4 LIVING ROOFS IN 3 LOCATIONS: DOES CONFIGURATION AFFECT RUNOFF QUALITY OR QUANITIY?

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ABSTRACT

Four extensive living roofs in Auckland have been monitored over periods of 8 months to over 2 yrs for stormwater quantity and quality compared to conventional roofs at the same locations. Up to 56% cumulative retention was measured from living roofs with 50-150 mm depth substrates designed to maximize water storage. Runoff rarely occurred from storms with less than 40 mm of precipitation. Peak flow was 62-90% less than the corresponding conventional roof per storm event. Flow path length through the drainage layer to vertical gutters and drainage layer material may influence peak flow control effectiveness and could be manipulated to increase mitigation. Neither living nor conventional roof surfaces produced elevated TSS or NO_x. Zinc and copper mass loads were statistically comparable to runoff from the conventional roofs at the same location, although copper may be sourced from living roof substrates. Soluble Reactive Phosphorus and Total Kjeldhal Nitrogen are the predominant nutrients discharging at elevated concentrations from living roofs, with mass loads unlikely to be off-set by hydrologic control. Installing living roofs in nutrient sensitive receiving watersheds should consider a treatment train. Initial hypotheses regarding substrate organic matter characteristics to minimise contaminant leaching are suggested (e.g. carbon:nitrogen, Olsen phosphorus, cation exchange capacity and carbon content).

KEYWORDS

Living roof, green roof, hydrology, water quality, performance indicators

PRESENTER PROFILE

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1 INTRODUCTION

Living roof technology is being used internationally to manage stormwater in dense urban centres. Rooftops comprise a significant proportion of the total impervious area in urban settings; considerable opportunity exists to reduce runoff volume and peak flow by retrofit of existing building stock, particularly flat roofs comprising gravel ballast over membranes. Living roofs offer two advantages for urban stormwater management: they act as at-source control to prevent runoff generation from an otherwise impervious area, and they provide a stormwater management opportunity in otherwise usually unused space (rather than valuable ground space).

Since 2006, several living roofs have been designed, constructed, and studied across Auckland through support from the former Auckland Regional Council, former Waitakere City Council (WCC), and the Foundation for Research, Science, and Technology, with on-going support from Auckland Council. Research aimed to link extensive living roof design to stormwater management performance (quality and quantity) to provide a numeric basis for design that achieves reliable stormwater management. The term 'living roof' has been adopted to acknowledge the vital role of plants in providing environmental and aesthetic benefits. A living roof is also commonly referred to as green roof, eco-roof, vegetated roof, roof garden or landscape over structure.

This paper documents performance monitoring of the extensive living roofs constructed on the roof of the University of Auckland's (UoA) Faculty of Engineering, "mini" living roofs at Landcare Research in East Tamaki (the Tamaki mini-roofs), and Waitakere City Council's Civic Centre in Henderson (WCC).

2 SITE DESCRIPTIONS

The studied living roofs are all classified as extensive living roofs, with substrate (growing media) 50 to 150 mm deep. The substrates are minimum 80% by volume (v/v) light-weight aggregate and maximum 20% v/v organic matter as recommended for extensive living roofs (FLL 2008) and were installed over a synthetic drainage layer with bonded geotextile providing separation. Full details on design and construction are provided in Fassman et al. (2010 and 2012 *draft)*.

2.1 UOA LIVING ROOF

This living roof was constructed in Sept. and Oct. 2006 on level 13 of the UoA Faculty of Engineering at 20 Symonds St in Auckland City. The living roof is 235 m^2 (94% of total roof area), including a gravel edge (200-800 mm width). Three substrates were developed in the laboratory (Fassman and Simcock, 2008; Fassman et al., 2010). All substrates have a base of pumice, with an overall light-weight aggregate to organic matter volumetric ratio of 0.8:0.2. Six hydraulically isolated plots allow comparison between substrate types and two finished substrate depths: 50 mm and 70 mm. Individual plot surface area ranges 17-54 m^2. Average roof slope is 1.2% towards vertical drainage points. A combination of native and non-native (*Sedum* species) plants was initially planted at 18 plugs/m^2 in 5 of the 6 plots. Plant cover reached at least 80% by the time monitoring commenced in 2008. The sixth plot was covered with a pre-grown *Sedum* mat. This had significantly higher water retention (Voyde et al., 2010a), and thus is excluded for analysis from this particular paper. The resultant living roof subject to analysis covers 217.4 m^2.

2.2 TAMAKI MINI-ROOFS

A 70% v/v pumice/ 10% v/v zeolite/ 20% v/v organic matter substrate blend was installed in May 2008 on four 4 m^2 "mini" living roofs at the Landcare Research office in East Tamaki. The mini living roofs are built on reinforced garden sheds with Colour Steel roofs. One additional shed was constructed without a living roof (a control roof) for concurrent monitoring.

Mini-roofs are covered with 100 mm or 150 mm depth of substrate. When combined with the UoA living roof, the hydrologic results for a full range of extensive living roofs is able to be compared (by definition up to 150 mm). Approximately 20 native plant species and 18 non-native plant species were established as plugs, root trainers, pots or plants salvaged from rock walls at about 22 plants/m^2. Monitoring commenced approximately 1.5 yr after construction.

2.3 WCC LIVING ROOF

The WCC living roof was constructed in mid-2006 and modified in 2009. This 500 m^2 nearly-flat roof has a substrate blend of 60% v/v pumice, 20% v/v imported expanded clay and 20% v/v compost-based garden mix[1]. Additional expanded clay was spread as a 4–8 mm deep mulch to provide an aesthetically pleasing cover until plants covered the surface. Only native plants were used on this roof.

In winter 2009, two areas of the roof with less than 100 mm depth were amended with a 70% v/v pumice/ 10% v/v zeolite/ 20% v/v compost blend based on specifications of the Tamaki mini-roofs. After supplementation, the majority of the living roof had a minimum 100 mm depth. Three isolated mounds with 150 mm average depth were also constructed. The mounds are intended to support dense vegetation up to 500 mm height as refuges for native skinks. The two amended areas were replanted with relocated and new native species and regularly irrigated throughout subsequent two summers using a basal irrigation mat to ensure rapid growth of native vegetation.

Adjacent to the living roof, but one storey higher is a conventional roof surface with a bituminous waterproofing sheet membrane system with a plain sand finish (Soprema Flam 180 / Soprema Jardine 2 layer torch-on membrane, according to design drawings). This roof serves as a control roof for runoff monitoring.

3 METHODOLOGY: DATA COLLECTION AND ANALYSIS

3.1 UOA LIVING ROOF

Rainfall data was collected on site using a Sigma 2149 0.25 mm tipping bucket rain gauge. Runoff was measured from each of the hydraulically isolated plots using a Global Water WL16USB pressure transducer rated for 0-0.91 m depth and custom-designed orifice restricted device (ORD). All data was logged continuously at 5-min intervals.

The UoA living roof replaced a conventional asphalt roof covered by a thin gravel ballast layer. Site limitations prevented direct measurement of a conventional roof surface (control roof) at the UoA site. Runoff volume from a control roof was modelled as 75% of total rainfall received, as per a traditional roof surface with 50 mm gravel ballast (Mentens *et al.*, 2006). Peak flow was modeled using the Rational Formula, with an assumed runoff coefficient of 0.75. The effect of the gravel ballast led to the adoption of a conservative value amongst literature reports for conventional roof runoff coefficients (0.75-0.95) (Bedient and Huber, 2002, American Society of Civil Engineers, 1992, Viessman and Lewis, 2003).

Inaccessibility of the UoA living roof outlets precluded runoff water quality monitoring at the site.

3.2 TAMAKI MINI-ROOFS

Runoff from each mini-roof was collected in a gutter draining to a down- pipe. Wire mesh over the opening of each down-pipe prevents clogging the orifice. In the down-pipe, runoff was measured using a similar ORD and Global Water WL16USB pressure transducer arrangement as on the UoA living roof. Rainfall was measured at 5-min intervals using a HOBO 0.2 mm tipping bucket rain gauge (Dec. 2009-May 2010) or a Sigma 2149 0.25 mm tipping bucket rain gauge (Oct. 2010-March 2011).

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[1] The specification here differs from older documentation by Waitakere City Council. The difference arises from an on-the-spot change in the recipe warranted by wet conditions during blending. The substrate component proportions in this document are considered accurate.

Based on the lack of statistical differences in either peak flow rate or total volume response between like mini-roofs, the average value between like roofs was used in the hydrological analysis for each substrate depth (100 mm or 150 mm) for comparison with the control roof.

180 L plastic bins under each down-pipe captured flow for water quality sampling. The capacity of the bins was estimated to hold the entire runoff volume from storms up to approximately 50 mm depth. This creates a composite sample, analysis of which yields an event mean concentration (EMC). Water samples were collected for storm events with at least 8 mm of precipitation to provide adequate sample volume for pollutant analysis. Field sampling equipment were cleaned between storm events with phosphate free detergent and rinsed with reverse osmosis water. Composite samples were sub-sampled into bottles provided by Watercare Services with appropriate preservatives for heavy metal and/or nutrient content. All samples were stored in a chilly bin with ice packs until being couriered to Watercare for analysis.

Seven composite samples were collected per event: one sample from each of the five sheds and two field replicate samples from a random shed. The two additional (replicate) samples from one random shed were analysed for each storm event to ensure data quality. Data presented are average values where replicate samples were analysed.

Water quality constituents for analysis include Total Suspended Solids (TSS), Total Dissolved Solids (TDS), Nitrate and Nitrite Nitrogen (NO_x), Total Kjeldahl Nitrogen (TKN), Soluble Reactive Phosphorus (SRP) and Total Phosphorus (P), dissolved and total Zinc (Zn), dissolved and total Copper (Cu). Total nitrogen (TN) was determined as the sum of NO_x and TKN. Parameters were selected based on relative concern over receiving water impacts in the Auckland region (TSS and heavy metals) or because of prevailing evidence in the literature regarding leaching potential. Table 1 summarises the testing methods and their respective analytical method detection limits (MDL).

Table 1: Watercare Services Laboratory Testing Methods and Parameter Method Detection Limits

Parameter & Abbreviation		Method	MDL
Nitrate & Nitrite Nitrogen	NO_x	APHA (2005) 4500-NO3 F, by Cd Reduction/SFA	0.002 mg/L N
Total Kjeldahl Nitrogen	TKN	USEPA 351.2	0.1 mg/L N
Total Nitrogen	TN	by calculation: NO_x + TKN	0.102 mg/L N
Soluble Reactive Phosphorus	SRP	APHA (2005) 4500-P F, modified	0.005 mg/L P
Total Phosphorus	TP	APHA (2005) 4500-P B, F, modified, by Persulphate Digestion	0.01 mg/L P
Suspended solids	TSS	APHA (2005) 2540 D, High Level by 125 mm GF/C	1 mg/L
Total dissolved solids	TDS	APHA (2005) 2540 C, modified	15 mg/L
Copper: Soluble or Total	SolCu Cu	USEPA 200.8, modified, by ICPMS-Trace	0.0002 mg/L
Zinc: Soluble or Total	SolZn Zn	USEPA 200.8, modified, by ICPMS-Trace	0.001 mg/L

3.3 WCC LIVING AND CONTROL ROOFS

An estimated 171 m^2 of the extensive living roof drains to a PVC pipe which channels runoff to a small weir box with a 90º v-notch weir. Runoff from the 79 m^2 control roof drains into a downpipe and separate weir box. A rating curve was developed in the laboratory for each weir box using Global Water WL16USB pressure transducers. Water depth was recorded by each logger at 5 minute intervals. Rainfall was recorded on-site or was obtained from the NIWA Waitakere Domain rain gauge.

Samples for runoff water quality assessment were collected using ISCO 6712 automatic samplers from each weir box. Minimum precipitation depth for sampling was 8 mm, as for the Tamaki mini-roofs. A time-based sampling method was used, with samples collected more frequently in the beginning of each event, but in all cases the entire storm, including rising limb, peak and recession limb of the hydrograph, were represented by samples. While sample collection was time-based, sample compositing followed standard volumetric flow-weighting protocols, the analysis of which generates EMCs.

All bottles for sampling were washed with phosphate free detergent, rinsed with diluted 10% hydrochloric and nitric acid, and a final rinse of de-ionised water. All equipment used for mixing composites was also washed according to this procedure. Each composite sample was tested for the same water quality parameters by Watercare Services as the Tamaki mini-roofs.

3.4 STATISTICAL ANALYSIS

All results were statistically analysed using SPSS to detect differences in means or distributions. Normal distributions were achieved for most water quality parameters via log-normal transformation, hence ANOVA with Post-hoc Tukey tests were used. Nonparametric tests (Mann-Whitney U or Kruskall Wallis) were used for all hydrologic analysis and some water quality parameters where data transforms failed to yield normal distributions.

3.5 SUBSTRATE CHEMISTRY

Chemical analysis of individual material components or mixes were performed by Landcare Research. Properties tested were: pH, organic carbon (C), total nitrogen (N), Olsen phosphorus, total phosphorus, 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.

Results are presented with water quality analysis, as interpretation warrants.

4 RESULTS AND DISCUSSION: HYDROLOGY

Data are analysed in terms of cumulative and event-based performance. Analysis of cumulative effects of living roofs includes all data. The event-based analysis primarily considers data for storms with rainfall events of at least 2 mm. Smaller rainfall events (< 2 mm) rarely generate meaningful runoff, but the predominance of occurrence creates significant skew in the data which might be considered as exaggerating the summary performance. A conservative event-based analysis is presented by including only events with rainfall of at least 2 mm. Coincidentally, there are no differences in the conclusions of statistical differences amongst any of the comparisons.

Rainfall events were defined by an inter-event dry period ≥6 h (Shamseldin, 2010). When runoff from the previous rainfall event was still discharging from a living roof at the start of the next rainfall event, events were combined as one larger event. From the UoA living roof, 28 of the 396 rainfall events analysed were generated by combining two or more individual events with extended runoff durations, while combinations were used for 8 of the 166 rainfall events from the Tamaki mini-roofs, and 8 of the 79 rainfall events were combined from the WCC living roof.

Because the UoA living roof was constructed from multiple substrates in isolated plots, an initial statistical analysis was performed to assess the effects of substrate type. Between the five living roof plots considered, no statistically significant difference was detected in terms of runoff volume, confirming findings in Voyde et al. (2010a) which were based on one full year of monitoring. Statistically significant differences in peak flow were observed between most plots ($p<0.05$ in all cases); however, the analysis is likely confounded by the very small magnitude of actual peak flow. Factors affecting peak flow are discussed in Section 4.2. Therefore, data from all plots were combined into a single representative 217.4 m^2 living roof for subsequent analysis.

4.1 EVENT-BASED PERFORMANCE

4.1.1 FULL MONITORING PERIOD

Runoff from all living roofs was significantly lower than that measured or modelled from control roofs (Table 2). The most frequently measured runoff depth (the mode) for living roofs was 0.0 mm for storms with 2-40 mm rainfall depth. Large performance data variability was measured amongst events, as evidenced by relatively large standard deviations. For storms with greater than 2 mm of rainfall, median peak flow mitigation ranged 62-90%, while median retention ranged 56-76%, depending on the site. When all storms are considered, the median %-mitigation statistics are greater because of the large number of storms with zero discharge (100% mitigation).

Table 2: Median (Standard Deviation) Mitigation Statistics per Rainfall Event Comparing Living Roof Runoff and Control Roof Runoff

Monitoring Site	Storms with $P \geq 2$ mm		All Storms	
	% Retention	% Peak Flow Reduction	% Retention	% Peak Flow Reduction
UoA	76 (26)	90 (14)	98 (23)	100 (12)
Tamaki 100	56 (29)	62 (34)	79 (32)	91 (33)
Tamaki 150	66 (25)	74 (29)	86 (25)	91 (28)
WCC	72 (21)	84 (20)	79 (23)	93 (19)

The volume of rainfall captured in an event depends on the substrate's ability to store rainfall against gravity drainage (Fassman and Simcock 2012). Table 3 provides the water retention potential of each substrate, based on characteristics of the individual media combined with installed depth (Fassman and Simcock 2012). The Tamaki mini-roofs have the greatest moisture storage capacity and UofA roof the least storage capacity. However, these differences in storage are not reflected in their rainfall attenuation; the shallow UoA roof performed as effectively as the deeper roofs. The additional potential storage from deeper substrates does not provide additional hydrologic mitigation because of the predominance of events with rainfall depths substantially less than the total storage capacity; more than 90% of the rainfall events were less than 25 mm depth, and >80% less than 15 mm depth.

Table 3: Living Roof Water Storage Potential According to Installed Depth

Measure of Water Storage Potential	UoA		Tamaki		WCC Original
	50 mm	70 mm	100 mm	150 mm	100 mm

Plant-Available Water	11.3-12.0	14.3-16.2	28.9	35.8	20.2
Maximum Water Holding Capacity	24.2-24.5	28.8-33.3	63.0	94.5	n/a

4.1.2 SEASONAL ANALYSIS

The level of mitigation of volume and peak flow by the UoA and Tamaki living roofs was similar across spring, summer and autumn (Table 4). Winter performance of the UoA roof dropped to 66% retention against the modelled runoff from control roof; insufficient winter data was available from the other two roofs. Lower winter performance is anticipated due to lower evapotranspiration and thus a reduced ability of a living roof to dry out between storm events (Voyde et al., 2010; Voyde, 2011).

Table 4: Median Performance when Compared to Control Roof Runoff for Rainfall Events ≥2 mm Depth[1]

Performance Measure	Living Roof Site	Spring	Summer	Autumn[2]	Winter
% Retention	UoA	83	92	75	66
	100	85	83	45	
	150	81	88	48	
% Peak Reduction	UoA	95	98	91	87
	100	66	66	63	
	150	71	70	82	
Event Count	UoA	63	38	32	65
	Tamaki	22	16	12	

1. Modeled for UoA living roof from on-site rainfall, measured for Tamaki mini-roofs
2. 5 of 12 monitored events had total depth > 20 mm at the Tamaki mini-roofs

4.2 CUMULATIVE RUNOFF RETENTION

Cumulative retention by the living roofs ranged from 39 to 57% (Table 5) and was statistically greater than the measured or modelled runoff from control roofs. From the UoA living roof, there was no difference in performance when the total monitoring period was broken down into individual years. Whether the apparent difference in long-term retention amongst sites is attributed to the differences in climate (i.e. difference in size, duration and frequency of rainfall events) during non-concurrent monitoring periods, or is due to system design, is further investigated.

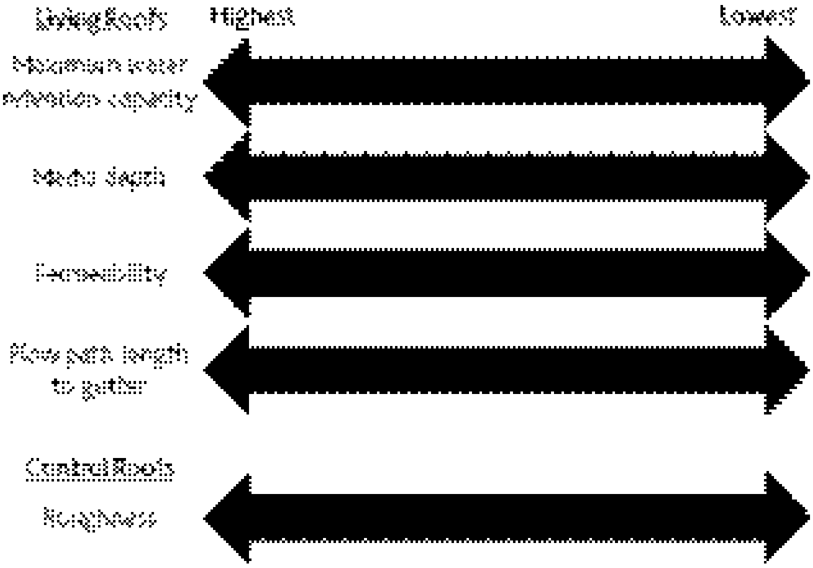
Table 5: Summary of Runoff Response from the UoA, Tamaki and WCC Living Roofs for the Full Monitored Period for Each Site

Location	Substrate Depth (mm)	Monitoring Length	Cumulative Rainfall (mm)	Number of Storm Events $\geq$ 75 mm	Cumulative Retention vs. Control (%)
UoA	50-70	28 months Sep 08–Dec 10	2395.6	0*	56[1]
Tamaki	100	14 months Dec 09–May 10 & Aug 10–Mar 11	1494.4	5	39[2]
	150				53[2]
WCC	100	8 months Aug 10–Mar 11	746.6	1	57[3]

* Maximum storm size 74.4 mm.

Substrates' water holding capacity and installed depth have the greatest impact on runoff retention (Table 3). Peak flow is influenced by substrate permeability and the travel time through the drainage layer to vertical drainage points (assuming adequate rainfall occurs to exceed storage capacity and percolate through the substrate). Relative properties of each living roof design are presented in Figure 1. The control roofs also varied (Section 2).

Figure 1: Design Components of Living and Control Roofs Compared Qualitatively



The four living roofs' and three control roofs' performance was compared over a four month period (Aug.-Dec. 2010) during which all sites were monitored concurrently. Although each site exhibited localised minor variation in rainfall patterns during the four months, the sites experienced very similar rainfall characteristics total rainfall depth (p=0.965) and peak rainfall intensity (p=0.233) were not significantly different, nor was control roof runoff depth on a per event basis (p = 0.148). Control roof runoff peak flow rates were significantly greater at Tamaki than WCC (p = 0.015).

The UoA and WCC living roofs demonstrated the same retention efficiency (66%), despite greater substrate depth and maximum water retention capacity on the WCC living roof. (Table 6). The frequency of small events entirely captured by all of the roofs and frequent (every 1-3 days) irrigation of the WCC living roof are likely contributing factors. Despite greater maximum water retention capacity, the reduced cumulative retention at Tamaki

(48-57% vs 66% at UoA or WCC) is likely influenced by the high efficiency of runoff from the control roof. The Colour Steel roof provides minimal retention or peak flow reduction potential compared to the flatter, rougher Waitakere and UoA control roofs.

The four living roofs were equally effective and efficient in reducing runoff volume compared to a control roof (Tables 6 and 7). Runoff depth within control roofs and within living roofs were not significantly different when analysed on a per event basis (Figure 2, $p = 0.148$, and $p=0.061$ amongst control roofs and living roofs, respectively).

The Tamaki mini-roofs demonstrated statistically higher peak flow (runoff rates) than either the WCC or UoA living roofs, and less mitigation compared to the control roof. (Figure 2, Tables 6 and 7). Four factors probably influence this result at Tamaki: (i) a short flow path to the outlet (maximum 2 m); (ii) higher substrate permeability; (iii) faster and greater runoff from the hydraulically efficient control roof; and (iv) a greater proportion of edge gravels.

Table 6: Performance Comparison Aug.-Dec. 2010: All Sites Monitored Concurrently

Living Roof		Cumulative Retention (%)	Event-Based Median	
			Retention (%)	Peak Flow Reduction (%)
UoA		66	75	89
Tamaki	100	48	55	73
	150	57	66	74
WCC		66	72	86

Table 7: Comparisons Amongst Living Roofs Yielding Statistically Significant Differences in Performance

	Peak Flow Magnitude			% Peak Flow Reduction from Control Roof		
	Tamaki 100	Tamaki 150	WCC	Tamaki 100	Tamaki 150	WCC
UoA	√	√		√	√	
Tamaki 100			√			
Tamaki 150			√			√
WCC	√	√			√	

Figure 2: Living roof runoff depth and peak flow rates per event for rainfall events >2 mm: Aug-Dec 2010

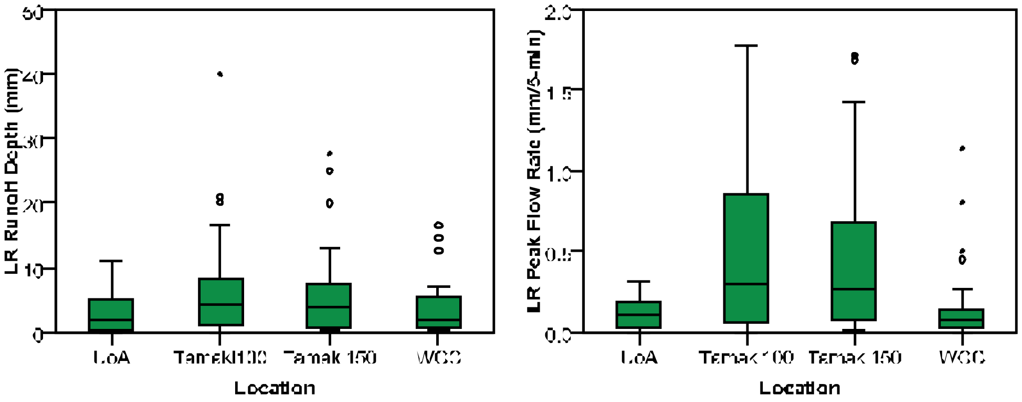


Figure 3: Incomparable Plot Sizes Amongst Sites Contributing to Differences in Horizontal Flow Path Length to Outlet

Substrates designed to maximize water holding capacity (Fassman et al. 2010) clearly benefits retention, as substantial control is realized on all roofs. Results suggest the configuration of a proposed living roof may influence the extent of peak flow control provided. To maximize peak flow mitigation, design should also extend the length of the horizontal flow path to the vertical gutters. Increased physical resistance within the drainage layer could also be used to increase peak flow reduction, for example, using a granular drainage media rather than the egg-crate type synthetic drainage layers used at the testing sites. Insufficient data has been collected to date to identify specific design thresholds for peak flow control, and it is recognized that peak flow control at Tamaki was still significant. However, future research on peak flow control should identify scaling influences such as flow path length.

5 RESULTS AND DISCUSSION: WATER QUALITY

The capacity of living roofs to retain and/or release pollutants is influenced by substrate composition, fertilisation practices, roof age, and the density of vegetation. International literature also identified that spatial differences in the dry deposition of dusts and atmospheric aerosols (local pollution sources based on zoning—industrial, residential, or commercial—or external influences such as traffic intensity etc.), supplemental irrigation and/or climate factors contribute to differences in runoff quality (Aitkenhead-Peterson et al., 2010, Berndtsson et al., 2009).

The annual pollutant load from a living roof is lower than a conventional roof since total annual runoff from a living roof is reduced by ~40~70% in the Auckland extensive living roofs studied However, pollutant concentrations in runoff from living roofs are not necessarily the same as in runoff from conventional roof surfaces.

In most applications, a living roof "treats" only the precipitation falling directly onto the living roof surface. The potential sources of contaminants in living roof runoff are 1) substrate or drainage materials; 2) plants; 3) atmospheric deposition in dust and rainfall; 4) fertilizer, herbicides, or pesticides used to maintain plants; 5) the underlying building/waterproofing surface or materials. Within the current research, substrate composition and chemistry were investigated to understand contaminant concentrations in runoff.

The key questions with respect to runoff quality are:

1. Does a living roof discharge runoff that contains contaminants? If so, what is the source of the contamination and are levels different to those of conventional roofs?

2. Do different living roofs discharge different quality runoff?

Eight storms were sampled from each of the Tamaki and WCC study sites (i.e. 3 living roofs and 2 control roofs). The Tamaki mini-roofs were approximately 2.5 yrs old when sampling commenced, whereas the majority of the WCC living roof was approximately 4 yrs old, with the retrofitted area having 1-yr-old material.

Capturing water quality samples from living roofs is problematic as a substantial amount of runoff must be generated for automatic samplers to operate successfully, and/or to generate adequate sample volume to fulfill analytical requirements. This means many of sampled storms were somewhat larger events (Table 8), and often occurred after a relatively short antecedent dry period. Runoff retention during the sampled events was generally lower than the majority of the hydrologic record (Table 8).

Table 8: Range of Hydrologic Characteristics of Sampled Events for Water Quality

	Tamaki 100	Tamaki 150	WCC
Rainfall Depth (mm)	13.2-58.4		8.8-57.4
Retention (%)	19-81	15-77	23-95

5.1 OVERALL WATER QUALITY: EMCS

Summary water quality EMC characterisation is presented in Table 9. Data for the Tamaki mini-roofs are the average of EMCs determined for sheds with the same substrate depth.

Table 9: Mean and Median Water Quality EMCs from Eight Sampled Events at Each Site

		Parameter	TSS (mg/L)	NOx (mg/L)	TN (mg/L)	SRP (mg/L)	TP (mg/L)	Sol Cu (µg/L)	Cu (µg/L)	Sol Zn (µg/L)	Zn (µg/L)
Tamaki	100 mm Living Roof	Mean	5.4	0.214	1.942	0.581	0.697	3.59	3.82	38.42	83.23
		Median	4.1	0.088	1.332	0.559	0.630	3.63	3.98	30.83	42.00
	150 mm Living Roof	Mean	8.0	0.313	2.220	0.776	0.934	4.14	5.00	41.67	88.79
		Median	5.2	0.231	1.680	0.633	0.710	3.79	4.73	30.00	43.00
	Living Roof Overall	Mean	6.7	0.263	2.081	0.679	0.815	3.86	4.41	40.04	86.01
		Median	4.8	0.143	1.601	0.596	0.669	3.63	3.98	30.83	42.00
	Control Roof	Mean	4.0	0.059	0.465	0.048	0.127	0.44	0.61	38.33	84.79
		Median	3.0	0.056	0.374	0.045	0.070	0.32	0.54	35.50	43.50
WCC	Living Roof	Mean	2.8	0.501	3.365	0.510	0.562	13.75	15.38	11.68	14.00
		Median	1.4	0.482	2.022	0.400	0.410	14.00	16.00	12.00	13.00
	Control Roof	Mean	1.8	0.065	0.414	0.006	0.012	14.60	15.84	13.90	15.53
		Median	1.8	0.040	0.235	0.005	0.011	8.20	9.00	7.55	8.65

<u>Abbreviations</u>

TSS = total suspended solids
NOx = nitrate + nitrate
TN = total nitrogen
SRP = soluble reactive phosphorus
TP = total phosphorus
SolCu = soluble copper
Cu = total copper
SolZn = soluble zinc
Zn = total zinc

5.2 IS LIVING ROOF WATER QUALITY DIFFERENT FROM CONVENTIONAL ROOF WATER QUALITY?

5.2.1 EMCS

The established living roofs are not a source of TSS or NOx in runoff. TSS EMCs from either living or control roof are quite low compared to typical runoff from streets or other ground-level urban land uses. With median TSS EMCs between 1.4 and 4.8 mg/L across all monitoring sites, TSS was barely above detection limits. Mean TSS and NOx EMCs do not differ statistically between living roof runoff or control roof runoff water quality ($p<0.005$);

Runoff from both living roofs is a source of nitrogen, primarily in the form of TKN as opposed to NO_x. NO_x is readily taken up by plants. Conversely, TKN is not plant-available, and is comprised of ammonia, ammonium, and organic nitrogen. Ammonia is toxic to aquatic organisms, whereas ammonium is not, but temperature and pH influence the balance between these two forms (higher temperature and higher pH increase the proportion of ammonia and its toxicity) (Abel, 2000; Camargo and Alonso, 2006; Emerson et al., 1975; Passel et al., 2007). Based on EMCs, living roof discharge may require additional treatment such as by bioretention with an internal water storage zone (Brown et al., 2009) prior to discharge to nutrient-sensitive receiving waters, or should be harvested. The low nutrient levels probably provide little fertilizer benefit for garden or living roof watering and does not prevent use for toilet flushing (e.g. as at the University of Otago's P3 building with a living roof).

Substrate chemistry including C:N, CEC, and base saturation leads to some hypotheses regarding conditions contributing to elevated TKN in the living roof runoff. A C:N (> 24) suggests that plants are under nitrogen stress, and therefore there should show low potential for N-leaching. High CEC (>40 me./100g [Blakemore et al., 1987]) is also indicative of low leaching potential for ammonium, if base saturation is less than 100% Barbarick (2006) found that ammonium tended to compromise the lowest concentration of nitrogen species sampled and hypothesized results were due to good cation exchange. Ammonia and organic nitrogen should not be influenced by CEC or base saturation.

The Tamaki zeolite showed a high C:N ratio (37 in 2008 and 2011) and CEC ($56.6\ \mathrm{cmol(+)\cdot kg^{-1}}$). As base saturation was 82%, some exchange sites should be available to capture positively charged nutrients such as ammonium. Both WCC substrates showed moderate C:N (15 for the original substrate measured in 2009 and 2011, 22-26 for the amended substrate measured in 2009 and 2011), high base saturation and low CEC, which indicates an overall reduced potential to store nutrients. Therefore there may be a balancing effect between CEC, base saturation, and C:N. Comparing nutrient needs for agricultural crops to those of stress-tolerant species suitable for living roof applications may be questionable; however, the new-ness of the technology leads to an absence of living-roof specific guidance.

Livings roofs discharge phosphorus; EMCs were substantially higher compared to the respective control roofs. Phosphorus is likely to originate from the organic component of the substrate. Most of the phosphorus measured in runoff was as SRP, which is readily available for plant growth. Olsen P measured for all substrates is considered relatively high (in 2011, 17 $\mathrm{mg\cdot kg^{-1}}$ for Tamaki mini-roofs, 32 $\mathrm{mg\cdot kg^{-1}}$ for WCC original substrates, and 45 $\mathrm{mg\cdot kg^{-1}}$ for WCC amended substrate), thus indicating a potential for leaching of SRP.

Heavy metals EMCs were site specific. Copper EMCs from the Tamaki mini-roofs were statistically greater (median 3.6 μg/L SolCu, 4.0 μg/L Cu) than those on control roof runoff (median 0.3 μg/L SolCu, 0.5 μg/L Cu), suggesting that the substrate and/or plants were a source of copper in the discharge. Copper can be highly mobile in soils, with moisture content and organic matter affecting mobility. As noted previously, sampled storms tended to be larger storms following short antecedent dry periods. It is hypothesized that a small storm which does not produce runoff may mobilize copper within the living roof substrate.

A subsequent storm occurring before the substrate completely dries and producing enough runoff to sample would therefore likely have elevated concentrations of copper.

Overall, copper EMCs from either of the living roofs are unlikely to be problematic. Median living roof SolCu EMCs (3.63 and 14.00 μg/L for Tamaki and WCC, respectively) are consistent with the range reported by Clark et al. (2008) for non-metal conventional roofs (2-14 μg/L), while living roof runoff Cu median EMCs (3.98 and 16.00 μg/L for Tamaki and WCC, respectively) is substantially lower than the given range for non-metal conventional roofing types (11-166 μg/L). SolCu from the Tamaki living roof has similar concentrations to three samples of Auckland rainfall (3.0-4.9 μg/L) reported by Pennington and Webster-Brown (2008).

Water quality EMCs were investigated for possible influences of rainfall characteristics. Pearson correlation coefficients were determined for LN transformed EMC data against rainfall depth, average rainfall intensity, and LN transformed peak rainfall intensity. NO_x and TN were negatively correlated with rainfall depth ($p=-0.406$ and $p=-0.488$, respectively), while SolCu and Cu were negatively correlated with peak intensity ($p=-0.446$ and $p=-0.416$, respectively). In other words, increasing rainfall depth dilutes nitrogen in living roof runoff, while increasing peak intensity dilutes copper concentrations. With respect to nitrogen, the implication is that smaller storms that do produce runoff but were not able to be sampled may generate higher nitrogen EMCs than were able to be measuredin this study.

5.2.2 MASS LOADS

Statistically significant differences in mass loads per event were detected between each living roof and its corresponding control for TN, SRP, and TP ($p<0.04$). At Tamaki, differences were also detected for SolCu and Cu ($p<0.03$), while at WCC, differences were also detected for NO_x ($p<0.04$). Copper is not likely problematic for either living or control roof runoff at Tamaki. The statistical difference in SolCu or Cu detected between the Tamaki living and control roofs are likely due to the very small EMCs in the runoff and its effect on the mass load calculation.

The mass load and EMC of TSS and heavy metals (soluble and total forms) from the living roofs per event are statistically comparable to runoff from the conventional roofs at the same location (Table 9). The shed itself is the likely source of any zinc in the runoff at Tamaki (Section 2). Many of sampled storms were somewhat larger events (Table 8), and often occurred after a relatively short antecedent dry period. As noted previously, runoff retention during the sampled events was generally lower than the majority of the hydrologic record. Therefore, the living roof's reduced hydrologic performance for these individual events may be the key reason that a difference in mass loads is not detected for these parameters on an individual event basis. Typically no runoff would be generated from the living roofs during storms smaller than 40 mm (Section 4.1.1), which also means there would be zero mass of pollutants discharged for these frequently occurring events. In a long-term cumulative mass loading, due to the substantial level of runoff retention, it is likely that the living roof at either site monitored contributes significantly less TSS or heavy metals' load than the corresponding control roof. However, in the case of TSS, it is noted that the very low EMCs from all of the sites suggest that the comparison is somewhat meaningless; TSS does not appear to be problematic in runoff from any of the monitored roofs.

Mass loads of nutrients from the living roofs are statistically greater than from the control roofs, per storm event. The result is generally consistent with the international literature. As the living roof nutrient EMCs are in the range of an order of magnitude greater than the control roof EMCs, an order of magnitude reduction in runoff volume would be required to balance the long-term load, despite the observation that typically no runoff would be discharged for the majority of individual events. Responsible stormwater design for living roofs located in nutrient sensitive receiving watersheds would consider a treatment train. The treatment train would direct living roof runoff from large storm events to ground-level or subterranean devices with nutrient-specific pollutant removal mechanisms, or be harvested for non-potable reuse. Alternatively, indicators or thresholds for organic matter (compost) that minimise contaminant leaching should be established (e.g. minimum C:N, maximum Olsen P, minimum CEC and maximum Carbon content) and applied to substrate specifications.

5.3 DOES LIVING ROOF WATER QUALITY DIFFER SIGNIFICANTLY BETWEEN SITES?

Amongst the three living roofs, there was no difference TSS or nutrient EMCs. For heavy metals, EMCs were not statistically difference when comparing each living roof to its corresponding control roof; however, copper EMCs were higher from WCC roofs overall, while zinc EMCs were higher from Tamaki roofs overall.

The Tamaki mini-roofs are constructed atop Colour Steel roofs, and atypically (for a living roof) without another waterproofing layer, and uses more than 20 galvanized zinc rivets. Timperley et al. (2005) reported 11 and 8.1 μg/L median Zn EMCS in runoff from Colour Steel roof runoff for residential and commercial areas, respectively. As a synthetic drainage layer does not act as a hydraulic barrier, mini-roof roof runoff will come into contact with the shed roof and rivets. As the majority of zinc detected in the runoff was in dissolved form (SolZn), and statistically, there is no difference in mean SolZn or Zn EMC from the living roof compared to the control roof, contact between runoff and the building materials are the most likely source. Low zinc in the Tamaki substrate (39 mg kg^{-1}) compared to either WCC substrates (70 mg kg^{-1} and 58 mg kg^{-1}, respectively for the original and amended substrates), but higher runoff zinc EMCs from the Tamaki mini-roofs further confirms that the living roof is not the source of zinc in runoff at either site.

Copper EMCs in the WCC living roof runoff are 3-4 times greater than the Tamaki living roof runoff, while the WCC control roof runoff copper EMCs are an order of magnitude greater than the Tamaki control roof. Several factors may explain why WCC living roof runoff has greater copper EMCs than the Tamaki living roofs. The Tamaki substrate contains three times less copper (5 mg kg^{-1}) compared to the WCC substrates (16 mg kg^{-1} and 14 mg kg^{-1} for the original and amended substrates, respectively). Combined with a lower C:N for the WCC substrates and lower plant cover, carbon mineralization and leaching could contribute to copper mobility. The original WCC substrate also has about half the CEC of the Tamaki substrate, hence a lower ability to capture positively charged heavy metal ions. Median copper EMCs from the WCC living roof are slightly, but not significantly higher than the WCC control roof EMCs. The difference (living roof EMC – control roof EMC) is comparable to the difference between the Tamaki living roofs and control roof. Thus, the explanation of higher copper EMCs from the Tamaki living roofs compared to control roof also applies to WCC.

Confounding the issue, copper EMCs from the WCC control roof are not statistically different from WCC living roof. The WCC living and control roofs are adjacent to a large copper dome, which may be the source. While this hypothesis has not been specifically tested, it is at present, a plausible source to explain the presence in both living and control roof runoff at elevated levels.

Altogether, results suggest that zinc or copper materials or adornment to building facades could elevate runoff EMCs at adjacent sites.

6 CONCLUSIONS

Significant and consistent runoff control was measured from four extensive living roofs with different design configurations and in three locations across Auckland.

6.1.1 PEAK FLOW CONTROL

All monitored living roofs effectively mitigated peak flow, with median living roof runoff peak flow measured at 62-90% less than a corresponding control roof per storm event. Peak flow control was not influenced by season at any site. Living roof configuration, namely flow path length through the drainage layer to vertical gutters and drainage layer material, may influence effectiveness and could be manipulated to increase mitigation.

6.1.2 VOLUME CONTROL

Living roofs achieved up to 56% cumulative runoff retention compared to a conventional roof surface on a long-term basis. Mitigation was maintained across seasons, with summer retention at 83-92% (depending on living roof site) decreasing to 66% in winter (one site). Between the four living roofs ranging 50 mm-150 mm substrate depth, sites were equally effective in reducing runoff volume compared to a control roof, despite design differences (namely in substrate composition and installed depth).

The predominance of small storm events (< 15-25 mm) in Auckland means that shallow substrates with high water holding capacity provide effective stormwater control because the system’s storage capacity is rarely exceeded.

Although a 50 mm depth living roof is probably less expensive to construct, greater substrate depth increases plant-available moisture, hence reducing plant stress or irrigation requirements (Fassman *et al.*, 2010; VanWoert *et al.*, 2005) and also allows taller plants and a wider ranges of species to be grown (Fassman and Simcock 2012). A minimum 100 mm substrate depth is recommended whenever structural loading is adequate to promote plant resilience and diversity in the absence of irrigation and/or shade.

6.1.3 WATER QUALITY

The effect of living roof on water quality is not as clearcut as on volume and peak flow control. Comparison of water quality from two sites with different substrates and different control roof surfaces on an event-basis indicates:

- Living roofs are not a source of TSS or NOx. Neither Auckland living roofs nor control roofs contribute elevated EMCs in roof runoff.

- Roof runoff quality in general appears highly site-specific. On a comparative basis with control roofs monitored concurrently, Auckland living roofs perform similarly to reports from the international literature, with the exception of nitrogen, which is likely due to differences in atmospheric deposition.

- Building materials and ornaments are likely sources of heavy metals in living roof runoff, either when runoff comes into contact with the material, or the material is in close proximity for air-borne deposition. Elevated zinc or copper in living roof runoff depends on site-specific building materials rather than the living roof itself. However, as copper can be mobile in soils and affected by organic content and moisture levels, living roof substrate composition should have low copper concentrations. As living roofs provide significant long-term hydrologic control, covering, replacing, or substituting a metal roof with a living roof will likely reduce the long-term mass loading from the site.

- Living roofs are likely to generate phosphorus in New Zealand. Living roofs located in nutrient sensitive receiving watersheds should consider a treatment train. The treatment train would direct living roof runoff from large storm events to ground-level or subterranean devices with nutrient-specific pollutant removal mechanisms, or be harvested for non-potable reuse. Organic matter composition requires careful specification to reduce potential for Cu, and nutrient leaching.

Future research to refine substrate and system components will further improve living roofs' capacity for stormwater management. Recommended research includes:

- Identifying indicators or thresholds for organic matter (compost) chemistry that prevent contaminant leaching. This paper contributes substantial initial hypothesis with only limited testing.
- Coupling of water quality results with a calibrated continuous simulation hydrologic model. While the sampling that has occurred to date provides analysis with statistical confidence, additional sampling is recommended particularly to determine the breakdown of nitrogen species in runoff.
- Quantifying the impact of introducing physical resistance within the drainage layer to peak flow control

ACKNOWLEDGEMENTS

This study was funded by the former Auckland Regional Council through the Stormwater Action Plan, the former Waitakere City Council, and the Foundation for Research Science and Technology. Continued work is supported through the Auckland Council Stormwater Technical Services Team. Viewpoints expressed in this paper are those of the authors and do not reflect policy or otherwise of the Auckland Council or former Councils. The authors would like to thank technician Chris Winks from Landcare Research for his assistance with this research.

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