Laboratory and Field Tests of the Up-Flo™ Filter

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ABSTRACT

The Up-Flo™ stormwater filter technology, developed under the US EPA's Small Business Innovative Research (SBIR) program, incorporates elements of a treatment train approach including screening, sedimentation and high-rate filtration in a compact modular device.

The Up-Flo™ Filter is a passive, modular proprietary upflow filtration system that incorporates multiple elements of a treatment train into a single, small-footprint device. The device uses a sedimentation sump and screening system to pre-treat stormwater runoff before it flows up through the filter media where final polishing via filtration occurs. A high-capacity siphoning bypass safeguards against upstream ponding/flooding during high-flow events. The siphon also serves as a floatables baffle to prevent the escape of floatable trash and debris from the Up-Flo™ Filter chamber (see Figure 1).

The Up-Flo™ Filter has undergone extensive testing, including laboratory and field testing of a prototype and full-scale unit. This paper describes some of these tests, especially relating to the flow treatment capacity of the filter. Comparisons of the different test protocols that are being followed during current full-scale testing are also made.

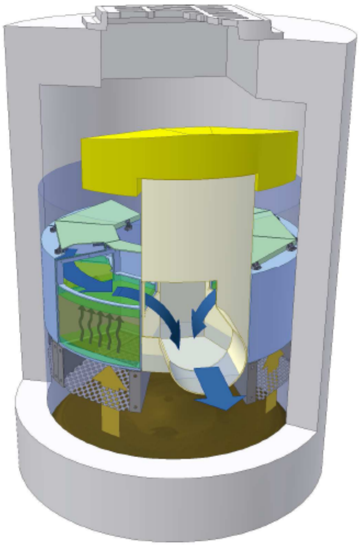

Figure 1. The Up-Flo™ Filter during normal operation.

KEYWORDS

Stormwater; filtration; laboratory testing; field testing; upflow filtration

INTRODUCTION

The upflow filter was developed in response to shortcomings inherent in conventional downflow stormwater filters. The most important limitation of downflow filters is their limited run time associated with clogging (Urbonas 1999). By directing stormwater through a filter from the top, most of the stormwater particulates will accumulate on the filter surface and the near-surface region of the filter. Testing of filtration media during laboratory trials by Clark and Pitt (1999) showed that most filtration media clogs (defined as a treatment flow rate of less than 1 m/day) when <1 to about 4 kg of stormwater particulates accumulates on 1m^2 of media (Table 1). The values in Table 1 are for small-scale lab tests with continuous flows. During large-scale field tests and actual intermittent rains, the maximum loading of particulates was found to be about 5 times these laboratory values, or from about 1 to 20 kg/m^2. These maximum loading rates were also found to apply to biofiltration devices when natural soils and amended soils are used to treat stormwater (Pitt, *et al.* 1999).

Table 1. Clogging results for filtration media – continuous flow laboratory tests (Clark and Pitt 1999)

Filtration media	Suspended solids loading at clogging (g/m^2)	Visual penetration depth into media (cm)
Filter sand	1200 to 4000	3.8
Composted leaf material	2100	5.1
Peat	200	0.6
Loam soil	630	0.3
Peat-sand mix	200 to 1700	2.5
Activated carbon-sand mix	500 to >2000	3.8
Zeolite-sand mix	1200 to >2000	5.0
Compost-sand mix	350 to 800	2.5
Non-woven filter fabric	3800	0.1-0.2[a]

(a) This is the height of the solids cake that formed on the top of the filter fabric, not a penetration depth into the fabric.

The clogging at the surface of the media during downflow filtering can also cause premature bypassing of the filter, with less stormwater being treated than expected (Urbonas 1999). In order to provide longer run times before clogging, upflow filtration was examined. University of Alabama and University of Alabama at Birmingham researchers that were supported by EPA and WERF (Johnson, *et al.* 2003; Pratap 2003; Gill 2004; Pitt and Khambhammettu 2006) found that upflow filtration, especially when used with a sump, resulted in greatly extended run times before clogging. During these upflow laboratory tests, we were able to confirm that particulate material that accumulated on the bottom of the media fell away into the sump after the flows ended. In addition, particulate material that had migrated into the media during the upward flows was partially rinsed downward and into the sump as the water drained from the media, further extending the run time. The sump also provided pre-treatment of coarser material. Upflow filtration therefore greatly extended the filter run time before clogging was observed because much of the trapped material fell into the sump and did not form a clogging layer on the filter surface. During actual rain tests reported later, Pitt and Khambhammettu (2006) found that a prototype upflow filter, having about 0.14 m^2 (1.5 ft^2) of filter surface, retained more than about 70 kg (150 lb) of particulates in an upflow filter unit having a sump (equivalent to about 500 kg/m^2) during a 10 month field trial serving a 0.36 ha (0.9 ac) impervious drainage area.

We also identified anomalous media behavior during our tests with upflow filtration. Fibrous media (such as peat and a cotton mill waste material) easily compressed during moderate to high hydraulic heads which resulted in the treatment flow rates being very low. We also found that the coarse particulate material (the zeolite, activated carbon, and granulated compost) had very high flow rates under most head conditions, with resultant minimal residence times and possibly decreased removal of targeted pollutants. We therefore examined media mixtures to moderate the flows, focusing on half and half mixtures of fine filter sand and the additional media. This added strength to the fibrous material and kept it from compressing, and also filled in the large voids in the coarse material. The results were more consistent flows. The full EPA report (Clark and Pitt 1999) contains complete descriptions of these media and tests. A copy of the report is located at: http://unix.eng.ua.edu/~rpitt/Publications/StormwaterTreatability/filter%20report%20Clark%20and%20Pitt%201999.pdf

Figure 2 is a plot of the treatment flow rates vs. hydraulic heads for a prototype upflow filter having 0.14 m^2 (1.5 ft^2) of media surface. As the head increased to about 35 cm (15 inches), the treatment flow rate reached about 75 L/min (20 gal/min), our target flow rate for an upflow filter that could be retrofitted into small stormwater inlets. Table 2 shows treatment flow rates for individual media for different hydraulic heads.

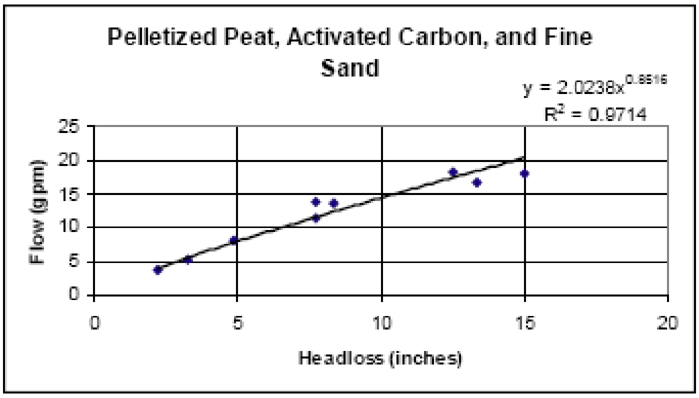

Figure 2. Upflow treatment flow rate for mixed media for different hydraulic heads (Pitt and Khambhammettu 2006).

Table 2. Upflow treatment flow rate measurements with available head for each media for 0.14 m^2 (1.5 ft^2) media area, restrained media, and continuous flows (Pitt and Khambhammettu 2006)

Mixed Media		Activated Carbon		Bone Char Carbon		Mn Coated Zeolite	
head (cm)	Flow (L/min)	head (cm)	Flow (L/min)	head (cm)	Flow (L/min)	head (cm)	Flow (L/min)
7.6	22	7.1	28	8.4	55	10	24
14	58	13	80	11	105	13	38
27	100	27	170	26	190	27	79

The treatment flow rates shown above are quite large for stormwater filters, being several times the rates usually considered for conventional downflow filters. With an upflow filter, the hydraulic head increases the energy available to drive the water through the filter, while in a downflow filter, increasing the hydraulic head has much smaller benefits, and can in fact cause compression of the media or captured particulates and other debris, causing decreased flows.

During the upflow filter tests, the different types of media and the particulate trapping mechanisms were found to behave in different ways. Light media (such as the fibrous peat) had a low bed expansion velocity and would readily be forced to the upper regions of the filter, causing a separation of the media and relatively complete stoppage of flow and failure of the filter. Coarse media would allow the particulates to migrate through the complete filter column, eventually breaking through. This migration velocity of the particulates was rapid for small particulates and coarser media, and slower for larger particulates and finer media. The retention of the particulates in these media was a function of the upflow velocity and the depth of the filter. Fine grained media and the mixed media minimized the migration of the particulates up into the media, with most of the trapped material concentrating near the bottom filter interface. In addition, the high rates of flow in the media always caused certain amounts of bed expansion of the media. As noted above, the lighter material in the mixture tended to migrate upward along with the particulates in the coarser material. If the media was restrained in a rigid container, and was prevented from blowing out of the filter, the filters would fail almost immediately due to compression of the material. Finally, it was noted early in the tests that it was desirable for the media to drain between each rain event. During the laboratory tests (Clark, *et al*. 2002), it was noted that media that remained saturated between events likely degraded and lost previously captured pollutants. It was desirable to therefore drain the media between events. This drainage also helped remove material from the media interface and from the larger pores.

A successful design for the upflow filter therefore had to address many of these issues. Some important features of the Up-Flo™ Filter therefore include:

- media was selected to provide a wide range of potential pollutant capture. The mixed media has a desirable flow-hydraulic head characteristic curve. The media is contained in fine mesh bags sandwiched between flexible layers of coarser spongy material that acts as giant springs restraining media expansion. The media containers are also made of flexible material allowing the slightly expanding media to “breath,” but also rapidly forcing the material back into shape. The amount of fibrous material in the mixed media is limited to decrease separation of the different media components. The media is also contained in two mesh bags preventing the material from gross displacement.

- the media drains down between events minimizing the development of anaerobic conditions, and to assist in the flushing of material from the media pores and the bottom interface

- the media is protected with a coarse inclined screen preventing large debris from clogging the media interface and the downwash rinses the screen of captured material

- the sump below the media filters and screen captures coarse material and particulate pollutants that slough off the media interface and from the media pores

- the siphoning overflow allows large flows exceeding the capacity of the filtration media to safely pass through the Up-Flo™ Filter without clogging or causing scour. The overflow siphon is designed to prevent floatable material from washing out of the filter.

METHODOLOGY AND REPORTED RESULTS

The Up-Flo™ Filter prototype, having a filter area of 0.14 m^2 (1.5 ft^2), was developed and tested by the University of Alabama as part of an EPA funded SBIR (Small Business Innovative Research) project. The device was installed in a modified catchbasin inlet in a parking lot adjacent to the Tuscaloosa, AL, City Hall. The drainage area was about 0.36 ha (0.9 acre) and included the city hall roof and two parking lot areas. The prototype was initially tested for flow capacity and particulate retention during controlled tests. It was then operated for ten months during which pollutant retention and flow capacity was monitored during actual rain conditions. A full-scale unit having a filter area of 0.55 m^2 (6 ft^2) was recently installed at another Tuscaloosa, AL, location where it will be tested during the coming months.

Controlled Tests

Challenge solutions of known concentrations of approximately 500, 250, 100, and 50 mg/L particulate solids were used as the influent at three different flow rates representing the highest the filter media could tolerate (high), about half that flow (medium), and about one-fourth the maximum flow (low). The solids mixtures were made using specific combinations of ground silica (Sil-Co-Sil Corp.) and sieved sand, covering the particle size range from about 0.45 to 2000 µm. The highest flows were 175 L/min (46 gpm) for the activated carbon media, and 190 L/min (51 gpm) for the bone char media. The highest flow for the mixed media was 110 L/min (29 gpm). Each experiment was conducted for 30 minutes, during which time measured aliquots of the dry sediment were carefully and constantly poured into the influent “clean” flows from an adjacent fire hydrant. Initial blank samples were collected from the upflow effluent location before any sediment was added to measure the background solids in the test water. Samples were collected using a dipper grab sampler every 1 minute and composited in a churn sample splitter for the 30-minute test period. Three samples of 1000 mL each were collected for each experiment for laboratory analyses. Samples of the added solids were also collected to verify the particle size distributions.

Total solids, suspended solids (by SSC methods - ASTM D3977-97B), total dissolved solids (by difference), and particle size distribution (PSD) analyses were carried out for each sample and its duplicate. Each sample was split into 10 equal volumes of 100 mL each using a Decaport/USGS cone splitter. The sample handling and PSD analytical methods are described by Clark and Pitt (2008).

Figure 3 shows a performance plot for the controlled flow Sil-Co-Sil challenge tests for particulate solids. These plots are for the mixed media (Mn-coated zeolite, bone char activated carbon, and peat mixture) tests which provided maximum flow rates of about 1,000 L/min/m^2 or 25 gal/min/ft^2 (140 L/min, or 38 gal/min). During actual storms, treatment rates ranging from 130 to 190 L/min (35 to 50 gal/min) were observed for the prototype Up-Flo^{TM} filter. These tests indicated excellent control of solids with the prototype Up-Flo^{TM} filter for a wide range of flow and concentration conditions.

Rain Test Results

Thirty-one separate rains occurred during the 10 month monitoring period from February 2 to November 21, 2005. The 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 100 mm (4 inches) per hour. The late summer was also notable for several hurricanes, including Hurricane Katrina on August 29, 2005 that delivered about 75 mm (3 inches) of rain over a 15 hour period, having peak rain intensities as high as 25 mm/hr (1 in/hr) in the Tuscaloosa area. During the monitoring period, the treatment flow rates were observed to decrease with time, as expected. The filter treatment flow rate was always greater than 95 L/min (25 gpm) during the 10 month period. It is estimated that the 95 L/min (25 gpm) treatment flow would be reached after about 75 mm (30 inches) of rainfall (in an area having 0.36 ha, or 0.9 acre, of impervious surfaces), or after about 1,250 m^3 (45,000 ft^3) of runoff, or after about 70 kg (160 lbs) of particulate solids, was treated by the filter (Figure 4).

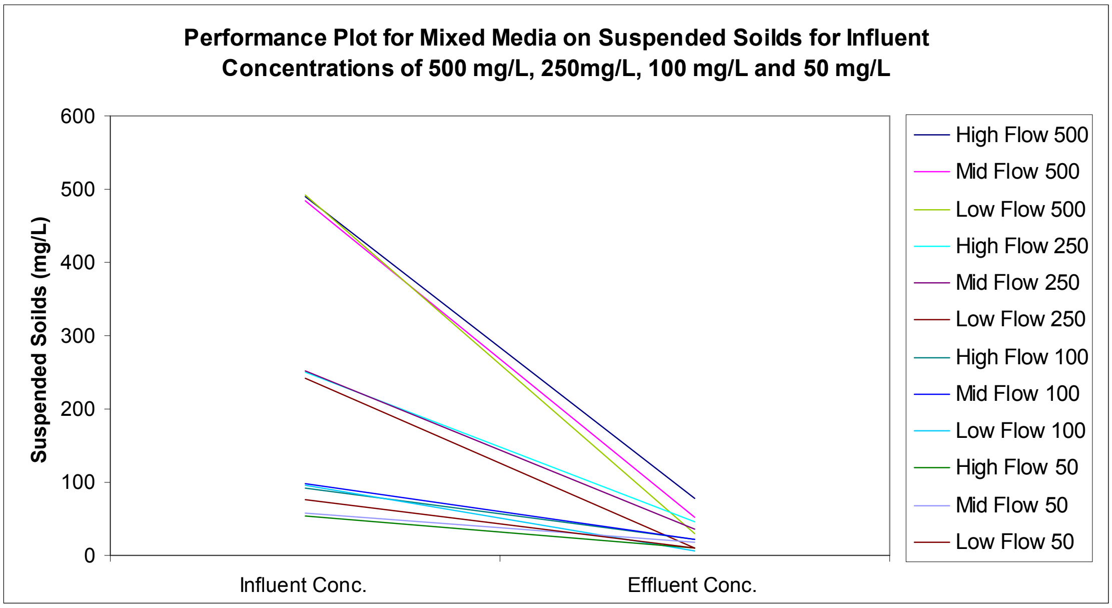

Figure 3. Performance plot using mixed media for suspended solids removal at influent concentrations of 500 mg/L, 250 mg/L, 100 mg/L and 50 mg/L (Pitt and Khambhammettu 2006).

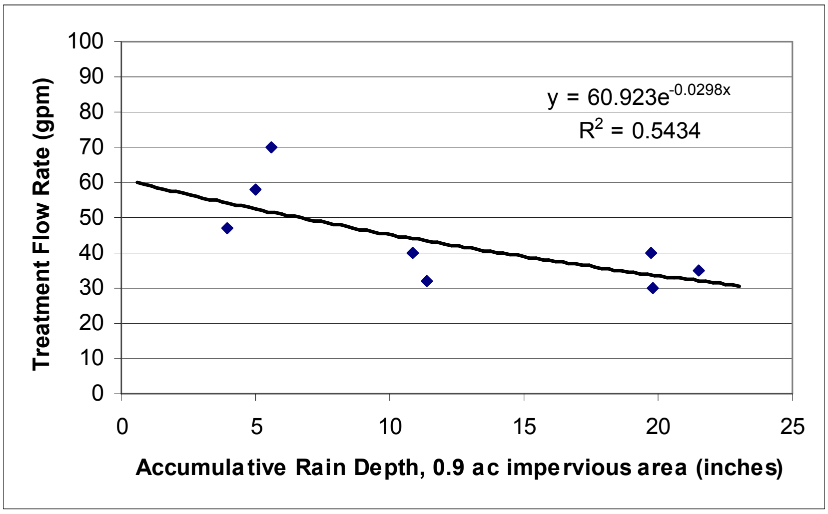

Figure 4. Prototype Up-Flo™ filter treatment flow rate vs. accumulative rain depth (0.14 m^2, or 1.5 ft^2 filter area) (Pitt and Khambhammettu 2006).

Table 3 summarizes the expected mass balance of particulate material removed by the prototype Up-Flo™ filter during the 10 month sampling period, considering both the measurements from the automatic samplers (for "suspended" particulate material <150 µm in size) and the larger material retained in the sump. 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.

Table 3. Calculated Mass Balance of Particulate Solids for Monitoring Period (Pitt and Khambhammettu 2006)

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	71
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	75
60-120	4.6	1.8	2.9	63
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

The long-term performance of the Up-Flo™ 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 0.4 ha (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). 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. This is due to the generally low rainfall intensities in that city. 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 one Up-Flo™ filter module per 0.1 ha of paved drainage area to treat about 90% of the runoff in Atlanta (similar to what was found for the Tuscaloosa test site during the monitoring period), while only ¼ to ½ as many modules would be needed for the same area and treatment level objective for Seattle.

Table 4. Example Flow Rates and Treatment Rates Needed for Different Treatment Objectives (Pitt and Khambhammettu 2006)

	Annual Flow Rate Distributions (L/min/ha pavement)			**Flow Rate Needed for Different Levels of Annual Flow Treatment (L/min/ha pavement)**		
Location	**50th Percentile**	**70th Percentile**	**90th Percentile**	**50%**	**70%**	**90%**
Seattle, WA	150	270	420	95	170	290
Portland, ME	290	490	760	170	290	500
Milwaukee, WI	330	570	790	190	330	620
Phoenix, AZ	360	570	1400	190	330	860
Atlanta, GA	430	620	1500	240	380	950

TESTING PROTOCOLS

US EPA ETV (Environmental Technology Verification) laboratory tests are currently being completed at Penn State - Harrisburg, and these results will be available for presentation at the conference, along with additional field data, for the full-size Up-Flo™ Filter. The initial series of

ETV tests (Year 1) were conducted using a simulated washwater of tap water, solids, automotive fluids, and soaps and were performed to test the hydraulic capacity of the unit, performance of the filter unit under varying hydraulic loadings, and performance to breakthrough under both design conditions and elevated flow conditions. Year 2 tests were designed to test the filter using a simulated stormwater (solids and a ground fertilizer for phosphorus). The Year 2 tests did not completely repeat the Year 1 tests, but focused only on operating the filter to breakthrough under the elevated flow loading conditions (80% of maximum design flow). The influent and effluent samples were collected periodically and analyzed for total suspended solids (TSS - EPA Method 160.2), suspended sediment concentration (SSC - ASTM D3977-97B), chemical oxygen demand (Year 1 only), and total and reactive phosphorus.

Table 5 summarizes some of the testing protocols developed by two of the groups of state agencies that have been evaluating stormwater controls. The full-scale tests being conducted in Tuscaloosa will be designed to meet both of these protocols.

CONCLUSIONS

The development and testing of the Up-Flo^{TM} Filter has occurred over a number of years as an outgrowth of research conducted on stormwater filtration. Early tests on conventional downflow filtration indicated early failure due to clogging and poor retention of captured pollutants during subsequent events. Tests using upflow filtration promised much more rapid treatment flow rates, but also indicated a number of problems that had to be overcome in order to produce a successful stormwater treatment device. Stability of the media in the filter had to be ensured, and a suitable sump to retain captured sediment had to be provided. Drainage of the media between events is also important to minimize problems associated with media going anaerobic. The Up-Flo^{TM} Filter has undergone extensive testing and evaluations in both prototype and now full-scale applications. Treatment performance for particulate pollutants has been shown to be very good, with very high treatment flow rates being sustainable for long periods of time. In many areas, a single Up-Flo^{TM} Filter unit, with up to 6 filter modules, can be used to effectively treat ½ to 1 ha of impervious drainage area. Full-scale Up-Flo^{TM} Filters are currently being tested during controlled laboratory and field tests and during extended periods under actual rain conditions.

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Table 5. Comparison of State Agency Protocols to Test Stormwater Proprietary Control Devices

	TAPE		**TARP**	
Feature	**Explanation**	**Criteria**	**Explanation**	**Criteria**
States Applicable	States following TAPE	Washington	States following TARP	California, Massachusetts, Maryland, New Jersey, Pennsylvania, Virginia
Number of events, minimum per application (#)	Also depends on statistical evaluation	12-35	At least 50% of the total annual rainfall must be sampled, for a maximum of 15 inches of precipitation	15-20
Minimum storm depth (inch)	Total rainfall amount during the sampling event	0.15	More than 0.1 inch of total rainfall	0.1
Storm start/end (antecedent dry period)	Defines the storm event's beginning and end as designated by minimum time interval without significant rainfall	6 hours minimum less than 0.04 inches of rain	A minimum inter-event period	6 hours
Sampling methods	Grab samples should only be used for certain constituents	Automatic samplers, except for chemical constituents that require manual grab samples	Grab samples should only be used for certain constituents	Programmable automatic flow samplers with continuous flow measurements
Flow-weighted composite sampling	Samples are collected over the storm event duration and composited in proportion to flow	10 aliquots should be composited, covering at least 75% of each storm's total runoff volume up to the design storm volume	A minimum of 10 water quality samples (10 influent and 10 effluent) should be collected per event. For composite samples, a minimum of 5 subsamples is acceptable	Obtain flow-weighted composite samples covering a minimum of 70% of the total storm flow, including as much of the first 20% of the storm as possible
Target pollutants	One or more of following parameters	TSS, nutrients, heavy metals (cadmium, copper, lead, zinc, phosphorus), petroleum hydrocarbons, and toxicity	In selecting test parameters, include TSS and SSC at a minimum, and consider other parameters	TDS, TSS, SSC, TPH, TKN, total (nitrogen, phosphorus, COD, BOD), E-coli, Total Coliform, enterococci, pH, conductivity, temperature, lead, copper, zinc, and nickel

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