POLLUTANT REMOVAL EFFICIENCY TEST

Rotondo Environmental Solutions Biopod Hi-Flow Media

FINAL REPORT

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EXECUTIVE SUMMARY

In September 2015 Rotondo Environmental Solutions, LLC retained MicroBAC Laboratories of Baltimore, Maryland to conduct a series of elution experiments to determine the efficiencies with which their Biopod High-Flow Media removed suspended solids, dissolved phosphorus, dissolved copper and dissolved zinc from synthetic stormwater runoff. The series of experiments consisted of three trials having different concentrations of solids (measured as total suspended solids, or "TSS"); 20 mg/L, 100 mg/L and 200 mg/L. The trial using the highest concentration of solids also included the addition of soluble phosphorus at a concentration of 0.5 mg/L, copper at a concentration of 0.02 mg/L and zinc at a concentration of 0.3 mg/L.

The Biopod High-Flow Media demonstrated the following removal efficiencies for TSS.

Table ES- 1. Biopod High-Flow Media removal efficiencies for TSS.

TSS Concentration (mg/L)	Estimated removal efficiency (%)	Lower 95% Confidence Level of Estimate	Upper 95% Confidence Level of Estimate
20	92.75	89.4	96.2
100	96.4	92.1	98.4
200	99.0	97.9	99.5

The efficiencies shown in Table ES-1 may actually underestimate the removal efficiencies that will be seen in actual stormwater runoff applications since the particle size distribution of the test solids emphasized particles in the smaller range of natural runoff where the highest concentration and loading of pollutants is found rather than the larger particles which contribute most of the mass of runoff solids.

The Biopod High-Flow Media demonstrated a removal efficiency of 17.6% (12.6%, 22.8%) for dissolved phosphorus. This removal efficiency exceeded the removal efficiencies for dissolved phosphorus exhibited by both proprietary and non-proprietary filtration devices for which data are available in the International BMP Database. Given the performance of the Biopod High-Flow Media in removing solids, the removal efficiency of the Biopod High-Flow Media for *total* phosphorus will likely be somewhat greater than that measured for *dissolved* phosphorus since a significant portion of total phosphorus in stormwater runoff is associated with solids.

The Biopod High-Flow Media demonstrated a removal efficiency of 75% for dissolved copper and 93.3% for dissolved zinc. These removal efficiencies exceeded the removal efficiencies for dissolved copper and zinc exhibited by both proprietary and non-proprietary filtration devices for which data are available in the International BMP Database. As with phosphorus, given the performance of the Biopod High-Flow Media in removing solids, the removal efficiency of the Biopod High-Flow Media for *total* copper and zinc will likely be somewhat greater than that measured for *dissolved* copper and zinc since a significant portion of total heavy metals in stormwater runoff is associated with solids.

INTRODUCTION

An important element of today's management of stormwater runoff is ensuring that runoff discharged to receiving streams does not adversely affect the quality of the habitat. Improving the quality of stormwater runoff in urban and suburban areas often requires that best management practices (BMPs) be installed in locations that receive runoff from areas having a high percentage of impervious surfaces. A factor that makes the design and siting of those BMPs difficult is that the locations available for BMPs often offer little room for the devices and they must be integrated into a cluster of developed spaces. Such devices, sometimes called "ultra-urban" BMPs, must be small and must be able to remove pollutants from runoff quickly. A significant number of such BMPs rely on filtration to remove pollutants from runoff. Thus, the nature of the filtration media is critically important if pollutants are to be effectively removed from a significant amount of runoff in a short time

An important characteristic of the media placed in ultra-urban filtration BMPs is the hydraulic conductivity. In order for such ultra-urban filtration BMPs to service a significant drainage area yet be small enough to be easily installed, the filtration media must be able to transmit water at rates of 100 inches per hour or more. Such high hydraulic conductivities require filter media with relatively large particles that will provide flow paths to support the high flows.

Elimination of solids contained in stormwater runoff by filtration is largely a physical separation process. However, the large particles and large diameter flow paths in a filtration media with high hydraulic conductivity are not conducive to eliminating the very small particles that comprise the solid load in stormwater runoff. Designing a filter media that can maintain such high hydraulic conductivities and at the same time remove small particles is an engineering challenge.

Removal of dissolved pollutants from stormwater runoff is often largely a physical absorption process. Such high hydraulic conductivities as seen in ultra-urban BMPs mean that runoff is in contact with the media for very short periods of time. The contact time for runoff water in a BMP with 24 inches of media and a hydraulic conductivity of 100 inches per hour is only about 14 minutes. Designing a filter media that can maintain such high hydraulic conductivities and at the same time remove dissolved pollutants in runoff water is an engineering challenge. Often, organic matter, zeolites, activated carbon or other additives are blended into the filtration media to improve its absorption characteristics.

The Rotondo Biopod High-Flow Media has been designed to provide the hydraulic conductivity necessary for its use in ultra-urban filtration BMPs and at the same time provide physical separation and physical absorption characteristics needed to remove particulate and dissolved pollutants from stormwater runoff. This document describes laboratory-scale experiments that were performed in order to quantify the effectiveness of the Biopod High-Flow Media in removing suspended solids and dissolved pollutants from stormwater runoff.

MATERIALS AND METHODS

This section describes the materials and methods used to evaluate the effectiveness of a laboratory-scale stormwater filtration unit containing Rodondo Environmental Solutions (RES) Biopod High Flow Media in removing several pollutants from synthetic runoff. The study focused on two key pollutants; total suspended solids (TSS) and total phosphorus (TP). In addition to the two key pollutants, one phase of the study investigated the removal efficiency with respect to two heavy metals; zinc (Zn) and copper (Cu).

MATERIALS

The following sections describe the materials used for the tests. All materials were bought new, or were constructed or prepared for these experiments. The materials consisted of the equipment used in the tests, the filter media being tested, and the synthetic runoff that simulated actual runoff with respect to the pollutants of interest.

Equipment

Equipment used in the tests consisted of:

- a 60-gallon HDPE water tank (U.S. Plastics Corporation, SKU 8696 – Full drain inductor tank with 2” MPT boss) was used to store the synthetic runoff for each test trial. A single tank was used, which provided synthetic runoff for all of the test columns.
- an electric mixer/stirrer (Tamco, Model 15231 – 2-blade mixer with 1/3 hp TEFC motor and 5/8” shaft) was used to stir the synthetic runoff. The stirrer was run constantly during each of the test trials.
- two 80-gallon per day peristaltic pumps (Chem Tech Model XP080LA3X – 80 GPD @ 25 psi)
- four 6”-diameter Schedule 40 PVC cylinders, 36” long with bottom cap and PVC butterfly drain valve

The test cylinders and peristaltic pumps were mounted on a support rack. The synthetic runoff was delivered to the peristaltic pumps via polyethylene tubing. Figure 1 shows the assembled test apparatus.

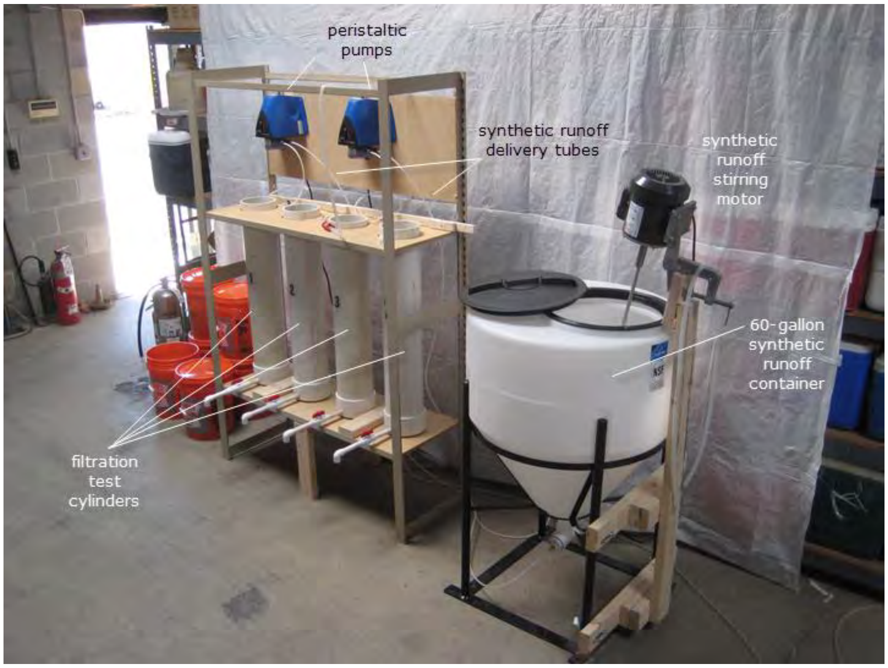

Figure 1. RES assembled test apparatus.

Filter media

The filter media tested was the Rotondo Environmental Solutions (RES) Biopod High Flow Media. The tests were also run on RES Biopod-SG High Flow Media, but those results are not the subject of this report; they will be addressed in a subsequent, separate report. All sets of media included a 6” bed of AASHTO No. 8 stone and a 3” surface layer of shredded hardwood mulch. Figure 2 shows a cross-section of the test cylinders.

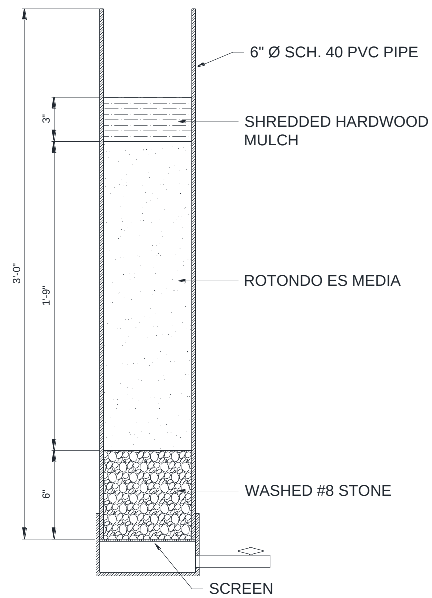

Figure 2. Cross-section of media test cylinder.

Synthetic runoff

The RES Biopod High Flow Media was tested using three formulations of synthetic runoff. One formulation (Solution A) tested the effectiveness of removing TSS at a concentration of 20 mg/Liter; one formulation (Solution B) tested the effectiveness of removing TSS at a concentration of 100 mg/Liter; the third formulation (Solution C) tested the effectiveness of removing TSS at a concentration of 200 mg/L plus the effectiveness of removing TP, total copper and total zinc.

TSS

All synthetic runoff formulations used Sil-co-sil 106 as a surrogate for naturally-occurring particulates. Sil-co-sil 106 is a product of the U.S. Silica Company of Berkeley Springs, West Virginia. It is a mixture of quartz particles of various sizes. A typical grain size analysis of Sil-co-sil 106 is presented in Table 1; a graph of the particle size distribution of Sil-co-sil 106 is shown as Figure 3.

Table 1. Grain size analysis of Sil-co-sil 106				
U.S. Standard Sieve Size		Typical Values		
		% Retained		% Passing
Mesh	Microns	Individual	Cumulative	Cumulative
70	212	0.0	0.0	100.0
100	150	0.1	0.1	99.9
140	106	1.4	1.5	98.5
200	75	5.5	7.0	93.0
270	53	11.0	18.0	82.0
325	45	7.0	25.0	75.0

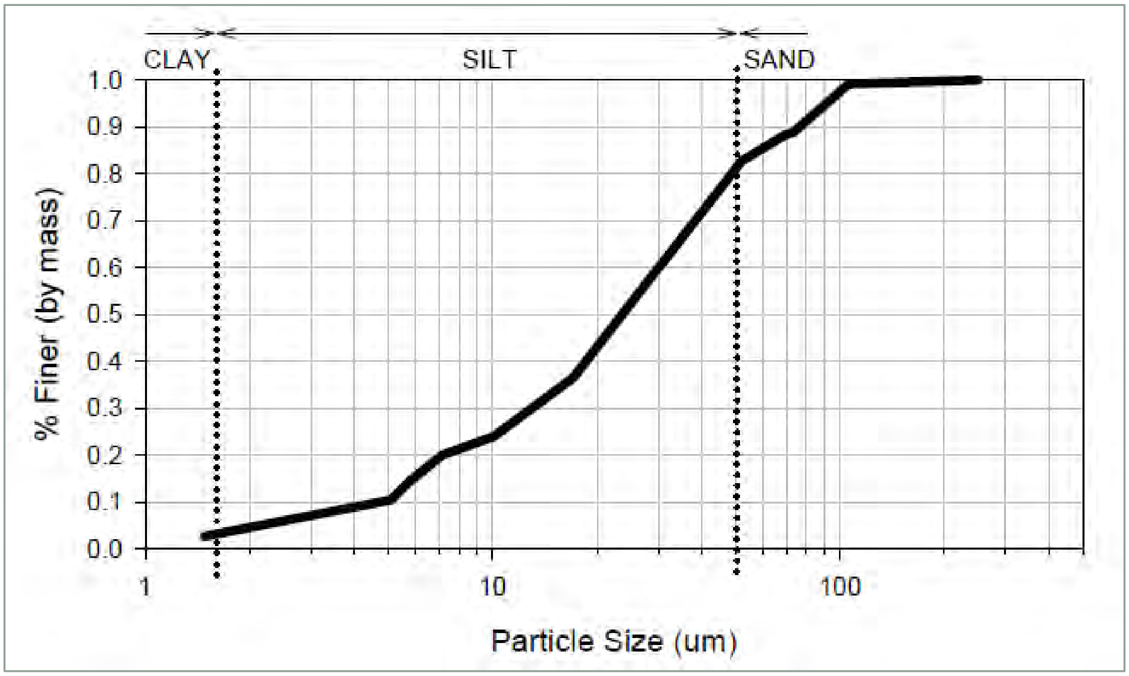

Figure 3. Particle size distribution of Sil-co-sil 106.

Sil-co-sil 106 is shown to be a silt-sized material with a median (D_{50}) diameter of about 22 µm.

Sil-co-sil 106 has a pH of 7, a hardness of 7 Mohs, and a specific gravity of 2.65. A typical chemical analysis of Sil-co-sil 106 is given below in Table 2.

Table 2. Typical chemical analysis of Sil-co-sil 106 (values in percent)	
SiO_2 (Silicon Dioxide) 99.8	MgO (Magnesium Oxide) .... <0.01
Fe_2O_3 (Iron Oxide) 0.035	Na_2O (Sodium Oxide) .... <0.01
Al_2O_3 (Aluminum Oxide) 0.05	K_2O (Potassium Oxide) 0.02
TiO_2 (Titanium Dioxide) 0.02	LOI (Loss on Ignition) 0.1
CaO (Calcium Oxide) 0.01	

The amounts of Sil-co-sil 106 added to 60 gallons (227.125 liters) of deionized water to obtain the various concentrations of TSS are given below.

- Solution A @ 20 mg/L TSS 4.54 grams Sil-co-sil 106
- Solution B @ 100 mg/L TSS 22.7 grams Sil-co-sil 106
- Solution C @ 200 mg/L TSS 45.4 grams Sil-co-sil 106

Phosphorus

Phosphorus was added to one of the test synthetic runoff solutions, Solution C. Liquid phosphorus (InorganicVentures inorganic ion chromatography solution – ICPP041 – Lot No. J2-POX01109), prepared using ammonium dihydrogen phosphate ($NH_4H_2PO_4$) at a concentration of 1,000 µg/ml (certified 997±3 µg/ml) was used to add phosphorus to Solution C. A volume of 113.5 milliliters of the liquid phosphorus solution was added to 60 gallons of deionized water to produce synthetic runoff with a total phosphorus concentration of 0.5 mg/L.

Heavy metals

Copper and zinc were added to one of the test synthetic runoff solutions, Solution C. Liquid copper (SCP Science AA standard solution – 140-001-291 – Lot No. S150225013), prepared using elemental copper and HNO_3 to formulate a copper solution of 1,000 µg/ml (certified 1002±3 µg/ml), was used to add copper to Solution C. A volume of 4.54 milliliters of the SCP copper solution was added to 60 gallons of deionized water to produce synthetic runoff with a total copper concentration of 0.02 mg/L.

Liquid zinc (SCP Science AA standard solution – 140-001-301 – Lot No. S150126014), prepared using elemental zinc and HNO_3 to formulate a zinc solution of 1,000 µg/ml (certified 996±3 µg/ml), was used to add zinc to Solution C. A volume of 68.1 milliliters of the SCP zinc solution was added to 60 gallons of deionized water to produce synthetic runoff with a total zinc concentration of 0.3 mg/L.

METHODS

The following sections describe the methods used to test the Biopod High Flow Media. Methods involved preparing the columns for testing, flushing the columns to attempt to eliminate particulates from the media, preparing the synthetic runoff test solutions, delivering the synthetic runoff to the test cylinders, sampling the effluent, and analyzing the samples.

Column Preparation

Columns #1 and #2 were used to test the RES Biopod High Flow Media. Columns #1 and #2 were used to test the media for TSS removal using Solutions A and B. After testing the media in Column #1 with Solution A, Column A was emptied, cleaned, and re-filled with Biopod High Flow Media in preparation for the test using Solution C. The filling and re-filling of both columns followed the procedure described below.

1. Wash #8 stone thoroughly in a colander with water to remove fines.
2. Place #8 stone in bottom of column to a depth of 6 inches.
3. After stone is placed, rod a minimum of 30 times to consolidate.
4. Place 1st layer of RES Biopod High Flow Media in column directly on top of #8 stone to a depth of approximately 10.5 inches and rod a minimum of 60 times to consolidate.
5. Place 2nd layer of RES Biopod High Flow Media in column directly on top of 1st layer to a depth of approximately 10.5 inches (21 inches total) and rod a minimum of 60 times to consolidate.
6. Flush column two times with water to consolidate the media.

7. Measure media depth to make sure there is a minimum depth of 21 inches, topping off with additional media if needed.
8. Place mulch on top of media and press down firmly to a depth of 3 inches.

Column Flushing Process

After preparing the columns as described above, each column was flushed to eliminate any particulate matter introduced with the #8 stone, the media and the mulch. The flushing process consisted of the following steps.

1. Pour de-ionized water into the column slowly, directing the flow toward the center of the column taking care not to disturb or displace the mulch.
2. Repeat the flushing process until the water leaving the column is visibly clear with a maximum turbidity reading of 20 NTU as measured with a Micro 100 Turbidimeter.
3. Once the flushing process is complete and a turbidity reading of 20 NTU or less has been reached, collect the required samples for the Blank Analysis to determine the amount of pollutants the media is leaching.

Synthetic Runoff Preparation

Synthetic runoff was prepared in the 60-gallon tank as a separate batch for each experimental run.

1. Fill the water tank with 60 gallons of de-ionized water and start the electric mixer.
2. Pour the pre-measured pollutants into the water tank making sure nothing remains on the weighing paper (for TSS) or in the dispensing bottle (for P, Cu and Zn).
3. After the pollutants have been added, allow the solution to mix for a minimum of 15 minutes to ensure it is thoroughly mixed.

Solution Dispensing

Peristaltic pumps were used to pump the synthetic runoff solution from the 60-gallon tank to the test columns. The dispensing hoses were placed approximately 6 inches above the top of the mulch layer and discharged the synthetic runoff solution into the center of the test columns.

Synthetic runoff was pumped into the test columns at a steady flow rate of 355 ml/min for approximately 8 ½ hours.

Media Testing Procedure:

The Media Testing Procedure consisted of packing the columns, running solutions with target concentrations of pollutants through the columns, and taking samples of the effluent to determine the pollutant removal efficiencies of the media. A summary of the overall procedure following the flushing process (described above) is given below.

1. Samples are to be obtained by grabbing with plastic bottles. Sample bottles are to be clearly marked with time the sample is taken and the sample designation (*i.e.*, Effluent Sample #3).
2. Once the Blank Sample has been taken close the valve and fill the column with the mixed solution to a level that is approximately 1 inch above the top of the mulch. Tap the side of the column to help fill in the air voids with water.

3. Once the bubbling has stopped and all air voids have been filled, shut off pumps and open the drain valve to allow the column to drain.
4. Once the column has thoroughly drained, close the drain valve and repeat steps 1-2 two more times to ensure that all de-ionized water from the flushing process has been removed.
5. Once the column has been filled and drained 3 times it is assumed that all free de-ionized water has been removed from the filter media and all that is left is the mixed solution.
6. Prior to beginning the testing cycle grab a sample of the influent from the end of the influent hoses extending from the peristaltic pumps.
7. Once the influent sample has been taken, begin the testing cycle by pumping the mixed solution into the column at the constant rate of 355 ml/min and begin the timing process.
8. Grab the first effluent sample after 24 minutes.
9. Grab the second effluent sample 48 minutes after collecting the first effluent sample.
10. Allow 48 minutes between all remaining samples until a total of 10 effluent samples have been taken.
11. Store each sample in a cooled location (4° C) for analysis.
12. Once all 10 samples have been taken the sampling process is complete – submit samples for analysis.
13. Repeat steps 1-11 for all column tests.

Sample Analysis

All samples were analyzed onsite at MicroBAC laboratories, Inc. (2101 Van Deman Street, Baltimore, MD 21224) using the following test methods.

- Total Suspended Solids (TSS): SM 2540 D-11
- Phosphorous (P): SM 4500-P B5+E-11
- Copper (Cu): EPA 200.7
- Zinc (Zn): EPA 200.7

RESULTS

Pollutant removal efficiency test were performed at the MicroBAC laboratories in Baltimore, Maryland on September 17, 21 and 23, 2015. The test for removal of TSS at 20 mg/L was performed using Column #1 on 9/17/2015. The test for removal of TSS at 100 mg/L was performed using Column #2 on 9/21/2015. The test for removal of TSS at 200 mg/L was combined with the test for removal of phosphorus and heavy metals using a re-packed Column #1 on 9/23/2015.

No problems were encountered implementing the procedures described in the Materials & Methods section of this report. The only non-compliance instances with respect to those methods were that 96 minutes elapsed between the 8th and 9th sample in the 20 mg/L TSS run (instead of the target 48 minutes), the first sample was taken after 74 minutes in the 100 mg/L TSS run and the first sample was taken after 57 minutes in the 200 mg/L TSS run (instead of the target 24 minutes). These sampling time non-compliance instances resulted in the tests being conducted for slightly longer than the target 8 hours (480 minutes). Test 1 (20 mg/L TSS) was run for 504 minutes, Test 2 (100 mg/L TSS) was run for 506 minutes, and Test 3 (200 mg/L TSS) was run for 489 minutes). There was sufficient synthetic runoff to complete each test.

The results of the sampling for TSS are given in Table 3.

Table 3. Results of TSS Removal Efficiency Tests

Sample ID	20 mg/L TSS Runoff		100 mg/L TSS Runoff		200 mg/L TSS Runoff	
	Elapsed Time (minutes)	Effluent Concentration (mg/L)	Elapsed Time (minutes)	Effluent Concentration (mg/L)	Elapsed Time (minutes)	Effluent Concentration (mg/L)
Blank		20.00		39.00		12.00
Influent	0	10.00	0	45.00	0	99.00
Effluent-01	24	2.50	74	26.00	57	1.60
Effluent-02	72	1.20 U	122	6.10	105	2.00
Effluent-03	120	1.40	170	4.40	153	2.20
Effluent-04	168	3.60	218	3.60	201	2.00
Effluent-05	216	1.80	266	10.00	249	14.00
Effluent-06	264	1.10	314	0.55 U	297	2.70
Effluent-07	312	0.72	362	5.50	345	0.78
Effluent-08	360	1.00	410	1.90	393	0.71 U
Effluent-09	456	0.51	458	1.10	441	7.40
Effluent-10	504	0.63	506	2.20	489	0.53 U
Average Effluent Concentration		1.45		6.14		3.39
Removal Efficiency*		92.75%		93.86%		98.31%

Note: Values with "U" qualifier indicates concentrations below detection level. Reporting limit was used to calculate the average concentration.
* Assumes the nominal concentration of TSS in the synthetic runoff is the average influent concentration.

These results demonstrate that the “Blank” sample, which was a sample of the column effluent at the start of each test, showed somewhat elevated concentrations of TSS. However, the concentration of TSS in the effluent of each test quickly fell to a concentration somewhat lower than the “Blank” concentration.

The results show that in each test the beginning TSS influent concentration was approximately one-half of the nominal test concentration. The initial influent concentration of the first test was 10 mg/L TSS (50% of the nominal synthetic runoff concentration of 20 mg/L). The initial influent concentration of the second test was 45 mg/L TSS (45% of the nominal synthetic runoff concentration of 100 mg/L). The initial influent concentration of the third test was 99 mg/L TSS (49.5% of the nominal synthetic runoff concentration of 200 mg/L).

The results of the test of the efficiency of the test media at removing phosphorus and heavy metals are given in Table 4.

Table 4. Results of Phosphorus and Heavy Metal Removal Efficiency Tests

Sample ID	Elapsed Time	0.50 mg/L TP in Runoff	0.02 mg/L Cu in Runoff	0.30 mg/L Zn in Runoff
		Effluent Concentration (mg/L)	Effluent Concentration (mg/L)	Effluent Concentration (mg/L)
Blank		0.110	0.005 U	0.020 U
Influent	0	0.430	0.054	0.330
Effluent-01	57	0.330	0.005 U	0.020 U
Effluent-02	105	0.380	0.005 U	0.020 U
Effluent-03	153	0.400	0.005 U	0.020 U
Effluent-04	201	0.420	0.005 U	0.020 U
Effluent-05	249	0.410	0.005 U	0.020 U
Effluent-06	297	0.440	0.005 U	0.020 U
Effluent-07	345	0.430	0.005 U	0.020 U
Effluent-08	393	0.420	0.005 U	0.020 U
Effluent-09	441	0.450	0.005 U	0.020 U
Effluent-10	489	0.440	0.005 U	0.020 U
Average Effluent Concentration		0.412	0.005	0.020
Removal Efficiency*		17.6%	75.0%	93.3%

Note: Values with “U” qualifier indicates concentrations below detection level. Reporting limit was used to calculate the average concentration.
* Assumes the nominal concentration of pollutant in the synthetic runoff is the average influent concentration.

These results demonstrate that the “Blank” sample, which was a sample of the column effluent at the start of each test, showed a low, but detectable concentration of phosphorus, while no copper or zinc was detected in the “Blank” sample.

The initial influent concentrations of phosphorus and zinc were close to the nominal concentrations of those constituents in the synthetic runoff. However, the initial influent concentration for copper (0.054 mg/L) was over twice the nominal concentration of copper in the synthetic runoff of 0.02 mg/L.

DISCUSSION

The following sections discuss the results of the tests with respect to the hydrologic loading rates and the removal efficiencies of TSS, phosphorus, copper and zinc.

HYDROLOGIC LOADING RATE

In each of the tests the synthetic rainfall was introduced at a rate of 355 ml/min. This rate corresponds to a hydrologic loading rate of 0.003 gallons/min/in^2 (0.48 gal/min/ft^2). This hydrologic loading would require the media to have an infiltration rate of at least approximately 46 in/hr in order not to overflow the test cylinder. This infiltration requirement is well within the reported infiltration capability (> 100 in/hr) of the media being tested. Thus, the hydrologic loading rate would not adversely affect the ability of the media to accept and treat the synthetic rainfall being introduced during the tests.

TSS REMOVAL EFFICIENCY

The effluent concentrations varied somewhat over time in each of the test runs. There was no clear pattern regarding the concentrations. Therefore, there was no indication that the media was more or less effective at removing TSS at any specific elapsed time during the test run. The relatively low influent concentration at the beginning of each test run may indicate that the influent TSS concentrations varied throughout the test and that the resulting effluent concentrations reflected the variation in influent concentrations.

The use of Sil-co-sil 106 to evaluate TSS removal by stormwater BMPs has been recommended by the Washington State Department of Ecology (2004) because they consider the Sil-co-sil 106 product to approximate the “typical” size distribution of particles found in stormwater runoff. The Sil-co-sil product has a particle size distribution that emphasizes particle sizes that are actually somewhat smaller than those found in “typical” stormwater runoff. While the median particle size (D_{50}) of Sil-co-sil 106 is approximately 22 µm, the typical D_{50} for stormwater runoff TSS is 100 µm (Minton, 2005, p. 34). The emphasis on smaller particles perhaps does result in a better indication of how effective the Biopod High Flow Media will be at removing pollutants associated with TSS since James (1999) observes that the higher *concentration* of pollutants have been found associated with the finer particles (<100 µm) while the *mass* of pollutants are associated with particles greater than 100 µm.

The concentrations of TSS in the effluent varied from a low of 0.51 mg/L to a high of 3.60 mg/L – giving a range of 3.09 mg/L. The effluent concentrations for the 20 mg/L TSS test were normally distributed and had a mean concentration of 1.446 mg/L with a 95% LCL of 0.76 mg/L and a 95% UCL of 2.13 mg/L. The mean concentration and its LCL and UCL indicate that at a 20 mg/L loading the media exhibited a removal efficiency of between 89.4% and 96.2% with the best estimate being 92.75%.

The effluent concentrations for the 100 mg/L TSS test varied from a low of 0.55 mg/L to a high of 26 mg/L – giving a range of 25.45 mg/L. The effluent concentrations had a mean concentration of 6.135 mg/L which indicates a removal efficiency of 93.86%. However, unlike the 20 mg/L test, the effluent concentration data for the 100 mg/L test were not normally distributed, but were lognormally distributed. The data show a geometric mean of 1.28 with a 95% LCL of 0.48 and a 95% UCL of 2.07. The geometric mean concentration and its LCL and UCL indicate that at a 100 mg/L loading the media exhibited a removal efficiency of between 92.1% and 98.4% with the best estimate being 96.4%.

The concentrations of TSS in the effluent of the 200 mg/L TSS test varied from a low of 0.53 mg/L to a high of 14 mg/L – giving a range of 13.47 mg/L. The effluent concentrations for the test had a mean concentration of 3.39 mg/L which indicates a removal efficiency of 98.31%. However, like the 100 mg/L test, the effluent concentration data for the 200 mg/L test were not normally distributed, but were lognormally distributed. The data show a geometric mean of 0.705 with a 95% LCL of -0.024 and a 95% UCL of 1.435. The geometric mean concentration and its LCL and UCL indicate that at a 200 mg/L loading the media exhibited a removal efficiency of between 97.9% and 99.5% with the best estimate being 99.0%.

Figure 3 compares the distribution of effluent sample concentrations for each of the test runs. The 100 mg/L TSS and the 200 mg/L TSS test runs both show one outlier concentration. The outlier occurred in the middle of the test run rather than at the beginning, perhaps also indicating that the influent concentration may have varied throughout the test.

Evaluation of the data indicate that the median effluent concentration for the 200 mg/L TSS test is not significantly different (at the 95% level) from the median concentration of the 20 mg/L TSS or the 100 mg/L TSS tests. However, the median concentration of the 20 mg/L TSS test is significantly different from the median concentration of the 100 mg/L test.

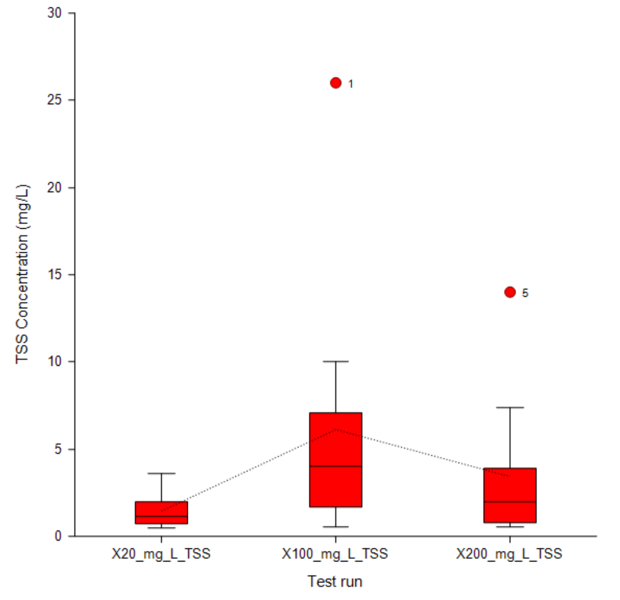

Figure 4. Box plots of effluent sample concentrations for each of the test runs. (Means are connected by dotted line)

Geosyntec Consultants and Wright Water Engineers (2012, 2014) present summaries of removal efficiency statistics for various filters with respect to total suspended solids (see Table 5) for which data are available in the International BMP Database.[1]

Table 5. Removal Efficiencies for Total Suspended Solids by Various Filtration Devices†

	Count of Studies and EMCs		25th Percentile		Median (95% CI)		75th Percentile	
	In	Out	In	Out	In	Out	In	Out
Non-proprietary Media Filtration devices	23; 381	23; 358	21.1	3.0	50.9 (42.8; 58.0)	8.4 (6.3; 9.8)*	110.5	19.9
Biological Filtration devices‡	4; 72	4; 72	12.0	2.4	20.5 (15.5; 25.9)	3.5 (2.5; 4.0)*	35.1	5.0
Filtration devices‡	7; 125	7; 125	15.0	6.7	32.3 (23.0; 40.0)	14.2 (10.0; 15.0)*	80.0	25.6

Values in mg/L
† See report text for descriptions of devices
‡ Data from Geosyntec Consultants and Wright Water Engineers (2012)
* Hypothesis testing shows statistically significant decrease in effluent concentration.
NA – Insufficient studies available to develop reliable statistics

[1] Available on-line at http://bmpdatabase.org

Non-proprietary *Media Filtration* devices for which statistics have been developed in Table 5 are largely sand filters. *Biological filtration* devices are proprietary media filtration devices that support plants or bacterial biofilms. *Filtration* devices are proprietary media filtration devices with a variety of media types and configurations (*e.g.*, cartridge filters, vertical bed filers, *etc*.). Table 5 shows that the general class of non-proprietary Media Filtration devices and proprietary (*i.e.*, manufactured) Biological Filtration devices have a TSS removal efficiency of about 83% and that proprietary Filtration devices have a TSS removal efficiency of about 56%.

The above studies were conducted at sites having relatively low TSS concentrations, so they should be compared to the current Biopod High Flow Media study that used 20 mg/L TSS influent. The Biopod High Flow Media of the current study at 20 mg/L TSS in the influent showed a TSS removal efficiency of between 89.4% and 96.2% with the best estimate being 92.75%. Thus, the Biopod High Flow Media of the current study removed TSS at a somewhat higher efficiency than the non-proprietary and proprietary filtration devices for which data are available in the International BMP Database.

PHOSPHORUS AND HEAVY METAL REMOVAL EFFICIENCIES

Phosphorus

The effluent concentrations for the phosphorus test were normally distributed and had a mean concentration of 0.412 mg/L with a 95% LCL of 0.386 mg/L and a 95% UCL of 0.437 mg/L. The effluent concentrations ranged from a low of 0.330 mg/L to a high of 0.45 mg/L – giving a range of 0.12 mg/L. The mean concentrations indicate that at a 0.50 mg/L loading the media exhibited a removal efficiency for phosphorus of between 12.6% and 22.8% with the best estimate being 17.6%.

An important consideration to note in interpreting the observed phosphorus removal efficiency is that the phosphorus used in the test was entirely dissolved phosphorus. The International BMP Database (2014) lists 28 studies of sand filters that recorded dissolved phosphorus concentrations in the influent and the effluent. Detailed statistical analysis reports are provided for ten of those studies. The results of statistical analyses of those studies with respect to dissolved phosphorus are given below in Table 6.

Table 6. Removal of Dissolved Phosphorus in Stormwater Runoff by Media Filters

Filter Name	Location	Mean Statistics			Median Statistics*		
		Influent	Effluent	% Increase (I) or Decrease (D)	Influent	Effluent	Significant Difference?
Termination	Norwalk, CA	0.05	0.04	20% D	0.03	0.03	No
5/78	Vista, CA	0.34	0.37	9% I	0.22	0.23	No
Barton Ridge SF	Austin, TX	0.11	0.08	27% D	0.07	0.06	No
Vertical Filter #6	Austin, TX	0.07	0.05	28% D	0.06	0.05	No
Upper SF	Sammamish, WA	0.01	0.01	NC	0.01	0.01	No
La Costa	Carlsbad, CA	0.23	0.12	48% D	0.19	0.13	No
Eastern SF	Whittier, CA	0.03	0.07	233% I	0.03	0.03	No
Jollyville SF	Austin, TX	0.10	0.06	40% D	0.08	0.06	No
Delaware SF	Newark, DE	0.15	0.25	167% I	0.07	0.07	No
Foothill SF	Monrovia, CA	0.09	0.09	129% I	0.07	0.08	No

Values in mg/L
* Note that the median may be more representative of the typical or average site storm event discharge concentration because the value is more robust in the presence of outliers, when compared to the mean. See Geosyntec Consultants and Wright Water Engineers (2009)

Table 6 shows that media (sand) filters vary greatly in their ability to remove dissolved phosphorus. Of the ten systems for which statistical summaries are available five of the systems showed from 9% to 48% removal efficiencies while four of the systems showed increases of dissolved phosphorus in the effluents of from 9% to 233% the concentrations found in the influent. One system showed no change in dissolved phosphorus concentration from the influent to the effluent.

The International BMP Database lists two studies of media filters that are described as "Filter – Peat Mixed with Sand." The media filters in Downey, California and San Dimas, California both showed slight increases of dissolved phosphorus in the effluents compared to the influents. The Downey site showed 0.1 mg/L dissolved P in the effluent vs 0.09 mg/L in the influent while the San Dimas site showed 0.13 mg/L dissolved P in the effluent vs 0.1 mg/L in the influent.

Geosyntec Consultants and Wright Water Engineers (2012, 2014) present summaries of removal efficiency statistics for various filters with respect to total, ortho-, and dissolved phosphorus (see Table 7).

Table 7. Removal Efficiencies for Phosphorus by Various Filtration Devices†

Form of Phosphorus	Count of Studies and EMCs		25th Percentile		Median (95% CI)		75th Percentile	
	In	Out	In	Out	In	Out	In	Out
Non-proprietary Media Filtration devices								
Total P	22;365	22;349	0.070	0.040	0.150 (0.140; 0.170)	0.089 (0.075; 0.097)*	0.283	0.160
Ortho-P	7; 116	7;115	0.020	0.015	0.037 (0.028;0.050)	0.030 (0.022; 0.040)	0.090	0.070
Dissolved P	10; 111	10; 100	0.013	0.016	0.047 (0.030; 0.060)	0.044 (0.030; 0.060)	0.097	0.097
Manufactured devices- Biological filtration‡								
Total P	4;64	4;64	0.06	0.04	0.10 (0.08; 0.11)	0.06 (0.05; 0.07)*	0.14	0.10
Dissolved P	NA	NA	NA	NA	NA	NA	NA	NA
Manufactured devices- Filtration‡								
Total P	7; 98	7; 98	0.05	0.04	0.08 (0.06; 0.09)	0.06 (0.04; 0.07)*	0.13	0.09
Dissolved P	4;71	4;71	0.02	0.02	0.03 (0.02; 0.03)	0.03 (0.03; 0.03)	0.05	0.04

Values in mg/L
† See report text for descriptions of devices
‡ Data from Geosyntec Consultants and Wright Water Engineers (2012)
* Hypothesis testing shows statistically significant decrease in effluent concentration.
NA – Insufficient studies available to develop reliable statistics

Non-proprietary *Media Filtration* devices for which statistics have been developed in Table 7 are largely sand filters. *Biological filtration* devices are proprietary media filtration devices that support plants or bacterial biofilms. *Filtration* devices are proprietary media filtration devices with a variety of media types and configurations (*e.g.*, cartridge filters, vertical bed filers, *etc.*). Table 7 shows that the efficiency of non-proprietary media filters with respect to the removal of dissolved phosphorus was about 6%, but that this apparent decrease in effluent median concentration was not statistically significant. Thus, the performance of the Biopod High Flow Media tested in this study with respect to the removal of dissolved phosphorus appears to be somewhat better than the effectiveness at removing dissolved phosphorus seen in the non-proprietary "Media filters" class of BMPs and better than "Media Filters with Peat."

Table 7 shows that the removal efficiency for dissolved phosphorus achieved by the proprietary filtration devices is zero. That is, there is no apparent change between the influent and the effluent median concentrations of dissolved phosphorus for proprietary (*i.e.*, manufactured) filtration devices. Thus, the Biopod High Flow Media tested in this current set of experiments performs significantly better with respect to removing dissolved phosphorus than the proprietary filter devices in the International BMP Database.

Phosphorus in stormwater runoff occurs in dissolved form and is also associated with particulate matter such as that reported as total suspended solids (Hsieh, Davis & Needelman, 2007). Wei, Simin & Fengbing (2013) found that about 66% of the phosphorus in stormwater runoff from two roads in Handan City, PRC was present as dissolved phosphorus, with about 33% being associated with particulate matter. The Water Environment Federation and the American Society of Civil Engineers (1998, as cited in Erickson, 2005) report that the event mean concentration for total phosphorus in urban runoff is 0.33 mg/L while the concentration of "soluble" phosphorus is 0.12 mg/L. This indicates that about 36% of the total phosphorus in runoff is dissolved phosphorus. Brezonik and Stadelmann (2002) report that urban runoff in the Twin Cities Metropolitan Area (Minneapolis and St. Paul, MN) exhibits event mean concentrations for total and dissolved phosphorus as a function of climatic season. The values of total phosphorus and dissolved phosphorus (respectively) that they observed were: 1.37 and 0.37 mg/L for winter, 0.85 and 0.53 mg/L for spring, 0.59 and 0.21 mg/L for summer, and 0.55 and 0.21 mg/L for fall. Thus, in that study the percentage of total phosphorus represented by dissolved phosphorus ranged from 27% to 62%. The EPA's Nationwide Urban Runoff Program (U.S. EPA, 1983) reported that the site event mean concentrations for total phosphorus ranged from 0.37 to 0.47 mg/L (with a median value of 0.33 mg/L) while the event mean concentrations for "soluble" phosphorus ranged from 0.13 to 0.17 mg/L) with a median value of 0.12 mg/L. Thus, dissolved ("soluble") phosphorus comprised about 36% of the total phosphorus.

The present study evaluated the effectiveness of the Biopod High Flow Media only with respect to its effectiveness at removing dissolved phosphorus. As the previous paragraph describes, dissolved phosphorus comprises roughly half of the total phosphorus found in urban stormwater runoff (with percent contributions ranging from about 30% to 66%). And, as Table 7 indicates, while media filters remove only about 6% of the dissolved phosphorus, they remove about 41% of the total phosphorus[2] – indicating that they are somewhat more effective at removing phosphorus associated with particulate matter. Therefore, we can expect the Biopod High Flow Media tested, when used in a "Media Filter" unit, to perform significantly better in terms of its effectiveness at removing total phosphorus from stormwater runoff than the observed effectiveness at removing only dissolved phosphorus.

Heavy metals

The effluent concentrations for both heavy metal tests were uniformly distributed. The mean effluent concentration for copper was below the detection limit of 0.005 mg/L; the mean effluent concentration for zinc was also below the detection limit of 0.020 mg/L. Using these reporting limits as the effluent concentrations gives removal efficiencies of 75% for copper and 93.3% for zinc.

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[2] Virginia DEQ indicates that filtration practices remove from 60% to 65% of total phosphorus from stormwater runoff (VADEQ, 2011). The Chesapeake Bay Program indicates that filtration practices remove 60% of the EMC of total phosphorus from stormwater runoff (Simpson & Weammert, 2009)

Table 8 shows removal efficiencies for dissolved copper and zinc in stormwater runoff treated by various filtration devices. Non-proprietary *Media Filtration* devices for which statistics have been developed in Table 8 are largely sand filters. *Biological filtration* devices are proprietary media filtration devices that support plants or bacterial biofilms. *Filtration* devices are proprietary media filtration devices with a variety of media types and configurations (*e.g.*, cartridge filters, vertical bed filers, *etc.*).

Table 8 shows that non-proprietary media filtration devices generally provide removal efficiencies of about 14% for dissolved copper and about 80% for dissolved zinc. For both of these dissolved metals the effluent concentrations were statistically significantly lower than the influent concentrations. No data were available for either dissolved copper or dissolved zinc from which to calculate removal efficiencies for proprietary Biological Filtration devices. With respect to proprietary Filtration devices, data were sufficient only for dissolved zinc to calculate a removal efficiency. Filtration devices showed a negative removal efficiency. That is, the median effluent concentration for Filtration devices was statistically significantly *greater* than the median influent concentration, indicating that, on average, Filtration devices contribute dissolved zinc to the treated runoff water. This result must be regarded with skepticism as there were very few studies upon which to base a calculated removal efficiency for dissolved zinc by Filtration devices.

Table 8. Removal Efficiencies for Dissolved Copper and Zinc by Various Filtration Devices†

	Count of Studies and EMCs		25th Percentile		Median (95% CI)		75th Percentile	
	In	Out	In	Out	In	Out	In	Out
Dissolved Copper								
Non-proprietary Media Filtration devices	11; 189	11; 176	1.64	1.50	3.75 (2.65; 4.1)	3.24 (2.47; 3.80)*	7.60	6.90
Biological Filtration devices‡	NA	NA	NA	NA	NA	NA	NA	NA
Filtration devices‡	NA	NA	NA	NA	NA	NA	NA	NA
Dissolved Zinc								
Non-proprietary Media Filtration devices	11; 189	11; 175	11.2	1.82	29.2 (21.0; 36.0)	5.78 (3.37; 8.10)*	84.0	21.0
Biological Filtration devices‡	NA	NA	NA	NA	NA	NA	NA	NA
Filtration devices‡	3; 43	3; 43	8.0	10.5	10.3 (8.0; 14.0)	13.5 (11.0; 17.0)**	29.5	25.5

Values in µg/L
† See report text for descriptions of devices
‡ Data from Geosyntec Consultants and Wright Water Engineers (2012)
* Hypothesis testing shows statistically significant decrease in effluent concentration.
** Hypothesis testing shows statistically significant *increases* in effluent concentration.
NA – Insufficient studies available to develop reliable statistics

The results of the present study indicate that the Biopod High Flow Media provides removal efficiencies for dissolved copper and zinc that exceed the removal efficiencies provided by both the non-proprietary Media Filtration devices and proprietary Filtration devices for which there are data in the International BMP Database.

CONCLUSION

Based on the information from the tests conducted by MicroBAC it can be concluded that the Biopod High Flow Media shows an average TSS removal efficiency of approximately 96.5% across the range of concentrations from 20 mg/L to 200 mg/L TSS. This removal efficiency of the Biopod High Flow Media is greater than the removal efficiencies seen for other filtration devices that were tested at an influent TSS concentration similar to the lower TSS influent concentration of this study. The removal efficiency of the Biopod High Flow Media at an influent TSS concentration of 20 mg/L was 92.75% which can be compared to removal efficiencies of 83% for non-proprietary Media Filtration devices and proprietary Biological Filtration devices, and to a removal efficiency of 56% for proprietary Filtration devices.

The removal efficiency of the Biopod High Flow Media for dissolved phosphorus of approximately 17.6% is somewhat lower than the efficiency seen for TSS. However, the removal efficiency for dissolved phosphorus by the Biopod High Flow Media was greater than the average removal efficiency for dissolved phosphorus seen in non-proprietary Media Filters in general, which is about 6%, and significantly greater than the removal efficiency for dissolved phosphorus by proprietary filter devices, which was shown by data in the International BMP Database to be zero. The removal efficiency of the Biopod High Flow Media for *total* phosphorus is expected to be somewhat greater than that observed for only dissolved phosphorus.

The removal efficiencies for the heavy metals studied is lower than the TSS efficiency, but higher than the phosphorus efficiency. The removal efficiency for copper was shown to be approximately 75% and the removal efficiency for zinc was shown to be approximately 93.3%. The removal efficiency of the Biopod High Flow Media for dissolved copper was significantly greater than the removal efficiency of non-proprietary Media Filter devices, which have an average removal efficiency of about 14% as calculated by the data provided in the International BMP Database. The removal efficiency of the Biopod High Flow Media for dissolved zinc was somewhat greater than the removal efficiency of non-proprietary Media Filter devices, which have an average removal efficiency for dissolved zine of about 80% as calculated by the data provided in the International BMP Database.

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