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Article

Characterising Recycled Organic and Mineral Materials for Use as Filter Media in Biofiltration Systems

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Abstract: Filter Media (FM) sourced from recycled organic and mineral material offers a low cost and effective means of treating urban stormwater. Using recycled materials rather than from an increasingly scarce source of virgin materials (typically sandy loam soil) can ensure a sustainable long-term economy and environment. This paper presents results from the laboratory analysis and mathematical modeling to highlight the performance of recycled organic and mineral material in removing nutrients and metals from stormwater. Analysis included physical and chemical characterisation such as particle size distribution, saturated hydraulic conductivity (K_{sat}), bulk density, effective cation exchange capacity, and pollutant removal performance. Design mixes (DM), comprising a combination of organic and mineral materials, were characterised and used to develop/derive modelling design within the Model for Urban Stormwater Improvement Conceptualisation (MUSIC v6) [1]. Comparison is made to the Adoption Guidelines for Stormwater Biofiltration Systems - Summary Report [2] which were based on the Facility for Advancing Water Biofiltration (FAWB) guidelines to assist in the development of biofiltration systems, including the planning, design, construction and operation of those systems. An observed outcome from over two decades of biofiltration guideline development has been the exclusion of alternative biofilter materials due to claims of excessive leaching. Results from this study indicate that high nutrient and metal removal rates can be achieved over a range of hydraulic conductivities using design mixes of recycled organic and mineral materials that have a demonstrated equivalence to existing guideline specifications.

Keywords: compost, nutrient leaching; pollutant removal; stormwater quality, system modeling

1. Introduction

In a world where natural resources are limited it is important to recycle organic and mineral waste materials for alternative uses [3]. The use of recycled organic material is one of Australia's greatest assets that can be utilised to address several of society's vexing challenges [4]. For example, recycling of municipal solid waste (MSW) prevents the need for further landfill areas which are a major source of greenhouse gas emissions [5]. Since the late 1970's, over 4,500 larger-scale recycling facilities are now in operation in Australia and manufacture "compost" from organic waste [3]. Compost has benefits for soil health and structure including increased moisture holding capacity and permeability [5], improved cation exchange capacity [6, 7], increased organic matter and buffering of soil pH [8], the supply of essential plant nutrients and aids the proliferation of soil micro-organisms [9, 10].

In stormwater management, sandy loam soils are typically recommended as the treatment substrate in biofiltration devices to their nutrient retention properties [2]. However, these soils are often excavated from areas of productive agriculture and this is not sustainable. Natural soils around the world are rapidly being lost due to land clearing and agricultural practices with estimates that we have lost over 38 % of our food-production land since 1950 [9]. Therefore, it is paramount that "new generation" sustainable substrates are found for water sensitive urban design (WSUD) approaches such as raingardens and similar biofiltration devices. Recycled organic and mineral waste materials have the potential to provide a sustainable solution with local economic and performance benefits. Previous reviews on the use of compost as biofiltration media highlight the need for further research on alternatives [6, 11] particularly those materials that potentially contain contaminants and/or are not sustainably sourced.

Use of recycled organic and mineral materials and amendment of media to improve bioretention performance is an active area of research [12]. The use of column leaching experiments have been described as "mesocosms" [12, 13] and studies, both in the lab and in the field, have demonstrated that various recycled organic and mineral materials can significantly reduce metals such as Cu, Pb and Zn [14, 15, 16, 17] and remove nutrients [6, 18, 19, 20] when used in a biofiltration scenario. Results also showed media with excess clay can clog and increase TSS discharge [12].

Biofiltration guidelines in Australia, including the Facility for Advancing Water Biofiltration (FAWB) guidelines and the more recent Adoption Guidelines for Stormwater Biofiltration Systems - Summary Report [2] aim to assist in the development of biofiltration systems, including the planning, design, construction and operation of those systems. Results from this study are used to develop/derive modelling design within the Model for Urban Stormwater Improvement Conceptualisation (MUSIC v6) [1], a common tool used in the Australian stormwater industry. A recent review on the research needs of bioretention highlight the need for improved modeling approaches [12] and this paper highlights some potential issues in using commercially available models and their applicability when using alternative filter media such as recycled organic and mineral materials.

This study aims to characterise recycled organic and mineral materials so that for use in biofiltration scenarios (as a design mix comprising different components), they can provide significant pollutant removal performance and a demonstrated equivalence to M165 FAWB specification. Results from this study indicate that many recycled organic and mineral materials may be used as suitable filter media (FM); particularly considering the pollutant removal performance and equivalence to the industry FAWB specification (sandy loam – coded "M165" from the supplier).

2. Materials and Methods

2.1 Materials

The characterisation of recycled organic and mineral materials is presented in this section to provide insight into their attributes and suitability for use in biofiltration devices. Recent Washington State monitoring data indicates that compost with sources other than yard waste may contain loosely bound heavy metals and nutrients which may result in an increase in these compounds in discharges, at least initially [12]. This is the main reason for characterising recycled organic and mineral materials before use as a biofilter media.

Determining attributes and suitability for use in biofiltration devices was achieved by comparing characterisation data to the FAWB specification (M165) for filter media. Once suitability of individual materials was determined the design mix configurations (DM1 and DMS) were created, and a series of column leaching experiments were undertaken to compare leaching/pollutant removal performance to the FAWB specification (M165).

The raw materials used in this study are shown in Table 1.

Table 1. Organic and mineral materials used in this study

Material	Type
Recycled Organics (RO – fine)	Organic
Recycled Organics (RO – medium)	Organic
Biochar	Organic
Calcium Carbonate ($CaCO_3$)	Mineral
Washed Sand	Mineral
FAWB specification (sandy loam – M165)	Mineral (with < 5% organic matter)

The materials were sourced from various recycling plants around the Greater Sydney region in NSW (Australia) that manage a range of wastes from urban centres. The materials tested consisted of both recycled organic and mineral components of varying particle size distributions (refer Figure 1, a - f). The RO-fine and RO-medium are composts created from green waste (leaves, clippings, grass, etc), the biochar and calcium carbonate ($CaCO_3$) were sourced from a commercial supplier, and the FAWB specification (sandy loam – coded M165 by the supplier) was sourced through a local quarry/soil supplier.

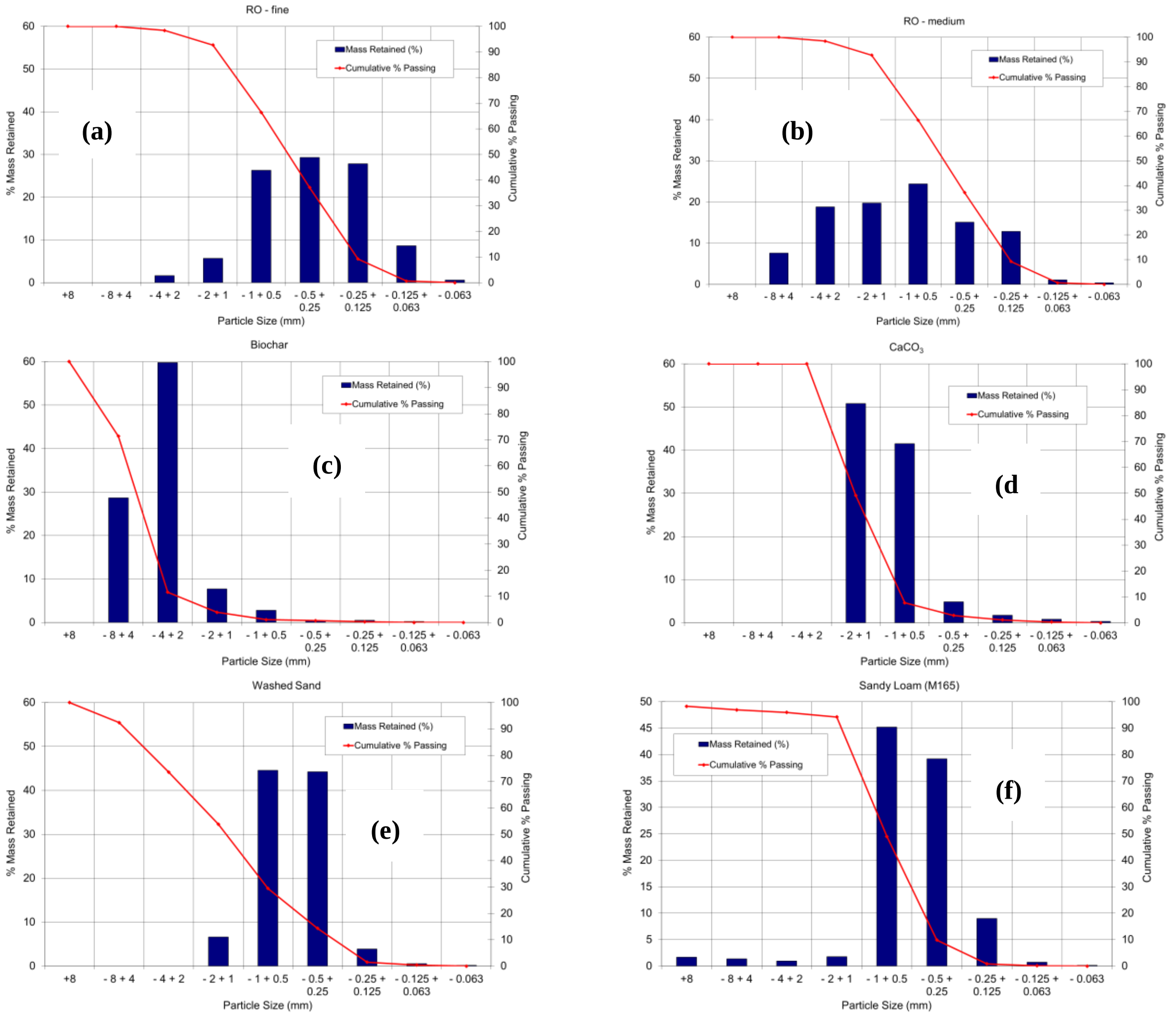

Figure 1: *Particle size distribution of raw materials used in this study, a) RO-fine, b) RO-medium, c) Biochar, d) CaCO3, e) Washed sand and f) FAWB specification (M165)*

Using a combination of the raw materials shown above, Table 2 shows the % composition (by volume) of the two design mix configurations (DM1 and DMS) and Figures 2-a and 2-b show the particle size distribution of DM1 and DMS respectively. The design mix configurations and M165 (from Figure 1-f) show a similar particle size in the 0.25 – 1 mm range.

Table 2. Design mix configurations for DM1 and DMS (% composition by volume)

Design Mix	RO	Sand	M165	CaCO$_3$	Biochar
DM1	40	30	15	5	10
DMS	50	35	0	0	15

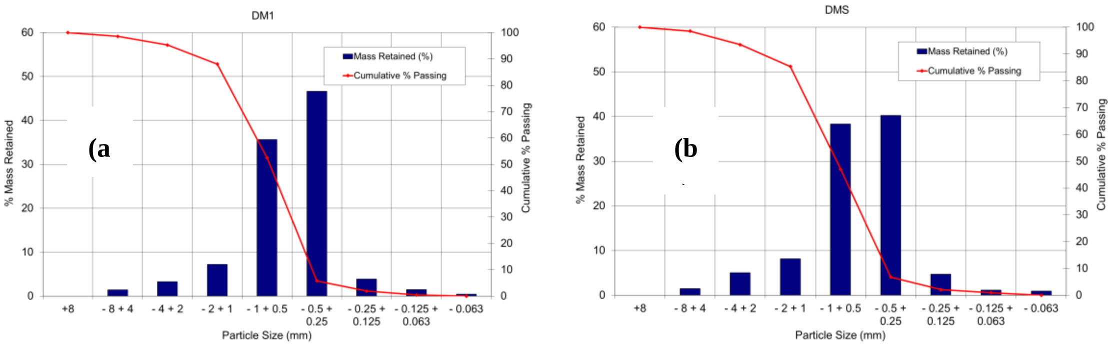

Figure 2: Particle size distribution of design mix configurations, a) DM1 and b) DMS

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2.2 Column leaching experiments

Three sets of column leaching experiments (CLE) were undertaken. The first CLE investigated leaching potential of individual materials and the design mixes (DM1 and DMS), the second CLE investigated pollutant removal performance, and the third CLE investigated Cu, Pb and Zn (conservative pollutants) removal from natural stormwater. The method for the CLE was similar for all tests and is described below.

Packing of the columns was based on volume. For each material, a column was packed with a known mass and the height in the column was measured. Each column was gently tapped on a hard surface to promote settling but no compaction was applied. Column depth was typically 200 mm.

The column was positioned as shown in Figure 3. For constant-head conditions, a 1L volumetric flask containing tap water was slowly poured into the top of the column. There is a point where the top of the column contains a "head" and at this time the volumetric flask is quickly inverted, and the spout submerged in the tap water above the material in the column. The volumetric flask is clamped in place and the tap water moves through the column under gravity.

The time taken for the tap water to be eluted through the column reflected the saturated hydraulic conductivity (K_{sat}) of the material and was determined by calculation (volume/time). The 1L of tap water applied under constant-head conditions was approximately equivalent to a 420 mm rainfall event. For example, 1L/m^2 = 1 mm rainfall depth and since the area of the column and applied tap water volume is known an equivalent rainfall depth can be calculated. The area of the 55 mm (ID) column is 0.00238 m^2 ($A = \pi r^2$) meaning 1L / 0.00238 m^2 = 420 mm of tap water was applied. If the 1L takes 1 hour to move through the column then the K_{sat} would be 420 mm/hr.

After elution, any losses from the 1 L of tap water were deemed to reflect the moisture holding capacity (MHC) of the FM and was calculated using mass by difference. For example, if 1L of tap water goes into the column and 0.8L is eluted out of the column (when freely drained) then the MHC equals 20 %.

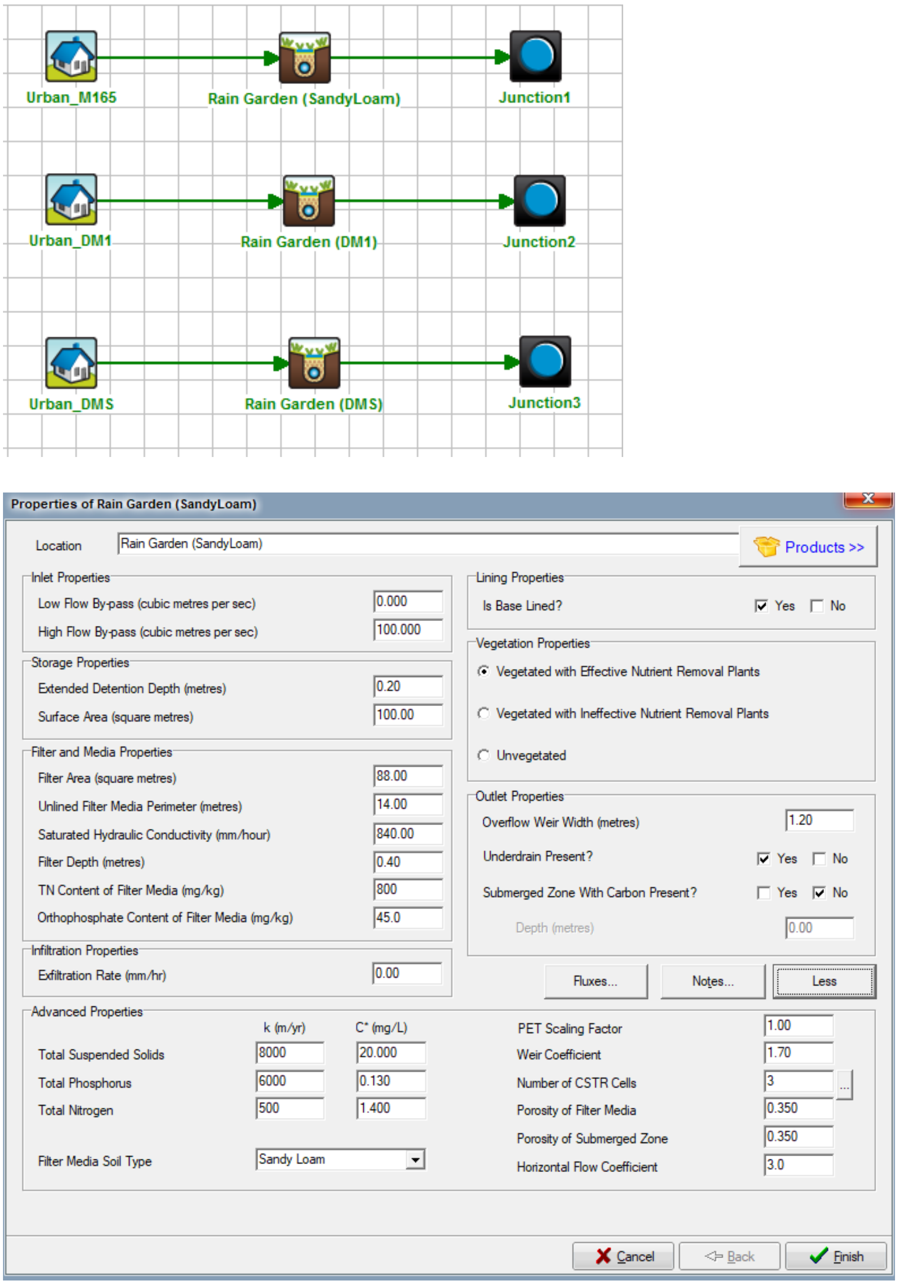
Tap water was used to create leaching curves based on electrical conductivity (EC, µS/cm) and pH. Tap water was applied to the column under constant-head conditions and column output was collected in approximately 100 mL increments and analysed using a HACH laboratory pH/EC meter.

Water from an urban creek was used as a surrogate for "runoff" in the second set of column leaching experiments (pollutant removal). The same water was used in the third set of column leaching experiments (metals removal) however was spiked with trace amounts of Cu, Pb and Zn to provide a positive presence of these metals in the eluent.

Figure 3: Setup for the column leaching tests (note the improving clarity of the eluted samples)

2.3 MUSIC v6 modeling

Conceptual modelling was undertaken using the Model for Urban Stormwater Improvement Conceptualisation (MUSIC v6); a continuous simulation conceptualisation model [1] used in the stormwater industry. The setup used in MUSIC v6 is shown in Figure 4, comprising of Urban source nodes flowing to a Raingarden and then to a junction (for the options M165, DM1 and DMS). Figure 5 shows the conceptual plan and longitudinal view of the "Bioretention Treatment Node" as used in MUSIC v6 [1].



Properties of Rain Garden (SandyLoam)

Location: Rain Garden (SandyLoam)

Inlet Properties
Low Flow By-pass (cubic metres per sec): 0.000
High Flow By-pass (cubic metres per sec): 100.000

Storage Properties
Extended Detention Depth (metres): 0.20
Surface Area (square metres): 100.00

Filter and Media Properties
Filter Area (square metres): 88.00
Unlined Filter Media Perimeter (metres): 14.00
Saturated Hydraulic Conductivity (mm/hour): 840.00
Filter Depth (metres): 0.40
TN Content of Filter Media (mg/kg): 800
Orthophosphate Content of Filter Media (mg/kg): 45.0

Infiltration Properties
Exfiltration Rate (mm/hr): 0.00

Lining Properties
Is Base Lined? ☑ Yes ☐ No

Vegetation Properties
● Vegetated with Effective Nutrient Removal Plants
○ Vegetated with Ineffective Nutrient Removal Plants
○ Unvegetated

Outlet Properties
Overflow Weir Width (metres): 1.20
Underdrain Present? ☑ Yes ☐ No
Submerged Zone With Carbon Present? ☐ Yes ☑ No
Depth (metres): 0.00

Advanced Properties

	k (m/yr)	C* (mg/L)
Total Suspended Solids	8000	20.000
Total Phosphorus	6000	0.130
Total Nitrogen	500	1.400

Filter Media Soil Type: Sandy Loam

PET Scaling Factor: 1.00
Weir Coefficient: 1.70
Number of CSTR Cells: 3
Porosity of Filter Media: 0.350
Porosity of Submerged Zone: 0.350
Horizontal Flow Coefficient: 3.0

Figure 4: Setup in MUSIC v6 and properties of the Bioretention Node (raingarden)

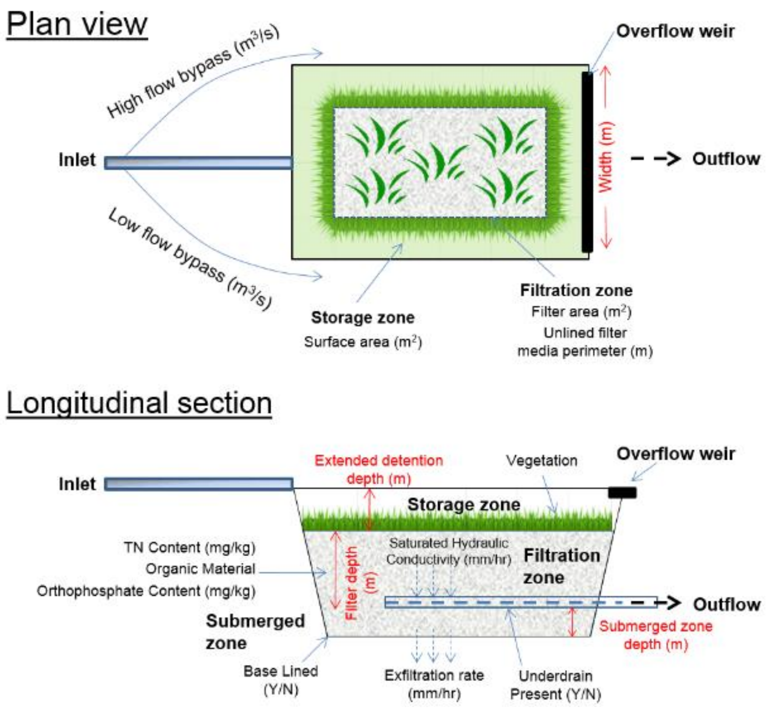


Figure 5: The Bioretention Node parameters used in MUSIC v6

Rainfall from Blacktown NSW was used in the case study (Blacktown Development.mlb, 1966 - 1976) and was obtained through the MUSICLink feature within MUSIC v6.

Source nodes – "Urban" source nodes were used in the modelling. Urban_M165, Urban_DM1 and Urban_DMS were all similar in properties, with a catchment area of 0.28 Ha and 90 % impervious area. Water quality (runoff) defaults and Rainfall-Runoff Parameters used in MUSIC v6 were not altered.

Treatment Nodes – "Bioretention" treatment nodes were selected for use in the model. Table 3 provides the properties of the raingarden and an example of the screenshot (for sandy loam) was shown in Figure 4. The only difference between options (M165, DM1 and DMS) were the inclusion of actual analysis data (in bold) for TN and orthophosphate (as Colwell P) (from Table 4). The base of the raingarden was lined and vegetated with effective nutrient removal by plants. An underdrain was present, and the overflow weir width was 1.2 m. Default values for *k* and C* for Total Suspended Solids (TSS), Total Phosphorous (TP) and Total Nitrogen (TN) were used in the modelling. Determining appropriate k and C* values are based on first assuming a representative particle size distribution of suspended solids (sediment) in urban stormwater and an assumed pollutant speciation distribution within this range [1].

Table 3: Biofiltration properties used in MUSIC v6

Properties	**M165**	**DM1**	**DMS**
Low Flow by-pass (m^3)	0	0	0
High Flow by-pass (m^3)	100	100	100
Extended Detention depth (m)	0.2	0.2	0.2
Surface Area (m^2)	100	100	100
Filter Area (m^2)	88	88	88
Unlined Filter Media (m)	14	14	14
Saturated Hydraulic Conductivity (mm/hr)	300	300	300
Filter Depth (m)	0.4	0.4	0.4
TN Content of Filter Media (mg/kg)	**235**	**1624**	**1745**
Orthophosphate Content of Filter Media (mg/kg)	11	38	45
Exfiltration Rate (mm/hr)	0	0	0

The parameter *k* lumps together the influence of several predominantly physical factors impacting on removal of stormwater pollutants. While the assumption of a predominance of physical removal processes during storm event operation is reasonable for particulate (inorganic) contaminants, other factors associated with chemical and biological processes can also be significant. These are currently not accounted for in the determination of *k*. [1]

The background concentration C* is assumed to be a constant at present although C* would be expected to be influenced by hydraulic loading, flow velocity and other factors affecting the re-mobilisation and maintenance of suspended solids in stormwater. However, C* can be expected to also vary during the inter-event period as chemical and biological processes alter the ambient concentrations of contaminants in waterbodies receiving stormwater. These processes are not modelled in the current version but are subject to-going research and development. [1]

From Appendix G in the MUSIC Help directory, "*At this stage the selection of default values for k and C* for music is therefore based on a combination of hypothetical (qualitative) and limited quantitative information, owing to the absence of any extensive data base for the range of stormwater treatment measures considered. Nevertheless, default values are required, and should address both the relative effectiveness of the various treatment nodes, and the relative behaviour of the different water quality parameters at a single node. This Appendix describes how the default values of k and C* were derived*".

Appendix G (12 pages) is attached to this paper for further reading. A sensitivity analysis was undertaken using a calibrated MUSIC scenario and results are presented and discussed in the next section.

3. Results & Discussion

The characterisation of recycled organic and mineral materials is presented in this section to provide insight into their attributes and suitability for use in biofiltration devices. For example, biofiltration media should not contribute excess salts, nutrients, metals and/or sediment. This is consistent with water quality objectives to receiving waterways [21] and with previous studies that have reviewed the use of filter media and biofiltration design [11, 12].

Once suitability was determined the design mix configurations were created (DM1 and DMS), and a series of column leaching experiments were undertaken to compare pollutant removal performance to the FAWB specification (M165) and Adoption Guidelines for Stormwater Biofiltration Systems [2] for filter media.

3.1 Characterisation of Materials

Table 4 summarises the detailed chemical and physical analysis of all materials and design mixes (DM1 and DMS). Chemical analysis was undertaken by EnviroAg EastWest Laboratory at Tamworth and the physical analysis undertaken at the University of Newcastle; based on standard soil analysis methods [26].

The extensive analysis suite was selected to provide data on soil function and the ability of the soil (or media) to sustain plant growth. Parameters such as pH, electrical conductivity (EC), exchangeable cations (Ca, Mg, Na, K), exchangeable trace metals (Cu, Zn, Fe, Mn), total nitrogen, total carbon, Colwell P (plant-available phosphorous) and effective cation exchange capacity (ECEC) are typically used to determine the suitability of a soil for plant growth. Physical parameters such as saturated hydraulic conductivity (K_{sat}), moisture holding capacity (MHC), and bulk density (BD) relate to biofiltration operational objectives. Data in Table 3 will be referred to in later sections when comparing the FAWB specification (M165) to DM1 and DMS.

Understanding soils and interpreting data is especially relevant to many other environmental and land management issues, including urban development, salinity control, clearing of native vegetation, prevention of land degradation, control of water and wind erosion, irrigation development, the management of effluent disposal, and management of acid-sulfate soils [10].

Table 4. All chemical/physical data for organic materials (RO – fine, RO-medium and biochar), washed sand, M165 (sandy loam), and the design mix configurations (DM1 and DMS)

Test Parameter	Method Description	Method Reference	Units	RO fine	RO medium	Biochar	Washed Sand	M165	DM1	DMS
pH (1:5 in H20)	Electrode	R&L 4A2	pH units	7.76	7.87	9.23	7.72	6.80	8.29	7.74
pH (1:5 in CaCl2)	Electrode	R&L4B2	pH units	7.18	7.31	8.15	6.74	6.38	7.45	7.28
Chloride Soluble	Electrode	PMS-05	mg/kg	2810	3030	1585	4.6	212	310	362
Electrical Conductivity	Electrode	R&L 3A1	dS/m	1.93	2.1	1.86	0.02	0.3	0.54	0.36
Total N (LECO)	LECO	R&L 7A5	mg/kg	13350	14590	6870	82	235	1624	1745
Extractable Nitrate-N	H20/UV-Vis	PMS-08	mg/kg	50.7	52.9	2.34	4.4	4.28	10	9.4
Organic Carbon (LECO)	LECO	R&L 6B3	%	32	36.5	5.9	0.11	0.4	3.11	2.01
Total Carbon (LECO)	LECO	R&L 6B2a	%	31.7	36.9	61.1	0.12	0.36	4.88	5.27
Phosphorus (Colwell)	Bicarb/UV-Vis	R&L 9B1	mg/kg	316	322	99.3	7.72	10.9	45.2	38
Sulphate-Sulphur	KCl40/ICP	R&L 10D1	mg/kg	144	78.7	91.2	3.19	115	31.2	13.6
Extractable Copper	DTPA/ICP	R&L 12A1	mg/kg	0.29	<0.2	0.59	0.2	0.41	0.97	0.67
Extractable Zinc	DTPA/ICP	R&L 12A1	mg/kg	3.47	1.66	1.46	0.25	2.06	3.63	4.5
Extractable Manganese	DTPA/ICP	R&L 12A1	mg/kg	6.98	4.86	2.4	<0.5	0.57	3.68	6.89
Extractable Iron	DTPA/ICP	R&L 12A1	mg/kg	6.52	6.05	4.91	7.7	19.5	15.9	30.3
Extractable Boron	Hot CaCl2/ICP	R&L 12C2	mg/kg	3.1	3.68	1.65	0.14	0.38	1.81	1.15
Exchangeable Potassium	NH4Cl/ICP	R&L 15A1	mg/kg	7386	7949	2534	10	161	850	723
Exchangeable Calcium	NH4Cl/ICP	R&L 15A1	mg/kg	8448	8380	3680	210	435	2194	2226
Exchangeable Magnesium	NH4Cl/ICP	R&L 15A1	mg/kg	1151	1197	124	18.4	73.4	161	255
Exchangeable Sodium	NH4Cl/ICP	R&L 15A1	mg/kg	452	483	142	19.2	88.9	101	249
Exchangeable Aluminium	KCl/ICP	R&L 15G1	mg/kg	0.7	0.6	<0.5	3.55	11.8	0.81	0.65
Exchangeable Potassium	Calculation	PMS-15A1	Cmol/kg	18.9	20.4	6.5	0.0	0.4	2.2	1.9
Exchangeable Calcium	Calculation	PMS-15A1	Cmol/kg	42.2	41.9	18.4	1.1	2.2	11.0	11.1
Exchangeable Magnesium	Calculation	PMS-15A1	Cmol/kg	9.6	10.0	1.0	0.2	0.6	1.3	2.1
Exchangeable Sodium	Calculation	PMS-15A1	Cmol/kg	2.0	2.1	0.6	0.1	0.4	0.4	1.1
Exchangeable Aluminium	Calculation	R&L 15J1	Cmol/kg	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Effective Cation Exchange Capacity (ECEC)	Calculation	PMS-15A1	Cmol/kg	72.7	74.4	26.5	1.4	3.7	14.9	16.2
Ca/Mg Ratio	Calculation	PMS-15A1	Cmol/kg	4.4	4.2	17.8	6.8	3.6	8.2	5.2
K/Mg Ratio	Calculation	PMS-15A1	Cmol/kg	2.0	2.0	6.3	0.2	0.7	1.6	0.9
Air-dried Moisture		UoN	%	28	33	9	2	8	10	13
Moisture Holding Capacity		UoN	%	66	62	52	19	22	33	33
Bulk density		UoN	kg/m^3	550	550	210	1520	1180	1100	1100
Saturated Hydraulic Conductivity (Ksat)	Calculation	UoN	mm/hr	720	1400	105	2100	840	840	840

The dataset shown in Table 4 is just one of many that have been used in the development of new organic biofiltration media guidelines recently published; the “Performance & Validation Standards for Organic Bio-Filtration Media” [22] which has been included as an addendum to this paper.

3.2 Column leaching tests - Leaching potential of individual materials and the design mixes (DM1 and DMS)

The aim of this experiment was to demonstrate the leaching behaviour of materials with respect to EC and pH as both are important trigger values in the ANZECC guideline [21]. Biofiltration media should not leach excessive salts and should have a suitable pH before discharged to natural receiving waters. Tap water eluted through all materials resulted in leaching of cation/anions (as increasing EC); however, all materials, except washed sand and biochar, produced a relatively high peak before returning near to initial tap water EC (at around 1.4 L). Washed sand did not produce a peak (low ECEC, minimal cations/anions to be leached). Biochar displayed hydrophobic properties that resulted in a longer wetting time and slower release of salts, hence the broadness of the "peak" before trending back to tap water EC values. Note that eluent EC for both DM1 and DMS did not exceed the ANZECC trigger value of 2,000 μS/cm; meaning it would be suitable for discharge to natural waterways.

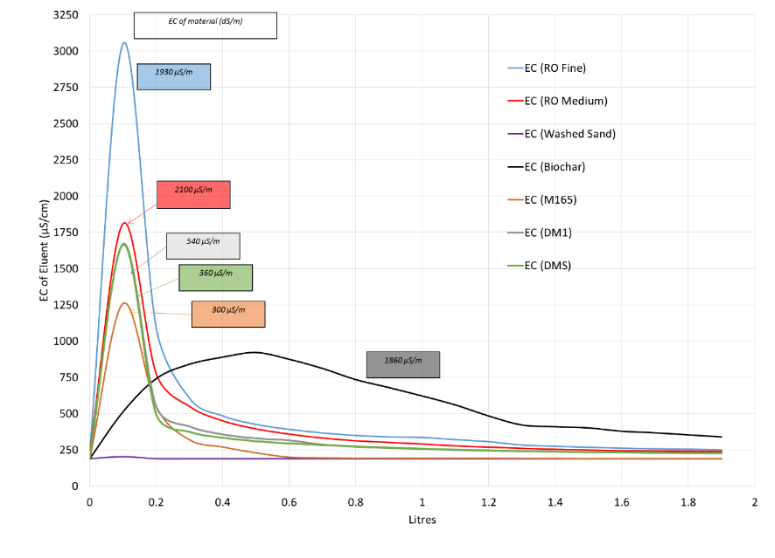


Figure 4: Change in EC based on applied volume

Change in pH is shown in Figure 5. ANZECC guidelines [21] guideline trigger values for aquatic ecosystems (SE Australia) range from 6.5 – 8.5 and all materials achieved this except biochar (high pH). Results indicate that discharge from these materials, from a raingarden or biofiltration device for example, would be within the desired pH range, and not impact on receiving waters.

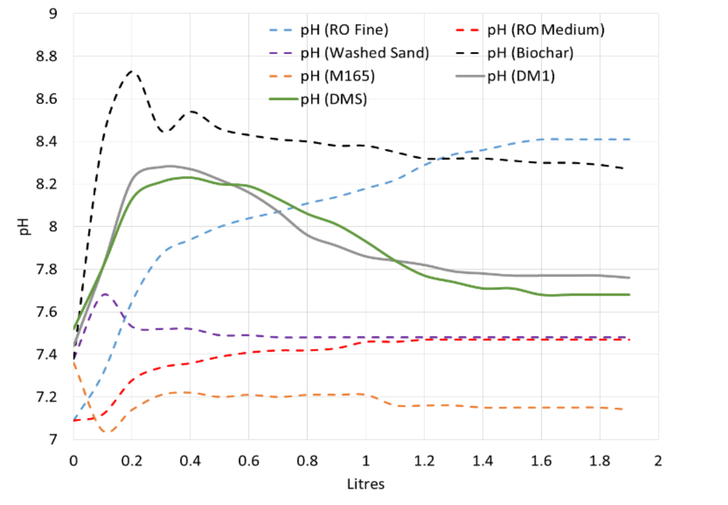


Figure 5: Change in pH based on applied volume

3.3 Column leaching tests – pollutant leaching

The second set of column tests attempted to demonstrate how the materials would behave under high flow conditions (saturated, low residence time) in leaching and/or removing pollutants. Water from a local urban creek was used as "stormwater runoff" for eluting through the columns. The runoff was collected from a local creek before the column tests. Analysis included pH, electrical conductivity (EC), Dissolved Oxygen (DO), Total Kjeldahl Nitrogen (TKN), Total Oxidisable Nitrogen (TON), Total Nitrogen (TN), orthophosphate (PO_4^{3-}), Total Phosphorous (TP), copper (Cu), zinc (Zn), Turbidity, Total Oil & Grease (TOG), and Total Organic Carbon (TOC); all based on standard water analysis methods [23]. Note that the experiment was undertaken in two batches where stormwater for each batch had a slightly different water quality profile. Table 4 shows initial stormwater quality (Stormwater1 and Stormwater2) and the change in pollutants after elution. Note that biochar and $CaCO_3$ were not included in this experiment as they are typically used as soil additives rather than a major component.

Table 4. Pollutant removal where stormwater used as influent to column experiments

	Units	**Storm water1**	**RO fine**	**RO medium**	.	**Storm water2**	**M165**	**Coarse Sand**	**DM1**	**DMS**	**ANZECC trigger Value (AE)**	**ARQ (2006)**
pH	-	7.5	7.7	7.6	.	7.5	7.4	7.5	7.5	7.6	6.5 – 8	6.2 – 7.6
EC	µS/cm	655	670	670	.	915	915	900	925	935	125 – 2200	-
DO	mg/L	8.53	9.08	9.25	-	8.64	8.99	9.11	9.04	9.06	> 6.5	-
TKN	mg/L	0.5	0.8	0.8	-	0.8	**2.2**	0.8	0.8	**1**	-	-
TON	mg/L	0.34	0.27	0.16	-	0.26	0.21	0.26	0.21	0.22	0.04	-
TN	mg/L	0.84	**1.07**	**0.96**	-	1.06	**2.41**	1.06	1.01	**1.22**	0.5	1.5 – 6
PO43-	mg/L	0.05	0.31	0.22	-	<0.05	<0.05	<0.05	<0.05	<0.05	0.02	-
TP	mg/L	0.1	**0.38**	**0.34**	-	0.1	**0.12**	0.08	**0.16**	**0.18**	0.05	0.15 – 0.7
Turbidity	NTU	20	17	**27**	-	9	**12**	**10**	9	8	6 – 50	50 – 350*
Cu	µg/L	4.9	**9**	**9**	-	2.7	**28**	**42**	18	22	1.4	18 – 150
Zn	µg/L	64	38	49	-	2.7	26	**41**	19	17	31	80 – 700
TOC	mg/L	6.4	**10.2**	**10.4**	-	7.6	**9**	7.7	**8.5**	**8.9**	-	13 - 45
TOG	mg/L	<2	<2	<2	-	<2	<2	<2	<2	<2	-	3 - 16

* based on TSS

Table 4 values shown in **bold** indicate an increase compared to initial stormwater quality. All pH, EC, DO and turbidity values, after elution, were within ANZECC guidelines (based on SE Australia, aquatic ecosystems) [21] and indicates minimal impact on receiving ecosystems. TOC and TOG showed negligible change from initial stormwater quality.

TN = TKN + TON, where TKN = bound N, and TON = soluble N. The RO-fine and RO-medium leached TN (as TKN) however TON decreased, meaning soluble TON was not leached from these materials. The RO-fine and RO-medium also leached some TP, Cu, and TOC to a small extent. The current specification (M165) leached more TN (as TKN) than the alternative filter media (DM1 and DMS).

Minimal leaching of TP occurred for M165, DM1 and DMS however there was some leaching of TP from RO-fine and RO-medium. This indicates that the use of RO in a design mix, such as DM1 and DMS, may provide a source of P for plant establishment in a raingarden (no amelioration required).

Surprisingly, washed sand leached the highest amount of Cu and Zn (42 and 41 µg/L respectively) and other materials leached minimal Cu and Zn. It is important to note that many parameters lie within Australian Runoff Quality (ARQ) [24] ranges, a document that "characterises" typical stormwater quality profiles in Australia (and from different landuses/surfaces) that biofiltration devices would be expected to treat. Compared to ARQ ranges [24], the Cu and Zn concentrations could be considered low.

3.4 Column leach tests – metals removal

The third column experiment investigated Cu, Pb and Zn (conservative pollutants) removal by M165, DM1 and DMS, from natural stormwater. Table 5 shows the initial stormwater quality for Cu, Pb and Zn (Inflow), the values after elution with natural stormwater, and the % reduction.

Table 5. Metal removal from stormwater

	Inflow (μg/L)	After elution (μg/L)			% Reduction		
	Stormwater	**M165**	**DM1**	**DMS**	**M165**	**DM1**	**DMS**
Cu	162	4.2	7.2	6.4	97	96	96
Pb	0.4	0.4	< 0.2	< 0.2	0	> 50	> 50
Zn	138	17	5	4	88	96	97

Significant removal rates for Cu and Zn were observed for M165, DM1 and DMS which are consistent with other studies [14, 15, 16, 17]. Removal rates for Pb were > 50 % for DM1 and DMS however there was no change in Pb for M165. Stormwater was continually applied to achieve an equivalent rainfall of 3,000 mm and M165, DM1 and DMS were then analysed for total Cu, Pb and Zn (Table 6). The applied rainfall would be equivalent to 5 years average rainfall in the city of Melbourne (Victoria, Australia).

Table 6. Metals in soil after 3,000 mm equivalent rainfall

		M165	**DM1**	**DMS**	**IWRG (Upper Limit – Fill Material)**
Cu	mg/kg	4.2	7.2	6.4	< 100
Pb	mg/kg	0.4	< 0.2	< 0.2	< 300
Zn	mg/kg	17	5	4	< 200

Values were compared to the Industrial Waste Resource Guideline (IWRG) [25] which provides limits on contaminated soils for disposal. Results indicate that once the filter media of a raingarden has been subjected to 3,000 mm of rainfall containing Cu (162 μg/L), Pb (0.4 μg/L) and Zn (138 μg/L) it would be suitable for fill material to be used for other purposes (landscaping and clean fill developments) and would not require special transport/disposal to a reuse area.

3.5 Comparison to Guidelines

In the stormwater management field in Australia, the Adoption Guidelines for Stormwater Biofiltration Systems - Summary Report [2] provides a summary of important parameters for biofiltration filter media and are shown in Table 8. Cells with a "√" and/or are in **bold** could be considered within specification; or can be, for example, with a degree of compaction one can reduce hydraulic conductivity and increase residence times. Values are given for other parameters to provide comparison to the M165 FAWB specification.

Table 8. Summary of important parameters for raingarden filter media (based on Adoption Guidelines for Stormwater Biofiltration Systems - Summary Report (Payne *et al*, 2015))

Parameter	CRC Guideline Objective	RO Fine	RO Medium	Biochar	Washed Sand	M165	DM1	DMS
Material	Engineered soil/sand	NA	NA	NA	√	√	√	√
Hydraulic Conductivity	100 – 300 mm/hr	√	√	√	√	√	√	√
Clay & Silt content	< 3%	√	√	√	√	√	√	√
Grading of particles	0.05 – 3.4 mm	NA	NA	NA	√	√	√	√
Nutrient content	TN > 1000 mg/kg	13,350	14,590	6,870	**82**	**235**	1,624	1,745
	Extractable Nitrate (no limit?)	50.7	52.9	2.34	4.4	4.28	10	9.4
	Available P (Colwell) < 80 mg/kg	316	322	99	**8**	**11**	**45**	**38**
Organic matter	≤ 5 %	100	100	100	**0.1**	**0.4**	50	65
Organic carbon	No data	32	36.5	5.9	0.1	0.4	3.11	2.01
Total carbon	No data	32	36.9	61.1	0.1	0.4	4.88	5.27
pH	5.5 – 7.5	7.76	7.87	9.23	7.72	**6.80**	8.29	7.74
Electrical conductivity	< 1.2 dS/m	1.93	2.1	1.86	**0.02**	**0.3**	**0.54**	**0.36**
Horticultural suitability	To be assessed by horticulturalist	NA	NA	NA	NA	√	√	√
Particle size distribution	Fine sand (10 – 30%)	NA	NA	NA	√	√	√	√
Depth	400 – 600 cm	NA	NA	NA	√	√	√	√
Once-off nutrient amelioration	Added to upper 10 cm	NA	NA	NA	Yes	Yes	No	No
Submerged zone	High HC or shallow depth	NA	NA	NA	√	√	√	√

Material – RO (fine and medium) and biochar cannot be considered as engineered soil/sand. Washed sand, M165, DM1 and DMS can be considered as engineered soil/sand and satisfy Guideline requirements.

Hydraulic Conductivity – All materials can be compacted to achieve desired hydraulic conductivity to be within the CRC Guideline requirement.

Clay and silt content – All materials contained < 3 % clay content and satisfy CRC Guideline requirements.

Grading of particles – RO (fine and medium) and biochar had a wider (and higher) range of particle sizes that exceeded CRC Guideline requirements. Greater than 95 % of particle sizes in the washed sand, M165, DM1 and DMS were within CRC Guidelines (0.05 – 3.4 mm) and are satisfactory for use in biofiltration.

Nutrient content – RO (fine and medium) and biochar contain TN that far exceeds CRC Guideline requirements (>> 1000 mg/kg). Washed sand and M165 are well below the CRC Guideline requirement and, since this is too low to sustain plant growth, is why potassium nitrate and superphosphate is typically added to M165 (at 300g/m^3). DM1 and DMS exceeded the CRC Guideline requirement however these values will be modeled in MUSIC v6 later in this paper to demonstrate the suitability of DM1 and DMS as filter media in raingardens. RO (fine and medium) and biochar contain orthophosphate (plant-available phosphorous as Colwell P in Table 2) that exceeds CRC Guideline requirements (< 80 mg/kg). Washed sand, M165, DM1 and DMS were all within CRC Guidelines.

Organic matter – RO (fine and medium) and biochar were all 100 % organic matter and do not satisfy CRC Guideline requirements. DMS and DM1 were 50 % and 65 % organic matter respectively and washed sand and M165 had minimal organic matter (0.1 % and 0.4 % respectively). This requirement (≤ 5 % organic matter) is currently the subject of debate in the stormwater industry due to claims of excess leaching of nutrients. However, the CRC for Water Sensitive Cities has recently added to its filter media guidelines (CRC Guidelines): *"There may be soil with higher organic content that the level specified that may not leach nutrients (TN and/or TP). It is also acknowledged that organic matter content does not have a direct link to nutrient leaching.* [2]

pH (1:5 in water) – The pH values in the CRC Guidelines essential specifications prescribe a value of 5.5. to 7.5. The FM materials ranged from 6.8 (M165) to 9.2 (biochar). The range of pH, after leaching tests, will be discussed in Section 3 in relation to ANZECC water quality guidelines [21].

Electrical conductivity (EC, 1:5 in water) – RO (fine and medium) and biochar exceeded CRC guideline values (> 1.2 dS/m). Washed sand, M165, DM1 and DMS were within CRC Guidelines (< 1.2 dS/m) and are satisfactory for use in raingardens.

Horticultural suitability – DM1 and DMS have been deemed as appropriate for use in raingardens based on the data in Table 2. Note that M165 requires an initial addition of fertilizer at a rate of 300 g/m^3.

Particle size distribution – The CRC Guideline states that the filter media should be 10 – 30 % fine sand. M165, DM1 and DMS ranged between 30 – 35 % fine sand and satisfy CRC Guideline requirements. Final mixes for DM1 and DMS have particles over the size range prescribed in the CRC Guidelines. However, no negative performance consequences were identified.

Depth – Washed sand, M165, DM1 and DMS can be used for the CRC Guideline requirement for depth.

Once-off nutrient amelioration – Not required for DM1 and DMS however M165 does need amelioration.

Submerged zone – Washed sand, M165, DM1 and DMS can be used to increase or decrease hydraulic conductivity (depending on compaction) to satisfy the CRC Guideline requirement.

The design mix configurations DM1 and DMS appear to be comparable media to M165 for use in biofiltration devices.

3.6 MUSIC v6 modelling

This report has characterised several materials (RO-fine, RO-medium, washed sand and M165) and design mixes (DM1 and DMS) in terms of physical and chemical properties, demonstrated leaching/pollutant removal behaviour of the same, compared the current CRC Guideline specification (FAWB specification, M165) to DM1 and DMS for use in biofiltration devices, and addressed life-span aspects of DM1, DMS and M165. However, in a bioretention setting, the non-conservative nature of some pollutants means that actual removal rates are dependent on plant growth in a media that utilise and alter the forms present during wetting and drying cycles over time. For example, nitrogen exists in several forms (see Figure 7).

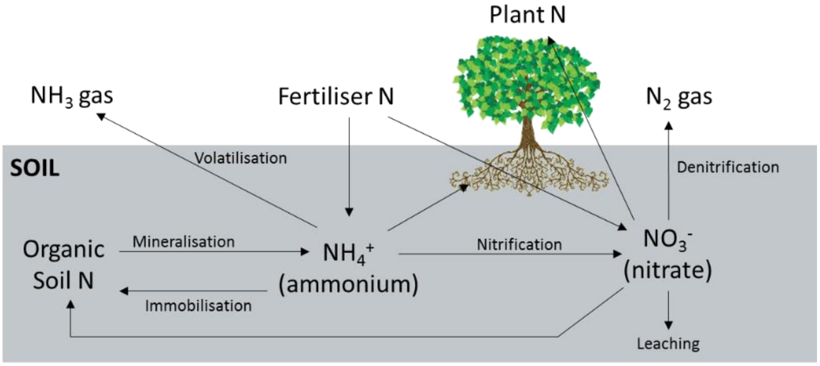


Figure 7: Nitrogen cycle

Forms of nitrogen in a soil (or filter media) are governed by several processes including inputs from runoff, microbial degradation, chemical transformation, wetting and drying patterns and uptake of nutrients by plants [10, 26]. As such, it is difficult to demonstrate the nitrogen removal performance based on (short-term) column leaching experiments as shown in this study without some long-term continuous modelling approach as provided by MUSIC v6.

Table 10 summarises the treatment-train effectiveness as modelled in MUSIC v6.

Table 10: Treatment-train effectiveness as modelled in MUSIC v6

M165	**Sources**	**Residual Load**	**% Reduction**
Flow (ML/yr)	1.96	1.86	5
Total Suspended Solids (kg/yr)	399	9.69	98
Total Phosphorous (kg/yr)	0.805	0.051	94
Total Nitrogen (kg/yr)	5.66	1.29	77
Gross Pollutants (kg/yr)	53.6	0	100
DM1	**Sources**	**Residual Load**	**% Reduction**
Flow (ML/yr)	1.96	1.86	5
Total Suspended Solids (kg/yr)	400	9.69	98
Total Phosphorous (kg/yr)	0.812	0.112	86
Total Nitrogen (kg/yr)	5.64	2.37	58
Gross Pollutants (kg/yr)	53.6	0	100
DMS	**Sources**	**Residual Load**	**% Reduction**
Flow (ML/yr)	1.96	1.85	5
Total Suspended Solids (kg/yr)	400	9.63	98
Total Phosphorous (kg/yr)	0.812	0.051	80
Total Nitrogen (kg/yr)	5.64	1.29	52
Gross Pollutants (kg/yr)	53.6	0	100

The raingarden reduced Flow by ~ 5 %, TSS by ~ 98 % and Gross Pollutants by 100 % for all options (M165, DM1 and DMS). TP was reduced by 94 %, 86 % and 80 % for M165, DM1 and DMS respectively. The difference between all options is a function of the initial orthophosphate concentration (as Colwell P) of the filter media entered into the model. For example, M165 has an orthophosphate content of 11 mg/kg and had the highest reduction (94 %) compared to DM1 (38 mg/kg) and DMS (45 mg/kg). The more orthophosphate contained in the filter media the lower the % reduction.

TN was reduced by 77 %, 58 % and 52 % for M165, DM1 and DMS respectively. The difference between all options is a function of the initial TN concentration of the filter media entered into the model. For example, M165 has a TN content of 235 mg/kg and had the highest reduction (77 %) compared to DM1 (1624 mg/kg) and DMS (1745 mg/kg). The more TN contained in the filter media the lower the % reduction.

The relationship between filter media TN and orthophosphate content and treatment performance may be based on the erroneous assumption that filter media with organic matter content ≥ 5 % leaches excessive nutrients; which this study has demonstrated not to be the case. So, how can DM1 and DMS be modelled in MUSIC v6 to provide equivalent treatment performance compared to M165?

From MUSIC v6:

"The selection of appropriate k and C values for modelling the removal of Total Nitrogen cannot easily follow the procedure applied for TSS and TP. The composition of particulate and soluble forms of N in stormwater is highly varied. There is significantly smaller particulate fraction of TN compared with TP, and even that fraction is associated with organic particles which have significantly lower specific gravities than sediment. Calibrated k values for TN in wastewater systems indicate significantly lower values (as much as two orders of magnitude) compared with TP and TSS. The default k and C* values for TN are thus based on very limited data. There is an expectation that the k values are likely to be an order of magnitude lower than corresponding values for TP, and that the ratios of C* to inflow Event Mean Concentration (EMC) are likely to be higher for TN than for TP."*

Therefore, the nature of DM1 and DMS in comprising 50 % and 65 % “organic matter” with an initial leaching peak that rapidly subsides back to stable levels, means that changes in k and C* need investigation. Selection of k and C* were based on Biofiltration Systems (Table 5 in [1], “Appendix G: Selecting Appropriate k and C* Values”). A simple sensitivity analysis was undertaken on three scenarios (changes in k and C*) and are described in Table 11. MUSIC v6 results (% reduction) are presented in Table 12.

Table 11. Changing k and C* in MUSIC v6 (sensitivity analysis inputs)

Bioretention		**TSS**		**TP**		**TN**	
		k	**C***	***k***	**C***	***k***	**C***
LOW	mg/kg	4,000	10	3,000	0.08	250	1.1
Default	mg/kg	8,000	20	6,000	0.13	500	1.4
HIGH	mg/kg	15,000	30	12,000	0.18	1,000	1.7

Table 12: Results from changing k and C* in MUSIC v6 (sensitivity analysis)

M165	**LOW**	**Default**	**High**	**Difference**
Flow (ML/yr)	5.3	5.3	5.3	0
Total Suspended Solids (kg/yr)	94.5	95.8	96.5	2
Total Phosphorous (kg/yr)	90	90.5	90.6	0.6
Total Nitrogen (kg/yr)	72.3	72.7	73.1	0.8
Gross Pollutants (kg/yr)	100	100	100	0
DM1	**LOW**	**Default**	**High**	**Difference**
Flow (ML/yr)	5.3	5.3	5.3	0
Total Suspended Solids (kg/yr)	94.6	95.6	95.5	0.9
Total Phosphorous (kg/yr)	83.4	84.1	86	2.6
Total Nitrogen (kg/yr)	52.6	55.5	69.5	16.9
Gross Pollutants (kg/yr)	100	100	100	0
DMS	**LOW**	**Default**	**High**	**Difference**
Flow (ML/yr)	5.3	5.3	5.3	0
Total Suspended Solids (kg/yr)	94.2	95.3	95.6	1.4
Total Phosphorous (kg/yr)	77.3	77.9	79.7	2.4
Total Nitrogen (kg/yr)	47.6	50.2	66.6	19
Gross Pollutants (kg/yr)	100	100	100	0

Sensitivity analysis shows that M165 was relatively unchanged with significant changes in k and C* and is likely a function of the fact that most research, and development of the CRC Biofiltration Guidelines [2], have used sandy loam (M165) as the filter media. However, DM1 and DMS were highly sensitive to changes in k and C* with respect to TN (difference in treatment performance of 16.9 % and 19 % respectively). Results from this study have demonstrated that DM1 and DMS are comparable filter media to M165 in terms of leaching/pollutant removal and treatment performance yet this performance is not captured in MUSIC v6.

Why? The treatment performance of biofiltration in MUSIC v6 is governed by an extensive “lookup table”, which determines outflow concentrations and/or removal rates for TSS, TP and TN and considers all important characteristics of the biofiltration system and its operating conditions. The “lookup tables” are based on extensive research and observations however the M165 (sandy loam) has been the preferred choice in most of the research over the past 20 years. Sandy loam contains silt and clay that provides the cation exchange capacity that contributes to attenuating pollutants in a biofiltration system.

The “engineered” filter media DM1 and DMS do not contain significant silt/clay content, as the exchange capacity is provided by the recycled organic matter (higher ECEC, refer Table 2). Therefore, future research should look to develop a “lookup table” suited to the use of filter media, such as DM1 and DMS, by monitoring flow and water quality (inflow and outflow) of "real-life" raingardens. Furthermore, since DM1 and DMS behave similarly (or better) to the M165 with respect to nutrient leaching and pollutant removal it makes sense to use similar "inputs" to MUSIC v6 for DM1 and DMS, i.e., the same values one would use for M165. This will be undertaken in future projects.

4. Conclusions

This paper has characterised several materials (RO-fine, RO-medium, washed sand and M165) and design mixes (DM1 and DMS) in terms of physical and chemical profiles, demonstrated leaching/pollutant removal behaviour of the same, compared the current CRC Guideline (FAWB) specification (sandy loam - M165) to DM1 and DMS for use in biofiltration, and validated the use of alternative filter media (DM1 and DMS) through MUSIC v6 modelling. The pollutant removal performance of DM1 and DMS, particularly for metals, is similar or greater than the industry FAWB specification (sandy loam - M165).

The CRC Water Sensitive Cities released their Adoption Guidelines for Stormwater Biofiltration Systems – Summary Report 2015 [2] containing Table 3, "Filter Media (top layer/growing media) Essential Specifications and Guidance". The Guideline (Table 3) asserts in the "Essential Specifications" that exceeding ≤ 5% organic matter will lead to nutrient leaching. Results from this study demonstrated that filter media (from recycled organic and mineral materials) containing up to 65% compost does not leach any more nutrients than soil. Previous research has also shown that different composts have different leaching properties, and this is likely a function of the what is in the compost [11, 12]; therefore, characterising any organic/mineral based materials should be mandatory to ascertain leaching risk before use in a commercial setting.

The industry model, MUSIC v6, appears to be sensitive to initial TN and orthophosphate inputs for treatment nodes, potentially underestimating the benefits of recycled organic and mineral materials as filter media. Results from this study indicate that "lookup tables" used for Biofiltration nodes in MUSIC v6 may not represent true behaviour of FM's as demonstrated in this study. More data is required to develop "lookup tables" (in MUSIC v6) for engineered soils that provide equivalent treatment performance to the current specification (M165); and the best way forward is to use actual case study sites and monitor their performance; and this will be the focus of future research. In contrast, MUSIC v6 inputs typically used for M165 could be used for both DM1 and DMS which would also provide comparable performance. A recent standard produced for the NSW EPA is appended to this paper which may assist in development of similar standards elsewhere [22].

One of the observed issues with long-term commercial based research (such as CRC for Water Sensitive Cities) is that many alternatives within the industry can be excluded if they don't "fit" the specification developed by the research over decades. Over decades, the uptake of specifications and models by local government has driven the procurement process to the FAWB specification (sandy loam), but we are running out of this resource and alternatives must be promoted. This is the case in Australia where, despite billions of dollars investment in recycling urban waste, the recycled organic and mineral materials presented in this paper have effectively been excluded by local government and Environmental Protection Authority (EPA) due to claims of excessive leaching and other negative impacts. These are erroneous claims if the recycled organic and mineral materials can be demonstrated to be similar to the FAWB specification or are benign to any receiving waters. Recent guidelines on the use of organic material as biofilter media are now available in Australia [22].

Recent acknowledgment by the CRC Water Sensitive Cities that suitable alternatives can be used provided they meet a verified performance-based requirement of addressing essential operational performance related to sustained acceptable infiltration rate, integrity of the surface vegetation community of the system and with acceptably low or no leaching from the biofiltration media; means that both DM1 and DMS can be considered suitable alternatives to using virgin resources (M165, sandy loam soil) in biofiltration systems. The recycled organic and mineral material alternatives can offer both a significant reuse industry whilst reducing our demand for virgin sandy loam soils and need for landfill sites.

Appended to this paper is:

1. CORE (2018) Performance & Validation Standards for Organic Bio-Filtration Media, CORE Standard CS-1510-18, CORE Water Division, a report for the EPA NSW by the Centre for Organic Research and Education (CORE), North Sydney, NSW, Australia.
2. From MUSIC Help - Appendix G: Selecting Appropriate k and C* Values

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