'Appreciating' Drainage Assets in New Zealand Cities: Rain Garden Treatment and Hydraulic Performance

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Abstract

Despite recognising rain gardens as a best management practice (BMP) to mitigate urban stormwater runoff, there is a dearth of knowledge about their treatment and infiltration performance. It is believed that organic substrates may enhance some contaminant removal but hinder hydraulic throughput although data showing this is sparse. In order to evaluate the influence of substrate composition on bioinfiltrative system effectiveness, mesocosm-scale (180 L, 0.17 m^2) laboratory rain gardens were established. Saturated (constant head) hydraulic conductivity was determined before and after the experimental treatment tests that employed stormwater collected from a neighbouring catchment to investigate contaminant removal efficiencies. The principal contaminant (Zn, Cu, Pb and nutrients) removal efficiencies were investigated for three substrates comprising various proportions of organic topsoil. All total metal concentrations in the effluent were <50% of influent concentrations, with the exception of copper in the topsoil-only system that had negligible reduction due to a high dissolved fraction. The system comprising topsoil only had the lowest saturated hydraulic conductivity of 162 mm/hr and demonstrated the poorest metal (Cu, Zn) removal efficiencies. Interestingly, the system with a combination of sand and topsoil demonstrated most promising metal removal of Cu (53%), Zn (81.2%) and Pb (89.1%) with adequate hydraulic performance (296 mm/hr) required for a stormwater infiltrative system. Overall, metal removal was greater at an effluent pH of 7.38 compared to the 6.24 pH provided in the raw stormwater. Some pH buffering was provided by the calcareous sand in two of the systems, whereas the topsoil-only system lacked such buffering potential to facilitate adequate metal removal. These data highlight the influence of organic topsoil on pH that clearly governs metal speciation and hence removal efficacy in bioinfiltrative systems. Nitrate was net exported from all the systems, especially topsoil contrary to what is believed to be easily removed.

Keywords

Rain garden, treatment efficiency, hydraulic conductivity

INTRODUCTION

Urbanization enhances stormwater runoff resulting in increased metal, sediment, and nutrient pollutant loads, decreased local infiltration and greater peak flow intensities (Palhegyi 2010). Heavy metal contaminants of concern, primarily Cu, Pb, Zn, originate from wear-and-tear of vehicle parts including brake linings (e.g. Cu) and tyre fillers (e.g. Zn) as well as additives in oil and petrol (Ward 1990; Sansalone and Buchberger 1997; Davis et al. 2001; Zanders 2005). These contaminants accumulate on impermeable surfaces such as roads, roofs, parking lots and are transported via stormwater networks impacting on local and downstream aquatic ecosystems (Karlen et al. 2001; Beasley and Kneale 2002; Wicke et al. 2009). Different technologies have been used to mitigate stormwater runoff including traditional drainage networks fitted with concrete proprietary devises (e.g. vortex-designed filters) and large detention systems such as infiltration basins, primarily designed to remove suspended solids and reduce flood risk (Wanielista and Yousef 1992). In New Zealand, stormwater engineered designs are guided by the Auckland Regional Council Technical Publication #10 (ARC 2003), which adopts an approach of removing 75% of Total Suspended Solids (TSS), interpreted in Auckland city on a long-term average basis and in Christchurch city for each storm event (Smythe et al. 2007). By removing TSS, it is assumed that other contaminants of concern, primarily metals, are concurrently removed through adsorption (Smythe et al. 2007) – an assumption which is debated amongst the engineering profession and water quality scientists since metals (i.e. Zn and Cu) can prevail in dissolved states (Zanders 2005; Boving and Neary 2006; Sansalone and Glenn 2007).

In 2003, Christchurch City (population 369,000), New Zealand underwent a paradigm shift in urban water management towards implementing ecologically integrated drainage infrastructure through recognising six values namely: culture, heritage, ecology, recreation, landscape and drainage in new and retrofitted urban developments. The Christchurch Councils aim to replace traditional piped structures, which incur inevitable maintenance and offer minimal benefits besides drainage, with natural treatment systems (CCC 2003; ECAN 2009), classified as Sustainable Urban Drainage Systems (SUDS) or Water Sensitive Urban Designs (WSUD) elsewhere (Lloyd et al. 2002; BCC. 2007). The Auckland region (population 1.3 million) is adopting a similar approach by spending >NZ $5 billion over the next 10 years to replace deteriorating pipe networks with natural low-impact (i.e. rain garden) designs to service all water and wastewater (including stormwater) demands from new developments (Pandey et al. 2005). Auckland Regional Council estimates they will save approximately $5 million/yr from this approach with potential for increased savings in the longer term (Pandey et al. 2005) highlighting recognition of the appreciating value of natural treatment systems (Figure 1). These ecological systems control peak flow stormwater volumes and can simultaneously reduce contaminant runoff to neighbouring waterways. They are integrated into the catchment by conveying stormwater runoff through their biologically-active landscaped design before infiltrating to groundwater or discharging to surface waters.

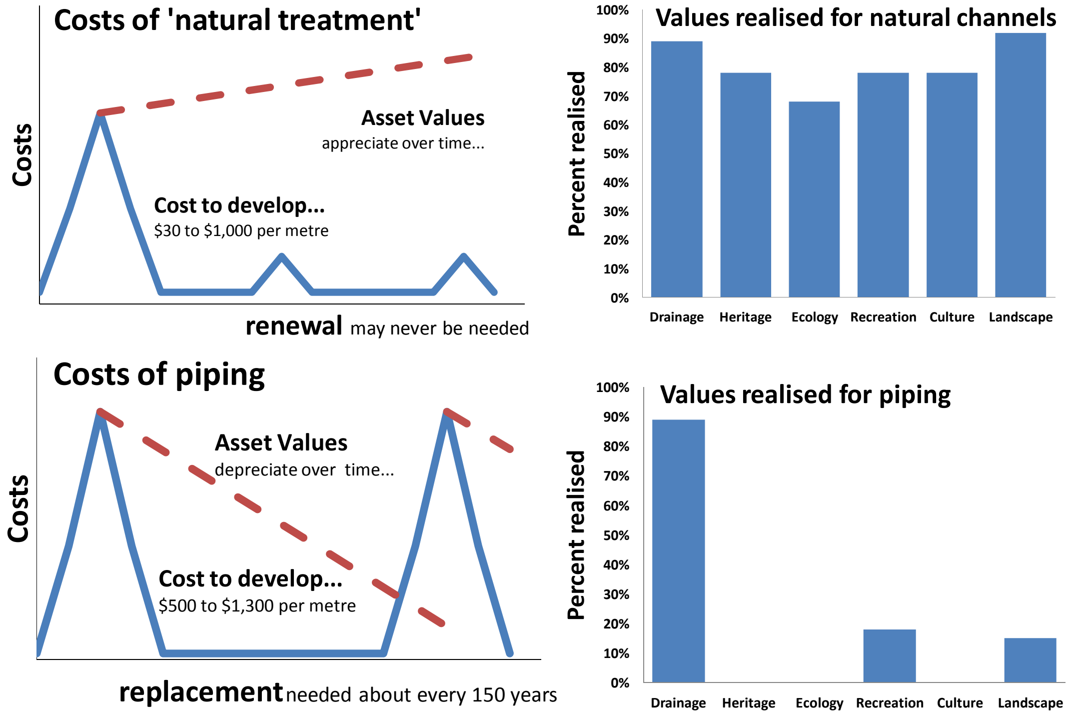

Figure 1: Comparison of piping and natural treatment of waterways (modified from CCC 2003).

Rain gardens are gaining popularity as a bioinfiltrative SUDS (e.g. Fletcher et al. 2004; Dietz and Clausen 2005) but large differences in their design criteria are apparent from the limited guidelines available (e.g. New Zealand systems propose a 13 mm/hr infiltration rate and >100 cm topsoil (ARC 2003) compared with 13-130 mm/hr and >45 cm topsoil recommended in Californian systems (SFPUC 2009)). Furthermore, design recommendations do not seem to be informed by performance data. Organic material, a key component in rain garden construction, reduces the overall hydraulic throughput but is believed to play a significant role in supporting above ground vegetation and in contaminant removal (ARC 2003; Trowsdale and Simcock 2008; FAWB 2009). However, there is a dearth of information on treatment and hydraulic responses of bioinfiltrative rain garden systems (Fletcher et al. 2004; Dietz and Clausen 2005; Henderson et al. 2007) to help inform robust rain garden design standards for their longer-term functionality. This research quantified the treatment efficacies and hydraulic performance of laboratory mesocosm-scale rain gardens as a function of their substrate complement. It was hypothesised that greater organic topsoil would positively influence the treatment capacity but somewhat compromise the hydraulic throughput compared to sand-only containing systems. Data derived from the experiments is expected to help inform and optimise rain garden design criteria.

METHODOLOGY

Experimental Design

Mesocosm-scale (180 L cylindrical, 0.17 m^2 surface area) rain gardens were established in a laboratory set-up (Figure 2). Substrates were varied to investigate the effect(s) of organic topsoil on heavy metal (Zn, Cu, Pb) and nutrient removal and hydraulic throughput under simulated rain events. A small (20 mm) layer of bark mulch was applied on top of each system in order to diffuse stormwater across the column and to simulate conventional rain garden construction practices. The volume of bark (on top) and drainage gravel (at bottom) remained constant across the three systems, while sand and topsoil volumes were varied maintaining a total rain garden depth of 670 mm (with 520 mm of reactive substrate) at the onset of the experiment (Table 1).

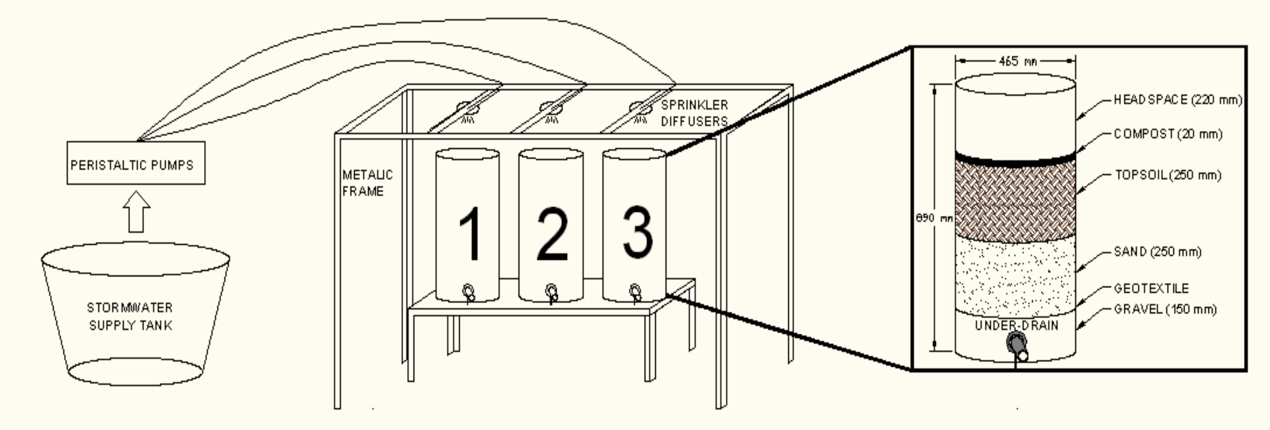

Figure 2: Laboratory mesocosm-scale experimental setup.

Table 1: Laboratory mesocosm-scale rain garden substrate complement.

Column Name	Depth of Reactive Substrate (mm)			Total System Depth[1] (mm)
	Bark Mulch	Topsoil	Sand	
Sand	20	0	500	670
Sand/Topsoil	20	250	250	670
Topsoil	20	500	0	670

Notes: 1. Includes a 150 mm depth gravel underdrain layer.

Constant Head Hydraulic Conductivity

All rain garden columns were initially fully saturated with tap water filtered through a 10 µm inline cartridge to remove potential particles that could clog the substrate. The inflow rate was adjusted to maintain a constant 110 mm head over the substrate throughout the hydraulic conductivity testing. This head was downsized to laboratory-scale from the maximum allowable rain garden ponded depth of 220 mm stipulated by the New Zealand design guidelines (ARC TP-

10). Flow rates through the saturated columns were calculated using a stopwatch and a 100 mL graduated cylinder used to collect effluent 25 times throughout the experiment. Data were inputted into a derivation of Darcy's equation (equation 1) to calculate the net hydraulic conductivity for each system. Hydraulic conductivity tests were then repeated following the completion of the contaminant removal efficiency experiments (see further below).

$$K = \frac{QL}{Ah} \tag{1}$$

K – Saturated hydraulic conductivity [m/s], Q - Flow [m^3/s], L – Depth of soil and sand layers [m], A – Cross sectional area [m^2], h – Head over the column substrate [m].

Treatment Efficiency

Experimental Operation

Raw stormwater runoff from a neighbouring Christchurch city catchment (where an operational rain garden is being monitored) was collected during three storm events and kept refrigerated at < 4^{o}C until the experiment commenced. A simulated 8 mm (10 mm/hr), 48 minute storm event over an approximately 1,950 m^2 subcatchment draining to a full scale (60 m^2) rain garden was scaled to the laboratory mesocosm-scale (0.17 m^2) rain garden. This storm event equalled 80% of the rain events in Christchurch (NIWA 2010) and translated to a total volume of ~ 26 L of stormwater applied to each system. This scaled rain event was applied to each system using individual peristaltic pumps connected to dedicated calibrated sprinkler diffusers. Two separate contaminant loading rates (high and low) were sequentially applied to the systems to investigate their contaminant removal capacities. Initially, a conservative low loading rate was tested in duplicate followed by a more intensive high loading rate (contaminant concentrations approximately twice low loading rate levels) once it was established that the low rate did not seem to compromise the systems' performance.

Sampling and Chemical Analysis

Water was manually sampled following the Australian and New Zealand Environment and Conservation Council guidelines (ANZECC 2000). In compliance with these guidelines, at least 10% of the samples were duplicated for Quality Assurance/Quality Control (QA/QC) purposes. Samples were collected head-space free in high-density polyethylene (HDPE) sampling bottles. Raw stormwater from the influent header tank was collected prior to each experimental run. Effluent stormwater (post rain garden) was sampled every five minutes for the first 30 minutes and every 20 minutes thereafter. Effluent measurements were continuously logged for pH, temperature and nitrate using an YSI professional plus water quality meter. Flow measurements were conducted at five minute-intervals throughout experimental runs. TSS was measured although inconclusive data due to the major earthquake in Christchurch on 22 February precluded it from further discussion here.

Total metal samples were preserved with concentrated nitric acid (HNO_3, Fisher, trace analysis grade) to reduce the pH to less than 2.0 (APHA 2005). All metals (Cu, Zn, Pb) were analyzed by ICP-MS (Agilent) following Method 3125B. Total metal samples for digestion were mixed thoroughly on a magnetic stir plate while 25 mL of sample were transferred to a 50 mL polypropylene centrifuge tube. After the addition of 5 mL concentrated HNO_3, tubes were placed in a heating block and samples were boiled for one hour. Cooled samples were then filtered through an encapsulated 0.45 µm PVDF filter (47 mm, Labserv) directly into the analysis tube and analyzed via ICP-MS. Dissolved metal samples were pre-filtered through disposable 0.45 µm filters before the HNO_3 acidification. Nitrate nitrogen (NO_3-N) was analyzed using the Hach Method 8192 based on the cadmium reduction method (Hach 1999).

RESULTS AND DISCUSSION

Metal Concentrations and Ecotoxicity

Raw stormwater metal concentrations exceeded the New Zealand thresholds for protecting 90% of aquatic species as defined in the contextual ecotoxicological effects-based guidelines (ANZECC 2000). Nitrate concentrations were typically lower and therefore not of concern (Table 2). While these guidelines are not legally binding, they are typically adopted in consenting processes so in effect become compliance targets. Rain gardens in New Zealand currently discharge to surface waters so are subjected to the ANZECC guidelines to control ecotoxicological impact from stormwater discharges. New Zealand Drinking Water Standards, which apply to groundwater discharges, are also provided should rain gardens eventually drain to the vadose zone as practiced elsewhere (Regenmorter et al. 2002).

Concentrations of metals throughout the storm events greatly exceeded the recommended 90% ANZECC guidelines by a factor of 12.3 (Cu), 12.2 (Zn) and 9.9 (Pb), while these magnitudes increased substantially for the first-flush samples (Table 2). These data confirm the presence of elevated metal loads in stormwater runoff whilst highlighting the degree to which first-flush loads can impact on a receiving ecosystem without adequate treatment. It is interesting to note that should rain garden effluent discharge to groundwater, the Drinking Water Standards would apply and only lead concentrations would be of concern from a regulatory perspective.

Table 2: Stormwater concentrations (µg/L), ANZECC permitted threshold values at 90% (ANZECC 2000), and New Zealand Drinking-Water Standards (NZMOH).

Contaminant	**Untreated Stormwater (µg/L)**		**90% ANZECC Guidance (µg/L)**	**90% ANZECC Exceedance Factor**		**New Zealand Drinking-water Standards (2005) (µg/L)**
	First Flush	**Average**		**First Flush**	**Average**	
Copper	25	22.1	1.8	13.9	12.3	2,000
Zinc	310	194.9	15	20.7	12.2	1,500
Lead	87	55.5	5.6	15.5	9.9	10
Nitrate	2,540	883	3,400	-	-	50,000

Notes: 1. The New Zealand Drinking-water Standards (2005) do not provide a standard for Zinc but give a 1,500 µg/L guidance value .

Treatment and Hydraulic Efficiency

Average (i.e. treated) effluent metal concentrations from each of the different rain garden systems (n = 27-56 per contaminant per system) were lower than the influent levels (Table 3). An exception was for Cu from the topsoil system, which had an average effluent concentration of 37.9±34.8 µg/L Cu compared with the raw influent of 22.1±9.1 µg/L. All effluent metal concentrations exceeded the ANZECC guidelines indicating that rain garden effluent from these designs does not comply with the current discharge guidelines. Removal efficiencies (expressed as a %) for each system under low and high loading rates were also calculated using measured hydraulic residence time and contaminant concentrations. Overall, metal removal was enhanced at the higher loading rate indicative that the systems have not yet reached treatment capacity (Table 4). While Pb removal was very promising (82-99%), Zn was removed generally better than Cu but not completely. For instance at the high loading rate, 94.5% Zn was removed in the sand system but only 71.4% in the topsoil system while Cu removal was 83.3% in the sand system and 69% in the topsoil.

Table 3: Water quality in raw stormwater (influent) and effluent (i.e. treated) from each of the experimental systems. Saturated Hydraulic Conductivity for each system is also given. Units for each parameter are given in parenthesis and average values are reported ± standard deviation.

Average Values	**Inflow**	**Treated Effluent**		
		Sand	**Sand/Topsoil**	**Topsoil**
Sat. Hydraulic Cond. (mm/hr)	**NA**	**5,144** ± 33	**296** ± 9	**162** ± 3
pH	**6.23** ± 0.08	**7.38** ± 0.03	**6.60** ± 0.04	**6.24** ± 0.08
Cu Concentration (µg/L)	**17.1** ± 3.6	**12.0** ± 11.1	**10.7** ± 2.3	**37.9** ± 34.8
% dissolved	16 %	24 %	56 %	80 %
Zn Concentration (µg/L)	**162.8** ± 28.1	**76.6** ± 125.6	**51.2** ± 57.3	**149.5** ± 96.1
% dissolved	51 %	30 %	54 %	94 %
Pb Concentration (µg/L)	**39.8** ± 11.3	**11.6** ± 14.8	**6.1** ± 5.0	**10.1** ± 6.3
% dissolved	4 %	1 %	9 %	35 %
Nitrate (µg/L)	**883** ± 126	**3,613** ± 1,602	**4,557** ± 1,106	**4,330** ± 1,317

Table 4: Total metal removal efficiency during low and high contaminant loading rates.

		Low Loading			**High Loading**		
		Sand	Sand/Topsoil	Topsoil	Sand	Sand/Topsoil	Topsoil
Cu	-Influent Conc. (µg/l)		17.1 ± 3.6			32.1 ± 8.4	
	-Removal Efficiency (%)	56.4	53.0	0.3	83.3	77.4	69.0
Zn	-Influent Conc. (µg/l)		162.8 ± 28.1			258.9 ± 66.2	
	-Removal Efficiency (%)	73.5	81.2	60.5	94.5	87.9	71.4
Pb	-Influent Conc. (µg/l)		39.8 ± 11.3			86.8 ± 25.7	
	-Removal Efficiency (%)	81.6	89.1	89.5	97.3	96.9	98.6

It was originally hypothesised that the topsoil-only system would yield the greatest contaminant removal due to its greater organic content; however, the converse was observed (Tables 3 & 4). This system also had the highest proportion of dissolved metals compared to the other systems with less (or no) topsoil (Figure 3). To investigate this further, pH regressions for each of the dissolved metals were derived (Figure 4) since it well reported that pH influences metal speciation in stormwater signatures (Pitcher et al. 2004; Sansalone and Glenn 2007). Clearly, pH values within the range of influent stormwater (6.23) to effluent sand-only system (7.38) influenced metal speciation, and hence removal capacity, in these systems. The pH within the sand and sand/topsoil systems was somewhat buffered to 7.38 and 6.60, respectively, as evidenced from their elevated pH compared with the raw stormwater of 6.23 (Table 3). This probably resulted from calcium carbonate in the sand component (Reynolds et al. 1986; Plassard et al. 2000) while the topsoil-only pH was not afforded the same degree of buffering so remained at 6.24 (i.e. influent) resulting in poorer treatment. This is problematic for most stormwater treatment systems in New Zealand that are designed on the premise that 75% of TSS (i.e. particulates) is removed with concurrent removal in metals through adsorption or settling. Neither the raw stormwater nor the organic topsoil is conducive to removing metals through settling or filtration since a higher pH is required to affect this. Without buffering capacity sourced from an alkalinity material or pH amendment, rain gardens (and other filtration systems relying on particulate removal) are unable provide adequate contaminant treatment in this stormwater signature. Lead was successfully removed (>80%) in all three systems probably since lead is prevalent in the particulate state and thus easier to remove with TSS such as stipulated in the New Zealand design guidelines.

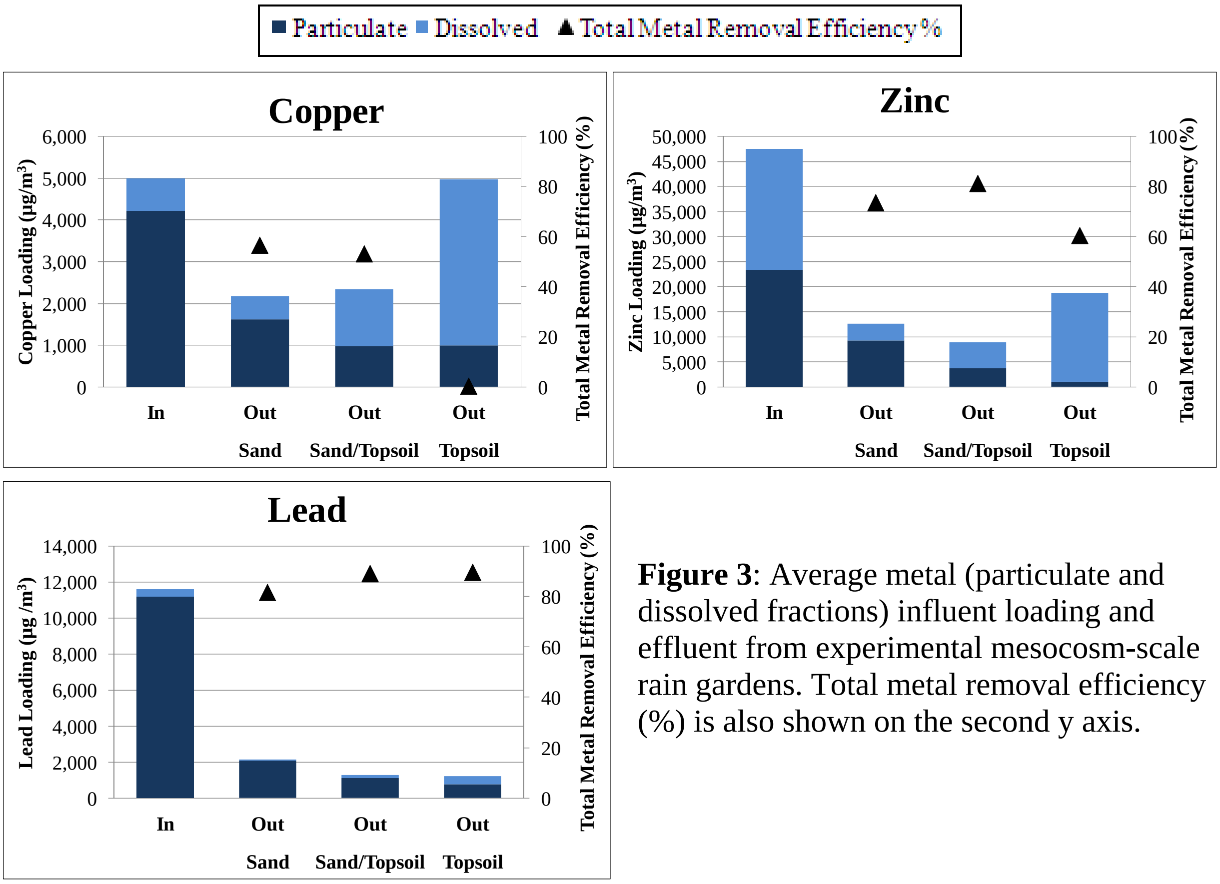

Figure 3: Average metal (particulate and dissolved fractions) influent loading and effluent from experimental mesocosm-scale rain gardens. Total metal removal efficiency (%) is also shown on the second y axis.

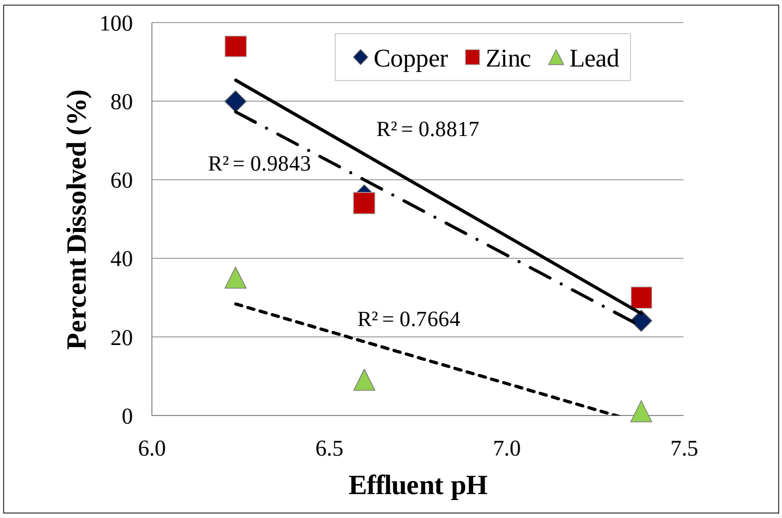

Figure 4: Metal regression trends as a function of stormwater effluent pH

Nutrient Export

It was anticipated that nitrate and phosphate concentrations might be of concern in stormwater as reported elsewhere (Taylor et al. 2005; Henderson et al. 2007) so these nutrients were monitored throughout the study. However, when stormwater concentrations were compared with the ANZECC guidelines (Table 2), concentrations for nitrate at 888 µg/L were less than the 90% ecotoxicological value of 3,400 µg/L. However, nitrate export concentrations from the rain garden systems (3,610, 4,560, and 4,330 µg/L for sand, sand/topsoil, and topsoil, respectively) were above the ANZECC guidelines demonstrating nitrate export from the systems, likely from the bark mulch and topsoil substrate. Despite the recognition of topsoil as an important component of rain garden in supporting vegetative (and probably microbial) communities, it should probably be used in minimal amounts on the surface of bioinfiltrative systems to avoid net nutrient export from the systems. (Phosphate was unable to be measured during this experiment due to disruption incurred by the major earthquake in Christchurch on 22 February 2011).

Hydraulic Performance

Saturated hydraulic conductivity, a measure of the infiltrative capacity of the systems, was quite different for each of the three different systems as expected. Measurements conducted before and after the three replicated treatment experiments for all systems remained constant with no apparent sign of system clogging. Values ranged from 5,144 mm/hr in the sand-only system to 162 mm/hr in the topsoil-only system equating to orders of magnitude greater than the minimum allowable conductivity of 13 mm/hr stipulated in the New Zealand design guidelines (ARC 2003). Future experiments are investing a mixture of various bulking and pH amendment materials suitable to achieve hydraulic and metal performance acceptable for implementation.

CONCLUSIONS

Elevated metal concentrations in Christchurch stormwater far exceed the contextual ecotoxicological guidelines recommended for healthy freshwater ecosystems. Therefore, appropriate treatment should be implemented to mitigate adverse ecological impact prior to surface discharge. In line with the City Council’s approach of implementing more ‘natural’ treatment systems, rain gardens are being adopted but their effectiveness is not well understood. Contrary to conventional belief, topsoil does not appear to enhance metal or nutrient removal and, in the absence of a buffering media, actually reduces treatment performance by promoting metal mobilisation at lower pH. Therefore, pH enhancement afforded by substrates that provide significant buffering capacity may help overcome this phenomenon associated with the topsoil that is actually important for upper surface vegetative growth. Increasing the pH will be critical in infiltration systems relying on heavy metal removal through associated suspended solids settling. Preliminary results indicated that experimental systems were not yet overloaded since metal removal efficiency was strongly correlated to contaminant loading and hydraulic conductivities remained constant before and upon completion of multiple treatment experiments. Nitrate export will need to be further investigated. Future experiments aim to improve the response of rain gardens to substrate complement for pH adjustment with the goal of informing more robust design guidelines for future implementation.

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