The hydrological performance of a green roof in Sydney, Australia: a tale of two towers.

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Abstract:

This study describes the sister buildings Daramu house and International house in Barangaroo, Sydney (Australia's largest metropolitan city), with and without a green roof, respectively. Trace metal samples were collected from both roofs and analysed using ICP-MS to determine the bioretention potential of the green roof to remediate soluble and particulate stormwater trace metal contamination. Retention of ambient trace metal contamination by the green roof substrate was deemed significant for soluble copper and particulate zinc, chromium and copper. In addition, hydrological models (DRAINS and SWMM) were applied to predict the performance of the green roof to identify its ability to manage stormwater runoff and frequency, as well as to analyse the green roof's performance in complex surface flooding situations where storage or backwater effects occur in overflow routes and surface flows. Our results demonstrate a reduction in peak stormwater flow by 18.29 L/s (~50%) for storms as infrequent as 1 in 5 years, and peak flow reductions up to 90% storms of lower intensities. These results are significant as it demonstrates that a green roof could remediating trace metals contamination, thus reducing the impact on aquatic environments through stormwater runoff. It also highlights their potential to reduce stormwater flow, and utilise this additional water for evapotranspiration, leading to cooler ambient temperatures. Future works should aim to quantify the remediation effect of various planted species on *in-situ* green roofs, as well as determine the specific retention capabilities of various substrate compositions.

Keywords: Green roof, Hydrological performance, Low impact development, Rainfall detention, Sustainability, Stormwater.

Highlights

- Green roof reduced substrate bound soluble copper
- Reduction in particulate bound zinc, chromium and copper
- Significant reduction of peak flow for severe storms up to 1 in 10 years

1. Introduction

In recent decades there has been a global population shift into highly urbanised areas [1,2]. As a result, many cities worldwide have experienced an increase in the conversion of permeable surfaces to impervious ones. This results in many hydrological issues including; increased flood risk, reduced infiltration, and altered environmental flows [2]. Therefore, solutions that can mitigate the hydrological risk posed by urbanisation are required [3]. In many urban spaces, stormwater drainage is largely achieved using an impervious infrastructure network such as concrete lined gutters, cast iron catchpits, pipe and manhole networks, and canalisation with creeks [4]. These networks inevitably lead to an increase in stormwater runoff volumes, flow and flood peaks downstream. One solution is the implementation of water-sensitive urban design (WSUD), otherwise known as low impact developments (LIDs) in the USA or sustainable urban drainage systems (SUDs) in the UK. These technologies are intended to achieve a 'natural' hydrology through various integrated control measures and site layout [5].

The US EPA describes several LIDs that are effective for the management of stormwater such as biofilter beds, rain gardens, tree filters and permeable pavement [6]. However, many of these solutions require the conversion or use of surface level spaces which may otherwise be occupied by alternative structures. As such, urban green infrastructure, specifically green roofs, have been proposed as an effective tool for managing increase runoff in urban catchments [7]. Green roofs can be installed on new or existing buildings, with relative ease and minimal structural impact [8]. Green roofs provide a myriad of benefits and ecosystem services [9], including the mitigation of air pollutants [10,11], reductions in urban noise [12–14], increases in urban biodiversity [15–17], enhanced indoor/outdoor thermal regulation [18–22], decreases in building energy consumption [23,24], and improved stormwater management and retention [24–27].

Green roofs typically consist of several layers with varying depths; the uppermost vegetation layer, underlaid by a substrate layer, a root barrier and a drainage/waterproofing layer [28]. These serve to manage the surface water holistically [29], in line with the ideals of sustainable development [30] where surface water can be stored and utilised by plants to reduce runoff and increase retention [31]. Urban stormwater trace metal contamination is often ubiquitous due to diffuse sources such as industrial activity, buildings, vehicular parts and emissions, fuel and oils, and metallic road structures [32–35]. In addition to their water management potential, green roofs are also capable of improving the quality of runoff through the filtration and retention of natural and anthropogenic atmospheric contaminants and leachable roofing materials [36] such as copper, zinc, lead, chromium and cadmium [32,37–41]. Previous studies have identified green roofs as capable of reducing polycyclic aromatic hydrocarbons in runoff when compared to non-green roofs [42], however there have been some instances with green roofs contributing to the levels of heavy metal contaminants on roof surfaces [42].

Extensive green roofs, those with substrate depths less than 150 mm, have been modelled as an affective mechanism to reduce both building and city-wide stormwater runoff. A study conducted by Mentens et al. [26] predicted 54% and 2.7% reductions in building and city level stormwater runoff if 10% of buildings in Brussels utilised extensive green roofs [26]. However, the actual performance of green roofs varies greatly depending on various factors, including rainfall, green roof coverage, soil media, plant selection, preceding dry periods and roof slope [43–45]. Conn et al. [46] proposed that there was a correlation between soil thickness and water retention, and that this may change through time due to soil compaction. Meanwhile, the work of Villarreal and Bengtsson [47] highlighted the effects of roof slope and rainfall intensity on water retention, showing that steeper slopes and greater rainfall intensities both act to lower green roof retention performance.

Many numerical models have been used to further the understanding of the hydrological behaviour of green roofs under varying conditions [48–51]. Numerical modelling is a useful tool for the exploration of theoretical performance in a consistent and comparative manner by removing many of the uncertainties associated with dynamic input variables, thus eliminating the constraints brought on by study location variability [28]. However, even with identical model parameterisation, two numerical models can yield different performance results, leading to inconsistencies in the literature on theoretical performance [52]. Nonetheless, there is currently a lack of research that confirms many of the well understood (but often anecdotal) benefits of green roofs, especially with respect to geographically relevant stormwater management.

There are currently two primary studies that detail the performance of green roofs for stormwater retention in Australia. One study, by Razzaghmanesh and Beecham [53] describes the stormwater retention performance of experimental green roofs in the dry South Australian climate to be up to 74%, which is 12% higher than the global average as estimated by Zheng et al [52]. The second study, conducted by Razzaghmanesh et al aimed to assess quality of stormwater filtrate (soluble fraction) in relation to nutrient content and trace metals. Unfortunately this study did not compare the trace metal profile of the two experimental green roof types to their respective controls, however they did report on the concentrations of Cd, Cu, Pb and Zn being less than average concentrations of surface runoff reported by Göbel et al [54], and attribute what was observed to the organic fertilisers used. Despite these two studies, there is currently a lack of *in-situ* data from large scale commercial green roofs in dense Australian metropolitan areas to confirm their filtration and retention performance.

Currently most empirical green roof studies utilise experimental-scale green roof plots and controls [25,47,55–65], or larger installations with internal controls, or reference sites [36,66–70] which may not be completely representative of the sites tested. To address this, we compare an operational commercial green roof, and a near-identical neighbouring reference roof, with minimal spatial confounding effects. We aim to investigate the potential for extensive green roofs to reduce peak stormwater runoff and mitigate trace metal contamination prior to entering the catchment, in the largest metropolitan city in Australia (Sydney).

2. Methodology

2.1 *Site description*

This study was conducted on two sister-buildings [71] in Barangaroo, Sydney (33.8643◦S, 151.2028◦E) atop Daramu house and International house (green and conventional, respectively) (Figure 1). Sydney has a humid, subtropical climate, with a median annual rainfall of 1164 mm. Sydney's recent (2017-2022) yearly rainfall distribution is centred around the Summer months [72]. The median rainfall is presented in this instance to more accurately describe Australian rainfall due to the effect of extreme weather events (drought and flooding) from effecting the mean rainfall.

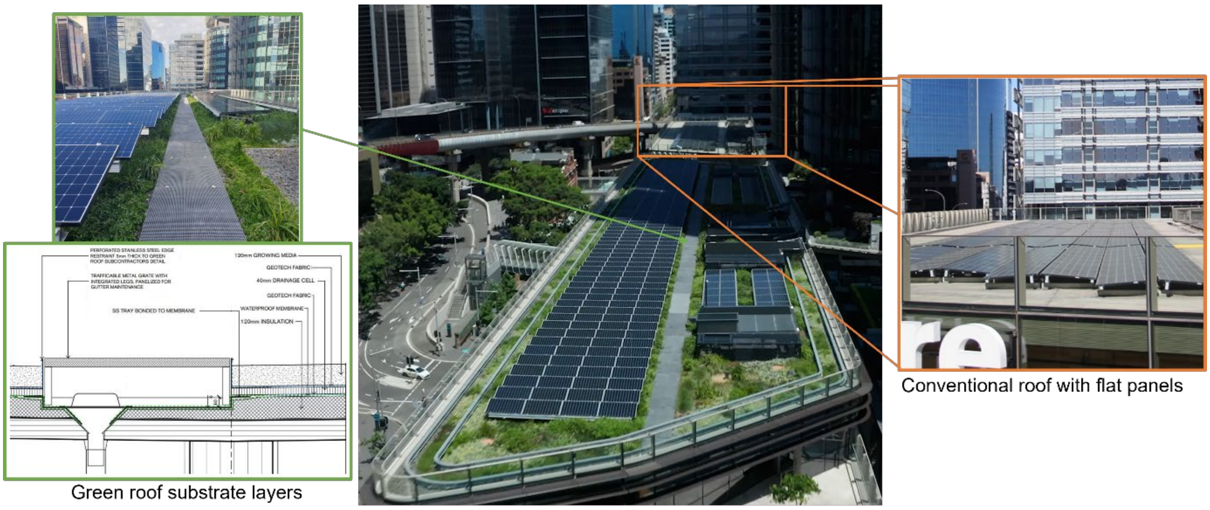

Figure 1. Aerial imagery of study site. Daramu house (green roof) featured in the foreground and International house (conventional roof) featured in the background. Sister buildings are near-identical with differences (excluding greenery) owing to BMU design, rooftop infrastructure, and solar panel layout. Left of image depicts the layering of the green roof, from substrate to insulation layers, as well as drain-outlet layout.

Both green and conventional roofs are 1863.35 m^2 with solar arrays covering 593.93 m^2 (~32%), and 567.44 m^2 (~30%) of roof space, respectively. The green and conventional roofs were completed in 2019 and 2017 and each feature a 0.8 m thick, grey concrete slab as the green roof foundation, or roof surface, respectively. Both buildings house rooftop infrastructure such as exhaust vents and machine rooms, with similar layout/positioning.

The green roof employs an extensive design and utilises an integrated subsurface irrigation system. Vegetation on the green roof covered an area of 1460.7 m^2 (78.4% of the roof space), with plant species and distribution being previously described in Wooster et al [17]. The green roof substrate has a variable depth of 0.1 and 0.12 m, a weight/weight particle size distribution of 48.6% < 2 mm, 48.4% 2-10 mm and 2.9% 10-20 mm, and a permeability of 3769 mm/h. More substrate details are provided in Fleck et al [22].

The two buildings are positioned side-by-side (Figure 1), with little confounding spatial variance. Due to their location, age, dimensions and construction, these two buildings presented a valuable opportunity to compare the *in-situ* performance of green roofs for stormwater flow reductions and trace metal retention/degradation.

2.2. Trace metal analysis

To determine the water quality of runoff from the green roof compared to the conventional roof, trace element analysis was conducted on composite samples collected on each roof. The method employed here is similar to previous work [63,73], with differences owing to the collection and preparation of solid samples, opposed to liquid samples.

Trace element samples were collected fortnightly from the North and South ends of each roof, provided there had been no rainfall in the preceding two-week period (Supplementary Figure 1). Previous literature [74] describes the build-up of contaminants prior to rainfall as achieving an equilibrium load after 10 days. In this instance a 14-day sampling period was deemed sufficient to ensure equilibrium load on each site was reached, provided there were no preceding rain events. As such, the trace element analysis conducted is representative of the potential trace contaminant load that could enter local stormwater management systems during rain events after a 10+ day dry period. *In-situ* runoff samples were not collected due to safe work procedures preventing roof access in poor weather.

Green roof substrate samples were taken by taking core samples of ~20 grams of substrate, and carefully removing any rocks or fertilizer pellets with plastic tweezers. Samples from the green roof were collected in areas which excluded the sub-surface irrigation to ensure leaching had not occurred prior to collection. Conventional roof samples were collected using a Ryobi One+Hand Vacuum (18V, Ryobi, Australia), where at least three 1 m^2 areas were sampled, per replicate to provide ~1 – 5 g of solid sample. Ten trace metal samples were collected per building over a three-month period (April – June 2021: gross rainfall 162.4 mm). Green roof substrate and conventional roof dust samples were collected as anthropogenic sources of trace metal contamination would be contained in the surface dust on rooftops. However, on a green roof there are many deposition surfaces for trace metals to settle. As such, substrate samples were taken as particulate matter would be deposited into the substrate through various mechanisms, and within the substrate there is the potential for bioretention and bioremediation. All samples were deposited into sterilised falcon tubes and transported to the laboratory for analysis.

Samples were dried in a drying oven at 65°C for 36 hours, weighed and transferred to sterile 50 mL falcon tubes and diluted with at least 45 mL of MilliQ water (Ω 18.2; Millipore, Germany). Samples were sonicated using a water bath sonicator for 15-minutes to disrupt any aggregated particles and ensure solubilisation of trace metals. Samples were then centrifuged at 4500 g, and the soluble fraction transferred to a new sterile falcon tube.

The particulate fraction was then digested in 1:1 69% v/v nitric acid and 30% v/v hydrochloric acid and made to volume with MilliQ to prepare for Solution Nebuilisation Induction Coupled Plasma Mass Spectrometry (SN-ICP-MS; 7700cx, Agilent, USA). Samples were processed in technical triplicate. A 12-point calibration curve was made from a 68-element standard (ICP-MS68A-500 Choice Analytical) in 2% HNO_3 / 1% HCl diluent. The calibration points were as follows: 5, 2.5, 1, 0.5, 0.25, 0.1, 0.05, 0.01, 0.005, 0.0025, 0.001 and 0 ppm.

Prior to analysis, samples were again digested in high purity nitric acid (15.6 M) in closed vessels using a microwave apparatus (MARS Xpress, CEM) according to US EPA method 3051A. Analysis of the collected samples focused on particulate phosphorus and the sorbed metals, primarily nickel (Ni), copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd) and chromium (Cr).

All SN-ICP-MS was performed using a 7700cx series ICP-MS (Agilent Technologies, USA) equipped with a micromistTM concentric nebuliser (Glass Expansion, Australia). A Scott type double pass sprat chamber cooled to 2°C was used for sample introduction. Platinum sampling and skimmer cones were used. ICP-MS analysis was controlled using the MassHunter 4.3 software (C.01.03) and all experiments used 99.9995% ultra-high purity liquid argon (Argon 5.0, Coregas Pty Ltd, Australia).

An Agilent integrated autosampler (AIS) was loaded with solutions for analysis. Solutions were transferred to the SN-ICP-MS using a 1.02 mm internal diameter Tygon tubing and a three-channel peristaltic pump. The solution was pumped at a continuous flow of 1.0 $mL.min^{-1}$. A 100 ppb Rhodium solution in 1% HNO_3 was used as an internal standard and introduced into the analyte flow via a T connector post-pump. ICP-MS settings and parameters are detailed in Table 1 below.

Table 1. SN-ICP-MS (7700cx, Agilent, USA) parameters used for trace metal analysis.

Sample Introduction	
RF power (W)	1500
Carrier gas flow rate ($L.min^{-1}$)	0.7
Makeup gas flow rate ($L.min^{-1}$)	0.5
Sample depth, mm	8
Ion lenses	
Extracts 1,2 (V)	3.8,-185
Omega bias, lens (V)	-120, 18
Cell entrance, exit (V)	-30,-40
Octopole parameters	
Octopole RF (V)	190
Octopole bias (V)	-8
Collision gas, flow rate ($mL.min^{-1}$)	0

ICP-MS trace element concentrations were mass corrected and differences between buildings for the soluble and particulate fractions were assessed using individual Mann-Whitney U tests. This analysis was chosen as the data did not satisfy the assumption of parametric testing. Analysis was conducted using R statistical software [75] and the packages; xlsx [76], tidyr [77] and dplyr [78].

Prior to sampling, a literature review (Supplementary Table 1) was conducted to predict the green roof's theoretical performance for the reduction of trace element concentrations. Roadside trace metal concentrations were sourced from the Qantas Drive (Mascot, Sydney) data set, and used as approximations of anthropogenic trace metal concentrations.

2.3. Modelling stormwater peak attenuation performance

Two models were used to assess the potential stormwater attenuation performance of the green roof in this study. The DRAINS Australian Rainfall and Runoff (2019) Initial Loss/Continuing Loss Model [79] was employed to predict the fluvial mitigation performance of the green roof from a design perspective. The USEPA Storm Water Management Model (SWMM) was employed to quantify the reduction in stormwater flowrates from the green and conventional roofs into the local stormwater management network based on locally sourced data (Observatory Hill, Sydney: Gauge 066062).

For DRAINS, both the green and conventional roofs were divided into four sub catchments representing uniform catchment characteristics of slope, impervious area, and Manning's roughness coefficient (n). The division of the catchments was based on the building hydrology design plans, drainage network information, aerial photographs and the information obtained from onsite field inspections. Pre-burst rainfall data was retrieved from the ARR Data Hub website, using the coordinates -33.861399, 151.201662 and historical rainfall data was sourced from ARR 2019 incremental pattern file and intensity-frequency-duration depth file [80]. Major and minor storms with 5-minute and 2-hour durations were modelled. Simulation parameters are presented in Table 2.

Table 2. Simulated roof top parameters for both the green and conventional roofs for DRAINS.

Model Parameter	Green Roof	Conventional Roof
Catchment Area	.18 ha	.18 ha
Impervious Area	10%	100%
Time of concentration	6 minutes	12 minutes
Impervious area initial loss	1.5	1.5
Impervious area continuing loss	0	0
Suburban pervious area initial loss correction	22.4	NA
Suburban pervious area continuing loss correction	0.64	NA
Sub-catchment areas	4	4
Total catchment areas	8	8
Substrate void space assumption	20%	NA
Detention basin nodes	0.03 m	0.03 m
Drainpipe design	Circular	Circular
K entry/bends	0.5	0.5
Outlet/underdrain pipes diameter	150 mm	150 mm
Weir coefficient C-value	1.75	1.75
Crest length	10 m	10 m
Downstream catchment flow carried by channel	0	0
Channel slope	1%	1%

SWMM is a physically based, spatially distributed model for simulating all aspects of hydrological and water quality cycles, primarily within urban areas [81–83]. The availability of data describing the hydrologic response of urban catchments is extremely limited [84] and due to concurrent construction in the study site area, there was a lack of on-site catchment monitoring data. Therefore, observational data between 1991 and 2010 from Observatory Hill, Sydney (Gauge 066062) was selected for this analysis (Figure 2). Simulation parameters are presented in Table 3.

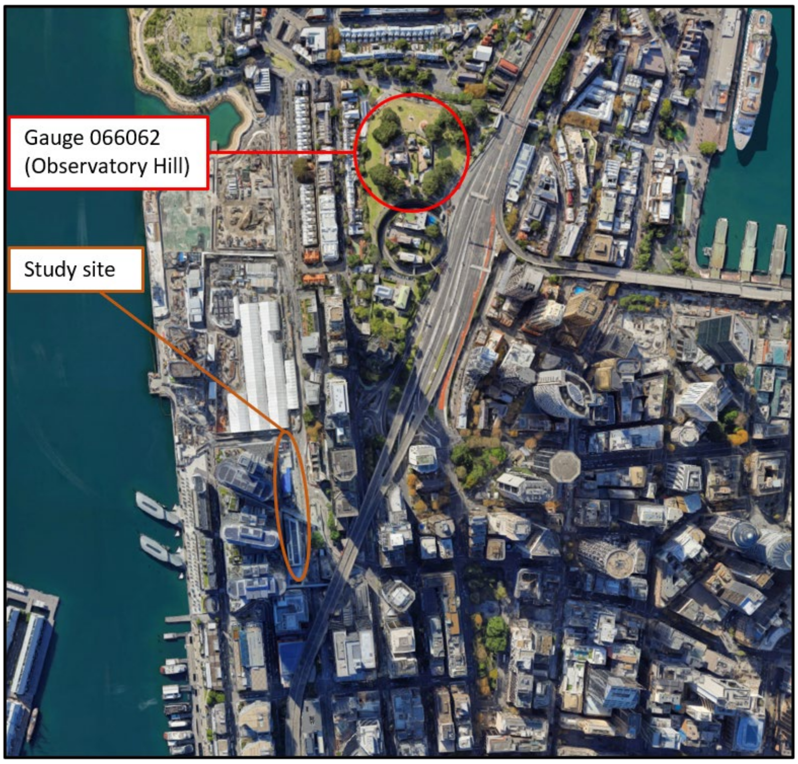

Figure 2. Proximity of Observatory Hill (Gauge 066062) from the study site – approximate linear distance is 590 m.

Table 3. Simulated roof top parameters for both the green and conventional roofs for SWMM.

Model Parameter	Green roof	Conventional roof
Total catchment area	0.09 ha	0.09 ha
Impervious fraction	10%	100%
Impervious depression storage	1 mm	1 mm
Roof slope	1.25%	1.25%
Green roof fraction	90%	N/A
Soil depth	120 mm	N/A

3. Results and discussion

3.1 Trace element retention

In-situ trace metal analysis detected, on both roofs; Li, Be, Na, Mg, Al, Si, P, K, Ca, Sc, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Rb, Sr, Y, Zr, Ag, Cd, In, Sn, Sb, Cs, Hg, Tl, Pb, Bi, Th. However, there were 21 metals observed above the detection limit solely on the conventional roof ; Ti, V, Nb, Mo, Te, Ba, La, Ce, Pr, Nd, Eu, Gd, Tb, Dy, Er, Tm, Yb, Lu, Ta, W, U. Analysis was conducted on Ni, Cu, Zn, Pb, Cd and Cr due to their prevalence in urban environments and their toxicity to human health and aquatic environments [32].

Results from the *in-situ* trace metal analysis show that the soluble fraction for all trace metals were similar between roofs ($p > 0.05$ in all cases; Figure 3), excluding copper. The concentration of soluble copper on the green roof was 32% lower than that reported on the conventional roof (Cu; $p = 0.022$), not dissimilar to the values predicted by Steusloff [60]. Atmospheric copper can have many sources in urban environments including windblown dust, sea spray, vehicle emissions and mechanical abrasion [85–87]. Due to the proximity of the site to a dense urban centre and major motorway (80,000+ vehicles per day [88]), it is likely the contribution of copper is derived primarily by human activities. A significant reduction in soluble copper on the green roof may be due to the binding to inorganic or organic constituents contained within the green roofs substrate, such as clay, organic matter or sulfides [89]. This reduction in soluble copper indicates green roofs are able to mitigate, to some degree, the impact of soluble trace metal pollution that stems from human activities in dense urban environments.

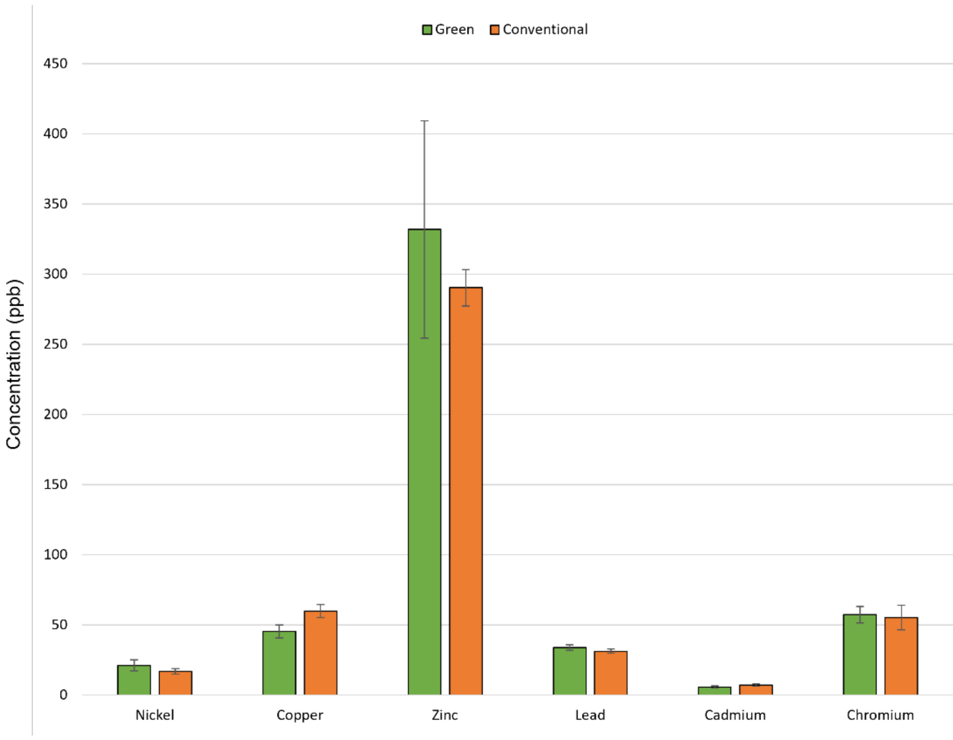

Figure 3. Soluble trace metal fraction for the green roof substrate and conventional roof surface dust. Error bars represent the SEM.

As mentioned previously in the introduction, an Australian study on experimental green roof plots by Razzaghmanesh et al [55] assessed the soluble trace metal contribution of green roofs to stormwater outflows. Interestingly, the results presented by these authors were substantially lower for both substrate types tested than those presented here (Cu ~10x; Zn ~17x; Pb ~30x and Cd ~90x), where the trace metal concentrations observed were attributed to organic fertilisers. It is hypothesised by the authors that the concentrations of trace metals presented in the current work are likely aerosolised from anthropogenic sources. Differences in concentrations observed in this study and that of Razzaghmanesh et al [55] are likely due to differences in site specification. The experimental green roofs monitored by Razzaghmanesh et al [55] were situated 22-stories above street level, in a city with 10,523 employed people (2016 census; [90]), compared to the current work in which the green and conventional roofs are 7-stories above street level, in a city with over 124,746 employed people (2016 census; [91]), and both adjacent to and level with an overpass motorway with a daily traffic count of 80,000 vehicles [88].

A similar study by Berndtsson et al [92] estimated that of the green roofs included in that study, one roof type was shown to be capable of retaining 8-93% of the total Zn, Cr and Pb present in precipitation loads. Our study was limited by the measurement of dry-deposition trace metals, and not the analysis of *in-situ* runoff. As such, only soluble concentrations of Cu were significantly reduced on the green roof, possibly through phytoremediation at the root level.

For particulate trace metals, the phytoremediation of contaminated soils is well documented, and considered to be a cost-effective technology for the remediation of contaminated sites [93]. In the current study, a reduction in particulate trace elements referred to a difference in the concentration (ppb) of each element present in the samples from the sites. In this sense, the green roof demonstrated an ability to significantly reduce particle bound Zn ($p = 0.007$), Cr ($p = 0.012$) and Cu ($p = 0.042$) (Figure 4) by 77.57%, 92.56% and 90.68%, respectively. Previous work carried out by Sun and Davis [38] on experimental bioretention systems for urban pollutants, demonstrated removal efficiencies for Zn, Cu, Pb and Cd of over 88% for low metal loading, and over 93% for high loading. Their study estimated trace metal removal to be 88-97% attributable to the substrate media, and only 0.5-3.3% to accumulation by plant material, over a 230-day period. It is therefore likely that over the lifespan of a green roof, aerosolised trace metals could be deposited and trapped within the substrate media and slowly integrated into plant material through bioretention, rhizofiltration or phytostabilisation [94,95]. Comparatively, the sole mechanism for trace metal removal on conventional roofs is disturbance and aerosolisation back into the atmosphere, or washing into stormwater catchments in storm events [96].

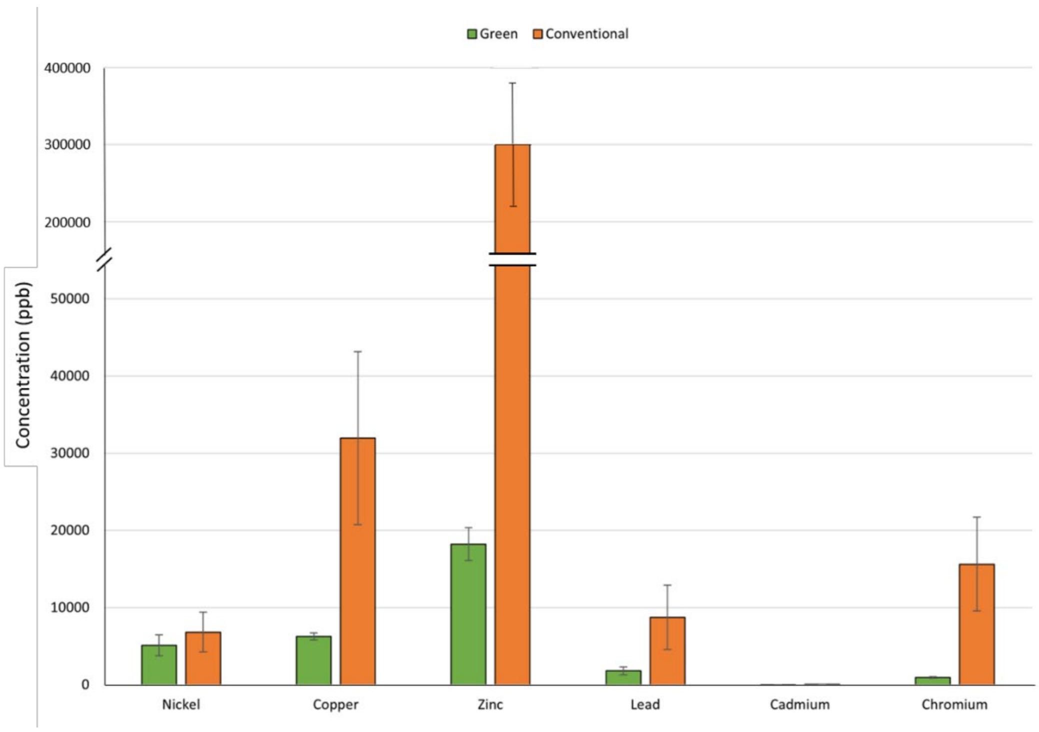

Figure 4. Particulate trace metal fraction for both green roof substrate and conventional roof surface dust. Y-axis break at 50,000 ppb to 200,000 ppb to display particulate Zinc concentrations. Error bars represent the SEM.

The trace metals detected here are common vehicle and industrial pollutants [39,87,97–102] and due to the proximity of the experimental site to a major motorway and extensive urban development, the concentration of dry deposited aerosol pollutants presented here should be considered high. This is reflected by the differences in concentration between the sites (Figure 3 and 4) and the predictive model (Figure 5). Despite the high pollutant loads, the green roof substrate demonstrated an ability to retain significant proportions of ambient particle bound Zn, Cr and Cu, and to remove significant soluble Cu with comparable removal efficiencies to various industrial filter materials [103]. However, the green roof was unable to filter Pb, Ni, Cd or Cr at any significant level when compared to the conventional roof. It is possible that under different weather conditions (during or post rainfall) there could be a reduction in runoff concentrations for these contaminants, however this could not be tested in this study. It is also possible that the reduction in both the soluble and particulate concentrations of trace metals observed in the substrate were lower than the conventional roof through the physical barrier provided by the plant leaves. While the dry deposition of aerosolised trace metals onto plant material was untested, the reduction should be considered a function of the green roof. Future analyses should aim to determine the efficiency of green roofs under varying weather events for their removal of trace metal contamination, as well as the contribution of the above-ground plant matter in respect to trace metal substrate concentration. Additionally, future work should be conducted on the optimisation of substrate depth, composition, and physiochemical properties to positively influence retention times and therefore phytoremediation potential for dry deposition anthropogenic urban trace metals.

Performance estimates of bioremediation and bioretention from the literature only described the total concentration of trace metals that could be removed on each roof, either accumulated in the substrate (green roof) or as surface dust (conventional roof) (Figure 5).

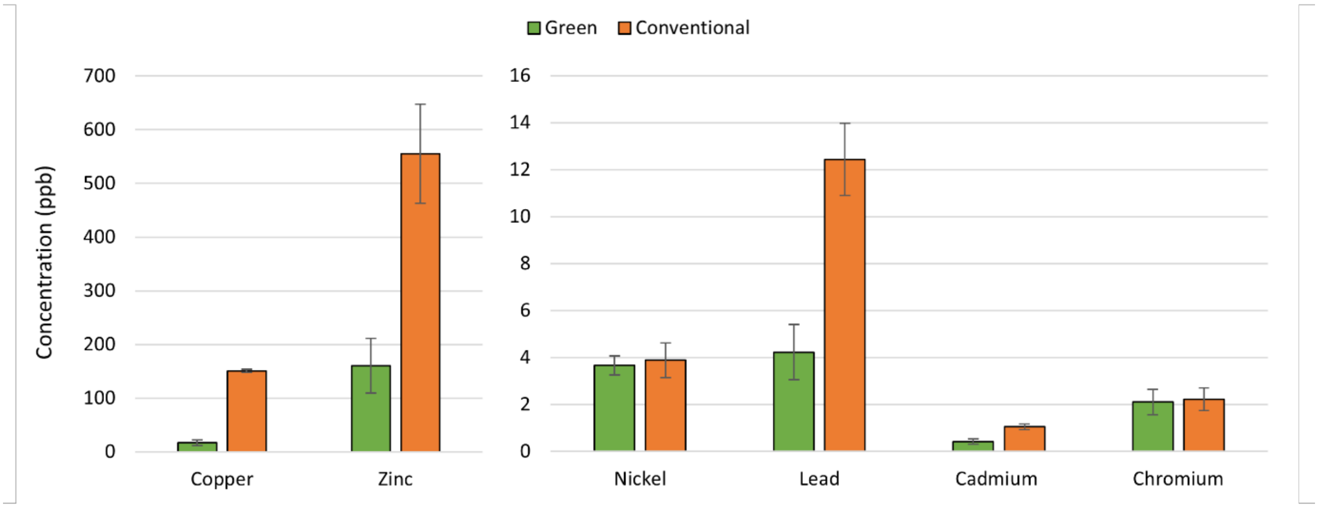

Figure 5. Predicted trace metal concentrations of trace metals to be expected in the substrate of the green roof and surface dust of the conventional roof. Data sourced from Supplementary Table 4. Error bars represent SEM.

Predicted total trace metal concentrations (both soluble and particulate), based on roadside observations showed predicted differences between buildings to be highest for zinc (Zn 71.2%; 395 ppb), copper (Cu 89%; 134 ppb), lead (Pb 66.13%; 8 ppb) and cadmium (Ca 60%; 0.6 ppb). Nickel (Ni) and chromium (Cr) were predicted not to differ between buildings. The predictive results presented here differ significantly to those previously reported. A study conducted by Steusloff [60] described the modelled filtration efficiency of wet deposition trace metals by an extensive green roof (substrate depth 0.1m) and a semi-intensive green roof (substrate depth 0.22m) reporting the removal efficiency of trace metals from runoff filtration to range between 43.7% and 99.8% for copper, depending on season and roof type. Differences in removal efficiency are likely owed to difference in input variables, such as substrate depth or total roof area. The predicted concentrations presented in the current study represent the total trace metal concentration (ppb), similar to the work of Brockbank [104], where Steusloff [60] simply describes the removal of theoretical wet deposition trace metal concentration starting at “100%”.

It should be noted that dry deposition concentrations of trace metals are substantially higher than wet deposition (aerolised pollutants deposited over a period of time vs solubilisation of trace metals during a rain event), but several orders of magnitude lower than road runoff concentrations. Here, the predicted concentrations (Figure 5) differed from the *in-situ* observations (Figures 3 and 4), likely due to differences in source pollution (solubilised roadside runoff from medium density traffic vs long-term accumulation of aerosolised trace metals from extremely high-density traffic). Despite this, the reduction in measurable concentrations were similar for zinc and copper (Zn 72% vs 77%; Cu 89% vs ~91%), but not the other trace metals. It is possible that bioretention and phytoremediation data input from our literature review differed significantly due to species variation, or climatic conditions, or simply the trace metal concentrations. However, both our *in-situ* results and the predictive model demonstrated a functional reduction in urban trace metal contamination on green roofs compared to conventional roofs (Figure 5).

3.2. Modelled stormwater performance

Hydrological models are frequently used for both design and analysis. In this study we present two models, DRAINS and SWMM, to assess differences in design (predictive) and modelled reductions in stormwater flow rates. DRAINS was utilised to predict the effect of the specific green roof design on flow rate, using data from the Australian Rainfall and Runoff (ARR) guide data [80]. Design prediction software relies on a simulated storm burst that has been designed to assist in the transformation of the Intensity–Frequency–Duration (IFD) statistic, which describes the rainfall rate in mm/h, frequency of events and duration into a flow statistic. DRAINS is one of the most commonly used software systems for prediction of design flows and volumes in Australia. SWMM was utilised to determine the specific effect of the green roof for the reduction in peak flow rates using environmental data collected for that specific region (Gauge 066062 [105]). In this instance, SWMM was used with no assumptions made regarding the transformation of rainfall frequency into flow frequency (such as the above simulation of burst rainfall), and therefore can be applied as an analytical tool, rather than a design-oriented tool.

3.2.1 DRAINS

DRAINS was used to calculate the detention nodes, the upper and lower water depths, and flowrate. The estimation of flood characteristics requires the determination of the magnitude of the hazard, and the likelihood of occurrence, referred to as Annual Exceedance Probability (AEP). Based on an AEP 5 storm event (1 in 5-years), the upper water level was a maximum of 1.04 m for each green roof catchment area (Figure 6; green text (A)) which indicates there is no risk of overflow (excessive water pooling). Further, the outlet flowrate from the green roof is predicted to be 7 L/s (Figure 6; blue text (C)), which is ~89% reduction in peak stormwater flow rates compared to the conventional roof (63.4L/s; not displayed here).

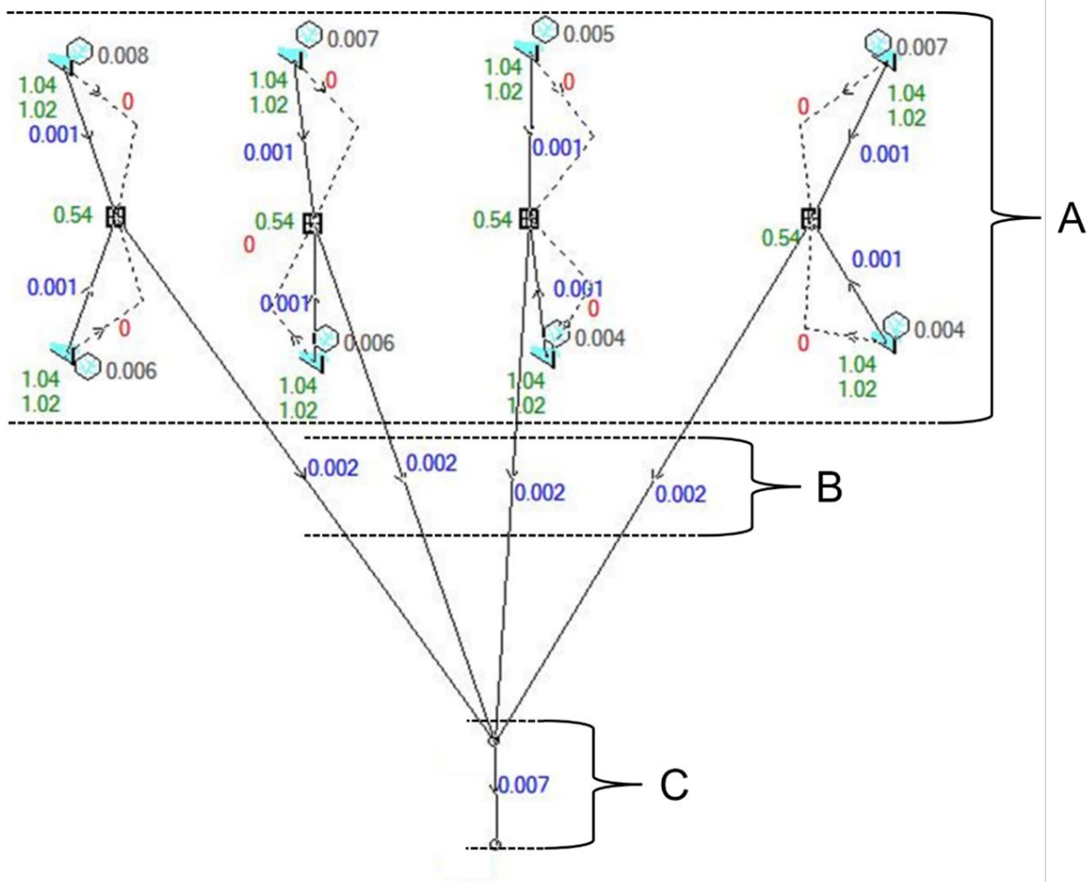

Figure 6. Green roof catchment model output from DRAINS representing an AEP 5 (1 in 5 years) storm event. Figure depicts the catchment areas (A), underdrains (B) and outlet pipe (C) flow rates (blue text; m^3/s). Upper and lower water levels for the catchment areas (A) are also depicted (green text; water height in cm above level (1.0)).

Feitosa and Wilkinson [106] demonstrated an increasing green roof substrate depth yielded greater peak attenuation linearly, with substrate depth having a greater effect on attenuation with an increase in green roof coverage. Based on the results of Feitosa and Wilkinson [106] the green roof in this study should have had a peak attenuation of ~35%, which is significantly lower than the DRAINS output prediction of ~89%. Differences in the predicted and modelled attenuation from the literature are likely owing to the nature of the chosen software (predicted: DRAINS vs modelled: HYDRIUS-1), or the data input parameters. Interestingly, a meta-analysis consolidating results from 75 investigations conducted by Zheng et al [107] describes the average extensive green roof runoff retention attenuation to be 56% [107], noting that the variability across investigations varied very widely (0%-100%).

As DRAINS is predictive modelling software, differences between prediction and observations are expected. Due to the green roof in this study being a commercial installation, we must rely on analytical models to more accurately predict the stormwater flow rates, such as SWMM.

3.2.2. SWMM

Both the theoretical runoff for varying storm conditions, and the depth of surface ponding were determined using the stormwater management model. Here we present the peak flow attenuation potential of an *in-situ* commercial green roof and a control roof within the same catchment with near-identical dimensions and drainage. In our analysis we observed a significant reduction in peak stormwater flow rates for all storm events between AEP 1.01 to 20 (Figure 7). Peak flow rates were predicted to be reduced by 90% (7.5 L/s) to 69% (18.21 L/s) for frequent storm events (1 in 1.01-2 years), and 50% (18 L/s) to 19% (9.2 L/s) for less frequent events: 1 in 5 or 1 in 20 years (Table 4). For storm events less frequent than 1 in 2 years, the SWMM flow rate values more accurately reflect the global averages as reported by Zheng et al [107].

Table 4. SWMM predictive modelling results for peak stormwater flow rate reduction of green and control roofs. AEP indicates the magnitude of a storm event, presented as a likelihood of occurrence.

AEP	Green roof (L/s)	Conventional roof (L/s)	Reduction (L/s)	Reduction (%)
1.01	0.8	8.3	7.5	90
1.5	5.4	21.96	16.56	75
2	8.22	26.43	18.21	69
3	12.44	31.43	18.99	60
5	18.38	36.67	18.29	50
10	27.77	42.75	14.98	35
20	38.89	48.09	9.2	19

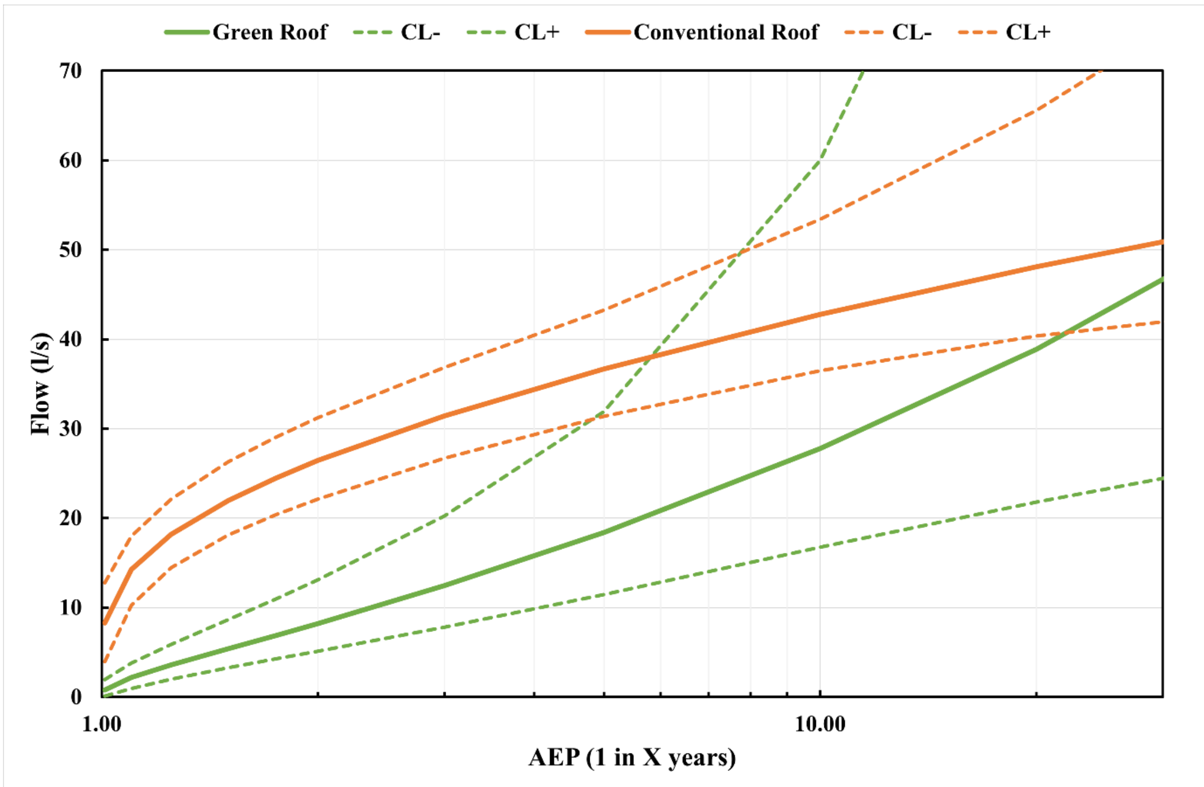

Figure 7. SWMM flood flow prediction model with upper and lower confidence limits for each roof type based on storm event AEP up to 1 in 30 years (log scale).

For AEP 3, 5 and 10 year storm events, the SWMM results indicate a reduction in peak flow rates by 35%, 50% and 60% respectively (Table 4). These values align with those previously discussed for green roofs with similar sizes and substrate depths [106,107]. A study conducted by Yang et al [108] found urban green roof and LID practises could reduce stormwater peak flow rates by 52.46%, similar to the results presented here for storm events as infrequent as 1 in 5 and 1 in 10 years. Additionally, Palla et al [109] describes both the effectiveness of a case study-sized green roof on the local hydrological response and the catchment-wide impact of retrofitting buildings with green roofs. Palla et al [109] determined that the hydrological performance of retrofitted green roofs could have an impact on the hydrological response for rainfall events with a total depth greater than 32 mm and that at the catchment scale, the use of retrofitting LIDs could significantly contribute to improved storm water runoff management in densely urbanised areas [109].

The results presented here demonstrate the practical use of green roofs to reduce the stormwater runoff from urban buildings in Sydney, Australia for storm events less frequent than 1 in 5 years, with the potential to reduce the runoff for events as severe as 1 in 20 years, although with lower confidence (Figure 7). As Australia experiences unique weather cycles through extreme rainfall and drought, the input data for the annual maximum flows were low, or close to zero, for 30% of the years analysed. Due to this, the degree of confidence the SWMM model can generate for the green roof increases with less frequent storm events, therefore the model output was limited to 30 years. Regions with more stable climates and predictable rainfall could expect significantly less variation in the predicted performance of green roofs. Despite the large confidence interval variation for larger rainfall event projections, there is clear evidence that green roofs can mitigate the severity of flow rates atop roofs in urban centres.

There is substantial literature available on the suitability of various international cities for the retrofitting of green roofs, and the approximate spaces available [66,110–112]. The current findings indicate that it is plausible that the widespread adoption of extensive green roofs in the Sydney metropolitan area could significantly reduce the flood flow of the underground stormwater management network and reduce the impact of short-lived heavy rain events on ground level urban spaces.

4. Conclusion

Here we demonstrate the performance of an *in-situ* commercial extensive green roof for both stormwater peak flow reduction, as well as reductions in both soluble and insoluble trace metals. Our analysis highlights the potential for Sydney urban green roofs to significantly reduce the flow rate of uncommon and extreme storm events through the use of analytical simulations (1 in 5, and 1 in 20 years, respectively), which may reduce the burden on the urban stormwater networks [66]. The east coast of Australia experiences infrequent flash floods and an overload of the stormwater network, therefore it is entirely possible that the mass implementation of green roofs on buildings suitable for a retrofit could reduce the severity or frequency of urban flooding [109], as experienced as recently as March 2022.

Additionally, removal efficiencies for soluble copper were similar to those modelled in previous work [60], as well as significant reductions in particulate zinc, chromium and copper, likely due to substrate retention or entrapment by plant roofs [113]. Future works should assess the substrate composition on flow rate reductions and particle retention, as well as to simulate rain events using realistic dry-deposition *in-situ* trace metal concentrations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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RF & PJI designed the study; RF recorded and collect *in-situ* data; RF and MW prepared and analysed the trace metal data; NK and JB designed and ran the hydrological models; RF, PJI and MW interpreted the data; RF, NK, MW, JB, FT and PJI drafted the manuscript.

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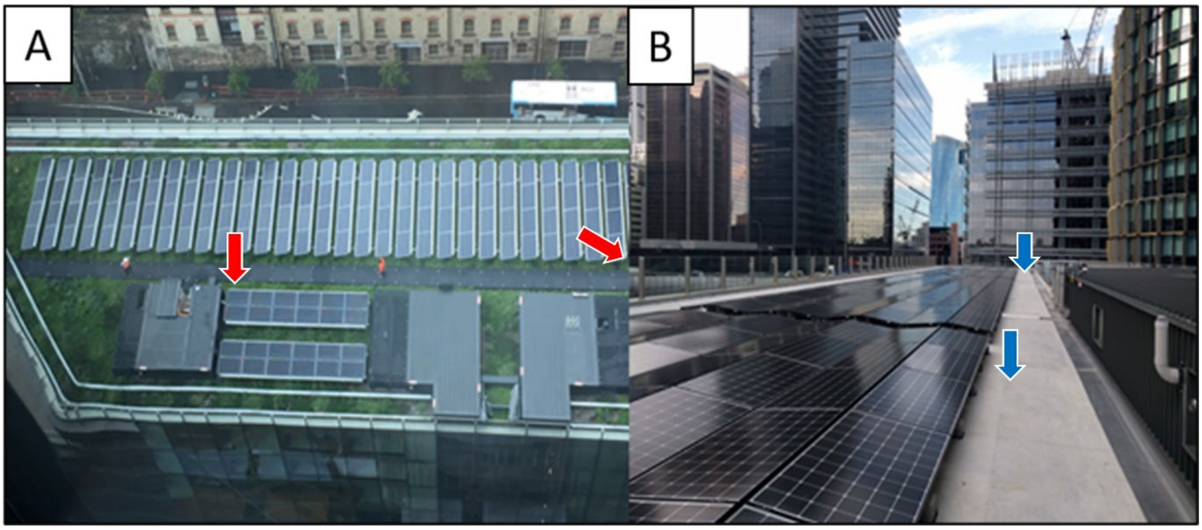
Supplementary:



Supplementary Figure 1. Image of both green and conventional roofs (A and B, respectively), including indicators for trace metal sampling location. Sampling was conducted on the North and South ends of each building, with substrate and surface dust samples being collected for the green and conventional roofs, respectively.

Progress videos:

https://www.youtube.com/watch?v=cE7-4A5DYMw

https://www.youtube.com/watch?v=TwMWJ9TX2gQ

Supplementary Table 1. Examined literature relating to the bioretention of trace metals from stormwater and impervious surfaces.

Study	Investigation	Location
Davis et al. [114]	Laboratory experiment	USA
Davis et al. [115]	Laboratory experiment	USA
Hsieh & Davis [116]	Laboratory experiment	USA
Glass & Bissouma [117]	Field observations	Washington DC, USA
Sun & Davis [118]	Laboratory experiment	USA
Hunt et al. [40]	Field observations	North Carolina, USA
Roseen et al. [119]	Field observations	New Hampshire, USA
Davis [120]	Field observations	Maryland, USA
Hunt et al. [121]	Field observations	North Carolina, USA
Chapman & Horner [41]	Field observations	Washing, USA