Development of a rapid bio-filtration media using local materials

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Abstract

Stormwater360 New Zealand, in collaboration with Callaghan Innovation, undertook laboratory development of innovative engineered soil media for use with a rapid bio-filtration system.

Bio-filtration systems typically use the media to control the hydraulic conductivity, corresponding contact time and performance. However variable compaction, sedimentation and plant growth effects mean hydraulic conductivity varies widely both spatially and over time. This study investigated media used in tandem with an external flow control to achieve consistent hydraulic conductivity and performance of 2500 mm/hr. The media developed in this project all have a hydraulic conductivity in excess of 2500 mm/hr.

Hence the primary aim of this study was to develop engineered media using locally available materials that achieved effective contaminant removal under high hydraulic conductivity. This approach allows the size (and cost) of the bio-filtration device required for a given catchment area to be reduced. The media were compared against a 'control' media used in USA.

Four engineered soil media with different active ingredients were tested in laboratory columns with storm water containing sediment from a wet pond. The media blends tested comprised of:-

- *proprietary engineered bio-filtration media developed by Contech, USA*
- *Compost and zeolite; and*
- *Phosphosorb (alumina activated perlite).*

Each soil media was tested for nitrogen, phosphorus, copper and zinc removal and the three media made with locally sourced materials were able to remove 42-48%, 26-75%, 74-83% and 82-90% of each pollutant respectively.

1. INTRODUCTION

Bio-filtration treatment devices are vegetated stormwater devices that detain and retain stormwater close to source, providing peak flow and/or volume control along with contaminant attenuation. Main contaminants of concern internationally are TSS, nitrogen and phosphorus, metals, temperature, and sometimes faecal matter (Fassman et al., 2013). Bio-filtration is a common component of Water Sensitive Urban Design (WSD). They are typically installed close to source, comprise 1 to 8% of a catchment and receive stormwater from 50 to 500 m^2 catchments.

New stormwater regulations in the Proposed Auckland Unitary Plan, move from 75% removal of TSS to more stringent requirements. Requirements include fixed effluent concentrations for TSS, metals (zinc and copper) and water temperature. Specific water retention and detention requirements are also required in areas located near sensitive catchments (SMAF zones). Bio-filtration is a treatment approach with demonstrated potential to meet all these requirements. A treatment device, the Urban Green BioFilter has been developed in the USA by Contech. This research compares the pollutant removal performance of NZ locally derived media with the Contech media with respect to Suspended Sediment Concentration (SSC), nutrient (phosphorus and nitrogen) and metal (zinc and copper) removal.

1.1. The Urban Green BioFilter

The ‘Urban Green BioFilter’ is a flow through treatment device comprising a small vegetated bio-filtration cell in a concrete vault. The engineered soil mixture developed for the BioFilter, has been optimized and standardized to consistently provide a high hydraulic conductivity while supporting growth of drought-tolerant plants (Figure 1). Stormwater runoff is filtered as it percolates through the media bed. Peak stormwater flows are internally bypassed around treatment components, eliminating the need for an external bypass structure. The BioFilter is a compact, high flow alternative to conventional bio-filtration designs.

The design filtration rate of the BioFilter is controlled by the initial media permeability and a flow control orifice. Testing conducted by Contech and which has been confirmed in our own laboratory testing has shown that the US engineered soil media has a hydraulic conductivity greater than 7500mm/hr at a driving head of 200 mm (Curry & Hannah, 2014). In practice however the external flow control limits the rate to 2500mm/hr. Using an outlet control to limit the hydraulic conductivity enables use of media with a higher void volume which in turn allows pollutant loads to accumulate for a longer period before the media hydraulic conductivity drops below the design rate, reduces the risk of clogging, and provides additional detention storage (peak flow reduction) in the device. The flow control also improves pollutant removal performance by reducing velocities in the pore space within the media.

Figure 1 BioFilter stormwater treatment device at Auckland Botanic Gardens, June 2015 (approximately aged three years)

2. METHOD

2.1. Engineered soil media tested

Four test columns were constructed. Each column was filled with 700 mm of media as described below:-

- Column 1: Rapid filtration soil media developed by Contech, USA, consisting of coarse sand and an active organic ingredient, referred to as Mix A,
- Column 2: A proprietary media blend consisting of well graded aggregate with a zeolite and aged compost component, referred to as Mix B,
- Column 3: A media blend similar to Mix B but with a higher percentage composition of aged compost, referred to as Mix C, and
- Column 4: A trial media blend containing Mix C (500 mm) placed on top of a 200 mm layer of Phosphosorb (Activated alumina bounded perlite)

2.2. Column test setup

The vertical column soil media test setup used by Contech (Tracy, 2012) was used as a guide for the four column test conducted (Figure 2 and Figure 3).

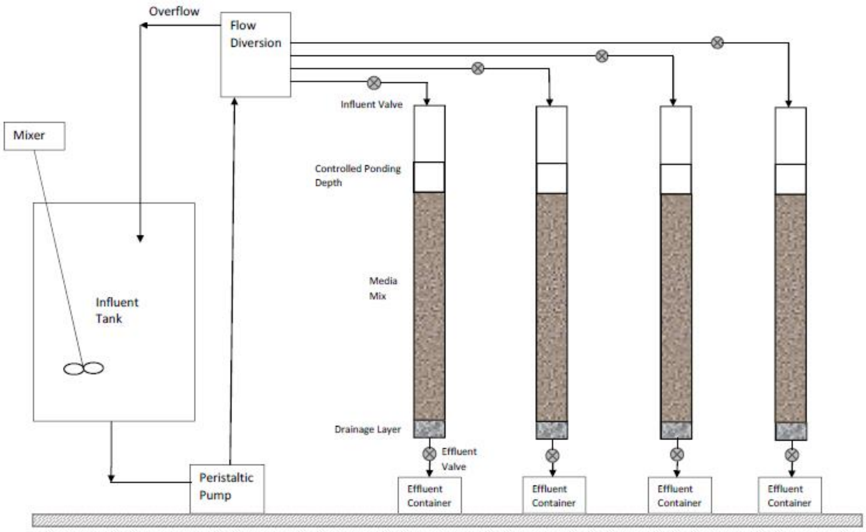

Figure 2 Diagram of the four column test setup

Figure 3 Photo of the four column test setup

The soil media was placed in 76 mm diameter clear plastic columns in lifts of 150-200 mm and was compacted by running water through the media for 10 minutes after each lift was placed. Influent was passed through small holes acting as a flow spreader to reduce scour potential and to distribute the water more evenly over the surface of the media.

2.3. Hydraulic conductivity and ponding depth

The hydraulic conductivity of each column was tested by first purging air from each column by submerging the media under 200 mm of water head for 10 minutes. Water flow through the media was then measured whilst maintaining a ponding depth of 200 mm. The hydraulic conductivities of each column stabilized in the first 5-10 minutes of the test. Mean flow rates measured from 5 minutes onwards were between 6100 and 16100 mm/hr (Table 1).

Table 1 Hydraulic conductivity of each engineered soil media

	Hydraulic conductivity (mm/hr)
Column 1	16100
Column 2	13300
Column 3	6100
Column 4	6100

For the leaching and column tests conducted, an externally controlled flow rate of 2500 mm/hr (100 in/hr) was used. This replicates the design flow rate for the Contech BioFilter (Contech, 2012).

The 200 mm ponding depth selected was selected to be less than the maximum allowable ponding depth specified in Auckland Regional Council's Design Guidance Manual Technical Publication #10 of 220 mm (ARC, 2003) and New Zealand Transport Agency of 300 mm (NZTA, 2010).

2.4. Semi-synthetic stormwater

Semi-synthetic stormwater influent was made using sediment sourced from a wet pond in Rosedale, Auckland, in accordance with Appendix F of the FAWB stormwater bio-filtration adoption guidelines (FAWB, 2009).

The Rosedale wet pond pollutant concentrations were compared to:-

- typical FAWB stormwater (FAWB, 2009),
- sediment from a wet pond in the neighbouring suburb of Silverdale characterised as part of a doctoral research project (Borne, 2013), and
- the Auckland Council recommendations (TR2013/011) for dosing concentrations of synthetic stormwater influent based on Water Quality Volumes (WQV) for 1 Auckland storm event (Fassman et al, 2013).

These stormwater pollutant concentrations are shown in Table 2.

Table 2 Pollutant concentration of stormwater measured in Rosedale and Silverdale wet ponds and recommended for tests using synthetic stormwater

	Rosedale Wet pond (mg/L)	FAWB Typical stormwater (mg/L)	Silverdale Wet pond (mg/L)	Auckland Council TR2013/011 (mg/L)
TSS		150		
SSC	302			
Total Nitrogen	1.43	2.2	~1	
Nitrates/Nitrites	0.64	0.74		
Ammonia	0.075	0.34	0.021	
Total Phosphorus	0.32	0.35	~0.09	
Reactive Phosphorus	0.016	0.12	~0.01	0.065
Total Copper	0.027	0.05	0.0092	
Dissolved Copper	0.0015			0.01
Total Zinc	0.24	0.25	0.035	
Dissolved Zinc	0.028			0.05

The Rosedale wet pond sediment was used to produce a semi-synthetic stormwater influent with an SSC of 200 mg/L for the column tests (Table 3). As some sediment settled in influent tubes, a second influent test was done using equal volumes of the influent entering the four test columns, collected at the end of the test. Average pollutant concentrations entering the test columns were found to be similar to the target pollutant concentrations (Table 3).

Table 3 Comparison of target and actual pollutant concentrations for the semi-synthetic stormwater influent made

Pollutant	Target (mg/L)	Influent Tank (mg/L)	Influent entering columns (mg/L)
SSC	200	-	-
Total Nitrogen	0.94	0.96	1.27
Nitrates/Nitrites	0.42	0.39	0.43
Ammonia	0.050	0.058	0.056
Total Phosphorus	0.21	0.36	0.011
Reactive Phosphorus	0.010	0.011	0.01
Total Copper	0.018	0.022	0.026
Dissolved Copper	0.0010	0.0016	0.0019
Total Zinc	0.159	0.188	0.210
Dissolved Zinc	0.019	0.029	0.051

2.5. Leaching tests

Leaching tests using tap water influent were conducted on the four engineered media. Before the leaching tests commenced, air was purged by submerging the media in the columns under 200 mm of water for 10 minutes. Test specimens were then collected from the effluent exiting each column. This was time = 0. The flow rates were then calibrated to run at a target 2500 mm/hr. Effluent samples from each column of 1 L were collected at 0, 60 and 120 minutes, and were used to fill various containers provided by Hill Laboratories for Total Nitrogen and Phosphorus tests. The filled test bottles were couriered to Hill Laboratories within 24 hours of sample collection. Suspended sediment concentration (SSC) concentrations were measured by Stormwater360 on 200 ml of effluent taken at 0, 30, 60 and 120 minutes.

2.6. Column tests

Column tests were conducted using the same the same process as was used for the leaching tests but used semi-synthetic stormwater instead of tap water. Semi-synthetic stormwater was passed through the four engineered soil media at a target flow rate of 2500 mm/hr to determine their removal capacity for nitrogen, phosphorus, zinc and copper. 1 L of effluent was collected from the outlet orifices of each column at 0, 60 and 90 minutes.

3. RESULTS

3.1. Leaching test results

During the leaching tests all four columns were observed to release sediment during the first volume exchange. By the 30 minute mark however, all the columns showed 0 or near 0 mg/L leaching of sediment (Figure 4 and Table 4).

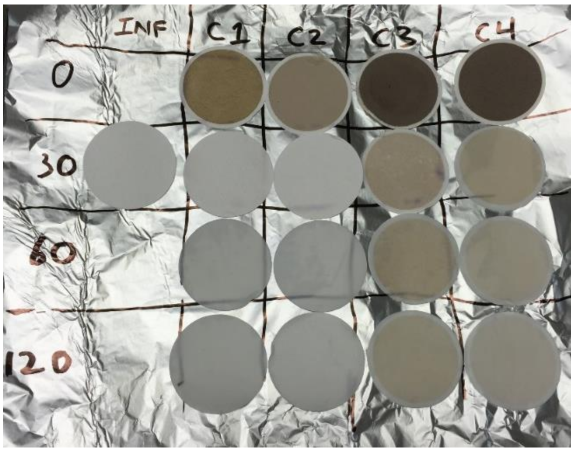

Figure 4 Filter paper with sediment from leaching tests

Table 4 Leaching column SSC concentrations over time at 2500 mm/hr

		SSC (mg/L)					Auckland Council PAUP requirements
		Influent	Column 1	Column 2	Column 3	Column 4	
Time (min)	0	0	60	200	1480	840	20
	30	0	10	20	20	10	
	60	0	10	0	0	20	
	120	0	10	10	0	10	

The measurements of nitrogen were highly variable at the beginning of the test (Table 5). The high total nitrogen concentrations are correlated with large spikes in Total Kjeldahl Nitrogen, indicating an initial release of organic sediment (Figure 4). This sediment release decreased to a negligible concentration after 30 minutes. Although no samples were taken between 0 and 30 minutes, the effluent had visually cleared after 5 minutes. Future tests should determine pollutant leaching between 0 and 30 minutes as the majority of the leaching occured during the first volume exchange (a volume change occurs every 17 minutes at a flow rate of 2500 mm/hr for a media depth of 700 mm). Samples taken at 60 and 120 minutes show negligible leaching of nitrogen.

Table 5 Leaching column Total Nitrogen concentrations over time at 2500 mm/hr

		Total Nitrogen concentration (mg/L)				
		Influent	C1	C2	C3	C4
Time (mins)	0	0.34	14	0.79	7.4	4.2
	60		0.43	0.32	0.39	0.37
	120		0.39	0.33	0.36	0.35

Phosphorus leaching mirrored that of nitrogen and SSC. The media containing a higher proportion of Mix C (C3 and C4) showed higher leaching rates of phosphorus at 60 and 120 minutes than C1 and C2.

While the decrease in the quantity of Mix C (500 mm of Mix C in C4 as compared to 700 mm depth in C3) partially explains the lower phosphorus leaching, the phosphorus removal effect of the Phosphosorb in C4 was observed in the results (presented in Table 6).

Table 6 Leaching column Total Phosphorus concentrations over time at 2500 mm/hr

		Total Phosphorus concentration (mg/L)				
		Influent	**C1**	**C2**	**C3**	**C4**
Time (mins)	0	0.007	0.172	0.159	3.4	1.96
	60		0.008	0.022	0.132	0.072
	120		0.009	0.02	0.092	0.056

3.2. Column test results

3.2.1. Copper and zinc removal

The four engineered media all showed total Zinc and Copper metal removal rates between 73 and 91% across all four media (Table 7 and Table 8). The values reported in the below tables report the average concentrations measured at 60 and 90 minutes. Dissolved copper removal results showed leaching characteristics but were inconclusive as the influent of 1.6 µg/L was very low to begin with. The PAUP specifies Copper concentrations in stormwater effluent to be reduced to 10 µg/L. Before treatment, the influent was already well below this concentration.

The metal removal results for Mix A are consistent with the Longview field test of the Contech medium. In Longview the Contech soil mixture achieved 85.2% and 76.3% total and dissolved zinc removal respectively and 72.0% Total Copper removal. The influent at Longview and the semi-synthetic stormwater used for the laboratory test were observed to share similar influent metal concentrations featuring high levels of Zinc and low levels of Copper.

Table 7 Removal rates of Copper

	Dissolved Copper (µg/L)			Total Copper (µg/L)		
	Influent	**Effluent**	**% removal**	**Influent**	**Effluent**	**% removal**
C1	1.6	1.35	15.6%	22	4.35	80.2%
C2	1.6	3.8	-137.5%	22	5.75	73.9%
C3	1.6	5.15	-221.9%	22	5.15	76.6%
C4	1.6	1.25	21.9%	22	3.65	83.4%

Table 8 Removal rates of Zinc

	Dissolved Zinc (µg/L)			Total Zinc (µg/L)		
	Influent	Effluent	% removal	Influent	Effluent	% removal
C1	29	11.85	59.1%	188	22.5	88.0%
C2	29	6.5	77.6%	188	20.85	88.9%
C3	29	3.9	86.6%	188	33.5	82.2%
C4	29	9.7	66.6%	188	18	90.4%

3.2.2. Nitrogen and phosphorus removal

All four engineered media were observed to reduce total phosphorus concentrations. Column 3 was least effective. This was partially attributed to the fresh organic component in the media (composted bark). The lower phosphorus concentrations in the effluent of Column 4 compared to Column 3 show the inclusion of 200 mm of Phosphosorb to be effective to remove phosphorus. Removal rates between 41-48% were measured across all four media tested. The Nitrogen data revealed that the majority of the decrease in Total Nitrogen resulted from the removal of Total Kjeldahl Nitrogen (TKN) which indicated that the media blends were filtering out organic material; with Mix B performing the best. The nutrient removal data is summarized below in Table 9.

Table 9 Removal rates of Nitrogen and Phosphorus

	Total Nitrogen (mg/L)			Total Phosphorus (mg/L)		
	Influent	Effluent	% removal	Influent	Effluent	% removal
C1	0.96	0.555	42.2%	0.36	0.0675	81.3%
C2	0.96	0.5	47.9%*	0.36	0.097	73.1%
C3	0.96	0.56	41.7%*	0.36	0.2665	26.0%
C4	0.96	0.55	42.7%	0.36	0.0905	74.9%

*Total nitrogen data points at 60 minutes were outliers and were excluded from the analysis

The total phosphorus and dissolved reactive phosphorus data (Table 10) showed that column 4 media (Mix C with 200 mm of phosphosorb) reduced the phosphorus concentrations in the effluent quicker than column 3 (Mix C only). A significant difference can be seen especially in the contrast of effluent phosphorus concentration at 0 and 60 minutes.

Table 10 Removal rates of Dissolved Reactive Phosphorus for C3 and C4

	Time mins	Dissolved Reactive Phosphorus mg/L	Total Phosphorus mg/L
Influent (tank)		0.011	0.36
C3	0	0.53	0.96

	60	0.146	0.5
	90	0.01	0.033
C4	0	0.014	0.05
	60	0.066	0.118
	90	0.036	0.063

4. DISCUSSION

4.1. Comparison of pollutant removal results with other media blends

The removal rates between the four media ranged between 26-81% for phosphorus, 42-48% for nitrogen, 74-83% for copper, and 88-90% for Zinc. With regard to nutrient removal, the four media tested performed better than other bio-filtration media by not leaching nutrients and achieving moderate nutrient removal. Both the BMP Database and the media reported in the FAWB report (summarized in Table 11) showed that treatment media containing soil, loam or compost were consistently found to leach Phosphorus and often Nitrogen as well. A similar finding was found in an assessment of bio-retention cells (rain gardens) in Redmond, WA (Herrera Environmental Consultants, 2014). While the bio-retention cells removed Zinc, motor oil and fecal coliforms, they leached copper, nitrogen and phosphorus even a year after construction. Follow up testing revealed the source of the pollutants to be primarily from compost with sand used contributing to a lesser degree.

The copper and zinc removal performance was comparable with the removal performance observed in field (BMP Database, 2014) and reported by FAWB (FAWB, 2009).

Table 11 Summary of BMP Database and FAWB media treatment performance

	Media	Total Phosphorus	Total Nitrogen	Cu	Zn
BMP Database [1] (BMP Database, 2014)	Biofilter – Grass strip	-26	16	69	75
	Biofilter – Grass swale	-55	-13	14	26
	Bioretention	-100	21	39	75
FAWB [2, 3] (Hatt, Fletcher, & Deletic, 2008)	S	97±1	38±1	97±1	99±1
	SL	-65±16	-18±15	97±1	99±1
	SLCM	-409±40	-111±41	94±1	96±1
	SLCMCH	-437±50	-164±14	93±1	96±1

[1] Removal rate calculated based on median reported influent and effluent concentrations

[2] S = Sand, SL = Sandy loam, SLCM = 8:1:1 sandy loam: compost: light mulch, SLCMCH = 8:1:1 sandy loam: compost: light mulch Charcoal

[3] ± indicates range of one standard deviation

4.2. First flush release of pollutants and sediment

The initial release of water from a column, or 'first flush', was consistently turbid with elevated pollutant concentrations. This indicated media was either shrinking or particles were breaking down during the dry periods when the column was not in use. The release of pollutants and sediment was most concentrated in Columns 3 and 4. Both Column 1 and Column 2 had a lower proportion of organic material and fines, as was shown through the higher hydraulic conductivity of the two materials (13300-16100 mm/hr) compared to the two columns containing Mix C (6100 mm/hr). The colour of the initial effluent had a tannin (brown) tinge and indicated that the composted bark could also be a source of pollutants generated within the media in Columns 3 and 4.

4.3. Issues with influent sediment

An SSC test conducted on the influent remaining in the tank at the conclusion of the column test showed a concentration of 110 mg/L. Since the influent SSC was initially made to a 200 mg/L concentration, it is likely that the sediment distribution in the influent tank was not homogenous despite the use of a mechanical stirrer throughout the duration of the test. The initial influent concentrations being fed into the test columns is likely to have had an SSC higher than 200 mg/L initially and decreased to 110 mg/L over the course of the 90 minute test duration. Despite the lower SSC concentration measured at the end of the test in the influent tank, tests conducted on influent water entering the four test columns (i.e. after passing through all the pipes) showed pollutant levels remained similar to that measured in the influent tank as shown in Table 3.

While the inclusion of wet pond sediment in the influent better replicates the real world characteristics of stormwater, the methods employed to mix and deliver the stormwater was not ideal. Sediment stuck to the surface of the pipes and influent sediment concentration varied over the duration of the test. Better methods will be used in the future to address these issues.

5. CONCLUSION

The three engineered media made using local NZ materials performed comparably with the Contech media with respect to both metal and nutrient removal. Each of the four engineered media tested showed high total Copper (74-92%) and Zinc (88-97%) removal capacity and moderate nitrogen removal (42-45%) and variable phosphorus (26-81%) removal capacity. These results were measured at a rapid infiltration rate of 2500 mm/hr and by subjecting the media with a semi-synthetic stormwater influent comprising of 200 mg/L SSC, low Copper and high Zinc concentrations. The semi-synthetic stormwater influent was prepared in accordance with the method described in the FAWB stormwater guidelines. Semi-synthetic stormwater was selected as it would better represent the range of pollutants present in real stormwater and better simulate the removal capacity of the media in the field.

Leaching tests showed that each of the engineered media blends released fine sediment during the first volume exchange. Media comprising of higher organic contents were shown to release more sediment than media with lower organic content. SSC measurements at 30 minutes showed all four columns ceased to leach any appreciable level of sediment. Visually the effluent exiting each test column was clear by the five minute mark. More research into the leaching profile of each media in the 0-30 minute time frame would be helpful to better mass and rate of sediment leaching from the four media.

The column tests show that SSC, metal and nutrient removal is attainable in a rapid bio-filtration treatment device made using local materials.

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