

RAINGARDEN SOILS AND EFFICIENCY

Sam Trowsdale & Robyn Simcock - Manaaki Whenua Landcare Research

ABSTRACT (200 WORDS MAXIMUM)

A raingarden (200 m³), receiving water from a light industrial catchment including a road travelled by about 10,000 cars and 5,000 trucks each weekday, has been monitored for soil composition and hydrological and hydrochemical efficiency. Raingarden soils had high metal removal potential and permeability to compensate for undersized garden volume. The inflow hydrograph was a series of very sharp peaks with little baseflow, typical of runoff from impervious surfaces. The raingarden smoothed the hydrograph by reducing peak flow and volume for all five events monitored. Overflow occurred in four of the events indicating the increased permeability has not fully compensated for the undersized volume. Runoff was heavily polluted with sediment and metals, particularly zinc. The majority of the zinc, lead and TSS were removed from the stormwater that flowed through the raingarden, with TSS and total zinc concentrations reducing by orders of magnitude. Despite high removal efficiency, median concentrations of zinc exiting the raingarden still exceeded ecosystem health guidelines and the raingarden was both a source and sink of copper. Metal concentrations increased dramatically in the mulch and sediment accumulated near inlets require landfill disposal.

KEYWORDS

Raingarden, stormwater runoff, hydrochemistry, soils

1 INTRODUCTION

Raingardens are biologically active soil and plant systems that delay and reduce stormwater peakflows, volumes and contaminants. Being a relatively new stormwater treatment device there are scant New Zealand data. The Paul Matthews Raingarden (200 m³) was installed in winter 2006 and received its first inflows in July 2006 as washoff from a "heavily trafficked local road" (Barry Carter, pers. comm. 2008) with a single carriageway in each direction in a light industrial catchment (5300 m²) in Auckland, New Zealand. Smythe *et al.* (2007) describe the catchment and the raingarden design and construction, including installation of an impermeable liner that extends above the ponding depth and the manholes and pipes that transport the inflows, overflows and outflows. To complete the story the key biological features (substrates and plants) are described below before operational data are used to assess the garden's efficiency.

The in situ soils were excavated and not reused because subsoils were weakly structured, low-permeability, anthropogenic soils created by landfilling clays and silts, and topsoils were poorly developed and had a rampant growth of kikuyu, a subtropical grass that spreads from both rhizomes and seed so demanding a great deal of weeding. Raingarden substrates were chosen to achieve high metal removal efficiency and permeability (>50 mm/h) because the volume of the raingarden was 60% of that recommended by local guidelines (ARC, 2003 in Smythe *et al.*, 2007). The guidelines specify a minimum permeability of 20 mm/h. The raingarden was built in multiple layers (Figure 1) because single-layer raingardens inhibit the use of organic-rich substrates as under anaerobic conditions breakdown of organic matter releases hydrogen sulphide and other substances toxic to plants.

A thin drainage layer of coarse sand (55% >2 mm diameter by weight) was installed at the base of the raingarden (Figure 1). The drainage layer was covered by a layer of subsoil 600–700 mm deep sourced from overburden at a limestone quarry. The subsoil was a mixture of free-draining, well-structured subsoils with appreciable clay content and underlying rubbly, weathered (reject) limestone. The subsoil was covered with a layer of topsoil 300–400 mm deep. The topsoil was purchased from a nearby landscaping depot, marketed as “lawn mix”, and contained a mix of pumice sand and fertile horticultural soils. The raingarden was completed with a 80-mm layer of long-fibre, sterile, closed-vessel, composted mulch created from city greenwaste. The key roles of the mulch were to suppress weeds (an unavoidable side effect of using a natural topsoil), to protect the soil surface from water erosion and clogging, to cushion the soil against compaction during planting, and of course remove metals from stormwater. The long-fibre mulch selected did not float. Alternative mulches were considered, including inorganic material such as gravels (c. 4–12 mm) and an erosion blanket such as jute matting. There are advantages to such mulches in that they can be aesthetically attractive and are potentially less likely to clog but they are unlikely to contribute substantially to the build-up of soil biology or removal of metals compared with organic mulches.

The landscape architect specified a single plant species for the raingarden to emphasise the raingarden’s boundaries and complement the industrial nature of the site. Relatively large plants of a native jointed rush, oioi (*Apodasmia similis*), were planted at a density of 3 plants/m² to ensure rapid raingarden cover desirable given the public nature of the site. Oioi is a low-risk species for a raingarden: its rhizomes spread to produce a dense, weed-suppressing canopy up to about 1 m tall and it is tolerant of both ponded and summer-dry conditions, full sunlight and wind. Thin stems and non-bunching habit offer little resistance to surface water flow, thereby avoiding concentrating surface flows and helping to filter litter.

2 METHODS

Vehicles using the road that drains to the raingarden were counted and typed during the week ending 29 July 2006. Rainfall was measured at a tipping bucket raingauge c. 500 m from the raingarden and on 13 December 2007 a 0.2-ml tipping gauge was installed onsite.

Soil samples were taken during raingarden installation (June 2006) and were analysed for the parameters listed in Table 1 using a number of standard methods (Landcare Research, 2008). Topsoil storage measurements were made on intact, 100-mm-diameter and 75-mm-deep stainless steel cores. After saturation, cores were subjected to 10 Kpa tension (nominally ‘field capacity’) until drainage stabilized, allowing calculation of nominal air-filled porosity. The cores were then sub-sampled using 50-mm-diameter and 25-mm-deep intact cores, which were placed in pressure pots at 100 kPa tension to determine soil moisture at this ‘readily available water’ level. Loose samples were placed at 1500 kPa tension to determine the lower boundary of moisture storage that was available to plants or ‘permanent wilting point’. Total porosity was calculated from measured particle density and bulk density.

Sediment build-up at the three inlets was tested after 1 year of operation in June 2007 (Table 2). At the same time mulch, and topsoil at four depths: 0–50 mm; 50–100 mm; 100–200 mm; and 200–300 mm, were sampled 1 m from each of the three inlets and analysed for pH and total copper, lead and zinc and were also sampled for key metal concentrations in leachate using the USEPA Toxicity Characteristic Leaching Procedure Method 131 (USEPA 1992). The sediment collected at a catchpit in an adjacent section of the same road was sampled just prior to its annual clean (June 2007). Infiltration rates

were measured at five subsoil sites during construction (June 2006) and in the topsoil (after removing the mulch layer) at six sites one year after construction (June 2007) using the twin-ring method, in which water was maintained at a ponded depth of about 20 mm until a constant rate of inflow was recorded.

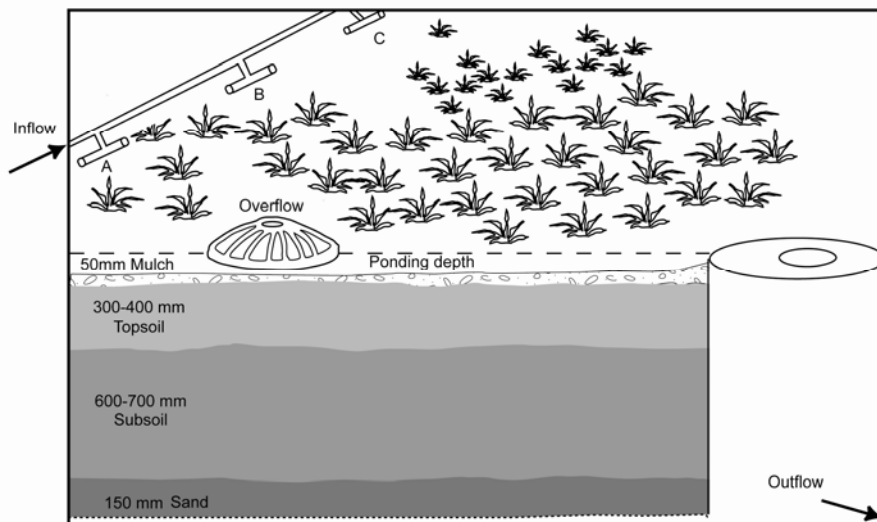


Figure 1. *Stratigraphy of the Paul Matthews Raingarden*

Hydrological stage was measured at 1- and 5-min intervals during stormflow and low flow respectively, at the raingarden inflow, overflow and outflow, using pressure transducers installed behind weirs. Bernoulli rating equations were used to calculate discharge. Automatic samplers collected discrete water samples at given discharge volumes at the inflow and outflow. Water samples were collected within 24 h and prepared and analysed for the contaminants total suspended sediments (TSS), total phosphorous and nitrogen, ammonium, nitrate, total petroleum hydrocarbons, and dissolved and total copper, lead and zinc, using standard methods (Landcare Research, 2008). Overflow water quality was assumed similar to inflow. This paper presents the sediment and metal data, of primary concern in the local context, collected between November 2007 and January 2008 inclusive.

3 RESULTS AND DISCUSSION

ROAD CHARACTERISTICS

There were 95,900 vehicle movements on the road that drains to the raingarden during the week monitored. Weekday traffic was nearly double that of weekend traffic, and saw 10,200 cars and light vehicles (<5.5 m length) and 5,800 trucks pass the site. This equates to nearly 5 million vehicles annually.

SOIL PERMEABILITY AND CHEMISTRY

Subsoil infiltration rates at the time of construction were high, with a mean of 224 mm/h (range 103–405 mm/h). The rates were expected to reduce by up to 30% after the placement of topsoil and settling over the first 6 months of operation. Topsoil infiltration rates after one year were generally high with a mean of 120 mm/h and a range of 12–212 mm/h (Figure 2). Topsoil total saturated storage was 120 mm in its 300 mm depth, which included 50 mm of “free water” or water temporarily stored in large pores normally air-filled between rain events (Figure 2). The subsoil had high anion (phosphate) retention to promote the removal of dissolved metals from stormwater through chemical adsorption (Table 1). Removal of zinc from stormwater (below) was aided by a high pH

(8.0) which assists precipitation of metals. The topsoil had a moderate carbon content and low C:N ratio so nitrogen fertiliser was not needed to establish plants in the raingarden and soluble nitrogen may have been released in the short term.

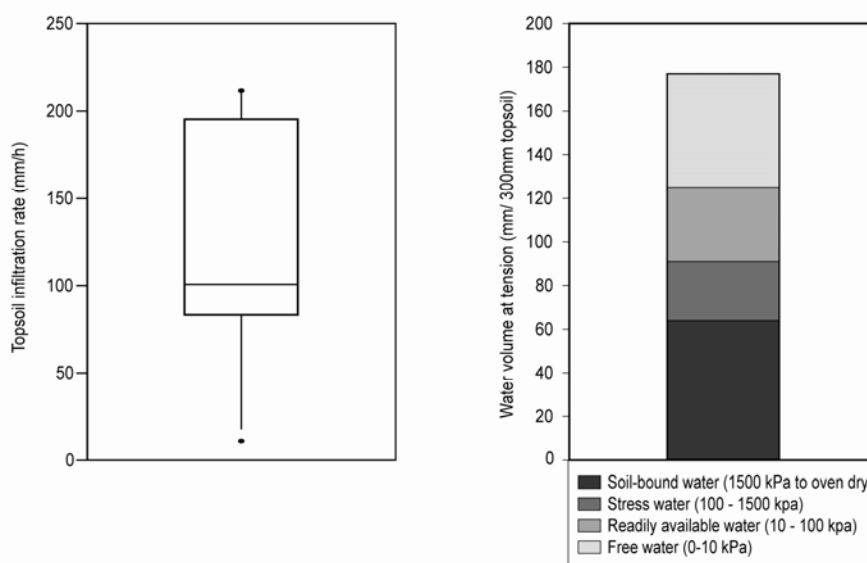


Figure 2. (Left) Topsoil infiltration rates measured in June 2007 as box and whisker plot where the horizontal line in the centre of the box identifies the mean value and whiskers show the 10 and 90 percentile values. (Right) Volume of water (mm) stored at different tensions per 300mm of the raingarden topsoil.

The sand drainage layer at the base was relatively inert, with a low anion and cation exchange capacity (Table 1) and was not expected to contribute to stormwater treatment, other than to protect the underlying drains from blocking with any fine material washed from the subsoils.

SOILS CHEMISTRY AFTER ONE YEAR OF OPERATION

Zinc concentrations in the raingarden mulch increased five-fold to 680 mg/kg (Table 2). The near-surface materials had US EPA Toxicity Characteristic Leaching Procedure (TCLP) zinc levels of 1.7–17.6 mg/l, requiring Class A landfill disposal. The Class A landfill screening levels of copper, lead and zinc are 5, 5 and 10 mg/l and Class B 0.5, 0.5 and 1 mg/l (MfE, 2004). The elevated zinc concentrations were restricted to the upper 100 mm of the raingarden soils, and increases in lead concentration to the upper 50 mm (Table 2). Of interest is the comparatively low metal concentration recorded in the road catchpit, presumably reflecting the coarser nature of the sediment trapped in catchpits.

Table 1. Chemical properties of the raingarden soil and mulch before raingarden operation

Analysis	Mulch	Topsoil	Subsoil	Sand
Stones >2 mm	0	0	2	55
pH	6.4	6.2	8.0	7.8
Total Carbon (%)	43.1	2.4	0.4	0
Total Nitrogen (%)	1.4	0.25	0.01	0.01
C:N Ratio	31	9	34	8

Total Phosphorus (mg/kg)	1780	890	460	180
Olsen Phosphorus (mg/kg)	340	10	2	1
Phosphate Retention (%)	0	29	87	2
Cation Exchange Capacity (cmol+/kg)	38	18	18	3
Base Saturation (%)	205	67	506	98
Total Copper (mg/kg)	46	18	39	2
Total Lead (mg/kg)	44	5	5	0
Total Zinc (mg/kg)	130	72	41	27

Table 2. Chemical properties of sediment, mulch and raingarden soil after one year of operation. "Inlet" samples of sediment accumulated at inlets where inlet A was closest to the road and had coarsest sediments and inlet C was furthest from the road and had finer sediments. "TCLP" represent Toxicity Leaching (USEPA 1992).

Analysis	Inlet A	Inlet B	Inlet C	Catchpit	Mulch 10-0 cm	Topsoil 0-5 cm	Topsoil 5-10 cm	Topsoil 10-20 cm	Topsoil 20-30 cm
pH	7.6	7.5	6.5	7.5	6.6	7.2	7.1	6.9	6.9
Total Cu (mg/kg)	30	59	94	82	47	26	23	23	25
Total Pb (mg/kg)	26	38	64	24	62	9	5	7	6
Total Zn (mg/kg)	386	630	2668	182	680	115	106	103	106
TCLP Cu (mg/l)	0.21	0.043	0.075	0.184	0.02	0.07	0.065	0.06	0.069
TCLP Pb (mg/l)	0.062	<0.024	<0.024	0.113	<0.024	<0.024	<0.024	<0.024	<0.024
TCLP Zn (mg/l)	6.32	8.46	17.6	3.26	1.71	0.2	0.09	0.04	0.03

1.1 EVENT HYDROLOGY

A total of five events were monitored that had six or more discrete water quality samples collected at both the inflow and outflow. Event duration, rainfall, inflow peak and raingarden discharge are shown in Table 3. The inflow hydrograph was a series of very sharp peaks with little baseflow, typical of runoff from impervious surfaces. The

raingarden smoothed the hydrograph by reducing peak flow and volume for all the events monitored.

Inflow ranged from a total of 44 m³ (event D) to 261 m³ (event C); during the latter there was 28.9 mm of rainfall. Assuming the catchment was 100% hydraulically efficient implies a catchment area of 9031 m², much larger than the design area (Smythe *et al.* 2007). The less intense events (A, B, D and E) gave estimates of catchment area similar to each other; c.6000 m³. Event C was the most intense event so there may have been some overflow or spill from neighbouring catchments (e.g. warehouse roofs). Assuming a more realistic 60% of rainfall becoming runoff, suggest a catchment area of 11000 m², which is still more than twice as large as the design area and makes the guideline (ARC, 2003) raingarden surface area 673 m². The actual raingarden is just 30% that size (200 m³). But soil permeability was increased to 50 mm/hr. Importantly, however, this does not account for storage of the runoff before treatment. The live storage of a 200 m² raingarden, assuming an average ponding depth of 220 mm, is just 44 m³. Of course, storage will be bigger than this due to the freely available soil storage. Nevertheless, guideline live storage was 90 m³ so the garden is expected to experience bypass flow. The calculations reinforce the need to accurately determine catchment boundaries and, more interestingly, highlight the value of treatment trains that slow the delivery of water, allowing the treatment of large volumes of water using small devices with high permeability.

The data show that between 26 and 66% of inflow drained through the garden to become outflow, the average being 46%. As expected, the two smallest percentages corresponded to the two largest events when much of the inflow bypassed the garden, while the largest was measured during the longest event. There was a small volume of rain in events B and D, resulting in small bypass flows. Event B was the shortest in duration and was relatively small volume resulting in 10% of the inflow becoming bypass flow. Event D was the only event not to experience bypass flow, reflecting the slightly longer time of delivery. Event E was the longest duration and, although comparatively intense at the 6-min and 1-h scale, there was less rainfall than in events A and C. The relatively slow delivery of water to the garden in event E was reflected in the smaller bypass volume that was 29% of inflow.

The volume of inflow not measured in either the bypass flow or outflow is referred to here as the "raingarden volume". The 200 m³ raingarden provides a steady-state total available soil storage volume of 76 m³ including 35 m³ of free water, assuming topsoil storage values throughout (Figure 2). Of course, raingarden volume will also include evaporation, transpiration and seepage loss around the impermeable liner. All events except C experienced less than the maximum 76 m³ soil storage, and raingarden volumes were closer to, or less than, the free-water volume. The largest raingarden volume (C) corresponded to the largest inflow volume where 42% of the inflow water was not accounted for, suggesting that there may have been some other form of bypass, perhaps a secondary leakage such as overflow of the outflow manhole.

Table 3. Rainfall, runoff and raingarden flows for five events at the Paul Matthews Raingarden

Event	Duration	Rainfall Intensity				Peak inflow	Total flow volume			Rain garden
		Total	6-min	1-h	24-h		Inflow	Bypass	Outflow	

	min	mm	mm/h	mm/h	mm/h	L/s	m ³	m ³	m ³	m ³
A	4110	28.9	10.7	4.3	0.9	18	178	82	47	49
B	2750	8.5	4.7	3.8	0.4	10	55	5	24	26
C	3775	28.9	22.7	8.2	1.0	53	261	57	96	108
D	3725	8.0	6.1	1.5	0.3	7	44	0	25	19
E	7225	20.2	17.8	10.3	0.7	39	123	35	82	6

1.2 EVENT HYDROCHEMISTRY AND RAINGARDEN EFFICIENCY

The concentrations of the water quality determinants in the inflow and outflow are presented as box plots in Figure 3. As expected there was little dissolved lead and concentrations were about detection limits so they are not discussed further. Maximum total lead concentrations in the inflow and outflow were 212 and 107 ug/L respectively. The raingarden reduced the median inflow concentration of 65 ug/L to 0.9 ug/L in outflow, which is lower than the ANZECC (2000) guidelines for the 95% species protection (3.4 ug/L).

The change in TSS concentration was visible in the field. Inflow samples were discoloured with sediment while outflow samples were clear. The data supported the observation and the concentration of TSS in the inflow (median 56 mg/L, max 375 mg/L) was reduced significantly by the raingarden. The median and maximum concentrations measured in the outflow were just 2 and 10 mg/L, respectively.

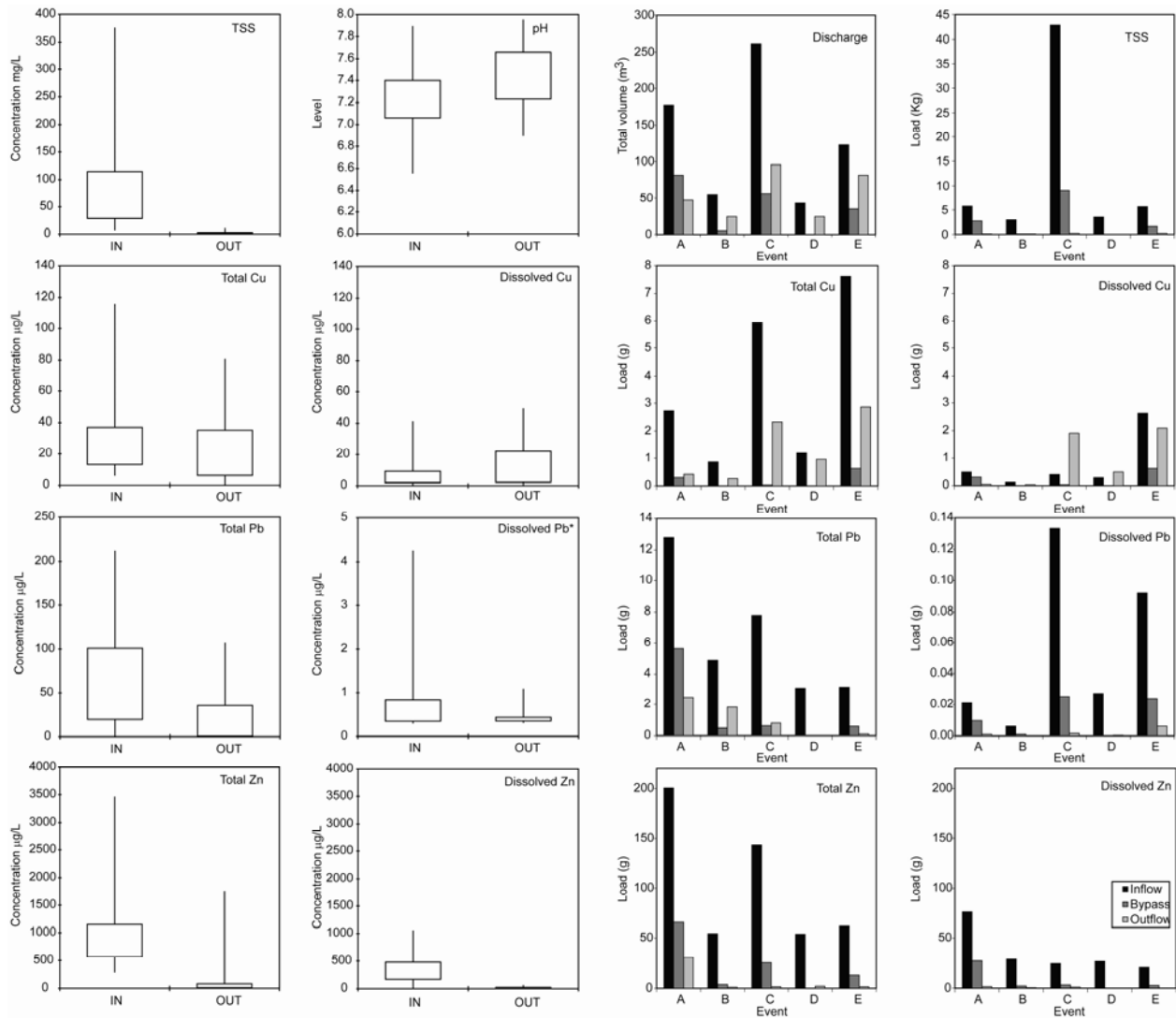


Figure 3. (Left) Box plots using quartiles of the concentrations of the water quality determinants in the inflow and outflow. (Right) Total load in the inflow, bypass and overflow for each event.

The concentrations of total and dissolved zinc were much higher than expected in the inflow, with medians of 746 and 374 ug/L respectively. The raingarden removed much of the zinc from the water reducing the median total concentration to 21 ug/L and the dissolved to 16 ug/L, but that is still twice the ANZECC 95% trigger value (8 ug/L).

Copper concentrations had a different pattern to the other metals and the median concentration of dissolved copper in the outflow (15 ug/L) was greater than that measured in the inflow (3 ug/L). The dissolved copper concentrations skewed the total concentrations so that the median was similar in the inflow and outflow (c. 20 ug/L) and the raingarden appeared not to reduce the concentration. The soils analysis at the time of construction (Table 1) suggests the substrates are not a copper source. The dissolved copper may have come from slow-release fungicides in the potting mix or used on plants in the nursery, apparently a common practice (Terry Wearmouth, pers. comm., 2007). Copper tends to move (equilibrate) between the solid and dissolved phases, so it may be that the garden is accumulating copper contaminated sediment (Table 2) and the copper is moving into solution. The relative loads of the metals are discussed in the next section.

Normal probability plots of log-transformed event mean concentrations (Figure 4) support the numerical results presented in the box plots and provide additional information about how the raingarden performed. Overall the inflow values were higher than outflows showing that the raingarden reduced contaminant concentrations, except for copper. The event mean concentration of TSS was low to average compared with local historical data (Williamson, 1993). There was a consistently high TSS reduction for the range of event concentrations monitored so that TSS in the raingarden outflow was very low. Dissolved zinc had a similar pattern to TSS.

Compared with historical data (Williamson, 1993) the event mean concentration of lead in inflow was low and the garden acted to reduce it further. But total zinc inflows were very high. The raingarden reduced the total zinc event concentration significantly, except in event A when it remained high in the outflow and so the probability plots show a decrease in raingarden efficiency with increasing concentrations of total zinc.

Event mean copper concentrations were in the range of low to above average compared with the Williamson dataset. The raingarden reduced the concentration of dissolved copper when event mean concentrations were low ($< 3 \text{ ug/L}$), but the garden increased the concentration of dissolved copper when event concentrations increased. Total copper concentrations were clearly skewed by the dissolved fraction, so that when dissolved concentrations were particularly high outflow concentrations were higher than the inflow.

The load of TSS in the inflow was quite closely correlated to the inflow volume. The outflow from the raingarden carried very little sediment. The load of TSS in the outflow was just 1–3% of the inflow so the raingarden can be said to perform really well at removing the load of TSS for flow through the garden. Interestingly there were 42 kg of sediment transported into the garden during event C (Figure 3), the largest and most intense rainfall event. Still, the amount of sediment was disproportionately large compared with the other events. The result suggests that the high-energy event C may have mobilised sediments that were not mobilised by the smaller events. The result also suggests that sediments were not source limited even though the catchment is impervious. Perhaps intense events transport sediment from adjacent properties. Bypass flow was responsible for short-circuiting large TSS loads where flows were large (events A, C and E). As expected, when bypass flow was insignificant so was the bypass load. High bypass flow compared to inflow in event A meant the total reduction of TSS was only 50%, but this was the outlier and the actual reduction may have been higher given that bypass TSS concentration was inferred from the inflow so was probably overestimated. In general, when TSS was high the metals tended to be high and vice versa but there was no clear statistical relationship between TSS and metals loads.

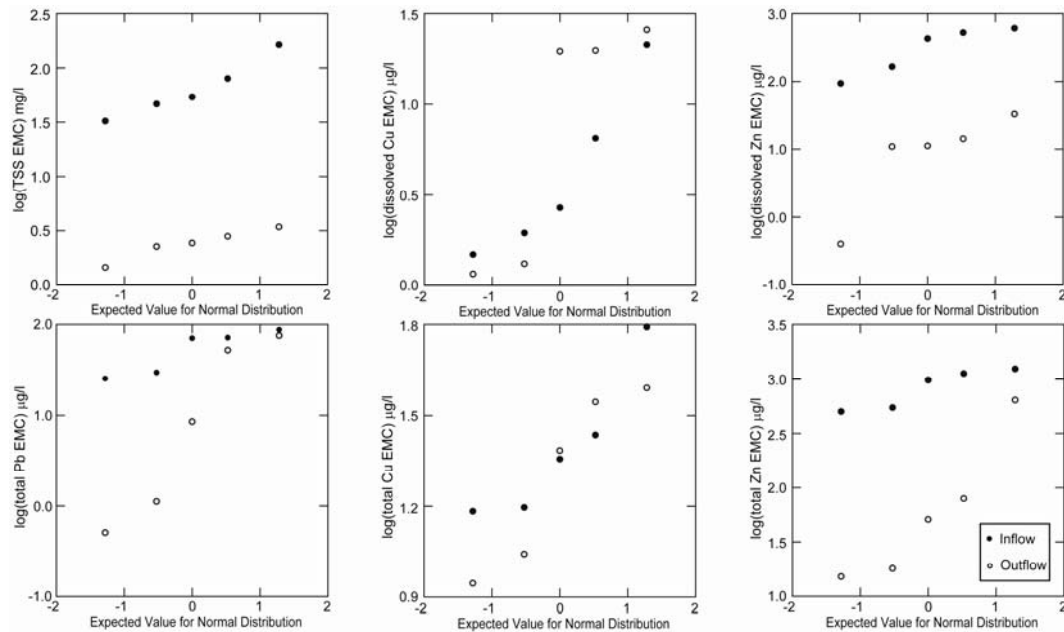


Figure 4. Normal probability plots of log-transformed event mean concentrations.

Dissolved copper was the only parameter that increased in load between the inflow and outflow (events C and D) as discussed above. The raingarden removed much of the particulate copper from the water, but the total copper was sometimes increased by the elevated dissolved copper in the outflow. The largest load of dissolved copper in the outflow was measured in events C and E, the largest volume outflows from the garden, suggesting that the flushing of dissolved copper was linked to the volume of flow.

The total zinc load peaked at 200 g flowing into the garden in event A and was above 50 g in all the events. The largest lead and total and dissolved zinc loads were measured in the inflow during event A. The loads were greater than expected compared with the other events. The relatively intense and large-volume event may have mobilised contaminants not mobilised during other events as discussed above for sediments. Perhaps in this hydrological situation zinc was washed off galvanised-clad warehouses abundant in this industrial catchment. The raingarden removed much of the load of dissolved zinc in all the events and substantially reduced the load of total lead and zinc.

The data presented here show that the raingarden goes some way to treating the polluted runoff and works particularly well for sediments and zinc. However, the garden remains a technological fix to the impacts of our actions (environmental degradation due to vehicles and buildings materials) and by doing so such devices may actually slow the adaptation of our behaviour to protect the environment. Interestingly, the data show that raingardens can rapidly accumulate polluted materials near to their surface; so polluted in fact that they require landfill disposal. Raingardens by their very nature are vegetated areas employed in cities and current trends promote their multi-purpose functionality. As a result raingardens are being installed in public places such as outside cafes and some even have public seating incorporated into them. Given the contaminated nature of the sediments perhaps it is time to reassess the wisdom of such initiatives. In the very least the raingardens should be maintained in dense vegetation to prevent dust being generated and people should be discouraged from treading the accumulation zone.

4 CONCLUSIONS

A light industrial catchment with a heavily trafficked road generated stormwater runoff with concentrations of sediment, zinc, lead and copper likely to cause degradation of ecosystems. Zinc was the contaminant of greatest concern, occurring at very high concentrations. A relatively small and hence overloaded, multi-layered-raingarden consistently reduced the concentration of sediment and zinc by orders of magnitude; however, median concentrations of dissolved zinc exiting the raingarden still exceeded ecosystem health guidelines. The raingarden acted as both a sink and source for copper and overall was relatively ineffective at reducing copper concentrations. The organic mulch was a major sink for contaminants and after one year of operation the sediments accumulated near to the surface require landfill disposal.

5 ACKNOWLEDGMENTS

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