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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. Media being developed 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 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 active ingredients in the media were as follows:-

- *USA proprietary engineered bio-filtration media developed by Contech,*
- *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 Design (WSD) or Sensitive Urban Design (SUD). They are typically installed close to source, comprise 1 to 8% of a catchment and receive stormwater from 50 to 500 m^2 catchments.

The research aimed to develop a rapid bio-filtration media capable of reliably and consistently achieving both high hydraulic conductivity and removal of pollutants, Suspended Sediment Concentration (SSC), nutrients (phosphorus and nitrogen) and metals (zinc and copper) from stormwater influent.

A rapid soil filtration media developed in the USA has been demonstrated as an effective rain garden mix (Contech, 2012). Performance over nine months at a parking lot at the Port of Longview, Longview, WA, showed high removal of TSS, Zinc and Copper (Table 1). The catchment comprised of 1008 m^2 of impervious of roadways and carparks, and over the test period 884 mm of rainfall was recorded. The BioFilter was checked and maintained monthly to ensure an operating hydraulic conductivity between 1250-2500 mm/hr. The top 75-150 mm of the media was replaced twice during the 9 month period.

Table 1 UrbanGreen BioFilter performance summary for 15 storm events. Port of Longview, Longview, WA (Contech, 2012)

Parameter	TSS (mg/L)		Total Zn (µg/L)		Dissolved Zn (µg/L)		Total Cu* (µg/L)	
	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
Minimum	10.0	1.0	33.6	4.5	179	5.1	1	1
Maximum	464	82	506	72	1070	291	34.6	8.1
Median	59	8	817	12.1	345	77	6.4	2.5
Mean	87.7	13	118	17.5	438	104	10	2.8
Mean Removal Efficiency	85.2%		85.2%		76.3%		72.0%	

* Dissolved copper influents were below the required range of 5-20 µg/L as required by the Washington State Department of Ecology and were hence not included in the data analysis

The removal capacity of three engineered soil media comprising of materials locally available in New Zealand were compared to the rapid filtration media sourced from the USA. Using semi-synthetic stormwater, prepared in accordance with FAWB (2009), all four media were tested in vertical columns at an externally controlled hydraulic conductivity of 2500 mm/hr. In addition to pollutant removal tests, the four engineered soil media were tested for leaching of nitrogen and phosphorus.

1.1. Advantages of bio-filtration treatment solutions

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 performance of NZ locally derived media with the Contech media.

1.2. 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. This allows pollutant loads to accumulate before the media hydraulic conductivity drops below the design rate and maintenance is required. Using an outlet control to control the hydraulic conductivity allows media with a higher void volume to be used. This 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 a unique medium as described below:-

- Column 1: Rapid filtration soil media developed by Contech, USA referred to as Mix A,
- Column 2: A Stormwater360 proprietary blend containing composted bark and zeolite, referred to as Mix B,
- Column 3: A trial media blend containing a high proportion of composted bark, referred to as Mix C, and
- Column 4: A trial media blend containing a high proportion of composted bark (500 mm of Mix C) placed on top of a 200 mm layer of Phosphosorb (Activated alumina bounded perlite)

2.2. Column test setup

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

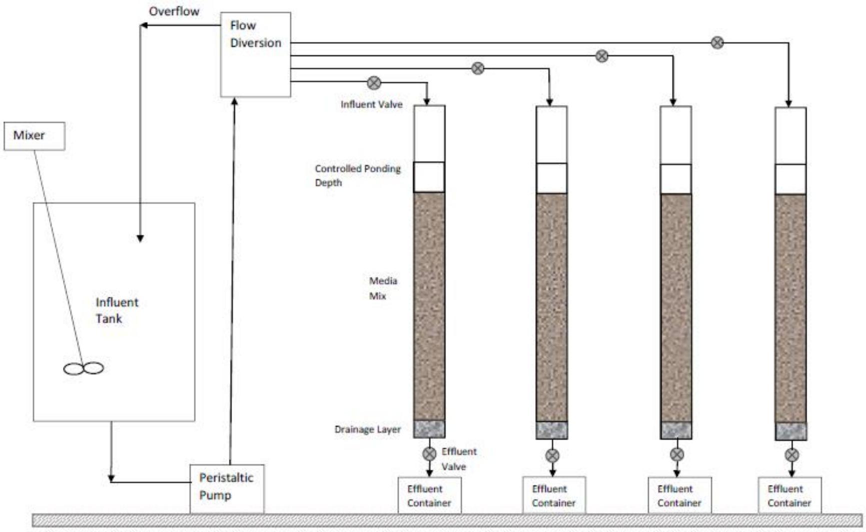

Figure 2 Diagram of the four column test setup

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 2).

Table 2 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 tests and the 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 is below 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 3.

Table 3 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 and without spiking other pollutants (Table 4). 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 similar to the target pollutant concentrations (Table 4).

Table 4 Comparison of target and actual pollutant concentrations for the semi-synthetic stormwater influent made

Pollutant	Target (mg/L)	Actual Influent Tank (mg/L)	Actual Influent at 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

3. RESULTS AND DISCUSSION

3.1. Leaching test results

Leaching tests were conducted on the four engineered media. Before the leaching tests were started, 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.

All four columns initially released sediment. This predominantly occurred 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 5).

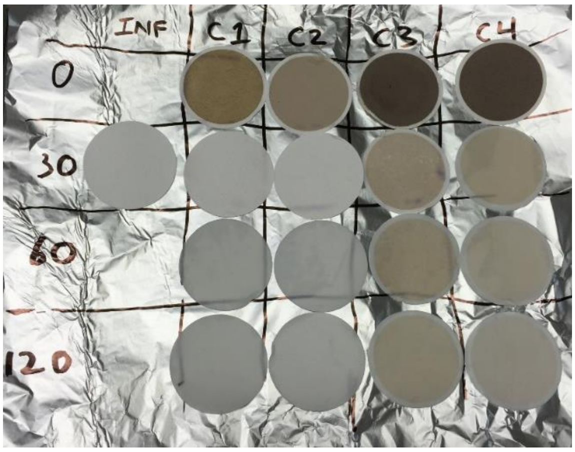

Figure 4 Filter paper with sediment from leaching tests

Table 5 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 are initially both high and highly variable (Table 6). 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. Effluent had visually cleared after 5 minutes. Future tests should determine pollutant leaching between 0 and 30 minutes as most of the leaching occurs during the first volume exchange, equating to 17 minutes at a flow rate of 2500 mm/hr for a media depth of 700 mm. Steady state flows at 60 and 120 minutes show minimal additional leaching of nitrogen.

Table 6 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 mirrors 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 Phosphosorb in C4 is contributing to phosphorus removal as can be seen in Table 7.

Table 7 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

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. The values reported in the below tables are the average of the measurements taken at 60 and 90 minutes.

3.2.1. Copper and zinc removal

The four engineered media all showed adequate total and dissolved metal removal (Table 8 and Table

9). Dissolved copper removal results are inconclusive as the influent of 1.6 µg/L was low and already satisfied the effluent quality requirements for Copper in Auckland of 10 µg/L without treatment.

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. Removal rates are influenced by the concentration of pollutants in the influent. The influent at Longview and the semi-synthetic stormwater used for the laboratory test shared similar metal characteristics of high Zinc and low Copper concentrations.

Table 8 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 9 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

Existing performance data in the BMP Database show bio-retention systems leach 100% total phosphorus, based on median measurements. However, bio-retention systems are amongst most effective existing stormwater treatment methods for nitrogen with an average removal rate of 20.7% based on median values reported (BMP Database, 2014). Bio-filtration and rain garden media are known to often have issues with leaching nutrients, and particularly so phosphorus, into stormwater and the inclusion of a layer of Phosphosorb in Column 4 was to test the effectiveness of including a Phosphorus removing layer as part of an engineered soil media.

All four engineered media reduced total phosphorus concentrations. Column 3 was least effective, with this partially attributed to the fresh organic component in the media (composted bark). Column 4 shows the 200 mm of Phosphosorb to be effective. Nitrogen removal was similar across all four media tested, recording between 41-48%. A closer look at the Nitrogen data revealed that the majority of the decrease in Total Nitrogen resulted from the removal of Total Kjeldahl Nitrogen (TKN) indicating the media were able to filter out organics well; with Mix B performing the best. The nutrient removal data is summarized below in Table 10.

Table 10 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 11) 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 11 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. First flush release of pollutants and sediment

The initial release of water from a column, or 'first flush', was consistently turbid with elevated pollutant concentration. This indicates 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.

4.2. 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 leaving the tank is likely to have had an SSC higher than 200 mg/L and to have decreased over the duration of the test to 110 mg/L by the end of 90 minute test run. Despite the lower SSC concentration measured at the end of the test in the influent tank, tests conducted on influent water comprising equally of the actual influent entering the four test columns showed pollutant levels remained similar to that measured in the influent tank as shown in Table 4.

While the inclusion of wet pond sediment in the influent better replicates the real world characteristics of stormwater in a test, the methods employed to mix and deliver the stormwater was not ideal and 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 at a rapid infiltration rate of 2500 mm/hr and using a semi-synthetic stormwater influent with 200 mg/L SSC, low Copper and high Zinc concentrations, and prepared in accordance with the method described in the FAWB stormwater guidelines. A method incorporating real stormwater sediment was selected as it would better represent a realistic stormwater influent composition and better replicate the removal capacity of the engineered media in practice. Target metal and nutrient concentrations were achieved.

Leaching tests showed that each of the engineered media generated or passed fine sediment in a ‘first flush’ of approximately 1/3 of a full volume exchange. Leachate concentrations varied. 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 and visually the effluent exiting each test column had cleared significantly by the five minute mark. More research in the leaching profile of each media in the 0-30 minute time frame would be helpful to better understand and quantify the 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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