Living Roof Review and Design Recommendations for Stormwater Management

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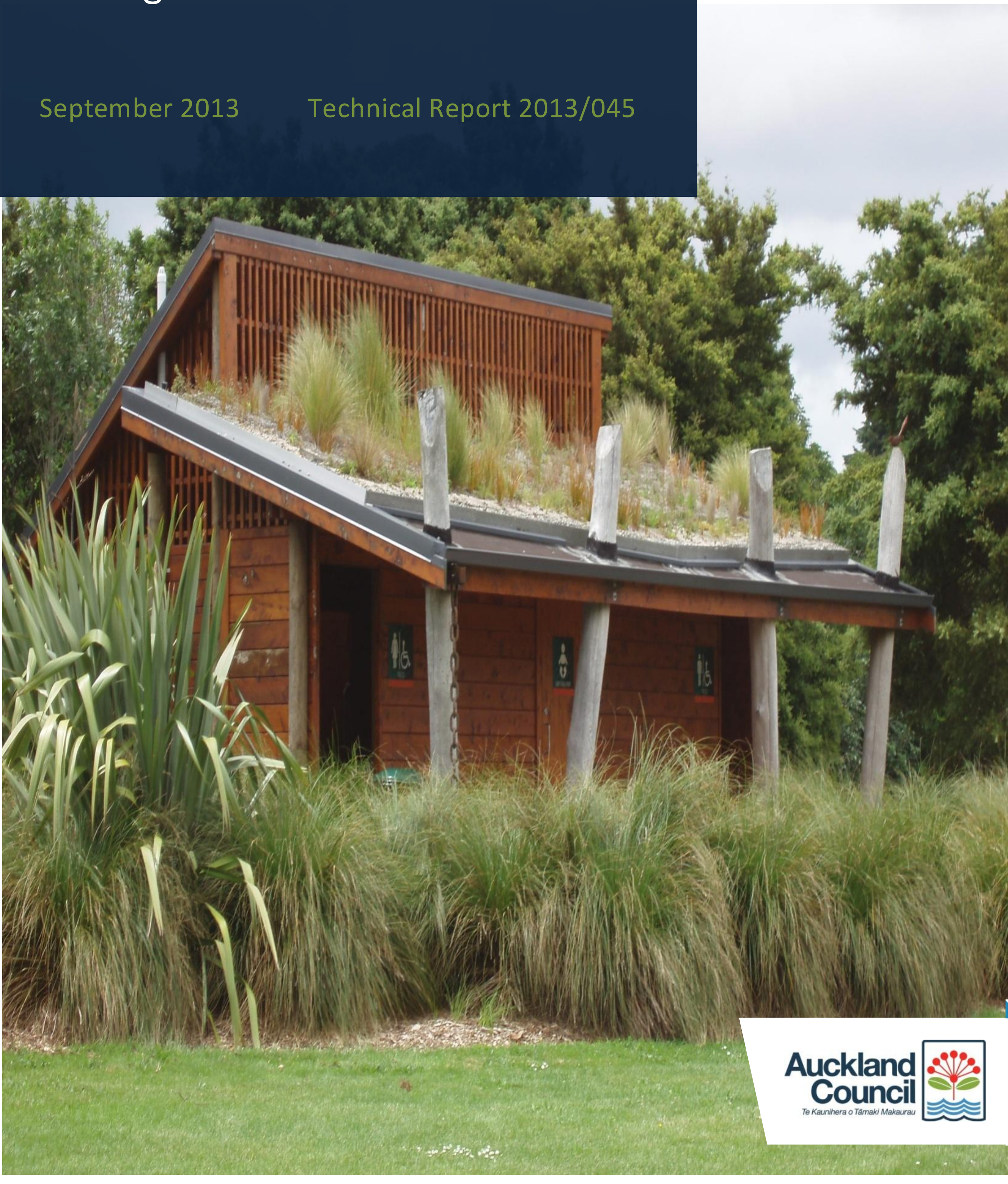

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Living Roof Review and Design Recommendations for Stormwater Management

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Executive Summary

Living roofs are a water sensitive design (WSD) technology for stormwater management. The term *living roof* is used to describe a substrate (growing media) and vegetation covered roof, while acknowledging the natural variation of system appearance and dynamics (e.g. as plants thrive or go dormant). Rooftops comprise a significant proportion of the total impervious area in urban settings. Considerable opportunity exists to reduce stress on stormwater and combined sewer reticulation and other receiving environments through living roof installation on new buildings and retrofits on existing roofs. 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). In addition, living roofs 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.

An extensive living roof is comprised of relatively thin drainage and 20-150 mm substrate layers, with low growing plants suited to droughty, windy environments. Despite the limited depth, extensive living roofs with substrate that is designed with adequate moisture retention properties are capable of providing substantial stormwater mitigation (Fassman and Simcock 2012). The majority of individual storm events produce low rainfall depths across the Auckland region (on average < ~31 mm (Shamseldin 2010)) which are well-proven to be completely or near-completely retained by field monitoring studies in Auckland and overseas.

Four living roofs in Auckland with substrate depths ranging 50 mm to 150 mm produced 39-57% less cumulative runoff than from a conventional roof surface at the same site, over monitoring periods ranging 8-28 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 56-76%, with appreciable year-round performance. Rainfall depth has been shown to be 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 (2-yr return frequency and larger) typically the subject of peak-flow mitigation objectives (Fassman-Beck et al. 2013a; Kasmin et al. 2010), but the presence of a living roof will nonetheless reduce the footprint of ground-level flow controls.

Peak flows are very effectively managed, regardless of storm size. From Auckland's monitored living roofs, median peak flow reduction compared to a conventional roof at the same site was 62-90% (Fassman-Beck et al. 2013a). Peak flow should always be well 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). Mitigation can be enhanced through drainage layer design. Through retention, detention, and creating a flow path through porous media rather than over a smooth surface, many field studies of living roofs indicate significant time lags in the onset of runoff with respect to rainfall, a delay in the time to peak compared to a conventional roof surface and/or peak rainfall intensity, and/or extended hydrograph duration (Carter and Rasmussen 2006; DeNardo et al. 2005; Getter et al. 2007; Liu 2003; Moran and Hunt 2005; VanWoert et al. 2005; Voyde 2011).

Living roofs address water quality primarily by preventing runoff from being generated by the rooftop. Per this guidance, living roofs 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 to conventional roofs at the same site, two living roofs in Auckland have shown that total suspended solids are not an issue in runoff. Building materials can be the 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 for nitrogen and phosphorus. 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.

The primary purpose of this technical report is to provide practical guidance for the design of extensive living roofs suitable to the Auckland climate, with the objective of completely retaining (zero discharge) the “frequently occurring” design storm event (e.g. the 85^{th}-95^{th} percentile event). Modular, pre-fabricated extensive living roof systems that provide substantial roof surface coverage are also considered. Intensive living roofs (those with substrate depths greater than 200 mm) are unlikely to provide superior stormwater control based on empirical evidence, while cost-effectiveness declines substantially due to the infrequency of larger events. Containerized “roof gardens” designed for aesthetics are not considered stormwater devices.

A living roof typically consists of multiple layers, including a waterproofing membrane, root barrier, drainage layer, substrate, and vegetation. Supplemental moisture storage layers may also be included. Each layer plays an important role in the overall system function (Chapter 2). Commercial products are usually sourced for several elements; guidance is offered in this report on selection of materials that are fit-for-purpose (Chapter 4 and 6). The design process in this report focuses on the drainage layer, substrate, and vegetation prioritizing stormwater management outcomes.

The majority of rainfall retention occurs within the substrate; thus, substrate design to promote water retention of the target rain event is critical. In practice, healthy, densely covered vegetated roofs provide superior stormwater control compared to unvegetated, substrate-covered roofs. It also prevents substrate loss from wind and rain. However, significant variation amongst individual plant species’ ET, interception, and/or other influences such as season of the year, precludes a stormwater design process or performance credit reliant on plant species information at this time. At present, there is also insufficient empirical evidence to reliably quantify the influence of roof pitch (slope) on runoff control.

Typical extensive living roof substrate is an engineered media[1] comprised of 80-95% (by volume) light-weight aggregate (LWA) and 5-20% (by volume) resilient organic matter; they do not contain natural topsoil or garden mixes. Substantial research has occurred in Auckland to develop appropriate recipes for substrate mixes which have also been field-tested (Fassman et al. 2010a, 2010b); the extent of this non-commercial research is unique in the international literature. Chapter

[1] The term “engineered media” is used to distinguish a blend of materials that would not necessarily be naturally sourced as a unique mixture, but individual components may be naturally sourced. Engineered media are designed to achieve pre-determined objectives for stormwater management; properties may differ substantially from natural soils.

4 identifies desirable substrate characteristics and testing methodologies. Chapter 6 sets out criteria for moisture holding properties (measured as plant available water [PAW]) and how it is used to determine the minimum required installed depth to retain the target design storm event. Regardless, the minimum allowable substrate depth is 100 mm for new construction. Retrofit projects limited by the existing structural support may be as shallow as 50 mm, but will retain less than the design storm depth. In all cases, substrate saturated permeability must exceed 0.05 cm/s as determined by ASTM E2399-11.

Regardless of the blend of materials used for the substrate, three key supply chain factors must be managed to maintain the desired substrate characteristics: source material quality control, the blending/mixing process, and post blending testing to ensure adherence to the design criteria. Relatively dry, completely weed-free materials must be blended using non-destructive methods, such as using a trammel (a rotating screened cylinder). Post-blending, pre-installation testing including wet weight and saturated permeability is required for all substrates. If a substrate exceeds the design weight, consultation with the structural engineer and the horticultural consultant is required, and may trigger remedial action.

For planning and consenting purposes, an extensive living roof may be considered to completely retain a maximum of 30 mm of precipitation. The extent of retention depends primarily on a combination of the substrate's moisture retention properties and finished (settled) depth. Calculations are provided in Section 6.4 to support the following planning assumptions:

- Where the finished depth meets or exceeds the minimum depth calculated in Section 6.4, there is no runoff that occurs from the living roof (runoff depth = 0; retention = 100%) for storms with rainfall depth $P \leq 30$ mm.
- Where the finished depth is less than the minimum depth calculated in Section 6.4, but media depth of at least 100 mm for new construction and 50 mm for retrofit is provided, there is no runoff that occurs from the living roof (100% retention) for storms up to the substrate's estimated storage potential.
- In all cases, a maximum of 30 mm may be considered retained based on the substrate's moisture retention properties and finished depth.
- In most cases for water quality, discharge from living roofs designed to retain the maximum allowable storm depth does not require additional treatment. The main exception may be in nutrient sensitive receiving environments, but must be considered on a case-by-case basis.

If/where runoff volumes are required to be calculated for storms larger than 30 mm, calculations shall use an appropriate curve number method, with CN=85.

If/where a continuous simulation is applied, and substrates satisfy minimum requirements of Section 6.4, equation 1 may be used to predict runoff depth:

$$Q=0.0046P^2 + 0.3603P + 0.0242 \qquad \text{Equation 1}$$

Where Q = living roof runoff (mm) and P = rainfall depth (mm). Additional research is necessary to expand the continuous simulation approach to include other site-specific variables such as ET rate, plant and substrate characteristics.

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 (Fassman et al. 2010b).

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). Living roofs on slopes of greater than 20° are feasible with anti-slip/anti-shear protection. The maximum pitch for living roofs to be considered as stormwater retention devices is 15°.

Extensive living roofs are typically designed for stormwater function as a priority, but can also promote amenity value. A healthy, dense plant cover is considered essential to the stormwater mitigation function of a living roof system. It is important to understand and inform the expectations of the client, occupiers, and others within the viewshed. Design and client communication must emphasise that living roofs are growing systems. Plant condition and colour will change with climate, age and stress condition of the plants. 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’. Nonetheless, design to minimize weight while promoting stormwater retention does not necessarily limit aesthetic outcomes and amenity value.

Lists of suitable native and non-native plant species for the Auckland Region, many of which have been grown for two to six years on a limited number of Auckland extensive roofs, are given in Appendix A and B, and develops further from recommendations in 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. In particular, the plants lists are based on lightweight, free-draining substrates as per Section 4.5, not natural or garden soils. Biosecurity risks are identified.

Plant specialists, for example a horticulturalist or landscape architect, must understand the limitations of substrate depth and roof exposure. They should select plants and planting patterns with an acceptable longevity and maintenance requirement, especially with respect to fertilization, irrigation and frequency of visits. Key decisions that impact the performance and success of plants on living roofs include substrate depth, severity of moisture stress, and method of establishment. Methods of managing risks of plant failure are identified in Section 7.6. 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.

Some design decisions depend specifically on installation methods and long-term operation and maintenance plans, thus these elements are discussed, where appropriate, as compliments to information in Auckland’s stormwater treatment devices construction, operation, and maintenance guides (Healy et al. 2010a, 2010b). The rooftop creates a unique environment for stormwater device maintenance, posing multiple hazards. Designing safe access for maintenance is the first step in creating a feasible maintenance regime; understanding maintenance requirements promotes good design. Weed management is largely governed by the time taken to achieve a dense, weed resistant plant cover and presence of local weed sources. A clearly-defined maintenance contract, preferably with the living roof supplier, is recommended for at least 18 months.

Living roofs for stormwater management must be designed in collaboration and consultation with other experts that contribute to the overall roof and building design. From the project outset, consultation between the stormwater engineer, structural engineer, architect, horticultural consultant, and landscape architect (if applicable) is strongly encouraged to identify major design elements, constructability, and long-term maintenance plans. Where the living roof is designed specifically for stormwater management (as per this document), aesthetics and location of building services should not compromise function for stormwater control.

Chapter 5 provides design guidance for a structural engineer, including a guide for calculating building loads resultant from a living roof system to be used in conjunction with the New Zealand Building Code. Weight of the substrate is determined using ASTM E2397-11 and E2399-11.

Chapter 5 also provides guidance for collaboration with architectural designers. Amongst considerations are: design and location of vertical drainage points (scuppers, inlets, drains, etc); parapets, balustrades, and anchor points; roof pitch (slope); edging and walkways; design and location of mechanical services; and the method and location of physical access by people. Design of the roof and its access must comply with all relevant Occupational Safety and Health requirements.

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1.0 Background

Living roof technology has emerged internationally as a viable water sensitive design (WSD) (also known as low impact design [LID]) technology for stormwater management. Rooftops comprise a significant proportion of the total impervious area in urban settings, thus considerable opportunity exists to reduce runoff volume and peak flow by retrofit of existing building stock. Installation of living roofs on new building stock and retrofits on existing roofs reduces stress on stormwater and combined sewer reticulation and other receiving environments. 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). In addition, living roofs 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.

Living roofs for stormwater management mitigate the majority of annual surface runoff primarily through excellent control of smaller, frequently occurring rainfall events, and meaningful reduction of larger, infrequent events. As the extent of living roof coverage increases across the city, so do the stormwater benefits. The primary purpose of this technical report is to provide practical guidance for the design of extensive (shallow, up to 150 mm substrate [growing media] depth) living roofs suitable to the Auckland climate, with the objective of retaining the 85^{th}-95^{th} percentile design storm event. Some design decisions depend specifically on installation methods and long-term operation and maintenance plans, thus these elements are discussed, where appropriate, as complements to information in Auckland's stormwater treatment devices construction, operation, and maintenance guides (Healy et al. 2010a, 2010b). Likewise, living roofs are often intended to provide aesthetic and amenity value as well as recreational space, thus design for stormwater mitigation coincides with architectural objectives. While the design approach recommended in this report places stormwater management as the first priority, potential interactions with architectural elements and objectives are also addressed.

The term *living roof* is used in this report to describe a substrate and vegetation covered roof. The term *living roof* is used commonly in England and Switzerland in reference to roofs designed for stormwater retention and/or biodiversity, acknowledging that systems may turn brown in the summer and/or winter when plants are dormant, and may 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 that the vegetation is always green (Emilsson and Rolf 2005), which may not be the case. The term *green roof* can provide false aesthetic expectations of a lush "green" garden or lawn. A variety of colourful flowers may be found amongst living roof vegetation, and the foliage may also change colour depending on season and dormancy periods. The Bureau of Environmental Services in the City of Portland, Oregon (USA) adopted the term *eco-roof* to emphasise the functionality of living roof systems, to differentiate from roofs painted green or with green shingles, and to avoid pre-conceived notions about plant colour. Discussion with architects in New Zealand indicated that the term *eco-roof* conveys a wide range of roof types, from *cool roofs* with high solar reflectance to *blue roofs* that hold water on a bare membrane, and *living roofs*, and thus does not convey the specific meaning intended.

1.1 Documentation history

The Auckland Council is currently undertaking a review and update of Technical Publication 10 (TP10): Stormwater Treatment Devices Design Guideline Manual. The first edition of TP10 was published in 1992 and provided what were then best practice guidelines for the design of stormwater management devices. As knowledge and philosophies advanced, the need was seen to update TP10 to bring it up to date with international best practice and changes in the approach to stormwater management in the Auckland region. The result was the Second Edition of Technical Publication 10, published in 2003 (ARC 2003).

The current review of TP10 is being undertaken 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 are to be written to investigate the individual devices contained within TP10 (2003). Each of these technical reports will examine the existing design guidelines in the current TP10 (2003) document and update these guidelines based on current international research and best practice documents while addressing the knowledge gaps identified during a gap analysis phase (see Section 1.2). The technical reports will 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. Each device will then be summarised (including detailed design methodologies) and included for release as part of Guidance Document 2010/001 (GD2010/001) to supersede the respective sections of TP10 (2003).

1.2 Gap analysis

During the early stages of the TP10 (2003) review and update project, the Auckland Regional Council undertook a gap analysis phase. This identified the strengths and weaknesses of the current TP10 document, potential organizational changes that could be made and comments on the individual device chapters. The gap analysis phase was carried out by ARC staff working in the field of stormwater management, external consultants with previous involvement with the TP10 (2003) document and/or who are considered specialists in the field of stormwater management, and representatives from various industry groups and end users.

The results of this initial gap analysis phase have been used as a starting point for preparing each of the device specific technical reports. Living roofs are an accepted stormwater management device for the Auckland region, according to TP10 (2003); the current TP10 (2003) guidelines include the chapter "Greenroof design, construction and maintenance" (Chapter 12). With respect to design, Chapter 12:

- Outlines components of a living roof system
- Discusses waterproofing
- Discusses structural loading based on overseas examples
- Lists desirable characteristics for the substrate (growing medium) and plants
- Comments on general irrigation and maintenance requirements
- States (greened) roof area does not require supplemental treatment (for stormwater quality)
- Recommends assigning a curve number (CN) of 61 for hydrologic design

The information provided is somewhat generic overall, without instructional guidance on materials available in New Zealand, or design considerations specific to the Auckland climate. The main items identified with respect to living roofs were:

- Living roof design guidance needs considerable expansion as the TP10 (2003) living roof chapter took a conceptual approach rather than a design one, due to a lack of locally verified data
- More guidance needs be provided on:
    - Design considerations specific to the Auckland climate
    - Structural loadings
    - Materials specification for drainage layer and impermeable liner
    - Substrate composition and depth
    - Recommended plants
    - Expectations for plant establishment
    - Construction, operations and maintenance requirements
    - Testing methods and construction considerations relevant to performance
    - Hydrological benefits
- Local case studies illustrating appropriate design methods need to be provided
- The lack of locally relevant design, operation and maintenance information is considered a barrier to uptake and widespread implementation of living roof technology for stormwater control

1.3 Abbreviations

ARC Auckland Regional Council
ASCE American Society of Civil Engineers
ASTM ASTM International, formerly American Society of Testing Materials
C_p Rational formula runoff coefficient
CEC Cation Exchange Capacity
CN Curve Number
EMC Event Mean Concentration
ET Evapotranspiration
FLL The German green roof design standards, which translates to: *Guidelines for the Planning, Execution and Upkeep of Green Roof Sites* (FLL 2002, FLL 2008)
GD Guideline Document
LWA Light-Weight Aggregate
NRCS Natural Resource Conservation Society
OSH Occupational Safety and Health
PSD Particle Size Distribution
PAW Plant Available Water
TP Technical Publication
TR Technical Report
TSS Total Suspended Solids
UoA University of Auckland
WCC Waitakere City Council
WQV Water Quality Volume
WSD Water Sensitive Design

2.0 Living Roof Principles

2.1 Overview

The increased impervious cover associated with urban development can significantly increase both the volume and peak discharge rate of stormwater runoff. Unmitigated, these hydrologic changes increase the risk of flooding to downstream properties and the degradation of in stream environments by erosion and more frequent bank full flow.

Living roofs are very effective at controlling the roof runoff volume and peak flow rate of small to medium storms (Fassman et al. 2010a, 2010b). Analysis of Auckland's rainfall frequency indicates that 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). In other words, the vast majority of all rainfall events are small storms, thus rooftop runoff management can make a large contribution to planning for comprehensive stormwater management.

When rainfall begins, a small amount that strikes the foliage is intercepted. As rain continues, water percolates into and begins to wet the substrate. The net volume of runoff is primarily reduced by rainfall retained (captured) within the substrate. Significant quantities of water do not begin to drain from the roof until the field capacity[2] of the substrate is filled, in theory. In practice, preferential flow paths and other heterogeneities in the system may cause some runoff to occur before the field capacity is reached. During small rainfall events, negligible (if any) runoff occurs and most of the precipitation eventually returns to the atmosphere by evapotranspiration (ET)[3]. 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. detains and delays runoff), as water must percolate through the substrate and drainage layers before reaching the outlet (the roof's vertical drainage). For these reasons, living roofs reduce pressure on storm and/or combined sewer networks.

Living roofs address water quality primarily by preventing runoff from being generated by the rooftop. Specification of components comprising the living roof system and maintenance activities should avoid impairing water quality in living roof runoff. Per this guidance, living roofs can be designed to prevent the water quality volume (WQV) from discharging from the rooftop, thus potentially eliminating the need for ground-level treatment of roof runoff.

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

[2] Field capacity is loosely defined as the amount of water that can be held (retained) by a soil matrix against gravity drainage.

[3] ET is the loss of water to the atmosphere via evaporation from substrate and plant surfaces, and via plant transpiration.

such as extending roof life, energy demand mitigation, and providing a visual amenity (Section 2.4) are not usually "counted" in construction or maintenance costs, but are nonetheless provided by living roof installation.

2.2 Living roof components

A living roof typically consists of multiple layers (Figure 1), each of which plays an important role in the overall system function, as described in the following sections. Not shown in Figure 1 is a building insulation layer. It is not shown as it is typically considered by an architect in the design of the building structure, rather than as a component of the stormwater management system that sits atop the roof deck.

Figure 1. Typical living roof composition

2.2.1 Waterproofing layer

The waterproofing layer, usually a synthetic membrane, protects the structure from water damage. Protection of the building structure from leaks is a critical aspect of construction regardless of the presence of a living roof. A properly designed and installed living roof should extend the useful life of a waterproofing membrane, as the living roof physically blocks incoming UV rays which cause mechanical breakdown of the membrane, eventually resulting in the need for repair or replacement.

2.2.2 Root barrier

A chemical or physical root barrier prevents root penetration into the waterproof membrane and the underlying roof surface. Some synthetic drainage mats are available with an integrated root barrier. Likewise, some waterproofing membranes developed specifically for living roofs contain a root-deterring chemical or metal foil at the seams to prevent root damage (Peck and Kuhn 2003).

The cost of a root barrier is small compared to the potential damage caused by aggressive root systems which may be introduced to the roof from wind-blown seeds, and may be overlooked by maintenance crews.

2.2.3 Optional moisture retention layer

A moisture retention layer or layers increase the volume of water retained on the roof before drainage. Where this moisture is accessible to plant roots, it can enhance 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 placed at the base of the root zone where the held moisture is accessible by plant roots. Retention layers have variable longevity and are likely to become less effective over time as they decompose.

2.2.4 Drainage layer

Drainage layers provide multiple functions. Their role for stormwater is to provide free (usually rapid) drainage for rainfall in excess of the system's rainfall (moisture) storage capacity to outlets (e.g. downpipes), preventing ponding of water. The drainage layer is typically made from a synthetic mat or granular material, typically coarse aggregate. Specialty products tend to have a bonded (attached) geotextile, and may also contain a root barrier.

The drainage layer itself does not provide waterproofing, but it can physically protect the waterproof membrane from shovels or other gardening implements that might damage waterproofing during planting or maintenance. It also provides a means for air circulation for plant roots, and an evaporation zone to help keep roof insulation dry. In cold environments, a drainage layer prevents free water on the roof, minimising freezing damage.

2.2.5 Geotextile separation

The geotextile supports the substrate and prevents migration of substrate fines to maintain a free-flowing drainage layer. It can be either a separate layer, or bonded to a synthetic drainage layer.

2.2.6 Substrate

The substrate supports plants both physically and nutritionally, stores precipitation up to field capacity for subsequent loss by ET, extends the flow path to reduce runoff velocity and delay peaks, and provides thermal mass and insulation. It can be used to provide ballast against wind uplift. The majority of rainfall retention (i.e. runoff volume reduction) by a living roof system occurs within the substrate.

2.2.7 Vegetation

Plants play an integral role to the overall function of the living roof system, including: enhanced ET, rainfall interception, and maintaining substrate porosity. ET dries out the substrate, restoring capacity to capture the next storm event. It is a cooling process; it is this phenomenon that contributes to urban heat island mitigation and the creation of cooler microclimates immediately above a living roof's surface. Healthy plants contribute to acceptance of the living roof by those within its viewshed[4], regardless of a living roof's technical intent. The plants also ensure the surface of the living roof is stable – resistant to rain, wind and animals. Stems and leaves physically protect the surface from impact while roots bind and hold the substrate in place.

2.3 Living roof types

2.3.1 Extensive

Extensive living roofs are low profile, relatively thin layers (drainage, substrate, and plants) (Figure 2). Low growing plants are established in 20–150 mm of substrate (ASTM 2006). These living roofs are usually less expensive and lower maintenance when compared to other types of living roofs (Dunnett and Kingsbury 2004). Roof structural requirements are lower than other living roof configurations, with saturated weights reported from 70–170 kg m^{-2} (Dunnett and Kingsbury 2004, Peck and Kuhn 2003), and thus may be applicable for retrofit construction. The thinness of the substrate 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). In general, extensive living roofs are not irrigated, except in climates with long summer drought periods, in the establishment period, on very steep roof slopes, or where aesthetic requirements prevail. 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.

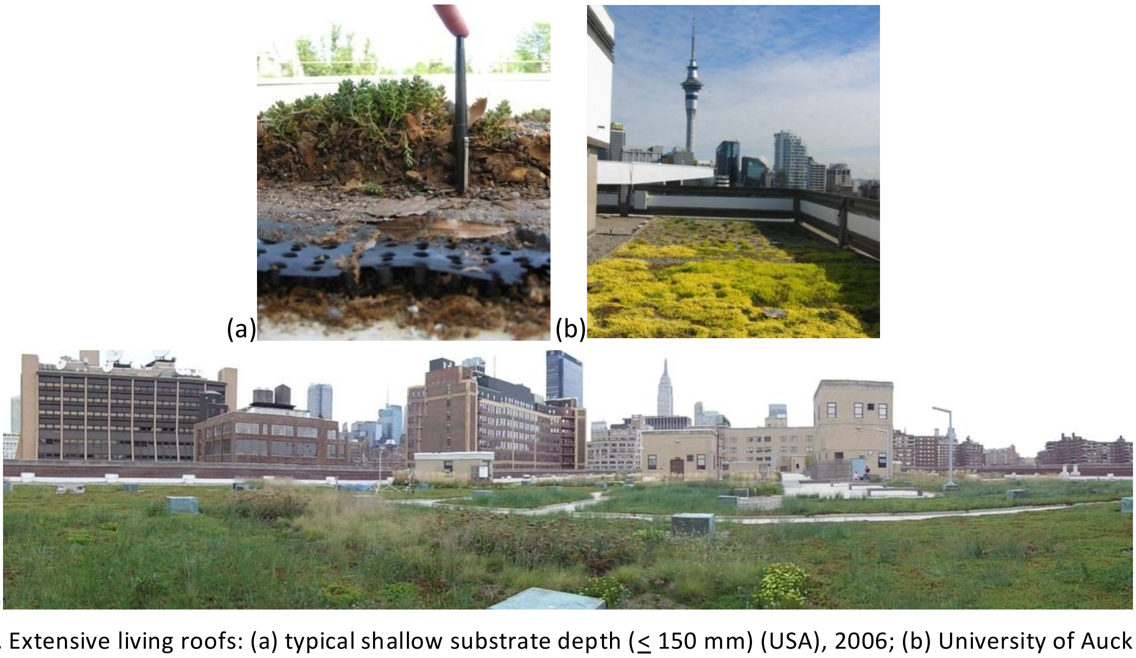


Figure 2. Extensive living roofs: (a) typical shallow substrate depth (≤ 150 mm) (USA), 2006; (b) University of Auckland demonstration and testing site, 2010; (c) US Postal Service, New York City, 2012.

[4] A viewshed is considered to be the full extent of area from which the living roof is visible. For example, adjacent buildings that look over a living roof are contained within the viewshed, without being owners or occupiers of the building upon which the living roof is installed. Publically accessible viewsheds are considered particularly important with respect to maintaining aesthetics, to ensure on-going support for a living roof project.

2.3.2 Intensive

Intensive living roofs have the deepest layers (drainage, substrate, and plants) and a wider plant variety, including herbaceous plants to shrubs or trees (Figure 3). The substrate is typically $\geq$200 mm, and up to 1000 mm (for trees), which promotes deeper potential root depth, and hence accommodates a wider height and variety of plant species (ASTM 2006). The associated high saturated weight (300–1000 kg m^{-2}) requires significant structural support for the roof, which means that they are usually only designed for new construction or concrete roofs of buildings designed for additional floor capacity or vehicle access. Larger plants requiring deep rooting depths (e.g. shrubs in 300–500 mm or trees in 500–1000 mm) may be located over the building's load-bearing elements, with shallower substrate in between, rather than strengthening the entire roof. Regular irrigation is often a required design element. Many intensive roofs are designed to be at least partially accessible (Dunnett and Kingsbury 2004). Design emphasizes form and accessibility.

The deeper substrate on an intensive living roof does not necessarily provide significant additional stormwater control compared to an extensive living roof. This is because the majority of individual storm events produce low rainfall depths (on average < ~31 mm across the Auckland region (Shamseldin 2010)) that are well-managed by relatively thin living roof systems, as long as the substrate is designed with adequate moisture retention properties (Fassman-Beck et al. 2013).

Figure 3. Intensive living roof with recreation space: (a) the University of North Carolina, Chapel Hill (USA), 2012; (b) London (UK), 2008; (c) Aotea Square, Auckland is an intensive roof over a multi-storey carpark (the Civic), 2012.

2.3.3 Containerized roof garden

Containerized roof gardens are accessible areas on a roof with isolated pot plants instead of layers of membranes and substrate that are installed directly on the roof deck (Dunnett and Kingsbury 2004) (Figure 4). Roof gardens can be referred to as "landscape over structure" (Weiler and Schloz-Barth 2009), and may sometimes be considered intensive living roofs. The lack of hydraulic connection between containers means that containerized roof gardens usually require regular irrigation. As aesthetic requirements are high or particularly important, roof gardens will usually be fertilized and irrigated. Containerized roof gardens do not usually provide appreciable stormwater management primarily due to poor extent of roof surface coverage. The high maintenance and energy inputs required are further deterrents to qualify as environmental mitigation systems. As containers themselves would add significant weight, a more effective alternative would be to distribute the load in an extensive living roof configuration, even if only a portion of the total roof is vegetated. Containerized roof gardens are not considered further in this report as they do not qualify as stormwater management devices.

Figure 4. Containerised roof garden used for growing vegetables, Melbourne 2012

2.3.4 Pre-fabricated, modular living roofs

Several "ready-to-install" living roof systems have been developed, which include the drainage layer, substrate, and pre-grown plants. These systems are usually modular, and encompassed in some sort of tray or pouch which is set in place on the roof. Examples are shown in Figure 5. Pouches or bag systems provide a light-weight mechanism to hold material together; plants can grow through the pouch. Rigid trays usually offer an interlocking mechanism. Biodegradable trays require formal edging on the roof, as the system is likely to break down over time. Anecdotal evidence suggests that the lack of horizontal connection between some types of modular elements may exacerbate drying along edges. Greater resilience is thought to be provided by systems that enable substantial contact between adjacent modules, enabling plant roots to travel between containers. Rigid plastic trays usually integrate a drainage layer. Pouches or biodegradable trays are usually installed over a formal drainage layer.

Pre-planted living roof systems ready for installation are likely to have higher cost (most of the labour is performed in advance by the supplier). The primary advantage is an instant aesthetic with high plant coverage and high erosion resistance. They are particularly suited to risk-averse clients as they may be removed – they therefore are common in North America (Snodgrass and McIntyre 2010). Modules also suit small retrofit applications as they can be carried up stairs and lifts, and placed over existing membranes.

In terms of stormwater management function, tray systems are not currently perceived to provide any specific benefit(s) over a continuous living roof system. Modular living roofs differ from containerized roof gardens in that they are usually installed to form continuous and substantial coverage of the roof's surface area.

Figure 5. Ready-to-install modular systems; (a) coir trays (USA); (b) Aluminium and plastic 100 mm modular trays (USA); (c) 220 mm plastic tray and 100 mm modular bag (USA); (d) plastic 100 mm modular system with removable divider panels (NZ) (e) flexible coir pouch and (f) rigid coir pouch systems (NZ, imported).

2.4 Additional (non-stormwater) benefits

Beyond stormwater management, environmental, economic, amenity and aesthetic benefits are provided by living roof systems. The relative degree of each benefit from an individual living roof varies dependant on system configuration (substrate depth, composition, vegetation characteristics) and management. Additional benefits may include:

- Reduce energy consumption
    - enhance building insulation (when dry) and thermal mass (when wet)
    - improve air conditioning efficiency and reduce operational cost where vents are located above the vegetation, as intake air temperature is cooler than ambient air (Castleton et al. 2010; Del Barrio 1998; Meier 1990; Sailor 2008)
- Extend the useful life of a roof surface by protecting it from damaging UV rays which cause mechanical breakdown of surfaces
- Mitigate the urban heat island effect (i.e. lower ambient temperatures)
    - reduce the amount of solar energy absorbed by building materials
    - create a cooling microclimate by ET
    - reduce reflected heat
- Create urban habitat
    - mitigate removal of some types of insect habitat from modifying existing land use; provide nectar and pollen sources for bees
    - provide additional feeding or roosting surfaces for some bird species
    - provide "green corridors" for some species
- Absorb and filter airborne pollutants, including dust, while releasing oxygen
- Reduce sound/noise transmission
- Provide amenity and community value as a recreational or plant-growing space
- Provide visible green space, contributing to health benefits (hence increasing use in hospitals overseas) (Kuo 2010; Ulrich 1984)
- Provide aesthetic value and/or blend a building into a sensitive landscape.

3.0 Living Roof Applications

3.1 Applications

Rooftops comprise a significant proportion of the total impervious area in urban settings, particularly in industrial areas and city cores where at least 70% total impervious area is common. Living roofs can be used as an effective source control in various commercial, residential and industrial applications. They provide a significant stormwater management opportunity in otherwise often unusable space, rather than more valuable ground space. Auckland's sub-tropical climate with regular rainfall can support living roof plant establishment and maintenance of vegetative cover with relatively minimal supplemental inputs (Fassman et al. 2010b).

The stormwater design objective for living roofs is to prevent rooftop runoff from being generated from frequently occurring, small(er) storm events, such as up to the 85^{th}-95^{th} percentile event in many climates. Runoff from these "everyday" storm events contributes the majority of the annual pollutant loads, compromises the physical habitat structure of receiving environments, and can cause nuisance flooding and combined sewer overflows (Fassman-Beck et al. 2013b). Extensive living roofs in Auckland are well-proven to retain runoff from storms less than ~25 mm (Fassman-Beck et al. 2013a). Performance is reduced for larger events (2-yr return frequency and larger) typically the subject of peak-flow mitigation objectives (Fassman-Beck et al. 2013a; Kasmin et al. 2010), but the presence of a living roof will nonetheless reduce the footprint of ground-level flow controls.

The increased depth of an intensive living roof does not necessarily correspond to increased stormwater control, 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 extensive living roofs with appropriately designed substrates as described in this report; the increased initial and long-term costs associated with intensive living roofs are not justified in terms of stormwater management.

Structural loading is one of the main factors controlling the feasibility and cost of a living roof. New extensive living roofs can be accommodated in building design for a minor additional cost (which may be off-set by the corresponding size reduction in ground-level stormwater controls). In many cases, the weight of an extensive living roof is similar to the weight of a ballasted roof. Retrofit projects need to consider foremost the bearing capacity of the structure. Due to structural loading requirements, only extensive living roofs are typically suitable for retrofit installation. In all cases, a thorough structural analysis performed by a licensed structural engineer is required.

The design of a living roof for stormwater management is influenced by the extent and accessibility of its viewshed. If a living roof is not readily visible, either directly or from adjacent structures and vantage-points, then the aesthetics of the living roof are relatively insignificant. Wherever a living roof can be seen, either by building occupants, by neighbours, or by the general public, aesthetics will influence the interpretation and acceptance of the living roof, regardless of its technical intent (i.e. stormwater management).

Living roofs may be installed with other "green infrastructure". Installation of a living roof beneath photo-voltaic (PV) cells protects the footings of the PV cells. The microclimate created by living roof ET helps keep circuitry cooler, thus maintaining PV cell efficiency. If rainwater harvesting is a goal for a particular site, it may be necessary to maintain at least some meaningful impervious area, as extensive living roofs in Auckland have proven to retain rainfall very effectively (Fassman-Beck et al. 2013a).

As the purpose of this report is to provide design guidance for stormwater management, the majority of this report is dedicated to extensive living roofs.

3.2 Site considerations and constraints

Living roofs for stormwater management must be designed in collaboration and consultation with other experts that contribute to the overall roof and building design. From the project outset, consultation between the stormwater engineer, structural engineer, architect, horticultural consultant, and landscape architect (if applicable) is strongly encouraged to identify major design elements, constructability, and long-term maintenance plans. Structural support, physical access for maintenance or viewing, vertical drainage features, safety considerations and location of other mechanical building services on the rooftop (e.g. HVAC, satellite TV, etc.), and the presence/absence of a maintenance contract, may affect living roof design and vice versa. Where the living roof is designed specifically for stormwater management (as per this guideline), aesthetics and location of building services should not compromise function for stormwater control.

While construction, operation, and maintenance are covered in Headley et al. (2010a, 2010b), some aspects are relevant to the design decision-making process, particularly with respect to plant selection and are thus discussed in this guideline. Considerations relevant to structural and architectural design advice are outlined in Chapter 5.

3.2.1 Structural requirements

The most significant constraint for a living roof system is the supporting roof structure. For installation on an existing building, it is essential to obtain a structural evaluation of the building to be retrofit by a licensed structural engineer. The evaluation will identify the maximum system weight the building is capable of supporting. The living roof will either need to be designed within this range, or additional structural support will be required. For a new build living roof, the living roof can be designed as desired, maximum weight calculated, and then the structural support designed accordingly to support the desired roof design.

Refer to Chapter 5 for calculations pertaining to structural requirements.

3.2.2 Building consent

Councils typically require building consent for the installation of a living roof, for either new or retrofit situation. It is also a requirement under the Building Code. A structural assessment must be carried out by a licensed professional as part of the design and subsequently submitted with the consent application. Auckland Council building inspectors should be consulted to verify consent requirements.

3.2.3 Roof pitch (slope)

Living roof installation is not limited to near-flat or non-pitched roofs, although low slope provides easier installation, configuration and maintenance, and minimizes plant moisture stress. Roof slope influences living roof design with respect to substrate stability, vegetation selection and safety of access.

Sloped roofs drain faster than roofs with a shallow slope and hold less water due to the laws of gravity. Plants growing near the bottom of a slope typically have access to higher substrate moisture content and less exposed conditions (lower ET) than plants near a ridgeline, and thus should be selected accordingly.

Living roofs up to 15° (26.8%) pitch are unlikely to require special design or construction techniques. Nonetheless, as a precaution, construction of a 15° pitch extensive living roof at the Auckland Botanic Gardens incorporated slope breaks made from substrate wrapped in coconut coir matting (Figure 6a), and light foot-tamping to secure substrate in place (Figure 6a) (Fassman et al. 2010b). The system has not suffered from materials' slumping in 3 years since installation.

Structural anti-shear/slip protection measures are suggested to be installed for roof pitch greater than 20° (36.4%) (FLL 2008). Commercial products such as a flexible synthetic matrix or a batten structure can promote substrate stability (Figure 6b). Roofs with pitch in excess of 30° (57.7%) require even more structural control, and a different approach to construction (FLL 2008). Such steeply pitched roofs are unlikely to provide adequate stormwater mitigation, and are not considered further in this report.

(a)  (b) 

Figure 6. (a) Coconut coir slope breaks on the Auckland Botanic Gardens 15°pitch living roof; (b) commercially-sourced flexible synthetic matrix to prevent substrate migration.

Sloped roofs and wind can easily dislodge new plantings before roots can establish. In these situations, an erosion control mat reduces supplemental replanting and is usually left in place indefinitely, as removal is problematic (Figure 7). While mats made of natural fibre such as coconut coir will eventually degrade, plastic or steel mesh products do not. Anecdotal evidence indicates that the plastic mesh is usually visible on the surface for the long-term, particularly when/if plant coverage is low or has less vigour (such as during a dormant season).

(a)  (b) 

(c) 

Figure 7. Erosion control for sloped or windy sites: (a, b) biodegradable coir mats; (c) permanent plastic lattice.

3.2.4 Protrusions, perforations, and mechanical services

Protrusions, perforations, and mechanical building services such as heating, ventilation, and air conditioning (HVAC) provide the most significant opportunity to compromise a building's waterproofing membrane, regardless of the presence of a living roof. Protrusions extend above the roof deck (e.g. parapet footings) while perforations extend below it (e.g., scuppers or vertical drains). Clustering and minimizing the number of protrusions, perforations, and services reduces potential disturbance to the living roof, facilitates waterproofing, and can contribute to easy maintenance access that minimises damage to plants when elements are bordered by aggregate or paving.

3.2.5 Installation access

Physically getting living roof materials onto a roof provides challenges best considered during the design process. As substrate installation likely requires mechanised equipment, new construction should coordinate substrate and vegetation installation when other mechanized equipment are on site (e.g. trucks, cranes or blower) to save cost. Retrofit installation will require separate crane or scissor lift hire and may necessitate road closures, and application for associated permits (Figure 8). Building height and external influences (such as existing structures, trees, and power lines near the building) will dictate crane size or lift mechanism required.

Adequate space must be allocated in the project site to store large equipment (if needed) and living roof components (Figure 8b). Substrate can rarely be stored on the roof without overloading the structure and should only be stored at ground level if in closed bags to minimise contamination. In cases where very fast vegetation establishment may be required, for example for roofs and parts of roofs vulnerable to erosion or weed invasion, pre-vegetated mats or pre-grown modules are favoured (Figure 5). Where accessed by stairs or ladders, the size of pre-grown elements may be a limiting factor for installation.

(a)


(b)


Figure 8. Installation access: (a, b) space for large equipment and materials' storage; (b) street closure in Henderson and Auckland CBD.

3.2.6 Maintenance and Other Access

Access needs may range from maintenance to congregation (e.g. picnic areas) or viewing. The rooftop creates a unique environment for stormwater BMP maintenance, posing multiple hazards. Behm (2012) identified that the reason many living roofs were not maintained was because of poor or unsafe access for workers. Designing safe access for maintenance is the first step in creating a feasible maintenance regime; understanding maintenance requirements promotes good design. The need for relatively frequent access for maintenance (compared to conventional roofs) and the potential for short time required to complete tasks may create situations where workers can be tempted to accept high levels of risk (Behm 2012, Cameron et al. 2007). Risk prevention through design should be promoted for every living roof project. In addition to safety, extensive living roofs are vulnerable to foot traffic. Suggested resources for designing safe access include:

- Behm, M. 2012. Safe Design Suggestions for Vegetative Roofs. *J. Constr. Eng. Manage.* 2012.138:999-1003.
- Cameron, I., Gillan, G., & Duff, A. R. 2007. Issues in the selection of fall prevention and arrest equipment. *Eng., Constr., Archit. Manage.,* 14(4), 363–374.
- Ellis, N. 2001. Introduction to fall protection, 3rd Ed. American Society of Safety Engineers, Des Plaines, IL.
- Health and Safety Executive. 2008. Working on Roofs, United Kingdom. http://www.hseni.gov.uk/hsg33_roof_work.pdf

Physical access must be designed in a manner that will not compromise the substrate, plants, and drainage. Foot traffic is discouraged over vegetated areas of extensive living roofs. Clearly defined paths are needed to identify the walkable areas (for example Figure 9a). . The inclusion of suitable parapets, balustrades, or restraining structures with non-vegetated zones are valuable to clearly define roof edges, and reduce maintenance costs, which increase once fully harnessed personnel are required. Figure 9b demonstrates a difficult living roof to maintain; the grass planting requires significant nutrient and water requirements to remain lush, the steep slopes make even nutrient and moisture distribution difficult. However, access is straightforward and safe. In contrast, the roof in Figure 9c is dangerous to maintain as the lack of balustrade is a safety issue and the loose edging stones can be thrown onto adjacent areas if the area is mown or weed-whacked, while Figure 9d provides a plethora of safety concerns.

Walkways may either be designated non-vegetated areas (e.g. aggregate paths) or structural elements elevated over plantings. Where walkways are elevated, people are less likely to step down onto the adjacent living roofs. For example, raised aluminium grates over plantings are used at the American Society of Landscape Architecture (ASLA) headquarters (Werthmann 2007), and University of Melbourne teaching living roof at Burnleigh (www.landfood.unimelb.edu.au/gree/news.html). It is thought that their shade and shelter reduces substrate temperature and ET (thus providing longer-term moisture supply for plants (Fifth Creek Studio 2012). Excessive shading may impact on plant suitability in the affected area.

(a) (b) (c) (d)

Figure 9. Examples of (a) simple or (b) difficult living roofs to maintain, (c) no mower access, no balustrade and loose gravels can be thrown by a lawn mower or weed whacker (safety), (d) overgrown with difficult access and inability to see the building edge.

3.2.7 Aspect, shade, and irrigation

A southerly aspect, shade and irrigation can help mitigate plant moisture stress induced by the harsh growing environment of a rooftop. North-facing roofs in particular benefit from shade (even temporarily) during mid-afternoon, for example from nearby buildings or trees. Moisture supplementation design elements including irrigation with non-potable water or moisture retention mats should be considered. A more detailed discussion is presented in Chapter 7.

3.2.8 Aesthetics

It is essential to understand and inform the expectations of the client, occupiers, and others within the viewshed. Design and client communication must emphasise that living roofs are growing systems. Plant condition and colour will change with climate, age and stress condition of the plants. The variability of a living roof system should be conveyed to clients, to present an accurate description of living roof aesthetics through time and to manage client expectations. For example, without some maintenance, the proportion of grasses is likely to increase over time (three to five years) on most roofs and the definition of any sharp planting pattern gradually blur.

Many architect drawings of living roofs have a plant cover that resembles mown lawn and nearly all are 'green'. Few fully-exposed, extensive roofs will achieve this aesthetic without supplemental input, increasing cost. Roof lawns are generally high maintenance and at least 150 mm substrate depth, requiring regular irrigation, fertilisation and weeding, and not necessarily efficient mitigators of stormwater. They are likely to have runoff that is high in nitrogen and phosphorus, and any fungicides or pesticides used on the roof. A significant range of alternative, low maintenance native and non-native plant options are discussed in this guidance (Chapter 7, Appendix A and B). Among other elements, the planting design information in Chapter 7 guides strategies for creating variable topography even where substrate depth is limited due to weight restrictions.

In Europe, particularly Germany, it is accepted that living roofs for stormwater mitigation may be brown in summer. However, 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. Hence, at least until living roofs are more common, living roofs constructed to mitigate stormwater impacts should be designed to have a high, non-weedy vegetation cover. Roofs with bare areas are likely to become weedy and have a higher maintenance requirement to prevent aggressive plants, such as legumes and pampas, establishing, especially if the roof is regularly irrigated. The coarse, initially weed-free substrates developed for use in Auckland generally have low numbers of weeds establishing in the first 12 to 18 months (Fassman et al. 2010a).

Design to minimize weight while promoting stormwater retention does not necessarily limit aesthetic outcomes and amenity value. Three New Zealand case studies illustrate how to match plant species with client requirements (Chapter 10). Cantor (2008), Earth Pledge (2005), Snodgrass and McIntyre (2010) and Dunnet et al. (2011) present a very wide range of international case studies covering extensive and intensive living roofs.

4.0 Discussion: Component Design and Stormwater Performance

4.1 Waterproofing

The presence of a living roof should not compromise the integrity of an appropriately specified and carefully installed waterproofing system. The best approach is to take extra care with specification and installation of the waterproofing system as prevention is almost always less costly than repair. Any/all waterproofing installations must be tested for integrity, which is best performed prior to installation of subsequent layers of the living roof system.

With a properly designed, installed, and maintained living roof, the system should last for at least 20-30 years (a conservative estimate). Several key considerations have been observed in specifying and installing waterproofing membranes:

- Use of at least a double-ply waterproofing membrane of high quality, or a purpose-made (for living roofs) heavy-duty membrane with felt layer, which may be single-ply, is advised. While the initial cost may be somewhat higher than the current typical New Zealand practice of single-ply installations, the up-front investment in a higher-quality product will help prevent future failure.
- Protection of the waterproofing membrane throughout construction is paramount. Most damage to waterproofing membranes occurs during the construction phase. Nails, screws, or cutting implements should not be present on the rooftop when the membrane is being laid, or ideally at any time during the construction. Drainage mats provide a physical block for shovels or other gardening implements which could poke holes. A drainage mat designed with a thick geotextile or felt on the bottom helps protect the membrane from sharp edges of the mat itself. Protrusions, perforations, services, or drainage features should not be installed after the waterproofing. Any activity that would entail cutting a hole in the waterproofing could compromise the integrity of the entire system.
- Test the integrity of the waterproofing layer in place before installing any other features. It is much more cost-effective to spend a bit more up-front to ensure the waterproofing achieves its purpose, rather than having to repair or retrofit once the substrate and plants have been installed. Testing should be performed by an unbiased third party, rather than the membrane installer. Testing methods are provided below.
- Flashing, aggregate or substrate should completely cover the waterproofing membrane. Any exposed membrane is susceptible to premature UV damage. Even small defects can cause a leak.
- Extra caution should be used when sealing around protrusions and perforations (e.g. parapets, footings, skylights, mechanical systems, vents, etc.).

Several methods for leak detection have been developed:

- Flood test: A standard approach for assessing integrity of a newly installed waterproofing membrane is via flood testing. Basically, the roof is filled with water and water level drop measured over approximately 24 hrs. The method only works for flat roofs before installation of drainage mat, substrate, or vegetation. Accuracy is subject to relatively coarse measurement limitations. Very small penetrations may not be detected. The method itself can cause damage to the roof if the membrane integrity was compromised.

- Electric Field Vector Mapping (EFVM): EFVM relies on electrical conductance. A low electrical voltage is applied over thin layer of water which has been spread over the surface to be leak tested. A watertight membrane will prevent detection of electric potential using a potentiometer. Compromised membrane integrity is indicated when voltage is detected. The technology enables isolating the location of the breach, and may also identify potential future failures (e.g., small punctures which may not have yet fully penetrated the membrane surface). EFVM is a non-destructive or invasive method, and may be performed on a sloped roof. It may be conducted between layers of living roof installation (e.g., to verify that drainage mat or other layers' installation has not compromised the integrity of the waterproof membrane) and/or any time after the living roof has been installed.

4.2 Edging

Edging maintains visibility and ease of access for drainage points, protrusions, perforations, and other features (Figure 10). Edging materials must allow water to freely discharge, and help to keep drainage features (inlets, gutters, scuppers and pipes) free of vegetation thus minimising maintenance needs. Blocked drains can create standing water on rooftops, increasing structural load, even for conventional roofs. Suitable materials include gravel, pumice, or other aggregate, paver blocks or permeable pavers, but not organic mulch. The material must be non-floating, or confined to prevent floating or wash-out.

Formal edging provides the following functions:

- Visual cues for maintenance staff or visitors
    - to identify and provide ready access to protrusions, perforations and drainage outlets for maintenance, reducing damage to plants
    - to identify the building edge
- Provides an extremely pervious zone
    - an aggregate edge or internal strip will provide an "emergency" drainage function in the event that a properly designed substrate loses permeability
- Can isolate or define drainage areas on large living roofs (Figure 10c), and provide a specific drainage path for steeply sloped living roofs to prevent surface erosion
- Prevents and captures substrate migration
- Protects metal flashing from contact with substrate
- Provides UV protection for waterproofing membrane
- Reduces risk of substrate slipping underneath drainage mat and reduces risk of wind uplifting drainage mat
- Protects substrate on edges from wind erosion (wind forces are typically greatest at corners and edges of structures)
- May reduce fire risk (FLL 2008). German living roof design guidance indicates that extensive living roofs are "adequately resistant to sparks and radiated heat" if a minimum 0.5 m aggregate edging separates the vegetation and any openings in the roof (skylights, windows) or any vertical elements such as a wall with windows, if the balustrade is at least 0.8 m above the level of the living roof substrate. Additional fire protection considerations provided include substrate characteristics (namely limiting organic matter and providing minimum overall thickness), vegetation characteristics, and requirements for non-flammable breaks for every 40 m of vegetation (FLL 2008).

Figure 10. Importance of edging material; (a) scupper inlet and protrusion protection; (b) edging material to promote drainage; (c) protection of footings, cue for building edge; (d) edging material used as a drainage "break" for a 6.5 acre living roof.

4.3 Testing procedures for living roof components

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[5]). The FLL is a comprehensive manual developed for German applications. While addressing many aspects of living roof design, it specifically describes laboratory testing methods, apparatus, and target numerical values for substrate design. The FLL is not a true standard, but is often interpreted as such.

The American Society of Testing Materials (ASTM) International originally issued living roof testing standards in 2005; with updates in 2011[6]. The ASTM standards currently only include a testing methodology and do not give numerical objectives to indicate suitability for the intended application. 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)

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

- 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 and weights. Actual structural loads are to be determined as per Chapter 5 of this report.
- 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)

Overall, the main differences between the guidelines are that the FLL guidelines provide test procedures, quality assurance (QA), and target objectives; while the ASTM standards provide test procedures and test QA without target objectives. The ASTM standards are currently targeted towards substrate and drainage layer assessment; the FLL guidelines cover all aspects of living roof design, including designing an appropriate substrate, plant selection, and managing drainage through to maintenance. The ASTM standards are intended to provide a basis for comparison and a common language for describing and specifying living roofs.

A side-by-side comparison was run between the FLL methodology, ASTM E2397-11 and ASTM E2399-05 (Fassman and Simcock 2012; Wang 2010). These standards provide equivalent (to each other) methodologies to calculate substrate water storage capacity, termed "maximum media water retention" (ASTM terminology) or "maximum water capacity" (FLL terminology). When applied to the same four test sites in Auckland, the ASTM and FLL method was shown to overestimate rainfall capture (Fassman and Simcock 2012). Either FLL or ASTM methods can be used to determine structural load. As guidance on suitability (fit for purpose) of substrate component materials, the FLL specifies a particle size distribution (PSD) envelope while ASTM does not. Although the FLL PSD guidance is mostly in relation to plant health, PSD has important implication in terms of permeability and weight (Section 4.5.4). Likewise, FLL provides target numerical objectives for permeability while ASTM does not. The FLL numerical objectives are defined to prevent ponding, however they are specific to German climates (e.g. rainfall intensity). Auckland-specific objectives are provided in Chapter 6.

ASTM methods are recommended for testing substrates' physical characteristics to ensure consistency in a new industry in New Zealand, as well as maintain comparability with international best practice. Fassman et al. (2010b) suggests locally (Auckland) derived target values for substrate characteristics, coupled with FLL and/or ASTM testing procedures which are adopted for design in Chapter 6 of this report. As the local knowledge base grows, numerical objectives may be further revised to suit the climate and native plants, but the methodology may not necessarily change.

4.4 Drainage layers

Many synthetic drainage mats are in the shape of a moulded, dimpled plastic, resembling an egg crate. These shapes may provide additional water retention capacity if installed with "cups up" (Figure 11a). "Cups up" configuration may not necessarily mean that additional water is available to plants. During establishment the geotextile separating cups from the substrate inhibits direct root contact with captured water, unless wicks are present to transfer the free water into the substrate. As plants mature, fine roots may penetrate into such cups, acting as wicks. If/when cups are filled, usually the only means of emptying is by ET, limiting capability to supplement stormwater function on a day-to-day basis. The load when wet of products sampled in New Zealand range from 0.79–11.68 kg m^{-2} (Fassman et al. 2010). Commercial products available overseas are reported to hold 4.1–20.4 kg m^{-2} of water (Cantor 2008).

Other synthetic drainage layer materials may be foam or a plastic mesh. Plastic mesh products such as in Figure 11b would likely promote good air circulation for roots, and will also contribute some drying function (evaporation) for insulation, if needed.

ASTM E2397-11 provides a methodology for determining the weight of drainage layers.

A granular drainage layer with a separate geotextile layer laid over top is an alternative to a synthetic drainage layer. Granular materials such as coarse aggregates could include 7 to 20 mm grade clean pumice, scoria, or gravel at a minimum depth of 30 mm (Figure 11c). Products must not contain fine particulates. ASTM E2396-11 describes methodology for determining the permeability of a granular drainage layer, and its wet density, which can be used by the structural engineer to determine weight.

While strongly recommended, a formal drainage layer is not strictly necessary if sufficient vertical and horizontal permeability can be maintained in the substrate, and roof slope promotes free drainage to prevent standing water (ponding) during rainfall events. Lack of a drainage layer may enhance peak flow mitigation, as runoff has to flow through substrate to reach the gutter. Living roofs without a formal drainage layer have not been studied in New Zealand to date, hence further investigation is recommended prior to implementing this method. It is noted that the FLL (2008) requires greater substrate permeability for systems without a formal drainage layer (see Section 4.5.2).

(a) (b)

(c)

Figure 11. Drainage layers: (a) synthetic “egg-crate” style moulded plastic with “cups up”; (b) plastic mesh; (c) installation of granular drainage layer and edging made from pumice.

The ease and speed of laying a synthetic drainage layer improves with (Fassman et al. 2010b):

- products with a plastic overlap zone without cups,
- products with an additional width of geotextile above the width of the drainage board to allow for overlap between sheets,
- avoidance of irregular living roof shapes (e.g. curves or a V shape) as this makes cutting and joining the drainage mat difficult,
- installation of the drainage sheets on sloped roofs parallel to the length of the slope (not crosswise) to prevent slippage before the substrate is installed.

4.5 Substrate design

Typical extensive living roof substrate is an engineered media comprised of 80-95% (by volume) light-weight aggregate (LWA) and 5-20% (by volume) resilient organic matter. The term "engineered media" is used to distinguish a blend of materials that would not necessarily be naturally sourced as a unique mixture, but individual components may be naturally sourced. Engineered media are designed to achieve pre-determined objectives for stormwater management; properties may differ substantially from natural soils. In living roof substrates, LWA provides pore space for air, water, and gas exchange, and ensures rapid drainage. However, the coarse texture and low organic content of most LWA means that key functions for plant growth must be supplemented, e.g. cation exchange capacity (CEC) for nutrient retention and chemical buffering and moisture storage and supply (Friedrich 2005). Selection of specific materials is critical to system viability.

The maximum allowable organic matter content is 20% (by volume) for extensive living roofs in Auckland. The majority of the organic matter used must be stable, such as bark fines, coir, and sufficiently composted and aged leaf or arborist mulch. A high proportion of young, incompletely composted materials can be unstable, initially withdrawing nitrogen from the remainder of the substrate leading to plant stress. Small volumes of fully-composted, nutrient-rich organic matter can be beneficial to boost establishment, e.g. mushroom or green-waste compost. These materials are not suitable as the total organic component because they are likely to leach excessive nitrogen and/or phosphorus. Composts containing standard fertilizer amendments are also likely to leach excess nitrogen and phosphorus, and are not appropriate for stormwater living roof installations. Peat and coconut coir will boost water holding capacity, however this also adds measurably to wet weight. Very fine organic matter, e.g., fine-milled peat, may be washed through coarse living roof aggregates, and substrates using only peat as an organic source are likely to require pH buffering to reduce acidity to above about pH 6.

Living roof substrates are substantially dissimilar to garden mixes used in ground-level landscaping applications. Extensive living roof substrates typically contain no natural soil, such as topsoil or garden mixes[7]. Typical topsoils are heavy (Auckland Region in-situ topsoil typically has a dry bulk density from 950–

[7] Some living roofs designed to promote biodiversity may deliberately use local soils to make use of local seed burdens, particularly for roofs that are designed to blend vegetation of the roof into the landscape (e.g. tussocks and pasture). If natural soils are used, the initial weed maintenance required will be high, and erosion control fabrics or organic mulches may be needed to ensure no movement of surface water across the roof, as natural soils have much

1100 kg m^{-3}), have inadequate drainage when placed at 100 mm depth (a propensity for water-logging), are prone to compaction, and have high variability – all undesirable characteristics for a living roof growing media. Humidity at the surface of garden soils is also likely to be higher, increasing risk of fungal diseases, to which many living roof plants are susceptible (namely succulents). Most sands are not light-weight (compared to natural or manufactured LWAs); fine sand can reduce permeability if added in significant proportion (>5% v/v) (Fassman and Simcock 2012).

Proprietary suppliers of living roof substrates are common in overseas markets, but are only emerging in New Zealand. Proprietary substrates are not required for living roofs, but careful consideration of components is necessary. To facilitate technology development, several former government agencies, including the Auckland Regional Council, Waitakere City Council and the Foundation for Research, Science, and Technology, sponsored collaborative research by the University of Auckland and Landcare Research. The research investigated:

- appropriate materials
- testing methodologies (including the FLL and ASTM methods in Section 4.3)
- sourcing, blending, and supply
- installation methods
- relationships between installed substrate depth, stormwater retention, water quality, and plant viability
- evolution of chemical composition over time (primarily with respect to sustaining plant life).

Details of the research investigations on substrates are published in Fassman et al. (2010a,b), and Fassman and Simcock (2012). A summary of key information is provided herein. Searches of international literature to date failed to discover other studies of comparable scope with respect to substrate development.

Fassman et al. (2010a, 2010b) are New Zealand-specific. Multiple materials' combinations were investigated in the laboratory and the best were also tested in field trials. While use of the combinations in Fassman et al. (2010a, 2010b) is not required, these substrates are well understood, thus their use may reduce project risk. New substrates may be developed. For example, there is growing interest in the use of recycled materials. Characteristics of any substrates used for stormwater management in Auckland must demonstrate minimum moisture retention and permeability properties described in Section 6.4.

Desirable living roof substrate characteristics to consider are:

- Moderate water holding capacity
    - provides runoff retention (storage)
    - supplies water for plants between rain events
- High permeability
    - rainfall that exceeds the retention capacity must percolate relatively quickly to the drainage layer to prevent overloading of the roof structure
    - prevents water-logging, assuming the drainage layer and outlets are adequate
    - prevents freezing in winter (not necessarily relevant in Auckland)

1.0

lower permeability and infiltration rates than engineered living roof substrates. The use of local, natural soils is likely to also increase the weight compared to an engineered extensive living roof substrate.

- Low system weight at field capacity and/or saturation
- Adequate bearing strength to prevent compaction
    - compaction decreases potential rainfall storage volume and aeration of roots
    - may occur from crushing or decomposition of organic matter
- Resistance to degradation
    - to physical compaction via reasonable bearing strength
    - via oxidation or breakdown of the substrate - such as substrates with high organic matter or some foams – as degradation reduces final substrate depth, and can also lead to water logging
- Ability to support plant life
    - appropriate physical and chemical composition
    - adequate depth and temperature regime

These desirable qualities are often at odds with one another. Saturated weight increases with substrate depth, thus increasing structural requirements, yet plant viability improves in deeper substrates (Durhman et al. 2006, 2007; Getter and Rowe 2008). Shallower substrates are less able to store water for plant growth than a similar, deeper substrate, and experience more extreme temperatures. A moderate to high proportion of fines increases moisture storage and may benefit plant growth but decreases permeability and increases weight. Maintaining high permeability of the substrate is important to prevent ponding and excess weight.

The predominant considerations in substrate design are safety, system weight, stormwater control (where this is a reason for construction), and plant viability. Table 1 identifies substrate characteristics relating to the key concerns.

Table 1. Specifications to consider in substrate development

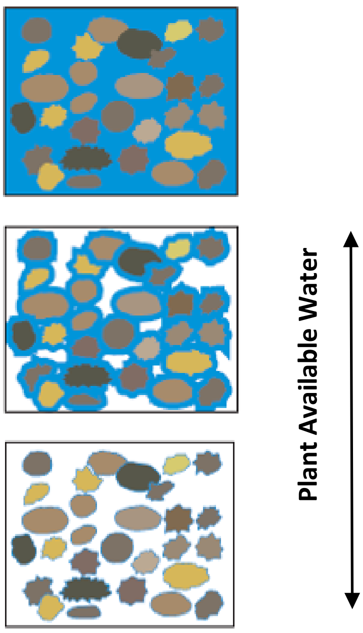
Substrate Characteristic	**Safety**	**Weight**	**Stormwater Control**	**Plants**
Water holding capacity	X	X	X	X
Weight at field capacity	X	X	-	-
Saturated weight	X	X	-	-
Permeability	X	X	X	X
Particle size distribution	X	X	X	X
Nutrient content & availability	-	-	-	X
pH	-	-	-	X
Cation exchange capacity	-	-	-	X
Organic matter stability	-	X	X	X

4.5.1 Water holding capacity

A substrate's water holding capacity is the most critical characteristic to promote stormwater retention and sustain plant life (Fassman and Simcock 2012). The water holding capacity is the ability of a substrate to hold (store) water against gravity. It is derived from characteristics of the media itself, installed depth, and is influenced by the underlying drainage layer (or its absence). For a given depth of substrate, a high water holding capacity is usually associated with low permeability, low aeration, high total weight, and can be detrimental to plant survival. Low water holding capacity limits stormwater retention and plant viability in the absence of regular irrigation.

For planning and design purposes, rainfall retention properties are estimated by the difference between a substrate's 'field capacity' and 'permanent wilting point' (Fassman and Simcock 2012). This quantity is known in agronomic or horticultural terms as plant available water (PAW, Figure 12). Four extensive living roof substrates in Auckland have been assessed for PAW (Table 2).

When dry, appropriate substrates for extensive living roof application should be capable of storing about 25-30% by volume PAW, or greater. For instance, a 100 mm cover with 30% PAW effectively controls the first 30 mm of rainfall (for planning purposes). The FLL (2008) suggests an upper limit of 65% water holding capacity by volume. As a planning tool, using a design storm approach (as opposed to continuous simulation), the designer may assume that during larger storms, the media will retain rainfall up to PAW, and then slowly release the rainfall in excess of the storage capacity. Studies on living roofs in Auckland showed substantial rainfall retention because PAW ranged from about 11 mm to 36 mm, depending on the roof, and 94% of individual events delivered less than 25 mm of rainfall (accounting for 58% of the total depth of rainfall received) (Fassman-Beck et al. 2013a). The maximum storage capacity of the living roofs is not fully utilised on a day to day basis, only when larger rainfall events occur.



Saturation. All pore spaces are filled with water. Engineered media designed for extensive living roof applications should drain freely so that it never reaches saturation.

Field Capacity. Pore space is air- and water-filled. Moisture is held against gravity by the media matrix in small and medium-sized pores. Large pores are air-filled

Permanent Wilting Point. Pore space is mostly air-filled, but some water is held tightly to the media particles. Moisture content below this point ('hygroscopic water') cannot be readily accessed by the plants for transpiration, and is only "lost" to the atmosphere very slowly.

Figure 12. States of soil moisture

Table 2. Moisture storage potential for Auckland living roof substrates[a]

Substrate[b]	Composition (% by volume)	PAW (%)	FLL/ASTM Water Holding Capacity (%)
UoA Pumice	20% 1-7 mm pumice 60% 4-10 mm pumice 20% composted pine bark fines	24.2	49.6
UoA Zeolite	50% 4-10 mm pumice 30% 1-8 mm zeolite 20% composted pine bark fines	23.1	46.6
Tamaki Zeolite	70% 4-10 mm pumice 10% zeolite $\leq$ 3 mm 15% pine bark fines+mushroom compost 5% sphagnum peak	28.9	63
WCC expanded clay	20% 1-4 mm pumice 40% 4-8 mm pumice 20% expanded clay 20% commercial garden mix	20.2	No data
Auckland Botanic Gardens	80% 1-7 mm pumice 5% 1-3 mm zeolite 10% CAN bark fines A grade[c] 5% coco-fibre coir "classic"	No data	75%

a. Data from Fassman and Simcock (2012) and Fassman et al. (2010b)
b. Substrates are general named by their distinguishing (not dominant) LWA component (pumice, zeolite, expanded clay) and/or the location of their field trial installation (University of Auckland [UoA], Tamaki, Waitakere Civic Centre [WCC], or Auckland Botanic Gardens).
c. CAN bark is a composted product manufactured from screened bark sourced from plantation-grown *Pinus radiata* and sourced from ports, timber mills and other log storage areas.

There is a potentially important difference in terminology between soil scientists, geotechnical engineers, stormwater engineers, horticultural experts and the methods used to measure water holding capacity in a porous media (i.e. the substrate). Water holding capacity is defined as "maximum water capacity" in FLL terminology is equivalent to the ASTM "maximum media water retention"; either is used to estimate substrate "field capacity", in science or geotechnical engineering terms, or the upper boundary of "plant available water" in horticultural terms. However, the analytical (laboratory) methods used to quantify each measure of water holding capacity differ, and results differ (Table 2).

Within the living roof industry, FLL tests are currently more widely used than standard agronomic testing, particularly as a marketing tool. Results from extensive living roof trials in Auckland suggest that while the FLL maximum water capacity metric provides a conservative estimate for typical structural loading when the substrate is wet (plants and other system elements must also be included), it overestimates stormwater retention (Fassman and Simcock 2012). In the absence of a continuous simulation model for living roof design, measurement of PAW as determined by agronomic methods provides a better estimator for stormwater retention, and offers a more conservative design approach. In addition, PAW is an important measure for horticultural consultants to help identify a range of plants suitable for individual living roof applications.

4.5.2 Saturated permeability

Substrate permeability is the rate at which water flows vertically through the substrate. Permeability is designed to prevent overflow, bypass, or surface ponding. Surface ponding adds excess weight, and may float and/or scour, or otherwise erode substrate if moving laterally across the surface. A well-designed substrate should NOT pond water on the surface, and is unlikely to ever reach saturation (where all pore space is occupied by water, Figure 12) unless vertical drainage points are blocked or outlets are otherwise obstructed. Freely draining media also protects plants and the roof structure from physical fluctuations associated with freeze-thaw cycles (as the living roof should not fully freeze).

The FLL (2008) recommends minimum saturated permeability determined on a core sample to exceed 0.01 cm s^{-1} for an extensive living roof with a separate drainage layer. Without a dedicated drainage layer, saturated permeability must exceed 0.1 cm s^{-1}. The test is performed using a falling head methodology with 35-50 mm of ponded water to drive water vertically through the substrate. The FLL indicates their minimum permeability reflects the local climate (Germany), and suggests it should be modified in other areas. ASTM does not recommend a target permeability for substrates.

Substrate development research in Auckland measured the saturated permeability of 32 substrate blends with 80-95% LWA using FLL methodology (Fassman et al. 2010a, 2010b). Saturated permeability ranged 0.015-0.481 cm s^{-1}, with an exceptional value of 1.202 cm s^{-1}. Variability was noted between results of testing substrate blends mixed from small samples and substrates prepared by bulk blending of large quantities for field installations.

The minimum required saturated permeability for Auckland living roofs must consider (Fassman et al. 2010a, 2010b; Fassman and Simcock 2012):

- differences between lab test methods and actual rain events,
- sensitivity of the test method,
- the likely ability to satisfy minimum requirements based on available materials while also supporting plant life objectives (very coarse media have high permeability but will not grow plants well),
- conservative design (e.g. “a factor of safety”).

Subject to these considerations and the range of rainfall intensities in Auckland, a saturated permeability of 0.04-0.05 cm s^{-1} (~1500 mm h^{-1}) is recommended.

4.5.3 Substrate weight

Weight at three moisture conditions is necessary to determine structural loading. ASTM E2399-11 and or FLL (2008) describe appropriate apparatus and sample preparation techniques for assessing living roof substrate weights and densities at different moisture states. The conditions are briefly described here:

DRY: The dry bulk density (mass/volume) is determined from a sample oven-dried (103–105°C) for 24 h. The measure is used to determine the conversion of gravimetric water content to volumetric water content. It also approximates the lowest probable substrate weight during drought conditions.

FIELD CAPACITY: The weight at "maximum water capacity" according to FLL (2008) or at the "maximum media moisture retention" as per ASTM refers to the (wet) weight of a substrate sample after it has been soaked in a water bath for 24 h, then drained by gravity for 2 h.

SATURATION: The substrate saturated weight is determined from a sample with all pore space occupied by water (Figure 12). A properly designed living roof substrate combined with appropriate drainage layer will have very high permeability, hence it is unlikely (and unintended) that a living roof should ever reach or maintain saturated conditions under Auckland rainfall conditions. Regardless, its measurement is required for structural calcualtions (Section 5.1).

In determining system weight, in addition to either dry or saturated substrate mass, it is essential to also consider the mass of the waterproofing layer, drainage layer, supplemental moisture retention techniques (if included), and vegetation. System weight as it pertains to structural loading in accordance with the New Zealand building code is described in Chapter 5.

4.5.4 Particle size distribution (PSD)

The particle size distribution (PSD) substantially influences living roof substrate characteristics. PSD is not strictly a design requirement; however, it can be beneficial in assessing suitability of candidate materials and substrates.

Increased fines are beneficial to plants as they increase moisture and nutrient storage (CEC), but are detrimental to permeability, drainage, and system weight. Excessive fines (> 5% of particles with diameter < 1 mm) may clog the media reducing permeability and drainage and increase weight (Fassman and Simcock 2012). These are key safety issues. Substrate that is heavier than the design allowance usually means the installed substrate depth is reduced to prevent overloading the structure, which may subsequently affect stormwater performance and plant viability. If permeability does not meet the required rate, then it may not be possible to use the substrate blend without amendment.

The FLL (2008) provides a PSD envelope for living roof substrates. Substrates developed in the laboratory and field tested in Auckland do not fully adhere to the FLL (2008) PSD guidelines, but associated implications are well understood (Fassman et al. 2010a). Auckland's substrates that best achieved combined design objectives for weight, permeability, and plant growth balanced a low volumetric addition of high-spec, small particles (zeolite < 3 mm) co-produced for the sports' turf industry with a majority composition of larger sized materials produced for the concrete industry (1-7 mm pumice), thus eliminating the need for specialty production.

4.5.5 Source material quality control

Physical and chemical characteristics vary between locally available, naturally occurring LWAs when extracted from different deposits (Brathwaite and Hill 2005, Malaghan 2007). Fassman et al. (2010a) confirmed a significant difference in both PSD and material composition between different sources of pumice from the Central North Island, resulting in variation of weight and bulk density. Scoria is similarly variable, as is fly ash from different sources.

Materials sourcing and blending procedures can affect PSD (Fassman et al. 2010a). Rain will flush small particles to the bottom of uncovered outdoor stockpiles. Blending by hand-mixing, or gentle tumbling in a trammel, preserves the integrity of component size, whereas rotating metal tines may physically break particles, particularly large, brittle, soft or wet materials.

Living roof design objectives generally require a substrate with minimised weight and consistent composition, thus detailed specifications, and post-blended, pre-installation testing is required. The primary concern is meeting weight restrictions or allowable loadings for each specific roof. The second major concern is the ability to support plant life while retaining stormwater. For example, changes in PSD affects plant establishment potential as well as pore space for moisture retention.

Preventing weed contamination of substrates or substrate components should be a priority for supply management. Supplying quarries should be free of weeds, particularly acacia, broom and gorse, which have large seeds that resemble aggregates, but also pampas (*Cortaderia* species) and butterfly bush. Outdoor, uncovered storage of living roof substrate components for extended periods increases the risk of weed introduction. All composts should be adequately heat treated prior to blending to minimise viable weeds. Any organic matter treatment should be done before it is blended with aggregates. A supplier specification documenting that organic matter has been tested for weed germination and oxygen respiration to ensure it is stable (Cantor 2008), or compliance with NZAS4454 (2012) standard for composts is recommended.

Transport costs can be can be significant when bringing the different components to a single place to be blended. Cost savings may be realized by identifying a single supplier for all (or most) of the components and bulk blending (Fassman et al. 2010a).

4.6 Plants

4.6.1 Role in stormwater management

A healthy, dense plant cover is considered essential to the stormwater mitigation function of a living roof system. Plant transpiration dries the substrate while roots maintain its permeability, and above ground cover may provide some rainfall interception. Of these processes, inter-event ET is the most influential on the ability of an extensive living roof to retain subsequent storms. Dependant on plant type, season and water availability, even low, herbaceous plants typical of extensive living roofs can contribute 20–48% of total ET via transpiration restoring capacity to capture the next storm event (Berghage et al., 2007; Rezaei and Jarrett, 2006; VanWoert et al., 2005a; Voyde et al., 2010; Voyde 2011).

When water is abundant (e.g. after a recent rain) and plants are not stressed (e.g. from drought), ET is significantly greater than evaporation from a bare substrate. ET from healthy, dense plant cover has been measured at 3-5 mm d^{-1} under well-watered conditions in Auckland (Voyde 2011). High plant transpiration rate quickly dries the thin substrate. Drought-tolerant plants well-suited to the living roof environment adjust their metabolism (water demand) to conserve water as it becomes limiting (e.g. as the substrate dries). This is observed as an exponential decrease in the daily transpiration rate (Voyde et al. 2010, Voyde 2011). Conversely, plants unable to adjust metabolic rates soon suffer moisture stress in the absence of rain or irrigation. Some horticultural literature suggests that Sedums, common succulent varieties frequently used in living roofs, demonstrate crassulacean acid metabolism (CAM) behaviour, which further conserves moisture as it becomes limiting (Snodgrass and Snodgrass 2006). Living roof-specific studies in New Zealand and Pennsylvania USA have shown that CAM behaviour does not occur for all sedum varieties (Berghage et al. 2007; Voyde et al. 2010). The living roof ET is an active topic of academic study internationally (DiGiovanni 2013; DiGiovanni et al. 2013; Rezeai 2005; Starry 2013; Voyde 2011 Wadzuk et al. 2013).

Voyde et al. (2010) demonstrated that high relative humidity and low solar radiation suppress living roof ET, leading to reduced rainfall capture when inter-event times are short[8]. Despite the obvious potential influence of ET on stormwater retention performance, an event-based design approach does not account for such processes.

4.6.2 Selection

Selecting plants to grow on extensive roofs is one of the most important challenges of living roof design (Snodgrass and Snodgrass 2006). Plant selection co-depends on planting method, installation access, long-term maintenance assurance, aesthetic objectives, and a variety of architectural factors.

Plant specification for extensive living roofs is quite different from a low-level, traditional garden or even a planter box. The plants selected need to do the following:

- Survive, as roof plants are subject to extreme conditions compared to ground-level landscaping
- Create pore space to store rainfall by using water from the substrate (transpiration);
- Protect the substrate surface from erosion by covering it with leaves and binding it with roots;
- Maintain infiltration through leaf and root networks keeping surface pores open.

Only a narrow range of plants can survive in windy sites with 50-150 mm deep, low organic content substrate in full sun with minimal irrigation, therefore design must adequately fulfil these primary functions. Plants can also provide amenity and habitat for insects, lizards and birds. Plants usually reduce reflected light, and cool both the air above a roof, and substrate on the roof, but these are usually secondary factors in plant selection – survival is the primary requirement. Plants suitable for extensive living roofs generally have the following characteristics (Snodgrass and McIntyre 2010; Dunnett and Kingsbury 2008), which are described in more detail in Section 7 of Fassman et al. (2010a):

- Shallow, lateral root system; no tubers or large storage organs
- Wind-tolerant through having permeable fine leaves (e.g. tussocks, lillies, and sedges) or, forming dense, low mounds of interlocking branches (<200-300 mm, generally <100 mm), e.g. prostrate *Coprosma* and *Pimelea* species, or ground-hugging and anchored at internodes, (e.g., *Selliera*, *Dichondra* and *Leptinella*) (Figure 13). This also reduces water demand and plant weight.
- Resilient to cyclic wet and dry conditions, in particular extended drought periods
- Low fertiliser and maintenance needs (resistance to insects and disease)

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[8] In this case, “reduced” rainfall capture was nonetheless measured at 59% during a winter storm event with 4 days of intermittent rainfall in Auckland. This is considered a significant level of rainfall retention, regardless of the context.

- Roots tolerant to high temperatures, as most large roofs receive full sun and substrates over concrete can have high thermal mass, radiating heat into the substrate

The main plant group used on extensive living roofs overseas are Sedums, a variety of succulent plant extremely tolerant of drought and easily propagated by seeds or cuttings. Sedums achieve the design objectives needed for stormwater management on extensive living roofs as shallow as 50 mm in Auckland. At least 25 cultivars are readily available, but Sedums are not native to New Zealand. The potential for biosecurity issues should be considered when using non-native species, particularly when the building is in a coastal zone or near low-growing native vegetation with conservation values.

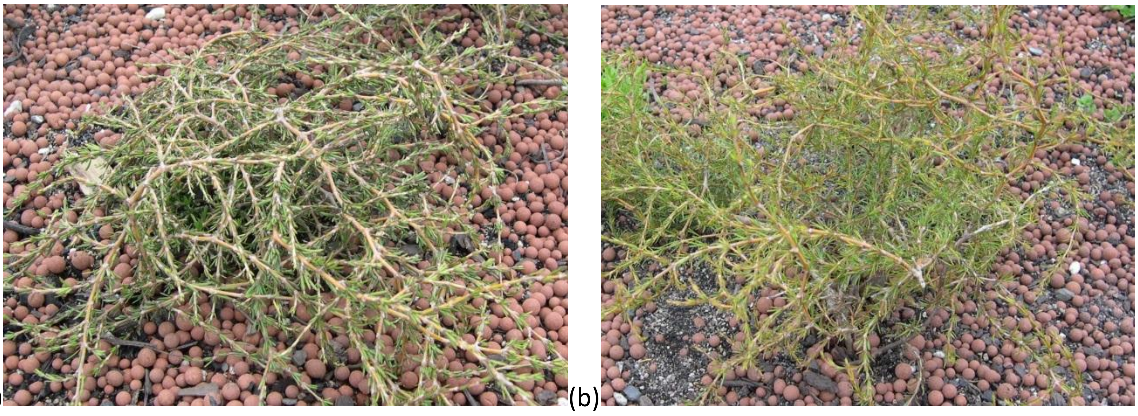
(a) (b)


Figure 13. Woody shrubs: (a) should branch at ground level and have a low, dense form (*Coprosma acerosa*); (b) shrubs with a more upright form are more susceptible to wind damage seen as collar rock, or stem breakage (left photo)

Native plants are less likely to become weeds off the roof, and more likely to provide habitat for some native insect and bird species; some Sedums may provide abundant nectar for honeybees. New Zealand plant species identified in Appendix A were initially selected because they are naturally found in places that have similar stresses to extreme conditions typical of extensive, non-irrigated living roofs such as exposed rock outcrops[9]. Appendix A lists native species likely suited to extensive living roofs with 100 to 150 mm of substrate depth. Deeper substrates, and substrates with higher plant available water, allow taller plants, and a more diverse range of plants to be grown respectively.

The Auckland Regional Council Technical Report 'Landscape and Ecology Values within Stormwater Management', Chapter 3 'Green roofs' (Lewis, et al. 2009) discusses plant selection and contains a table with New Zealand native perennial species and annual or semi-annual species that are suitable for extensive living roofs in the Auckland region, given minimal supplemental irrigation. Information provided in this report is complementary, and non-native plants are included. The New Zealand native plants table. Appendix A contains updated notes taking into account performance on six living roofs across the Auckland region over two to five years. Appendix B contains information on non-native plants, with focus on Sedum species that have been successful on intensive living roofs designed for stormwater mitigation in Auckland.

[9] While plants found in rock outcroppings and other living roof analogues in native environments are likely candidates, plants should be trialled in actual living roof conditions before recommending widespread use.

All of the Sedum species used in the field trials were reviewed by the former Auckland Regional Council's biosecurity team prior to installation.

4.7 Stormwater management performance

Living roofs provide a range of environmental benefits, identified in Section 2.1. This section focuses only the ability of living roof systems to mitigate stormwater runoff volume (retain runoff) and peak flow (detain and delay runoff), and discusses performance related to water quality. Detailed discussion of laboratory testing and field monitoring of living roof systems in Auckland are found in Fassman et al. (2010a, 2010b), Fassman and Simcock (2012) and Fassman-Beck et al. (2013a). Although performance reported in the literature varies amongst studies, these characteristic of retention, detention, and runoff delay can reduce the burden on storm or combined sewers that exceed capacity in small events. Stormwater mitigation benefits increase with the proportion of roofs vegetated in a catchment.

4.7.1 Stormwater retention (volume control)

Field monitoring of full scale (field installation) extensive living roofs show a substantial contribution to site runoff volume control with international studies reporting 49–80% of precipitation retained over extended periods of data collection (Mentens et al. 2006; Berghage et al. 2009; Carter and Rasmussen 2006; Monterusso et al. 2004; Getter et al. 2007; Hutchinson et al. 2003; Moran et al. 2005; Villarreal and Bengtsson 2005). Excellent performance for small storm events is usually observed, with reduced retention in very large, infrequent events (Fassman-Beck et al. 2013a; Stovin et al. 2012).

Multiple extensive living roofs ranging in depth from 50 mm – 150 mm have been monitored across Auckland (Fassman et al. 2012; Fassman-Beck et al. 2013a; Voyde et al. 2010; Voyde 2011): the roof of the UoA Faculty of Engineering in the CBD, four "mini" living roofs at Landcare Research in East Tamaki (the Tamaki mini-roofs), and an extensive living roof constructed on the roof of the Waitakere City Council Civic Centre (WCC) in Henderson. Substrate composition at all sites was 80% by volume LWA with 20% organic matter. All roofs had at least 80% plant coverage during the time of monitoring. A synthetic drainage layer with geotextile separation layer supported the substrate. Performance was assessed against a conventional roof surface at each site, since the living roof is assumed to be placed in lieu of a conventional roof.

Despite apparent performance differences when results from full monitoring periods of different durations are compared (39-57% less cumulative runoff than from a conventional roof surface at the same site), statistically, there was no difference in cumulative retention amongst the studied systems for a 4-month period in which data was collected at all sites concurrently (Table 3). All of the sites demonstrated comparable event-based retention. The median runoff depth across all of Auckland's monitored living roofs for rainfall events from 2–25 mm was 1.9 mm while the mode was 0.03 mm. In other words, during the majority of rainfall events, there was no meaningful runoff from any of the living roofs monitored. Auckland living roof runoff depth was shown to be adequately predicted by rainfall depth, as given by a quadratic equation (Fassman-Beck et al. 2013):

$$Q=0.0046P^2 + 0.3603P + 0.0242 \qquad \text{Equation 1}$$

$$R^2 = 0.81$$

Where Q = living roof runoff (mm) and P = rainfall depth (mm). Monitoring of three extensive living roofs in New York City produced similar quadratic relationships between living roof runoff and rainfall depth (Carson et al. 2013). Equation 1 further demonstrates excellent mitigation potential for small to medium storm size events.

The excellent performance of extensive living roofs in Auckland is attributed to a combination of substrates designed with moderate to high water-holding capacity and plant coverage, and most storms having less than 25 mm rain per event. Slightly reduced retention performance on an individual-event basis was observed during the few very large storms (i.e. greater than 75 mm rainfall) and in winter when ET is suppressed; however, significant runoff reductions were always observed compared to conventional roof surfaces (Fassman-Beck et al. 2013a). For example, median retention per event in winter was 66% from the UoA living roof.

Table 3. Summary 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
WCC	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
WCC	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; WCC: 8 months continuous 2010-2011

Across individual studies, climate factors such as rainfall depth and intensity, antecedent dry period, solar radiation, relative humidity, temperature, and ET influence performance (Carpenter and Kaluvakolanu 2011; Kasmin et al. 2010; Voyde et al. 2010), as do substrate moisture storage capacity and depth (Fassman and Simcock 2012). In addition to climate variability, one of the reasons for the relatively wide retention range reported in the literature is that there is very little consistency in living roof design (Theodosiou 2009). Variability is also associated with water retention cells and fabrics, and roof slope (Moran et al. 2005; Villarreal and Bengtsson 2005; Getter et al. 2007; VanWoert et al. 2005).

Regardless of the ranges reported across various climates and locations, living roofs retain rain and reduce the frequency of runoff from roofs. The frequency of runoff from an urban catchment has been identified as a key contributor to stream ecosystem degradation (Walsh et al. 2005, 2009).

4.7.2 Peak flow attenuation

As with rainfall retention, a wide range of peak flow reduction efficiencies have been reported, likely in response to variation in climate and living roof design between studies. Peak flow reduction reported in literature from an individual living roof ranges from 31–87% (Hutchinson et al. 2003; Moran et al. 2005; Uhl and Schiedt 2008; Villarreal 2007; Berghage et al. 2007; DeNardo et al. 2005). Median peak flow reduction per event for Auckland's extensive living roofs ranged 62-90%, depending on the site (Table 3). During the 4-month period of concurrent monitoring, amongst the full scale living roofs at UoA and WCC, peak flows between living roofs or percent peak flow reduction compared to its control roof were not statistically different. However the smaller scale experiments of the Tamaki mini-roofs produced statistically greater peaks and less percent reduction compared to its control, but nonetheless measurable, beneficial flow attenuation (Fassman et al. 2013). Amongst all extensive living roofs, peak flow should always be well 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).

In practice, the configuration of vertical and horizontal flow paths in a proposed living roof influence the peak flow control provided. A granular (aggregate) drainage layer may provide greater peak flow reduction compared to a synthetic drainage layer, as runoff has to flow through a porous media to reach the gutter. The horizontal distance to a roof's vertical drainage system (e.g. scuppers and downspouts) and the roughness of the drainage layer may also influence peak flow attenuation (Fassman-Beck et al. 2013a).

4.7.3 Hydrograph timing

Through retention, detention, and creating a flow path through porous media rather than over a smooth surface, many field studies of living roofs indicate significant time lags in the onset of runoff with respect to rainfall, a delay in the time to peak compared to a conventional roof surface and/or peak rainfall intensity, and/or extended hydrograph duration (Carter and Rasmussen 2006; DeNardo et al. 2005; Getter et al, 2007; Liu 2003; Moran and Hunt 2005; VanWoert et al. 2005; Voyde 2011). Liu (2003) and Van Woert et al. (2005) distinguish effects based on rainfall intensity for time to peak and delay in runoff initiation, respectively, where heavier rainfall intensities shortened delays. Specific performance metrics vary significantly amongst the literature, likely partially due to the size of the living roof, or more specifically, the length of the flow path to the drainage point.

Compiling data even within a single study is challenged by a wide variation in results from event to event. For example, one year continuous 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. However, the overall range was from 0 min 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). Van Woert et al. (2005) offer the perspective that data summaries are further confounded by the observation that many storms do not produce runoff from a living roof. In other words, a measure of time delay is infinite. Significant retention capacity also means that runoff duration is shorter than rainfall duration; for much of the event, rainfall is simply captured by the living roof – there is no runoff to extend the hydrograph duration (Voyde 2011).

4.7.4 Simple hydrologic models for planning purposes

Presently, to estimate runoff characteristics from at-source stormwater devices (e.g. living roofs or permeable pavement), some jurisdictional design manuals assign a runoff curve number (CN) for application of the NRCS TR-55[10] method (a.k.a. the "curve number method" (USDA 1986)) to determine runoff volume, or runoff coefficient (C) for computation of peak discharge using the Rational formula. The value of the CN or C is usually based on an assumed similarity of the source control to a natural surface, for example, Auckland assigns 61 (ARC 2003) which is equivalent to "open space in good condition" for hydrologic soil group B soils (ARC 1999), while Michigan uses 65 for extensive green roofs for rainfall events up to three times the moisture retention capacity (SEMCOG 2008).

In reality, living roofs are significantly engineered, pseudo-pervious systems with constrained storage capacity. The limitations of using such simplified estimators such as CN and C are significant when applied to a hydrologically complex system such as a living roof, and ultimately are not recommended. More refined methods for simulating living roof hydrology are necessary, for example a physically based continuous simulation (Fassman-Beck et al. *under review*).

4.7.4.1 Runoff curve numbers

The NRCS TR-55 "CN method" was modified for use in Auckland in TP108: Guidelines for Stormwater Runoff Modelling in the Auckland Region (ARC 1999). The primary modification to the original method arises from the assumption of the initial abstraction (I_a). In TP108, I_a is assigned a value of 5 mm for pervious areas and 0 mm for impervious areas. In TR-55, I_a is equal to a value of 0.2xS, where S is the maximum potential storage in the catchment, and is determined entirely from the CN.

Few studies were identified that estimate CNs for living roofs. Applying a regression procedure based on TR-55, Carter and Rasmussen (2006) derived a CN of 86 for a living roof in Georgia. Getter et al. (2007) calculated CNs by the same method to be 84, 87, 89, and 90 for living roof plots with 2%, 7%, 15%, and 25% slopes, respectively, for systems in Michigan. Fassman-Beck et al. (*under review*) compiled data from 18 sources in the literature and some previously unpublished data. Two approaches were used to determine a "best" estimate CN based on published methods in scholarly papers: the regression method of Carter and Rasmussen (2006), and another method introduced by Ponce and Hawkins (1996) which was also used by Bean, Hunt, & Bidelspach (2007) for CN estimation for permeable pavement. A significant drawback of the latter method is that only events with rainfall depths of at least 50 mm are used for the calculation, which leads to significantly less data. However, this constraint is in accordance with the original TR-55 method (USDA 1986), and an analysis by Hawkins et al. (1985) that concludes that CNs should only be determined from "large" to "very large" events.

Data originated from extensive living roofs in New York City, Chicago, Pennsylvania, North Carolina, Auckland, Georgia, Michigan, and Portland. In many cases, multiple extensive living roofs were monitored in each city or state. All sites were field studies subject to natural rainfall, while the living roof footprints

[10] Natural Resources Conservation Service Technical Release 55 is usually simply referred to as TR-55.

ranged from shed-scale experiments (1-4 m^2) to full-scale roofs (approximately 40-7000 m^2). Test roofs ranged from "flat" to 8% pitch, with one site at 25%. One pre-fabricated modular tray system was included.

CNs ranged from 68 to 95 for the method which uses all data versus 78 to 91 when data are limited to storms larger than 50 mm. In most cases, the two different methods of calculation yield similar CN results (within 3-4 of each other). There appeared to be some effect of scale; shed-scale experiments yielded generally higher CN values. For full-scale living roofs, average CN was 85 for the method which uses all data, and 83 for the method which limits data to storms larger than 50 mm. Auckland's living roofs yielded CNs of 87 (UoA), 88 (WCC), 91 (Tamaki 100 mm depth), and 86 (Tamaki 150 mm depth). Variations in resultant CN are substantial, without any clear indication of trend.

Fassman-Beck et al. (*under review*) clearly describe limitations of a "one-size-fits-all" approach such as CNs to describe living roof hydrology. The physical flow path differs substantially. TR-55 determines surface runoff via overland flow. Conversely in a living roof, the flow path of excess precipitation is usually via percolation through a porous media with significant storage capacity followed by sheet flow through a synthetic drainage layer to vertical drainage points. Influences of rainfall intensity and duration are overlooked. CNs are based on runoff volumes, while peak flows might subsequently be determined using either a graphical method (USDA 1986) or synthetic unit hydrograph methods, neither of which have been developed or verified for living roofs. Detailed attempts to calibrate a CN for living roofs in Auckland through other means have not yielded consistent results for either runoff depth or peak flow (unpublished data). At best, the CN method yields a poor representation of living roof hydrology. Thus, deeper analysis into the variability of results is unjustified.

Where use of a CN is absolutely necessary, Fassman-Beck et al. (*under review*) recommend a value of 85 for events that exceed the actual moisture storage capacity of the living roof substrate (Section 6.4). The slightly lenient value is suggested for planning purposes to acknowledge the variability in results, and the wide range of benefits provided by living roofs beyond stormwater control. For small storms, runoff is assumed to be equal to zero (i.e. CN $\leq$ 1). Although the derivation of the CN deviates from the method used in TP108 (ARC 1999), no further modification is recommended to determine Auckland-specific CN since overall the use of a CN is deemed an over-simplification of the complex hydrology of a living roof.

4.7.4.2 Rational formula coefficients

The term "runoff coefficient" is loosely defined as ratio of runoff to rainfall. It could be (1) the ratio of total runoff volume over total rainfall (C_v), on either annual, seasonal or event basis, or (2) the ratio of the peak runoff to rainfall intensity (C_p), on specific event basis. The FLL (2008) presents a range of C_v according to substrate depth and roof pitch. The values for C_v are determined on small plots subjected to constant rainfall intensity. The FLL testing procedure requires media to be saturated and drained (over 24 hr) initial conditions before determining C_v. The FLL explicitly states that the values for C_v are primarily for use in sizing pipes for vertical drainage in a manner consistent with municipal sewage system design.

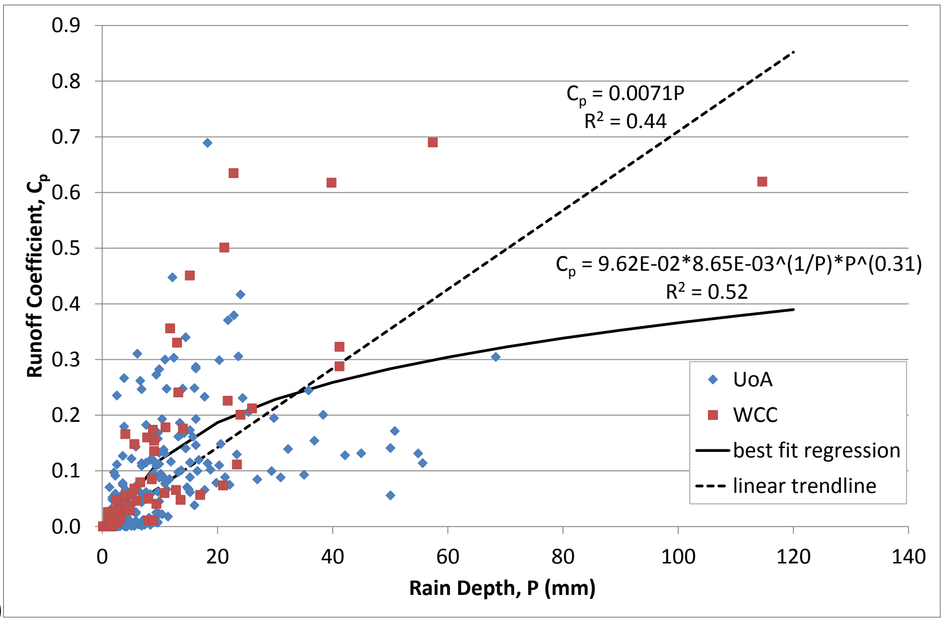
Table 4 includes results of C_p studies performed on living roof plots subjected to simulated constant intensity rainfall events. The choice of simulated rainfall intensity appears to have a significant influence on results. Alfredo et al. (2010) demonstrate C_p decreases with increasing substrate depth, with rainfall simulating a 5-yr, 6-min storm in New York. DeCuyper et al. (2005) targeted the 250-year, 15-min storm in Belgium, which resulted in much higher runoff coefficients from similar size test plots. Variation in C_p was attributed to variations in substrate thickness, type, and/or drainage layer. Test plots under simulated conditions are considered to be of limited use for practical application.

Table 4. Literature values: peak runoff coefficients for living roofs

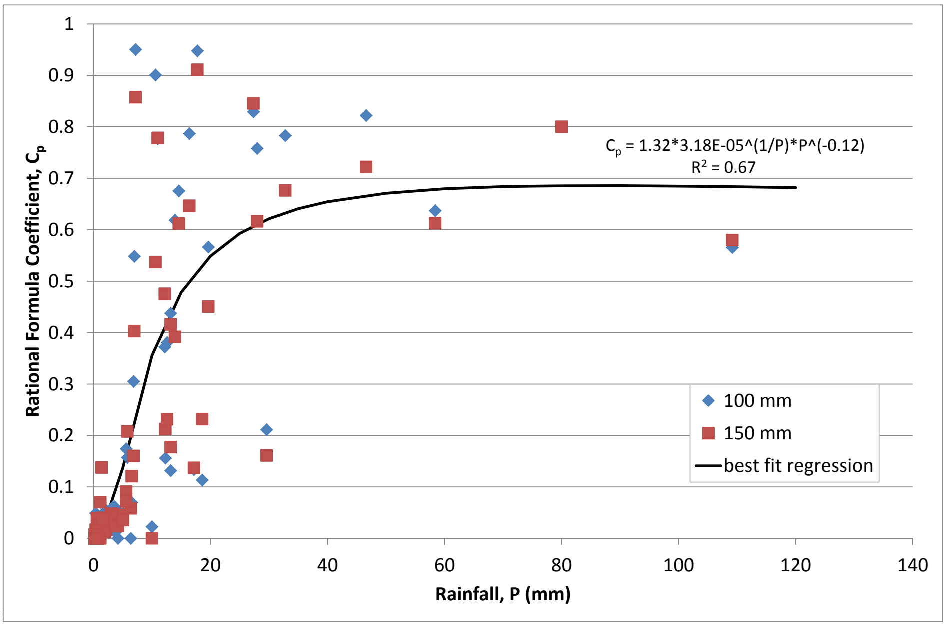
Source	Rainfall	Living Roof Size & Slope	Substrate thickness (mm)	C_p
DeCuyper et al. (2005)	Simulated intensity of 0.033 L s^{-1} m^{-2} until a constant discharge for 10 min	Multiple Plots: @ 7.5 m^2 Slope: 2%	20	0.87
			40	0.89 & 0.92
			50	0.53
			65	0.96
			80	0.57 & 0.9
Alfredo et al. (2010)	Simulated intensity of 0.04 L/s•m2 for 6 min	Plot: 0.74 m^2 Slope: 2%	25	0.53
			63	0.39
			101	0.21
Moran et al. (2005)	Field measured for 10 storms with P > 38 mm	70 m^2 Slope: 0%	75	0.50 (average for 10 events)
Carpenter & Kaluvakolanu (2011)	Field measured for 21 storms with 4 mm $\leq$ P < 75 mm	325.2 m^2 Slope: 4%	102	0.11

Attempts were made to relate C_p to rainfall depth for Auckland's living roofs. Fassman-Beck et al. (2013a) determined that experimental scale affects peak flows, thus data from the UoA and WCC living roofs were investigated to determine C_p separately from the Tamaki mini-roofs. Data were grouped together for regression (Figure 14).

The regression shows relatively poor fit, but conclusions are drawn in order to provide a "best estimate" for a very simple model. Statistical assessment shows that C_p is positively correlated to rainfall depth ($p<0.01$); it is recommended to provide C_p for different design storm events (Table 5). Since the model has relatively poor fit (R^2), it is recommended to limit C_p to one significant digit in practice, and use the non-linear trendline due to slightly better model fit.



(a)



(b)

Figure 14. Rational formula coefficient determination for Auckland living roofs: (a) full-scale roofs (UoA and WCC); (b) shed-scale experiments (Tamaki mini-roofs).

Table 5. Rational formula coefficients for Auckland living roofs.

P (mm)	Full Scale Roofs: UoA & WCC		Tamaki mini-roofs
	Linear Trendline	Non-linear trendline	
5	0.04	0.06	0.14
10	0.07	0.12	0.36
15	0.11	0.16	0.48
20	0.14	0.19	0.55
25	0.18	0.21	0.59
35	0.25	0.23	0.64
50	0.36	0.28	0.67
75	0.53	0.33	0.68

4.7.5 Water quality

Unlike most ground-level stormwater devices, a living roof usually “treats” only the rain falling directly over its surface. Thus, the primary sources of potential contaminants in living roof runoff is limited to atmospheric deposition, and the materials comprising and used to manage the living roofs, their runoff, and underlying building themselves. These sources may include substrate or drainage materials, edging materials, plants, atmospheric deposition in dust and rainfall, and maintenance additions (e.g. fertiliser, herbicides, or pesticides). In sites with roof-mounted air-conditioning units using copper piping, discharges of water may be elevated in copper (O’Sullivan et al. 2012). Copper adornments are likely to have similar effects, if allowed to come into contact with rain water.

Results reported to date for the water quality of living roof runoff for total suspended solids (TSS), total dissolved solids (TDS), nutrients and heavy metals are inconclusive for general comparisons. Methods used to collect data vary (specifically, very few report event mean concentrations [EMCs]) 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.

4.7.5.1 Total suspended solids

Whether a living roof acts as a source or sink of TSS is inconclusive in general. Of the Auckland roof systems monitored for water quality (Tamaki mini-roofs and WCC), neither living nor control roofs contributed elevated TSS EMCs in roof runoff (Fassman et al. 2010b). Carpenter and Kaluvakolanu (2011) found that living roof runoff demonstrated significantly higher TSS concentrations than a conventional asphalt roof, with a gravel ballast roof having the second-highest measured TSS concentration. Conversely, Mendez et al. (2011) and Lang (2010) found that TSS in roof runoff from a living roof was not significantly different to conventional roof runoff. Wanielista et al. (2007) did not identify any significant trends in TSS amongst living roofs. Mendez et al. (2011) identified that a first flush effect was not evident from the living roof, while conventional roof surfaces did demonstrate clear first flush effects. Carpenter and Kaluvakolanu (2011) identified a direct correlation between the size of the rainfall event and TSS mass released from both the living and conventional roofs, with larger volume events exporting higher TSS.

4.7.5.2 Nitrogen

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 international 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). Conversely, Auckland living roofs were found to be a source of nitrogen compared to conventional roofs monitored concurrently (Fassman et al. 2010b).

4.7.5.3 Phosphorus

Phosphorus monitoring studies largely conclude that living roofs are a source of either total phosphorus (TP) or phosphate (PO_4-P) when compared to either rainfall or conventional roof runoff (Aitkenhead-Peterson et al. 2010, Berndtsson et al. 2006, 2009, Bliss et al. 2009, Fassman et al. 2010b, Gregoire and Clausen, 2011, Hathaway et al. 2008, Lang 2010, Long et al. 2007, Moran et al. 2005, Wanielista et al., 2007). Teemusk and Mander (2007) note that during large storm events, PO_4-P and TP concentrations were higher in bituminous roof runoff, due to dust and other contaminants, but both were retained by the living roof in moderate events. Carpenter and Kaluvakolanu (2011) found PO_4-P concentrations in living roof runoff were lower than those for the conventional asphalt and gravel ballast roofs, but not with statistical significance.

4.7.5.4 Other considerations

Substrate composition, fertilisation practices, roof age, the presence or absence of vegetation, and system disturbance or alteration (when plants and/or substrates are manipulated in situ) have been consistently identified as key parameters influencing runoff water quality. In addition, for each study, spatial differences in the dry deposition of dusts and atmospheric aerosols (local pollution sources based on zoning—industrial, residential, or commercial—or external influences such as traffic intensity etc.), supplemental irrigation, and climate/drought factors all contribute to leachate differences (Aitkenhead-Peterson et al. 2010; Berndtsson et al. 2009). 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).

Berndtsson et al. (2009) and Berndtsson et al. (2006) conclude that, when established, living roofs do not substantially impair water quality. However, they recommend that living roofs should not be seen as a tool for improving runoff water quality by reducing the concentration of pollutants found in precipitation; they do not contribute to rain water “treatment” (Berndtsson et al. 2006, 2009). 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 and zinc (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). The primary benefit of living roofs is the ability to provide water quantity benefits (rainfall retention = runoff volume reduction) that conventional roof surfaces do not.

Limited assessment of living roof water quality from the Auckland sites allows the following conclusions to be drawn (Fassman et al. 2010b):

- Roof runoff quality in general is highly site-specific.
- When compared with paired control roofs monitored concurrently, Auckland living roofs performed similarly to reports from the international literature, with the exception that living roofs were a source of nitrogen, rather than a sink, when compared with control roofs, likely due to lower atmospheric deposition in Auckland.
- Living roofs were not a source of TSS. This is consistent with international literature.
- Building materials and ornaments were likely sources of zinc and copper in living roof runoff, either when runoff came into contact with the material, or the material was in close proximity for air-borne deposition. Even colour-steel roofs will contribute measurable zinc into runoff. The presence of elevated zinc or copper in living roof runoff depends on site-specific building materials rather than the living roof itself. However, as copper is very mobile in soils and affected by organic content and moisture levels, living roof substrates should have minimal copper concentrations. As living roofs provide significant long-term hydrologic control, covering, replacing, or substituting a metal roof with a living roof will likely reduce the long-term mass loading from the site.
- Living roofs are likely a source of nutrients in New Zealand. Responsible stormwater design for living roofs located in nutrient sensitive receiving watersheds is essential. Organic matter composition and initial volume requires careful specification, as does the fertilisation type and frequency. While the runoff hydrology is significantly mitigated, there may not be enough of a reduction on an annual basis to compensate for the elevated nutrient concentrations in terms of total pollutant mass loads.

A design aim is to ensure runoff from living roof installations will not have a lower quality than that from conventional roofs. Long et al. (2007) states that engineering a living roof substrate for water quality improvement is possible, but careful consideration is required for both the mineral (aggregate) portion, which contributes the majority of volume and mass, and the organic fraction, which may be a source of nutrient leaching. Berndtsson (2010) identifies selection of the organic component and maintenance regimes as being the main factors governing nutrient leaching. In Auckland’s monitoring studies, substrate composition and chemistry were investigated to attempt to explain contaminant concentrations found in runoff from the Tamaki mini-roofs and the WCC living roof (Fassman et al. 2010b). Further research is necessary to develop indicators for water quality based on substrate composition.

Living roofs should primarily be considered as a tool for runoff volume and peak flow reduction, with some associated benefit in contaminant mass reduction, rather than as a specific water quality control tool.

4.8 Design for multiple objectives

Living roof design is a rapidly developing field. The discussion and recommendations in this report maintain a priority focus on design for stormwater management. 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. The following books are suggested:

- Cantor L. S. 2008. Green roofs in Sustainable Landscape Design. W.W. Norton & Company, New York. London. 352pp.
- Dunnet, N. and Kingsbury, N. 2004. Planting Green Roofs and Living Walls. Timber Press. Cambridge, UK.
- Earth Pledge. 2005. Green roof ecological design and construction. Schiffer Books.
- 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. 314pp.
- Dakin, K., Benjamin. L., Pantiel M. 2013. The Professional Design Guide to Green Roofs. Timber Press. Portland, Oregon.

5.0 Structural and Architectural Design Procedure

Living roofs are unique amongst stormwater devices in the sense that their design is inherently inter-related with structural engineering and architectural design[11]. A successful stormwater living roof project requires open communication between the stormwater designer, structural engineer, and architect, among other design professionals. The potential for living roof implementation should be considered early in the building's design process, so that undue costs are not later realized for structural or drainage redesign (at a minimum). Planting strategies are integrated with function, aesthetic outcomes and architectural design. The complexity of planting decisions warrant detailed discussion, and are presented as a separate design chapter.

5.1 Structural design

Living roof feasibility is first and foremost predicated on the structural capacity of a building's roof. A licensed professional with appropriate expertise shall investigate the structural integrity and capacity of the roof to determine its suitability for living roof installation.

Properties related to living roof system weight should be determined according to ASM E2399-11: Standard Test Method for Maximum Media Density for Dead Load Analysis of Green Roof Systems. It is noted that ASTM E2399-11 provides a measure of media moisture retention; however it is not equivalent to PAW and cannot be used in equation 8. Furthermore, use of the standard is limited to determining component weights and densities. Total structural load should be determined as per this chapter.

Structural requirements for New Zealand buildings are dictated by AS/NZS 1170 (2002) Structural Design Actions (SNZ and SAA 2002). As there is no current mention of living roofs in AS/NZS 1170, Associate Professor Charles Clifton (Department of Civil and Environmental Engineering, University of Auckland) was consulted to help elucidate calculation procedure for determining structural design requirements for living roof support. Associate Professor Clifton served on the AS/NZS 1170 (2002) Standards Committee, contributing primarily to the seismic design section.

It is assumed that the reader/user has access to the standard. The information contained herein is meant to provide supplemental or explanatory information; it does not replace anything in the standard, nor should a structural assessment proceed without the standard. It is beyond the scope of this document to address determining structural loading from roof elements other than the living roof system, including landscape architecture elements such as pavers or walkways, or such as the concrete or timber of construction, air conditioning units, vents, or any other mechanical plant features that are often located on rooftops. The information contained herein has not been formally reviewed by the Standards Committee.

The following discussion specifically relates to Part 0-General Principles, with the exception of Section 5.1.3 below, which refers to Part 1-Permanent, imposed, and other Actions. It is meant to define how load factors such as permanent (G) or imposed action (Q) (formerly referred to as "dead" and "live" action or load) are determined for a living roof system.

[11] The term "architectural design" is meant to include the building's architecture and the landscape architecture of the living roof.

5.1.1 Permanent Action

The permanent action, G, is the mean weight of the "regular" roof plus the components of the living roof system under normal operating conditions. The components of a living roof system include a water-proofing layer, root barrier, drainage layer, geotextile, substrate, plants, and potentially supplemental moisture storage layers. The water-proofing layer should be impermeable to water; hence its weight should not change due to a storm event. The root barrier, drainage layer, and geotextile may have some capacity to store water (e.g., they may act like a sponge). The field capacity of these layers is likely to be minimal compared to the substrate and plants; nonetheless their contribution to the total load should be considered in both dry and wet conditions.

Since a living roof is specifically designed to maintain high permeability (i.e., free drainage), saturation should not be reached. During a storm, it is likely that the substrate weight will increase to a maximum determined by the "maximum media moisture retention" as per ASTM E2399-11.

Plant mass will change as the system becomes established. For determining the permanent action, mass should be assessed for fully mature plants. Plants have some ability to intercept rainfall; water stored on the plant leaves during a storm event may increase the total load. Insufficient data is available to date regarding interception storage; but it is likely less than 3 mm for typical plant species on an extensive living roof.

Under normal operating conditions, G must be calculated as:

$$G = \text{average}(G_{dry}; G_{wet}) \qquad \text{Equation 2}$$

$$G_{dry} = RB + DL_{dry} + GEO_{dry} + S_{dry\ bulk\ density} + P_{dry} + E_{dry} + SMR_{dry} + WM + + M_{regular\ roof} \qquad \text{Equation 3}$$

$$G_{wet} = RB + DL_{wet} + GEO_{wet} + S_{water\ holding\ capacity} + P_{wet} + E_{wet} + SMR_{wet} + WM + M_{regular\ roof} \qquad \text{Equation 4}$$

Where:

RB	= mass due to root barrier
DL_{dry}, DL_{wet}	= mass due to drainage layer under dry or wet conditions, respectively, determined using ASTM E2396-11 and/or E2397-11. For a synthetic drainage layer installed "cups up", DL_{wet} includes the weight of water filling the cups.
GEO_{dry}, GEO_{wet}	= mass due to geotextile under dry or wet conditions, respectively, determined using ASTM E2397-11 and E2399-11.
$S_{dry\ bulk\ density}$	= mass due to substrate under dry conditions, calculated from dry bulk density determined using E2397-11 and E2399-11.
$S_{water\ holding\ capacity}$	= mass due to substrate under wet conditions, calculated from E2397-11 and E2399-11 maximum media moisture retention (field capacity)
P_{dry}, P_{wet}	= mass due to mature plants under dry or wet conditions, respectively (recommended 17 kg m^{-2} for well-established plants with > 80% coverage)
$E_{dry,\ wet}$	= mass due to edging materials under dry or wet conditions, respectively
$SMR_{dry,\ wet}$	= mass due to supplemental moisture retention materials under dry or wet conditions, respectively, using ASTM E2397-11
WM	= mass due to waterproofing membrane

$M_{regular\ roof}$ = mass due to the "regular" roof. Further breakdown of this term is beyond to scope of this report.

5.1.2 Imposed Action

AS/NZS 1170.1 §3.5 addresses requirements for structures to withstand imposed action, Q. Minimum support for non-greened roofs depend on accessibility and the potential for people to be present on the roof:

1. A non-trafficable roof accessed for maintenance only must support Q = 25 kg m^{-2} (0.25 kPa).
2. A roof accessible for any kind of congregation must support:
    a. Q = 150 kg m^{-2} (1.5 kPa) if people can climb onto it (e.g., during a parade, the public is known to climb atop bus stop shelters for a better view); or
    b. Q = 400 kg m^{-2} (4.0 kPa) if the roof is designed for general access (e.g., with the same imposed load for a normal floor).

Extensive living roofs are not normally intended for people to walk directly on the vegetated areas, except perhaps for limited maintenance. Intensive living roofs are often aesthetic features and may be used as public space, picnic areas, etc. The value of Q should be determined based on the access planned and/or provided.

5.1.3 Static Liquid Pressure and Rainwater Ponding

AS/NZS 1170.0 §4.2.3(b) is the applicable consideration for static liquid pressure, S_u for a living roof. S_u is determined by the maximum water level that can be achieved if the primary drainage system is blocked. The primary drainage system includes the gutters or downpipes of the roof as well as the drainage layer which supports the living roof substrate. If the primary drainage system is clogged, then the substrate may reach saturation. This is considered a "worst-case scenario" for a living roof system, in terms of structural loading, and is unlikely to be encountered if properly designed, constructed, and maintained. Nonetheless, the load is determined by the saturated system weight as determined by ASTM E2399-11.

AS/NZS 1170.0 §4.2.3(d) refers to the influence of rainwater ponding and §4.4 of AS/NZS 1170.1. As described above, a living roof is designed for high permeability. Hence, the height of any impermeable boundary should be the only factor influencing the potential for rainwater ponding. For a living roof, the action resulting from rainwater ponding, F_{pnd}, is determined by the height of any impermeable layer on the perimeter of a living roof. In many installations, substrate edging is actually permeable. However, if a formal edge (e.g., flashing or a balustrade) prevents water from seeping from the edges of the substrate, or as overland flow over the top of the substrate, the height of the impermeable boundary must be taken into account.

The physical load for a saturated system will always be greater than the calculations which consider ponding. If the strength is determined to support a saturated living roof, then the ponding calculation is not required.

5.1.4 Strength

AS/NZS 1170.0 §4 sets requirements for structure strength to support specific combinations of loadings with relevant safety factors. Cases §4.2.2(b) and (g) of these combinations are the critical determinations for strength of a structure to support a living roof. These combinations rely on the definitions of G, Q, and S_u as per above. Per Table 4.1 of AS/NZS 1170.0, the value of the combination factor, Ψ_c, depends on the provision of access, per Section 0:

- For condition 1 or 2(a): Ψ_c=0.0; or
- For condition 2(b) (general access roof): Ψ_c=0.4.

5.1.5 Wind Loads

Wind loads must be considered for long-term design as well as during construction. The potential for uplift of the living roof materials as well as the roof deck must be considered (the latter often applies to conventional roof design).

The layered living roof structure of waterproof membrane, root barrier, and drainage layer may be subject to uplift from wind. While overall minimizing weight (load) from a living roof is a typical design goal, certain design circumstances related to wind loads may suggest that depth should be increased or heavier materials (e.g. gravel or paving slabs) used to secure edges or corners. Design calculations related to wind loads should be considered for dry conditions, when the living roof will impose the least weight.

Part 2 of AS/NZS 1170 (2002) Structural Design Actions specifies wind loads, and Part 0 specifies load combinations (SNZ and SAA 2002).

It is possible that the minimum weight design focus for the extensive living roof might be too light to satisfy ballast requirements for flat roofs. As required, deepening the substrate can increase the weight of the system.

5.1.6 Wind Serviceability

A living roof may provide a damping effect on a building's response to wind loads if the drainage layer is flooded with water. Technically, the damping phenomenon is referred to as wind serviceability acceleration mitigation. The water in the drainage layer provides a mass damper function under in-service high wind loading conditions, which might exceed the occupant acceleration limits specified in the appropriate standard or design guide. The place for such a limit would be in Appendix C of AS/NZS 1170.0 however there is no limit specified. A potentially useful and relevant equation is given in the Heavy Engineering and Research Association (HERA) Steel Design and Construction Bulletin (Clifton 2002, 2003), along with the graphical representation of that equation. However, at this stage, further investigation is considered beyond the scope of this report.

In the case of a living roof, damping is enabled by the water layer in the drainage layer; however, the substrate could be described by a range of moisture conditions. Under normal operating conditions, the drainage layer should not be flooded; however, a temporary flooded condition might be enabled by an irrigation system triggered by high wind loads, and might be worthwhile if the damping benefits prove to be significant. This is a new state for living roofs and will require new definition, range of operating conditions, control and monitoring mechanisms. It will affect the above calculation of various loadings.

5.1.7 Pre-installation load verification

The calculations contained in this chapter are predicated on the specific composition of the substrate. Prior to installation, substrate weight shall be verified for blended materials (Section 6.4.5). If a blended substrate exceeds the design weight, the licensed professional responsible for structural assessment must be consulted. Remedial action may be required, including supplementing structural support, re-blending substrate, or reducing the installed substrate depth.

Where additional structural capacity is available, an increase in substrate depth and/or other supplemental moisture storage techniques will benefit plant health over the long term, and is strongly encouraged.

Modifications to the substrate composition and/or installed depth may affect stormwater retention characteristics and/or the ability to support the intended plant palate. Thus, in this case, the stormwater designer and horticultural expert must also be consulted before remedial action is pursued.

5.2 Architectural design

It is beyond the scope of this report to address building or landscape architecture; however, consultation and regular communication between the architect and stormwater designer are strongly encouraged. Architectural elements that may affect living roof design for stormwater control include, but are not limited to:

- Design and location of vertical drainage points (scuppers, inlets, drains, etc).
- Parapets, balustrades, and anchor points
- Roof pitch (slope)
- Edging and walkways
- Design and location of mechanical services
- Method and location of physical access
    - Access for maintenance
    - Public access
- Substrate (planting) depth

Metal materials containing zinc and copper shall not be used as components of the living roof system where they are allowed to come into contact with rainfall or runoff, due to the potential to leach into roof runoff.

5.2.1 Vertical drainage

The two primary components of drainage from a living roof are: the mechanism to convey runoff from the vegetated area(s), and the building infrastructure including scuppers, gutters and downspouts (vertical drainage to ground level). The presence of a living roof does not preclude the need for vertical drainage. Vertical drainage shall comply with all relevant building codes.

Locate roof gutters, drains, or downspouts in a manner that provides the longest runoff travel distance through the drainage layer, and ensure a minimum of two outlets (i.e., to avoid ponding even if one outlet is blocked). Evaluation of roof topography may be necessary. If the roof is to be monitored, minimize the total number of vertical drainage points.

Vertical drainage elements and related joinery or flashing must be flush with, or below, the roof deck. Vertical drainage elements shall be installed prior to the waterproofing. Levels should be verified during construction to ensure positive drainage.

Provide a pervious edge of 200-500 mm around vertical drainage points to maintain their visibility to keep free from vegetation growing over or from substrate migrating into it.

5.2.2 Parapets, balustrades, and rated anchor points

Provide safe access and egress according to all relevant Occupational Safety and Health codes. Safety requirements differ according to accessibility of the roof, e.g. ranging from maintenance-only access to public amenity space.

Location of anchor points may need to consider access to building facades, as well as the living roof itself, depending on site-specific requirements (e.g. window washing).

Footings for parapets, balustrades, services, and anchor points must not compromise free drainage from the living roof system.

5.2.3 Pitched (sloped) roofs

Design and installation on pitched roofs should follow best practice for erosion control and slope stability, and considerations for working with low-cohesion soil (the living roof substrate).

For retrofit installation on non-pitched (flat) or near-flat roofs, and/or where slope is not clear, perform a roof survey on a 1 m x 1 m grid to identify flow paths to the vertical drainage points and local depressions that may cause ponding within the drainage layer.

For new buildings, provide a minimum roof slope of 2% to ensure free drainage so that water does not pond on the roof. A slope of 3% is encouraged. For retrofits with roof slope less than 2% or on uneven roof surfaces that may cause localized ponding after rain events, a formal drainage layer is required.

For living roofs with 5°-15^{o} (8.8-26.8%) pitch, provide a biodegradable mat on the substrate surface to hold plants in place until establishment (e.g. Figure 7). Install plants through the mat. Alternatively, use a pre-grown living roof system (Section 2.3.4).

For living roofs with greater than 15-20^{o} (36.5%) pitch, provide a structural anti-shear and slip protection measure (e.g. Figure 6). Any wood materials must be carefully considered. Wood treated with copper chromium and arsenic is not permitted for use in living roofs due to the potential to leach harmful contaminants into runoff. Anti-slip or anti-shear measures shall not compromise drainage. Cover the substrate with an erosion control mat, and plant through it. Living roofs with greater than 15^{o} pitch will not be considered for stormwater retention credit.

5.2.4 Edging and walkways

Provide pervious edging to identify safety hazards (i.e. the building edge), to maintain visibility and accessibility for drainage points, mechanical services, and other protrusions, and to prevent substrate migration.

Suitable materials include washed gravel, pumice (restrained in a non-zinc gabion if it will float or blow away), or other washed LWA, paver blocks or permeable pavers, and rigid drainage boards, but not organic mulch. Edging must not generate undue pressure or puncture potential on the waterproofing, root barrier, or other lining layers. Structural loading calculations (Chapter 5) must account for edging materials.

Edging materials may include the following considerations:

- LWA may need to be contained within a plastic-coated wire mesh (Figure 15a). Metal mesh (e.g. galvanized zinc) shall not be used.
- Perforated or permeable perimeter edging material may be continuous as it promotes free drainage (Figure 15b).
- Non-permeable paver edging must provide adequate inter-paver separation to allow free drainage (Figure 15c). An alternative method may be needed to hold substrate in place in inter-paver separation zones.

(a)


(b)


(c)


Figure 15. Edging materials: (a) pumice wrapped in plastic-coated mesh; (b) rigid drainage board; (c) non-pervious pavers with gaps to allow drainage.

The extent of edging should be provided as:

- ≥200 mm edging around living roof perimeter using 15–20 mm diameter washed LWA or gravel, if aggregates are to be used.
- ≥100 mm LWA or gravel around all protrusions.
- Where the living roof does not extend to the edge of the waterproof layer, ensure the waterproof layer is suitably covered (with aggregate or the like) to protect from UV exposure or other physical damage.

- Fire breaks every 40 m of vegetated living roof (i.e. aggregate or paver strip [preferably permeable]).
- Consider wider edging if/where foot traffic is expected.

Provide a dedicated and easily identifiable walkway if a roof is publically accessible or regular maintenance access for mechanical building services is anticipated. Walkable areas should be at least 2 m distance from roof edges (for example Figure 9a), and compliant with any relevant Occupational Safety and Health (OSH) requirements. Exclude main paths, irrigation fixtures and any storage areas from this 2 m edge zone. The walkway must not interfere with the horizontal or vertical drainage of the living roof system, nor shall it generate undue pressure on the waterproofing, root barrier, or other lining layers (e.g. Figure 16).

Figure 16. Rigid drainage boards allow foot traffic without damage to vegetation or compromising drainage.

5.2.5 Design and location of mechanical services

Cluster and minimize the number of protrusions, perforations, and services to reduce potential disturbance to the living roof, and contribute to maintenance egress.

Provide a clearly defined path for maintenance crews that prevents trampling of vegetation to the maximum extent possible, but compliant with relevant OSH requirements. Consider space required for storing/placing temporary maintenance equipment. This may include window washers (who may belay over the roof edge) in addition to servicing features located on the roof itself.

5.2.6 Method and location of physical access

Living roofs should be designed so they are safe to access and maintain with minimal risk to waterproofing, plants and people. Even if a living roof is unintended for physical public access, egress points must be provided for maintenance. Maintenance crews must be able to reach all areas of the living roof safely while potentially carrying equipment. Stairs, lifts, ladders, or external lifting/hoisting mechanisms may be considered, among others. Design must comply with OSH requirements.

5.3 Design for Safety During Maintenance

Suggestions to reduce risk associated with working on living roofs are taken predominantly from Behm (2012), with minor modifications. In all cases, design must comply with minimum OSH requirements. These suggestions are presented in order of preference.

To encourage safe access:

1. Design designated fixed stairs and/or elevator to the roof through the building's core so that workers and necessary equipment can access the roof in a safe and efficient manner.

2. Where an interior stairwell or an elevator is not designed into the structure for worker roof access, an exterior building caged ladder should be designed for roof access. Designation of a rooftop storage area for maintenance equipment is recommended if this option is used. Reliance on this option could limit the safe access of equipment, or use of pre-grown systems that don't fit within the cage.

To address fall prevention and protection:

1. Specify a minimum 1-m parapet around the roof perimeter to serve as fall-protection during living roof installation, inspection, and maintenance.

2. Specify a minimum 1-m guardrail around the roof perimeter to serve as fall-protection during living roof installation, inspection, and maintenance.

3. Where parapets or guardrails are not specified as in option #1 or #2, specify roof-edge restraint systems that limit work where workers could fall.

4. Where parapets or guardrails are not specified as in option #1 or #2, and roof-restraint systems, are not specified as in option #3, specify that horizontal-lifeline systems be installed.

    a. On "flat" roofs, the system must be at least 2 m from the roof's edge, and accessed easily from fixed stairs through the building's core such that the entrance to the roof facilitates access, ensuring the worker does not need to be unattached within 2 m of the edge.

    b. On sloped or pitched roofs, the system must be able to be accessed immediately when stepping onto the roof.

    c. A horizontal life-line should not be installed within the width of any walkways.

5. Where no other fall-protection is designed into a flat roof, specify vegetation and any edging or border be installed 2 m from the roof's edge. This form of fall-protection would only be acceptable if there is access to the roof through the building's core leading to the centre of the roof, and if water spigots are available on the roof within 2 m of the roof's edge. It is noted that Behm (2012) and Ellis (2001) suggest a minimum of ~3.6 m.

Suggestions that address skylights and unique building hazards:

1. When specifying rooftop vegetation, borders which require maintenance, and any irrigation-system components near skylights or other fragile roof materials, consider specifying permanent guardrails around these roof openings, or that permanent protective screens are installed within the skylight to prevent falls through to lower levels.
2. Consider the roof and the work to be performed in relation to existing electrical power lines. Power lines should be moved, or vegetation not be placed on roof areas where the work may encourage workers and their equipment to be within 3 m of the overhead power line.
3. When specifying rooftop vegetation, borders which need maintenance, and any irrigation-system components near other mechanical or electrical rooftop equipment, specify physical guards on that equipment to prevent accidental contact.

6.0 Stormwater Management Design

6.1 Waterproof layer

Specify a fit-for-purpose waterproofing membrane. For many living roof applications, a double-ply waterproof membrane of high quality, or a purpose-made (for living roofs) heavy-duty membrane with felt layer (which may be single-ply) is recommended. In selecting a product, review the warranty, particularly for any conditions which might be affected by the living roof. Consult with the supplier to ensure the product is suitable for the intended purpose, and any special considerations that may be necessary for installation and on-going maintenance.

Waterproofing details must consider installation around protrusions, footings, mechanical services, parapets, etc. Design full cover for waterproofing with drainage material, substrate, edging material, and/or other suitable elements to prevent UV exposure.

6.2 Root barrier

To avoid aggressive plant roots penetrating the waterproofing membrane, or otherwise puncturing the roof structure, include a chemical or physical root barrier in the living roof design. The range of active ingredients in root barriers available in New Zealand is currently unknown, detailed investigation into the active ingredient is required prior to specifying any particular product to ensure suitability. Use of root barriers containing copper or pesticides should be avoided because of the potential to leach contaminants of concern into runoff.

Suitability of product specification is a site-specific decision that should consider expertise or experience of the installer. An integrated system (membrane or drainage mat with incorporated root barrier) has the advantage of one less layer and installation step; however, the installation may be more difficult than a separate membrane and root barrier system.

6.3 Horizontal drainage

A formal drainage layer must be used on retrofit living roofs with slope less than 2% or on uneven rooftops. The drainage layer should be deeper than is strictly necessary, to prevent potential pooling of water in localised depressions under the substrate which keep plant roots wet, causing potential root damage. In most extensive living roof applications and in all intensive living roofs, a formal drainage layer will be placed between the waterproof membrane and the substrate (Figure 1).

Weight must be determined for the specific drainage product, using ASTM E2398-11 and/or ASTM E2396-11, or equivalent. If a synthetic drainage layer with “cups up” is specified, the structural engineer must consider the added weight if cups are filled with water (Chapter 5).

When using a commercial synthetic drainage layer, refer to the manufacturer’s product specifications for which depth or type of drainage layer to use based on the living roof design depth, weight, and permeability. Any drainage layer must have adequate bearing capacity to prevent compaction under anticipated loads. Long-term loads may include the wet weight of the substrate, plants, edging, walkway materials, and foot traffic. During installation, significant loads may include but are not limited to: people, wheelbarrows, mechanised equipment, or substrate stockpiles.

The hydraulic capacity of the drainage layer must be adequate to safely convey the design unit flow rate at the roof grade without water ponding in or on the substrate (i.e. water will freely drain into it from the substrate). If flow converges near drains and gutters, the design unit flow rate should be increased accordingly. Use of an aggregate drainage layer may enhance peak flow mitigation, but horizontal permeability must be maintained so as to not create ponding in/above the substrate.

Use ASTM E2398 - 11 Standard Test Method for Water Capture and Media Retention of Geocomposite Drain Layers for Green Roof Systems to assess the hydraulic properties of a synthetic drainage layer. The procedure applies to a synthetic sheet, mat, or panel that is specifically designed to convey water horizontally toward a roof deck, drains, gutters, or scuppers. Use ASTM E2396 - 11 Standard Test Method for Saturated Water Permeability of Granular Drainage Media [Falling-Head Method] for Green Roof Systems to determine the water permeability of coarse granular materials used as drainage layers of a living roof system (e.g. pumice, gravel, or rock in lieu of a synthetic drainage product). It does not apply to characterizing substrate or synthetic drainage layers.

The capacity of any drainage layer must exceed the rate of water that passes through the geotextile above, so as to not impede flow (Equation 6-1):

$$\mathbf{k_{drainage}} \geq \mathbf{k_{geotextile}} \qquad \text{Equation 5}$$

Where k = saturated permeability of respective materials.

The following criteria are recommended for all geotextile layers used as separation or filter layers (FLL 2008):

$$\mathbf{AOS_{fabric}} = \mathbf{D_{90}} \qquad \text{Equation 6}$$

$$0.06\ \mathrm{mm} \leq \mathrm{D}_{90} \leq 0.2\ \mathrm{mm} \qquad \text{Equation 7}$$

Where;

AOS = apparent opening size of geotextile

D_{90} = diameter of the grains for which the geotextile retains 90% (by weight) of the substrate and allows 10% (by weight) to pass through

A minimum weight of 100 g m^{-2} is recommended for the geotextile, with a typical range of 100–200 g m^{-2} for substrate depths up to 250 mm (FLL 2008). For deeper substrates and steeply sloping roofs, it may be necessary to increase the geotextile density.

A formal drainage layer is not strictly necessary, but is nonetheless recommended, if the roof pitch is greater than 5%, and if the saturated permeability of the substrate exceeds the criteria described in Section 6.4.2. Living roofs without a formal drainage layer have not been studied in New Zealand to date, hence further investigation is recommended prior to implementing this method.

6.4 Substrate design

For the purposes of this report, extensive living roof design intent is to prevent rooftop runoff from the majority of individual rainfall events. Aligning with international best practice, Auckland's "frequently occurring event" is defined as the rainfall depths with 85-95% exceedance probability (Fassman-Beck et al. 2013b).

The majority of rainfall retention occurs within the substrate; thus, substrate design to promote water retention of the target rain event is critical. In practice, healthy, densely covered vegetated roofs provide superior stormwater control compared to unvegetated, substrate-covered roofs. However, significant variation amongst individual plant species ET, interception, and/or other influences precludes a stormwater design process or performance credit reliant on plant species information at this time. Nonetheless, vegetation plays several technical roles contributing to overall system success. In particular, full and healthy vegetative cover physically anchors substrate in place, preventing erosive loss by wind and rain, and minimizes weed colonization. Plant roots help maintain substrate porosity and permeability over the long term. The canopy contributes rainfall interception and helps to reduce peak flows. Additional functions of plants are elaborated upon in Section 4.6 and 7.

At present, there is also insufficient empirical evidence to reliably quantify the influence of slope on runoff control.

6.4.1 Minimum substrate depth

Equation 8 recommends the minimum substrate criteria when designing for stormwater management. 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 strongly encouraged to be given by the deeper of:

$$D_{lr} \geq \frac{DSD}{PAW} \qquad \text{Equation 8}$$

$$D_{lr} \geq 100 \text{ mm}$$

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 85th-95th 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 17. PAW typically increases with smaller particle size distribution and greater organic content. Section 4.5 discussed potential negative influences of decreasing particle size distribution and increasing organic content on weight, permeability, and plant growth, thus although PAW may be manipulated by design, designers must be cognizant of effects other than simply PAW.

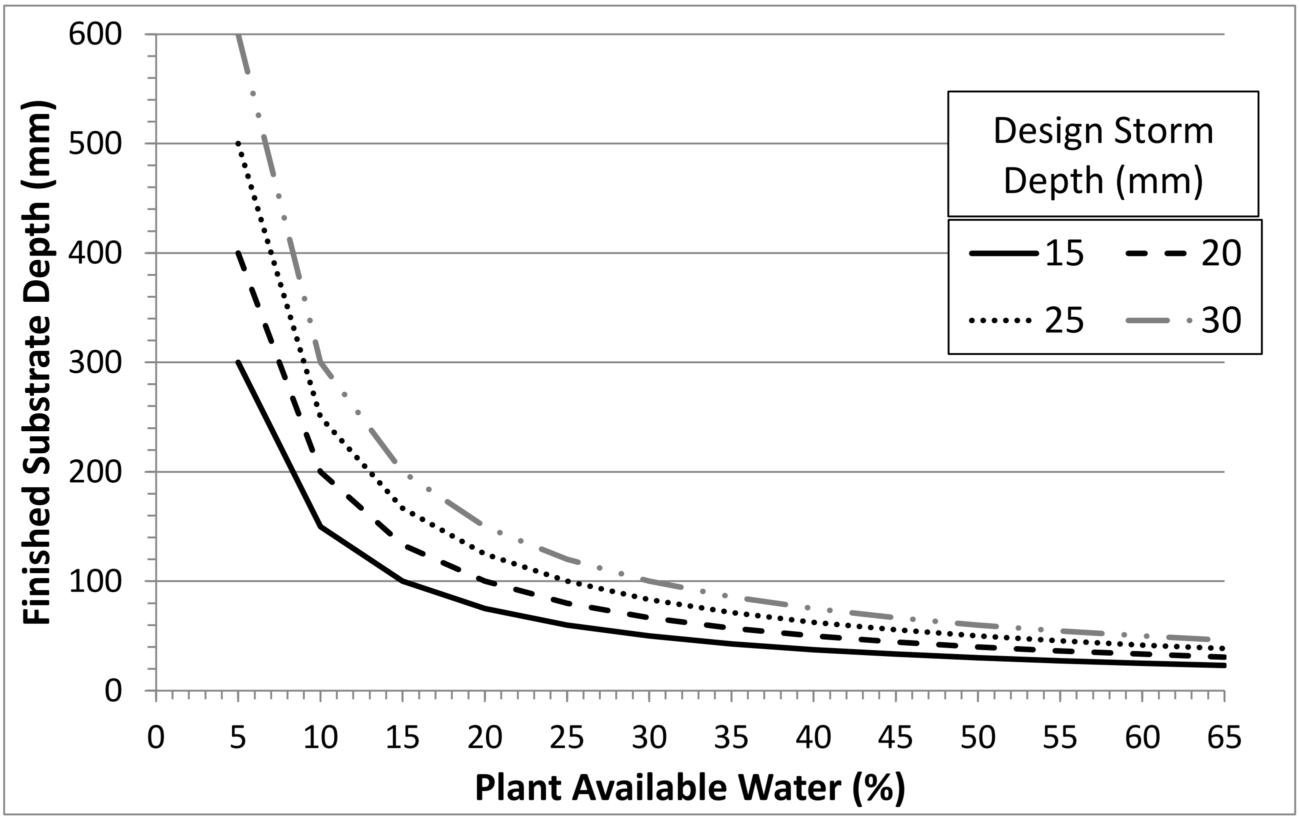


Figure 17. Effects of PAW and DSD on D_{lr}.

For planning and consenting purposes, the maximum amount of water that will be stored by the media can be estimated by (Fassman and Simcock 2012):

$$S_w = D_{lr} \times PAW \qquad \text{Equation 9}$$

$$0 < S_w \leq 30 \text{ mm}$$

Where S_w = maximum water storage in the substrate (mm) per unit area of living roof. It is noted that in practice, at least this much rainfall must occur in order to fill up the entire storage capacity.

The upper limit of this relationship is S_w = 30 mm. In other words, doubling substrate depth does not equate to doubling rainfall capture for water holding capacity greater than 30 mm. Local (Auckland) and international empirical performance data do not currently support extending the relationship in equation 9 beyond 30 mm (Fassman-Beck et al. *under review*).

S_w and D_{lr} are determined based on providing minimum stormwater retention. D_{lr} as per equation 8 is considered a minimum requirement for new construction. A finished substrate depth of 100–150 mm allows for both stormwater management and plant needs, minimising the need for additional irrigation under typical Auckland climate conditions. Shallow substrate depth (considered D_{lr} < 100 mm) likely compromises plant health and increases the risk of inadequate plant cover in the absence of regular irrigation due to the high temperatures and evapotranspiration demands related to exposure.

For retrofit applications where structural support is limiting, D_{lr} can be reduced to 50 mm, but a high proportion of sedums and permanent irrigation strategy/system (operated based on substrate moisture rather than only timed intervals) is strongly recommended. In all cases, if a range of native New Zealand plants is desired and the roof does not receive afternoon shade or irrigation, then at least 100 mm substrate depth should be provided.

The rooftop is a harsh growing environment, regardless of species' adaptations. Increasing substrate depth in limited areas over the minimum requirements determined from equation 8 is suggested to reduce plant stress or mortality by creating areas with increased moisture supply, while still restricting weight. Place the deepest area in the most sheltered roof areas with the greatest afternoon shade, e.g., the south side of parapets or lift wells to gain the greatest moisture supply benefit. Where weight restrictions are significant, consult the structural engineer for feasibility of placing deeper areas over load-bearing elements (e.g. columns and structural walls). Deepest areas should be at least 100 and preferably 150 mm to take advantage of a natural surface mulch layer that develops as coarse living roof substrates dry out and restricts water loss from underlying substrate.

6.4.2 Saturated permeability

Measure substrate permeability using ASTM E2399-11, Standard Test Method for Maximum Media Density for Dead Load Analysis of Green Roof Systems. The minimum acceptable permeability for Auckland living roofs is 1500 mm h^{-1} for living roofs with a dedicated drainage layer and 3600 mm h^{-1} (0.1 cm/s) for extensive living roofs without dedicated drainage layer. Double or single-ring infiltration methods are not appropriate to test living roof systems as they have been shown to produce substantially greater permeability than ASTM E2399-11 (Fassman and Simcock 2012), and in part because they cannot be performed in a laboratory for prediction purposes.

6.4.3 System weight

Properties related to component weight shall be determined according to ASTM E2397-11: Standard Practice for Determination of Dead Loads and Live Loads associated with Green Roof Systems and ASTM E2399-11: Standard Test Method for Maximum Media Density for Dead Load Analysis of Green Roof Systems. Application of these ASTM methods is limited to determining component weights. A licensed structural engineer must be consulted to evaluate the requisite structural support in accordance with the local building code and structural design as per Chapter 5. It is noted that ASTM E2399-11 provides a measure of media moisture retention; however it is not equivalent to PAW and cannot be used in equations 8 and 9.

6.4.4 Materials' sourcing and blending specifications

Regardless of the blend of materials used, three key factors must be managed to maintain the desired substrate characteristics: source material quality control, the blending/mixing process, and post blending testing to ensure adherence to the design criteria.

Verify with suppliers that components are weed-free to minimise the maintenance required during establishment. Use of materials stored inside or under cover and composted materials is preferred over methods used to kill weeds post-exposure. Bag blended substrates, or otherwise protect from weeds, slug and insect colonisation throughout the supply process, including post-delivery to the site. Even bags should be covered to prevent weed introduction if stored outside for extended periods of time.

Source materials from covered stockpiles, or specify drying-out of organic and pumice components before blending. Alternatively, blend materials in summer, and at least five days since a significant rainfall event. The recommended maximum moisture content during blending is 15%. Very dry substrates may create a dust and health hazard (associated with use of composts). Mixing very moist or wet materials enhances consolidation and break-down of individual particles, leading to less material delivered for construction;

very wet substrates are slower and more difficult to spread, and heavier – risking localised overloading of roof if mounds of substrate are created. Where materials are supplied based on weight, mixing when wet may compromise mass-to-volume conversions (the recommended composition in this report is prescribed by volume).

Blend at least 20% by volume more raw materials over “finished” depth to account for consolidation and losses during the mixing and supply process, and settling by ~10% (depth) once installed. Mechanical mixing may be achieved by gentle tumbling in a trammel (a rotating screened cylinder). Do not use heavy-duty, rapidly-rotating metal tines.

The main substrate design considerations are safety, substrate weight, and stormwater control. It is essential that the substrate be tested post-mixing, prior to installation, to ensure the parameters do not violate design criteria. Consistent testing procedures with meaningful outcomes are required to promote consistent stormwater management and reduce perceived components of risk.

Post-blending testing of physical characteristics including wet weight and saturated permeability is required for all substrates. If a substrate exceeds the design weight, consult with the structural engineer and the horticultural consultant, as per Section 5.1.7. Remedial action may be required, including supplementing structural support, re-blending substrate, or reducing the installed substrate depth. Modifications to the substrate composition and/or installed depth may affect stormwater retention characteristics and/or the ability to support the intended plant palate.

Table 6 identifies what tests need to be performed, their purpose, methods of testing, and the minimum requirement.

Table 6. Substrate specifications to test post-mixing

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 $\geq$ 90th percentile design storm depth

6.5 Runoff calculations

Extensive living roofs provide storage within the substrate. At present, insufficient quantitative information is available in the international or local literature to develop calculations that account for the dynamic hydrologic behaviour of living roofs including influencing factors such as vegetation species, roof slope, or climatic influences. Consistent with GD02, an event-based design storm approach is currently adopted.

Living roofs must have a minimum of 100 mm substrate depth in new construction and 50 mm substrate depth in a retrofit to be considered as providing stormwater volume or peak flow control, or water quality treatment. The maximum pitch for living roofs to be considered as stormwater retention devices is 15^{o}.

6.5.1 Rainfall retention/runoff volume

For consenting purposes, an extensive living roof may be considered to completely retain a maximum of 30 mm of precipitation. The extent of retention depends primarily on a combination of the substrate's moisture retention properties and finished (settled) depth as described in Section 6.4.1:

- Where the finished depth meets or exceeds the minimum depth calculated by Equation 8, there is no runoff that 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 depth calculated by Equation 8, but media depth of at least 100 mm for new construction and 50 mm for retrofit is provided, there is no runoff that occurs from the living roof for storms with $P < Sw$ as determined by Equation 9. 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.

If/where runoff volumes are required to be calculated for storms larger than 30 mm, calculations shall use an appropriate curve number method, with CN=85.

Rainfall retention occurs only on the portion of the roof that is vegetated, including typical permeable edging used for drainage and media restraint (Section 4.2). For example, if 35% of the total roof area is created as an impervious patio, then only 65% of the roof area is available to retain rainfall. However, a rainwater harvesting system that captures runoff from the patio area to be later used for dry-weather irrigation or toilet flushing would contribute to additional runoff control. At present, a lack of research precludes quantifying managing additional impervious roof area with an extensive living roof, but the potential has been demonstrated and should be further investigated (Fassman-Beck et al. 2013a).

Additional retention credit may be awarded for supplemental moisture retention fabrics or materials that are in direct contact with plant roots and/or the substrate. Some synthetic drainage layers claim capacity for supplemental stormwater storage through cup-like structures. Volume credit is not currently awarded for synthetic drainage layers where cups/retention features are isolated from plant roots and/or substrate, for example by a geotextile. In this case, the water is unlikely accessible for evapotranspiration, thus cups are not readily emptied. In some cases, plant roots may grow into the cups, effectively occupying all potential water storage space.

If/where a continuous simulation is applied, and substrates satisfy minimum requirements of Section 6.4, equation 1 may be used to predict runoff depth. Additional research is necessary to expand the continuous simulation approach to include other site-specific variables such as evapotranspiration rate, plant and substrate characteristics.

6.5.2 Peak Flow Calculations

The Rational Formula may be used to estimate peak flows from living roofs. At present, there is no justification from the international literature to distinguish peak flow control capability between extensive and intensive green roofs. Peak flow mitigation diminishes with increasing rainfall, which is reflected by varying Rational C_p Coefficients with rainfall depth, as per Table 5 for full scale roofs:

$$C = 0.1 \text{ for } P \leq 10 \text{ mm}$$
$$C = 0.2 \text{ for } 15 \leq P < 30 \text{ mm}$$
$$C = 0.3 \text{ for } P \geq 35 \text{ mm}$$

6.5.3 Water Quality

Living roofs that provide a minimum of 100 mm substrate depth for new construction and 50 mm for retrofit construction are considered to be an at-source control for TSS and heavy metals. At-grade treatment may be required in nutrient sensitive catchments, and should be considered on a case-by-case basis.

7.0 Planting Design

7.1 Overview

Plant selection for living roofs should be based on the overall objectives for living roof design (e.g. this guidance places priority on design for stormwater management), an assessment of each individual living roof, and across sections of a roof, as afternoon shade allows a wider range of plants that can be grown. A horticultural consultant should visit the future roof site if possible to assess shading, especially shade between 1 and 4pm as this greatly reduces plant heat stress and allows a wider range of species to be grown. Other features to identify are: areas where wind or water is likely to concentrate (including vents from air conditioning units), aspect, and how the roof will be accessed, and worked on, safely (from plans, if the structure is not built). It is important to assess potential ground-level weeds that may establish on the living roof, the conditions under which they might be a problem, and timing of their dispersal and growth, as this helps design a vegetation establishment practice and maintenance regime that minimises the risk of weed ingression.

Lists of suitable plant species for the Auckland region, many of which have been grown for two to six years on a limited number of Auckland extensive roofs, are given in Appendix A and B and updates TR2009/083 'Landscape and Ecology Values within Stormwater Management' (Lewis et al. 2009). Appendix A and B must be read in conjunction with the plant selection criteria in Section 4.6.2 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. In particular, the plants lists are based on lightweight, free-draining substrates as per Section 4.5, not natural or garden soils.

If weight restrictions dictate that less than 100 mm of substrate is able to be supported, the site has no afternoon shade, and no or minimal irrigation, the plant palate should have at least 50% by area of low-growing, non-weedy Sedum species and succulents (Appendix B). However, as many of these plants could establish on native coastal cliffs and displace native species, non-native species should not be used near such sensitive environments.

Establishing and sustaining a dense (75%) plant cover within 12 to 18 months greatly reduces long-term maintenance costs. A dense plant cover can be successfully established using a range of methods depending on growing season, media fertility and moisture supply, density of planting or initial plant cover, and the plant species used. The methods need to consider likely weeds, timing of weed establishment and weed propagation characteristics. In very weedy sites, or sites where maintenance is extremely expensive, pre-vegetated mats or trays may be cost-effective. Another approach to exclude weeds is including annuals in the first year. Key maintenance activities include weed management and drainage management. Weed management is largely governed by the time taken to achieve a dense, weed resistant plant cover and presence of local weed sources. Rapid cover can be achieved by using a high plant density that includes plants with high growth rates (as well as long-lived plants), and reducing plant stress during establishment (i.e., using hardened-off plants and managing moisture deficit). Understanding these characteristics and relationships will allow the installer to be ahead of the game. The designer should ensure a commitment to maintenance is gained from all the stakeholders before designing the living roof.

Plant placement and selection can influence the risk of plant material entering, or being blown into, edges and drainage outlets. Avoid using species with aggressive roots or taproots (e.g. bamboo) – these are not suitable for a living roof due to the potential for blocking of drainage outlets or damaging the waterproofing layer.

When developing a plant specification, consider the flexibility needed for competitive plant supply against the risk of inappropriate substitution. Identification of specific plant cultivars or provenances generally reduces the range of potential suppliers. It is particularly important to specify hardened-off plants[12] with compact growth forms (especially for woody plants) to avoid the soft, lush-leafed and often upright plants typically produced for ground-level gardens. Such 'garden' plants are highly vulnerable to wind damage and drought. The additional value of hardened-off plants specifically grown for a living roof in low-organic matter growing mixes needs to be recognised.

If using plugs, order 5–10% more plants than required to allow rejection of damaged or out-of-specification plants (Snodgrass and McIntyre 2010). Some Sedums and many succulents tend to be brittle, and have leaves which may separate from the root mass on handling, leaving a non-viable plant. Plants that harbour pests (particularly aphids and root-sucking insects) should be discarded, as treatment with insecticides is generally not possible because insecticides may contaminate stormwater.

It is always useful to consult a plant specialist, for example a horticulturalist or landscape architect when selecting plant species for an extensive roof. Ensure they understand the limitations of substrate depth and roof exposure, and select plants and planting patterns with an acceptable longevity and maintenance requirement, especially with respect to fertilization, irrigation and frequency of visits:

- Post-establishment fertiliser rates should be very low (if at all) to minimize nutrient leaching.
- Irrigation if used, needs to be designed remembering living roof substrates hold little water (are very 'droughty'), do not allow water to 'wick' or spread far, and roofs are windy (spray irrigation will travel). Subsurface irrigation with an underlying moisture retention mat may be preferable, or emitters closely spaced to avoid creating bands of stressed and unstressed vegetation in summer.
- Organic mulches are not generally used on roofs as they can blow away or add weight.
- Low maintenance regimes are particularly suited to roofs that are difficult or expensive to access (e.g., needing a scissor-lift or people with training in working at heights). Some plants require maintenance to maintain aesthetics (e.g. removing dead seed heads of Dianthus and rengarenga), larger tussocks and sedges may require annual trimming or stripping to reduce fire risk. A significant range of low maintenance native plant options include no-mow, native groundcovers Selliera *radicans, Dichondra brevifolia, Leptostigma setulosa*, and some *Leptinella* species. These species typically create a slightly undulating surface. Low-maintenance is enhanced when established roofs are allowed to dry out in summer (without killing the desirable plants!). This is why extensive sedum roofs are very low maintenance once established – most weeds cannot easily establish in the dry substrate with a high plant cover.

The following sections discuss the key decisions that impact the performance and success of plants on living roofs: substrate depth, severity of moisture stress, and method of establishment. One of the greatest risks for successful implementation of extensive living roofs in Auckland is the perception the roofs are 'gardens'

[12] The growing environment of a rooftop is quite harsh. Plants grown inside (e.g. a nursery or green house) should be moved outside at least a few weeks in advance of living roof installation to encourage climate adaptation. If/wherever possible, plant seedlings or plugs should be raised in living roof growing media.

and should be both aesthetically attractive and ‘green’ – ways to address this are discussed. Methods of managing risks of plant failure are identified in 7.7.

7.2 Plant selection to avoid weeds

Avoid selecting plants that can establish new populations from seed or plant fragments blowing off the roof into neighbouring properties or along watercourses because many plants suitable for living roofs are potential weeds, and rooftops are an effective place from which to disperse wind-blown seed. This is particularly important for living roofs on coastlines, cliffs and sub-alpine areas, as these habitats share many similarities with living roofs and native species can be vulnerable to weed invasion, for example *Sedum acre* is a weed in Central Otago. No plants should be used that are in any categories of the Auckland Regional Pest Management Strategy[13] (ARC 2007). Environmental weeds are also listed by Howell (2008). The status of a plant species in NZ can also be checked on two Landcare Research databases of New Zealand naturalised and native plants[14]. Weed control strategies are given by Weedbusters New Zealand[15]. Examples of common plants that should not be used, and their replacement species, are given in Table 7. Lists of living roof plant species from overseas should be screened for potential weeds before final plant selection.

Table 7. Common drought-tolerant plants that should not be used on living roofs, and their replacement species (N = native)

Weed	Replace with
Agapanthus	*Arthropodium cirratum* Rengarenga lily, small cultivars such as ‘Downtown’ and ‘TePuna’ (N), *Astelia banksii* (N),
Sedum acre, S. album	*Crassula sieberana* (semi-annual N) Non-weedy Sedums (Appendix B)
Carpobrotus edulis	*Disphyma australe* NZ iceplant (N), *Senecio serpens*, and *Lampranthus* species
Centranthus ruber, Crassula multiclava	*Allium sativum* ornamental garlic, Bromeliad and Sempervivium species, large-leafed Sedums
Ivy	*Dichondra brevifolia (N), Calystegia soldanella (N), Coprosma acerosa ‘Hawera’(N),*

7.3 Substrate depth

A shallow (50 to 200 mm deep) substrate can only support (anchor) low-growing plants. Taller plants require deeper substrate, which can be provided by mounding over structural supports or as specially

[13] Available from http://www.aucklandcouncil.govt.nz/EN/environmentwaste/pestsdiseases/Pages/ourbiosecurityrole.aspx

[14] Nga Tipu o Aotearoa – New Zealand Plants database http://www.landcareresearch.co.nz/databases/db_details.asp?Database_Collection_ID=3, and Ecological Traits of New Zealand Flora database http://ecotraits.landcareresearch.co.nz/

[15] Available from http://www.weedbusters.co.nz/

constructed troughs below grade (tree pits), and individual plants may need to be anchored. Weiler and Scholz-Barth (2009) and Cantor (2008) contain comprehensive information for designing roof gardens (landscape over structure) with tall vegetation, including trees. Consult with the structural engineer regarding implications for mass loadings.

7.4 Severity of summer moisture stress

Moisture stress is determined by substrate depth, moisture storage, underlying thermal mass, duration and timing of shade, wind exposure (including discharges from air conditioners), and local climate. On sloping roofs, the aspect and location on the roof influence water availability and moisture stress, with stress higher towards the ridgeline and on north-facing aspects and lower near the eaves and south-facing roofs (Figure 18). Moisture stress can be decreased by increasing the water stored in the substrate by:

- Using water retaining materials in discrete layers, e.g., fabric (e.g., coir, wool, felt), mat (e.g., peat, sphagnum, coir) or foam moisture retention layers (Figure 1, Section 2.2.3). This type of layer is placed at the base of the root zone where the held moisture is accessible by plant roots and less vulnerable to evaporation than when placed on the surface. This also protects the retention layer from UV degradation.
- Using water retaining 'pockets' in plastic drainage layers that roots can access
- Adding water-retaining materials to a substrate: organic materials (both temporary and long-lived) and inorganic materials ('fines' and water-absorbing minerals)[16]

Figure 18. The aspect and location on the roof influence water availability and moisture stress. Stress is highest near the ridgeline and on north-facing aspects (left photo) and lower near the eaves and south-facing roofs (right photo).

These increase the design loads if applied across a roof, therefore the loads must be communicated to the structural engineer. Reducing plant water demand (ET) also decreases summer moisture stress, and this can be done by:

- Reducing exposure to sun and reflected glare, to lower peak temperatures and radiation, e.g. placing photovoltaic cells, balustrades, or plant rooms to cast mid-afternoon shade in summer.

[16] Increasing water retention increases the weight of substrates and may also impact permeability; consult chapter 5 for structural loading implications.

- Using baffles to reduce the speed and heat of wind or air conditioner exhaust (Figure 19a). Creating vertical layering of plants using successional and seasonal planting (summer dormant) to decrease evaporative demand and surface temperatures.
- Applying inorganic surface mulches to slow evaporation from the surface, subject to implications for structural mass loading.
- Creating small non-vegetated zones that shed water onto adjacent planted areas, e.g. paths (with lightweight pavers), invertebrate or lizard refuges. The area covered by the pavers or refuges does not use water, and reduce evaporation from the underlying substrate (Figure 19b).

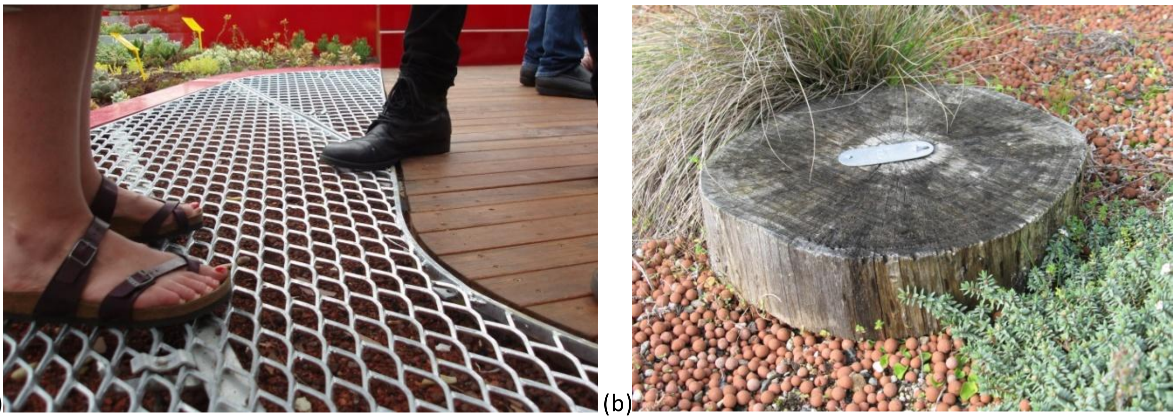
(a) (b)


Figure 19. (a) Exposure to sun is reduced by covering plants with an aluminium grating that also allows concentrated traffic without damaging plants. (b) An insect refuge sheds water onto adjacent planted areas.

Even if the living roof is designed to minimise moisture stresses, it is necessary to consider water supply on the rooftop. Regardless of whether or not a fixed irrigation system will be installed, water supply with adequate pressure is required to allow irrigation during the establishment period and potential periods of extreme or unusual drought. Non potable water, for example, stored roof runoff, is ideal for use in irrigation.

7.5 Balancing aesthetics and maintenance

Where an extensive living roof is viewed "up close", e.g. outside windows or from another level of the same building, achieving aesthetics requires careful species choices; maintenance may be higher (to remove specific weeds and seed heads and possibly irrigate). Extensive living roofs that are rarely seen or visited can achieve moderate to high aesthetic values by using large, simple patterns based on groups of plant species with the same colour and/or texture, using contrasting-coloured, inorganic mulches, or installing a variety of substrate depths (Figure 20). Inorganic mulches are permanent as they do not usually break down, however they usually have a short-term impact as they are covered by plants within 12 months, unless plants are deliberately excluded by using large-diameter mulches (e.g. 50 mm diameter, hence usually heavy), and over a large enough area that prevents plant establishment. Maintaining sharp lines between groups of species requires more maintenance effort, especially when species produce viable seed or spread laterally.

(a) 

(b) 

(c) 

(d) 

Figure 20. Extensive living roofs that can be seen from a distance (from other buildings), can enhance aesthetic values by using simple patterns using contrasting-coloured, or textured inorganic mulches (a, b, c), or a variety of substrate depths, or planting patterns using groups of plants with similar leaf colour and texture (d). Single species blocks are not recommended (c, d).

A dense, self-repairing plant cover is usually highly desirable. Plants can “self repair” by creeping across the surface. Upright, tussock-type plants generally have limited ability to self-repair and need to be inter-planted with groundcovers. Bare or sparsely-vegetated areas are usually only desirable when the main purpose of the roof is enhancement of animal biodiversity, particularly where the target ecosystems are ruderal (urban “wastelands”) or river-beds, because some species of invertebrates, birds and lizards require bare areas for nesting, burrowing or basking. Sparsely-vegetated areas can be created using very thin or gravelly substrate, by with-holding irrigation, and/or using gravel mulches, but using gravelly and/or substrate <50 mm depth is likely to reduce stormwater retention.

7.6 Managing risks of plant failure

Key risks to plant failure, or perception of failure, should be identified. It is particularly important to minimise the risk of plant failure on sites where access is expensive (e.g. no lift to the roof top), there are few similar living roofs in the area, aesthetics are extremely important and/or the plants are expensive or difficult to replace.

Four key strategies reduce the risk of poor plant establishment or growth:

1. Use a variety of species, including plants that spread or seed into gaps, plants of different heights, and long-lived plants. Avoid large (>2 m^2) blocks of just one or two species (Figure 20c);
2. Use a minimum 100 mm depth of substrate (preferably with some localized areas of 150-200 mm) unless sedums will be the dominant plant cover, or the site receives afternoon shade;
3. Include an irrigation system and plant the roof in autumn or winter;
4. Have a clearly-defined maintenance contract, preferably with the living roof supplier, for at least 18 months. The contract will define, at a minimum, what are considered weeds and the minimum plant cover required by 18 months post-installation.

Using a variety of plant species reduces the risk of any single species failing. If weight restrictions dictate that less than 100 mm of substrate is able to be supported, and the client requires a fully-vegetated system with no or minimal irrigation in full sun, the plant palate should include non-weedy Sedum species that have performed consistently on extensive living roofs in Auckland, temperate parts of Europe and the United States, and can enhance establishment of non-Sedum species (either established at the same time, or planted later). Identification of sedums by nurseries is sometimes inconsistent. The risk of inadvertently using *S. acre* and *S. album* can be reduced by checking identification and, if in doubt, avoiding sedums that have similar leaf shape and arrangement (Figure 21).

If some of the specified plants have a relatively short life span, there must be plants on the roof to occupy those spaces when short-lived plants die, and a maintenance strategy that takes into account the potential need to remove dead plants, especially if aesthetics are important. An example where short-lived species are used is the sowing of annual species to boost first-year flowering (aesthetics), exclude weeds and stabilize the living roof surface while slower-growing perennial species establish. *Disphyma australe* has also been a short-lived species that provides flowers and bright green aesthetic for 1-2 years. A similar strategy is important when using long-lived, slower growing species such as bromeliads, orchids, and native epiphytic lilies. These need to be planted with faster-growing, low groundcovers (*Coprosma acerosa* and *Dichondra repens*) that can occupy space in the short to medium term.

If the client demands a 'green' aesthetic, regular summer irrigation will be required, as most extensive roofs will otherwise go dormant (brown) during summer. Operators must be able to access irrigation controls safely, considering best practice, and OSH requirements while working at height. The irrigation system must have adequate pressure and flow. It should be operated based on substrate moisture, not regularly timed intervals.

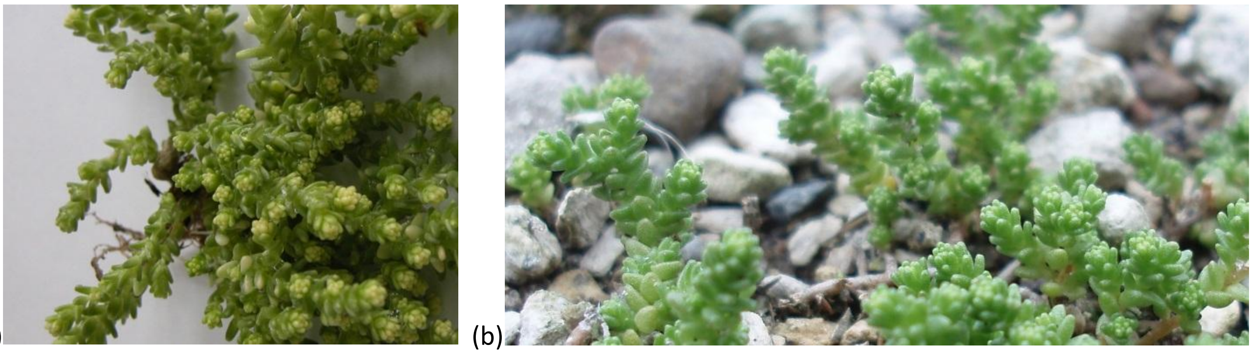

(a) (b)

Figure 21. The risk of inadvertently using (a) *S. acre* and (b) *S. album* can be reduced by avoiding Sedums that have similar leaf shape and arrangement

8.0 Design Checklist

Table 8 summarizes the minimum steps in the design process, and provides quick reference to sections in this technical report where relevant information may be found. Successful living roof projects incorporate into the design process how the system should be constructed and maintained.

Table 8. Design elements checklist

Design Element	Reference Section
1. Assess site suitability	
Structural capacity	5.1
Safety issues	5
Access for construction/installation and long-term maintenance	3.2, 5.2
Location and number of protrusions and perforations	3.2
Other conditions: e.g. slope, mechanical services, exposure	3.2
2. Determine and prioritize design objectives	
Primary objective: retain the 85th -95th percentile design storm event	6.4,6.5
Secondary objective: establish and maintain dense plant cover	7
Tertiary objective(s): e.g. visual amenity, glare reduction, biodiversity, energy demand mitigation, water harvesting	2.4
3. Determine substrate composition and characteristics (esp. PAW and weight) based on available materials	4.5,6.4
4. Determine minimum final substrate depth	6.4.1
Apply Equations 8 & 9	6.4.1
Verify loadings with structural engineer	5.1.7
• If additional structural capacity is available, increase substrate depth (max. 150-200 mm) to enhance plant viability and long term health.	
• If minimum substrate depth across roof cannot be met:	
o Revise substrate composition	4.5
o Provide supplemental moisture storage techniques	7.4, 7.6
o Provide permanent irrigation system operated according to substrate moisture content/plant needs	7.6
o Reduce individual plant competition for water	7
o Consider (last resort) an alternative retention objective (smaller storm, less retention credit), potentially in combination with ground-level stormwater controls. Communicate changes to horticultural consultant.	

5.	**Create planting design in conjunction with or by horticultural consultant**	
	Select a variety plant species based on site conditions, substrate characteristics and depth, and likely presence/absence of irrigation	4.6, 7, App. A and B
	Identify method(s) of plant establishment, and installation density (if applicable)	11.2
	Establish likely maintenance requirements (activities and frequency) during establishment and once full cover is achieved.	7, 11.2, 11.3
	Establish plant parameters for defects liability/project sign-off	7
	Design supplemental moisture system(s), if needed, as determined through consultation.	7.4
	Establish terms of maintenance contract	7, 11.3
6.	**Select waterproofing system and leak detection testing regime**	4.1, 6.1
7.	**Select horizontal drainage layer**	4.4, 6.3
	Verify it can withstand imposed loads and carry anticipated flow without ponding within the substrate.	
	Coordinate horizontal drainage design with vertical drainage design to comply with all relevant building codes (may require consultation with architect or structural engineer)	
8.	**Select root barrier**	6.2
9.	**Identify permeable edging materials for living roof perimeter and around any protrusions or perforations**	4.2,5.2
10.	**Provide additional safety elements (for people and vegetation)**	
	Secure access and safe working environment for maintenance of living roof and other building services	3.2, 5.3
	Public gatherings (if/where needed)	3.2
11.	**Final checks**	
	Substrate depth meets or exceeds minimum requirements for rainfall retention	6.4
	Protocols established for ensuring waterproofing membrane and vegetation protection for anyone accessing the living roof	4.1
	Plant species list, installation method, and maintenance plan feasibility verified by horticultural consultant	7, 11
	System weight (all components) within allowable loading verified by structural engineer	5.2
	Overall review for safety for anyone accessing the roof	3.2, 5.3

9.0 Substrate Design Example

9.1 New build

A 250 m^2 living roof is to be designed for a new high-rise commercial building is to be constructed in Pakuranga for on-site retention of the 90^{th} percentile design storm event.

An initial meeting with the structural engineer and architect establish that lift access will be brought to the roof level to aid in long-term maintenance. HVAC and other building services are to be clustered along the northern side of the roof, adjacent to the lift to prevent maintenance crews from having to walk across the living roof. A 500 mm width non-greened walkway will provide a separation between the lift, HVAC units and the vegetation. Consultation with the future property management team identifies a staging area between the lift and the HVAC units to be able to temporarily store tools and parts needed to work on services without providing a separate walkway to protect the vegetation. The location along the northern side will provide limited shading from afternoon sun, at least for plants nearest to the services.

Casual users will not have physical access to the roof, but it will be visible from neighbouring buildings. Structurally the roof must support maintenance crews in addition to the components of the living roof. Balustrades will be provided to at least the minimum OSH requirement such that maintenance workers do not require specialized training for "working at height".

For the substrate composition, two alternatives are considered, each with a blend of pumice, zeolite, and organic matter based on the Tamaki zeolite and the Auckland Botanic Gardens substrate (Table 2). Laboratory testing quantifies plant available water at ~29% for the Tamaki zeolite. Data is not available for the Auckland Botanic Gardens mix, but based on similar composition, and a greater maximum water holding capacity, it is assumed that at least the same PAW would be provided.

Substrate Depth

Shamseldin (2010) identifies the 90^{th} percentile design storm event as 28.2 mm for Pakuranga. The minimum substrate depth to completely retain this event is determined from equation 8:

$$D_{lr} \geq \frac{DSD}{PAW} = \frac{28.2}{0.29} = 97\text{mm} \qquad \text{Equation 10}$$

Where

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

DSD = design storm depth (28.2 mm for Papakura [Shamseldin 2010])

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

The required depth to fully retain the 90^{th} percentile design storm event is slightly less than the minimum depth required by this guidance (100 mm); thus 100 mm will be used.

Sample Substrate Testing

Samples of the components are obtained from the suppliers. ASTM E2396-11, E2397-11, and E2399-11 tests for physical characteristics are summarized in Table 9. Both blends satisfy minimum requirements, but Blend 2 provides three minor advantages:

- greater water holding capacity will likely translate to greater stormwater retention (despite PAW data not being available at the decision-making time)
- higher permeability provides a greater safety factor, thus peace-of-mind against unanticipated abuse over the long-term
- a single supplier has been identified for all components, thus saving costs on materials' supply and transport.

Data from substrate 2 and the required depth are shared with the structural engineer for determining the roof's structural capacity as per Chapter 5. After consideration of loadings, the structural engineer determines that substrate may be installed to an average depth of 150 mm within the estimated budget, if the synthetic drainage layer is installed "cups down". The allowable depth exceeds requirements for stormwater management, but will give the plant specialist a wider palate from which to select, which the client considers important because of the roof's visibility.

Table 9. Data shared with structural engineer

SUBSTRATE CHARACTERISTICS						Synthetic Drainage Layer		Mature plants (kg m^{-2})
Candidate Blend*	Dry Bulk Density (kg m^{-3})	Maximum Water Holding Capacity (%)	Wet Density (kg m^{-3})	Saturated Density (kg m^{-3})	Saturated Permeability (mm h^{-1})	"cups down" (kg m^{-2})	"cups up" (kg m^{-2})	
1	537	63	1150	1320	1584	3.6	6.1	17
2	365	75	1095	1341	2880			

*Substrate composition:

1.70% 4-10 mm pumice; 10% zeolite ≤ 3 mm; 15% pine bark fines + mushroom compost; 5% sphagnum peak

2.80% 1-7 mm pumice; 5% 1-3 mm zeolite; 10% CAN bark fines A grade; 5% coco-fibre coir "classic"

Materials’ Specification

Finished depth:	150	mm	
Installation depth:	165	mm	(10% greater than finished depth)
Roof area to be greened:	250	m^2	
Minimum volume:	41.25	m^3	(based on installation depth)

Table 10. Design example: component volume specification for new build

Individual Components	Minimum Volume (m^3)	15% Mixing Consolidation Allowance (m^3)	Total Materials (m^3)
80% 1-7 pumice	33	5.0	38.0
5% 1-3 mm zeolite	2.1	0.3	2.4
10% CAN bark fines A grade	4.1	0.6	4.7
5% coco-fibre coir “classic”	2.1	0.3	2.4

Post-blend Testing

Post-blending, pre-installation testing indicates the substrate is slightly heavier with permeability of 2000 mm h^{-1}. As permeability still exceeds minimum requirements, the structural engineer is consulted regarding the loading. Two solutions are considered:

1. Reject the material. Consult with the supplier to investigate the source handling and blending. Re-blend and re-test.

2. Compromise on the substrate depth –e.g. reduce depth over the majority of the roof to the minimum allowable depth (100 mm). Create unplanted mounds over load-bearing columns in several locations, to a depth of 150 mm for supplemental moisture storage and to promote biodiversity potential.

Final Design

Solution 2 is selected since reducing the substrate depth will not compromise stormwater design objectives, while also reducing cost and eliminating delays compared to Solution 1. The horticultural consultant is also informed of the change, in case the plant palate needs to be modified. As enough material was originally specified for 150 mm finished depth, adequate substrate will be available for creating the mounds.

Additional fertilizer may be required for initial plant establishment. Rates and formulation depend on organic components of the substrate and may be determined through substrate testing for nutrient availability.

9.2 Retrofit

It has been determined that 35 mm of rainfall must be retained on an Auckland CBD site to alleviate pressure on the storm sewer network. Blend 1 is considered (Table 9). A living roof may only be credited for retaining a maximum of 30 mm of rainfall. To fully retain a 30 mm design storm, equation 11 yields a minimum substrate depth of 103 mm:

$$D_{lr} \geq \frac{DSD}{PAW} = \frac{30}{0.29} = 103\text{mm}$$ Equation 11

The structural engineer indicates that a maximum depth (D_{max}) of 60 mm may be supported on the roof, but also allows for supplemental moisture mat retention (MR) of 5 mm of water. The amount of rainfall anticipated to be stored by the living roof system is 22.4 mm, as given by equation 12 (based on equation 9):

$$S_w = (D_{max} \times PAW) + MR$$ Equation 12

$$S_w = (60\text{ mm})(0.29) + 5\text{ mm} = 22.4\text{ mm}$$

To fully satisfy stormwater management objectives, 35.0 mm - 22.4 mm = 12.6 mm of runoff must be managed using a ground-level device.

10.0 Planting Design Examples

10.1 Bright green, mossy look

A residential client wants a bright green, mossy look for the lower storey of a private dwelling overlooked from a living area (Figure 22). The roof can support a 100 mm deep pumice-based substrate and has a 4° slope. It faces south-east and receives light afternoon shade cast from a high-pruned, eucalyptus tree.

A green colour is required throughout the year, so the roof will be able to be irrigated in summer and the roof weeded quarterly to remove invading grasses and legumes; leaves and twigs from the tree will be removed quarterly, and gutters kept free of leaf debris. Over 75% plant cover is required after 18 months.

Plant selection: a randomly-placed mix of 7 very low-growing (<100 mm height), native species that are all green, but have a range of shade and drought tolerance: *Leptostigma setulosa, Selliera radicans, Coprosma* 'Hawera', *Scleranthus uniflorus* and *S. biformis, Dichondra repens* (sunniest areas), *Acaena microphylla* (green bidibid, mid-shade areas) and *Leptinella dioeca* (the latter two species have feathery leaves). *Lobelia (Pratia) angulata* and *Selliera radicans* have white, star-shaped flowers. *Scleranthus biformis* will provide fast cover but may die out in patches over time; however, the other groundcovers will fill these gaps. All the plants can be walked on without damage, so no paths are required for maintenance. The roof will be established using between 12 and 16 plant plugs per m^2 (plugs 60-80 mm deep and 30-40 mm diameter) and clusters of 500 ml pots of *Scleranthus,* grown in a low organic matter pumice sand.

Figure 22. Mossy NZ native roof in afternoon shade Clockwise from top left*: Acaena microphylla, Lobelia (Pratia) angulata, Leptostigma setulosa*; Auckland 'Chicken shed' with mix of these species and *Coprosma* 'Hawera', *Leptinella dioeca, Pyrossia eleagnifolia* and *Gunnera aff. monoica* (purple leaves)

10.2 Colourful palate

A commercial client wants a colourful palate for near-flat living roof (2° slope) that has 100 mm pumice-based substrate depth, receives full sun and will not be walked on. The roof will receive very little irrigation and minimal maintenance, and needs to look impressive for the building opening at the completion of construction. Construction schedule limitations mean the roof will have only two to five weeks of growth before the opening.

A pre-grown modular living roof is proposed with a mixture of non-native sedums and succulent plants. Red splashes created using using clumps of red *Bromeliads* and red-edged *Sempervivium* divisions (both expensive, \$3 to \$6 each) under-planted with *Sedum x rubroctinctum, S. forsterium, S. spurium* 'Dragons Blood' and ' Voodoo' and *S. coccineum* (all inexpensive, \$1.50–\$2.50 each) (Figure 23 and 24); green/grey matrix provided by iceplants (*Disphyma australe* – New Zealand iceplant, *Lampranthus aurantiacus* and *Delosperma cooperi*) that flower in early summer (white, red or pink flowers) under planted with green/grey sedums including *S. ternatum* (precocious small white flowers), *S. dasphyllum, S. oreganum, S. rubroctinctum, S. rupestre, S. ogon S. spathuifolium, S. azore* and *S.reflexum*, with additional seasonal interest in these areas created by planting native *Microtis* (onion orchid), crocus (*Crocus sativum*) and ornamental garlic (*Allium sativum,* pink flowers). Sedums will also flower (white, yellow, pink or red). Large, tubular-leafed *Senecio serpens* can also provide blocks of textural and colour contrast within the grey-green area point of interest, but these, and the larger *Sempervivium* and *Echeveria* should not cover more than about 10% of the roof area unless an additional weight allowance is made, as they are much heavier than the small Sedums. Narrow 400 mm wide paths of coarse pumice that wind across the roof allow weeding without damaging the *Bromeliads, Sempervivium,* and larger, brittle *Sedums*. The paths also act as backup 'drains' across the slope of the roof.

Figure 23. Kingsland Railway Station toilets, Auckland City (June 2012): A colourful low-maintenance roof with 'kiwi' of Mondo grass on deeper substrate surrounded by Sedums species including *S.spurium* (red), *S. rupestre* (grey), *S. ternatum* (green) and S. *mexicanum* (yellow)

Figure 24. A selection of colourful non-native plants, clockwise from top left: *S. ternatum, Stachys byzantina, S. spurium* 'Dragons blood', *S. oreganum, Bromeliad* 'Red of Rio', *Sempervivium* cultivar

10.3 Native plant demonstration project

A council client wants a native plant roof for 5° and 8° pitched roofs over a public toilet in the city centre adjacent to a playground and extensive rain gardens planted in native sedges and 'spikey' groundcovers; a mixture of native species are required that complement the rain gardens; some seasonal colour desirable and 150 mm substrate depth (Figure 25). Only part of the roof is viewable from the ground; maintenance will be quarterly from ladders, and irrigation through summer is available.

Planting dominated by grey-green native grasses and lillies, using waves of *Festuca mathewsii* and *Poa cita* (tussocks), and *Apodasmia similis* and *Fincia nodosa*, with the occasional *Astelia banksii*, with a stabilising groundcover of purple *Acaena microphylla* (bidibid), *Leptinella* 'Platt's Black' and red *Sedums*. Between the grassy waves are green lenses of *Hebe obtusata* and *Athropodium* (rengarenga), underplanted with *Coprosma* 'hawera', *Dichondra repens, Leptostigma setulosa* and *Calystegia soldanella* (large white/pale pink flowers, deciduous). Native hibiscus and *Senecio lautus* are seeded for short-term colour (yellow flowers, will eventually die out as cover increases) until the *Hebe*, rengarenga and *Calystegia* grow larger (white flowers). The tussocks are likely to spread across the roof over a three to five year period.

Figure 25. Spikey native roof, Auckland Botanic Gardens (April 2012) Plants along the top are, from Left to Right: Pimelea prostrata with Libertia peregrinans, Acaena microphylla 'pururea' and Astelia banksii

11.0 Construction, Operation, and Maintenance

Construction, operation, and maintenance guidance for living roofs for stormwater control is generally provided by Healy et al. (2010a, 2010b). Supplemental information, especially pertaining to the vegetation is provided herein and intended as a companion document.

11.1 Substrate installation

The two primary options available for installing substrate are: use of a crane or mechanical lifting device, or to blow or spray the substrate to height.

Cranes may be on-site for new construction. As the building shell is often the first task for completion, a living roof may be able to be installed before the end of the project, thus allowing time for plants to become established while the building interior is completed. For retrofit installations, the crane must be able to get close enough to the building. During construction of the UoA living roof, the limiting factor in specifying crane size was reach, rather than lift (weight) capacity in order to avoid damage to street trees (Fassman et al. 2010a).

When blowing or spraying substrate to height, the length of the hose may limit the height to which substrate can be blown. Contingency costs should be incorporated for blower installation, as substrate may coat building facades and thus require post-installation cleaning (Roehr 2004). Operation of blowers may be compromised in cold weather, as the system may clog (in which case bag hoists would be a preferred option).

Extensive living roof substrates should be hand-spread using rakes (with small tines so as not to break the geotextile) or other methods which do not promote compaction. The substrate materials will settle due to planting, initial irrigation, and weeding activities (which require limited foot traffic), self-weight, and plant mass. It is recommended to anticipate compaction of 10%; substrate depth should be increased accordingly during installation. When installing substrate on sloped roofs, install the substrate from the base of the slope back towards the ridge to prevent slippage.

11.2 Vegetation specification and installation

Success of planting is influenced by the extent of stress plants receive during establishment. In Auckland the ideal planting time is from mid-autumn to early-spring (April to September). If plants are established using seed or cuttings, summer planting should be avoided. If substrate must be installed in summer, outcomes are likely to be enhanced by covering the substrate with an erosion control netting or mat, and delaying seeding or planting until April. Outside Auckland, in areas where frost, snow or frozen substrates could occur, planting in winter is best avoided. However the feasibility of delaying planting depends on building configuration and availability of irrigation – large roofs and multi-story buildings without direct roof access from the lift generally need to be planted when cranes are available.

In terms of construction sequencing, containerised plants or pre-grown mats will take two to 12 months to be grown (the longer times generally for growing plants from seed) and may only have limited viability before becoming root-bound or over-mature. Plant suppliers therefore need to be kept informed of timing, construction sequencing, particularly within a month of delivery, to allow adequate hardening off[17] and timely pest control. Once plants are delivered to site, they should be planted within several days to reduce stress. Plants at ground level are at risk of damage from drought stress, pest invasion, and cannot be stored for more than a few days without adequate light or air circulation, particularly when stacked in pallets. Plants must therefore arrive on site just before planting.

In New Zealand, most roofs are established using plugs or root trainers, however, four other methods are also used overseas: seed, cuttings, pre-grown mats, and pre-planted modules.

11.2.1 Plugs and Root Trainers

Planting using plugs or root trainers offers the most design control in terms of visual effect. Most ground covers should be planted at 15–25 plugs m^{-2}. Higher densities are used where growth rates are expected to be slower, or the maintenance period is required to be shorter. Pot depth should be shallower than the total substrate depth to ensure plants can be planted deeply to increase wind stability. Large plants (e.g. 1 litre pots) and mature plants should generally not be used, except as sparse or clustered planting for instant visual impact as they do not establish as readily. Plants are best established in a juvenile state when they are most adaptable (Snodgrass and McIntyre 2010).

Most propagation mixes are highly organic and susceptible to shrinkage both when dry, and over time; coir-based mix is an exception. When cores shrink away from the living roof substrate, plants can be stressed and can be blown out. Ordering plants grown in sandy, low organic-content living roof substrates reduces this risk. Plants should have well-developed root systems and be hardened off for several weeks before planting on the roof by being exposed outdoors to full sun. Woody shrubs should branch at ground level to reduce the potential for collar rock and wind throw when planted (Figure 26) – such forms need to be specified in the plant order. Within a plant species, cultivars will vary in drought and wind tolerance – select the most tolerant forms and populations.

Initial plantings can be held in place using erosion netting or fabric (Figure 7). These can be biodegradable, e.g. coir and wool or permanent, e.g. some plastics and metal lattices. Straight-sided or gently tapering plugs should be specified as this shape is resistant to wind; bowl-shaped or pyramid-shaped plugs should be avoided as they are prone to being blown out, and the roots, being close to the surface, lose moisture quickly.

Trays of plants may be delivered to the roof stacked in pallets and in a relatively dry state to reduce their weight. Plugs should be visually inspected before planting so any weeds, pests and out-of-specification plants can be removed. This process should occur on a groundsheet on the ground or roof to minimise the movement of unwanted plants and insects to planted areas. The underside of trays and gap between potting mix and pot are common places for invertebrates (insects and slugs) to hide.

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[17] The growing environment of a rooftop is quite harsh. Plants grown inside (e.g. a nursery or green house) should be moved outside at least a few weeks in advance of living roof installation to encourage climate adaptation. If/wherever possible, plant seedlings or plugs should be raised in living roof substrate.

11.2.2 Cuttings

Sedum living roofs are commonly established in North America by spreading cuttings during favourable seasons at a density of about 12 to 25 kg 100 m^{-2} (Snodgrass and McIntyre 2010). Many sedum species will readily sprout from stem segments or leaves. Sedum cuttings do not need to be inserted into the substrate, but they should be held down until plants take root using erosion mat, netting or tacifier (sticky substance). Under Auckland autumn conditions, Sedum cuttings root in two to four weeks and remain viable for several months; temporary irrigation increases the likelihood of good establishment.

Some native NZ plants can be established from rooted cuttings and divisions planted into the surface. Rooted cuttings have been used to successfully establish *Coprosma* (*C. acerosa* incl. 'Hawera') and *Libertia peregrinans*. *Hebes* and *Disphyma* (iceplants) can also be readily-established from rooted cuttings at favourable times of the year, while some *Arthropodiums, Phormiums* and tussocks are readily divided; however, few roofs have used these techniques to establish native plants on living roofs to date. Bromeliads and many succulents can also be established using partly-rooted 'pups' from adult plants.

11.2.3 Seed, straw and bulbs

Living roofs can be vegetated by broadcasting seed, or hydroseeding seeds, moss and plant fragments (Figure 26). Conventional pasture seeding methods were likely used to establish grass covers on some Auckland reservoirs. In the United States few roofs are established solely with seed because the longer establishment period increases the risk of weed establishment and erosion (Snodgrass and McIntyre 2010). Supplemental seeding, of both annual and perennial plants is used in the United Kingdom, using local experience with establishing species-rich, flowering meadows (Dunnett and Kingsbury 2008).

Figure 26. Living roofs can be vegetated by broadcasting seed – the spring-flowering annuals on this roof were sown in autumn (photo taken in September)

Small, summer-dormant bulbs (native onion orchid, wild garlic, chives, South African sun-star) can be established as dormant or just-emerging plants, and provide seasonal colour, as do annual species, including New Zealand hibiscus, bluebell and daisy (*Senecio lautus*). Small, early-flowering, summer-dormant bulbs in the onion (*Allium*), tulip (*Tulipa*), and Iris genera are used in Europe and North America to add seasonal interest and height to extensive living roofs (Snodgrass and Snodgrass 2006). Dunnett and Kingsbury (2008) recommend planting bulbs 'in small groups combined with plants that cover the ground throughout the year' to avoid large, unsightly areas of dead leaves in late summer.

A sparse cover of annuals achieved using a 1 g m^{-2} sowing rate (Gedge and Little 2008) can be useful to provide short-term cover and colour while perennial plants are establishing.

Pre-seeded biodegradable coir (coconut fibre) and wool-based blankets have also become available in New Zealand over the last few years. These products have been used primarily for establishing grasses in erosion-prone areas. Blankets must be securely fixed, to avoid being blown from the roof, as traditional pegs cannot be used without potential damage to the waterproofing layer.

In Switzerland and London, on sites where the design objective is a local ruderal ('wasteland or river-gravels') or meadow flora and insect fauna, substrates may be left uncovered at ground level to naturally 'inoculate' with local seeds and non-flying insects. Storing substrate on pallets that are then craned onto the roof minimises disturbance to invertebrates (Gedge 2003). Hay containing seed heads, spread at about 20 mm depth, is also used on some projects (Gedge and Little 2008). Both approaches require vigilant, informed weeding and control of fertility to minimise establishment of very aggressive species (Snodgrass and McIntyre 2010). In urban and rural New Zealand, this approach is unlikely to be favour establishment of native species.

11.2.4 Pre-grown mat, sod and containers

Pre-grown mat, sod and modular systems offer an instantaneous effect upon installation and are particularly suited to roofs with high potential for wind erosion or water erosion (due to slope). Spectacular examples of use of Sedum mats are presented by Cantor (2008), and include construction of Copenhagen airport's domed roof.

Some New Zealand nurseries can supply pre-grown mats that are rolled out like ready lawn or placed together like carpet tiles (Figure 27). Such mats require 4–8 months to grow before installation. Mats and sods are often rolled up for transport and installation (Figure 27b, c). In this form plant roots are exposed and must be protected from drying out (wind and sunshine); they also need to be protected from sunlight to minimise the risk of 'composting'. Effective coordination between the mat or sod supplier, living roof installation team and main building contractor is therefore required to avoid storage by ensuring lifting equipment is available (e.g. a crane or forklift).

Sods should be grown in the living roof substrate to ensure consistency with roof loading and infiltration rate specifications. Irrigation is necessary until roots grow into underlying substrate. If mats are prone to shrinkage on drying, irrigation is needed to avoid exposing underlying roof components (Snodgrass and McIntyre 2010). Living roofs could be designed to receive sod cut from suitable native ecosystems with shallow rooting depths, if hydrological conditions and weight-loading can be matched to natural levels.

Figure 27. Pre-grown mat: (a) establishment; (b) arrival on-site (c) installation; (d) instantaneous effect

Modular systems may be “pre-grown” or “pre-planted”. In the former, modules should be delivered fully or near-fully established vegetation. In the latter, modules may be populated with cuttings or plugs, therefore requiring significant additional attention and time for establishment.

Biosecurity checks to remove potential weeds and particularly slugs and snails, ants and introduced skinks is particularly important for pre-grown systems. On the UoA living roof, a Sedum mat was the source of some ‘weeds’ (narrow leaf plantain and dandelion), the beneficial earthworm population, and four slug and snail species (all non-native) (Fassman et al. 2010a). Insects or their eggs are often found down the sides of plant pots and under plant trays. Remove plants from pots before taking them up to the roof as a simple method of reducing unwanted pests reaching the roof.

11.3 Vegetation operation and maintenance

11.3.1 Establishment period

Plants should be soaked before, and watered immediately following installation, then watered for the first few weeks or months unless ample rainfall occurs. After the first summer, irrigation is dependent on the site conditions, plant species chosen, substrate moisture holding, and aesthetic requirements.

Most extensive living roof installations take 12–18 months to establish a high vegetative cover (>75%) and this is the critical time for maintenance as it impacts the long-term success of the roof (Snodgrass and Snodgrass 2006). A ‘construct and maintain’ contract with a living roof construction company or landscaping firm with a minimum 18 month duration (two growing seasons) and budget for bi-monthly visits during the first 6 months, then quarterly visits, will also help early identification and correction of potential problems. Visits should be timed to enable removal of unwanted plants before they set seed. Areas with poor plant establishment or evidence of erosion need to be identified early, and amended. Erosion netting or stone mulch can be used with plants to reduce erosion. The most common problem is failure to remove invasive weeds before they seed. The most common invasive and visually intrusive ‘weeds’ in Auckland living roofs are legumes (especially clovers, *Trifolium*), flatweeds (cats ear, plantain and dandelion), fleabane (*Conyza albida*), spurges (*Euphorbia*), sowthistle (*Sonchus spp.*), and daisies (*Senecio*). Adventive legumes (*Trifolium repens* white clover, *Lotus pedunculatus* and *L. suaveolens*, hairy trefoil among others) were consistently weeded from the living roofs designed for stormwater management that were studied in Auckland (Fassman et al. 2010a, 2010b). Other adventive plants were not controlled; these generally had an upright growth form and were annuals, for example *Senecio vulgaris*, *Epilobium ciliatum*, *Euphorbia peplus* and the cosmopolitan native species *Pseudognaphalium luteoalbum*.

A maintenance contract is ideally complemented by an on-site person (e.g., the building manager) who will observe the roof on a fortnightly basis during summer, depending on substrate water holding capacity, as timing of any supplementary irrigation can be important to ensure plant survival, and avoid costly plant losses. Ensure that the building operator knows when and how to operate irrigation if it is not included in the maintenance contract, especially if an automatic irrigation system is installed.

11.3.2 Ongoing maintenance

Many of the maintenance requirements are similar to any landscaping project (Weiler and Schloz-Barth 2009). Typical on-going maintenance activities for extensive living roofs include weeding and other vegetation management (cutting). Specific living roof maintenance includes inspection and clearing of gutters and other drainage points in the roof. Activities undertaken and lessons learned from the UoA and Waitakere living roofs are described in Fassman et al. (2010b).

A weedy roof is a common reason for public perception of a 'failed' living roof (Weiler and Scholz-Barth 2009). However, what is a 'weed' depends on the objectives of the living roof, and on the potential for plants to establish on the living roof, or escape from the roof into neighbouring areas. The plant species composition of nearly all roofs changes over time; in Auckland, as in Europe, thicker roofs are likely to become dominated by grasses that die off in summer without regular removal and/or adequate drought stress.

On all roofs, 'weeds' include plants with aggressive root systems or high biomass that may impact waterproofing layers either by root invasion, or by exposure of the drainage mat when they topple over. Most tree species will fail to establish on extensive living roofs, as they die in summer, however those that are not dead by autumn will need removing. On the Auckland research roofs aggressive weed species include pampas (*Cortaderia* species), *Cotoneaster* and butterfly bush (*Buddleja davidii*). The WCC living roof studied in Fassman et al. (2010b) is adjacent to a source of native shrubland species. Self-established, native plants that were removed due to stability concerns include karamu (*Coprosma robusta*), cabbage tree (*Cordyline australis*) and kanuka (*Kunzea ericoides*). An annual early-autumn visit is usually adequate to ensure removal of these weeds before they set seed or become a risk to the roof.

Roofs designed specifically for stormwater mitigation, not aesthetics, can allow a wide range of adventive species to establish (Figure 28). On these roofs weeding focuses on removing only aggressive adventive species that have the potential to smother planted vegetation, then die to leave large bare patches on the roofs (e.g. legumes). The bare patches reduce stormwater mitigation.

Figure 28. Roofs designed specifically for stormwater mitigation, not aesthetics, can allow a wide range of adventive species to establish

Visits may need to be as frequent as two-monthly during the growing season (typically April to November) if significant bare areas suitable for weed establishment are present. Required weeding effort decreases as vegetation cover increases, and the roof becomes established enough to be subjected to the drought-stress that inhibits establishment of adventive plants. Removal of plants with stolons that root at each node, or underground rhizomes, e.g. *Trifolium repens* and kikuyu grass can be very time consuming once they are established.

The highest weeding intensity is required for young 'roof gardens' with areas of bare substrate where there is low tolerance for any adventive plants. Some roofs have vegetation that requires removal of dead flower and seed stalks, or regular biomass removal (e.g. annual mowing) to maintain high aesthetic values or reduce potential fuel-loads in fire-prone areas. In England, annual mowing is used to enhance the plant diversity in meadow roofs by reducing the competition of grasses with orchids, herbs and annual species.

Testing of substrate chemistry and visual assessment of plant growth helps identify if fertilisation is required. For stormwater living roofs, fertiliser addition is strongly discouraged after establishment to prevent leaching of nutrients into runoff. Signage can be used to educate viewers about managing stormwater with living roofs. If used at all, fertilisation should generally be restricted to a low rate of slow-release fertiliser low in phosphorus. Fertiliser is only applied when substrate moisture and temperature mean plants are actively growing, so able to use the nutrients. Supplemental fertilisation of the UoA roof was restricted to a nine-month 13-5.7-10.8 (N-P-K) fertiliser applied at 25 g m^{-2} applied in spring of the second and third years (Fassman et al. 2010a).

Most herbicides, fungicides (particularly copper), and insecticides (including slug and snail poisons) should be avoided to prevent contaminating stormwater. Roof tops are not suited to spray application due to the windy, elevated nature of rooftops; adopt practices that avoid drift (e.g. weed wands, wicks or brushes). Some chemicals have the potential to hasten degradation of the roof membrane.

All activities occurring on a living roof, whether associated with vegetation management or not, must be done by people who are fully aware of the need to protect and maintain the integrity of the plants, drainage, and waterproofing. People should be kept off vegetation as much as possible; paths should be defined around plant rooms and key access points. The use of 200 to 400 mm high, grated walkways allows vegetation to grow undamaged by foot traffic. Cutting or sharp tools, equipment, or footwear should never come into contact with the waterproofing membrane. Ideally, sharp items should not be allowed onto the roof at all and any cutting done off the roof.

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Appendix A NZ Native Plants Table

Native New Zealand species for living roofs with 100 to 200 mm media depth in the Auckland Region

[1] Proof of performance is based on the number of roofs and length of time the species has been grown on roofs. 'i' indicates the species should be irrigated over summer if it forms >10% of the roof and afternoon shade is not available, at 100 mm substrate depths. Only plants observed successfully growing on roofs can be given an 'a' rating

[2] Height and spread are strongly influenced by media fertility and water availablity. Most plants should have the bulk of their leaves <300 mm height on exposed roofs to reduce the potential for wind-throw

Genus	species	Common name	Plant Form	PROVEN [1]	HEIGHT [2]	SPREAD [2]	SUN	SEMI	SHADE	Notes
Acaena	species	Piripiri	Ground Cover	bi	0.15	1	Y	Y	Y	Acaena microphylla (purple and green forms) is most common used. Requires afternoon shade or irrigation. Attractive spikey seed head balls. Fast growing.
Anaphaloides	bellidiodes	Everlasting flower	Ground Cover	ci	0.15	0.5	Y	Y	N	Limited success to date in Auckland but not trialled with irrigation. White conspicious daisies flower in summer. Main stems are prostrate.
Apodasmia	similis	Oioi, Jointed Rush	Rush-like	b	0.6	0.5	Y	Y	N	Select <300 mm tall forms from dry areas like rock outcrops; dense but spreads slowly from rhizomes
Arthropodium	species	Rengarenga	Lily & Iris-like	a	0.6	0.5	Y	Y	Y	Select shortest growth forms from driest rock oputcrops; Compact rengarenga cultivars include 'Downtown' and 'Te Puna'. High aesthetic values with strap-like grey-green leaves and mass flowering. Dead flower spikes may require removal to maintain amenity. Frost tender and coastal.
Austrostipa	stipoides	Buggar grass	Tussock	b	0.7	0.5	Y	Y	N	Plants selected from dry coastal cliffs are performing well on Botanic gardens sloped roof with some irrigation
Astelia	banksii	Wharawhara	Lily & Iris-like	a	0.6	0.9	Y	Y	N	Highly drought tolerant once established. Fine silver flax-like leaves. Coastal. Clump-forming. Slow growing.
Blechnum	penna-marina	Alpine hard fern	Fern	c	0.2	1	Y	Y	Y	Forms a dense mat. Hardy in both sun and shade. Not trialled on living roofs yet.
Calystegia	soldanella	Shore bindweed	Ground Cover	bi	0.1	2	Y	N	N	Deciduous, winter-dormant coastal vine with large bright green leaves and large mauve to pink flowers in summer. Needs to grow tuber to become resilent to drought
Carex	pumila	Blue dune sedge	Rush-like	b	0.3	1.5	Y	N	N	Rhizome spreading sand sedge.
Carex	raotest	Orange dune sedge	Rush-like	c	0.6	1	Y	Y	Y	Bright green-orange coastal tussock.
Centella	uniflora		Ground Cover	c	0.1	1	Y	Y	Y	Fast growing with adequate moisture.. Forms weed-supressing mats. Not trialled on living roofs yet.
Coprosma	acerosa	Coastal coprosma	Ground Cover	a	0.4	1	Y	Y	N	Sprawling coastal plant with small thin leaves on wiry branches. Highly variable form. Specify dense plants <200 mm height branching at the base to avoid collar-rock. Most cultivars are orange to brown, 'Hawera' is bright green and extremely prostrate. Resprouts from underground stems when drought-stressed. Successful on many roofs with occasional summer irrigation
Coprosma	brunnea		Ground Cover	b	0.4	1	Y	Y	N	Openly sprawling coastal ground cover. Blue berries amongst dark brown foliage. Prostrate forms of *Coprosma repens* are useful plants for green roofs.
Dichondra	brevifolia	Mercury Bay groundcover	Ground Cover	b	0.01	1	Y	Y	N	Very low ground cover suitable for a rough 'lawn' look. Coastal. Fast growing and resprouts from rhizomes after drought, so valuble resilient species with other creeping groundcovers and where it can grow under Coprosma and Libertia.
Disphyma	australe	Native Iceplant	Ground Cover	c	0.02	1	Y	N	N	Coastal creeping succulent forming mats. Large white-pink-mauve flowers (summer). Frost tender. Self-seeding but on most roofs has been almost eliminated in year 2 or 3 by insects and disease. May be best on coastal sites where natural plantings are nearby. Probably requires high fertility for best outcomes.
Doodia	australis	Pukupuku	Fern	c	0.3	0.5	Y	Y	Y	Short creeping. Pink new fronds in the sun. Very hardy fern in sunny, dry conditions. Was named Doodia media.
Festuca	actae	Banks Peninsular Festuca	Tussock	b	0.3	0.4	Y	Y	N	Tussock endemic to Banks Peninsular. Blue leaves with dense form and attractive flower heads, will seed and spread. All three native fecues are highly drought tolerant and have tended to dominate roofs on which they are established and probably lower plant diversity.
Festuca	coxii	Chatham Island Blue Grass	Tussock	a	0.4	0.5	Y	Y	N	Fine, rolled blue-grey leaves with graceful seed heads. Seeds will establish as new plants. Outstanding survivor on roofs tending to increase in cover and displace less drought-tolerant species. Surface mulch may reduce new seedlings establishing.
Festuca	matthewsii	Blue Grass	Tussock	a	0.3	0.3	Y	Y	N	A green-leafed tussock local to the Auckland area so preferred in Auckland
Festuca	novae-	Tawny tussock	Grass		0.4	0.4	Y	Y	N	Fine-leaved tufted, tawny tussock. Spiky in habit.

Ficinia	nodosa	Knobby club rush	Rush-like	b	0.6	0.6	Y	Y	N	A fine green to orange sedge forming fountain like clumps. Self-established on trial greenroofs but none planted. Formerly called Isolepis nodosa.
Hebe	obtusata	Coastal hebe	Shrub	a	0.5	1	Y	Y	N	Prostrate habit, bright-green leaves and 'Bottle brushes' of flowers. Coastal (Waitakere). Specify bushy plants spreading from the base as for Coprosma and Pimelea. Other low-growing hebes such as H. toparia and H. elliptica (prostrate) also likely to be suitable. Seedlings self-establish. Out-competed for water by Festuca without adequate water availability.
Hibiscus	diversifolius	native hibiscus	Shrub	c	1	1	Y	Y	N	The prostrate form is best. Large yellow flowers. Coastal and frost tender. As with most species, the plant will be shorter on living
Leptinella	species	Shore Leptinella	Ground Cover	b	0.1	1	Y	Y	Y	L. perpusilla, Leptinella squalida 'Platt's Black' and L. aff. dioica. Feathery, soft spreading groundcovers can be used as no-mow lawns. *L. dioica* is extremely variable. Requires some irrigation in media with low moisture holding. Spreads moderately quickly in
Leptospermum	Prostrate'	Manuka	Ground Cover	c	0.5	1.5	Y	N	N	Ensure the most prostrate plants are selected (below 200 mm height); White or pink flowers (spring/autumn/winter) are very valuble
Leptostigma	setulosa		Ground Cover	b	0.1	0.5	Y	Y	Y	Small bright green mounds to 0.1 m high suitable for includion in a no-mow lawn; very vigorous and resprouts from summer
Libertia	cranwelliae	Native Iris	Ground Cover	bi	0.4	1	Y	Y	Y	Also *Libertia peregrinans* . Variety of leaf colours from green to yellow to orange responsive to stress and sunshine or shade. Spread slowly by rhizomes. White flowers (spring) and attractive orange seed pods very wind resistant once established.
Lobelia	anceps	Punakuru	Ground Cover	c	0.1	0.3	Y	Y	Y	Dark green creeping foliage. Light pink-mauve flowers (spring-autumn). Not trialled on roofs yet.
Microlaena	stipoides	Rice Grass	Grass	c	0.3	1	Y	Y	Y	Turf forming. Use only with tussock and grass roofs as it seeds freely and easily percieved as weed-like. Self-seeds. 'Finer-leaved
Muehlenbeckia	axillaris	Pohuehue	Ground Cover	c	0.15	1	Y	Y	N	Forms a dense dark green mat of interlaced branches with small white/green flowers (summer) and fleshy opaque fruits. Trialled on three roofs with variable sucess; do not plant more than 20% by area unless irrigated and moderate fertiilty. Another no-mow turf
Oplismenus	hirtellus	Basket Grass	Grass	c	0.15	3	Y	Y	N	Prostrate grass with a loose spreading habit. Will tolerate light foot traffic. A grass suitable for inclusion in no-mow and tussock roofs.
Poa	cita	Silver tussock	Grass	b	0.6	0.6	Y	Y	N	Graceful smaller silver tussock tolerant of infertile soil and full sun; spreads via seedlings.
Phormium	cookianum subsp. Hookeri	Mountain flax, wharariki	lily and iris-like	bi	1	1	Y	Y	N	Source smallest plants from exposed, droughty coastal cliffs. Propagates readily from division or seed. Many varieties have been propagated; these may be less tolerant in the absence of irrigation and fertiliser. Used only on irrigated roofs to date.
Pimelea	species	NZ daphne	Ground Cover	bi	0.15	1	Y	Y	Y	Pimelea prostrata and P.urvilleana have been planted. Rapidly-growing plants under irrigation with fine grey to green foliage. Clusters of small, insect-attracting white flowers (spring-autumn). Select very prostrate forms to achieve a dense, weed-resistant
Pyrrosia	eleagnifolia	Leatherleaf fern	Fern	c	0.1	0.3	Y	Y	Y	Creeping epiphyte on rocks, trees and shaded clay tile roofs. Needs afternoon shade. Slow to establish, anchor and spread but highly resilent once established; moderate mortality during establishment. Microsorum pustulatum is another fern worth trialling in
Pteris	tremula	Turawera	Fern	b	1	1	Y	Y	Y	Easy to grow vigorous fern, often colonises under decks or in rockeries.
Raoulia	hookerii	Scabweed	Ground Cover	c	0.01	0.3	Y	N	N	Alpine species. Silver foliage. Cushions may be invaded by low weeds such as Oxalis without regular maintenance
Scandia	rosifolia	Native Angelica	Shrub	c	1	1.5	Y	Y	N	Aromatic glossy dark green foliage. Dill-like flower head. Plant deeply to avoid stem-rock.
Scleranthus	biflorus		Herb	ci	0.1	0.5	Y	N	N	Bright yellow-green, moss-like mounds can be prone to patches dying out after several years so useful for early results and plant
Selliera	radicans		Ground Cover	b	0.03	2	Y	Y	N	Small, strap-like, bright green leaves develops undulating 'lawns'. Variable leaf size and shape. Small white scented flowers
Tetragonia	implexoma		Ground Cover	ci	0.1	1	N	Y	Y	Semi-succulent bright green leaves turn yellow/red when stressed. Large red berries. Coastal. Prefers some shade and can be openly branching allowing other plants to inter-grow.
Annual or semi-annual species suited for living roofs or roofs planned for summer dieback (seasonal bare ground)										
Crassula	sieberiana		ground cover	a	0.05	0.1	Y	Y	Y	Green feathery herb forming dense patches in winter and spring; insignificant flowers and fruit. Some other native crassulas are perennial.
Haloragis	erecta	Toatoa	Herb	bi	1	1	Y	Y	Y	Rapidly-spreading, bright green or olive-purple bushes, self seed abundantly in suitable conditions. Consider an annual on living roofs that are irregularly irrigated.
Hibiscus	richardsonii	Puarangi	Herb	b	0.5	0.3	Y	Y	N	Previously known as Hibiscus trionum. Will establish from seed and re-seed in suitable conditions. Consider as an annual on living roofs
Whalenbergia	albomarginata	NZ bluebell	herb	ci	0.15	0.3	Y	Y	N	Attractive mauve flowers on thin stalks above a mound of vegetation; spreading

Appendix B Non-Native Species

Non-native species for extensive living roofs in Auckland have been divided into Sedums, and other, generally succulent species.

Sedum species available in New Zealand

Sedums are succulent, incredibly drought tolerant plants. Sedums are the main genus grown on thin green roofs in Europe and the United States. *Sedum acre*, *S. album* and *S. reflexum* are probably the most common species used overseas, however, *S. acre* and *S. album* (and maybe cultivars bred from these species) are weeds in parts of New Zealand[18] – There are no native Sedums. It is doubtful any new sedum species would be allowed to be imported into New Zealand (P Williams pers. comm. 2007). Some Sedums have self-established on coastal cliffs from Dunedin to Auckland. In 1959, A.J. Healy first recorded wild *S. album, S praealtum* and *S. reflexum* on cliffs in the Redcliffs-Sumner area amongst native iceplant. *S. acre* is recognised as weed in parts of the South Island high country (Department of Conservation website). Given the ability of some Sedums to spread outside gardens, people should avoid using Sedums in areas where they could spread into native vegetation, particularly in windy coastal areas (cliffs and sand dunes).

The colour of sedum leaves intensifies when plants are under stress, whether drought, cold or nutrient stress. This is expressed as leaves changing from green tones to red, purple or yellow. This response is slight for grey-coloured plants (e.g. *S. dasphyllum, S. rupestre*) but can be dramatic for green and red-coloured plants (*S. rubroctinctum, S. hintonii, S. suprium*). A mix of small- and large-leafed Sedums is advised as smaller leafed Sedums are generally not as long lived (Ed Snodgrass pers. comm.2012)



Sedum kamtschaticum FT *Sedum rubroctinctum (large leaf)RT* *Sedum spurium 'Dragon's blood'*

[18] Auckland Regional Council biosecurity advised the research programme in 2007 that *Sedum acre* (stonecrop) and *Sedum album* (white stonecrop) should not be established on Auckland green roofs – this includes cultivars bred from these species such as *Sedum album* 'Minima' and *Sedum acre* 'Golden Carpet'.



Sedum *pachyphyllum* T

Sedum oaxacanum

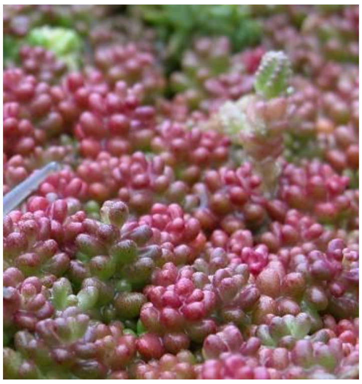
Sedum murabilis



*Sedum dasphyllum *LR*

Sedum mexicanum FTS

*Sedum rupestre **

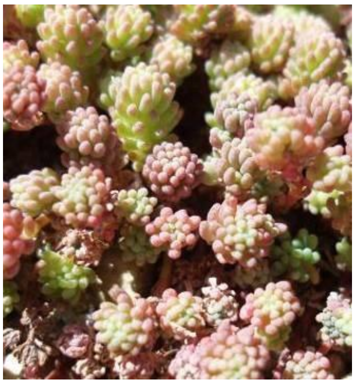




Sedum spathufolium L

Sedum x rubrocintum (small leaf)LR

Sedum ternatum F





Sedum azore L

Sedum makinoi 'ogon' (yellow & green) L

Sedum hintonii LR



Sedum reflexum (syn. *rupestre*) *Sedum spurium* 'voodoo' ***Sedum moranense*** **S**



Sedum selsuianum FT *Sedum decumbens FT* *Sedum acre* (yellow flowers)

Not shown, but available in New Zealand: Sedum aizoon, Sedum hispanicum (R), Sedum oreganum, Sedum populifolium (TF deciduous), Sedum forsterianum (similar to S. rupestre). Other Sedums may also be available.

Key:

F- Sedums that grow very rapidly over the first 6 to 24 months, and then may die back, particularly as fertility drops

L – Sedums less than 10 mm height on average that are likley to be smothered when interplanted with taller, dense species but inter-twine with more open taller species

T – taller species 50 to 100 mm height

R – Spread readily from leaf and stem fragements with suitable media

S - stressed colour; often much greener

S.album and S.acre should be avoided in the Auckland Region. S. acre may be sometimes mis-identified as S. moranense or S.sexangulare

Sedum albums **genotypes from around the world collected by Ed Snodgrass, Emery Knoll Farms, Maryland, USA (photo taken at Emory Knoll Farms)**

Non-native species excluding Sedums

Note

1. In areas nearby, or within, low-stature, exposed native vegetation it is important to select species that are unlikely to ‘escape’ from the roof, invade and displace native ecosystems; for example, *Aloe saponaria* and some Crassulas are unwanted weeds on Rangitoto Island. In these situations and full sun, use native plants and minimum 100 mm substrate depth.
2. Within the Genera shown below, select smaller species with prostrate (ground-hugging) form that are tolerant of hot, sunny, windy sites. The species shown are generally 50 to 150 mm tall when fully grown. Aloe, Crassula, Echeveria, Bromeliad and Senecio genera include very large plants that will unsuitable for extensive roofs and add substantial weight loading.
3. Many of these plants are damaged by foot-traffic; some have spikes. When using such plants, include access areas by strategically planting tolerant species (most natives and sedums).

Sempervivium species

Crassula perforata

Kalanchoe sp

Allium sativum (variegated garlic)

Senecio serpens

Aloe humilis & A. Aristata**



Bromeliad neoregelia 'red of Rio' *Mesembranthum 'yellow'* *Lampranthus 'pink'*

Summer-dormant bulbs

Bulbs provide a burst of seasonal colour. Those suitable for living roofs are usually short (<200 mm height), early-flowering with small bulbs, such as chives, crocus and some tulip and iris species. New Zealand onion orchids (Microtis species) have colonised many roofs in Auckland. Small, summer-dormant South African bulbs may also be suitable, e.g. sunstar,*Ornithogalum dubium*.



Allium schoenprasum (chives) *Crocus sativum* (Autumn crocus) *Iris reticulata*

Early afternoon shade, deeper media and/or summer irrigation is required to expand the range of plant species to include native plants and many herbs. Some stress is still valuble to minimise weed growth.

Dimondia margaretae *Lavendula angustifolia* ***Stachys byzantine (Lamb's ear)***