Stormwater Filter Testing Procedure.

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ABSTRACT

This paper presents a methodology used to conduct a laboratory test of a stormwater filter. In the absence of any published protocols for filters the methodology was developed based on protocols for hydrodynamic separators, combined with scientifically defendable and practical procedures. The reasoning behind the protocol is discussed. The result was data that was relatively easy to generate, thus allowing different filters to be tested and compared on a reasonable basis. The filter was tested for removal performance and maintenance lifetime. Recognizing that a laboratory test will only be able to approximate actual installed performance, its main value lies in simplifying the end user's task of comparing technologies.

KEYWORDS: stormwater filters, laboratory testing, standard protocols, performance, lifetime.

INTRODUCTION

As stormwater discharge regulations become increasingly strict there is growing interest in using manufactured filters to catch the fine fractions of the particulate matter conveyed by stormwater that cannot be practically removed by gravity based devices. Of course, improved removal comes at an additional cost. Filters are more complex and expensive than gravity settling devices and they generally require more maintenance. So the decision to install a filter is not one that should be taken lightly.

The general principles of using of filters in stormwater is described in the literature (Minton, 2005) and there are numerous published filed studies, including (Liu & Sansalone, 2007 and Lenhart & Calvert, 2007). Some modeling work and lab results are presented by (Sansalone, *et. al*., 2008) and there is lab and field work published in the New Jersey Corporation for Advanced Technology (NJCAT) Verification Database http://www.njstormwater.org/treatment.html. However, all of this data was gathered under very different conditions and is presented in different ways that do not allow for direct comparison of the devices.

The protocols used for the testing presented on the NJCAT website were loosely based on the NJCAT Technology Assessment Reciprocity Program (TARP) protocol for hydrodynamic separators. Details of this protocol are available on the NJCAT website, http://www.njcat.org/verification. So, in principle the data would be somehow standardized but in practice, because the TARP protocol is not specific for filters and was interpreted differently by different manufacturers, the test conditions were not consistent.
A gravity device protocol cannot be easily converted to a filter protocol. Not only are the principles of operations of the device different, an end user that is asking for a filter is likely to be trying to protect a sensitive water body. The requirement for superior performance and the increased expense of filters suggests they should be held to a higher standard than gravity devices.

The bottom line is, a potential end user does not have a list of criteria that can be used as the basis for choosing a device. In addition, there is very little data available that allows an “apples to apples” comparison of devices. Some filter manufacturers are able to provide field results but no two sites are alike so data from different sites is difficult to compare. Unless the end user has a site very similar to the studied site the data is of limited use to them.

On the other hand, setting a very high bar for filter testing makes the process prohibitively expensive and prevents innovations from entering the marketplace. This also does a disservice to the end user. A good protocol will balance the information needs of the user with the testing capabilities of manufacturers while maintaining scientific integrity.

Also, a test protocol must recognize that because a filter is going to have some associated wet volume there will be two processes occurring: filtration and settling. Because of this, the two key performance parameters: removal efficiency and lifetime are not related in a simple way. So it is necessary for any filter testing program to account for both removal mechanisms and to include separate tests of both parameters.

METHODOLOGY

All testing was conducted in a typical hydraulics lab with standard equipment. The test could be reproduced industry wide without creating an undue burden. No doubt details would need to be changed to accommodate different geometries and available equipment but the principles of the test are universal.

In this test a single filter was tested in a tank with 1/7th the volume of a typical 7 filter system. Sediment was injected as a concentrated slurry approximately 1 m upstream of the mouth on the filter chamber inlet. A schematic of the set up is shown in Figure 1.

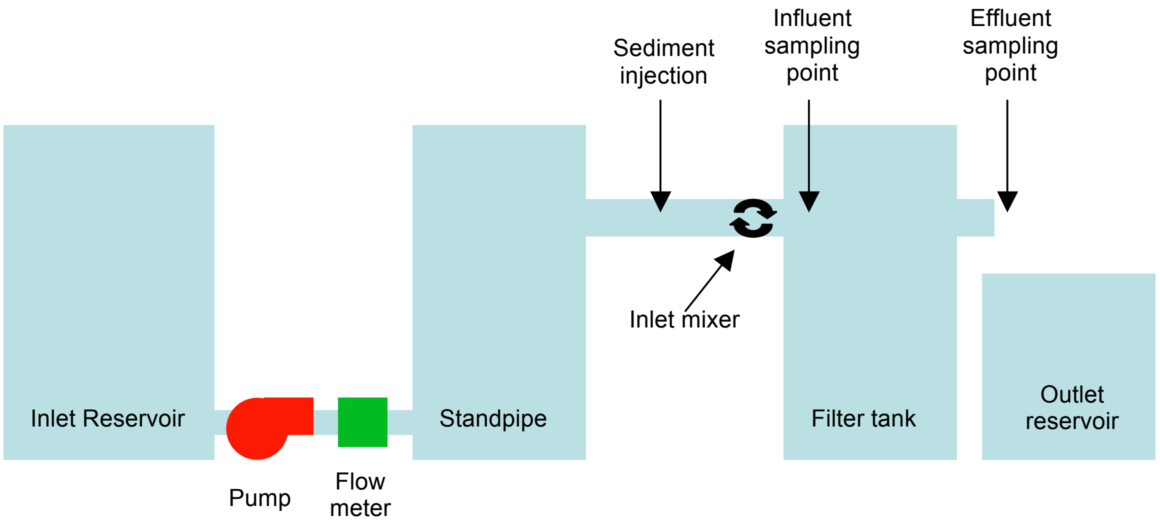

Figure 1. Schematic of Lab set up

Hydraulics set up:

- inlet fresh water reservoir capacity = 4,000 L
- outlet reservoir capacity = 800 L.
- Inlet pipe & outlet pipe ID = 19 cm
- Filter tank diameter = 91 cm
- Main centrifugal water pump, Electromec KF5141 20 HP pump.
- Flow meter, FLS model BP215 paddle wheel type flow meter.

The slurry injection system consisted of a standard 25L bucket with a high speed impeller to keep the sediment suspended. The slurry was kept at a concentration of 6,842mg/L. In order to keep the mixing and pumping consistent, the water level was maintained at a nearly constant level by regular additional of water (3.8 L/batch). In order to keep the concentration constant, pre-weighed (26 g) bags of sediment were added along with the water. This process was labour intensive but it gave very repeatable results and it was practical for relatively short run times.

Slurry was pumped into the inlet stream using a peristaltic pump. The peristaltic pump does create pulses but they were rapid enough that the overall concentration delivered to the flow stream was effectively constant.

Slurry system equipment:

- MasterFlex® I/P® peristaltic pump, model No: 7592-82
- MasterFlex® 6424-82 tubing
- 25L bucket
- Power Fist 3/8˝ electric drill
- Flex shaft to connect impeller to electric drill

With a slurry concentration of 6,842 mg/L a slurry flow rate of 5.54 L/min was required to maintain a concentration of 300 mg/L in the main flow of 190 L/min

A mixer was placed immediately downstream of the injection point to keep the particles in suspension. This was found to be necessary due to the relatively low flow rates typical of filter operation. A close up of the mixer is shown in Figure 2. The inlet to the filtration chamber is on the right. The mixer is actually an impeller blade attached to a flexible drill extension running of a handheld drill. The impeller is held in position by attaching it to an L shaped piece of wood that is fixed to the side of the filter chamber and pointed into the inlet.

Figure 2. Picture of inlet mixer

Thus influent grab samples were taken right at the mouth of the inlet to the tank, near the invert. This was found to give repeatable results that were consistently very close to the expected results based on mass balance calculations for the sediment feed. This was true for both concentration and particle size distribution (PSD), indicating that there was minimal settling upstream of the filter chamber.

Removal Testing

For the performance test, the sediment used was Sil-Co-Sil™ 106. The flow rate tested was 100% of the design flow rate (also called maximum operating flow rate) and the inlet concentrations were 100, 200 & 300 mg/L. These values were chosen based on the NJCAT TARP protocol for hydrodynamic separators and the Washington State Department of Ecology (WADOE) Technology Assessment Protocol – Ecology (TAPE) protocol for stormwater.

For each run sediment injection was started and the first inlet samples was taken after 1 detention time and then every 2 minutes until a total of 5 samples, 500 mL each, were taken. Outlet samples were taken 1 detention time after the inlet samples, so the first outlet sample was taken 2 detention times after sediment injection started. There were 4 runs in total, 1 each at 100, 200 & 300 mg/L and a replicate run at 100 mg/L. A total of 20 inlet outlet/pairs were collected. The runs were relatively short so the filter was not replaced between runs. It was allowed to run through its self cleaning cycle between runs.

All samples were tested for Total Suspended Solids (TSS) at an independent laboratory using the method American Public Health Association (APHA) 2450D. Data was reported simply as the mean removal percentage with the associated 95% confidence interval. The equations used are presented below:

$$\%removal = \frac{[Inlet]-[Outlet]}{[Inlet]}\text{x}100 \qquad (1)$$

$$Mean\%removal = \frac{\%removal_1 + \%removal_2 + ...\%removal_n}{n} \qquad (2)$$

$$95\%CI = \pm\frac{t_{(n-1,\alpha)} * s.d}{\sqrt{n}} \qquad (3)$$

Where *95%CI* = 95% confidence interval (there is a 95% chance any data will fall in this range)
$t_{(n-1,\ \alpha)}$ = the Student’s t value for n-1 & α
n = the number of data points
α = 1 - the confidence interval (0.05)
s.d = the standard deviation

All of these are basic statistics equations and the result is unambiguous. The quality of the data obtained by this method was good, there was relatively little scatter. There was a slight trend of increased removal at higher concentrations but it was small enough that the data was aggregated and a single value was reported. So, in addition to values for each run a single value, for example 90.0 ± 1.0%, was reported.

Lifetime Testing

For the lifetime testing the same equipment was used but two of the test parameters were changed. The sediment used for this testing was changed from Sil-Co-Sil 106™ to the one recommended by the NJCAT TARP protocol for testing of hydrodynamic separators (d_{50} = 67 microns). This PSD is based on actual sediment captured in New Jersey. The data generated, in kg/filter element, can be compared to the sediment loading on a site in New Jersey, in kg/hectare, to allow for direct sizing in filters/hectare.

The flow rate was changed from constant maximum operating rate to a storm cycle. The storm cycle was based on recommendations in the TARP protocol. The TARP recommended flow weighting is given in Table 1. These values are representative of actual conditions in New Jersey.

Table 1. Simulated storm events, flow and volume

% of maximum operating rate	% of event total influent volume
125%	10%
100 %	15%
75%	20%
50%	30%
25%	25%

Since most filters are designed to bypass at flows >100%, even if an event generates 125% of the maximum operating rate (MOR) the filter will only be exposed to 100%. For the testing done in this study the 125% and 100% volumes were combined so that the flow was 100% of the MOR for 25% of the time.

A total storm duration of 15 minutes was used. This number was chosen to be reasonably representative of a typical storm event in the mid-Atlantic but it is admittedly arbitrary. The most important consideration is to use a consistent value for duration.

Table 2. Duration of Simulated Storm Events

% of maximum cartridge flow capacity	% of storm event total influent volume	Storm event duration (minutes)
100 %	25%	1.75
75%	20%	1.9
50%	30%	4.25
25%	25%	7.1

A series of such artificial storm events were run until the filter was exhausted. Since many filter systems have some kind of automatic drain down or backwash capability that provides a degree of self-cleaning of the filter, the storm events were separated by intervals of no flow to allow the self-cleaning mechanism to operate. The minimum no flow interval was approximately half an hour. Testing was stopped overnight and on weekends since the system was stable once the backwash flow stopped after half an hour or so. The backwash time did increase to slightly over an hour near the end of filter life.

Removal performance was measured periodically during the lifetime test and it never fell below 80%. Given the use of a coarser PSD and periods of low flow rates, removal was actually better than in the performance test. As expected, removal actually increased as the filter clogged. The lifetime test results were reported as sediment mass input per cartridge.

DISCUSSION

In this study a scale model was tested in order to keep testing costs down and to maintain greater control over the test procedure. Stormwater filter systems generally include a significant wet volume around each filter cartridge so that there will be some settling in the device. So each system will act as a settling device and a filter. Scaling needs to address both of these mechanisms.

Scaling

Scaling in hydrodynamic separators has been the subject of numerous papers, notably a review by (Fenner& Tyack, 1997) and a more recent paper by (Wilson *et. a*l., 2009). There is a sub-committee of the America Society of Civil Engineers (ASCE) and Environmental and Water Resources Institute (EWRI) Task Committee on Guidelines for Certification of Manufactured Stormwater Best Management Practices (BMPs) currently addressing the issue of scaling. The Task Committee recommendations are expected in early 2010.

Despite the work that has been done, there is still no consensus on an appropriate approach to scaling separators so there is no concrete direction as to the scale to use for lab tests. Even if the debate is settled, there is still the practical problem of how to get the right particles to test. This problem is discussed in the following paragraphs.

The two important parameters in gravity settling are the critical settling velocity, V_{sc} and the settling velocity, V_s. When $V_{sc} > V_s$ the particle will be captured (Tchobanoglous, 2003). V_{sc} is mainly a function of flow rate and reactor volume. It is relatively easy to scale down flow rate and decrease reactor size so that they stay in proportion and detention time is constant. It is difficult to scale down settling velocity.

The basic equation governing gravity settling is Stokes' Law:

$$V_S = \frac{gD^2(\rho_p - \rho_m)}{18\mu} \tag{4}$$

Where:
V_S = settling velocity (m/s)
g = acceleration of gravity, 9.81 (m/s^2)
D = particle diameter (m)
ρ_p = particle density (kg/m^3)
ρ_m = medium density (kg/m^3)
μ = dynamic viscosity of medium (kg/m·s)

There are more complex equations (Cheng 1997) that likely yield better predictions of actually settling velocity but for the purposes of scaling it is the variables that need to be considered and they are the same in Stoke's Law and the Cheng equation. Assuming that the medium used will be water, within a defined departure range, the only variables available to scale down settling velocity are particle diameter and density.

Most model particles used in lab studies are silica with a density of 2.15. So, density can only be decreased by a factor of 2 before the particles become buoyant and the equation fails. Diameter can, in principle be decreased by an order of magnitude or more if required but there are two problems with scaling down diameter. One is that very fine particles are difficult to handle and feed. The other is that testing generally requires a particle size distribution (PSD) and reducing all the sizes proportionally so that the distribution does not get skewed is very difficult.

The end result is, while it easy to produce a 1/10th scale reactor and to run it at 1/10th the flow rate you can only scale down the settling velocity by ½ or ¼. As a result the particles will settle disproportionately fast and the scale model will over predict settling.

Filtration is easier to scale. Pilot scale studies for filtration are common practice in the wastewater industry (Asano, 2007). The main variables of concern are the hydraulic loading rate, also called the filtration rate, in $L/m^2 \cdot min$, and the hydraulic driving force. Stormwater filters are gravity fed so the hydraulic driving force is the head, in m, available upstream of the filter. The hydraulic loading rate can be kept constant by decreasing flow rate in proportion to the amount that the filter area is decreased. Hydraulic driving force would not need to scale.

Sedimentation and filtration cannot be scaled down separately. If the test is designed to, for example, 1/6th scale for sedimentation then the filter must also be scaled down by 1/6th. If scaling for sedimentation involves decreasing particle then the filter pore size will need to be decreased or removal will under predicted. In this example the filter pores will be 6x too large unless they are scaled. This will in turn affect headloss, which may force the flow to be out of proportion.

Scaling both sedimentation and filtration in one test is not practical and may not even be possible. The solution is to separate the processes. Since the most important consideration for a filter is the filtration process, testing should focus on that. There are a number of steps that can be taken to minimize settling during testing.

One way to minimize settling is to minimize the volume of the filter chamber in the test. However, arbitrary selection of chamber volume will complicate comparison of results. A reasonable standard is to match the chamber volume to the volume per filter in a commercial unit. No forebay or upstream detention volume should be included in the calculation since these volumes often vary for a given number of filters.

Another way to minimize settling is to use a fine PSD. The other advantage of using a fine PSD is that filters are typically going to be installed to treat fines so the data will be more relevant than if a coarse PSD is used. Sil-Co-Sil 106™, from US Silica, is a fine PSD (D_{50} = 23 microns) that is readily available so different manufacturers can test with the same material.

While all of the above considerations suggest testing as small a unit as possible, minimizing scaling error dictates testing as large a unit as possible. A reasonable compromise is to test a single commercial scale filter element. Most filter systems will have multiple elements so testing a single element will give a scaling factor of ¼ or more. This also avoids any issues that may come with trying to downsize a single filter element, making the filter smaller complicates the scaling calculations and may present manufacturing challenges. A single full scale filter can easily be made truly representative of the commercial product.

Most filters are designed for 5-50 gpm which is a manageable range. Water, sediment and filter consumption will not be excessive. Set up costs will be reasonable. Also, using a single cartridge in a smaller vessel should make the vessel inlet easily accessible for grab sampling.

For all the reasons presented, a single cartridge was tested. Performance was determined by testing with Sil-Co-Sil 106™. The data generated was the mean removal efficiency, with a 95% confidence interval, at maximum flow rate with a clean cartridge. This is an easy number to understand and to use as a basis for comparing technologies. It is effectively a worst case scenario since higher concentrations, lower flows and cartridge clogging all lead to better removal so an end user can be confident that the filter will give good removal in the field.

Lifetime

The conditions used for performance testing should give a result that is conservative but realistic. Using the same conditions for lifetime testing would give results that are very conservative and unrealistic and thus of little value to an end user.

The fines, which filters target for removal, may only be a small part of the total mass that goes to the filter. Providing a number for Sil-Co-Sil 106 will not be useful to an end user unless the user knows how many kilograms of sediment on the site in question has the same mass of fines as a kilogram of Sil-Co-Sil 106.

For this testing the coarser NJCAT PSD was tested. The results did show that when increased settling due to the larger coarse fraction in the NJCAT PSD was accounted for there was a good correlation between the filter sediment mass capacity for both NJCAT and Sil-Co-Sil 106™ sediments. So, Sil-co-Sil 106™ could be used and the result modified based on some other target PSD but this could lead to calculations that will reduce the clarity of the result. The issue of which PSD to use for lifetime testing will require further thought.

The use of varied flow rates and durations was another effort to make the lifetime test realistic, yet still reproducible. A filter test could certainly use simulated storms based on hydrology from a different region, perhaps a region that is a target market, but that should be in addition to a standard test common to all filters. The flow rates and flow durations specified in the NJCAT TARP protocol have already been used and are practical so that is as good a standard as any.

Since many filter systems have some kind of automatic drain down or backwash capability that provides a degree of self-cleaning of the filter, the storm events were separated by intervals of no flow to allow the self-cleaning mechanism to operate. No further cleaning will happen once the self cleaning mechanism, typically some kind of backwash, is finished operating so the interval between storms can be long. Some minimum time should be specified to allow for at least some self cleaning.

The most meaningful result to report is sediment mass per cartridge accumulated over the lifetime of the cartridge. Lifetime needs to be defined. Some filter designs allow for head to increase while the MOR remains constant as the filter clogs. At some point head increases so much that then filter chamber is bypassed entirely. This is the point of failure for constant flow type filters.

Other designs provide a constant head to the filter chamber and allow flow to decrease as the filter clogs. It can be shown that if a filter removes 90% of fines, once it has reached the point of treating only 90% of the flow the net removal is 81%. If the target is 80% removal of fines, then once the filter is only able to pass 90% of the design flow the filter can no longer be performing to its design specification. This is a logical point to require maintenance for constant head devices. Of course if the filter removes less than 90% of fines initially then failure will occur at less than a 10% decrease in flow rate.

CONCLUSIONS

What this paper presents is a stormwater filter test program that has been executed in a typical hydraulics lab and which could be easily reproduced elsewhere. The test program included testing the removal performance and lifetime of the filter. A simple way to present the resulting data, so that an end user can compare technologies with confidence, is described. The rationale behind the methodology and data interpretation is discussed, with the hope that this will provide a basis for progress on a standard protocol.

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