# Hydrology and Water Quality of Living Roofs in Auckland

## Hydrologie et qualité de l'eau de plusieurs toitures végétalisées à Auckland

Elizabeth Fassman-Beck[1], Ph.D., Robyn Simcock, Ph.D.[2]

1:University of Auckland, Dept. of Civil and Environmental Engineering, Private Bag 92109, Auckland Mail Centre, Auckland 1142, New Zealand
2:Landcare Research, Ltd., Auckland 1142, New Zealand

## RÉSUMÉ

Trois toitures végétalisées extensives (TVE) ont fait l'objet d'un suivi sur des périodes de 8 mois à environ 1 an afin de réaliser un bilan hydrique. Pour chaque TVE, 8 évènements pluvieux ont été échantillonnés pour évaluer la qualité de l'eau et la comparer à des données de toitures conventionnelles situées au même endroit. L'analyse de chaque évènement pluvieux a mis en évidence que les TVE, conçues avec un substrat de 100-150 mm d'épaisseur pour maximiser le stockage de l'eau, ont retenu 56 à 72 % du volume de ruissellement. Les eaux de ruissellement provenant des toitures végétalisées et conventionnelles ne contenaient pas de teneurs élevées en matière en suspension (MES) ou nitrite + nitrate (NOx). Alors que cuivre et zinc proviennent tous deux des matériaux de la toiture, le cuivre peut également provenir des substrats de TVE. L'orthophosphate et l'azote Kjeldhal sont les principaux nutriments rejetés à des concentrations élevées par les TVE. En cas d'installation dans des bassins versant sensibles aux nutriments, l'intégration des TVE dans une chaine de traitement devrait être envisagée. Des hypothèses concernant les caractéristiques en matière organique des substrats sont suggérées pour minimiser la lixiviation des polluants (i.e. rapport carbone/azote, phosphore Olsen, capacité d'échange cationique et contenu en carbone). Cependant des recherches complémentaires sont nécessaires afin d'adapter l'interprétation de ces paramètres d'un point de vue agricole pour des applications spécifiques.

## ABSTRACT

Three extensive living roofs in Auckland have been monitored over periods of 8 months to ~1 yr for stormwater quantity, while 8 storms were sampled at each location for water quality compared to conventional roofs at the same locations. Individual event analysis measured 56%-72% runoff retention by living roofs with 100-150 mm depth substrates designed to maximize water storage. Neither living nor conventional roof surfaces produced elevated suspended solids (TSS) or nitrate+nitrite ($NO_x$). Copper may be sourced from living roof substrates, while both copper and zinc are sourced from roofing materials. Soluble Reactive Phosphorus (SRP) and Total Kjeldhal Nitrogen (TKN) are the predominant nutrients discharging at elevated concentrations from living roofs. 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), but more work is required to adapt agricultural interpretations of these parameters to the specific application.

## KEYWORDS

Green roof, Hydrology, Living roof, Performance indicators, Water quality

# 1 INTRODUCTION

Living roof technology is increasingly being used to manage stormwater in dense urban centres. Rooftops comprise a significant proportion of the total impervious area in urban settings; considerable opportunity exists to mitigate runoff hydrology by retrofit of existing building stock, where building structures can support the additional weight. 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 typically unused space (rather than valuable ground space). Living roofs generally also reduce roof temperatures and reflectivity, co-benefits that are not offered by ground-level devices

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, social and aesthetic benefits. A living roof is also commonly referred to as green roof, eco-roof, vegetated roof, roof garden or landscape over structure.

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 (growing media) or drainage materials; 2) plants and animals (namely birds); 3) atmospheric deposition in dust and rainfall; 4) fertilizer, herbicides, or pesticides used to maintain plants (that can also drift from adjacent areas onto the roof); 5) the underlying building/waterproofing surface or materials.

Living roof water quality data is relatively scarce in the literature. Consolidation of information across studies is challenging. Methods used to collect data vary (specifically, very few report event mean concentrations) as does data analysis and presentation. Studies rarely report living roof water quality results in comparison to rainfall and/or conventional roof runoff, either as absolute magnitudes or as %-differences. Even within studies, difficulties were encountered interpreting water quality results due to contrary or inconclusive results from different runoff events (Carpenter and Kaluvakolanu 2011, Teemusk and Mander 2007).

Published studies are inconclusive regarding whether a living roof acts as a source or sink of TSS is (Carpenter and Kaluvakolanu 2011, Lang 2010, Mendez et al. 2011, Wanielista et al. 2007). A wide variation of results is reported for nitrogen species in living roof runoff. In some cases, living roofs were found to be a sink for rainfall-derived nitrogen (Berndtsson et al., 2009, Bliss et al., 2009), whereas others found the living roofs to be a source of nitrogen concentration compared with rainfall (Aitkenhead-Peterson et al., 2010, Berndtsson et al., 2006, Moran et al., 2005, Teemusk and Mander, 2007). All studies comparing conventional roof runoff with living roof runoff identified living roofs as a nitrogen sink, or of negligible difference in response (Carpenter and Kaluvakolanu, 2011, Gregoire and Clausen, 2011, Lang, 2010, Mendez et al., 2011, Moran et al., 2005, Teemusk and Mander, 2007, Wanielista et al., 2007, Bliss et al., 2009). Phosphorus monitoring studies largely conclude that living roofs are a source of either total phosphorus (TP) or phosphate when compared to either rainfall or conventional roof runoff (Aitkenhead-Peterson et al. 2010, Berndtsson et al. 2006, 2009, Bliss et al. 2009, Gregoire and Clausen, 2011, Hathaway et al. 2008, Lang 2010, Long et al. 2007, Moran et al. 2005, Wanielista et al., 2007).

Although living roofs may provide inconsistent water quality improvement, conventional roof surfaces generally do not provide any water quality improvement. Several studies have shown that conventional roof materials may add to water quality impairment, particularly for copper (Clark et al. 2008, Lamprea and Ruben 2011, Timperely et al. 2005), but also for pathogens. The latter, primarily within the so-called ‘first flush’ is the key constraint is use of roof runoff for potable water supply in cities (Abbot et al. 2006, Eason 2007).

Within the current research, substrate composition and chemistry from three living roofs with two different substrates 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?

Performance monitoring of four “mini” living roofs (i.e. pilot-scale) at Landcare Research in East Tamaki, (East Auckland, the Tamaki mini-roofs) and a full-scale system atop Waitakere City Council’s Civic Centre (WCC) in Henderson (West Auckland) is used to address these questions.

## 2 METHODOLOGY

The studied living roofs are all classified as extensive living roofs, installed on low- or nearly flat roofs (≤ 2% pitch) (Figure 1). The 100 to 150 mm deep substrates are 80% by volume (v/v) light-weight aggregate and 20% v/v organic matter and were installed over a synthetic drainage layer with a geotextile providing separation. Substrate composition and plant species selection were determined as part of a larger research programme to develop locally (Auckland) suitable, non-proprietary specifications for living roofs intended for stormwater management. Additional details regarding design, specification, and construction are provided in Fassman et al. (2010), while discussion specifically related to substrates is found in Fassman and Simcock (2012).

Figure 1. Site descriptions.

### 2.1 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” (pilot-scale) living roofs at the Landcare Research office in East Tamaki. The mini living roofs are built on reinforced garden sheds with Colour Steel roofs. Mini-roofs are covered with 100 mm or 150 mm depth of substrate (referred to as Tamaki 100 mm and Tamaki 150 mm, respectively). Within the larger research programme, duplication of systems with equal substrate depths was primarily intended to verify hydrologic performance, the results of which are presented elsewhere (Fassman-Beck et al. 2013). At least 80% plant coverage (New Zealand native and non-native species, including succulents, low-growing groundcovers, grasses, and herbs) was established by the time of water quality monitoring. The systems were ~2.5 years old by the time water quality monitoring commenced in Dec. 2010.

One additional shed was constructed without a living roof (a control roof) for concurrent monitoring. Resource limitations precluded duplication of the control roof.

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 custom-designed orifice restricted device (ORD) and Global Water WL16USB pressure transducer rated for 0-0.91 m depth (Voyde et al. 2010). Rainfall was measured 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). All data was logged continuously at 5-min intervals.

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). 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 (an IANZ-accredited laboratory) with appropriate preservatives for heavy metal and/or nutrient content. All samples were stored with ice packs until being couriered within 24 hr to the laboratory for analysis. Water quality constituents assessed, testing methods, and their respective analytical method detection limits (MDL) are summarized in Table 1.

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.

Table 1: Laboratory Testing Methods and Parameter Method Detection Limits (MDL)

| 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 |
| Copper: Soluble and Total | SolCu<br>Cu | USEPA 200.8, modified, by ICPMS-Trace | 0.0002 | mg/L |
| Zinc: Soluble and Total | SolZn<br>Zn | USEPA 200.8, modified, by ICPMS-Trace | 0.001 | mg/L |

## 2.2 WCC Living and Control Roofs

The WCC living roof was constructed in mid-2006 and modified in 2009. This 500 $m^2$ roof has a substrate blend of 60% v/v pumice, 20% v/v imported expanded clay and 20% v/v compost-based garden mix, with an additional 4–8 mm deep expanded clay “mulch”. Only native plants were used on this roof. The 2009 modification supplemented substrate depth in isolated areas using substrate based on the mini-roof recipe, such that an overall ~100 mm depth was achieved, with isolated mounds of up to 150 mm. Although a different substrate recipe was used, the majority of the roof draining to the monitoring point was not amended. Water quality monitoring commenced ~1 yr after the modifications.

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.

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. Sample collection settings ensured that the entire storm hydrograph was well-represented. Sample compositing followed standard volumetric flow-weighting protocols, the analysis of which generates EMCs.

All bottles for sampling and equipment used for compositing were washed with phosphate free detergent, rinsed with diluted 10% hydrochloric and nitric acid, and a final rinse of de-ionised water. Each composite sample was tested for the same water quality parameters by Watercare Services as the Tamaki mini-roofs (Table 1).

## 2.3 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 some water quality parameters where data transforms failed to yield normal distributions.

## 2.4 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 (P), total phosphorus, cation exchange capacity (CEC), base saturation, total copper, and total zinc. 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.

# 3 RESULTS AND DISCUSSION

## 3.1 Hydrology

Data are analyzed per event, considering only data for storms 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.

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. Combinations were used for 8 of the 166 rainfall events from the Tamaki mini-roofs, and 8 of the 79 rainfall events on the WCC living roof.

Runoff depth from all living roofs was significantly lower than that measured from control roofs ($p<0.001$ for all sites) (Figure 2). Large performance data variability was measured amongst events, as evidenced by extent of the interquartile ranges. Compared to adjacent control roofs, median volumetric retention was 56%, 66%, and 72%, for the Tamaki 100 mm, 150 mm, and WCC living roofs, respectively. Despite the apparent difference in median %-retention amongst the mini-roofs of differing substrate depths, there was no statistically significant difference ($p=0.05$) in runoff depth between them.

The most frequently measured runoff depth (the mode) amongst living roofs was 0 mm for storms up to ~20 mm. This is due to substrates having a moisture storage capacity of 20-36 mm and most storms being less than this depth; a frequency analysis indicating that 80% of individual events delivered less than 15 mm of precipitation (Fassman and Simcock 2012; Fassman-Beck et al. 2013).

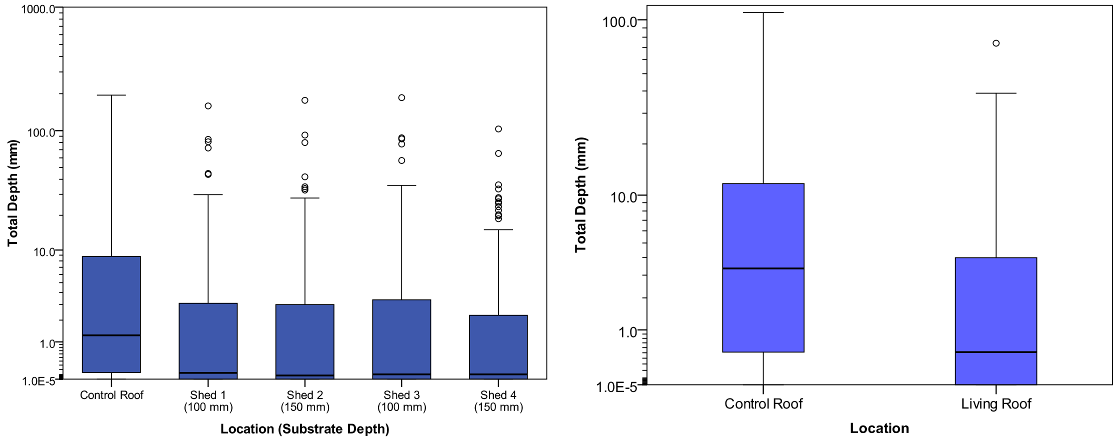

Figure 2. Runoff depth from the Tamaki mini-roofs (LEFT) and WCC roofs (RIGHT)

## 3.2 Water Quality

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 fulfil analytical requirements. Many of sampled storms were somewhat larger events with rainfall median 28.5 mm and maximum 58.4 at Tamaki, and median 21.5 mm and maximum 57.4 mm at WCC, 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 (Section 4.1) with median 32% and minimum 19% at Tamaki 100, median 40.5% and minimum 15% at Tamaki 150, and median 51.5% and minimum 23% at WCC.

### *3.2.1 Overall water quality: EMCs*

Summary water quality EMC characterisation is presented in Table 2. Statistically, there were no differences in living roof water quality amongst the Tamaki mini-roofs for any parameter. Average data are presented from these systems for each parameter. With the exception of TSS, Fairly significant variation was measured between storm events, as indicated by the relatively large extent of the 95% confidence intervals compared to the median value.

Table 2: Median Water Quality EMCs ± 95% Confidence Interval from Eight Sampled Events at Each Site

| | Tamaki | | WCC | |
|---|---|---|---|---|
| Parameter | Living Roof | Control Roof | Living Roof | Control Roof |
| TSS (mg/L) | 4.8 ± 2.7 | 3.0 ± 2.1 | 1.4 ± 1.6 | 1.8 ± 0.5 |
| $NO_x$ (mg/L) | 0.143 ± 0.17 | 0.056 ± 0.02 | 0.482 ± 0.24 | 0.04 ± 0.05 |
| TN (mg/L) | 1.601 ± 0.73 | 0.374 ± 0.19 | 2.022 ± 2.97 | 0.235 ± 0.28 |
| SRP (mg/L) | 0.596 ± 0.20 | 0.045 ± 0.01 | 0.40 ± 0.15 | 0.005 ± 0.0 |
| TP (mg/L) | 0.669 ± 0.25 | 0.07 ± 0.13 | 0.41 ± 0.16 | 0.011 ± 0.0 |
| Sol Cu (µg/L) | 3.63 ± 0.7 | 0.32 ± 0.2 | 14.0 ± 2.2 | 8.2 ± 9.3 |
| Cu (µg/L) | 3.98 ± 1.0 | 0.54 ± 0.2 | 16.0 ± 2.0 | 9.0 ± 9.7 |
| Sol Zn (µg/L) | 30.83 ± 11.3 | 35.5 ± 10.2 | 12.0 ± 1.5 | 7.55 ± 10.0 |
| Zn (µg/L) | 42.0 ± 50.3 | 43.5 ± 75.6* | 13.0 ± 2.4 | 8.65 ± 10.7 |

* One storm event generated 350 µg/L. Excluding this event results in median 39.0 ± 16.4 µg/L.

### *3.2.2 Is living roof water quality different from conventional roof water quality?*

The established living roofs are not a source of TSS or $NO_x$ 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. ANOVA on LN-transformed data indicates mean TSS EMCs do not differ statistically between living roof runoff or control roof runoff water quality ($p<0.005$). Likewise, non-parametric tests did not show statistical differences between between living roof or control roof $NO_x$, despite seemingly large differences in medians (Table 2). The lack of statistical difference is potentially due to testing distributions rather than means with the non-parametric approach.

Runoff from all the living roofs monitored 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 less plant-available, and is comprised of ammonia, ammonium, and organic nitrogen. Based on EMCs, living roof discharge may require additional treatment prior to discharge to nutrient-sensitive receiving waters, or should be harvested. The low nutrient levels provide little fertilizer benefit for garden or living roof watering and does not prevent use for toilet or urinal flushing.

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 high 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 cmol(+)·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 and statistically ($p=0.000$) higher compared to the respective control roofs. 1-2.5 yrs' establishment does not appear to reduce the potential for phosphorus leaching below levels of concern for sensitive receiving environments. 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 mg·kg$^{-1}$ for Tamaki mini-roofs, 32 mg·kg$^{-1}$ for WCC original substrates, and 45 mg·kg$^{-1}$ for WCC amended substrate), thus indicating a potential for leaching of SRP. New Zealand sheep farmers would likely not fertilize grass if Olsen P > 20 and dairy farmers would not fertilise if Olsen P was > 40 to 50.

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 that is completed retained may nonetheless mobilize copper within the living roof substrate. A subsequent larger storm would likely flush out this mobilized 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).

### *3.2.3 Does living roof water quality differ significantly between sites?*

Amongst the living roofs, there was no difference TSS or nutrient EMCs ($p>0.05$). 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 on Colour Steel roofs, and atypically (for a living roof) without another waterproofing layer (i.e. a membrane), and use more than 20 galvanized zinc rivets per shed. Timperly 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 is 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 ($p>0.7$). The WCC living and control roofs are adjacent to a large copper dome, which may be an additional 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.

## 4 CONCLUSIONS

The effect of a living roof on water quality is not as clearcut as the substantial hydrologic benefits. 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 $NO_x$. 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.
- Living roofs are likely to generate phosphorus and some forms of nitrogen 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.

## 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 former students Yit Sing Hong and Dr. Emily Voyde, and technician Chris Winks from Landcare Research for assistance with this research.

## LIST OF REFERENCES

Abbott S.E., Caughley B.P. and S.J. Bell 2004: Microbiological health risks of roof-collected rainwater. *Water & Wastes in New Zealand.* 134; 26-27.

Aitkenhead-Peterson, J. A., Dvorak, B. D., Volder, A. & STANLEY, N. C. (2010). Chemistry of growth medium and leachate from green roof systems in south-central Texas. *Urban Ecosystems*, 1-17.

Barbarick, K. A. (2006). Nitrogen sources and transformations. *Crop series. Soil; no. 0.550* Fort Collins, CO, USA: Colorado State University Extension Service.

Berndtsson, J.C., Bengtsson, L., Jinno, K. (2009). Runoff water quality from intensive and extensive vegetated roofs. *Ecological Engineering,* 35**,** 369-380.

Berndtsson, J.C., Bengtsson, L., Jinno, K. (2006). The influence of extensive vegetated roofs on runoff water quality. *Science of The Total Environment*, 355(1–3): 48-63.

Blakemore, L. C., Searle, P. L., Daly, B. K. (1987). *Methods for chemical analysis of soils*, Lower Hutt, N.Z. : NZ Soil Bureau, Dept. of Scientific and Industrial Research, 1987.

Bliss, D. J., Neufeld, R. D. & Ries, R. J. (2009). Storm Water Runoff Mitigation Using a Green Roof. *Environmental Engineering Science,* 26**,** 407-418.

Carpenter, D, and P Kaluvakolanu. (2011). Effect of Roof Surface Type on Storm-Water Runoff from Full-Scale Roofs in a Temperate Climate. *Journal of Irrigation and Drainage Engineering* 137 (2011): 161-169.

Clark, S. E., K. A. Steele, et al. (2008). Roofing materials' contributions to storm-water runoff pollution. *Journal of Irrigation and Drainage Engineering* 134(5): 638-645.

Eason C. (2007). Low Impact Urban Design and Development (LIUDD), raintank water quality and human health. Report prepared for Landcare Research NZ Ltd, May 2007. CE Research Associates.

Fassman, E. and Simcock, R. (2012). Moisture Measurements as Performance Criteria for Extensive Living Roof Substrates. *Journal of Environmental Engineering* 138(8):841-851.

Fassman, E.A., Simcock, R., Voyde, E. (2010). Extensive Green (Living) Roofs for Stormwater Mitigation: Part 1 Design and Construction. Auckland UniServices Technical Report to Auckland Council. Auckland Council TR2010/017.

Fassman-Beck, E., Simcock, R., Voyde, E. Hong, Y.S. (2013). 4 Living Roofs in 3 Locations: Does Configuration Affect Runoff Mitigation? *Journal of Hydrology* 490(2013):11-20.

Gregoire, B. and Clausen, J. (2011). Effect of a modular extensive green roof on stormwater runoff and water quality. *Ecological Engineering* 37(2011):963-969.

Hathaway, A. M., Hunt, W. F. & Jennings, G. D. (2008). A field study of green roof hydrologic and water quality performance. *Transactions of the ASABE,* 51**,** 37-44.

Landcare Research (2008). Methods used to analyse soils and water. http://www.landcareresearch.co.nz/services/laboratories/eclab/eclabtest_list.asp.

Lang, S. (2010). *Green roofs as an urban stormwater best management practice for water quantity and quality in Florida and Virginia.* Doctor of Philosophy, University of Florida.

Long, B., Clark, S., Baker, K. & Berghage, R. D. (2007). Selecting a Green Roof Media to Minimize Pollutant Loadings in Roof Runoff. *2nd National Low Impact Development Conference.* Wilmington, North Carolina, USA.

Mendez, C. B., Klenzendorf, J. B., Afshar, B. R., Simmons, M. T., Barrett, M. E., Kinney, K. A. & Kirisits, M. J. (2011). The effect of roofing material on the quality of harvested rainwater. *Water Research,* 45**,** 2049-2059.

Moran, A. C., Hunt, W. F. & Smith, J. T. (2005). Hydrologic and Water Quality Performance from Greenroofs in Goldsboro and Raleigh, North Carolina. *Green Roofs for Healthy Cities Conference.* Washington, D.C.

Pennington, S. and Webster-Brown, J. (2008). Stormwater runoff quality from copper roofing Auckland. *NZ Journal of Marine and Freshwater Research,* 42:99-108.

Shamseldin, A.Y. (2010). Review of TP10 Water Quality Volume Estimation. Prepared by Auckland UniServices Ltd for Auckland Regional Council. Auckland Regional Council Technical Report 2010/066.

Teemusk, A. & Mander, Ü. (2007). Rainwater runoff quantity and quality performance from a greenroof: The effects of short-term events. *Ecological Engineering,* 30**,** 271-277.

Timperly, M., Williamson, B., Mills, G., Horne, B., Hasan, M. Q. (2005). Sources and loads of metals in urban stormwater. *Technical Publication No. ARC04104.* Auckland: Auckland Regional Council.

Voyde, E., Fassman, E. A., and Simcock, R. (2010). Hydrology of an Extensive Living Roof under Sub-tropical Climate Conditions in Auckland, New Zealand. *Journal of Hydrology*, 394(2010), 384-395.

Wanielista, M. P., Hardin, M. D. & Kelly, M. (2007). The Effectiveness of Green Roof Stormwater Treatment Systems Irrigated with Recycled Green Roof Filtrate to Achieve Pollutant Removal with Peak and Volume Reduction in Florida. Florida Department of Environmental Protection.