APPLICATION OF LIVING (GREEN) ROOF DESIGN RECOMMENDATIONS FOR STORMWATER MANAGEMENT

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ABSTRACT

Living (or green) roofs are a Water Sensitive Design device particularly suited to attenuating stormwater peak flow rate and volume in areas where space for more traditional at-grade devices, such as raingardens and swales, is limited. Applying a living roof, i.e., a substrate (growing media) and vegetation cover, transforms impervious, often under-utilised spaces into stormwater assets. The at-source control eliminates runoff generation for most storms.

The Auckland Council's Living Roof Review and Design Recommendations for Stormwater Management (Technical Report 2013/045) updates the TP10 (2003) chapter on Green Roofs. Stormwater calculations are based on a 5-year, multi-scale, multi-roof research programme, with results published in peer-reviewed international journals. Research included development of substrates from locally available resources and plant trials. For planning purposes, results enable design that completely retains up to approximately 30 mm of rainfall, with limited substrate depths. Peak flows are effectively detained, regardless of storm size.

The primary purpose of the report is practical guidance for design of extensive (50–150 mm-deep) living roofs in Auckland. This paper outlines the design objectives on which the research was based. These objectives inform how living roof performance may differ when they are not primarily designed for stormwater mitigation, and how to enhance their performance.

KEYWORDS

Living roof, green roof, stormwater management, design, Auckland

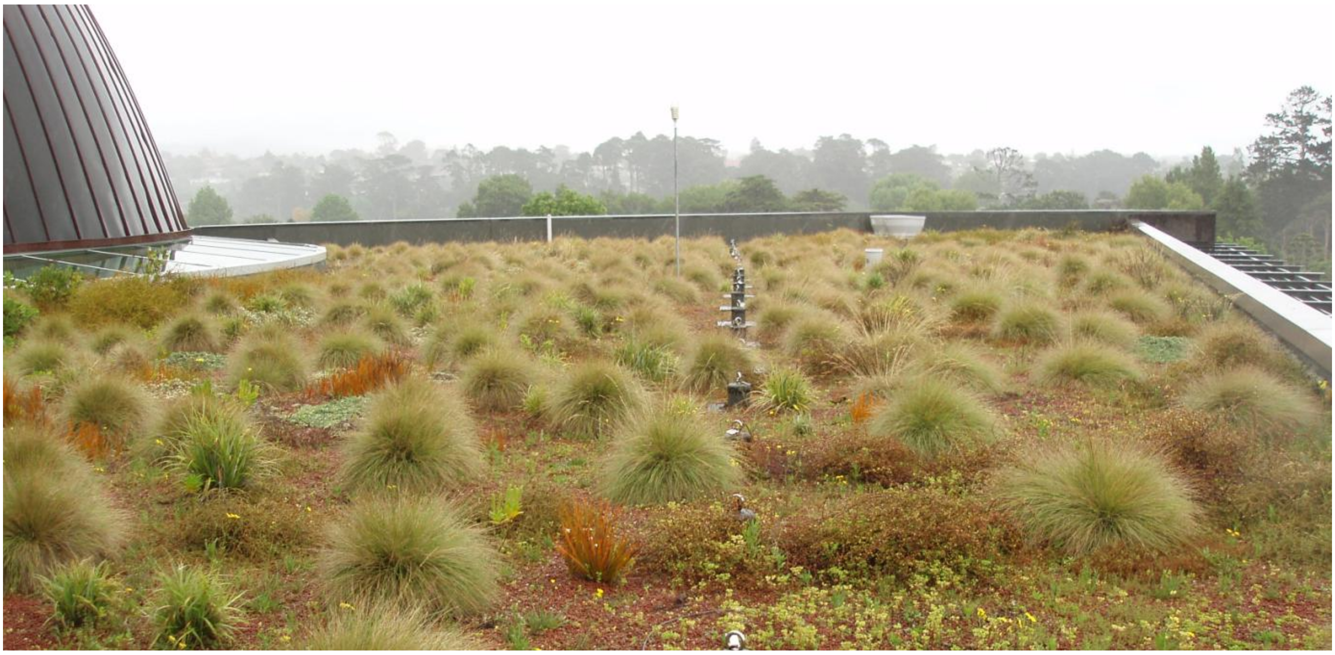
PRESENTER(S) PROFILE

Robyn Simcock is a soil scientist and ecologist working with Dr Elizabeth Fassman-Beck, senior lecturer in stormwater engineering, and University of Auckland's environmental engineering students, particularly Dr Emily Afoa, to understand the interrelationship of plants, media and stormwater in bioretention devices. The team's design, construction and monitoring of devices over the last nine years provided data and experience that underpins revised recommendations for living roofs in Auckland (TR2013/045).

1 INTRODUCTION

Living roofs are a water sensitive design (WSD) device for stormwater management. The term *living roof* is used to describe a substrate (growing media) and vegetation covered roof, while acknowledging the appearance is dynamic, e.g. as plants thrive or go dormant. The term *living roof* is used commonly in England and Switzerland to refer to roofs designed for stormwater retention and/or biodiversity, acknowledging systems may turn brown in the summer and/or winter when plants are dormant. They may also have a significant proportion of non-vegetated surface. The term *green roof* is also commonly used to refer to a living roof. However, *green roof* implies the plants are always green (Emilsson and Rolf 2005), which is not usual for non-irrigated, extensive roofs. The Bureau of Environmental Services in the City of Portland, Oregon (USA) uses *eco-roof* to emphasise functionality, and differentiate from roofs painted green or with green shingles. However, in New Zealand the term *eco-roof* can include roof types ranging from *cool roofs* (high solar reflectance) to *blue roofs* (hold water on a bare membrane with no media), to *living roofs*. Eco-roof thus does not convey the specific meaning intended.

Rooftops are a significant proportion of the total impervious area in urban settings. Downpipes are often connected directly to piped stormwater networks and surface waters. Management of rooftop runoff can therefore make a large contribution to comprehensive stormwater control. Stress on stormwater and combined sewer reticulation and other receiving environments can be reduced by installing living roofs on new buildings and retrofitting existing roofs that have adequate structural strength, or can be strengthened. 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 stormwater management opportunity in otherwise usually unused space (rather than more valuable ground space). Living roofs can also provide a range of other benefits from urban heat island and energy demand mitigation to biodiversity and habitat creation to aesthetic improvements and amenity value (Photograph 1).



Photograph 1: Auckland Council Henderson Office Living Roof (December 2012)

A living roof typically consists of multiple layers: a waterproofing membrane, root barrier, drainage layer, substrate, and vegetation (Figure 1). Supplemental moisture storage layers may also be included. Each layer plays an important role in the function of the overall system. An extensive living roof has 20–150 mm of substrate supporting low growing plants suited to droughty, hot, windy environments. Despite the limited depth, extensive living roofs with substrates designed with adequate moisture retention properties provide substantial stormwater mitigation. This is because the majority of all individual rainfall events across the Auckland region are small storms with low rainfall depths; 80% of individual events are less than approximately 22 mm on average across the region, while 90% of events are less than approximately 31 mm (Shamseldin 2010). Such events were completely or near-completely retained in field monitoring studies in Auckland (Fassman-Beck et al. 2013). This is consistent with overseas studies.

Figure 1: Typical extensive roof components with synthetic drainage layer

Living roofs are an accepted stormwater management device for the Auckland region, according to Technical Publication 10 (TP10): Stormwater Treatment Devices Design Guideline Manual. The current, second edition TP10 (ARC 2003) guidelines include the chapter 'Greenroof design, construction and maintenance' (Chapter 12). The Auckland Council is again updating TP10 to reflect further advances in stormwater management device design and incorporate results of recent local and international research into the regional guidelines. As part of this review, a series of individual technical reports investigate the individual devices within TP10 (2003). These technical reports provide background information on each device, examine existing and new design methodologies and determine the methodology considered most suited to implementation in the Auckland region.

This paper provides an overview of 'Living Roof Review and Design Recommendations for Stormwater Management' (Technical Report 2013/045 Fassman-Beck et. al. 2013). The focus is on living roofs constructed primarily to attenuate stormwater in Auckland. The paper also identifies how to enhance stormwater mitigation using living roofs and how function and requirements may differ if other design objectives, such as aesthetics, have precedence.

2 DESIGN OBJECTIVES FOR STORMWATER MITIGATION

The primary objective of the research supporting TR 2013/045 was to provide practical guidance for the design of extensive living roofs suitable to the Auckland climate that completely retain (i.e. achieve zero discharge) the "frequently occurring" design storm event; the 85^{th}–95^{th} percentile event. Designing a non-proprietary substrate to promote water retention of this storm event was a critical step, as the majority of rainfall retention in a living roof system occurs within the substrate. The ideal substrate components were identified as locally-available and inexpensive, particularly the aggregate components which form the bulk of a living roof substrate.

Healthy, densely covered vegetated roofs provide superior stormwater control compared with unvegetated, substrate-covered roofs. Plants also bind and protect substrate from wind and rain erosion. Hence an important objective was to identify resilient plants that would survive and grow on extensive living roofs. Over 40 native and non-native plant species were trialed. Evapotranspiration rates of two species were quantified to examine the potential to manipulate plant selection to optimize stormwater mitigation performance.

2.1 STORMWATER PERFORMANCE

The increased impervious cover associated with urban development typically increases the volume and peak discharge rate of stormwater runoff from both small and large storms. Unmitigated, these hydrologic changes degrade in-stream environments as more frequent bank-full flows destabilize banks and contaminants in stormwater stress aquatic life. In catchments with combined wastewater and stormwater systems, as in parts of Auckland, stormwater runoff increases sewer overflows, impacting recreational use of beaches. In large storms, increased imperviousness also increases risk of flooding to downstream properties.

Living roofs mitigate both peak flow and volume of stormwater runoff at source. When rainfall begins, a small amount is intercepted by plant leaves. As rain continues, water percolates into the substrate (growing media). The net volume of runoff is primarily reduced by rainfall retained within the substrate. In theory, significant quantities of water drain from the roof when the field capacity[1] of the substrate is filled. In practice, preferential flow paths and other heterogeneities in the system allow some runoff to occur before field capacity is reached. During small rainfall events, negligible (if any) runoff occurs. Most of the precipitation eventually returns to the atmosphere by evapotranspiration (ET)[2]. For larger storms, even shallow depth (extensive) living roofs can retain a measurable portion of the total rainfall, and will delay and reduce the runoff peak significantly. Rainfall retention almost always coincidentally mitigates potential peak flow rate, and delays its timing. A living roof further attenuates peak flows (i.e.

[1] Field capacity is practically defined as the amount of water that can be held (retained) by a soil matrix against gravity drainage.
[2] ET is the loss of water to the atmosphere via evaporation from substrate and plant surfaces, and via plant transpiration.

detains runoff), as water must percolate down through the substrate and along drainage layers before reaching outlets (the roof's vertical drainage). For these reasons, living roofs reduce pressure on storm and/or combined sewer networks.

Four living roofs in Auckland with substrate depths ranging from 50 to 150 mm produced 39–57% less cumulative runoff than from a conventional roof surface at the same site, over monitoring periods ranging from 8 to 28 months. On an event-by-event basis, during the majority of rainfall events up to 25 mm, there was no meaningful runoff from any of the living roofs monitored. Including all events, median retention ranged from 56 to 76%, with appreciable year-round performance. Rainfall depth is the most significant predictor of runoff depth from a living roof, despite the well-documented influence of evapotranspiration (ET) on a day-to-day basis (Fassman-Beck et al. 2013a; Kasmin et al. 2010; Voyde 2011). Performance is reduced for larger events, i.e. those of 2-yr return frequency and larger. Such events are typically the subject of specific peak-flow mitigation technologies (Fassman-Beck et al. 2013a; Kasmin et al. 2010), however, living roof nonetheless reduce the footprint of ground-level flow controls.

Photograph 2: Living roof designed for specifically for stormwater mitigation, Faculty of Engineering building, University of Auckland, 2013

For Auckland's monitored living roofs, median peak flow reduction, compared with a conventional roof at the same site, was 62–90% (Table 1, Fassman-Beck et al. 2013). Peak flow should always be mitigated (even during large storms) as adequately designed permeability ensures rainfall percolates through the substrate rather than flows across the vegetated surface (Fassman and Simcock 2012). However, peak flow varies enormously from event to event. While side-by-side field monitoring of six living roof configurations at UoA reported a median delay in the onset runoff from the onset of rainfall of 50 min, with a mode of 10 min, the overall range was from 0 min (i.e. an infinite delay) to 7.5 h. Median time delay between peak rainfall intensity and peak runoff flow rate was 20 min with a mode of 10 min, while the overall range was 0 min to 33.7 h (Voyde 2011).

Table 1: Summary of mitigation performance for Auckland living roofs vs. conventional roof surfaces

Monitoring Site	**Substrate Depth**	**Cumulative Retention (%)**	**Event Based Median[a]**	
			Retention (%)	**Peak Flow Reduction (%)**
All data, various durations of monitoring[b]				
UoA	50–70 mm	56	76	90
Tamaki mini-roof	100 mm	39	56	62
Tamaki mini-roof	150 mm	53	66	74
AC Henderson	100 mm	57	72	84
All sites monitored concurrently (Aug-Dec 2010)				
UoA	50–70 mm	66	75	89
Tamaki mini-roof	100 mm	48	55	73
Tamaki mini-roof	150 mm	57	66	74
AC Henderson	100 mm	66	72	86

a. Individual events with rainfall depth >2 mm
b. UoA: 28 months continuous 2008-2010; Tamaki mini-roofs: 6 months 2009–2010 + 8 months 2010–2011; AC Henderson (Auckland Council Henderson Office): 8 months continuous 2010–2011

2.2 DESIGN GUIDANCE FOR STORM ATTENUATION IN AUCKLAND

For planning and consenting purposes, an extensive living roof in Auckland may be considered to completely retain a maximum of 30 mm of precipitation. Extensive living roofs designed to retain stormwater may be installed on roofs with pitch of up to 15° with relative little design modification compared to those on ‘flat’ roofs (at least 2° slope is required for new construction projects). The maximum pitch for living roofs to be considered as stormwater retention devices is 15°.

Fassman and Simcock (2012) found that stormwater retention in the field was reasonably predicted by the combination of a laboratory measurement of the substrate’s water holding capacity measured as plant available water (PAW), and its installed depth. In TR 2013/045, this observation provides the basis for design of living roofs for stormwater retention. At a minimum, the substrate should store at least the design storm depth (DSD) appropriate to the location within the Auckland region. For new construction, the minimum required substrate depth for stormwater retention is given by the deeper of:

$$D_{lr} \geq \frac{DSD}{PAW} \qquad \text{Equation 1}$$

$D_{lr} \geq 100$ mm

Where

D_{lr} = finished living roof substrate depth (mm)

DSD = design storm depth (a "frequently occurring" storm e.g., the WQ design storm, or the 85^{th}-95^{th} percentile, 24 hr event)

PAW = plant available water (%) as determined by agronomic methods (tension test over range 10-1500 kPa, or equivalent (Gradwell and Birrell 1979))

The relationship between PAW, DSD and D_{lr} is illustrated in Figure 2. PAW typically increases with smaller particle size distribution and greater organic content. PAW may be manipulated by design, but designers must also be cognizant of effects on weight, permeability, and plant growth when combining materials.

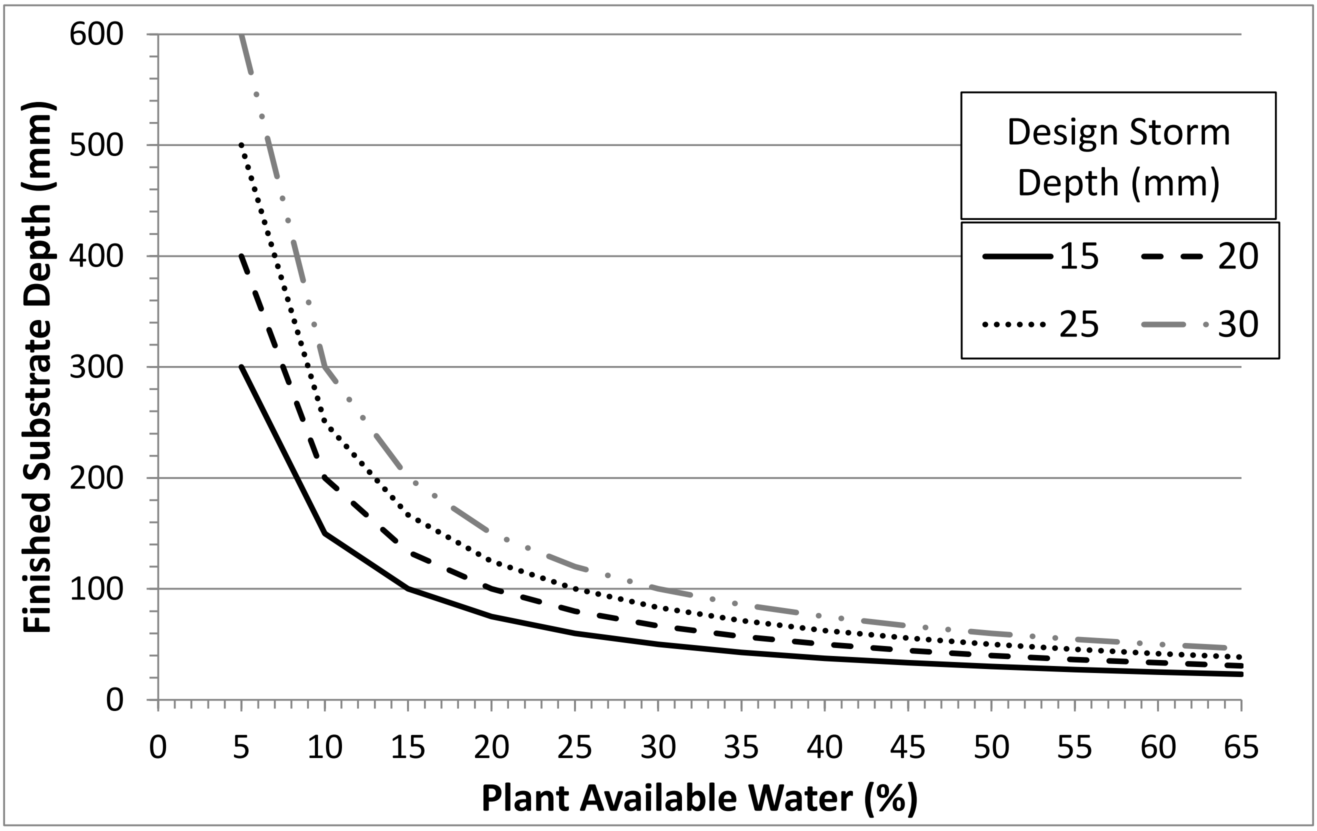
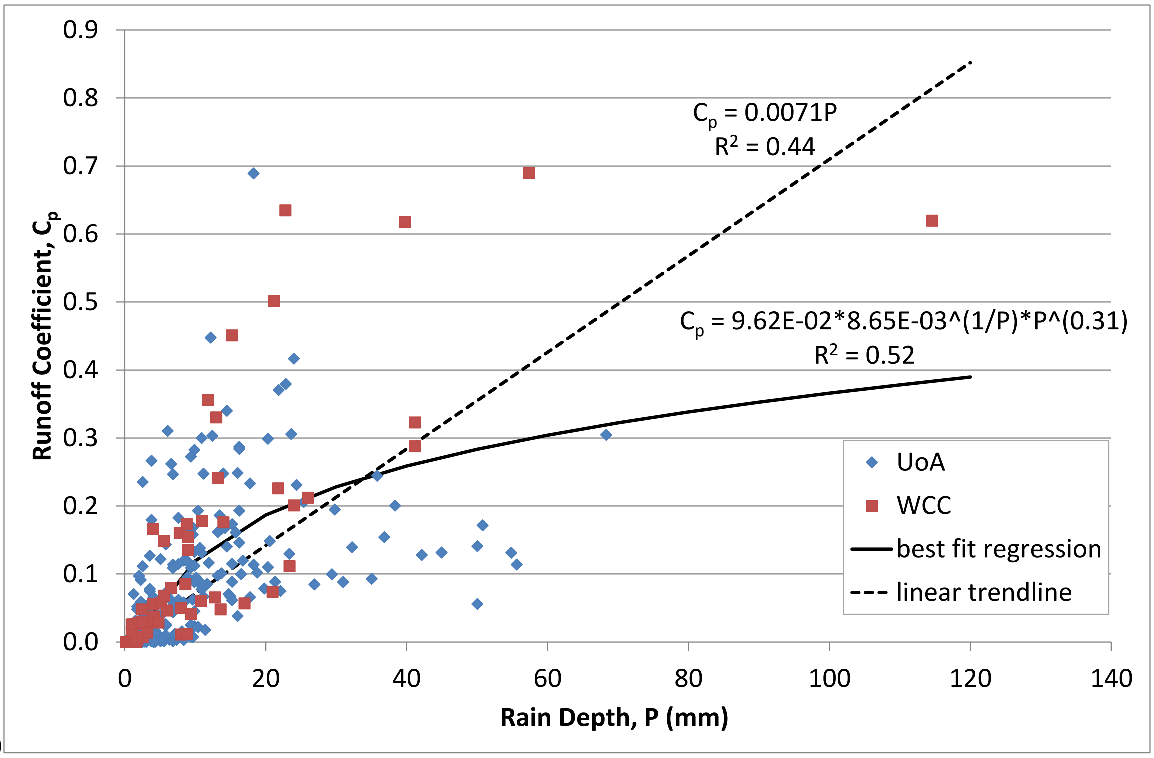


Figure 2: Effects of Potential Available Water and Substrate Depth on Design Storm depth attenuated

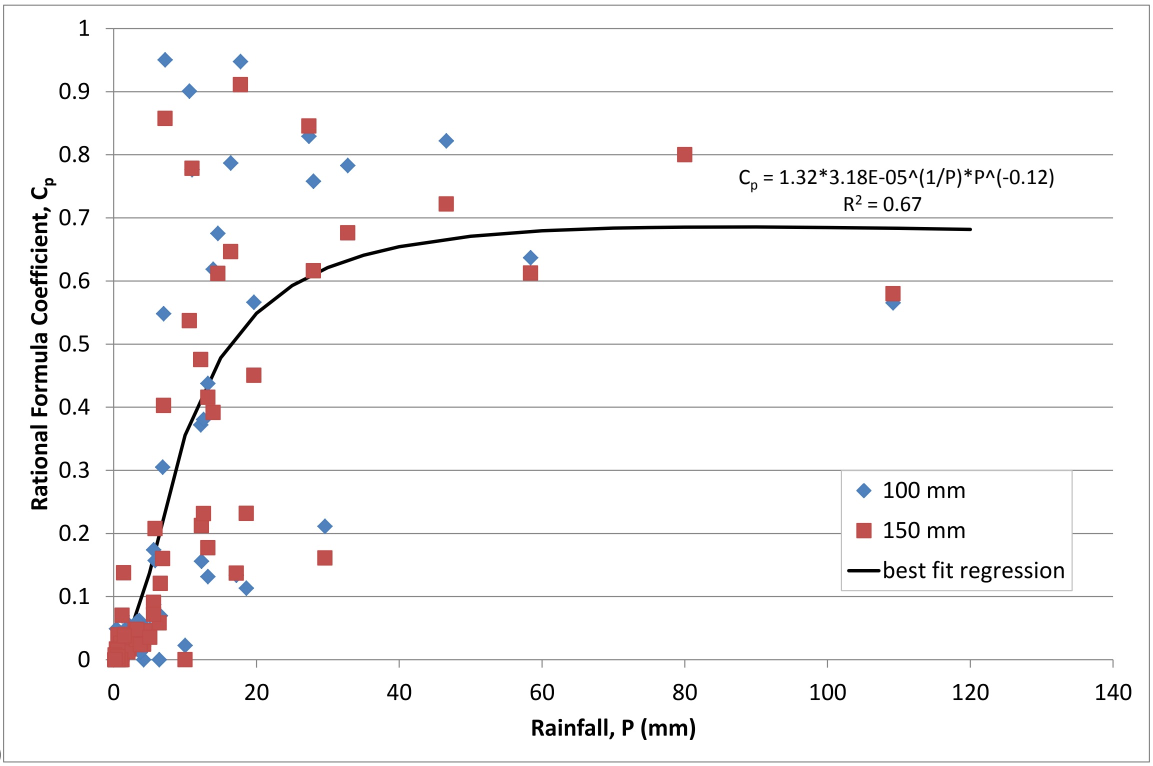
Empirical evidence from living roofs monitored around the world suggests that the maximum retention provided by living roofs is about 30 mm, regardless of configuration. In other words, in consideration of Eq. 1, doubling substrate depth does not equate to doubling rainfall capture for water holding capacity greater than 30 mm. In terms of stormwater planning, the following interpretation applies:

- Where the finished depth meets or exceeds the minimum calculated depth from Eq. 1, no runoff occurs from the living roof (runoff depth = 0) for storms with rainfall depth P $\leq$ 30 mm.
- Where the finished depth is less than minimum calculated depth for Eq. 1, but a media depth of at least 100 mm for new construction, or 50 mm for retrofit is provided, there is no runoff that occurs from the living roof for storms up to the substrate's estimated storage potential. For example, if a specific substrate at its finished depth stores a maximum of 15 mm of water, then there is no runoff for storms with P $\leq$ 15 mm.
- In all cases, a maximum of 30 mm may be considered retained based on the substrate's moisture retention properties and finished depth.

Jurisdictional design manuals often require a curve number (CN) or Rational formula C value for living roofs, based on an assumed similarity of the source control to a natural surface. In reality these are significantly engineered, pseudo-pervious systems with constrained storage capacity. Nonetheless, recommendations are made as the "best" estimate from empirical data, noting the high variability of results and methodological departure from the original USDA (1986) method. If/where runoff volumes are required to be calculated for storms larger than 30 mm, calculations should use an appropriate curve number method, with CN=85, based on a compilation of data from international living roof studies. The Rational Formula may be used to estimate peak flows from living roofs. Peak flow mitigation diminishes with increasing rainfall, which is reflected by varying Rational C Coefficients with rainfall depth: C = 0.1 for P $\leq$ 10 mm; C = 0.2 for 15 $\leq$ P < 30 mm; C = 0.3 for P $\geq$ 35 mm (Figure 3) (Fassman et al. 2010b).



(a)



(b)

Figure 2: Rationale formula coefficient determination based on full-scale living roofs at the University of Auckland and Auckland Council Henderson Office

2.3 LIVING ROOF STANDARDS AND TESTS

Currently, the only complete living roof "standards" for designing living roofs and/or testing materials are contained in the German "Guidelines for the Planning, Construction and Maintenance of Green Roofing" (FLL 2002, FLL 2008) (referred to as the FLL[3]). The FLL is a comprehensive manual developed for German applications. While addressing many aspects of living roof design, it also describes laboratory testing methods, apparatus, and target numerical values for substrate design.

The American Society of Testing Materials (ASTM) International originally issued living roof testing standards in 2005; with updates in 2011[4]. The ASTM standards currently only include a testing methodology and do not give numerical objectives to indicate suitability for the intended application. However, the ASTM standards provide a basis for comparison and a common language for describing and specifying living roofs. Relevant ASTM standards include:

- ASTM E2396-11 Standard Test Method for Saturated Water Permeability of Granular Drainage Media [Falling-Head Method] for Vegetative (Green) Roof Systems (ASTM 2011a)
- ASTM E2397-11 Standard Practice for Determination of Dead Loads and Live Loads Associated with Vegetative (Green) Roof Systems (ASTM 2011b). Use of this standard in New Zealand is limited to determination of component densities

[3] Available from http://www.fll.de/shop/english-publications.html
[4] Available from http://www.astm.org/

and weights. Guidance for determining actual structural loads is provided in Chapter 5 of TR2013/045.

- ASTM E2398-11 Standard Test Method for Water Capture and Media Retention of Geocomposite Drain Layers for Vegetative (Green) Roof Systems (ASTM 2011c)
- ASTM E2399-11 Standard Test Method for Maximum Media Density for Dead Load Analysis of Vegetative (Green) Roof Systems (ASTM 2011d)
- ASTM E2400-06 Standard Guide for Selection, Installation, and Maintenance of Plants for Green Roof Systems (ASTM 2006)

The ASTM methods are recommended for testing physical characteristics of substrates to ensure consistency in a new industry in New Zealand as they are easier to follow. Table 2 identifies the tests that need to be performed, their purpose, methods of testing, and minimum requirements. The FLL and ASTM ASTM E2397-11 and ASTM E2399-05 provide equivalent (with each other) methodologies to calculate substrate water storage capacity, termed Maximum Media Water Retention (ASTM terminology) or Maximum Water Capacity (FLL terminology) but both overestimate rainfall capture for Auckland (Fassman and Simcock 2012; Wang 2010). FLL provides target numerical objectives for permeability designed to prevent ponding; however these are specific to German climates (e.g. rainfall intensity). A saturated permeability of 0.04 – 0.05 cm s^{-1} (~1500 mm h^{-1}) is recommended for Auckland. As the New Zealand knowledge base grows, numerical objectives may be further revised to suit local climates and native plants, but the methodology may not necessarily change.

Table 2: Substrate specifications to test post-mixing, purpose and method

Characteristic	Purpose	Method	Minimum Standard
Dry bulk density	Structural loading	Standard geotechnical test, ASTM E2399-11	Depends on roof structure design
Weight at field capacity	Structural loading	ASTM E2397-11, or equivalent	Depends on roof structure design
Saturated weight	Structural loading	ASTM 2397-11 or equivalent	Depends on roof structure design
Saturated permeability	Structural loading, plant health	ASTM E2399-11, or equivalent	$\geq$ 1800 mm h^{-1} $\geq$ 3600 mm h^{-1} (if no dedicated drainage layer)
Particle size distribution	Structural loading, plant health	Dry sieve, e.g. ASTM C136-06 or AS1289.3.6.1-1995	Check this if there is a problem with weight or permeability
Plant available water	Stormwater control, plant health	Tension test 10-1500 kPa, or equivalent	@ finished depth $\geq$ 85^{th}-95^{th} percentile design storm depth

3 HOW TO ENHANCE STORMWATER PERFORMANCE

3.1 PEAK FLOW REDUCTION

Peak flow should be well mitigated by living roofs, even during large storms, as the minimum substrate permeability ensures rainfall percolates through the substrate rather than flows across the vegetated surface (Fassman and Simcock 2012). Minimum substrate permeability is important to avoid surface ponding; hence improving peak flow mitigation should focus on drainage layer design and/or extending the length of drainage path. Note, however, an adequate number of drainage points must be present to ensure redundancy (back-up) if any drainage point is impeded (this is a standard requirement of the NZ building code for any roof).

Increasing roughness of a drainage layer can slow runoff. However, the hydraulic capacity of the drainage layer must safely convey the design unit flow rate at the roof grade without water ponding in or on the substrate. This means the capacity of any drainage layer must exceed the rate of water that passes through the geotextile above. Reducing roof slope towards the minimum recommended 2° may also reduce peak flows. Research has not defined the relationship between slope and retention; however, gravity increases efficiency of drainage layers. At present, there is insufficient data to reliably quantify the influence of roof pitch (slope) on runoff control.

3.2 VOLUME REDUCTION

The volume of stormwater that can be attenuated can be increased, to a point, using a range of methods: increasing the depth of substrate, adding moisture retention layers, selecting water-holding drainage layers, and by amending the substrate to increase water retention per unit volume. The engineered components are discussed below. A healthy, dense plant cover is also essential to the stormwater mitigation function of a living roof system. In addition, plant selection influences the potential volume reduction, due to differences in ET rates, however plant species are not considered when calculating stormwater retention for planning purposes.

Increasing the depth of substrate of an intensive living roof beyond 150–200 mm does not necessarily correspond to increased stormwater control in the Auckland climate, as the majority of individual events produce relatively little rainfall. For example, during the 28 months of continuous monitoring of the University of Auckland (UoA) living roof (2008–2010), 80% of the 396 events were less than 15 mm of rainfall, while 90% of events were less than 25 mm. These events are satisfactorily retained by 50 to 100 mm- deep extensive living roofs with appropriately designed substrates. The increased initial and long-term costs associated with living roofs having substrate depths greater than 200 mm (extensive roofs) are therefore unlikely to provide superior stormwater control (for Auckland), while cost-effectiveness declines markedly as larger events are infrequent.

A moisture retention layer, or layers, increases the volume of water retained on the roof before drainage. If this moisture is accessible to plant roots, it enhances plant health by decreasing the duration of plant stress between rain or irrigation events. Fabric (e.g. coir, wool, felt), mat (e.g. peat, sphagnum, coir) or foam moisture retention layers are best placed at the base of the root zone. Living roof drainage products usually have a bonded geotextile separation that prevents migration of substrate fines to maintain a free-flowing drainage layer. Some of these geotextiles retain significant amounts of moisture. Living roof drainage products often also have a lower 'protection' layer; usually a felt, and this also has some moisture retention capacity, although this moisture may not available for plant uptake. Subsurface irrigation systems may include a moisture-holding fabric to enhance distribution and retention of applied water. Retention layers have variable longevity and may become less effective as they decompose.

A drainage layer's primary role is to prevent water ponding by providing free (rapid) drainage for rainfall in excess of the system's moisture storage capacity to outlets (e.g. downpipes). Drainage layers that retain water can also enhance volume control. In synthetic drainage mats, water can be retained in 'cups' or 'bowls', if installed 'cups up'. This water may not be available for plant uptake, particularly during plant establishment when roots do not reach the cups. Root entry allows water removal via ET, as roots act as 'wicks'. The 'wet' load of commercial drainage products sampled in New Zealand range from 0.79 to 11.68 kg m^{-2} (Fassman et al. 2010a). Commercial products available overseas are reported to hold up to 20.4 kg m^{-2} of water (Cantor 2008). Granular drainage layers are typically coarse aggregate, for example, 7–20 mm grade clean pumice, scoria or gravel at a minimum depth of 30 mm. If the aggregate has vesicles, such as pumice, it can contribute to moisture storage.

The water-holding capacity of a substrate is largely determined by the amount and type of organic matter, the type of aggregate used, and the particle and pore size of the substrate. Increased water holding capacity means increased weight. Permeability is also usually reduced as the fines content increases – hence both minimum permeability and maximum weight constrain the water holding capacity of a substrate. The type and particle size of organic matter also influences water holding capacity, e.g. fine coir holds more moisture than pine bark fines; coarse components hold more water than fine components. Fassman et al. (2010a, 2010b) gives results of investigations into a range of potential substrate components available in Auckland. The investigations show the effects of varying substrate components and proportions. Blends of 70–75% of 4–10 mm pumice, 10% zeolite $\leq$ 3 mm, and 15–20% by volume compost were developed that met permeability criteria, while balancing water retention and weight. The mixes held between 20 and 29% Plant Available Water (PAW, 10–1500 kPa). The PAW represents the volume that is critical for attenuating stormwater.

A maximum organic matter content of 20% by volume appears suitable for Auckland and is also used internationally. Auckland studies indicate that if plant cover is established and maintained, this level of organic matter can be sustained by plant inputs, hence minimizing risk of shrinkage (volume loss) and decrease in water holding capacity.

3.2.1 STORMWATER CONTAMINANTS

Living roofs address water quality primarily by reducing the volume of runoff generated by a roof. They can be designed (for planning purposes) to prevent the water quality volume (WQV) from discharging from the rooftop, potentially eliminating the need for ground-level treatment of roof runoff depending on the contaminant(s) of concern. Compared with conventional roofs at the same site, two living roofs in Auckland have shown that total suspended solids are not an issue in roof or living roof runoff. Building materials (copper, zinc) can be a source of heavy metals even where living roofs are present, although the actual runoff concentrations were quite low. In nutrient-sensitive receiving environments, additional ground-level treatment may be required to reduce nitrogen and phosphorus concentrations, especially during establishment. Organic matter used to create the substrate, and other materials used in the living roof system, must be carefully assessed to avoid generating potential contaminants of concern.

3.3 LIVING ROOFS IN TREATMENT TRAINS

Treatment trains should take advantage of the effectiveness of living roofs to mitigate the WQV and peak flow. Living roofs in nutrient-sensitive catchments partner well with bioretention designed to strip any excess nutrients. The volume reduction means such at-grade devices can be smaller. Retention tanks are also natural partners to living roofs, where water is used for non-potable uses such as toilet flushing and landscape irrigation. Some discolouration of water should be expected immediately following installation and after activities that disturb the substrate (e.g. weeding).

Buildings with roofs containing vegetated and unvegetated areas may allow runoff to be directed to areas of living roof to enhance stormwater losses via ET. The additional water can enhance the living roof. by reducing severity of drought stress for the living roof. Run-on water must directly contact the substrate or basal moisture retention mat for it to be accessible by the plants. However, care must be taken to ensure run-on velocity is attenuated. Living roof media are vulnerable to water erosion – they are very light, single grained, and non-cohesive. Pumice floats. Run-on water must not be too hot or plant roots may be damaged.

4 PERFORMANCE OF LIVING ROOFS WHERE STORMWATER IS NOT THE PRIMARY PERFORMANCE OBJECTIVE

The performance of living roofs where stormwater is not the primary performance objective can impact stormwater performance. Some management influences are discussed below where aesthetics, food production, and biodiversity are key objectives. Living roof design is a rapidly developing field. Where living roofs are intended to achieve multiple outcomes (energy demand mitigation, biodiversity, aesthetic, amenity, etc.), designers are encouraged to seek additional references. A range of websites provide useful information and the following books are suggested:

- Cantor L. S. 2008. *Green roofs in Sustainable Landscape Design*. W.W. Norton & Company, New York. London. 352 p.
- Dunnet, N. and Kingsbury, N. 2004. *Planting Green Roofs and Living Walls*. Timber Press. Cambridge, UK.
- Gedge D. & Little J. 2008. The DIY guide to green and living roofs. E-book available online (no specified publisher).
- Snodgrass, E.C. and McIntyre, L. 2010. *The Green Roof Manual: A Professional Guide to Design, Installation, and Maintenance.* Timber Press. Portland, Oregon.
- Weiler, S.K. and K. Scholz-Barth. 2009. *Green Roof Systems. A guide to the planning, design and construction of landscapes over structure.* John Wiley & Sons, Inc. Hoboken, New Jersey. 314 p.
- Dakin, K., Benjamin. L., Pantiel M. 2013. *The Professional Design Guide to Green Roofs*. Timber Press. Portland, Oregon.

4.1 AESTHETICS AND CAMOUFLAGE

The thinness of the substrate (50–150 mm depth) of an extensive roof designed for stormwater attenuation limits how much water can be retained in the system, and hence the diversity and height of plants that can be grown in the absence of irrigation (ASTM 2006). Extensive living roofs are generally not meant to support foot traffic, other than for occasional maintenance. Extensive living roofs are typically designed for function as a priority, but can also promote aesthetic value. Where roofs are visible from within the building or from near-by buildings it is usual for them to look ‘good’ from the point of view of general public. Defining ‘good’ aesthetics is an important part of the design brief and is a key influence on plant selection and maintenance. Design and client communication must emphasise that living roofs are dynamic systems. Plant condition and colour changes with climate, age, and plant stress. In an emerging market such as New Zealand where there are few living roofs, and great interest in new roof projects, visible living roofs are more rapidly accepted if they are aesthetically pleasing. One of the greatest risks for successful implementation of extensive living roofs in Auckland is the perception the roofs are 'gardens' or 'lawns' and should be 'green'. However, a design that minimizes weight and achieves stormwater retention can be aesthetic and have high amenity value (Photograph 3). After all, a healthy plant cover is essential to the stormwater mitigation function of a living roof system.

Lists of suitable native and non-native plant species for the Auckland Region are given in Appendix A and B of the TR2013/045 and TR2009/083 'Landscape and Ecology Values within Stormwater Management' (Lewis et al. 2009). Appendix A must be read in conjunction with the plant selection criteria in Section 4.6 as the plant list is not exhaustive, and the variability of living roof designs and environments makes it impractical to list all living roof plant candidates. Although recommendations are made on 3–6 years of growth, only a limited number of Auckland extensive roofs are available from which to make observations, and each roof is somewhat different.

Plant specialists, for example a horticulturalist or landscape architect, must understand the limitations of substrate depth and roof exposure. Plants and planting patterns selected must have with an acceptable longevity and maintenance requirement, especially with respect to fertilization, irrigation, and frequency of maintenance. Key decisions that impact the performance and success of plants on living roofs include substrate depth, severity of moisture stress, and method of establishment. With the exception of establishment or extended drought periods, irrigation may not be necessary for extensive living roofs in Auckland, as long as adequate moisture-holding properties are provided by the substrate and/or supplemental moisture retention layers are incorporated. Fertilizers are not typically applied after establishment due to the potential for nutrient leaching in runoff.

Photograph 3: Living roof with native herbaceous groundcovers created to provide amenity by covering a garden shed, Auckland 2013

4.2 FOOD PRODUCTION

Few living roofs are used for food production in New Zealand. Restaurants and supermarkets with roof-top gardens in the United Kingdom and North America tend to highlight them as the ultimate in local production and zero food miles. In Melbourne, moveable planters are hired out to inner-city residents and businesses, and located on the roof of a former carpark (Photograph 4). Such planters are not regarded as providing stormwater benefits. First, only a small proportion of the roof is typically covered, and second, drainage is likely to contain high concentrations of nitrogen, phosphorus and dissolved organic materials. Most intensive gardening requires luxury levels of nutrients and regular watering to ensure plants sustain rapid growth and high productivity. Nutrients, either supplied directly as fertilisers, or indirectly as large volumes of rapidly-decomposing composts, are leached from the media by excess watering. Further, regular media disturbance (weeding or crop replacement) and periodic nil, or low, vegetation cover increase nutrient discharges.

A form of food production that complements use of living roofs for stormwater is cultivation of short-stature, perennial, drought-tolerant herbs in standard living roof build-ups with 150–200 mm media depth. This approach minimises the need for irrigation and excess nutrients. Thymes, chives and some lavenders (*Lavendula angustifolia*) have been successfully grown on living roofs in New Zealand with minimal summer irrigation.

Photograph 4: Containerised roof garden used for growing vegetables, Melbourne 2012

4.3 BIODIVERSITY & CONNECTIVITY

Living roofs can contribute to both plant and animal biodiversity objectives. The primary driver for living roofs in London and in Basel and Zurich in Switzerland was to mitigate habitat for birds and insects impacted by brownfield developments (Gedge 2003; Brenneisen 2006). Most extensive roofs provide habitat for insect species tolerant of exposed, dry conditions. In New Zealand these are mainly non-native species and cosmopolitan native species (Davies et al. 2012). Infrequent disturbance and buildup of leaf litter and layers of plants generally increase the value of insect habitat. Another technique to increase habitat diversity for insects on most roofs is placement of stones or stable wooden features (e.g. untreated wood rounds). Some insect species can be attracted by providing the plants they feed on as caterpillars. However, the plants must first be able to survive in the stressful roof environment. As Snodgrass and McIntyre (2010) warn, 'designing a roof for habitat requires deep and specific knowledge of the species you are seeking to attract'.

A fundamental method to enhance diversity and resilience of invertebrate and plant communities is to vary the media depth and/or media water holding capacity by varying particle size. In the early 2000s, the use of local soils was advocated in parts of Europe, and many examples are small, private roofs, especially sod roofs (Dunnett et al. 2011). However, local soils are now not generally used for commercial living roofs in England. Using local soils is not encouraged for Auckland as they are unlikely to meet minimal permeability requirements (important for peak flow mitigation and minimizing risk of overland flow). In addition, local soils are generally much heavier than pumice-based substrates, and intensive early maintenance is required to remove unwanted weed propagules. If local soils are used, their permeability and water retention need to be quantified, along with the concentration of contaminants (especially Cu and Zn and herbicides) where soils are sourced from brownfield sites.

5 APPLYING TR2013/045 OUTSIDE AUCKLAND

5.1 STORMWATER MITIGATION

Specification for bioretention devices should be tailored to the performance requirements of the device. The media used for bioretention has an important role in water quality treatment, water attenuation, and supporting associated vegetation. Specifications also need to take account locally available materials and local hydrologic and soil conditions. Auckland specifications should be examined against local conditions to ensure they are fit for purpose.

If the device is being used to provide hydrologic mitigation, retention and detention requirements should be examined against expected evapotranspiration rates and the volume of storage in the media. In larger events, the ability of living roofs to mitigate stormwater to predevelopment levels may be reduced.

5.2 SUBSTRATE SELECTION

The choice of substrate has the greatest impact on the weight of a living roof, and the supporting roof structure is often the most significant design constraint on a living roof system. For retrofit installation on an existing building, it is essential to obtain a structural evaluation of the building by a licensed structural engineer. The evaluation must identify the maximum system weight the building is capable of supporting and any variation across the roof. The living roof either needs to be designed within this range, or additional structural support constructed. For a new-build, the living roof can be designed as desired, maximum weight calculated, and then the structural support designed accordingly to support the desired roof design.

The substrates developed and tested in Auckland are based on 70 to 80% pumice. Some Taupo, Waikato and Bay of Plenty quarries had pumice deposits with minimal contamination by heavier rock or fines, and processing controls that ensured the fines content could be controlled to specified (low) levels. Together, this meant the substrates were light. Nearly all other aggregates will be substantially heavier than pumice, and have a lower water holding capacity. In England recycled, crushed bricks and, to a lesser extent, concrete, are used as aggregates. These have not been explored in New Zealand to date.

5.3 PLANT SELECTION

Plants are fundamental to living roof performance and resilience. Plant water use creates air-filled pore volume available to attenuate up to 40% v/v of annual rainfall (Voyde et al. 2010b). Plant water use is highest when plants are actively growing, and may become negligible when plants become drought stressed. Hence it is important to ensure plants will survive on a roof – and this means providing adequate moisture in summer. In most eastern and northern areas of New Zealand, this means substrate depths are likely to be greater than those required for stormwater attenuation. Relying solely on irrigation decreases the resilience of a roof, especially where the roof is not visible for two reasons: people may not notice broken irrigation, regular surface irrigation tends to increase weed establishment, especially where bare surfaces are present.

Auckland has a favourable climate for living roofs as regular rainfall and mild temperatures mean plant moisture stress is short, and limited to January to March. Mild temperatures also mean plant growth that generally begins in autumn continues through winter, allowing carbohydrate reserves that are depleted during drought stress (with leaf death) to be rebuilt. Frosts at roof level are uncommon and snow does not fall. However, even in Auckland, few native plants have been identified that are both readily or easily available and can survive in less than 100 mm substrate depth without either minimal supplementary irrigation or afternoon shade (to reduce moisture losses). The most successful plant groups are shallow-rooted, short tussocks (e.g. Festuca and Austrofestuca) from dry coastal sites or rock outcrops. Rock outcrops appear to be particularly useful natural analogues for living roofs, and source of likely plant species and regional ecotypes (Farrell et al. 2013; MacIvor and Lundholm 2011). Within these habitats, plants that tolerate both drought stress and high root temperatures are ideal candidates. Another analogue is epiphytes that grow in exposed areas of tree canopies, for example, New Zealand *Astelia banksii* and the leathery *Pyrossia serpens* have generally been successful, once established. World-wide, succulents that are small and able to regenerate after severe drought are most successful, particularly Sedums (Dunnett and Kingsbury 2010; Snodgrass and Snodgrass 2006).

In the absence of local living roofs, a low-risk option is to use a mix of local species from natural analogue sites, within a matrix of known drought-tolerant plants which are likely to be non-native, but must be non-weedy, i.e. not present a risk to the local ground-level ecosystems. Media depth can be increased, water-retaining layers included, and a variety of methods adopted to reduce water losses, particularly during establishment (Simcock et al. 2012). Significant variation amongst individual plant species ET, interception, and/or other influences such as season of the year, currently precludes a stormwater design process or performance credit reliant on plant species information.

6 CONCLUSION

An approximately seven year research program conducted in partnership between the University of Auckland, Landcare Research, (former) Auckland Regional Council and Auckland Council Stormwater Unit provided place-based research to develop practical guidance for living roof design for stormwater management. Relationships between the composition and depth of the growing media, stormwater retention, and plant viability and health have been established. This information culminated in Auckland Council Technical Report 2013/045, which is freely available online to enable design and implementation for stormwater management. The TR should be used in lieu of TP10 (2003) chapter 12.

Determining the true value of a living roof is challenging, and may not appear cost-effective if only stormwater management benefits at the building scale are considered under the current stormwater permitting and legislative regime in Auckland. Living roofs typically manage only the precipitation falling directly on the roof's surface, therefore other stormwater devices maybe necessary to mitigate runoff from ground-level source areas. However, when roof area is managed by a living roof, it reduces the footprint of ground-level stormwater devices needed to treat the remainder of the site (if required). Ancillary benefits such as extending roof life, mitigating energy demand, and providing a visual amenity are not usually "counted" in construction or maintenance costs, but are nonetheless provided by living roof installation.

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