

# DEVELOPMENT OF A BIORETENTION MEDIA MIX TO BALANCE HYDRAULICS AND WATER QUALITY

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## ABSTRACT

Bioretention devices are a Low Impact Design device used to treat pollutants found in stormwater runoff. Research assessed combinations of manufactured materials readily available in Auckland which create physical and chemical properties of filter media to satisfy objectives for stormwater management. The investigation included: establishing physical characteristics and performance criteria; investigating available materials; particle size distribution testing (PSD); compaction assessment; hydraulic conductivity testing; media chemistry analysis; and water quality testing.

Two commercial media achieved the target hydraulic conductivity with light tamping compaction. Three mixes composed of different fine sands with added compost, satisfied the hydraulic conductivity criteria with wetting and settling compaction or light tamping. These five media were chosen for water quality testing.

For an equivalent of 15 years of pollutant loading, the 90% v/v sand with 10% v/v compost media are capable of removing copper and zinc in synthetic stormwater runoff below 5 µg/L and 10 µg/L respectively, and reduce mass loads by 60% and 70% respectively. Over all, the two commercial media were less effective than the sand based media, however, treatment improved over time as more "runoff" was applied. All five media leached phosphorus over the simulated 15 years. Media chemistry analysis suggests that phosphorus concentrations may be able to be reduced in commercial mixes. The level of phosphorus leaching should be mitigated before media are considered for practical implementation in field trials, unless receiving waters are unlikely to be impacted by phosphorus.

## KEYWORDS

**Bioretention, rain garden, filter media, hydraulics, water quality, LID treatment device.**

## PRESENTER PROFILE

Simon Wang has recently completed a Master of Engineering thesis as a part of this research program on bioretention media at the University of Auckland. Simon has previously worked on living (green) roofs for stormwater management, and has an active interest in LID devices. Elizabeth Fassman was Simon's academic supervisor, and overall project principle investigator. Robyn Simcock provided valuable technical input, and lead the investigation on media chemistry.

## 1 INTRODUCTION

With increasing urban development, impervious surfaces replace the natural soils and vegetation that provided substantial stormwater management benefits through intercepting, infiltrating and retaining runoff. The quantity of stormwater runoff in urban developments is therefore increasing, while the quality is decreasing, leading to increased

accumulation of sediment, heavy metals (Cu and Zn) and nutrients in Auckland's fresh waters, estuaries and inner harbours.

A popular Low Impact Design (LID) device is the bioretention cell, also known as a rain garden. A bioretention cell is an on-site terrestrial device generally consisting of a drainage layer, transition layer, filter media, mulch layer, and plants. Bioretention cells are typically 5 to 10% of the catchment area.

During and after a rainfall event, runoff flows from a catchment towards the bioretention cell and optimally enters as sheet flow. Ideally, runoff ponds on the surface of the cell to a maximum depth of 200 to 300 mm (providing flow attenuation), and slowly infiltrates into the filter media (providing the majority of contaminant removal, further flow attenuation and some retention). Captured runoff is removed by a combination of evapotranspiration, exfiltration to the surrounding soils, or flow through an underdrain to a subsequent system (e.g. reticulated stormwater system, the next operation in a treatment train, or a receiving water).

The bioretention cell uses a combination of filter media, microorganisms and plants to reduce pollutants in urban stormwater runoff. Pollutant removal mechanisms include both physical (sedimentation, filtration, adsorption, ion exchange, phytoremediation, volatilization, and thermal attenuation) and biological processes (microbial activity, plant uptake/ assimilation, and decomposition) (Prince George's County 2007). In combination with runoff retention, bioretention cells reduce mass loads of contaminants.

Bioretention filter media needs to balance four major design criteria:

- Have a high enough hydraulic conductivity to allow for surface infiltration of stormwater within a reasonable time (maximum 24 to 48-hrs depending on public accessibility) to prevent extended water ponding (i.e. minimum hydraulic conductivity).
- Have a low enough hydraulic conductivity to provide adequate contact time (minimum 2-hr, but dependant on the contaminant) between runoff and filter media to allow for pollutant removal mechanisms to be effective (i.e. maximum hydraulic conductivity).
- Have chemical composition to remove pollutants from stormwater
- Provide plants with adequate water to allow for sustained long term growth and short to medium-term nutrients (most runoff will contain enough N and P for plant growth in the medium to long term growth).
- Be structurally stable and maintain even flow through media (avoiding preferential flow that occurs with cracking).

Three general specifications for bioretention media have emerged overseas (Table 1). The common defining characteristic is a very high proportion of aggregate coupled with low organic content. While bioretention can provide significant amenity value, they are primarily stormwater treatment systems, thus they should not be designed in the same manner as a landscaped area. For example, the majority of nutrients required medium and long-term should be provided by urban runoff, therefore they should need no fertilisation and only low organic matter levels are required to sustain plants.

Table 1. Bioretention Media Mixes from Leading Jurisdictions in LID

"North Carolina Mix" <sup>1</sup>	"Washington State Mix" <sup>2</sup>	Melbourne: Facility for Advanced Water Biofiltration (FAWB) <sup>3</sup>
85-88% Sand <i>by volume</i>	60% "loamy sand" <i>by volume</i>	< 6% clay (<6 mm)
8-12% Fines (Clay+Silt) <i>by volume</i>	40% compost <i>by volume</i>	< 5% organic matter
3-5% Organics	10% organic <i>by weight</i>	no natural topsoil
		up to 10% vermiculite or perlite

1. Hunt and Lord (2006). 2. Hinman (2009) 3. FAWB (2009)

Through funding from the Auckland Council, the University of Auckland and Landcare Research conducted a two-stage investigation to identify physical and chemical characteristics of locally-available, 'manufactured' materials intended for application as bioretention filter media. The aim of the first stage of research was to find candidate bioretention filter materials and assess the hydraulic response to different compaction treatments. The second stage was designed to use the best candidate media from the first stage in leachate (water quality) tests. Water quality tests aim to quantify the pollutant removal ability of the media and understand how the pollutants are being removed in a laboratory setting i.e. synthetic stormwater with no sediment and substrates with no plants. The full report (Fassman et al., *draft* 2012) is currently under review, and will eventually available online via Auckland Council technical reports.

## 2 SOIL CHEMISTRY

Chemical analysis of individual material components or mixes were performed by Landcare Research. Properties tested were: pH, organic carbon, total nitrogen, Olsen phosphorus, total phosphorus, organic phosphorus, anion (phosphate) retention, cation exchange capacity (CEC), and base saturation. Chemical tests were carried out on the < 2 mm fraction (samples are sieved, then ground) and results were reported on a dry mass basis. The majority of soil chemistry test methods are after Blakemore et al. (1987), which are briefly described on the Landcare Research website: [http://www.landcareresearch.co.nz/services/laboratories/eclab/eclabmethods\\_soils.asp](http://www.landcareresearch.co.nz/services/laboratories/eclab/eclabmethods_soils.asp).

Results are presented with those of hydraulic and water quality testing sections, as interpretation warrants.

## 3 HYDRAULIC TESTING

### 3.1 METHODOLOGY

#### 3.1.1 VISITING SUPPLIERS AND GATHERING MATERIAL INFORMATION

Suppliers of sand and organic materials were visited to identify types of material available around the Auckland Region. Specific information from suppliers about the possible materials included: material type (e.g. original sources: pumice, river sand, beach sand, scoria), specific particle sizes, grading, weight, washed or unwashed (determines content of fine material), product quality control, availability and consistency of supply, typical uses/applications (other than bioretention) and price.

The materials and/or product tested during the course of this research were largely selected due to availability and consistency of product. For this reason, no natural soils

were tested, although previous research has shown some soils are highly effective bioretention media. In any section, the information presented is not intended to endorse any particular product or company. Evaluations are limited to satisfying specific design objectives.

### **3.1.2 PARTICLE SIZE DISTRIBUTION OF INDIVIDUAL COMPONENTS**

Particle size distribution (PSD) was used as a primary screening process for candidate materials. Maximum and minimum PSD guidelines for bioretention media have been established by Seattle Public Utilities (SPU 2008), Washington State University (WSU) (Hinman 2009), and the Facility for Advanced Water Biofiltration in Melbourne (FAWB 2009). The maximum and minimum PSD guideline for sand filters from Auckland Regional Council's (ARC) Technical Publication (TP) 10 (2003) was also considered. PSD tests were carried out using a dry sieve analysis as per ASTM C136-06: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates (ASTM International 2011a).

International guidelines for bioretention aggregate gradation were used to screen candidate sands, assuming media within PSD limits would produce acceptable hydraulic conductivities and hence water drawdown times, given adequate compaction. As well as meeting gradation limits, media should be well-graded over the entire range to avoid structural collapse due to particle migration (FAWB 2009).

### **3.1.3 COMPACTION TESTING**

Compaction testing quantified the relationship between moisture content and bulk density for media with different levels of organic content. Compaction testing used ASTM D1557-09: Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (2,700 kN-m/m<sup>3</sup>) (ASTM International 2011b). The standard uses repeat tests.

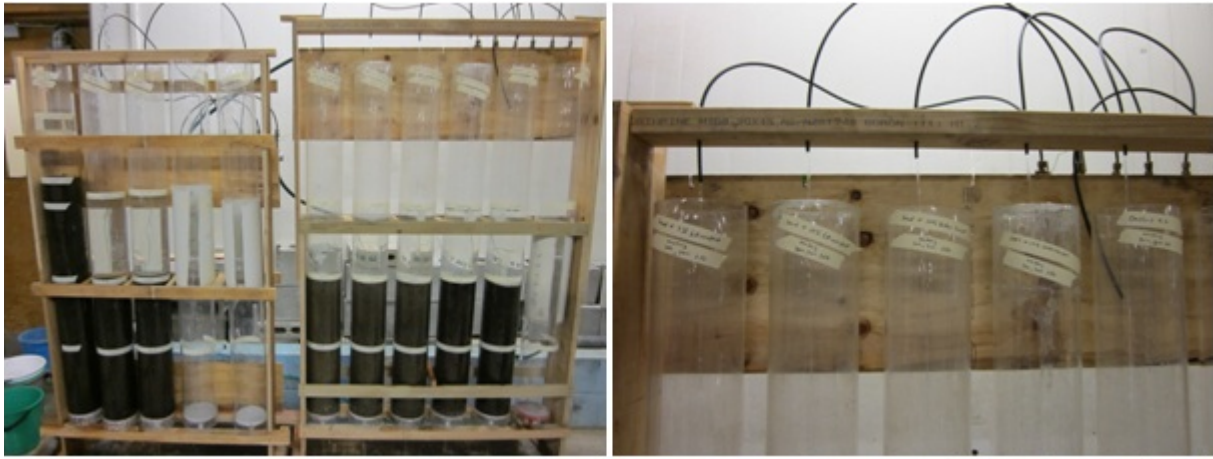
### **3.1.4 HYDRAULIC CONDUCTIVITY TESTING**

Hydraulic conductivity assesses the ability of a bioretention filter media to meet the surface infiltration/drawdown from maximum ponding objectives and pollutant removal in the field. The test set up was intentionally simple in an attempt to limit the scope of the project and focus on the filter media itself. A mulch layer, transition layer and drainage layer were not tested.

1500 mm length columns of transparent Perspex pipe with a 140 mm inner diameter were used to replicate bioretention cells in the lab (Photo 1a). Water was applied through individual pipes and valves for each bioretention column (Photo 1b). A relatively shallow media depth of 600 mm and deep ponding depth of 300 mm were chosen for testing in accordance with current recommendations in international guidelines and literature (Fassman et al. *draft* 2012). Compaction was either by wetting and settling, or the equivalent of light tamping with a backhoe bucket (which was estimated to be 15 blows with a modified proctor for the column setup).

A falling head permeability test from the maximum ponding depth (300 mm above media surface) was performed for ten test runs for each different media column. A target hydraulic conductivity range of 12.5 to 1,500 mm hr<sup>-1</sup> was set to balance hydraulic and water quality objectives for a range of contaminants. The lower range is limited by maximum 24 hr ponding time, and a minimum saturated hydraulic conductivity of 0.3 m d<sup>-1</sup>, as is recommended in TP10 (2003). The upper range is limited by a desired minimum runoff to media contact time while acknowledging the potential for sediment loads to decrease hydraulic conductivity over the life of the system. Identifying the "recipes" in Table 1 as international best practice, various ratios of sand and compost were blended in the laboratory and subject to testing.

*Photograph 1: Hydraulic testing setup: a) full columns; b) inflow*



## 3.2 RESULTS AND DISCUSSION

### 3.2.1 VISITING SUPPLIERS AND GATHERING MATERIAL

The initial visit to landscape suppliers located around Auckland resulted in a range of possible materials for further investigation. Only a sub-sample of materials is discussed in this paper. Full results are described in Fassman et al. (*draft 2012*).

Two proprietary rain garden mixes are available in New Zealand. Chemistry analyses indicates both mixes have in excess of 30% v/v organic material, as total carbon levels are ~17% (Supplier 1) and 14% (Supplier 2) organic matter. Supplier 1 indicated their mix includes 50% v/v organic material (composted bark and bark fines). High organic contents encourages plant growth by enhancing nitrogen supply, nutrient storage and moisture storage, but may lead to physical degradation of the media and nutrient leaching, which is undesirable in a stormwater treatment system. Organic content is substantially greater than specified in Table 1.

East Coast Sand (ECS) is dredged marine sand with trace amounts of shell visible, available from three different suppliers at an average of \$94/m<sup>3</sup>. Woodhill Black Sand (WBS) is heavy due to its high iron content. It is excavated from the west coast of Auckland and costs an average of \$55/m<sup>3</sup> across three different suppliers. Winstone Pumice Sand (PS) is graded to finer than 2 mm and is from Cameron Quarries in Otamarakau, and was available at \$51/m<sup>3</sup>. Auckland Landscape Supplies (ALS) No. 3 sand was available at \$74/m<sup>3</sup> and provided the “best” fit for international PSD guidelines for bioretention media.

The limiting factor when finding suitable composts are supply issues: namely consistency of supply and quality control of the supply (weed free, acceptable levels of contaminants, meeting size grading limits) while supplying in bulk quantities. Few suppliers in Auckland can meet such standards, hence only three compost products were sampled. Little guidance on physical characteristics of composts (which may affect hydraulic performance) is available from the international literature. SPU (2008) provide PSD guidelines for composts, but the main emphasis of the limit is to minimize large grained particles. In this paper, mixes used various proportions of the same bark-based compost, with the exception of the commercial rain gardens mixes. Greenwaste based compost was not considered due to the potential for elevated nutrient leaching.

Discussions with the concrete and aggregate industry yielded key information regarding suitability and supply of particular aggregates. For example, the resource consent to extract at least one of the aggregates considered will expire soon, and is unlikely to be renewed. Dialogue with suppliers and industry ultimately saves time and resources that would have been put into testing an unsuitable material.

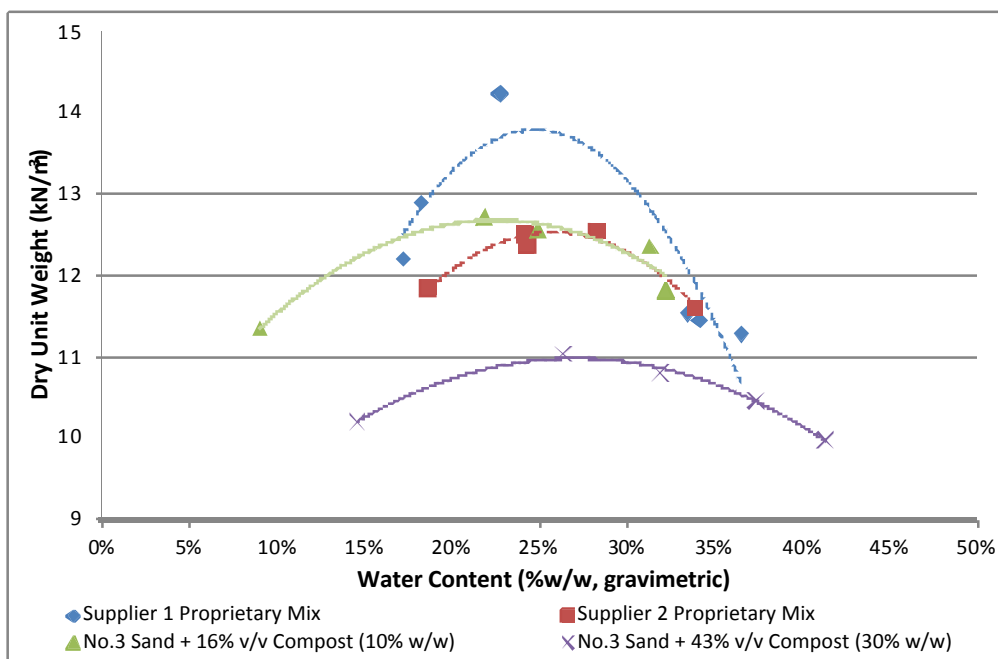
### 3.2.2 COMPACTION TESTING

The behaviour of different media under a constant level of compaction and varying water contents was investigated. A higher density for the same material reflects less pore volume, and hence a lower hydraulic conductivity as large pores are most impacted. A larger volume of smaller pores should also increase storage of plant-available water, which also enhances runoff retention.

Media with high organic content have a greater potential for compaction as evidenced by the difference between the No. 3. Sand mixes in Figure 1, one of which has three times more compost than the other. In the field compaction occurs either by mechanized equipment during construction, maintenance crews or the pedestrians walking over the surface, or by natural settling due to self-weight (particularly during wet weather) over time and vibration (from vehicle traffic). Compaction of bioretention media in situ may require remedial works to maintain design ponding depth, root depth for plant stability (particularly trees), or pollutant removal.

Media moisture content also affects the extent of compaction of a medium. Again a high organic content creates media less resistant to compaction. Organic materials can hold greater than 100% of its weight in water. For the three media in Figure 1 with greater than 16% v/v organic content, the compaction density varies substantially as moisture content changes, evidenced by the sharper curves over a greater range compared to the No. 3. Sand + 16% v/v compost. Material strength and large fraction of the sand provides resistance to compaction in the latter mix.

Figure 1: Moisture-density curves of selected media



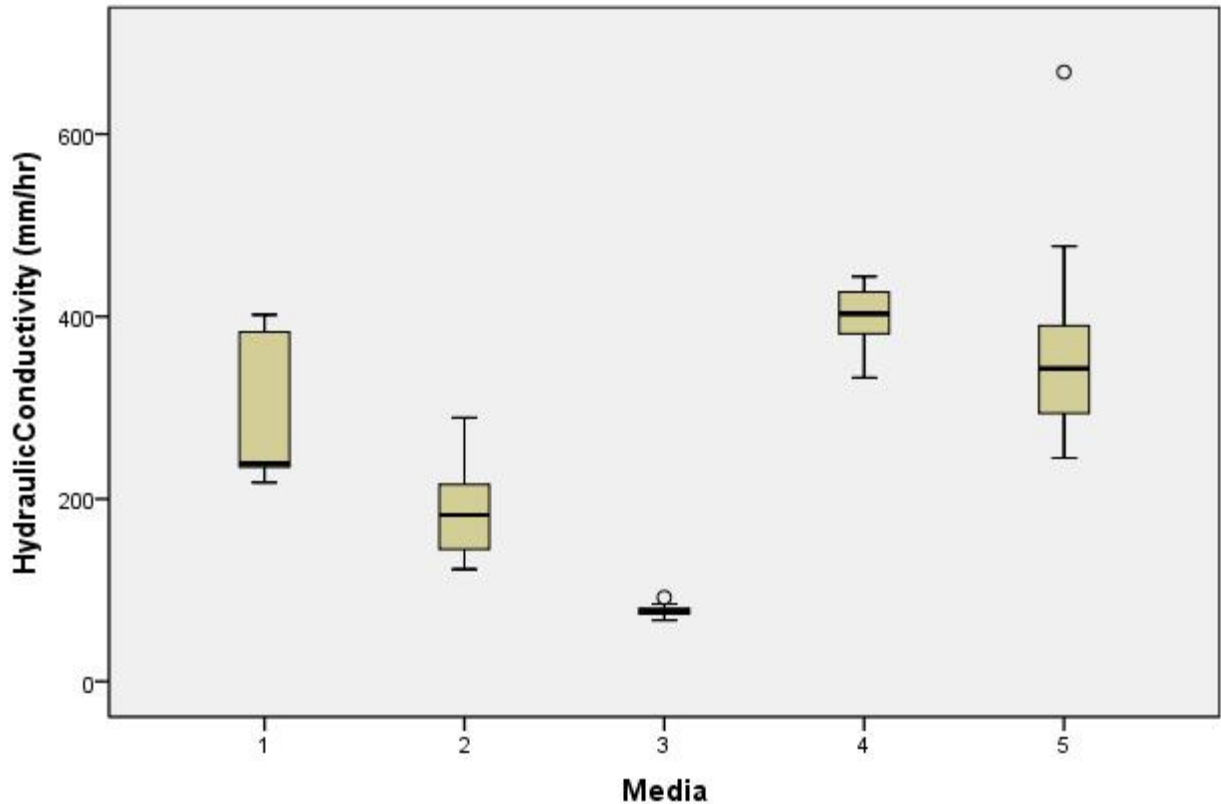
### 3.2.3 PSD AND HYDRAULIC CONDUCTIVITY TESTING

Mixes using the best fitting aggregate (ALS No.3 Sand) according to all of the international PSD guidelines resulted in excessively high hydraulic conductivity (ave. > 2300 mm hr<sup>-1</sup>), until the compost fraction was increased to 43% v/v (ave. ~1450 mm hr<sup>-1</sup>). The most successful non-proprietary mixes in terms of hydraulic conductivity were 10% v/v compost mixed with ECS, WBS or PS (80 mm hr<sup>-1</sup>, 400 mm hr<sup>-1</sup>, and 340 mm hr<sup>-1</sup>, respectively), achieved via "natural" compaction by installation in 300 mm lifts and wetting. The result was surprising because none of the aggregates alone fit PSD guidelines: ECS and WBS are fine and poorly graded (100% passing 0.425 mm); while PS is a fairly good fit for the coarse section of the PSD guidelines (the fraction greater than

0.2 mm), has a greater amount of fines than recommended, but is well graded. All three have PSDs that substantially different from the “best fitting” No.3 Sand. Results indicate PSD-based guidelines should not be used as a substitute for hydraulic conductivity testing under typical compaction levels.

The commercial mixes required compaction by “light tamping with a backhoe”, a standard construction technique, for the hydraulic conductivity to fall below 1500 mm hr<sup>-1</sup>. Figure 2 shows hydraulic conductivity results for the five mixes and compaction treatment that were selected for water quality testing, based on hydraulic conductivity performance.

Figure 2: Saturated hydraulic conductivities of selected media



- 1 = Supplier 1 [lightly tamped]
- 2 = Supplier 2 [lightly tamped]
- 3 = ECS + 10% (v/v) compost mix [wetting]
- 4 = WBS + 10% (v/v) compost mix [wetting]
- 5 = PS + 10% (v/v) compost mix [wetting]

## 4 WATER QUALITY TESTING

### 4.1 METHODOLOGY

Synthetic stormwater was applied to laboratory bioretention columns in alternating “doses”. The dosing schedule was developed to obtain a balance between two objectives:

1. Determining storm event-based pollutant removal efficiency of the media
2. Estimation of total pollutant removal potential and life of the media

Media-filled columns were initially flushed with clean tap water, in an attempt to pass any “first flush” through the system. Subsequently, doses equivalent to loadings of the water quality volume (WQV) (ARC 1999, 2003) were used to determine short term (event-

based) pollutant removal efficiencies of the filter media. Doses were based on stormwater pollutant concentrations reported in the "freeway" category of the (USA) National Stormwater Quality Database v. 1.1 (<http://unix.eng.ua.edu/~rpitt/Research/ms4/mainms4.shtml>) (Table 2). Overseas data was used due to the extensive, quality assured data set compared to any readily available New Zealand data base for urban runoff.

Concentrated doses (5 year and 1 year) were used to "age" the filter media by simulating multiple years' worth of dissolved pollutant loading in a short period of time. The purpose was to attempt estimation of total pollutant removal potential of the media (determined by the occurrence of a pollutant breakthrough), and therefore estimate the life of the media. Alternating WQV doses between concentrated doses was used to estimate efficiency performance for media when aged 0, 5, 10, and 15 years.

The synthetic stormwater contained only dissolved zinc, dissolved copper, and dissolved phosphorus. Dissolved contaminants are generally bioavailable, leading to impacts for aquatic species when contaminants exceed threshold levels. For example, ANZECC water quality guidelines for heavy metals are written in terms of dissolved fraction concentrations. Dissolved contaminants are considerably more difficult to remove in stormwater treatment devices (particulates are relatively easily removed through sedimentation and filtration); hence working with only dissolved contaminants is conservative by operating at worst case scenario. Sediment was not considered. Long-term sediment loading to bioretention cells has been reported as impacting performance, as it may contribute to clogging (thus creating potential for bypass), decreased hydraulic conductivity and decreased storage volume. Unfortunately, obtaining consistent or reproducible ranges of particle sizes where the size of concern is silt, as well as controlling the particulate pollutant concentrations, (which both require testing and adjusting) is problematic. Dosing concentrations and analytical methods are shown in Table 2. Samples were analysed by the University of Auckland, Hill Laboratories (heavy metals) or Watercare Ltd. (phosphorus) depending on the parameter. Laboratory replicates were collected and analysed for 20% of total samples, while each media was tested in duplicate (two columns each).



Table 2: Influent dosing concentrations

	Analysis Method	Influent Concentration (mg/L) for Dose		
		WQV	1 year concentrated	5 year concentrated
Dissolved zinc	APHA (2005)	0.050	2.500	12.400
Dissolved copper	3111 or 3125B	0.010	0.500	2.480
Dissolved phosphorus*	APHA (2005) 4500-P F	0.065	3.226	16.000

\*Measured in the laboratory as Soluble Reactive Phosphorus

## 4.2 RESULTS AND DISCUSSION

In this section, candidate bioretention mixes are labelled as ECS+, WBS+, or PS+, where + indicates a 90% v/v sand-based mixture with 10% v/v compost.

### 4.2.1 RUNOFF TO MEDIA CONTACT TIME

The potential link between the runoff to media contact time and pollutant removal efficiency was investigated by using hydraulic conductivity as a representation of runoff to media contact time. A low hydraulic conductivity represents a high runoff to media contact time, and vice versa. Results showed no link between hydraulic conductivity and removal efficiency for Cu, Zn or P. There was also no direct relationship between hydraulic conductivity and the range of effluent concentrations. The inherent chemical properties of the media, such as CEC, base saturation, anion retention, and mineralogy were therefore more likely to determine pollutant removal efficiency.

Hydraulic conductivity is likely to play a larger role in field bioretention applications for other contaminants (particularly nitrogen) and in terms of hydrologic control. A relatively low hydraulic conductivity ensures runoff is retained in the filter media or temporarily retained as ponding. The retained volume is then available for loss via evapotranspiration or infiltration into sub-soils, hence reducing volume of runoff discharged as well as the pollutant load entering aquatic environments. Runoff volume reduction has been found to be a large factor in removing pollutant mass in field conditions (Brown & Hunt 2011; DeBusk & Wynn 2011; Carpenter & Hallam 2010). Lower hydraulic conductivity filter media are therefore preferable to higher hydraulic conductivity, as long as other conditions in section 1 are being met. Pollutant removal by runoff volume reduction was not reproduced in this study.

### 4.2.2 CUMULATIVE POLLUTANT MASS LOADING AND BREAKTHROUGH

Cumulative loading results should be recognised as only an indication of media pollutant removal performance over the long term. Limitations necessitated by laboratory-scale experiments means the true pollutant load removal will be different. Influences leading to underestimates of pollutant load include data assumes 100% of influent volume becomes effluent; i.e., no runoff is held in the media. In field bioretention cell situations, there are extra mechanisms such as evapotranspiration, interception and infiltration into surrounding soils which work to reduce hydrologic loads reaching discharge points. Plants were not simulated for this laboratory study. The ability of plants to uptake heavy metal concentrations has been found to be up to 10% of total heavy metals removed (Davis et al. 2001), while plants may increase long-term phosphorus retention by up to ~20% (Lucas and Greenway 2008) and plant root exudates can enhance pollutant detention. A further assumption was made in assuming consistent, non-deteriorating performance during the simulated 5 year and 1 year aging processes; in other words, the pollutant removal performance was assumed to be the same from the beginning of the 5 year aging period, to the end of the 5 year aging period (and same applies for the 1 year aging periods). Importantly, the organic component of the material in the leaching columns was relatively constant, whereas field bioretention plantings will tend to increase organic

content over time (through root and leaf inputs), while the original organic components oxidise to some degree (depending on the aeration of the rain garden and availability of nitrogen).

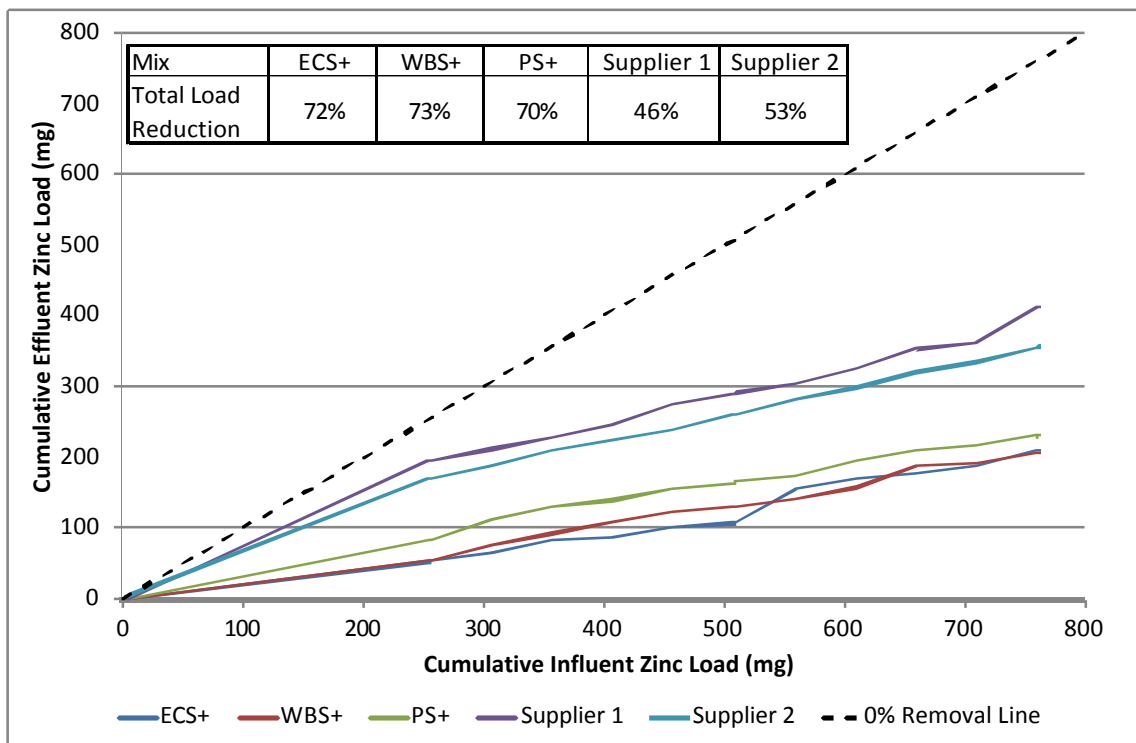
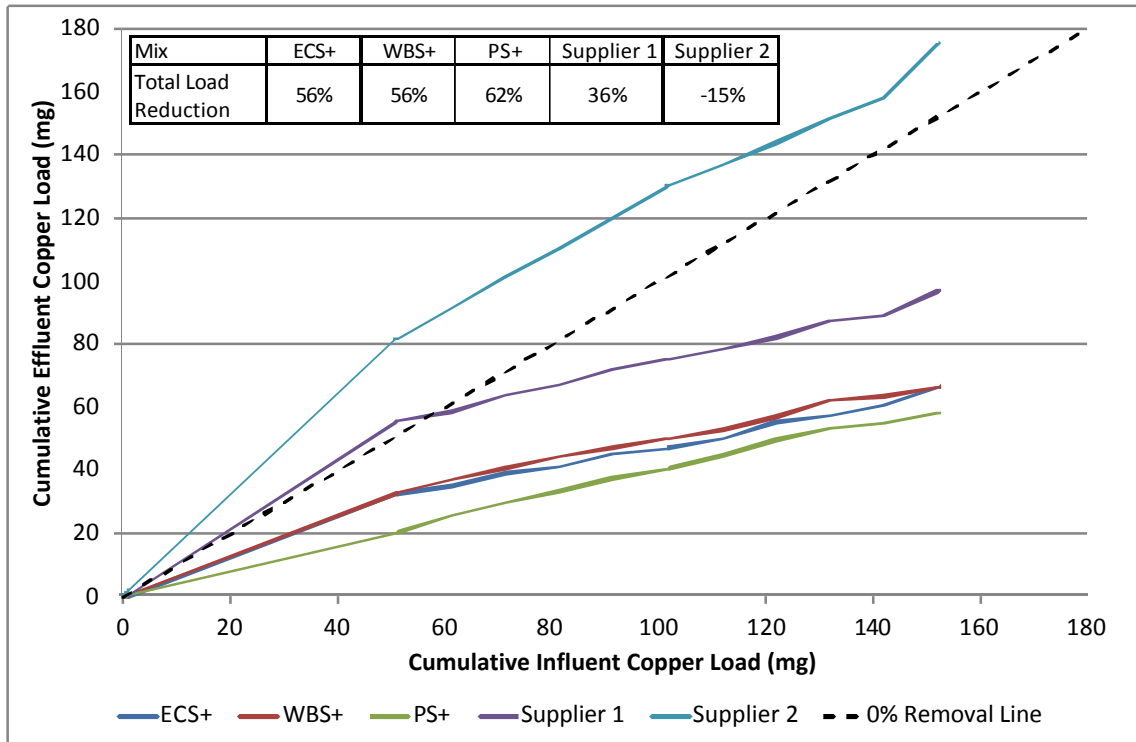
For the purposes of this research, a "breakthrough" is classified as the time or loading at which media no longer consistently reduces pollutant concentration. A breakthrough is identified on a cumulative mass loading curve as when the gradient of the curve suddenly becomes steeper, indicating effluent mass is no longer increasing slowly, but rather relatively quickly.

Simulated over 15 years, dissolved copper mass loads (Figure 3a) are estimated to be reduced by around 60% for the sand based mixes, and 36% for Supplier 1. Net export of 15% copper mass was measured from Supplier 2 (i.e. -15% "removal") over a 15 year period, and breakthrough occurred immediately during the initial dosing. Overall leaching of copper indicates copper present in the Supplier 2 at installation. Over 15 years' worth of loading, with the exception of Supplier 2, none of the mixes showed signs of copper breakthrough. If the initial break-through of Supplier 2 was removed, this medium was a net sink for Cu. The size of the initial breakthrough of contaminants associated with organic material (Cu and P) would be expected to be lower for the proprietary mixes if used fresh, as these highly organic materials undergo some mineralisation during storage.

For dissolved zinc loading over 15 years (Figure 3b), mass reductions were estimated to be around 72% for sand based mixes. The two commercial media were estimated to reduce zinc mass load by about 50%. None of the media showed signs of breakthrough over 15 years of mass loading.

A phosphorus cumulative loading curve was not generated because the first 6 WQV doses were not analysed for this parameter.

Figure 3: Cumulative pollutant mass loading: a) Copper; b) Zinc



The higher Cu and Zn removal rate displayed by sand based media compared to the commercial mixes was somewhat unexpected. The commercial mixes contained organic contents of 14-17%, compared to  $\leq 2\%$  for the sand based media. Organic matter contributes a high CEC, and is expected to be beneficial in removing a wide range of heavy metals (Clark & Pitt 2011). CEC of commercial medias greatly surpassed the CEC of sand based medias (all expressed as  $\text{cmol}(+)/\text{kg}$ : Supplier 2 = 32, Supplier 1 = 25, compared to ECS = 1.1, WBS = 1.8, PS = 6.3). However, base saturation of Supplier 2 was high (140%), indicating low availability of 'vacant' positively-charged sorption sites. Organic matter produces dissolved organic carbon (DOC) when it is mineralised. DOC

enhances the mobility of copper in soil, by acting as a colloidal transport (Altaher 2001). The same process is exhibited by zinc to a far lesser extent (Christensen et al. 1996). Since commercial mixes contain more organic material, it is likely there is more DOC and hence greater mobility of copper and zinc when compared to sand based media. Lower C:N ratio of Supplier 2 are consistent with greater generation of DOC.

Elevated levels of heavy metals in compost are possible due contamination in the handling and processing stages of creating it (for example, contact with machinery residues, metal storage/sheds), or as part of the constituents in compost itself (for example, copper fungicides are used on some raw sources of green waste compost). While heavy metals' contamination does not necessarily indicate leaching potential, it could limit the potential for additional pollutant removal (as observed by a high base saturation in Supplier 2).

#### **4.2.3 EVENT-BASED POLLUTANT REMOVAL EFFICIENCY AND EFFECT OF MEDIA AGING**

Figure 4 shows the media columns effluent copper concentrations after WQV doses at different stages of aging. ECS+, WBS+, and PS+ media columns consistently produce effluent copper concentrations below 5 µg/L across 15 years of media aging, indicating cleaner effluent and consistent performance. Supplier 1 was similarly below 5 µg/L except at 5 years of aging, where the mean was closer to 10 µg/L and there was high variability between tests. Trigger concentrations for 95% level of protection of species for freshwater and marine water are 1.4 µg/L (depending on hardness) and 1.3 µg/L copper respectively (ANZECC 2000). Despite significant copper removal, effluent from the medias do not meet the in-stream ANZECC guidelines for copper. Regardless, treatment creates a substantial improvement compared to untreated stormwater, while the effluent pollutant concentrations will be further diluted once it enters the stream/estuary.

Supplier 2 discharged effluent copper concentrations (19 µg/L) at 0 years aging that were higher than the influent copper concentration (10 µg/L). However, effluent copper concentrations from Supplier 2 systematically reduced to below influent concentrations as the media was 'aged', indicating eventual copper removal potential (50% removal at 10 years of aging). The initial leaching of copper occurred despite the initial treatment in experimental set up to remove a "first flush". Soil chemistry shows base saturation of 140%, indicating further cation capture was limited, and suggesting that additional copper concentrations found in the effluent originated from the media itself. The data suggests that Supplier 2 required a significantly longer flushing period before consistency could be achieved. However, the pollutant mass released during a first flush after installation would likely be insignificant compared to the quantity of pollutants removed from stormwater runoff throughout the life of the bioretention cell. Furthermore, slow mineralising and composting of organic materials in storage means it is likely the first flush measured in the laboratory would be higher than in field installations.

Figure 5 shows effluent dissolved zinc concentrations after WQV doses at different stages of aging. ECS+, WBS+, PS+ and Supplier 1 media columns typically produced consistent zinc removal across all 15 years of media aging. The mean effluent zinc concentration for these medias was 10 µg/L. Supplier 2 initially had an 8% removal rate of zinc, however similarly to Supplier 2 behaviour with copper, the removal efficiency of zinc increased with 5 and 10 years aging (59% removal and 73% removal respectively). In-environment trigger concentrations for 95% level of protection of species for freshwater and marine water are 8 µg/L and 15 µg/L zinc respectively (ANZECC 2000). In terms of zinc pollution, effluent from all media except Supplier 2 was cleaner than marine water trigger levels.

Figure 6 shows effluent phosphorus concentrations after WQV doses at different stages of aging. Effluent phosphorus for every media is often several orders of magnitude higher than the influent concentration (65 µg/L). Phosphorus in freshwater aquatic environments creates concern over eutrophication.

At 5 years, 10 years, and 15 years, it is clear Supplier 1 has a higher effluent phosphorus concentration compared to the other media (approximately 3,200 µg/L for 5 to 10 year,

and 2,300 µg/L for 15 year). The decrease in concentration after 15 years indicates phosphorus in the media is depleted over multiple "storms".

PS+ effluent phosphorus remains stable across 5, 10 and 15 years of aging (1,200 µg/L). ECS+, and WBS+ have effluent phosphorus concentrations increasing significantly after 10 years aging when compared to after 5 years aging (600 µg/L to 1,300 µg/L for ECS+, 1,000 µg/L to 1,400 µg/L for WBS+). Effluent phosphorus at 15 years is similar to at 10 years. The result suggests a change in ECS+ and WBS+ media occurred after the equivalent of 10 years of phosphorus dosing, prompting greater phosphorus leaching. Supplier 2 leached less phosphorus than all other mixes (average effluent concentration of 500 µg/L), however still much higher than the influent concentrations.

As there were no plants in the laboratory setup, the net export of phosphorus is overestimated. However, plant uptake alone may not be capable of reducing effluent phosphorus to target levels. Field testing needed.

Organic matter can be associated with phosphorus leaching (Bratieres et al. 2008; Peltier & Carbone 2011), yet few studies specifically investigate soil chemistry for more complete explanations. Supplier 1 and Supplier 2 had the highest organic contents, but contrasting behaviour in terms of phosphorus leaching. Chemistry analyses indicate both commercial media have plant-available phosphate concentrations well in excess of bioretention plant requirements. Regardless, both commercial mixes displayed moderate anion retention potential (51-52%), but at pH 6, Supplier 1 would be unable to form calcium-phosphate precipitates which would remove phosphorus whereas the Supplier 2 with pH 7 would provide this mechanism. Only the ECS+ provided comparable anion retention (51%) potential, but phosphorus release via mineralisation of P bound to organic materials is also enhanced by low carbon: nitrogen and low carbon: phosphorus ratios.

Triggers for soluble phosphorus concentrations for "slightly disturbed" ecosystems in New Zealand are 9 µg/L and 10 µg/L for upland rivers and lowland rivers respectively (ANZECC 2000). Effluent phosphorus concentrations from any of the media columns are orders of magnitude higher than the trigger concentration. This is undesirable and would prevent use of such substrates in catchments sensitive to P. Additives could be mixed into media to enhance phosphorus removal; however testing is required to establish the quality and suitability of local additives.

Figure 4: Effluent copper concentrations at different media ages

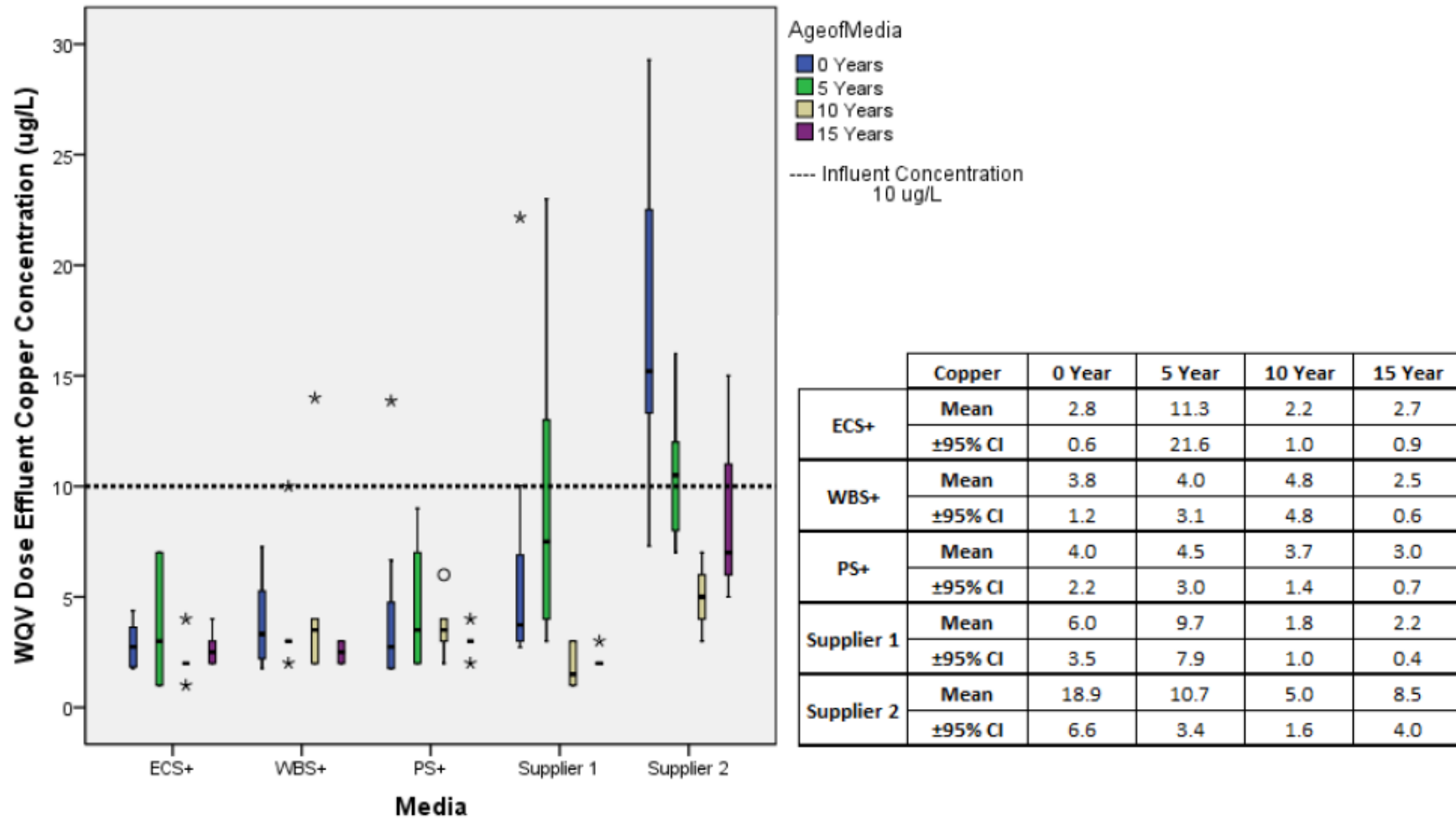


Figure 5: Effluent zinc concentrations at different media ages

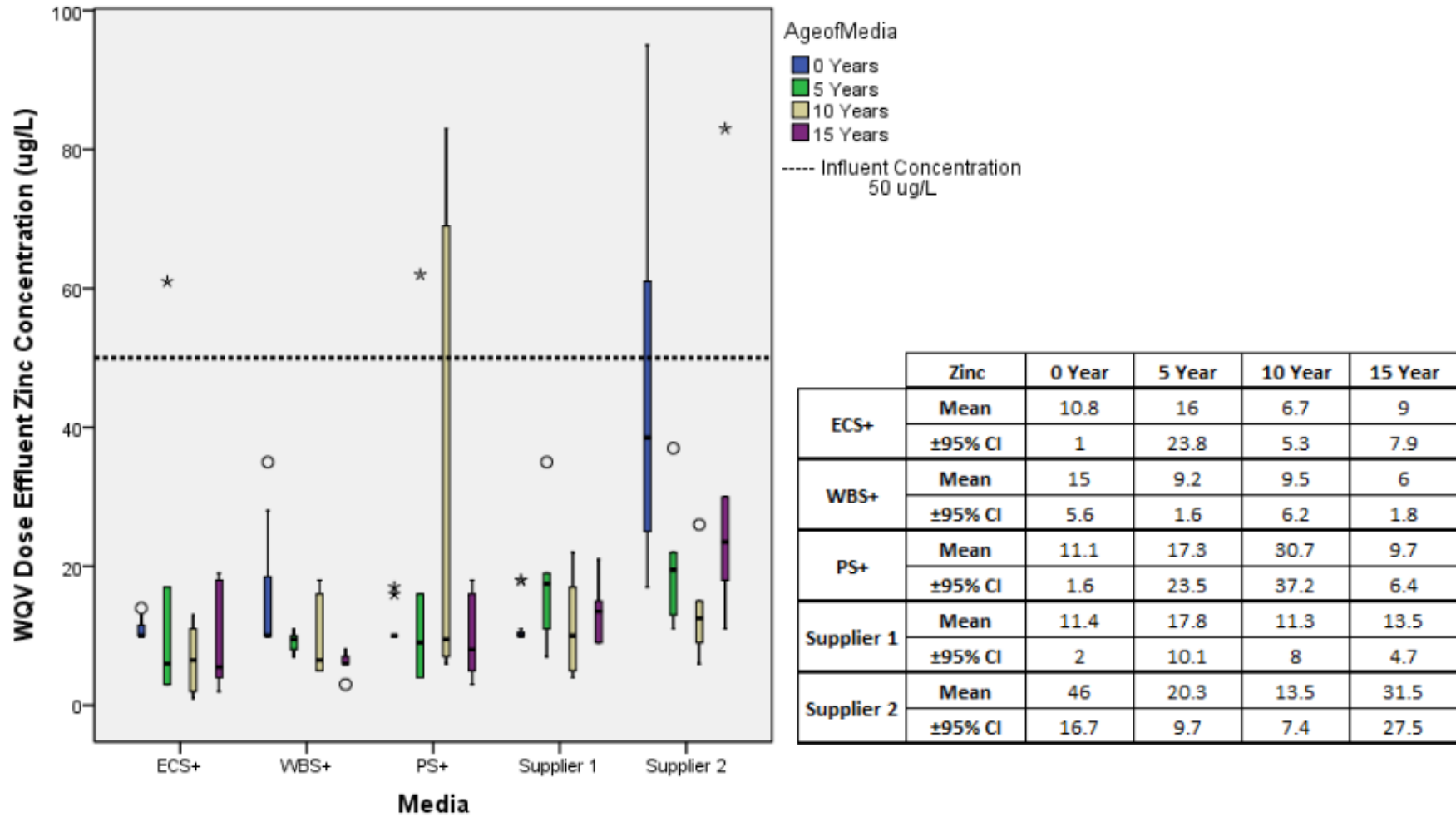
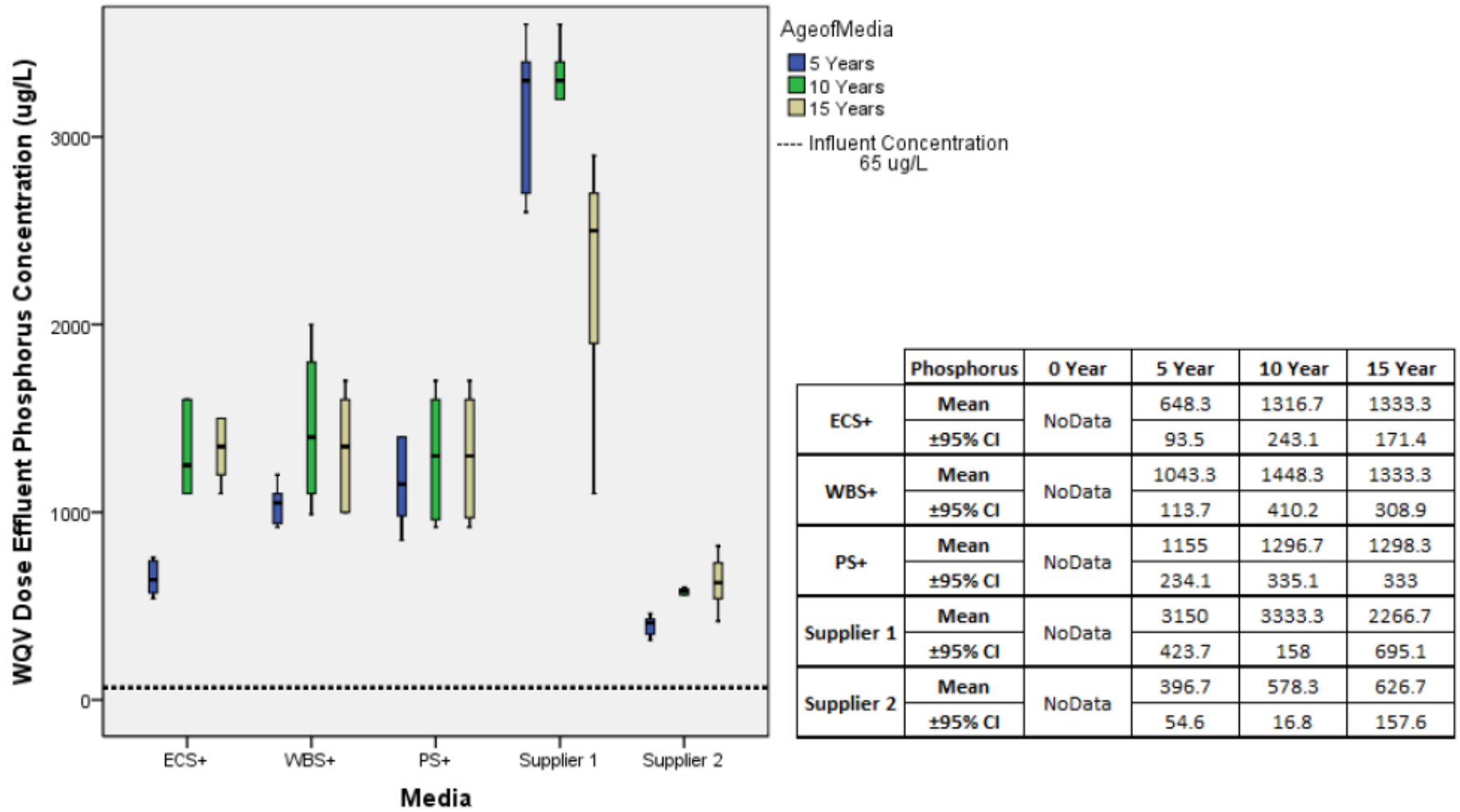


Figure 6: Effluent phosphorus concentrations at different media ages





## 5 CONCLUSIONS

Landscape and aggregate suppliers in the Auckland region provide a limited range of sands and composts that might be suitable for bioretention filter media. Talking with suppliers is important to determine quality control, availability and consistency of supply of various products.

Compaction testing shows water content is important for filter media with high organic matter contents (>~20%) as different water contents will produce significantly different densities of media under the same compactive effort. A higher density for a material of particular mass is reflective of less large pore volume, and hence a lower hydraulic conductivity. A comprehensive compaction strategy which takes into account water content and organic content are recommended for any construction specification.

A hydraulic conductivity range of 12.5 to 1,500 mm hr<sup>-1</sup> was established to meet objectives for limited ponding times and runoff to media contact times for pollutant removal.

Based on comparison of candidate sand's particle size distributions against international bioretention design guidelines, No.3 sand from ALS was initially chosen to be the sand base for hydraulic tests. Hydraulic testing with homogeneous mixes based on No.3 sand found the sand to be excessively permeable (over 2,000 mm hr<sup>-1</sup>) and unable to meet the target conductivity range without >40% compost addition. This result indicates particle size distribution guidelines should not be used as a substitute for hydraulic testing.

Finer sand (East Coast Sand, Woodhill Black Sand, Pumice Sand) mixed with 10% v/v compost resulted in media requiring only wetting and settling compaction to reach the target hydraulic conductivity range. The mean hydraulic conductivities for the three finer sand based medias were 80, 400, and 340 mm hr<sup>-1</sup>, respectively. Both commercial rain garden products were able to meet the target hydraulic conductivity range when mechanical light tamping compaction was applied. The hydraulic conductivities for the two commercial products were 240, and 180 mm hr<sup>-1</sup>, respectively.

Water quality testing involved dosing media with synthetic stormwater containing realistic concentrations of dissolved zinc, dissolved copper and soluble phosphorus. Media were aged to 5 years, 10 years, and 15 years using concentrated dosings.

There was no correlation between runoff to media contact time and pollutant removal efficiency. Low(er) hydraulic conductivity media is nonetheless recommended to promote exfiltration to surrounding soils and evapotranspiration.

Estimation of cumulative pollutant mass loading over 15 years suggested sand based media could remove around 60% of copper loading and 70% of zinc loading. Supplier 1's rain garden mix is estimated to remove 36% and 46% of copper and zinc loading respectively.

Supplier 2's rain garden mix is estimated to remove 53% zinc loading, but leach 15% copper over 15 years. Copper leaching is likely due to a combination of media chemistry characteristics, the media already containing substantial amounts of copper, and/or because of the formation of dissolved organic carbon in the organic portion, which in turn facilitates copper mobility in soils (Altaher 2001). The removal of Cu in the field is likely to be higher than measured in the laboratory leaching for both proprietary mixes due to DOC likely to be somewhat elevated as organic matter would be expected to be mineralised during storage, and could be initially flushed.

All media except Supplier 2's rain garden mix consistently reduced typical stormwater copper concentrations to below 5 µg/L, and zinc concentrations to 10 µg/L. The removal

was replicated for media of 0, 5, 10, and 15 years of aging, with no signs of deteriorating performance. Supplier 2's rain garden mix initially displayed leaching for copper and only slight removal for zinc, possibly due to an initial saturation of cation exchange and/or formation of dissolved organic carbon. As testing progressed, Supplier 2's rain garden mix showed improved effectiveness at reducing heavy metal concentrations.

For phosphorus, all media exhibited extreme leaching within 5 years of media aging. Effluent phosphorus concentrations were often two or three orders of magnitude higher than influent. Supplier 1's rain garden mix effluent contained the greatest concentrations of phosphorus (3,200 µg/L for media aged 5 and 10 years, 2,300 µg/L for 15 years), while Supplier 2's rain garden mix contained the lowest (550 µg/L). Effluent from East Coast Sand based media had phosphorus concentrations of 600 µg/L at 5 years of aging, increasing to 1,300 µg/L at 10 years. Effluent from Woodhill Black Sand based media similarly increased from 1,000 µg/L to 1,400 µg/L after 10 years. Effluent from Pumice Sand based media was consistently leaching 1,200 µg/L across 15 years. The effluent concentrations are extremely high when compared to influent concentrations of 65 µg/L and ANZECC trigger concentrations for slightly disturbed ecosystems of 9 µg/L and 10 µg/L for upland and lowland rivers respectively.

In all cases and for all pollutants, chemistry analysis yielded important insights to performance. Combinations of chemical characteristics are more important than isolated factors (i.e. CEC should be considered with base saturation). For treatment of heavy metals in stormwater, the three sand based media and Supplier 1's rain garden mix showed the best performance. However, all media investigated performed poorly with high levels of phosphorus leaching. Additives could be used to amend media for phosphorus performance. Further research would be required to study the availability, effectiveness, and suitability of bioretention media additives for Auckland conditions.

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## **REFERENCES**

- ANZECC, 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality, Australia & New Zealand. Available at: [http://www.mincos.gov.au/data/assets/pdf\\_file/0019/316126/wqg-ch3.pdf](http://www.mincos.gov.au/data/assets/pdf_file/0019/316126/wqg-ch3.pdf).
- Altaher, H.M., 2001. Factors affecting mobility of copper in soil-water matrices. Available at: <http://scholar.lib.vt.edu/theses/available/etd-02062001-154844/> [Accessed April 28, 2011].
- ASTM International, 2011a. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. Annual Book of ASTM Standards, (C), pp.6-10.
- ASTM International, 2011b. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft<sup>3</sup>(2,700 kN-m/m<sup>3

Auckland Regional Council. (2003). Stormwater treatment devices: Design Guidelines Manual. Technical Publication 10, Chp. 7. Auckland, New Zealand. Retrieved from [http://www.arc.govt.nz/albany/fms/main/Documents/Plans/Technical\\_publications/1-50/TP10\\_Design\\_guideline\\_manual\\_stormwater\\_treatment\\_devices\\_Chapter\\_7\\_-\\_2003.pdf](http://www.arc.govt.nz/albany/fms/main/Documents/Plans/Technical_publications/1-50/TP10_Design_guideline_manual_stormwater_treatment_devices_Chapter_7_-_2003.pdf)</sup>

- Bratieres, K. et al., 2008. Nutrient and sediment removal by stormwater biofilters: a large-scale design optimisation study. *Water Research*, 42(14), pp.3930-40.
- Brown, R.A. & Hunt, W.F., 2011. Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells. *Journal of Irrigation and Drainage Engineering*, 137(March), p.132.
- Carpenter, D.D. & Hallam, L., 2010. Influence of Planting Soil Mix Characteristics on Bioretention Cell Design and Performance. *Journal of Hydrologic Engineering*, 15(6), p.404. Available at: <http://link.aip.org/link/JHYEFF/v15/i6/p404/s1&Agg=doi>.
- Christensen, J.B., Jensen, D.O.R.T.H.E.L. & Christensen, T.H., 1996. Effect of Dissolved Organic Carbon on the Mobility of Cadmium, Nickel and Zinc in Leachate Polluted Groundwater. *Science*, 30(12), pp.3037-3049.
- Clark, S.E. & Pitt, R., 2011. Selecting Stormwater (Bio)Filtration Sites and Soil-Based Media. *Urban Water*, (May), pp.774-785.
- Davis, A.P. et al., 2001. Laboratory study of biological retention for urban stormwater management. *Water Environment Research*, 73(1), pp.5-14.
- DeBusk, K.M. & Wynn, T.M., 2011. Stormwater Bioretention for Runoff Quality and Quantity Mitigation. *Journal of Environmental Engineering*, (0303).
- Fassman, E.A., Simcock, R. & Wang, S., *draft* 2012. Bioretention Media Specification, Prepared by Auckland UniServices for Auckland Council. Auckland Council. Under review.
- FAWB, 2009. Guidelines for Filter Media in Biofiltration Systems (Version 3.01), Available at: <http://www.monash.edu.au/fawb/products/obtain.html>.
- Hinman, C. 2009. *Bioretention Soil Mix Review and Recommendations for Western Washington*, Washington, USA. Prepared for the Puget Sound Partnership by Washington State University Pierce County Extension. Available at: [http://www.psparchives.com/publications/our\\_work/stormwater/BSMResults-Guidelines Final.pdf](http://www.psparchives.com/publications/our_work/stormwater/BSMResults-Guidelines Final.pdf).
- Hunt, W. F., & Lord, W. G. (2006). *Urban Waterways - Bioretention Performance, Design, Construction, and Maintenance*. North Carolina Cooperative Extension Service, North Carolina, USA. Retrieved from: <http://www.bae.ncsu.edu/stormwater/PublicationFiles/Bioretention2006.pdf>
- Lucas, W. C., and Greenway, M. (2008). Nutrient retention in vegetated and nonvegetated bioretention mesocosms. *Journal of Irrigation and Drainage* 134(5), 613–623.
- Peltier, E. & Carbone, G., 2011. Bioretention Design and Performance in Johnson County, KS. In *World Environmental and Water Resources Congress 2011*. pp. 356-363.
- Prince George's County, 2007. Bioretention Manual, MD Department of Environmental Resources, Prince George's County, Md. Available at: [http://www.princegeorgescountymd.gov/Government/AgencyIndex/DER/ESG/Bioreten tion/pdf/Bioretention Manual\\_2009 Version.pdf](http://www.princegeorgescountymd.gov/Government/AgencyIndex/DER/ESG/Bioreten tion/pdf/Bioretention Manual_2009 Version.pdf).
- Seattle Public Utilities. (2008). *Supplemental text to the 2008 edition of the Standard Specifications* (Vol. 3, pp. 1-7). Seattle, Washington, USA. Retrieved from [http://www.seattle.gov/util/groups/public/@spu/@usm/documents/webcontent/spu02\\_019920.pdf](http://www.seattle.gov/util/groups/public/@spu/@usm/documents/webcontent/spu02_019920.pdf)

## NOMENCLATURE

ECS	East Coast Sand	ECS+	East Coast Sand + 10% Compost
WBS	Woodhill Black Sand	WBS+	Woodhill Black Sand + 10% Compost
PS	Pumice Sand	PS+	Pumice Sand + 10% Compost
Supplier 1	Commercial/Proprietary Rain Garden Mix	Supplier 2	Commercial/Proprietary Rain Garden Mix