm treatment flow would be reached after about 30 inches of rainfall (in an area having 0.9 acre of impervious surfaces), or after about 45,000 ft^3 of runoff, or after about 160 lbs of particulate solids, was treated by the filter.
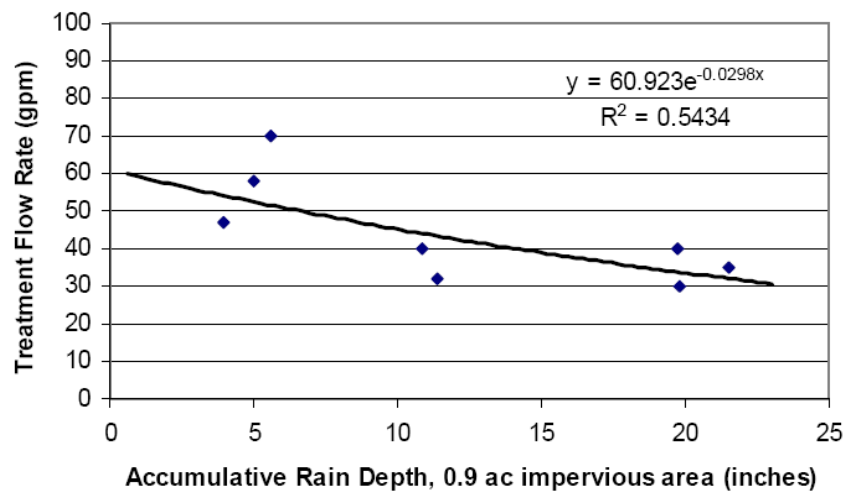

Figure 8. UpFlo[TM] filter treatment rate with rain depth.

Tables 2 and 3 and Figures 9 through 14 summarize the performance of the UpFlo[TM] filter during the actual monitored storms for suspended solids. Similar analyses were conducted for the other pollutants, and for each particle size range. This set of illustrations presents a comprehensive review of the performance of the filter. Simple statements concerning the percentage removal, for example, are inaccurate, as that indicator of performance is highly dependent on the influent concentrations and particle size distributions. In Table 2 the sample numbers are numbered by the storm

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event monitored and the sample collected. E.g. A sample number 2-1 indicates monitored storm 2, 1st collected sample.

Table 2. Observed Suspended Solids Concentrations

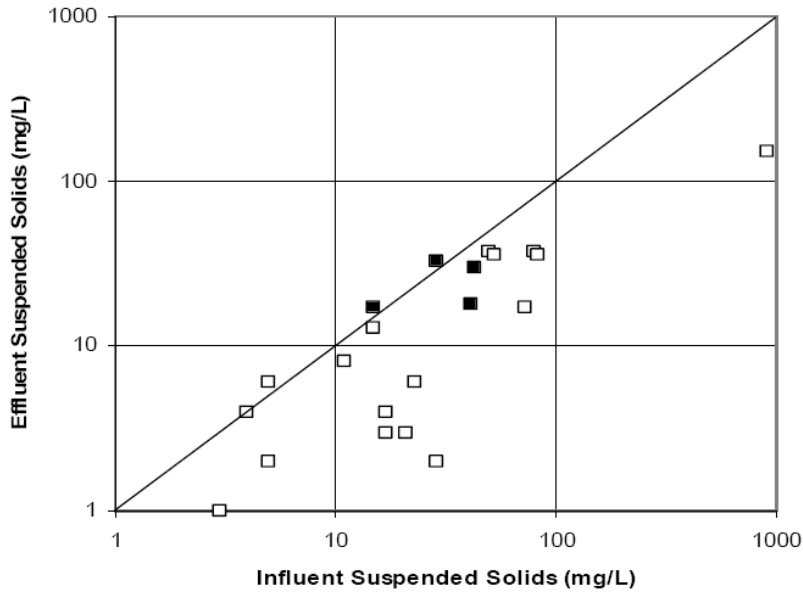| Sample Number	Influent (mg/L)	Effluent (mg/L)	Sample Number	Influent (mg/L)	Effluent (mg/L)
1-1	17	4	6-4	17	3
2-1	53	36	6-5	21	3
2-2	50	37	7-1	83	36
3-1	6	0	7-2	43	30
3-2	3	1	7-3	29	33
4-1	1	0	7-4	23	6
4-2	1	0	7-5	5	2
5-1	80	37	7-6	4	4
5-2	15	17	8-1	913	150
6-1	5	6	8-2	41	18
6-2	11	8	9-1	29	2
6-3	15	13	10-1	72	17

Figure 9. Scatterplot of observed influent and effluent suspended solids concentrations (filled in symbols indicated events that had minor bypasses around the filter).

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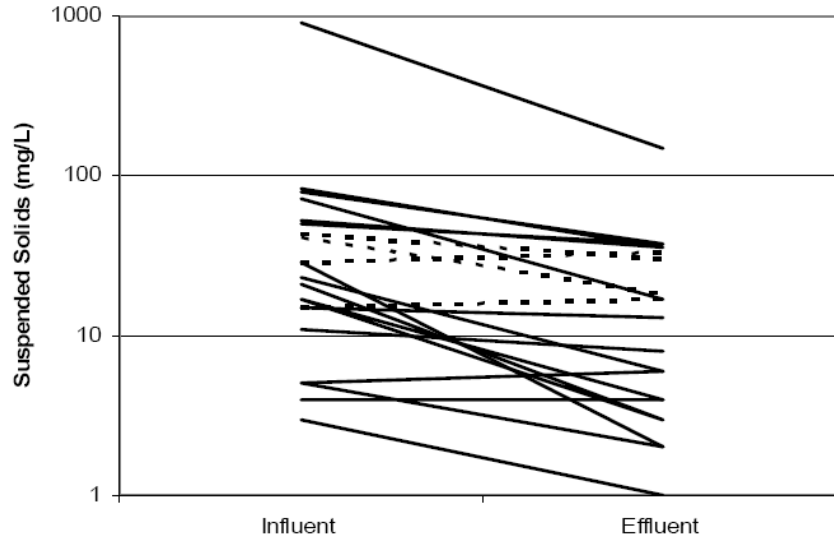so vertical dimension
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Figure 10. Paired influent and effluent suspended solids concentrations.

Fitted Equation:

Effluent Suspended Solids, log mg/L = 0.730 * (Influent Suspended Solids, log mg/L)

Table 3. Regression Statistics on Observed Influent vs. Effluent
Suspended Solids, log mg/L

Multiple R	0.94
R Square	0.89
Adjusted R Square	0.85
Standard Error	0.37
Observations	24

ANOVA	df	SS	MS	F	Significance F
Regression	1	25.4	25.4	187	3.11E-12
Residual	23	3.12	0.136		
Total	24	28.55			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
X Variable 1*	0.730	0.053	13.7	1.56E-12	0.620	0.841

* The intercept term was determined to be not significant

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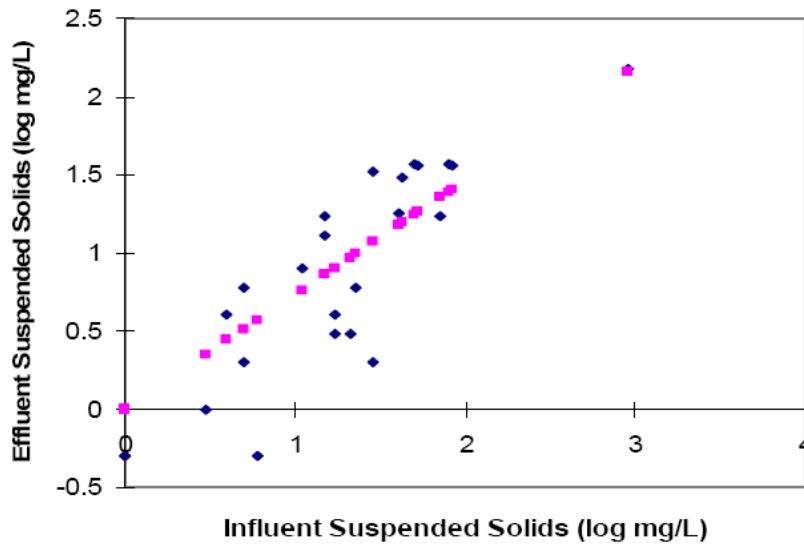of page remains correct

Figure 11. Fitted equation and data points for influent and effluent suspended solids.
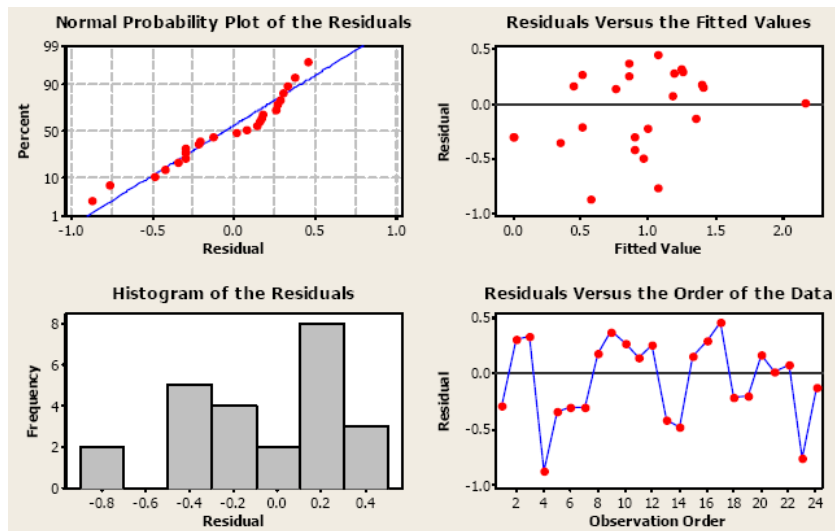

Figure 12. Residual analyses of fitted equation for suspended solids influent vs. effluent.

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As expected, the UpFlo^{TM} filter performance followed traditional patterns, with greater percentage reductions as the influent concentrations increased (Figure 14). However, effluent quality is likely a more important consideration for many analyses, as shown in Figure 13. The effluent suspended solids was found to be less than 30 mg/L for all influent concentrations less than about 100 mg/L, and the effluent was less than 100 mg/L when the influent was less than about 600 mg/L. The measured percentage reductions for suspended solids was found to be greater than 70%, when influent concentrations were greater than 90 mg/L.
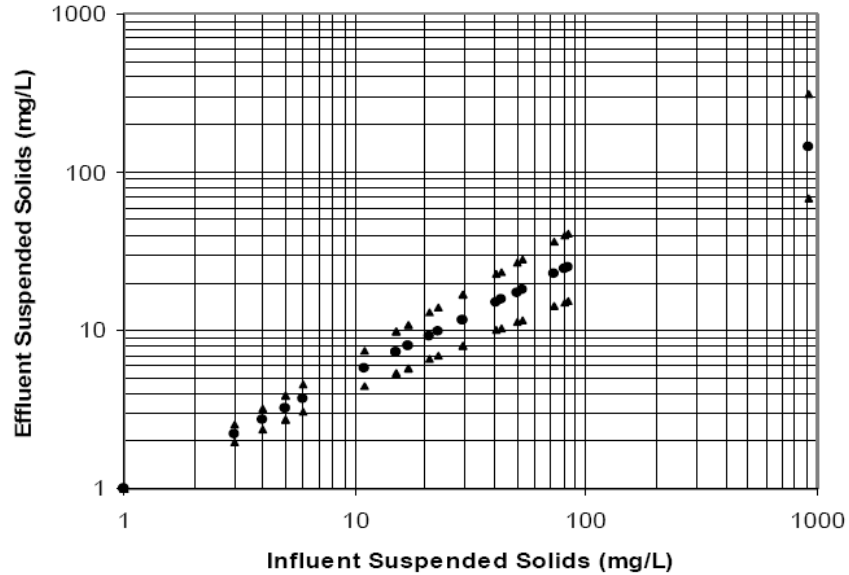
Figure 13. Predicted effluent suspended solids concentrations for different influent concentrations, with 95% confidence limits.

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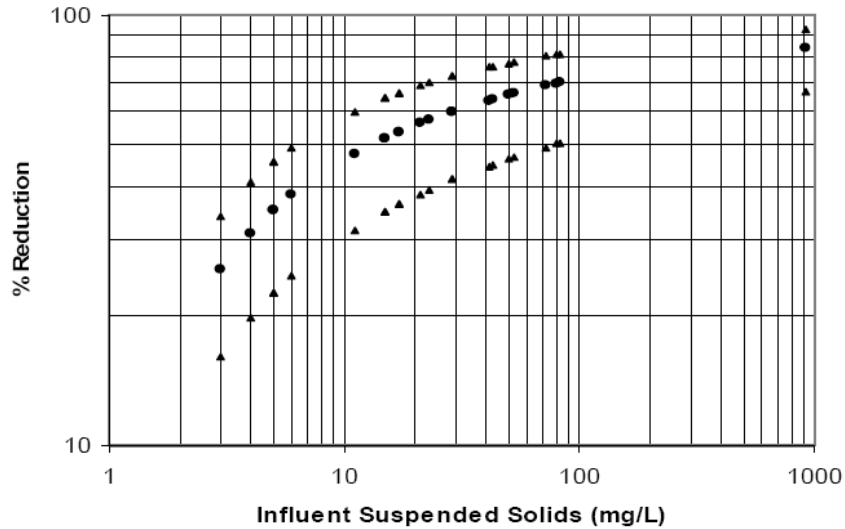so vertical dimension
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Figure 14. Percentage reductions of suspended solids as a function of
influent concentrations, with 95% confidence limits.

The long-term performance of the UpFlo^{TM} filter is highly dependent on the percentage of the annual runoff that is treated by the unit, like all treatment devices. A series of calculations were made, using WinSLAMM, the Source Loading and Management Model, to determine the distribution of flows that could be expected for several sets of conditions. Sizing plots for one acre paved parking or storage areas for five locations in the US having very different rainfall conditions were examined (Seattle, WA; Phoenix, AZ; Atlanta, GA; Milwaukee, WI; and Portland, ME). Figure 15 shows the annual runoff distributions for Portland, ME. Figure 16 shows the calculated percentage of the annual flows for Portland that would be treated at different treatment flow rates. Table 4 summarizes these calculations showing several treatment objectives. It is interesting to note that Seattle, typically known as a wet and rainy city, has the lowest flow rates for the probability points shown, and the smallest required treatment flow rates for the different treatment objectives. In this sampling of cities, the needed treatment flow rates for the same treatment objectives are seen to range by a factor of about three or four: it would require four UpFlo^{TM} filter modules per acre of paved drainage area to treat about 90% of the annual runoff in Atlanta (similar to what was found for the Tuscaloosa test site during the monitoring period),

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while only one or two modules would be needed for the same area and treatment level objective for Seattle.
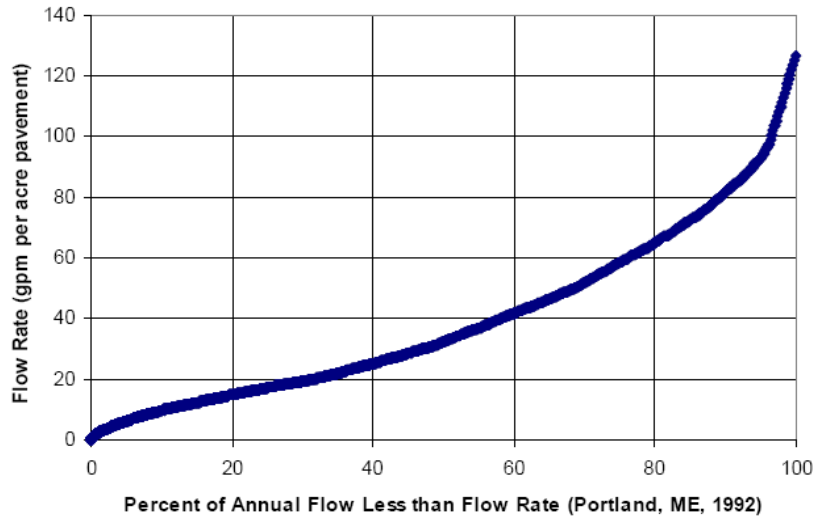

Figure 15. Treatment flow rates needed for Portland, ME.
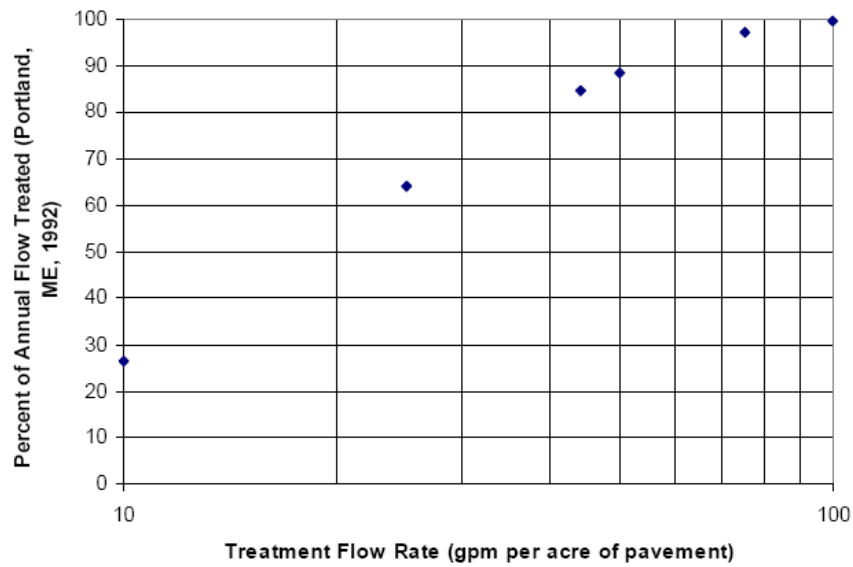
Figure 16. Treatment flow rates needed for Portland, ME.

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Table 4. Example Flow Rates and Treatment Rates Needed for
Different Treatment Objectives

Location	Annual Flow Rate Distributaries (gpm/acre pavement)			Flow Rate Needed for Different Levels of Annual Flow Treatment (gpm/acre pavement)		
	50th Percentile	70th Percentile	90th Percentile	50%	70%	90%
Seattle, WA	16	28	44	10	18	30
Portland, ME	31	52	80	18	30	53
Milwaukee, WI	35	60	83	20	35	65
Phoenix, AZ	38	60	150	20	35	90
Atlanta, GA	45	65	160	25	40	100

XX.5 Conclusions

The UpFlo^{TM} filter is most effective in reducing pollutants associated with particulate matter and less effective for dissolved constituents. Table 5 summarizes the overall performance of the UpFlo^{TM} filter for the 24 pairs of samples evaluated, without considering the additional benefits of the sump.

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Table 5. Summary of UpFlo^{TM} filter actual storm event monitoring results
(filter only, no sump effects)

	Average influent concentration** (and COV*)	Average effluent concentration** (and COV)	Percent Removal***	Probability that influent ≠ effluent****
Turbidity (NTU)	43 (2.4)	15 (1.3)	65 (45)	>99% (significant reduction)
Suspended solids	64 (2.9)	19 (1.6)	70 (58)	>99% (significant reduction)
Total solids	137 (1.7)	90 (1.3)	34 (17)	>99% (significant reduction)
COD	111 (1.6)	81 (1.4)	27 (18)	>99% (significant reduction)
Phosphorus	0.94 (1.1)	0.77 (1.4)	18 (13)	98% (significant reduction)
Nitrates	0.7 (1.2)	0.7 (1.3)	0 (0)	93% (not significant reduction)
Ammonia	0.44 (1.5)	0.24 (1.30)	45 (24)	97% (significant reduction)
E. coli	4,750 (0.8)	3,290 (0.8)	31 (21)	>99% (significant reduction)
Total coliforms	12,400 (1.0)	6,560 (0.7)	47 (37)	>99% (significant reduction)
Total Zinc (µg/L)	169 (1.2)	130 (1.3)	23 (23)	>99% (significant reduction)
Total Copper (µg/L)	13 (1.5)	8.7 (1.2)	33 (26)	64.1% (not significant reduction)
Total Lead (µg/L)	15.5 (1.9)	5.5 (1.9)	65 (50)	90.8% (significant reduction)
Dissolved Lead (µg/L)	11.3 (2.7)	2.8 (2.2)	75 (58)	97.8% (significant reduction)
<0.45 µm	0.087 (3.1)	0.69 (4.6)	-690 (60)	90.4% (not significant reduction)
0.45 to 3 µm	4.4 (1.7)	1.7 (1.6)	61 (65)	98.9% (significant reduction)
3 to 12 µm	13.4 (3.3)	3.9 (1.5)	71 (67)	90.7% (not significant reduction)
12 to 30 µm	28.7 (3.6)	6.1 (2.2)	79 (65)	>99% (significant reduction)
30 to 60 µm	12.0 (2.1)	4.5 (1.9)	63 (72)	>99% (significant reduction)
60 to 120 µm	3.1 (1.7)	1.5 (2.0)	52 (47)	97.4% (significant reduction)

*Co-efficient of Variation
** all mg/L, except for bacteria that are #/100 mL and turbidity that is NTU
*** based on average concentrations, excluding additional removal by sump component
**** nonparametric sign test, significant reduction at 95% level

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Table 6 summarizes the expected mass balance of particulate material removed by the UpFlo^TM filter during the sampling period, considering both the measurements from the automatic samplers (for suspended material <150 µm in size) and the larger material retained in the sump, assuming all the runoff was treated by the filter, with no bypass. The suspended solids removal rate is expected to be about 80%, while the removal rates for the other monitored particulate constituents are expected to be about 72 to 84%, depending on their associations with the different particle sizes, as shown on Table 7 and 8 for particulate phosphorus and particulate zinc.

Table 6. Calculated Mass Balance of Particulate Solids for Monitoring Period

particle size range (µm)	SS influent mass (kg)	SS effluent mass (kg)	SS removed (kg)	% reduction
0.45-3	9.3	2.8	6.6	70
3-12	18.7	6.4	12.3	66
12-30	22.4	7.7	14.7	66
30-60	26.7	6.8	19.9	74
60-120	4.6	1.8	2.9	61
120-250	19.8	4.3	15.5	78
250-425	11.5	0.0	11.5	100
425-850	17.1	0.0	17.1	100
850-2,000	10.5	0.0	10.5	100
2,000-4,750	4.8	0.0	4.8	100
>4,750	3.5	0.0	3.5	100
sum	148.9	29.8	119.2	80

Table 7. Calculated Mass Balance of Particulate Phosphorus for Monitoring Period

particle size range (µm)	P influent mass (grams)	P effluent mass (grams)	P removed (grams)	% reduction
0.45-3	33.4	9.9	23.5	70
3-12	66.9	22.9	44.0	66
12-30	80.3	27.5	52.7	66
30-60	95.6	24.5	71.1	74
60-120	7.5	2.9	4.6	61
120-250	10.1	2.2	7.9	78
250-425	3.6	0.0	3.6	100
425-850	8.5	0.0	8.5	100
850-2,000	9.0	0.0	9.0	100
2,000-4,750	6.7	0.0	6.7	100
>4,750	6.0	0.0	6.0	100
sum	328.0	90.4	237.6	72

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Table 8. Calculated Mass Balance of Particulate Zinc for Monitoring Period

particle size range (µm)	Zn influent mass (grams)	Zn effluent mass (grams)	Zn removed (grams)	% reduction
0.45-3	12.5	3.7	8.8	70
3-12	25.0	8.6	16.5	66
12-30	30.0	10.3	19.7	66
30-60	35.8	9.2	26.6	74
60-120	4.4	1.7	2.7	61
120-250	9.9	2.1	7.8	78
250-425	6.2	0.0	6.2	100
425-850	4.6	0.0	4.6	100
850-2,000	4.3	0.0	4.3	100
2,000-4,750	2.2	0.0	2.2	100
>4,750	2.0	0.0	2.0	100
sum	137.2	35.8	101.4	74

XX.6 Acknowledgements

The SBIR1 (Small Business Innovative Research) and SBIR2 projects were sponsored by the US EPA, under the direction of Richard Field. The industrial partners included USInfrastructure (Ramjee Raghavan), Hydro International, Ltd., (many staff members), and StormTrain, LLC.'s Dave Woelkers. The City of Tuscaloosa (especially Chad Christian), and the Tuscaloosa Water Department assisted in the test site installation. Numerous University of Alabama graduate students and staff also assisted in numerous aspects of the project. The help and support of these project participants is gratefully acknowledged.

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