GREEN ROOF TECHNOLOGY – RESEARCH, DESIGN AND IMPLEMENTATION OF A GREEN ROOF AT THE UNIVERSITY OF CANTERBURY

(EcoFriendly, 2008)

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EXECUTIVE SUMMARY

In cooperation with the University of Canterbury Sustainability Office and the Department of Civil and Natural Resources Engineering, this study aimed to identify and investigate the benefits of green roof systems and how they could be implemented in Christchurch conditions. Green roofs have successfully been installed throughout Europe and North America with proven success and are becoming a popular option for stormwater reduction, urban heat island effect mitigation and insulation. In a New Zealand context the Auckland Regional Council has published ‘Extensive Green (Living) Roofs for Stormwater Mitigation’ which was compiled by Elizabeth Fassman, Robin Simcock and Emily Voyde. This technical report publishes work and findings from green roof projects that were completed in Auckland; namely the University of Auckland Green Roof and the Tamaki Mini Roofs.

‘Extensive Green (Living) Roofs for Stormwater Mitigation’ is the only official New Zealand set of guidelines and covers comparison to overseas standards, substrate development, site construction, plant criteria and selection, structural analysis and codes and technical implementation. The document goes into extensive detail regarding substrate testing, development and properties which this report does not cover. The Auckland Regional Council document has been used as a guide to green roofs for our study and along with a detailed literature review has allowed a knowledge base to be gained. Unlike Auckland scenarios, which took a development approach, our goal is to establish a green roof in Christchurch from proven materials, with the intent to monitor the system and provide data to emphasize the effectiveness of green roofs in local conditions.

The system consists of vegetation grown in a predominantly mineral substrate of varying depths, atop drainage and protective layers. The substrate material is engineered to be lightweight yet with a high water holding capacity – characteristics which are often at odds to each other. Much research has been completed into the ideal make up of a green roof and the results are varied. However the prevailing conclusion is that a green roof system should be designed to optimize the intended purpose and to suit the local conditions.

The structural capacity of a building, particularly for a retrofit application is often the limiting factor for design specifications and it is necessary to account for the complete saturated system weight in calculations. In such a case the substrate depth and the vegetation have to be chosen to meet these criteria. However research has shown that even thin substrate layers can still provide positive stormwater retention along with other benefits.

Where weight is not an issue deeper ‘intensive’ systems can be installed which allow for a diverse plant pallet that may require maintenance. Shallower ‘extensive’ systems are common options where maintenance is intended to be minimised. Plant growth is dictated by the substrate depth along with climatic conditions and it is necessary to choose plants that are hardy and/or suited to local conditions for green roofs. The vegetation holds the substrate together along with playing the vital role of evapotranspiration, transpiring water from the system back into the atmosphere along with direct evaporation.
As a result of a number of large earthquakes Christchurch faces a large rebuild which encompasses much of the central city. A clear desire from the public was to have a greener city and green roofs stand as an appealing option if such a path is taken. Green roofs will provide habitat establishment and ecological corridors for wildlife along with enhancing the visual appeal of the city. Due to urbanization cities face a growing problem with the pollution of stormwater and the ability of green roofs to decrease runoff volumes from roof tops may provide one of the largest benefits to Christchurch.

This report elaborates on the benefits of green roof systems, explores the characteristics associated with material and vegetation selection and outlines the necessary structural considerations; culminating with the design schematic for implementation of a green roof at the University of Canterbury.
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(1) Basic Hydrological Budget: \( \Delta S / \Delta t = P - Q_R - ET - I \)

(2) Annual Green Roof Response Model: \( D_{gr(i)} = D_{gr(i-1)} + ET_i - R_i \)

(3) Reference Evapotranspiration Equation: \( ET_{ref} = \frac{0.408 \Delta (R_n - G) + \gamma \frac{c_n}{T+273} (e_s - e_a) u_2}{\Delta + \gamma (1 + C_d u_2)} \)

(4) Crop Coefficient Equation: \( K_c = \frac{ET_c}{ET_{ref}} \)

(5) HIRDS 100 Year, 10 Minute Rainfall Calculation: \( \frac{13.2 \text{ mm}}{10 \text{ minutes} \times \frac{60 \text{ seconds}}{\text{ minute}}} = 0.022 \text{ mm/second} \)

(6) Load and Factor Resistance Design (LFRD) equation: \( \Sigma \gamma_i E_i \leq \emptyset R_n \)

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1.0 RESEARCH OBJECTIVES

In the face of a changing climate and the increasing issues stemming from human industrialization, the need for and importance of green technologies is becoming increasingly acknowledged around the world and implementation rates have begun to rise. As part of this, green roofs are emerging as an increasingly popular low impact development (LID) tool for storm-water control (Voyde et al., 2010).

Christchurch is poised in a unique situation where, after a number of significant earthquakes, a large proportion of the city’s infrastructure needs to be rebuilt. This presents the opportunity to incorporate environmentally sustainable technologies such as green roofs into the rebuilding process.

2.0 INTRODUCTION

This report builds upon the work conducted by Dr. Elisabeth Fassman of the University of Auckland and Dr. Robyn Simcock of Landcare Research regarding the green roof installed at the University of Auckland.

Green (or living) roofs use vegetation to improve the performance of an ordinary roof in regards to stormwater management, energy consumption, lifespan and amenity (Snodgrass et al, 2010). Green roofs are generally categorised into two types; extensive and intensive. The general structure of a green roof is shown in the below figure.

![Figure 5: Typical cross section of a substrate-based extensive green roof. Diagram modified from Safeguard Europe website.](image-url)

Intensive green roofs can be likened to traditional roof gardens as they feature a thick substrate layer (above 200 mm depth) with a higher organic content enabling them to support a wider variety of plants (Snodgrass & McIntyre, 2010). This thick substrate layer results in higher imposed loading of 300 to
1000 kg/m² on the structure (Fassman & Simcock, 2011), making them less suitable for retrofit application and also more costly for new builds.

Extensive green roofs are thinner, generally under 150 mm in substrate depth (Fassman & Simcock, 2011). These roofs are primarily functional and generally will not feature pedestrian access (Davies, 2007). Because of the thin layer of substrate employed, plant choice is limited somewhat to sedums and other drought-resistant and low-growing plants (Snodgrass & McIntyre, 2010). This thin substrate depth also reduces the load of the system with 70-200 kg/m² imposed at fully saturated conditions (Fassman & Simcock, 2011).

For the purpose of this report, the design of a green roof has been split up into three key criteria: hydrological considerations, substrate and vegetation design and structural considerations. Each of these three main criteria impacts on the other two, with the limiting criteria changing on a case by case basis, depending on the conditions.

2.1 BENEFITS

2.1.1 STORMWATER

A related benefit of green roofs is the retention of stormwater (Teermusk and Mander, 2007), and because of this green roofs are emerging as an increasingly popular low impact development (LID) tool for storm-water control (Voyde et al., 2010). Maintaining a site’s pre-development hydrology or ‘hydrologic neutrality’ is becoming the low impact development (LID) approach to stormwater management. Thus the importance of volume control is stressed in LID guidelines to achieve this goal (Shaver, 2000).

It is often stated that green roof systems provide storm water retention, with the degree of retention based upon the substrate selected, its hydraulic properties, and depth of substrate used in the green roof (Oberndorfer et al., 2007). However the vegetation also aids this process as plants with high photosynthetic capacity, growth rates, productivity, biomass accumulation and capacitance can increase the rate of transpiration (Lundholm et al., 2010). This maximizes the evaportranspiration from the roof which may decrease the total amount of water running off into the sewer system.

2.1.2 WATER QUALITY

Several studies have shown that green roof systems retain pollutants introduced through rainwater (Berndtsson et al. 2009; Köhler et al. 2002), which would otherwise be washed off impervious surfaces. This is not only beneficial to subsequent waste water discharges but also decreases the amount of contaminants in the water. In urban areas up to 30% of total nitrogen and total phosphorus released into receiving waterways is derived from dust that accumulates on rooftops or directly from the roof materials. Vegetated roofs act as natural bio-filtration devices to reduce this water contamination. Therefore concentrations of heavy metals in green roof runoff are generally lower than concentrations of heavy metals in urban runoff from impermeable surfaces so offer improved stormwater quality. Green roofs also influence runoff water quality pH through inducing a higher pH from between 5 and 6 (in rain water) to between 7 and 8 in green roof runoff water. This contributes to lowering the degree of acidification of natural water recipients, (Justyna, 2010), along with affecting metal speciation (Allen et al., 1980)
2.1.3 ENERGY

The vegetation layer present in a green roof serves to moderate temperature change and heat transfer through a roof’s surface in comparison to a typical surface (Stovin et. Al., 2010, Fassman et al., 2011). This results in energy savings during both summer and winter. During summer, transpiration cools the surrounding air, thus lowering the temperature of the surface of the soil and thus decreasing the heat flow through the roof. In winter the insulation provided by the substrate and vegetation layer serves to keep heat in, especially when the soil remains dry (Miller, 2011).

2.1.4 URBAN HEAT ISLAND EFFECT

Urban heat islands form as cities replace natural land cover with pavement, concrete, and other surfaces that absorb and retain heat. This displacement of trees and vegetation minimizes the natural cooling effect on the surrounding environment (Gedge, 2011) which can create a temperature difference of up to 2.5 °C between urban and rural sites in large cities worldwide (Susca et al., 2011).

Covering dark conventional roofs with vegetated roofs can significantly reduce the temperature above the roof and has been proven to provide comparable benefits to white or reflective roof surfaces in reducing the ambient air temperature (Miller, 2011). Unlike white roofs, which tend to lose the ability to reduce temperature as they age, vegetated roofs continue to have the ability to mitigate the heat island effect.

2.2 PROMINENT GREEN ROOF EXAMPLES IN NEW ZEALAND: RETROFIT AND NEW BUILD

A prominent example of a green roof retrofit is the roof of the University of Auckland’s School of Engineering. Spanning 217 m², this roof was designed with structural load at premium and as such was specified as having a maximum saturated load of 100 kg/m² or 1.0 kPa (ARC TR17/2010). To achieve this, lightweight substrate blends featuring pumice, zeolite and organic matter were used at depths ≤70 mm.

Figure 6: Left - Waitakere Civic Building green roof (c. ARC TR17/2010), Right - University of Auckland, School of Engineering green roof (c. livingroofs.org.nz).
An example of a green roof new build is the roof of the Waitakere Civic Centre in Auckland. As a new build, the weight of the green roof was factored into the structural design of the building, allowing a less restricting maximum load of 230 kg/m² or 2.3 kPa (Davies, 2007). This allowed a thicker substrate depth of 150 mm to be employed. Substrate composition included expanded clay, pumice and potting mix (Davies, 2007).

### 2.3 CLIMATIC CONDITIONS OF CHRISTCHURCH

When implementing a green roof the local climatic conditions must be considered in the design process so that vegetation, substrate material, depth and water holding capacity can be optimised to promote maximum performance while still adhering to the weight restrictions imposed by the existing structure.


<table>
<thead>
<tr>
<th></th>
<th>Rainfall</th>
<th>Wet days</th>
<th>Sunshine</th>
<th>Temperature</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>≥ 1.0 mm</td>
<td>hours</td>
<td>°C</td>
<td>°C</td>
</tr>
<tr>
<td>Auckland</td>
<td>1240</td>
<td>137</td>
<td>2060</td>
<td>15.1</td>
<td>30.5</td>
</tr>
<tr>
<td>Christchurch</td>
<td>648</td>
<td>85</td>
<td>2100</td>
<td>12.1</td>
<td>41.6</td>
</tr>
</tbody>
</table>

The main reference document for green roof systems in New Zealand is the Auckland Regional Council technical report, ‘Extensive Green (Living) Roofs for Stormwater Mitigation’ (Fassman et al., 2010). The hydrological data as well as the decisions regarding substrate and vegetation choice are however considering only Auckland conditions. However from studying the difference in climatic conditions between Auckland and Christchurch (as seen in Table 1 above), it stands to reason that the hydrological processes that occur within a green roof will be vastly different in Christchurch conditions.

These weather observations highlight the need for the vegetation used in Christchurch to be hardy and well suited to the local conditions of long dry periods and frosty winters. From a stormwater runoff perspective the water holding capacity of the substrate used will not need to be as high as in Auckland scenarios as less rainfall and longer antecedent dry periods will allow for greater water storage recovery. However from a vegetation viewpoint, a lower permeability and high water holding capacity is necessary to counteract the high degree of evapotranspiration and long antecedent periods to allow for greater soil moisture retention and successful plant growth.

A more extensive set of climatic data for Christchurch is shown in Appendix A.3. This data highlights the factors that need to be considered when implementing a green roof in Christchurch in comparison to successful applications that have been made in Auckland. The vegetation needs to be able to survive low winter temperatures, high summer temperatures, possible prolonged periods of no rainfall, and the substrate needs to be able to adequately hold the received rainfall.
3.0 HYDROLOGICAL CONSIDERATIONS

3.1 HYDROLOGICAL BALANCE

A green roof system receives water from the atmosphere, or alternatively via irrigation and runoff. Water is stored through interception by the plants, within the substrate and drainage layers of the green roof or taken up by the vegetation. This water is then returned to the air via evaporation from the substrate and vegetation or transpired by the vegetation. Once the water holding capacity of the substrate is reached, water will be removed from the green roof via runoff.

The substitution of vegetated roofs for conventional roofs has the potential to reduce roof runoff by 100% in some cases (Oberndorfer et al., 2007), with regional reductions of up to 2.7% predicted in a scenario of 10% green roof coverage (Mentens et al., 2006). Field monitoring of full-scale extensive living roofs has shown substantial contribution to site runoff volume control, with 50–78% of precipitation retained over periods of data collection (Berghage et al., 2009). Cumulative retention efficiencies of 66% were also found in pumice-based substrates developed in New Zealand with the system also retaining a median of 82% of rainfall per rainfall event (Voyde et al., 2010).

The hydrological response of a living roof cannot be linked to one factor alone; multiple parameters such as rain depth, rain intensity, climatic conditions (namely solar radiation and humidity) and antecedent dry days all play a role in influencing the hydrology of a living roof (Fassman et al., 2011). Therefore, it is necessary to quantify the hydrology of the area and green roof in order to gauge the stormwater retention of the system or lack of it, which may affect the growth of vegetation. Specific climatic data for an area can be gained through NIWA database systems along with possible local weather stations. Data for Christchurch is displayed in the Appendices.

For evapotranspiration in green roof systems, soil water content is generally the major limiting factor, but the rate at which this water is lost from the system and the subsequent cooling effect achieved may depend on the type of vegetation present and the resulting evapotranspiration (Wolf and Lundholm, 2008).

The maximum rate of transpiration (T) is generally dictated by the supply of energy required to vaporize water, the amount of water available to the plant (soil moisture), the ambient humidity and the subsequent water vapor pressure differential between sub-stomatal cavities and the boundary layer of air that surrounds the plant (Mellor et al., 1964).

Planting a green roof with several species may also optimize water loss throughout the growing season if different species have high water uptake rates under different soil moisture conditions, adding to the viewpoint that the use of greater plant species diversity can improve green roof performance (Wolf and Lundholm, 2008).
3.1.1 HYDROLOGICAL MODELS

Various models can be applied to estimate the storage or retention capacity pre and post implementation, such as the basic hydrologic budget applied to a green roof (Fassman et al., 2011):

\[
\frac{\Delta S}{\Delta t} = P - Q_R - ET - I
\]

Where:
- \(\Delta S\) = change in storage
- \(\Delta t\) = change in time
- \(P\) = precipitation
- \(Q_R\) = roof runoff
- \(ET\) = evapotranspiration
- \(I\) = interception

This equation gives the change in substrate and plant storage. Such a model needs to be applied to a green roof as the storage capacity or conversely the amount of water in the system dictates the amount of retention after a rainfall event, the amount of runoff and how much water is available to the vegetation (Fassman et al., 2011). It has also been found that antecedent dry days have a significant effect on retention along with influencing the contribution of vegetation to rainfall retention capacity (Voyde et al., 2010).

Therefore it is necessary to factor antecedent dry days into green roof hydrological equations. This can be achieved when equating the above equation over time as \(P\) and \(I\) will be zero for antecedent dry days and hence storage will increase.

The **Annual Green Roof Response (AGRR) Model** developed by (Jarret et al., 2006) quantifies the available water storage in a green roof and its vegetation on a daily basis.

The model is based on three assumptions:

1. That a daily (24-hour) rainfall record was available to be used as input.
2. That a reliable estimate of daily evapotranspiration (ET) was available.
3. That the maximum water retention available within the roof and its vegetation is known or available.

The daily roof water deficit, \(D_{gr}\), can be expressed as:

\[
D_{gr(i)} = D_{gr(i-1)} + ET_i - R_i
\]

Where:
- \(D_{gr}\) = Pore space available in the drainage layer and roof media below field capacity plus the water holding capacity of the plants.
- \(D_{gr(i-1)}\) = The roof water deficit on Day \((i-1)\)
- \(ET_i\) = The evapotranspiration on Day \(i\)
- \(R_i\) = The rain on Day \(i\)

The daily deficit cannot exceed the retention capacity in the roof; \(D_{gr}\) may not be larger than \(D_{max}\). The daily deficit may never be less than zero as this is when the green roof system is filled to field capacity.
If the daily deficit reaches zero, the green roof cannot retain any more water and thus additional water becomes runoff (Jarret et al., 2006).

The capillary and hygroscopic water in the drainage layer and roof media are considered to be part of the retention storage and have the potential to be depleted by evaporation and transpiration as shown in the figure below. The water deficit also includes the water within the plants used as vegetation on the roof.

**Figure 3: Soil-water characteristics with respect to influence on plant viability. Source: (Hawkes Bay Regional Council, 2006)**

### 3.1 EVAPOTRANSPIRATION

Evapotranspiration (ET) represents the loss of water from the soil through the combined processes of evaporation (from soil and plant surfaces) and plant transpiration. Reference evapotranspiration (ET\textsubscript{ref}) is the potential rate at which readily available soil water could be vaporized from specific vegetated surfaces (Jensen et al., 1990).

ET\textsubscript{ref} can be calculated using the **Penman – Monteith Combination Method**:

\[
ET_{\text{ref}} = \frac{0.408 \Delta (R_n - G) + \gamma \frac{C_n}{T + 273} (e_s - e_a) u_2}{\Delta + \gamma (1 + C_d u_2)}
\]  

(3)

**Where:**

- \( ET_0 \) = *grass reference evapotranspiration (mm d\(^{-1}\)*)
- \( \Delta \) = *slope of vapor pressure curve (kPa °C\(^{-1}\))*
- \( R_n \) = *mean daily net radiation (MJ m\(^{-2}\) d\(^{-1}\))*
- \( G \) = *heat flux (MJ m\(^{-2}\) d\(^{-1}\))*
Evapotranspiration is directly measured using lysimeters. Lysimeters are tanks filled with soil in which crops are grown under natural conditions to measure the amount of water lost by evaporation and transpiration. This method provides a direct measurement of ET and is frequently used to study climatic effects on ET and to evaluate estimating procedures (Romero and Dukes, 2009).

Effective water management and allocation requires knowledge of evapotranspiration for a particular crop at various growth stages. Crop coefficients ($K_c$) can be used to relate reference evapotranspiration ($ET_{ref}$) to actual crop evapotranspiration ($ET_c$); accounting for crop characteristics and phonological growth stages. Dimensionless $K_c$ values can be calculated as (Irmak, 2005):

$$K_c = \frac{ET_c}{ET_{ref}}$$

(4)

Most of these $K_c$ values have been determined for agronomic crops and the availability of experimentally determined $K_c$ values for nursery crops is extremely limited making it difficult for growers, researchers, and water management districts to accurately determine water use, allocations, and to make water management decisions (Irmak, 2005). This is due to reliable research-based data on landscape plant water requirements being very limited in general, with few sources of information offering quantitative estimates (Pittenger and Shaw, 2005). One of the main reasons why there is little availability of scientific information is the large number of plant species, and the substantial resources needed to identify the water requirements of an individual species (Irmak, 2005).

### 3.2 SUBSTRATE PERMEABILITY

As Christchurch conditions are unique, the suitable permeability range for a green roof substrate varies from elsewhere in New Zealand. For example the green roof developed at the University of Auckland had a saturated permeability target of $\geq 0.1$ cm/second; an objective set from the FLL 2008. However Auckland has around twice the annual average rainfall that Christchurch receives and on average 137 wet days per year compared to 85 in Christchurch (NIWA, 2011).

Due to the harsher Canterbury conditions (high summer temperatures, sunshine hours, warm prevailing winds and frosty winters) a low permeability of between 0.01 – 0.05 cm/s has been recommended by Colin Meurk of Landcare Research. A lower permeability aids the survival of plants by increasing the retention time of water in the substrate thus increasing soil moisture. This could also be achieved by coupling the green roof to a water harvesting system to reuse runoff. Decreasing the permeability would be achieved by increasing the volume of smaller particles as opposed to adding additional organic matter, however this has load implications (Meurk, 2011). The FLL guidelines specify a permeability of $\geq 0.1$ cm/s for a single-coarse extensive green roof without an additional drainage layer and $\geq 0.001$ cm/s for extensive green roofs with a drainage layer.
Such guidelines have been set to ensure that ponding of water on the green roof does not occur (Kohler, 2010). Ponding adds excess weight, can float and scour substrate and potentially drown plants (Fassman et al., 2011).

### 3.2.1 HIGH INTENSITY RAINFALL DESIGN SYSTEM (HIRDS)

NIWA’s High Intensity Rainfall Design System (HIRDS) can estimate rainfall frequency at any point in New Zealand and hence be used to estimate rainfall depths for hydrological design purposes. The HIRDS system offers planners and engineers more certainty about the frequency of high-intensity rainfalls, enabling them to better design stormwater drainage systems and other structures (NIWA, 2011). Analysis of HIRDS data as displayed in Appendix 2 shows that the most intense rainfall event has an Annual Recurrence Interval of 100 years and duration of 10 minutes. For this event a rainfall depth of 13.2 mm is expected; giving a permeability rate of 0.022 mm/s.

\[
\text{Permeability rate of a 100 year; 10 minute rainfall event with a rainfall depth of 13.2 mm:}
\]

\[
\frac{13.2 \text{ mm}}{10 \text{ minutes} \times \frac{60 \text{ seconds}}{\text{minute}}} = 0.022 \frac{\text{mm}}{\text{second}}
\]  

(5)

Therefore it is necessary to have a soil permeability of greater than 0.022 mm/s for the medium to be able to handle such an event. A soil permeability ranging from 0.1 to 0.5 mm/second was recommended by Colin Meurk of Landcare Research; a substrate with permeability within the range recommended would therefore be able to handle the drainage demands of a 100 year, 10 minute storm event.

### 4.0 SUBSTRATE AND VEGETATION CONSIDERATIONS

#### 4.1 SUBSTRATE COMPOSITION

An “extensive” green roof is the most commonly deployed type of green roof system and is characterized by a shallow substrate (<200 mm deep), relatively lightweight components and low costs (Dunnett and Kingsbury, 2004). Typical extensive green roof growing media, or substrate, is comprised of 80-90 % (by volume) light-weight aggregate (LWA) and 10-20 % (by volume) organic matter (Fassman et al., 2011).

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. These key functions include cation exchange capacity (CEC) for nutrient retention and chemical buffering along with moisture storage and supply (Friedrich, 2005). This can be achieved through addition of zeolite for CEC, organic matter and particle size distribution. However strict quality control on particle size distribution and bulk blending operations need to be key criteria for design specifications due to influences on permeability and weight (Fassman et al., 2011). The ideal physical properties to aim for when designing a substrate are included in the below summary;
Table 2: A green roof substrate should have a composition that provides the following properties ((GRO) 2011):

<table>
<thead>
<tr>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td> Lightweight</td>
</tr>
<tr>
<td> Resistance to wind and water erosion</td>
</tr>
<tr>
<td> Free from weeds, diseases and pests</td>
</tr>
<tr>
<td> Good plant anchorage to reduce the risk of wind uplift due to the binding effect of the roots within the growing medium</td>
</tr>
<tr>
<td> Fire resistance through avoiding high proportions of organic matter</td>
</tr>
<tr>
<td> Appropriate water retention/release tendencies to retain sufficient water to meet the plants’ needs, yet facilitating permeation to avoid water logging of the substrate</td>
</tr>
<tr>
<td> Good aeration at water saturation to prevent the roots from suffering the detrimental effects of water logging</td>
</tr>
<tr>
<td> Resistance to compaction to prevent saturation due to removed drainage paths</td>
</tr>
<tr>
<td> Appropriate supply of nutrients (e.g. slow-release fertilizers) to allow development in accordance with the plants’ needs (Note: extensive roofs have a low nutrient requirement, whilst intensive and semi-intensive roofs have higher nutrient requirements).</td>
</tr>
</tbody>
</table>

While the primary considerations for substrate composition are largely concerned with sustaining plant growth, the allowable weight of the green roof system can often govern the composition and thickness of the substrate. This is especially pertinent for retrofit applications. Sustainability should also be viewed as a criterion in substrate selection, with local and/or recyclable alternatives to be considered.

Table 3: Some key physical properties for substrates ((GRO) 2011).

<table>
<thead>
<tr>
<th>Properties</th>
<th>Reference Values (Extensive)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>60-200 mm</td>
</tr>
<tr>
<td>Porosity</td>
<td>Varied</td>
</tr>
<tr>
<td>Pore Size Distribution (d \leq 0.063) mm</td>
<td>(d \leq 0.063) mm (\leq 15%) (by mass), (d \geq 4.0) mm, (\leq 50%) (by mass)</td>
</tr>
<tr>
<td>Maximum Water Holding Capacity</td>
<td>25% (\leq) MWHC (\leq 65%)</td>
</tr>
<tr>
<td>Air Content at MWHC</td>
<td>(\geq 10%) (by volume)</td>
</tr>
<tr>
<td>Water Permeability</td>
<td>0.001 – 0.1167 cm/sec</td>
</tr>
<tr>
<td>pH Value</td>
<td>6.0 – 8.5 (The standard is high for natural New Zealand soils, which range pH from 4.5-6.5 (with the exception of limestone soils)).</td>
</tr>
<tr>
<td>Organic Content</td>
<td>(\leq 20%) by volume</td>
</tr>
</tbody>
</table>

4.1.1 ORGANIC MATTER

Organic material must be present in the substrate mix in order to support plant life by storing and providing nutrients (especially nitrogen) and moisture (Fassman et al., 2011). The following table outlines some key specifications for organic matter.
Table 4: Specifications for Organic Matter from Literature

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (of total substrate) (Fassman et al., 2011)</td>
<td>5 – 20 %</td>
</tr>
<tr>
<td>Max. Content (FLL, 2008)</td>
<td>65 g/L</td>
</tr>
<tr>
<td>Particle Size (Fassman et al., 2011)</td>
<td>&lt; 5-10 mm</td>
</tr>
<tr>
<td>Specified Organics (FLL, 2008)</td>
<td>Peat moss, composted bark</td>
</tr>
<tr>
<td>Increasingly Popular Recycled Resources</td>
<td>Composted bark, shredded wood waste, coconut coir fibre, macadamia</td>
</tr>
<tr>
<td>Stability (American Hydrotech Inc., 2006)</td>
<td>Does not decompose within 5 years</td>
</tr>
</tbody>
</table>

An organic component must be free of weed seeds and pathogens, low in salts and heavy metals, and relatively stable so as not to decompose within 5 years (American Hydrotech Inc., 2006). Although the organic fraction of an extensive green roof is small, the generally fine particle size and high moisture retention typical of organic matter contributes significantly to saturated weight and reduces permeability. Organic matter should be screened to remove excessively large fragments greater than 5-10 mm in most cases (Fassman et al., 2011).

4.1.2 SUBSTRATE WEIGHT

While the primary considerations for substrate composition are largely concerned with sustaining plant growth, the allowable weight of the green roof system can often govern the composition and thickness of the substrate. This is especially pertinent for retrofit applications.

The typical substrate composition used in extensive green roofs consists of around 80 % (by volume) lightweight aggregate with the remaining amount organic matter (ARC TR17/2010).

Lightweight aggregates that have typically been used overseas for extensive green roofs include expanded clay and expanded slate (Fassman, 2010). As the ‘expanding’ process typically involves rapid heating to over 1000 °C (ARC TR17/2010), these products typically have a high embodied energy associated with them and are not considered as a sustainable option (Fassman, 2010). While these proprietary products are available in New Zealand, they are imported and are expensive in the volumes associated with a green roof (Own Research, 2011). Because of the high embodied energy associated with the creation and transport of these products, they were not prefered for use but have been included for reference compared to other substrates.

4.2 VEGETATION

An ideal green roof is self-sustaining and requires minimal maintenance, including irrigation (Snodgrass and McIntyre, 2010). As a consequence, green roof plants must be able to survive frequent harsh conditions. Often the largest stressor is the summer water deficit, which is exacerbated by extreme heat and high wind (Butler and Orians, 2011). This is often typical of Canterbury’s climate, where temperatures can reach above 30 °C and wind speeds average 15 km/h.
Drought conditions are common due to exposure and the free draining nature of the substrate. High winds and intense solar radiation that comes with the exposed positioning also decrease the survival of plants. Therefore plants that naturally survive in similar conditions are sought after. As maintenance is often raised as a potential discouragement of green roof implementation, designs requiring mandatory irrigation should be avoided. Once established, an extensive system should be largely maintenance free (MacIvor and Lundholm, 2011).

Native plants have evolved to grow and survive in their regional microclimatic conditions, and resist regional pests and diseases (MacIvor and Lundholm, 2011). Therefore recently there has been interest in the use of native species in green roof plantings as they have been shown to provide benefits over traditional Sedum monocultures such as enhanced biodiversity of native insect and avian taxa (Monterusso et al., 2005). Such ecosystem services from green roofs can be improved by planting certain life-form groups in combination, directly contributing to climate change mitigation and adaptation strategies. Certain mixtures of life-forms, especially tall forbs, grasses and succulents have been found to have successful growth together (Lundholm et al., 2010). It has also been found that dryland plants perform better than wetland plants, and increasing the number of dryland species in mixtures tends to improve functioning (MacIvor et al., 2011). Studies highlight the need for more regionally appropriate plant choices for green roofs and increased evaluation of plant species across a range of environmental conditions is needed to develop regional vegetation designs that optimize stormwater function (Schroll et al., 2011).

The primary role of vegetation in most extensive green roofs is to provide stability to the substrate by protection against the elements along with the roots binding the substrate in place (Fassman et al., 2011). However, green roof plants also provide the important role of evapotranspiration, with either direct evaporation from the canopy or via transpiration; thus a dense, self-repairing plant cover is desirable (Fassman et al., 2011). As extensive green roofs are less than 200 mm deep the species of plants that are able to be grown is limited yet functionality still needs to be ensured. The conditions are also a major factor in selecting the type of vegetation that can be used in an extensive green roof system.

4.2.1 RESEARCH/DESIGN OBJECTIVES

The management and minimization of stormwater runoff is a key design parameter for the design of a green roof to be implemented at the University of Canterbury. Plants will therefore be chosen for their functionality within the system, with selection criteria involving:

1. Minimal irrigation or fertiliser needs.
2. Shallow root depth.
3. Dense self-repairing foliage cover.
4. Low mature plant height.
5. Drought and wet season tolerance.
6. Tolerant to full sunlight.
7. Unlikely to spread off roof to neighbouring properties.
8. Locally sourced; pre-adapted to Canterbury conditions.

### 4.2.2 SUITABLE PLANT SPECIES

From personal communication with Colin Meurk of Landcare Research, a list of plants has been recommended that are thought to be suitable for green roofs in Canterbury. These plants are specified below, grouped according to the depth that they thought would be most suited to growing in. It is necessary to note that the depths specified may not be able to be achieved due to structural loading limitations; however these plants may be able to be successful at lesser depths with limited growth.

Table 5: Recommended vegetation grouped according to depth (Meurk, 2011).

<table>
<thead>
<tr>
<th>Depth 120 mm</th>
<th>Depth 200mm (along with all adjacent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxalis exilis (watch for exotic weedy spp)</td>
<td>Acaena spp</td>
</tr>
<tr>
<td>Hypericum gramineum (NZ St John’s wort)</td>
<td>Calystegia soldanella</td>
</tr>
<tr>
<td>Poa imbecilla (this and next 7 are grasses)</td>
<td>Euphorbia glauca</td>
</tr>
<tr>
<td>Poa colensoi (Blue Tussock)</td>
<td>Haloragis erecta</td>
</tr>
<tr>
<td>Poa lindsayi</td>
<td>Ficinia nodosa</td>
</tr>
<tr>
<td>Deyeuxia avenoides</td>
<td>Libertia ixioides</td>
</tr>
<tr>
<td>Rytidosperma spp (Danthonia)</td>
<td>Hierochloe fuscata</td>
</tr>
<tr>
<td>Lachnagrostis spp</td>
<td>Pyrosia eleagnifolia</td>
</tr>
<tr>
<td>Dichelachne crinita (Plume grass)</td>
<td>Senecio glomeratus</td>
</tr>
<tr>
<td>Zoysia minima</td>
<td>Poa cita (silver tussock)</td>
</tr>
<tr>
<td>Carex resectans (Sedges)</td>
<td>Festuca actae</td>
</tr>
<tr>
<td>Geranium sessiliflorum</td>
<td>Festuca novae-zelandiae</td>
</tr>
<tr>
<td>Cotula australis</td>
<td>Festuca coxii</td>
</tr>
<tr>
<td>Disphyma novae-zelandiae (NZ ice plant)</td>
<td>Carex comans (Sedges)</td>
</tr>
<tr>
<td>Microtis unifolia (Orchid)</td>
<td>Carex breviculmis (Sedges)</td>
</tr>
<tr>
<td>Epilobium cinereum</td>
<td>Muehlenbeckia axillaris</td>
</tr>
<tr>
<td>Leptinella minor</td>
<td>Muehlenbeckia ephedroides</td>
</tr>
<tr>
<td>Leptinella serrulata</td>
<td>Coprosma atropurpurea</td>
</tr>
<tr>
<td>Linum monogynum</td>
<td>Coprosma petriei</td>
</tr>
<tr>
<td>Luzula ulophylla</td>
<td>Leucopogon fraseri</td>
</tr>
<tr>
<td>Dichondra repens</td>
<td>Blechnum penna-marina</td>
</tr>
<tr>
<td>Raoulia monroi</td>
<td>Dianella nigra</td>
</tr>
<tr>
<td>Raoulia tenuicaulis</td>
<td>Leptinella Platts black</td>
</tr>
<tr>
<td>Raoulia australis</td>
<td>Luzula spp</td>
</tr>
<tr>
<td>Senecio quadridentata</td>
<td>Myosotis australis</td>
</tr>
</tbody>
</table>

In accordance with the ARC TR17/2010, a density of 15 - 20 plugs per meter squared would be appropriate, although it is also stated that some larger tussocks may be better suited to a density of 4 - 5 plugs per meter squared. Due to the harsh Canterbury conditions, plants with less above ground mass may be more suited and a dense planting may help reduce aeolian erosion. It may be necessary to seek further advice from nurseries or Colin Meurk as to an appropriate density once plants have been sought as not all recommended species will be available and this may influence the ideal density. It is also
standard green roof practise that the plants are soaked immediately before planting and watered on the
day of planting to reduce planting shock (Fassman et al., 2011).

5. STRUCTURAL CONSIDERATIONS

The allowable structural load is often a major design constraint on the retrofit of an existing building
with a green roof. This allowable load is dependent solely on the existing capacity of the roof and hence
the amount of structural redundancy afforded under this design.

5.1 THE IMPORTANCE OF LIMITING THE STRUCTURAL LOAD

The installation of a green roof is significantly more expensive than conventional roofs (Gedge, 2004),
especially in New Zealand where a market has not yet been established for them. Because of this, steps
must be taken to ensure that extra costs are not incurred in terms of required strengthening of the
under-structure because of a heavy structural load imposed by the green roof system.

5.1.1 RETROFIT OF EXISTING BUILDINGS

For retrofit applications, limiting structural load is particularly important. Buildings that have been
constructed in New Zealand since 1984 have been designed using standards utilising Load and Factor
Resistance Design (LFRD) (Macrae, 2007). LFRD splits the factor of safety into two components, one
recognising variation in loading conditions, the other accounting for the variation in capacity. The
Standard form of the LFRD equation is shown below;

\[ \sum \gamma_i E_i \leq \varphi R_n \]

where the expression on the left represents the sum of factored loads on the structure and the
expression on the right represents the dependable resistance. The two factors \( \gamma \) and \( \varphi \) increase the size
of the load and reduce the capacity of the structure respectively. These variations were accounted for in
the previous Allowable Stress Design (ASD) method by a catch-all safety factor (Macrae, 2007). This
splitting of the factor of safety allows for a more succinct design than the previous ASD method,
increasing structural efficiency and ensuring the structure is not overdesigned for the specified loading.
(Clifton et al, 2011).

This means that older buildings can often have extra capacity for gravity loads over in comparison to
more modern buildings. An example of this is the design of reinforced concrete buildings, with older
stock from 1940s and 1950s designed such that some elements in the gravity system (floors, beams, but
fatally excluding connections) were able to give a near elastic level response to earthquake loading
(NZSEE, 2006). This means that these older reinforced concrete buildings are likely able to withstand the
extra permanent load imposed by a green roof without the need for retrofit.

Thus an attempt to minimise the green roof load should be made during the design process for green
roof retrofit and is especially pertinent for newer structures, as to improve the chance of installation
without the need for strengthening.
5.1.2 GREEN ROOF ON A NEW BUILD

Because of the increased initial capital cost of a green roof, the benefits gained in terms of reduced stormwater runoff, energy efficiency and roof durability are often overlooked. Consequently, a green roof is often the first thing to be struck off a green building strategy for a new build (Fassman & Simcock, 2011). Because of this, the imposed load on a new building should be minimised as to ensure that the option of a green roof doesn’t entail significantly larger and more costly structural elements than an ordinary roof.

Under normal operating conditions, the extra load imposed by a green roof is classified as a dead or permanent load, G (KPa). Thus a green roof makes a contribution to all load combinations; both serviceability and ultimate limit state under Section 4 of AS/NZS 1170.0.

5.2 DETERMINATION OF THE ADDITIONAL PERMANENT LOAD, G

The method for determining the additional permanent load imposed by the green roof is taken from the ARC TR17/2010: Extensive Green Roofs for Stormwater Mitigation, which has been formulated as a guideline for use in conjunction with AS/NZS 1170. This method goes into great detail as not to overestimate the green roof load for reasons discussed previously. Furthermore, as a green roof is designed specifically to maintain high permeability, the imposed load G, can be calculated by taking the average of the dry and wet loads (ARC TR17/2010, Section 8).

The contributions of the majority of the green roof components to the system weight can be found from tabulated and manufacturer values for common materials. As no extensive testing of material has so far been planned, the saturated weights of components such as the substrate and drainage layer will be taken from the results of the University of Auckland project (ARC TR17/2010, Section 5).

Values of the imposed load at a particular substrate depth will then be compared with the maximum extra loading (calculated from the floor section dimensions). If loading exceeds this maximum value, the substrate depth can be reduced and the load re-calculated. This may affect the species of plants possible for use.

5.3 WORST CASE LOADING – SATURATED DRAINAGE LAYER, Su

This is the worst case loading for a green roof system and can only occur when the primary drainage layer is blocked (ARC TR17/2010, Section 8.3). This load is determined by the saturated system weight only (unlike the average used in the determination of G). This action takes the place of snow loading, Su, in the load combinations checking ultimate and serviceability strength in section 4.2.2 of AS/NZS 1170.0.

5.4 CONTRIBUTION TO SEISMIC LOADING OF THE STRUCTURE

The contribution of the green roof to the seismic performance of the structure is greatly influenced by the initial weight of the system. Because of the large difference in system size and weight between the two options, the contribution to the seismic loading of each structure is likely to be very different.
5.4.1 DAMPING EFFECT OF GREEN ROOF ON STRUCTURE

In addition, work by Clifton et al., (2008) has also found that the addition of a green roof retrofit may have a positive impact on the damping of a building in wet conditions by acting as an energy dissipating mechanism, which in turn reduces the amount of base shear felt by the structure. From these tests it was found that by using the sloshing and mixing of free water in the drainage layer, an extra 0.2% of damping for a single storey model with a natural period of \( T = 0.22 \) s was gained.

5.5 WIND LOADING CONSIDERATIONS

Wind loads must also be considered in long term design due to the uplift forces that the roof is subjected to and can sometimes govern substrate depth (ARC TR17/2010, Section 8.5). Although unlikely to govern, these wind loads will be calculated using the method and equations outlaid by AS/NZS 1170.2. This method calculates the expected wind load on the structure accounting for the regional location of the structure, topography and level of shelter as well as the roof pitch. These wind loads on a roof can either act in a downward or upward direction.

6.0 CASE STUDY – EXPERIMENTAL GREEN ROOF AT THE UNIVERSITY OF CANTERBURY

As part of the research into applying a green roof for Christchurch conditions, a test scale green roof has been proposed for a roof around campus. This test green roof is of modular design and aims to test a variety of substrate depths and vegetation types subject to the limitations of the local conditions and existing capacity of the roof.

6.1 SITE SELECTION

6.1.1 SELECTION CRITERIA

In looking for possible locations for an appropriate site around campus the following general criteria were considered:

- The existing roof must be of moderate pitch, so a maximum slope of less than 15 °. This will ensure that accessing the roof is not too difficult, the tray system can be easily kept in place and that no issues arise with the stability on the substrate layer from sloping.
- The roof must also have relative ease of access (for a roof) as to allow for regular readings and monitoring if necessary.
- The roof must be structurally adequate to withstand the extra green roof load – i.e. not obviously weak like a corrugated plastic roof.
- The Roof must not be completely shaded as it would negatively affect the plant growth (Wilkinson & Reed, 2009) and would not accurately reflect the likely real-world conditions for most green roofs.
From the criteria outlaid above, the roof outside of the Environmental Lab on the 3rd Floor of the Civil / Mechanical building was chosen.

6.1.2 SITE DESCRIPTION - STRUCTURAL DETAILS

The selected roof is a precast floor slab outside of the Environmental Lab, 3rd Floor of the Civil Mechanical Engineering building.

**Construction:** Pre-stressed, precast concrete flooring units with a non-structural concrete topping. Features a butynol waterproofing layer on the surface.

**Description:** The structural elements of the floor consist of 500mm deep, precast single tee floor units. These units are spaced so that 6 units are present per 6400mm bay. These units are then topped with a 100mm thick concrete topping reinforced with 333 mesh to stop cracking. On top of this sits non-structural topping and the butynol layer. Structural Plans of this roof are included in Appendix B.1.

**Date Designed:** Structural drawings are dated 1995, so flooring units were selected to withstand loads determined by NZS 4203: 1992, General structural design and design loadings for buildings. This has since been superseded by AS/NZS 1170. Flooring units are seated on members designed using the concrete structures design standard, NZS 3101:1995. This standard has likewise been superseded by NZS 3101: 2006.

6.1.3 POSITIVES AND NEGATIVES OF THE SITE

- Close proximity to researcher's department and weather monitoring station. This is convenient and allows for accurate weather data for hydrological calculations.
- Relative ease of access in comparison other roofs around campus as there is a door access to the roof.
- The nature of the construction material; precast concrete units, means that it is unlikely that any extra load imparted by an extensive green roof will exceed the existing capacity of the roof.
- Large size and weight of overall structure. This means that extra load imposed by the green roof is unlikely to impact on the seismic performance of the building.

- The butynol waterproofing layer on top of the roof is brittle and easily damaged. This would require extra care to be taken when on top of the roof.
- Roof is elevated above 3 m, raising safety concerns.
- Roof consists of precast single tee units; a type of flooring that is no longer widely in use in New Zealand with precast double tees preferred now instead. This means that it is harder to track down load span tables to accurately assess existing capacity.

6.1.4 SITE CAPACITY

As described in Section 6.1.2, the roof consists of precast single tee units with a depth of 500mm per tee unit. Precast, prestressed concrete flooring units such as these are proprietary products that are
selected from the manufacturer to withstand a particular loading for a desired span. This means that the usual process for determining floor capacity is to look up the load span table provided by the manufacturer.

Since this floor has been designed, precast single tee flooring units have fallen out of favour with double tee units now the preferred option in New Zealand as they provide benefits in transport and construction (Precast New Zealand, 2008). Load span tables also often feature variable topping thickness depending on the table. Because of this, it is hard to obtain a similar load span table, with the right topping thickness to determine existing capacity. A comparable load span table for a double tee unit from a large New Zealand manufacturer has thus been used to get a “ballpark” estimate of capacity.

Stahlton, a subsidiary of Fulton Hogan and a large manufacturer of precast units provides a load span table for their double tee products featuring a topping of 75 mm. From this table, a double tee of depth 500mm can support an unfactored superimposed load of 5.7 KPa for a 14 m clear span (Stahlton Product Data Sheet, 2011) like the one featured in this floor. Even when accounting for the increased topping included in the design (100 mm instead of 75 mm) as well as the non-structural topping present on the roof, the existing flooring has plenty of extra capacity.

From the structural plans of the building, the precast single tee slab used in this roof is also used elsewhere on level 3 of this building, with the roof appearing to be a continuation of the floor slab from the adjacent Environmental Lab and the hallway leading to it. This will mean that it is designed to take the imposed loading used for a corridor, 5.0KPa (NZS 4203: 1992, table 3.4.1). This is similar to the estimate provided by the load span table. Both these figures are much higher than any load imposed by an extensive green roof so structural loading is thus not seen to govern design.

6.2 HYDROLOGICAL CALCULATIONS

It is necessary to calculate the hydrological response of a green roof in order to quantify the effectiveness of the system. Such calculations can be completed after monitoring of a green roof system has occurred or alternatively can be predicted through previous local trends.

The amount of retention a system has is reflective of its ability to mitigate the effects of stormwater runoff. The retention capacity of the system is dictated by the amount of rainfall compared to
evapotranspiration and once this capacity is reached runoff will occur. Therefore measuring runoff from a system with a known water holding capacity, receiving a known amount of rainfall will allow the amount of evapotranspiration to be approximated.

The actual evapotranspiration from a green roof varies from the reference evapotranspiration by the crop coefficient. In the calculations below, coefficients of 0.3 – 0.5 are used to provide example $ET_c$ calculations; these are not necessarily representative of the actual coefficient for the systems but demonstrate the effect the vegetation has on the level of evapotranspiration.

$$ET_c = ET_{ref} \times K_c$$

For January: $ET_c = 146.9 \text{ mm} \times 0.3 = 44.07 \text{ mm}$

Due to higher rainfall levels than evapotranspiration rates for most months, the opportunity arises to have a rain water harvesting tank to capture the stormwater runoff from the roof for the use of irrigation back onto the roof in times of low water input. This is especially relevant in Christchurch as the area has long periods of antecedent dry days.

Table 6: Examples of evapotranspiration rates for various crop coefficients.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall (mm)</td>
<td>42</td>
<td>39</td>
<td>54</td>
<td>54</td>
<td>56</td>
<td>66</td>
<td>79</td>
<td>69</td>
<td>47</td>
<td>53</td>
<td>44</td>
</tr>
<tr>
<td>ET (mm)</td>
<td>146.9</td>
<td>119</td>
<td>91.1</td>
<td>43.7</td>
<td>23.9</td>
<td>11.9</td>
<td>17.1</td>
<td>23.6</td>
<td>49.1</td>
<td>69.1</td>
<td>105</td>
</tr>
<tr>
<td>ET (0.3)</td>
<td>44.07</td>
<td>35.7</td>
<td>27.33</td>
<td>13.11</td>
<td>7.17</td>
<td>3.57</td>
<td>5.13</td>
<td>7.08</td>
<td>14.73</td>
<td>20.73</td>
<td>31.5</td>
</tr>
<tr>
<td>ET (0.4)</td>
<td>58.76</td>
<td>47.6</td>
<td>36.44</td>
<td>17.48</td>
<td>9.56</td>
<td>4.76</td>
<td>6.84</td>
<td>9.44</td>
<td>19.64</td>
<td>27.64</td>
<td>42.0</td>
</tr>
<tr>
<td>ET (0.5)</td>
<td>73.45</td>
<td>59.5</td>
<td>45.55</td>
<td>21.85</td>
<td>11.95</td>
<td>5.95</td>
<td>8.55</td>
<td>11.8</td>
<td>24.55</td>
<td>34.55</td>
<td>52.5</td>
</tr>
<tr>
<td>Difference between rainfall and evapotranspiration:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ET (0.3)</td>
<td>-2.07</td>
<td>3.3</td>
<td>26.67</td>
<td>40.89</td>
<td>48.83</td>
<td>62.43</td>
<td>73.87</td>
<td>61.92</td>
<td>32.27</td>
<td>32.27</td>
<td>12.5</td>
</tr>
<tr>
<td>ET (0.4)</td>
<td>-16.76</td>
<td>-8.6</td>
<td>17.56</td>
<td>36.52</td>
<td>46.44</td>
<td>61.24</td>
<td>72.16</td>
<td>59.56</td>
<td>27.36</td>
<td>25.36</td>
<td>2.0</td>
</tr>
<tr>
<td>ET (0.5)</td>
<td>-31.45</td>
<td>-20.5</td>
<td>8.45</td>
<td>32.15</td>
<td>44.05</td>
<td>60.05</td>
<td>70.45</td>
<td>57.2</td>
<td>22.45</td>
<td>18.45</td>
<td>-8.5</td>
</tr>
<tr>
<td>ET / day</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_c = 0.3$</td>
<td>1.42</td>
<td>1.27</td>
<td>0.88</td>
<td>0.44</td>
<td>0.23</td>
<td>0.12</td>
<td>0.16</td>
<td>0.23</td>
<td>0.49</td>
<td>0.67</td>
<td>1.05</td>
</tr>
<tr>
<td>$k_c = 0.4$</td>
<td>1.89</td>
<td>1.7</td>
<td>1.17</td>
<td>0.58</td>
<td>0.31</td>
<td>0.16</td>
<td>0.22</td>
<td>0.30</td>
<td>0.65</td>
<td>0.89</td>
<td>1.40</td>
</tr>
<tr>
<td>$k_c = 0.5$</td>
<td>2.37</td>
<td>2.12</td>
<td>1.47</td>
<td>0.73</td>
<td>0.38</td>
<td>0.20</td>
<td>0.28</td>
<td>0.38</td>
<td>0.82</td>
<td>1.11</td>
<td>1.75</td>
</tr>
</tbody>
</table>

The table above shows historical evapotranspiration rates. It is important to note that not all of the water received by the green roof from rainfall or by other means is available to be evapotranspired. Readily available water and plant stress water are the main components of storage for rainfall events (Fassman et al., 2011). It also needs to be noted that the difference between rainfall and evapotranspiration as shown above will not all be seen as runoff as water will be held within the substrate and by vegetation.

Below are the runoff calculations for a 100 m² roof with various substrate water holding capacities (WHC) and depths. The following assumptions were made in the calculations:
• The mean monthly historical wet days are consecutive and the mean historical monthly rainfall falls in that period (giving a high water intake scenario).
• Theoretical calculation that if the water holding capacity of a substrate is 60% and the substrate is 100 mm deep then 60 mm of water should be retained, this fluctuates slightly due to plant water stress demands but can be reasonably assumed for the purposes of these calculations.

Table 7: Runoff volumes from 100 m² roof of varying depths and water holding capacities.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHC (40%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>3.7</td>
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<td>WHC (60%)</td>
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<td>3.5</td>
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<td>WHC (70%)</td>
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<td>70 mm</td>
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</tbody>
</table>

### 6.3 SUBSTRATE CALCULATIONS

Testing is needed in order to obtain the water holding capacities, permeability and other physical properties of a substrate mix. This is due to smaller particles filling void spaces between larger particles and thus altering the theoretical values that may be obtained by adding properties of different materials together. Such testing has not been completed within the scope of this project as the key research objective was to install a green roof in order to monitor the effectiveness of such a system in Christchurch. However when the maximum water holding capacity of a substrate is known along with the dry bulk density for a substrate then the system weight at maximum water holding capacity can be found:

\[
\text{Maximum Water Holding Capacity (\%)} \times 1000 \left( \frac{kg}{m^3} \right) + \text{Dry Bulk Density} \left( \frac{kg}{m^3} \right) = \text{System Weight at Maximum Water Capacity} \left( \frac{kg}{m^3} \right)
\]

It is then necessary to calculate the saturated system weight or system weight at maximum water capacity as this will give the largest loading on the structure. Due to the permeability of most green roofs this saturated state along with possible ponding is very rarely reached, thus meaning that if a structure has the load bearing capacity to hold such a state with a factor of safety then the green roof will be able to be adequately maintained.
The table below shows the properties of the Stormwater 360 Roofmix that will be used for the University of Canterbury green roof implementation along with other common green roof materials.

Table 8: Specification of Substrate Mix

<table>
<thead>
<tr>
<th>Material</th>
<th>Dry Bulk Density (kg/m³)</th>
<th>Maximum Water Capacity (%)</th>
<th>Weight at Maximum Water Holding Capacity and Depth (kg/m³)</th>
<th>Saturate Permeability (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stormwater 360 Roofmix</td>
<td>540.0</td>
<td>60.0</td>
<td>1161.0, 135.0, 192.0, 0.04</td>
<td></td>
</tr>
<tr>
<td>Pumice 4 – 10 mm</td>
<td>540.1</td>
<td>41.8</td>
<td>979.1, 116.8, 164.7, 0.794</td>
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</tr>
<tr>
<td>NuGreen Zeolite</td>
<td>587.9</td>
<td>67.1</td>
<td>1279.9, 147, 210, 0.006</td>
<td></td>
</tr>
<tr>
<td>Pacific Pumice 2 – 9 mm</td>
<td>530.0</td>
<td>44.0</td>
<td>991, 118, 166.5, -</td>
<td></td>
</tr>
<tr>
<td>Expanded Clay</td>
<td>547.5</td>
<td>13.9</td>
<td>707.5, 89.65, 124.0, 5.00</td>
<td></td>
</tr>
</tbody>
</table>

Note: Includes 21 kg/m² for plant and drainage layer weight.

6.4 LOADING CONSIDERATIONS

6.4.1 ADDITIONAL PERMANENT LOAD IMPOSED

The ARC TR17/2010: Extensive Green Roofs for Stormwater Mitigation, outlines a very precise method of determining the expected additional permanent load (Section 8, ARC TR17/2010). This level of detail is taken to account for the likely case of low extra roof capacity in a retrofit situation.

For this case however, there is enough existing capacity to conservatively design for a dead load equal to the maximum possible loading scenario. This occurs in the unlikely event that the drainage layer is completely saturated, i.e. G = Sₜ. After consultation with the manufacturer of the proprietary substrate, a maximum weight of 210 kg/m² (= 2.1 KPa) was taken as the saturated and hence permanent load imposed by the structure.

6.4.2 SEISMIC LOADING CONSIDERATIONS

The contribution of the green roof to the seismic performance of the structure is greatly influenced by the initial weight of the system. Because of the large difference in system size and weight between the two options, the contribution to the seismic loading of each structure is likely to be very different.

Because of the small planned area of the trial roof (~20 m²), the likely low limit for additional permanent loading and the size of the overall structure, the addition to the seismic weight, W (Section 4.2, NZS 1170.5) and hence the base shear, V (Section 6.2.1.2, NZS 1170.5) is likely to be low. For example, a thick extensive roof imparting 2 KPa would only add an additional 40 KN to the overall weight, a fraction of
the existing value for this building. Because of this small change in weight, it has been assumed the change in seismic performance is small and is therefore not considered in the investigation.

6.4.3 WIND LOADING

Wind loads must also be considered in long term design due to the uplift forces that the roof is subjected to and can sometimes govern substrate depth (ARC TR17/2010, Section 8.5).

The ultimate limit state (ULS) wind load and in particular the uplift load, was then calculated using the methods detailed by AS/NZS 1170 parts 0 and 2. For full details of the calculation method see Appendix C.1. As part of the calculations, the following assumptions were made to simplify calculations;

− It was assumed that the steel handrails lining the east and west sides of the roof disrupted the wind flow enough to stop any meaningful wind pressure on the sides of the test rig. As part of this, it was also assumed that the testing rig would be less than 600 mm from the ground, which was the clearance provided by the steel handrails. This meant that only the uplift force induced by the wind was calculated.

− Relating to this, it was also assumed that any lateral loading from wind that was not blocked by either the east and west handrails or south facing podium would not be larger than the lateral load accounted for in the rig design (Appendix C.1).

− It was assumed that the scanned architectural plans of the roof remained in scale as the height of each of the handrails and podium relative to the highest point on the roof were measured from these drawings.

− Assumptions were also made during the calculation process in regards to the design factors used for classifying the wind conditions and building type. These assumptions were roundly conservative. See Appendix C.1 for details.

From these calculations, it was estimated that an uplift wind pressure of 0.49 KPa was induced during a ULS wind load of return period 1000 years. As the green roof system imposes a weight of 2.1 KPa, it was concluded that no uplift of the test system would occur.

Because of the assumptions made in this calculation, a more thorough analysis of the wind flow over this roof may be desired, but because of the conservative nature of the assumptions and the relatively heavy weight of the system, uplift is not likely to be an issue.

6.4.4 LOADING COMBINATIONS

The following ULS loading combinations were considered when assessing the load on the existing roof;

− $1.35G$
− $1.2G + 1.5Q$
− $1.2G + W_u + \Psi_cQ$

− $0.9G + W_u$
− $1.2G + S_u + \Psi_cQ$
Loading combinations featuring earthquake loads were excluded from consideration because of the lack of a seismic analysis and the assumption that the slab roof would more likely be governed by gravity loads instead of seismic.

The live loading for the roof during the testing phase was also assumed to be 0.25KPa, which is the loading specified for maintenance only (AS/NZS 1170.1, section 3.5).

The snow loading for the site was below the threshold for sub-alpine regions and was thus taken as 0.4KPa (AS/NZS 1170.3, clause 4.2.1).

Calculations were made for each of the combinations. From this, it was found that the gravity only load, 1.35G governed at the ultimate limit state, with a factored loading of 4.5KPa to be considered for the roof load. For details of the calculations made in this process, see Appendix C.2.

This loading is less than the approximations made for slab capacity in section 6.1.4, which roughly estimated the slab capacity at 5.7KPa and 5.0 KPa respectively, meaning the roof is able to take the loading from the test green roof. These findings were also in line with that of the campus’s Facilities Management which approved the site for the green roof test.

6.5 DESIGN SCHEMATIC OF TESTING SYSTEM

6.5.1 SUBSTRATE DEPTH

LiveRoof systems will be employed; utilising depths of 100 mm and 150 mm as are standard for LiveRoof Standard and LiveRoof Deep systems. Such depths will be more adequate to support plant life during long dry periods that are common in Christchurch conditions. The deeper substrate depths also open up the opportunity to expand the plant pallet and include native grasses.

6.5.2 PLANTING

The implementation of 6 systems allows for:

- Native grasses and groundcover at 100 mm and 150 mm
- Sedums at 100 mm and 150 mm
- Substrate at 100 mm and 150 mm
- The roof itself acting as a control

Monitoring will be able to indicate the difference in vegetation growth and stormwater retention for the two different depths and two different vegetation types, with the ability to compare to non-vegetated substrate and the exposed roof top (the control).

Substrate properties and vegetation type along with the local climatic conditions determine the hydrological response of a green roof system, hence vegetation and plant diversity affect runoff reduction from green roofs. Therefore understanding the hydrological performance of different vegetation makes it possible to choose the appropriate plants to maximize the benefit of reduced water runoff from green roofs (Nagase & Dunnett, 2012).
The proposed plant selection for the University of Canterbury green roof system will allow comparisons to be drawn between proven sedum species, native grasses and bare substrate. The use of native species is an appealing option and research has shown that grasses may be an effective stormwater reduction option. In the study by Nagase & Dunnett (2012) it was found that grass species were the most effective at reducing water runoff, followed by the forbs and sedums (Nagase & Dunnett, 2012). From these findings it was recommended that grasses and forbs, which have a tall height, large diameter, and large shoot and root biomass are recommended if reduction of water runoff is the main purpose of installing a green roof. This result agrees with previous hydrology studies; height, canopy size and density have been reported to determine interception fluxes (e.g., Crockford & Richardson, 2000). These findings are of relevance as one of the main focuses of the University of Canterbury trial is to monitor the hydrological performance of the green roof system.

8.3 MODULAR TRAY SET-UP

Five trays approximately 2 m x 1.2 m will be implemented on the roof. These trays will house 9 modular Stormwater 360˚/LiveRoof systems. Due to the free drainage of these systems coupled with the slight slope (<2%) of the setup there will be no need to provide additional under drainage. The 6 trays will be lined with a polyethylene liner to act as a root and water barrier along with the impermeable trays. A drainage port will be present at the lower end of the modular housing tray to allow infiltrate to be collected. This port will be design to be able to allow for flow at the maximum expected rate so as to not induce water logging in the system. At this stage the trays available have tapered edges which are not ideal as this allows for water to bypass the vegetated/substrate layer. Alternative square trays are being investigated; otherwise a covering of some description will be devised to resolve this problem.

Full details and schematics of a possible green roof testing rig are included in Appendix D, with design calculations included in Appendix C.3.

7.0 FUTURE ACTIONS

The green roof to be implemented at the University of Canterbury will be monitored throughout the year as part of a 3rd professional year Natural Resources Engineering project. The outcomes and conclusions drawn from this monitoring will contribute towards the first data of living roof systems in Christchurch and benefit the rebuild of our city. The following parameters will be measured during monitoring of the green roof on campus:

Precipitation (mm) – measurement of the rainfall received by the green roof system.

Runoff (m³) – water exiting the system which will enter the stormwater system.

Reference Evapotranspiration (mm d⁻¹) – the evapotranspiration levels calculated from local climatic data. This value will vary from the actual evapotranspiration by a factor known as the crop coefficient. This coefficient will be able to be approximated by evaluating the difference between the precipitation and runoff.

Slope of Vapour Pressure Curve (kPa °C⁻¹) – parameter for evapotranspiration calculation.

Mean Daily Net Radiation (MJ m⁻²d⁻¹) – parameter for evapotranspiration calculation.
Soil Heat Flux (MJ m\(^{-2}\) \(d^{-1}\)) – parameter for evapotranspiration calculation.

Mean Daily Air Temperature (\(^{\circ}\)C) – parameter for evapotranspiration calculation.

Wind Speed at 2 m Elevation (\(ms^{-1}\)) – parameter for evapotranspiration calculation.

Saturated/Actual Vapour Pressure (kPa) – parameter for evapotranspiration calculation.

Photo-synthetically active radiation (W/m\(^2\)) – parameter for evapotranspiration calculation.

Soil Temperature (\(^{\circ}\)C) – temperature of the soil effects plant growth.

Humidity (%) – moisture in the air effects plant growth and evapotranspiration rates.

Soil Moisture (%) – soil moisture influences plant growth, stormwater retention and potential evapotranspiration rates.

The data gathered will enable green roof system designs to be critiqued to suit Christchurch conditions. This work will also open up opportunities for further research into green roof systems such as using the system to treat stormwater, irrigation efficiency and investigating alternative substrates.

ACKNOWLEDGEMENTS

Aisling O’Sullivan – Civil and Natural Resources Engineering

Matt Morris – University of Canterbury Sustainability Office
9.0 REFERENCES


10.0 APPENDICES

APPENDIX A : HYDROLOGICAL DATA

- Appendix A.1: Average Daily Evaporation per Month in Christchurch Conditions
- Appendix A.2: High Intensity Rainfall System Data
- Appendix A.3: Christchurch Climatic Data

APPENDIX B: SITE PLANS

- Appendix B.1: Structural plan of Level 3, Civil / Mechanical Roof
- Appendix B.2: Roof Slope Calculations

APPENDIX C: HAND CALCULATIONS

- Appendix C.1: Wind Load Calculations
- Appendix C.2: Load Combination Calculations
- Appendix C.3: Green Roof Test Rig Calculations

APPENDIX D: GREEN ROOF TEST RIG DESIGN