

# Enhanced Biofilter Treatment of Urban Stormwater by Optimizing the Hydraulic Residence Time in the Media

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## ABSTRACT

Selecting the best media for a specific situation is critical when designing a biofilter or bioinfiltration stormwater control practice as the media affects the amount of runoff that is treated and the level of treatment that can be obtained. Appropriate hydraulic characteristics of the media, including treatment flow rate, clogging capacity, and water contact time, are needed to select the media and drainage system. This information, in combination with the media's ability to capture targeted pollutants with minimal clogging given the appropriate contact time, can be used to predict the performance of a biofilter device. This paper presents a series of tests being conducted to determine the hydraulic characteristics of sand-based filter media (having a variety of particles sizes representing a range of median particle sizes and uniformity coefficients) during pilot-scale trench tests. The drainage rate in bioinfiltration devices is usually controlled using an underdrain that is restricted with a small orifice or other flow-moderating component. These frequently fail as the orifices are usually very small (<10 mm) and are prone to clogging. A series of tests are conducted using a newly developed foundation drain material (Capiphon<sup>TM</sup> (also referred to as SmartDrain in this paper)) that offers promise as a low flow control device with minimal clogging potential. A pilot-scale biofilter using a fiberglass trough 3m long and 0.6 x 0.6m in cross section is used to test the variables affecting the drainage characteristics of the Capiphons<sup>TM</sup> (such as length, slope, hydraulic head, and type of sand media). The results indicated that slope of the Capiphon<sup>TM</sup> material had no significant effect on the stage-discharge relationship whereas the length had a small effect on the discharge rate. The information collected during this study will assist stormwater managers in the design of biofilters needing a slowly draining device.

## INTRODUCTION

Biofilters can be effective pollutant removal stormwater management devices, and

can also enhance stormwater infiltration for runoff volume reduction. Most of the removal benefits of biofilters and bioinfiltration devices are through physical removal as the particulate-bound pollutants are trapped in the media, and through water infiltration into the natural soil surrounding the device. The presence of plants in these devices is common and assists in enhancing removal through many biological processes, such as described by LeCoustumer, et al. (2008) as part of the extensive biofilter research conducted by Monash University. Plants can enhance the treatment flow rate and time period before clogging by penetrating the surface clogging layer, allowing water to flow to deeper filter layers. Biochemical reactions may also be enhanced near the root zones of some plants. Evapotranspiration losses of runoff in most biofilters are usually relatively small though as the incoming water volumes are relatively large compared to the available planted area.

The effectiveness of a biofilter is commonly reduced through clogging of the media, through short-circuiting of infiltrating water through an under-drain, or by short resident/contact times of the stormwater and the treatment media. Several studies have demonstrated the pollutant removal efficiency of stormwater biofilters (City of Austin 1988; Clark and Pitt 1999; Clark 2000; Winer 2000). With the exception of some highly mobile contaminants (such as chlorides), they can be designed for good pollutant removal.

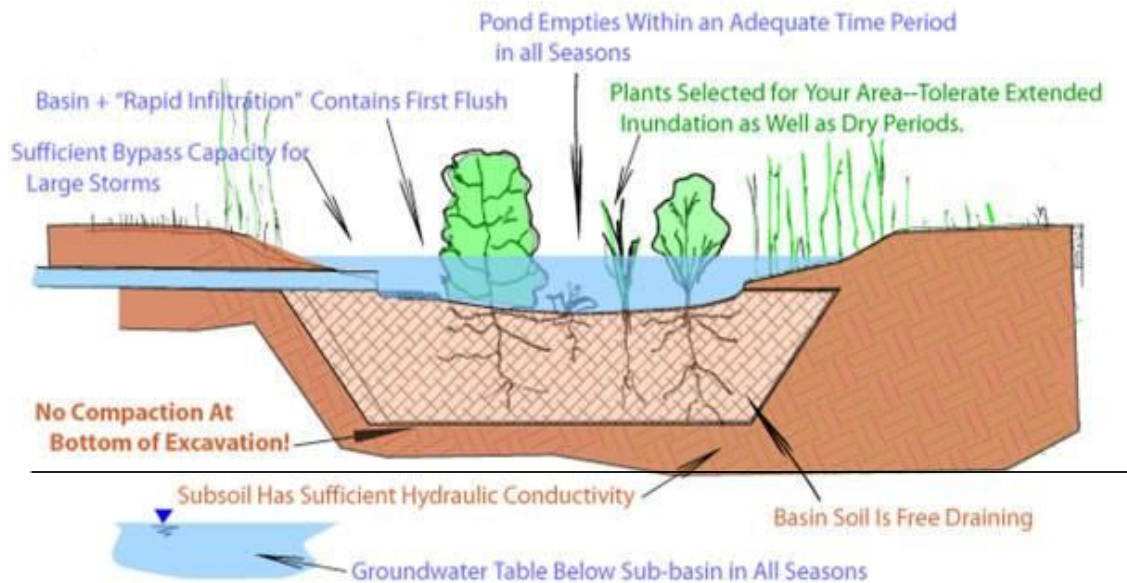


Figure-1. Cross-section of a bioinfiltration stormwater treatment device. A biofilter would have an underdrain to capture much of the stormwater filtered through the media and return it to the surface flow regime (Villanova Urban Stormwater Partnership: [http://www3.villanova.edu/VUSP/bmp\\_research/bio\\_traffic/bio\\_des\\_comp.htm](http://www3.villanova.edu/VUSP/bmp_research/bio_traffic/bio_des_comp.htm)).

The removal of soluble forms of many stormwater pollutants is dependent on the residence time of the stormwater in the media, the stormwater characteristics, and the media type. However, Clark (2000) found that failure of these systems is mostly caused by clogging, which can occur well before the contaminant removal capacity of the media is exceeded. Outlet control can be more consistent in providing the desired resident times needed for pollutant control. However, most outlet controls (underdrains) are difficult to size to obtain long residence times. Perforated pipe underdrains short-circuit natural infiltration, resulting in decreased performance. Orifice outlet controls that allow long residence times usually are very small and clog easily. We are studying a foundation drain material (Capiphon™) that can be applied to biofiltration devices and provide another option for outlet control.

A typical biofilter that is 1 m deep, 1.5 m wide and 5 m long would require about 8 hours to drain using the Capiphon™ material as the underdrain. This is a substantial residence time in the media and also provides significant retention of stormwater before being discharged to a combined sewer system. In addition, this slow drainage time will allow infiltration into the native underlying soil, with minimal short-circuiting to the underdrain. Even sandy-silt loam soils frequently used in bioretention devices can result in extended surface ponding, requiring an underdrain. Conventional underdrains (perforated pipe) reduce ponding, but also decrease infiltration opportunities. Capiphon™ also reduces the ponding time but does not allow as much short-circuiting of the infiltration water. Capiphon™ operates under laminar flow conditions (Reynolds number of 100 to 600). The Capiphon™ has a low sediment carrying capacity due to the low Reynolds numbers and therefore has a reduced clogging potential by the fines that are in the stormwater. It has 132 micro channels about 1 mm in diameter that are connected to the bottom of the 200 mm wide strip with smaller slots. This arrangement results in very small discharge rates (Figure 2).

The pilot scale tests being conducted are determining the drainage characteristics of the Capiphon™ material (such as length, slope, hydraulic head, and type of sand media) under a range of typical biofilter conditions. A sand filter media purchased from a local supplier in Tuscaloosa, Alabama is being used for the test setup to measure the hydraulic characteristics of the Capiphon™ drainage material. The filter sand has a median particle size ( $D_{50}$ ) of about 700  $\mu\text{m}$  and a uniformity coefficient ( $C_u$ ) of 3.3. The particle size distributions of the sand filter media and the US Silica Sil-Co-Sil 250 ground silica materials (manufactured by U.S. Silica Company) that is being used during the clogging tests are shown in (Figure3).

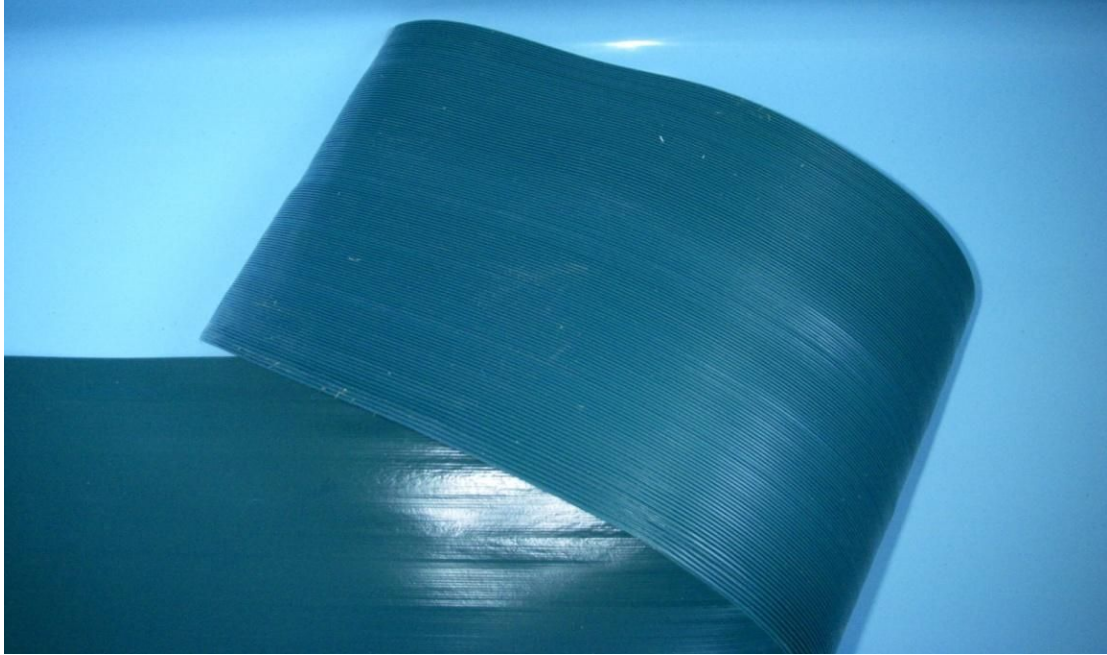


Figure2. Capiphon™ material showing the microchannels on the underside of the 200 mm wide strip.

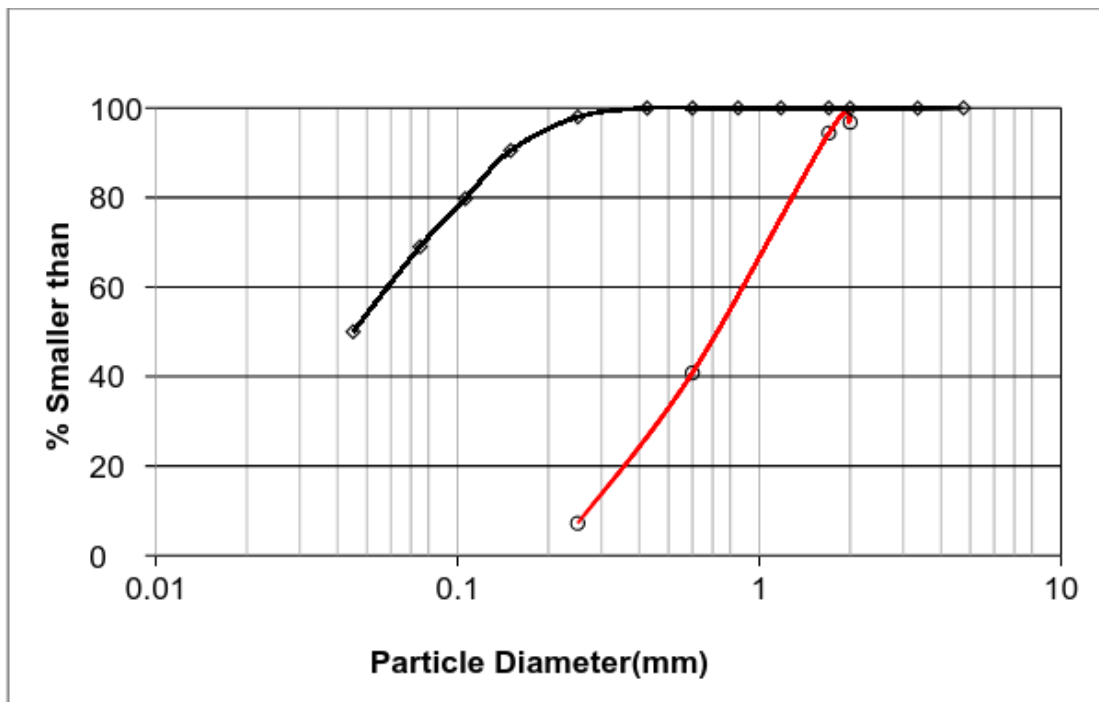


Figure 3. Particle size distributions of the sand filter media material (coarse material on graph) and the U.S Sil-Co-Sil 250 (fine material on graph) used for the clogging test.

## MATERIALS and METHODS

The first phase of the experiment was conducted using a pilot-scale biofilter that consists of a fiberglass trough 3 m long and 0.6 x 0.6 m in cross section. The outlet end of the Capiphon™ was inserted into a slit cut in the PVC collection pipe and secured with screws and silicone sealant (Figure 4(a)). The Capiphon™ material is installed with the microchannels on the underside of the strip. The Capiphon™ directs the collected water into the PVC pipe, with a several inch drop to enhance a siphoning action. The Capiphon™ was installed on top of a 100 mm layer of the drainage sand, and another 100 mm layer of the sand was placed on top of the Capiphon™ (Figure 4(b)). The PVC pipe is 50 mm in diameter and is placed at the bottom of the trough. The pipe outlet is located so the flows can be measured and water samples collected for analyses. During the tests, the trough is initially filled with clean water to a maximum head of 55 cm above the center of the pipe and then allowed to drain, resulting in head vs. discharge data. A hydraulic jack and blocks are used to change the slope of the trough (Figure 4(c)). Different lengths of the Capiphon™ were tested for a range of slopes. Each test was also repeated several times and regression analyses were conducted to obtain equation coefficients for the stage- discharge relationships for these different conditions.

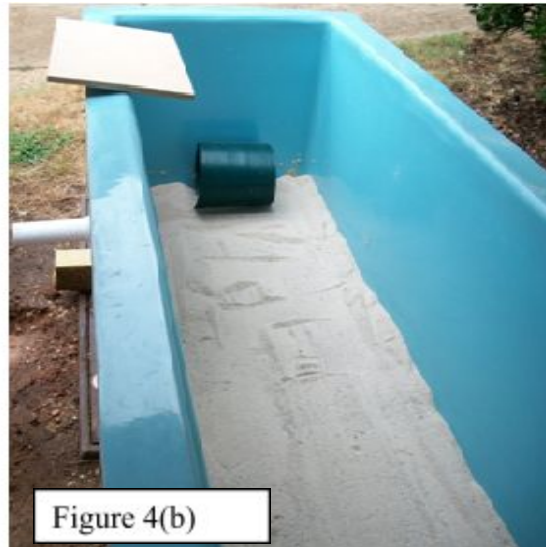


Figure 4. Capiphon™ installations procedures in a fiberglass trough 3m long and 0.6 x 0.6m in cross section.

Phase two of the experiment was conducted to examine the clogging potential of the Capiphon™. U.S Sil-Co-Sil 250, having a median particle size of about 45 µm, was mixed with the test water at a concentration of about 1,000 mg/L. A tall Formica-lined plywood box 0.90 m by 0.85 m in cross sectional area and 1.20 m tall was used to verify the stage-discharge relationships for deeper water and used for the clogging tests.

The box was filled with tap water using a hose to produce a maximum head of 1.20 m above the center of the pipe..



Figure4. Capiphon™ installations procedures in a fiberglass trough 3m long and 0.6 x 0.6m in cross section.

## RESULTS and DISCUSSION

### Variables affecting the drainage characteristics of the sand filter

Five replicates for each of the five different lengths (2.9 m, 2.2 m, 1.6 m, 0.95 m and 34 cm) were conducted to study the variables affecting the drainage characteristics of the material as a function of length, slope, and hydraulic head. Two different lengths of the Capiphon™ (2.9 m and 2.2 m) were tested for five different slopes (0%, 3%, 6%, 9%, and 12%) and three different lengths of the Capiphon™ (1.6 m, 0.95 m and

34 cm) were tested for three different slopes (0%, 3%, and 12%). Flowrate measurements are manually obtained at the effluent of the biofilter at 25 to 30 minute intervals until the clean water was completely drained from the trough. The flows were measured by timing how long it took to fill a 0.5 L graduated cylinder. Stage-discharge relationship plots (Figure 5) are shown for five different length of Capiphon™ material. Linear regression analyses were used to determine the intercept and slope terms of these stage vs. discharge relationships. The p-values of the estimated coefficients were used to determine if the coefficients were significant ( $p < 0.05$ ). All of the five lengths tested for the given slopes showed that coefficients were statistically significant ( $p < 0.05$ ), while many of the intercept terms were not found to be significant on the stage-discharge relationship. The physical slope of the Capiphon™ had no significant effect on the stage-discharge relationships, while length only had a small, but significant effect.

Figure 5 also shows stage-discharge relationships for three very small orifices (2.5, 5, and 6.5 millimeters) superimposed on the Capiphon™ drainage characteristics. The Capiphon™ stage-discharge relationships are represented by first-order linear equations and have flows generally in the range of orifices in the size range of 2.5 to 5 millimeters for typical head conditions.

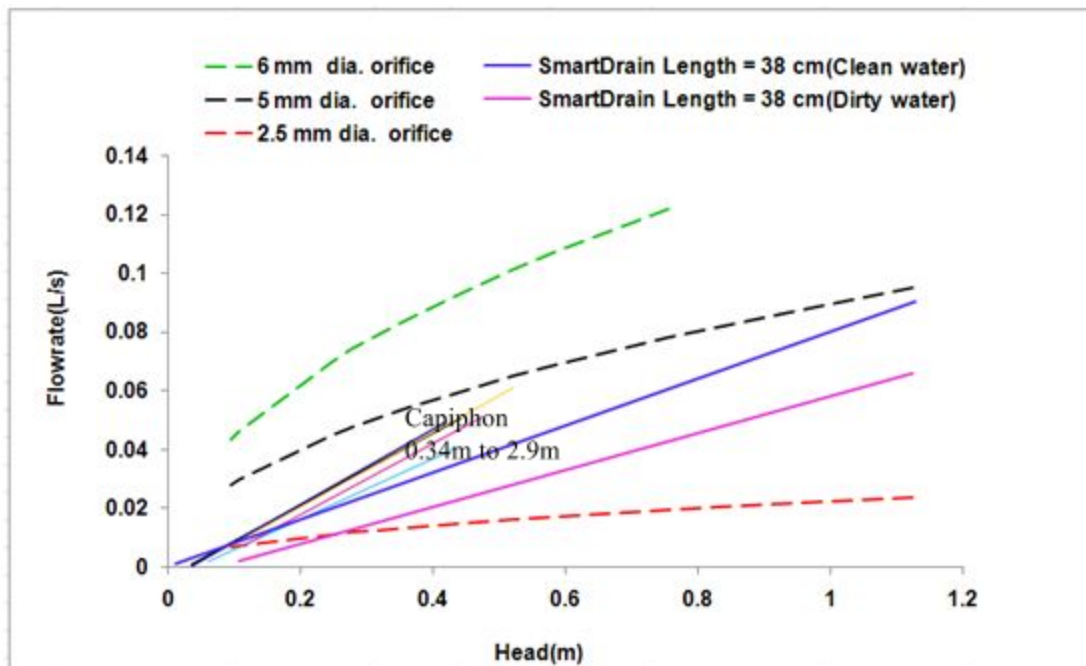


Figure 5. Stage-discharge relationship plots for five different lengths of Capiphon™ (0.34m to 2.9m) tested for five different slopes using a fiber glass trough 3 m long

and 0.6 x 0.6 m in cross-section. The stage-discharge relationship plot shown for the clean vs. dirty water tests had a Capiphon™ length of 38 cm. These tests were conducted in a formica-lined plywood box 0.90 m by 0.85 m in area and 1.20 m tall.

### Examining the clogging potential of the Capiphon™

Flowrate measurements were taken from the effluent of the device at 25-30 minute intervals until the water completely drained from the 1.20 m tall lined box used to verify the stage-discharge relationships for deeper water. Only a moderate reduction in flow rates was observed with time, even after 38 kg/m<sup>2</sup> load (the total US Sil-Co-Sil 250 loadings in kg per square meter of the biofilter area) on the biofilter (2 to 4 times the typical load observed before clogging for most biofilter media). Turbidity measurements of the effluent were also obtained at 25 to 30 minute intervals at the same time as the flowrate measurements until the water completely drained from the tank. The turbidity (NTUs) measurements rapidly decreased with the head of water in the tank (and effluent flow rate).

The initial turbidity levels were about 1,000 NTU in the tank at the beginning of the test (and with similar effluent water turbidity at the beginning of the tests), but with significantly decreasing effluent turbidity values as the test progresses and the flow rates decrease.

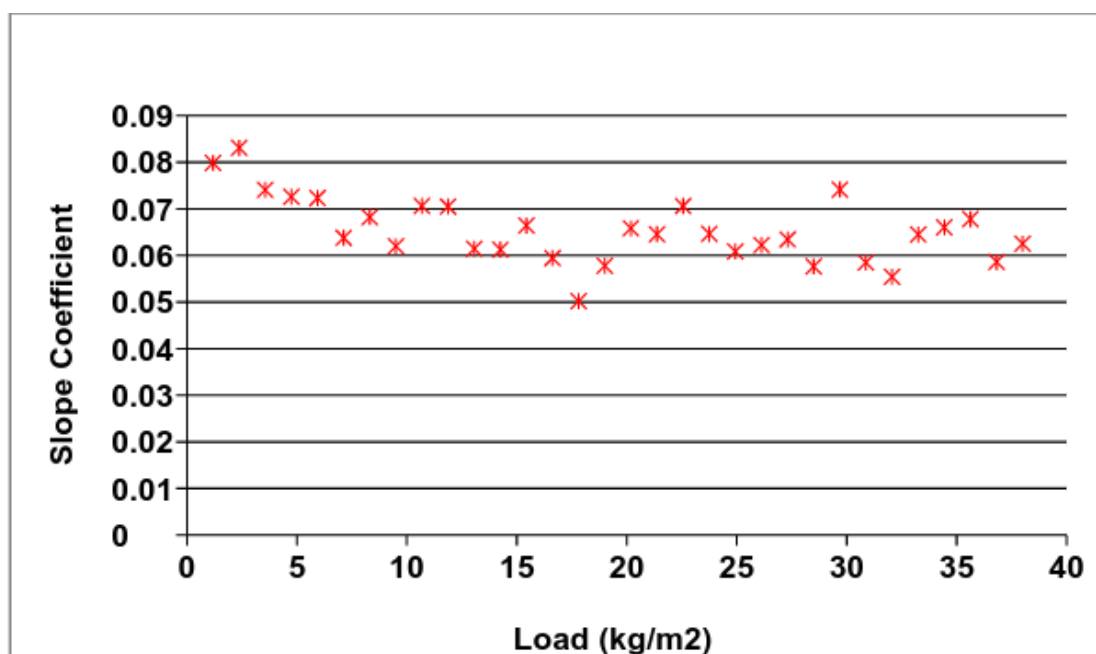


Figure 6 Sil-Co-Sil 250 load (kg/m<sup>2</sup>) vs. equation slope coefficients for the clogging



tests. There was about a 25% reduction in flow rate after about 15 kg/m<sup>2</sup>, compared to the initial flow rate, and this reduced flow continued to the end of the tests with no further reductions in flow rate observed.

Table-1 linear regression analysis result for clogging tests. About 0.95 kg of Sil-Co-Sil 250 was added at each trial, for a total of about 30kg applied during the complete test series. The experimental procedures remained the same for all trials. The cumulative Sil-Co-Sil 250 loading on the biofilter is the only variable changing throughout the trial.

	Trial-1		Trial-2		Trial-3	
	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>
Intercept	0	#N/A	-0.008	p < 0.05	0	#N/A
Slope	0.080	p < 0.05	0.083	p < 0.05	0.0741	p < 0.05
	Trial-4		Trial-5		Trial-6	
	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>
Intercept	0.001	p < 0.05	0	#N/A	0.006	p < 0.05
Slope	0.073	p < 0.05	0.072	p < 0.05	0.064	p < 0.05
	Trial-7		Trial-8		Trial-9	
	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>
Intercept	0	#N/A	0.0026	p < 0.05	0	#N/A
Slope	0.068	p < 0.05	0.0620	p < 0.05	0.071	p < 0.05
	Trial-10		Trial-11		Trial-12	
	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>
Intercept	0	#N/A	0.0011	p < 0.05	0	#N/A
Slope	0.0705	p < 0.05	0.0615	p < 0.05	0.0613	p < 0.05

	Trial-13		Trial-14		Trial-15	
	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficient</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>
Intercept	-0.0025	p < 0.05	0	#N/A	0.00561	p < 0.05
Slope	0.0664	p < 0.05	0.0595	p < 0.05	0.05019	p < 0.05
	Trial-16		Trial-17		Trial-18	
	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficient</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>
Intercept	0.0024	p < 0.05	0	#N/A	-0.0013	p < 0.05
Slope	0.0578	p < 0.05	0.0658	p < 0.05	0.0646	p < 0.05
	Trial-19		Trial-20		Trial-21	
	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficient</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>
Intercept	-0.0045	p < 0.05	-0.0030	p < 0.05	-0.00280	p < 0.05
Slope	0.0706	p < 0.05	0.0646	p < 0.05	0.06084	p < 0.05
	Trial-22		Trial-23		Trial-24	
	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficient</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>
Intercept	-0.0020	p < 0.05	-0.0039	p < 0.05	0	#N/A
Slope	0.0622	p < 0.05	0.0634	p < 0.05	0.0577	p < 0.05
	Trial-25		Trial-26		Trial-27	
	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficient</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>
Intercept	-0.0105	p < 0.05	-0.0060	p < 0.05	-0.0027	p < 0.05
Slope	0.0742	p < 0.05	0.0585	p < 0.05	0.0554	p < 0.05
	Trial-28		Trial-29		Trial-30	
	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficient</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>

	s		s		s	
Intercept	-0.0087	p < 0.05	-0.0071	p < 0.05	-0.0109	p < 0.05
Slope	0.0645	p < 0.05	0.0660	p < 0.05	0.0678	p < 0.05

	Trial-31		Trial-32	
	Coefficients	P-value	Coefficient	P-value
Intercept	-0.0038	p < 0.05	-0.0046	p < 0.05
Slope	0.0586	p < 0.05	0.0625	p < 0.05

## CONCLUSIONS

The results from the experiments conducted to test the variables affecting the drainage characteristics of the filter media indicate that the slope of the Capiphon™ material had no significant effect on the stage-discharge relationship, whereas the length had a small effect on the discharge rate. Effluent turbidity (NTU) measurements decreased rapidly with time, indicating significant retention of silt in the test biofilter. These preliminary tests indicate that the Capiphon™ material provides an additional option for biofilters, having minimal clogging potential while also providing very low discharge rates. We have started further tests to investigate biofouling of the Capiphon™ material. We expect to continue these tests through the coming warm season.

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