DESIGN, STORMWATER BUDGETS AND WATER QUALITY OF CHRISTCHURCH GREEN ROOF SYSTEMS.

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ABSTRACT

Engineered green roofs are becoming prevalent as low impact designs (LIDs) since they offer multiple benefits including stormwater control. Christchurch's rebuilding plans strongly encourage LIDs including green roof systems but no performance data for these under local conditions are reported. In order to understand the hydrological response, and hence sustainability, of green roofs in Christchurch, different experimental systems were established and monitored for a year at the University of Canterbury. Six (each 2.4 m x 1.2 m) systems comprising unvegetated, sedum blends and native grasses blends of two substrate depths (105 mm and 152 mm) were installed on a 2% slope roof. Each modular system contained nine pre-grown Liveroof™ vegetated units enclosed in a watertight frame. Precipitation, effluent volume, water quality and soil moisture were measured following each rainfall event along with various continuously logged meteorological parameters to calculate evapotranspiration rates and hydrological budgets. Detailed design, hydrological and water quality results from monitoring these systems for their first year are presented to demonstrate how green roof systems respond under Christchurch's climate.

KEYWORDS

Green roofs, design, hydrological budgets, stormwater, water quality, Christchurch

PRESENTER PROFILE

Dr Aisling O'Sullivan is a Senior Lecturer in the Department of Civil and Natural Resources Engineering at the University of Canterbury. Her research group (www.hydroeco.info) focuses on many different stormwater research projects including more recently, pilot-scale green roof systems.

1 INTRODUCTION

Impervious surfaces characteristic of urban areas lead to increased stormwater runoff, decreased local infiltration or groundwater recharge, and the deterioration of receiving stream water quality in New Zealand (CCC, 2010). Consequently, Low Impact Design (LID) systems, such as green (or living) roofs are being investigated nationally (Voyde et al, 2011) and elsewhere to mitigate these impacts (Snodgrass and McIntyre, 2010, Ahiablame et al., 2012). Green roofs can also reduce temperature fluctuations passing through the roof membrane, resulting in lower energy consumption of buildings and improve local air quality by trapping air particles and smog (Teemusk and Mander, 2009) but are most commonly used for storm water management by facilitating a reduction of peak runoff flow rates and volumes (Mentens et al., 2006). Furthermore, green roofs have the potential to prevent pollutant migration from impervious roof materials themselves (Berndtsson et al. 2009; Köhler et al. 2002) that would otherwise migrate into local waterways in runoff.

Green roof systems consist of a waterproof roof membrane overlain with a drainage layer, roof barrier and vegetated substrate. They are generally categorised into two types; extensive and intensive. Intensive green roofs have a deeper substrate layer (>250 mm) enabling them to support a wider variety of plants (Snodgrass and McIntyre, 2010), whereas shallower substrates (<150 mm) in extensive green roofs limit the vegetation they can support to sedums and other drought-resistant and low-growing plants (Snodgrass and McIntyre, 2010). A deeper substrate provided by intensive green roofs results in higher imposed loading of 300 to 1000 kg/m^2 on the structure (Fassman and Simcock, 2011), making them less suitable for retrofit application and also more costly for new builds but intensive green roofs typically only exert an additional 70-200 kg/m^2 load imposed at fully saturated conditions (Fassman and Simcock, 2011).

The ability of a green roof to detain and evapotranspire precipitation depends not only on the prevailing meteorological conditions but also on the substrate and vegetation employed. For instance, hydraulic conductivity, depth, bulk density and organic content can all influence the detention and evapotranspiration of green roof systems (Oberndorfer et al., 2007). The water holding capacity of a substrate and its organic content will influence plant growth and therefore evapotranspiration. Additionally, effluent water quality from each system can be impaired depending on the age, maturation and substrates employed. Substrate with high ratios of organic matter (> 15%) can lead to elevated nitrogen and phosphorus concentrations in effluent water (Moran et al. 2003). Overseas, research has suggested that green roofs can act as a sink for nitrogen and as a source of potassium and phosphorus (Berndtsson et al., 2009). However, the effluent water quality will be reflected by a particular substrate mix and prevailing storm characteristics so must be quantified for each design.

Primary roles of vegetation in most extensive green roofs is to stabilise the substrates through root cohesion, provide aesthetics as well as afford some level of soil protection against the elements (Fassman et al., 2011). However, plants also evapotranspire through direct evaporation from the canopy and transpiration from the plant's leaves. Thus, a dense, self-repairing vegetation cover is desirable (Fassman et al., 2011). Vegetation types are very important considerations as plants can have a different photosynthetic capacity, growth rate, productivity, biomass accumulation and capacitance, all of which can influence transpiration (Lundholm et al., 2010). In choosing the vegetative community for green roof systems, their ability to withstand prolonged drought periods and colder winter temperatures is essential. However, other considerations may include their ability to resist disease, provide habitat and offer aesthetic benefits. Native plants have evolved to survive in their regional microclimatic conditions, and resist regional pests and diseases (MacIvor and Lundholm, 2011) so may be preferred over traditional exotic species such as *Sedum* (Monterusso et al., 2005). Mixed communities, especially tall forbs, grasses and succulents have successfully grown 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).

Various international research efforts monitored full-scale field experimental living roof systems over extended periods of time (>1 year) finding that they retained between 50-78% of precipitation (Berghage et al., 2009; Villarreal and Bengtsson, 2005). According to DeNardo et al. (2005) studies over a shorter period (<6 months) are less efficient in reducing the runoff (47-63%), due to statistical limitations with only a limited number of significantly large precipitation events. Deriving hydrological budgets from critical climatic variables including precipitation, wind and temperature measurements can provide data on the evapo(trans)piration rates, soil water storage capacity and effluent volume that influence the viability of green roof systems in drier climates (Berghage et al., 2009). These variables are of particular importance as they are location-specific which are likely to change substantially with climate. Nonetheless, a selection of species is always desirable as it allows for succession, and quick establishment preventing erosion and maintaining acceptable aesthetics.

The 2010-2012 Canterbury earthquakes resulted in extensive building and infrastructural damage throughout the region. As part of rebuilding Christchurch City, green roof systems could be encompassed into the design of new buildings. While a number of intensive and extensive green roof systems have recently been installed in Central Otago (typically for aesthetic goals), the majority of green roof technology monitored in New Zealand has been implemented in the Auckland region (ARC, 2010) and existing guidelines are primarily for Auckland's climatic conditions. Since Christchurch receives approximately half as much annual rainfall, two thirds the number of wet days, and greater extremes in daily temperatures (NIWA, 2012), designs developed in Auckland are not directly applicable in Christchurch that experiences different meteorological conditions. Consequently, having a good understanding of how green roof systems respond to climatic conditions in Christchurch is crucial to ensure their sustainability. This can be achieved by measuring the different hydrological and water quality parameters from different system designs across all climatic conditions prevailing.

This paper presents detailed information on the design and first year performance of different pilot-scale green roofs systems in Christchurch, New Zealand. Performance was assessed on how much of a reduction in storm water runoff was achieved in response to different types of rainfall events coupled with each systems ability to maintain health growing plants. Influences of different substrate depths and vegetation types were investigated. Data includes hydrological and water quality monitoring across all seasons, including an especially extended dry summer period. To-date, these systems have not received any irrigation water and have experienced meteorological extremes of periods of snow and drought.

2 EXPERIMENTAL DESIGN AND MONITORING

2.1 EXPERIMENTAL DESIGN

Six green roof modules (each 2.4 m x 1.2 m), were established at the University of Canterbury (43°31'18.27"S; 172°34'59.25"E) in May 2012 on a 2% slope butyl roof (Figure 1) on top of the two storey portion of a building. Each module consists of a plastic trapezoidal basin that houses nine LiveRoof™ units, which contain light-weight coarse sand and fine gravel aggregate engineered substrate (20% organic) (conforming to international FLL German standards) and an integrated drainage material layer. Each unit affords soil-to-soil cohesion facilitating water and nutrient transfer as well as root growth within each system. Each module is connected to catchment tanks (E) that collect all the runoff from each system for quantifying and water quality testing. Three modules have a shallower substrate depth of 105 mm, with the remaining three having a deeper substrate of 152 mm. Each system was either left unvegetated or grown with native tussock grasses or a blend of sedums pre-grown in February 2012 in Cromwell (45.04˚ S, 169.20˚ N). Each constructed system was braced with a timber frame to minimize disturbance during on-going seismic events at the research site. The systems have been monitored for a year to-date.

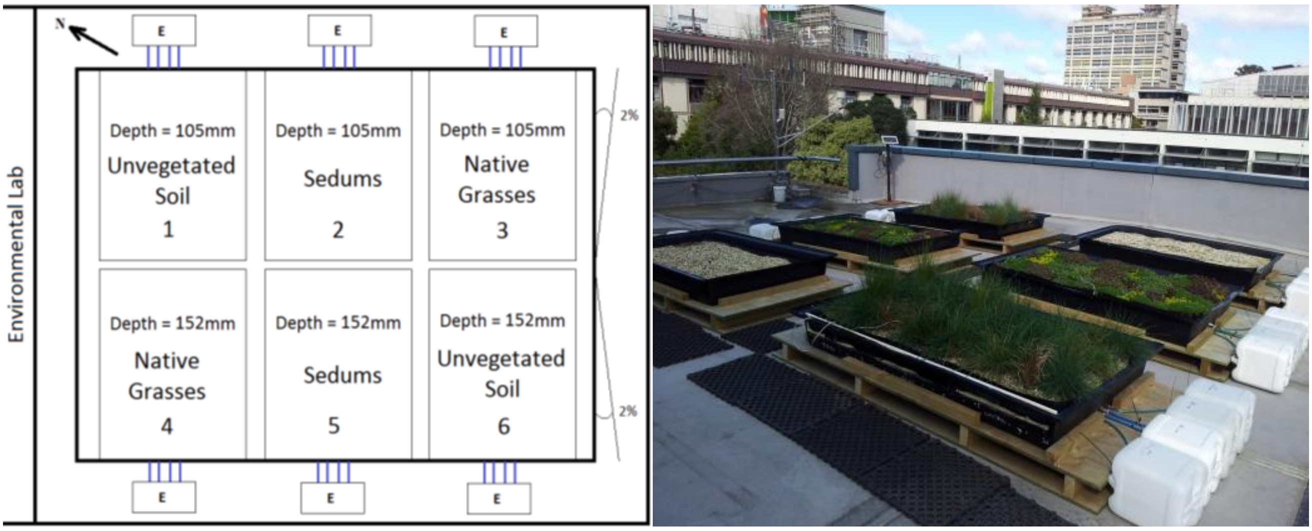


Figure 1: *Schematic and overview photo of setup.*

2.2 SUBSTRATE AND VEGETATION PROPERTIES

Physical properties of the light weight engineered substrate used in the pilot-scale green roof systems are provided in Table 1. Analysis of NIWA's High Intensity Rainfall Design System (HIRDS) revealed that for an intense rainfall event in Christchurch with an Average Recurrence Interval (ARI) of 100 years (or AEP of 0.01) and a duration of 10 minutes, a rainfall depth of 13.2 mm is expected, providing an intensity of 0.022 mm/s. In order to prevent ponding from occurring that could add weight to the systems or, float and scour substrates (Fassman et al., 2011), a substrate permeability > 0.022 mm/s was required.

Table 1:Substrate properties for the UrbanGreen Roofmix™ in the pilot-scale green roofs in Christchurch

Depth (mm)	Dry Bulk Density (kg/m^3)	Porosity (%)	Water Holding Capacity @1500 kPa (%w/w)	pH	Saturated Permeability (mm/sec)	Saturated bulk density (100 mm depth) (kg/m^2)	Particle Size (Equivalent spherical diameter, mm)
105 or 152	0.59	60	15	5.37	0.40 cm/s	130	1.0-10.0 (80%) 0.01-1.0 (20%)

Vegetation in the systems comprised or a blend of sedums identified as *S. acre, S. spurium, S. mexicanum, S. rubroctinctum, S. kamtschaticum and S. rupestre or S. reflexum* while native New Zealand grasses included *Poa cita (Silver Tussock), Festuca coxii and Festuca novae zelandiae* in order to assess the effect(s) of different vegetative communities on evapotranspiration rates.

2.3 STRUCTURAL AND WIND LOAD CONSIDERATIONS

Structural elements of the research site roof consist of 500 mm deep, pre-stressed, precast concrete single tee floor units, spaced at 6 units per 6400 mm bay. On top of this sits a 100 mm thick concrete layer reinforced with 333 mesh to prevent cracking and the butyl impervious layer. Flooring units were designed to withstand loads determined by NZS standards 4203: 1992 (which are since superseded by AS/NZS 1170) while they are seated on members designed using NZS 3101:1995 (similarly superseded by NZS 3101: 2006).

Under 'normal' operating building conditions, the extra load imposed by a green roof is classified as a dead or permanent load, G (KPa), and determined from the ARC TR17/2010 guidelines used in conjunction with the AS/NZS 1170 building standards. The existing flooring has plenty of existing load capacity to conservatively design for a dead load equal to the maximum possible loading scenario that could occur from all the experimental systems in the unlikely event that the drainage layers become completely saturated, i.e. $G = S_u$ (snow load), comprising a maximum saturated weight and hence permanent load of 210 kg/m^2 (≈ 2.1 KPa).

2.4 MONITORING

Meteorological data used to calculate evapotranspiration were continuously logged by a Campbell weather station adjacent to the systems. Precipitation, wind speed, relative humidity, radiation and temperature were recorded every 5 minutes. Additionally, values were compared with the nearest weather station provided by the Cliflo database (NIWA 2012) for quality assurance purposes. Soil moisture was measured using one Odyssey soil moisture logger per tray. Soil temperature was collected using Odyssey temperature loggers. Effluent water volume (following each precipitation event) was measured by weighing (accounting for tare weight) dedicated collection containers assuming the specific gravity of water to be one. Water quality parameters were measured in precipitation before it entered the green roof systems as well as in effluent from each system. Samples were instantaneously measure for pH (YSI Model 60 pH field meter) with a pre-calibrated instrument each time. Nutrient speciation was determined by R. J. Hill Laboratories, an International Accreditation New Zealand certified laboratory. Total Nitrogen (TN), Nitrite (NO2-), Nitrate (NO3-), Total Kjeldahl Nitrogen (TKN), Total Phosphorus (TP) and Dissolved reactive Phosphorus (DRP) analyses were conducted following APHA (2003).

2.5 SOIL MOISTURE DEFICIT

The soil moisture deficit (SMD) is the amount of rain (or irrigation) required to bring a soil back to field capacity. It is a simple way of determining the amount of available water for plant growth. If the soil moisture deficit is zero, water is abundant and no plant stress is expected. As soil dries out, the soil moisture deficit increases. The modules only hold a limited amount of water, about 20 mm in total. The permanent wilting point of the substrate lies at 11 mm. This means that of the 20 mm of water in the profile only 11 mm is available to plants (although sedums can probably abstract a bit more). The remaining 9 mm is too tightly bound to the soil particles for plant to abstract. The SMD can be calculated from equation 1.

$$SMD_t = SMD_{t-1} + P - ET_c \tag{1}$$

Where; *SMD = soil moisture deficit at time t or t-1, P = precipitation, ET_c = crop evapotranspiration.*

Reference evapotranspiration (ET_{ref}) is the rate at which readily available soil water can vaporize from specific vegetated surfaces (Jensen et al., 1990) and can be calculated using the P ASCE Standardised Reference Evapotranspiration Equation (equation 3).

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} \; e_s - e_a \;\; u_2}{\Delta + \gamma \;\; 1 + C_d u_2} \tag{2}$$

where: ET_{ref} = standardized reference crop evapotranspiration for a short crop (mm d^{-1}); Δ = slope of vapour pressure curve (kPa ºC^{-1}); R_n = net radiation (MJ m^{-2} d^{-1}); G = soil heat flux density (MJ m^{-2} d^{-1}); γ =psychrometric constant (kPa ºC^{-1}); C_n = numerator constant (K mm s^3 Mg^{-1} d^{-1}); T = mean daily temperature (ºC); u_2 = mean daily wind speed at 2 m height (m s^{-1}); e_s = saturation vapour pressure (kPa); e_a = mean actual vapour pressure (kPa); and C_d = denominator constant (s m^{-1}).

Dimensionless crop coefficients (K_c) for the different vegetation relate reference evapotranspiration (ET_{ref}) to crop evapotranspiration (ET_c) by accounting for different vegetative characteristics and phonological growth stages as shown in equation 2.

$$K_c = \frac{ET_c}{ET_{ref}} \tag{3}$$

3 RESULTS AND DISCUSSION

3.1 METEOROLOGICAL DATA

Although the document on green roof systems produced by the Auckland Council (ARC TR17/2010) is the foremost current New Zealand design guide, differences in weather parameters between Auckland and Christchurch (Table 2) highlight the importance of designing for local climates. It might be expected that less rainfall and longer antecedent dry periods in Christchurch will allow for greater water storage recovery but a high water holding capacity is necessary to counteract the high degree of evapotranspiration and long summer antecedent periods to enable greater soil moisture retention and successful plant growth. Vegetation needs to survive low winter temperatures, high summer temperatures and possible prolonged periods of no rainfall.

Table 2:Weather summaries for Christchurch and Auckland 1971 – 2000 (NIWA, 2012).

	Rainfall	**Wet days**	**Sunshine**	**Temperature**			**Wind**
				Mean	Highest	Lowest	Mean Speed
	mm	*≥ 1.0 mm*	*hours*	*°C*	*°C*	*°C*	*km/hr*
AUCKLAND	1240	137	2060	15.1	30.5	-2.5	17
CHRISTCHURCH	648	85	2100	12.1	41.6	-7.1	15

3.2 HYDROLOGICAL RESPONSE

The hydrological response of a living roof cannot be linked to one factor alone; multiple parameters such as rain depth, rain intensity, climatic conditions (primarily 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.

Table 3 provides an analysis of 45 recorded discrete rainfall events (to April 2013) since the green roof systems were established in May 2012 according to rainfall magnitude (or depth), in which volumes were converted to depth to make them independent of area and more directly comparable with rainfall. Effluent depth results indicate that for rainfall events less than 15 mm depth (77.8%), the green roof systems retain the majority of precipitation. Results also indicate that for rainfall events of magnitude 15-40 mm, while the systems do not provide complete retention, they do substantially reduce the volume of potential stormwater runoff. Whether rainfall is completely retained or not likely depends upon the rainfall intensity and antecedent dry period. Voyde et al. (2010) found that antecedent dry days have a significant effect on retention in green roof systems in Auckland. Preliminary results of the Christchurch systems suggest that longer antecedent dry days may afford slightly greater retention of rainfall although due to the 2013 extended summer periods in Canterbury, we have insufficient data (due to lack of rainfall events) yet to establish such a sufficiently clear relationship.

Table 3: Relationship between rainfall magnitude and green roof effluent. Rainfall depth variations are the average of first standard deviation values derived from three sets of rainfall measurements taken for each event. Similarly, variations in the average effluent depth measurements are the averages of first standard deviation values derived from effluent measurements recorded for all six systems during each rainfall event.

Rainfall Depth Range (mm)	Rainfall Frequency (# of Events)	Proportion of All Rainfall Events (%)	Proportion Producing Effluent (%)	Average Rainfall Depth ± Variation (mm)	Average Effluent Depth ± Variation (mm)
<2	5	11.1%	0.0%	1.4 ± 0.3	0 ± 0
2 - 5	13	28.9%	53.8%	3.4 ± 0.7	1.5 ± 0.4
5 - 10	10	22.2%	70.0%	6.8 ± 1.6	2.2 ± 0.5
10 - 15	7	15.6%	85.7%	12.5 ± 2.9	3.3 ± 1.1
15 - 25	4	8.9%	100.0%	22 ± 2.8	7.3 ± 2.1
25 - 40	4	8.9%	100.0%	31.1 ± 5.4	7.2 ± 1.8
>40	2	4.4%	100.0%	57.2 ± 9.8	22.4 ± 6
Sum	45	100.0%			

Performance of each system with in terms of effluent volumes is presented in Figure 2. The total cumulative volume of effluent throughout from each system since systems were first established is given along with the total cumulative volume of storm water runoff that would be expected from an impervious roof surface of the same area (solid black line). Deeper substrate systems (dashed lines) have consistently produced less storm water effluent due to their greater water holding capacity and longer flow path, while native grassed systems seem to produce less effluent than sedums. The volume of effluent from the shallow substrate systems was half and one third in the deeper systems compared to the unvegetated roof, with native grassed systems offering greater evapotranspiration potential. It is interesting to note that even the unvegetated (blue line) systems provided significant detention and hence evaporation of the precipitation compared to the bare roof. However, it is not yet clear why the shallow (100 mm) unvegetated system (solid blue line) slightly consistently produces less effluent than the equivalent depth vegetated systems.

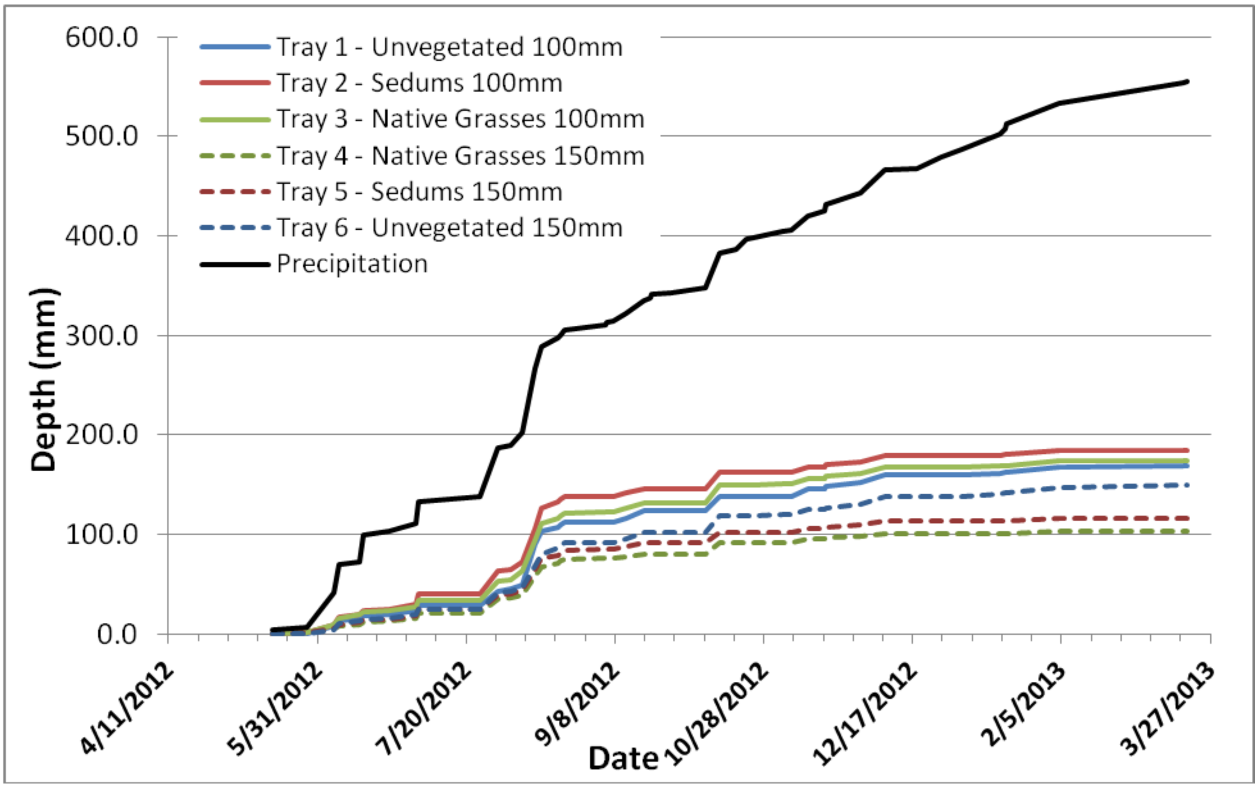


Figure 2: *Total effluent from each green roof pilot-scale system since their installation*

3.3 SOIL MOISTURE AND WATER BALANCE

Soil water content is generally the major limiting factor for transpiration, and hence survival, of green roof systems, but the rate at which this water is lost from the system and the subsequent cooling effect may depend on the type of vegetation 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 vegetation (soil moisture), ambient humidity and the subsequent water vapour pressure differential between sub-stomatal cavities and the boundary layer of air surrounding plants (Mellor et al., 1964).

Soil moisture data logged in the green roof systems in response to rainfall is presented in Figure 3. Absolute values are treated with some caution as accurate calibration of soil moisture sensors for a highly porous engineered substrate was challenging to achieve. Nonetheless, results are helpful as an indicator of potential water deficit and show that soil moisture responded typically instantaneously to substantial precipitation but was not influenced much with lower precipitation events. Effectively, the systems responded like a bath tub analogy – with sufficient precipitation, the substrate water content rapidly increased and was thereafter consumed by vegetation, most noticeably during extended dry periods when they were rapidly transpiring. The data infer that soil moisture levels in the systems were progressing towards water deficit by Spring (Sept.).

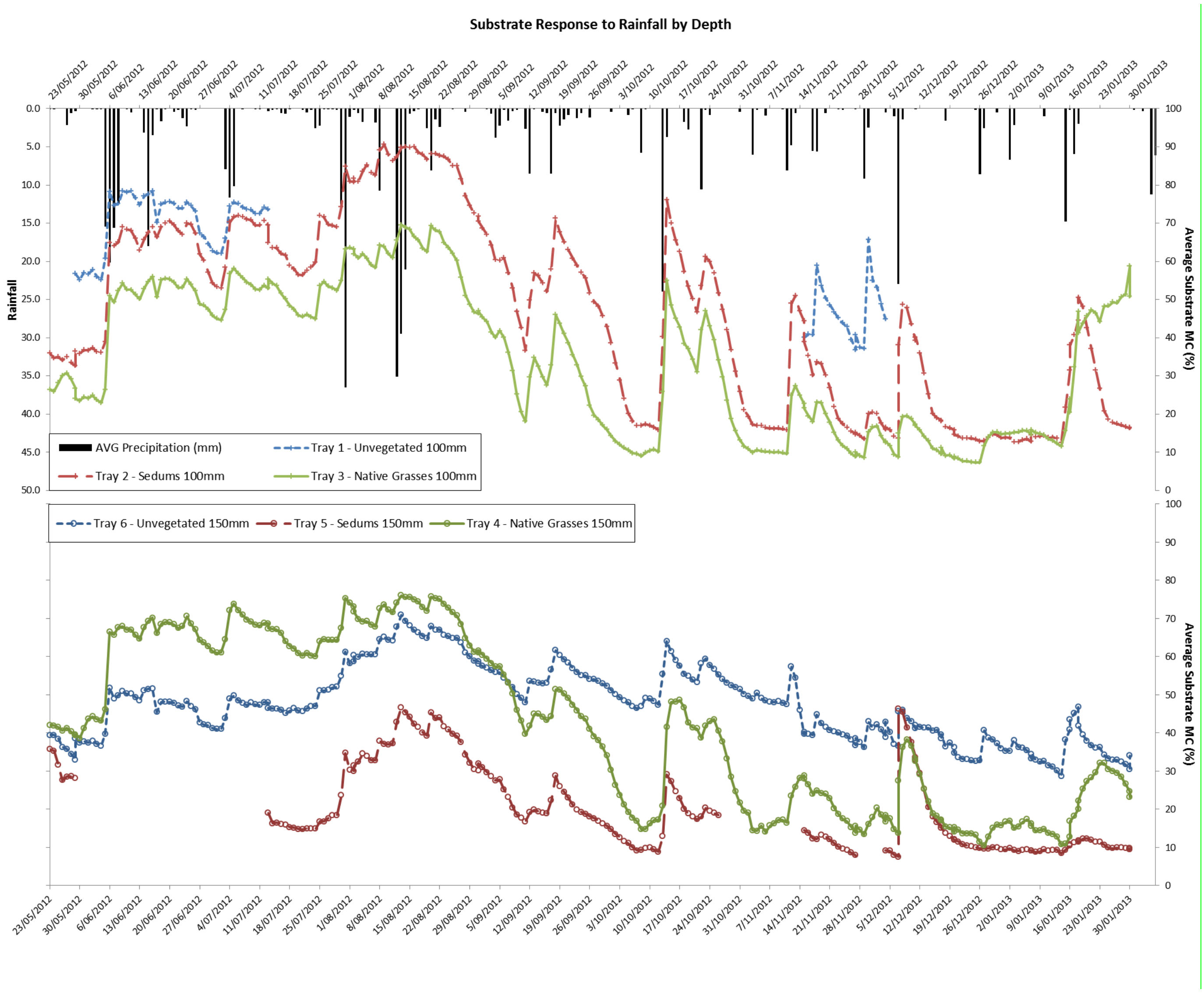


Figure 3: *Soil moisture response to rainfall*

Figure 4 presents the soil moisture deficit for native grasses in the deeper 152 mm substrate, as an example. During the winter months (June-August), soil moisture deficit is low as shown by the values hovering around zero. During this period, rainfall is frequent and generally exceeds evapotranspiration. However, in spring, the soil moisture deficit steadily increases as represented by the growing negative values. Not all rainfall events during this period are sufficient to reduce the soil moisture deficit to zero. However it can also be seen in figure 4 that the permanent wilting point is never reached. Although plant may have experienced some stress during the spring months, they still would have had some water available. By early summer (December) evapotranspiration rates are high enough for plants to regularly experience soils moisture deficits below the wilting point. At this point they no longer can take up any water. In the native grasses this resulted in the browning/dying of the above ground biomass.

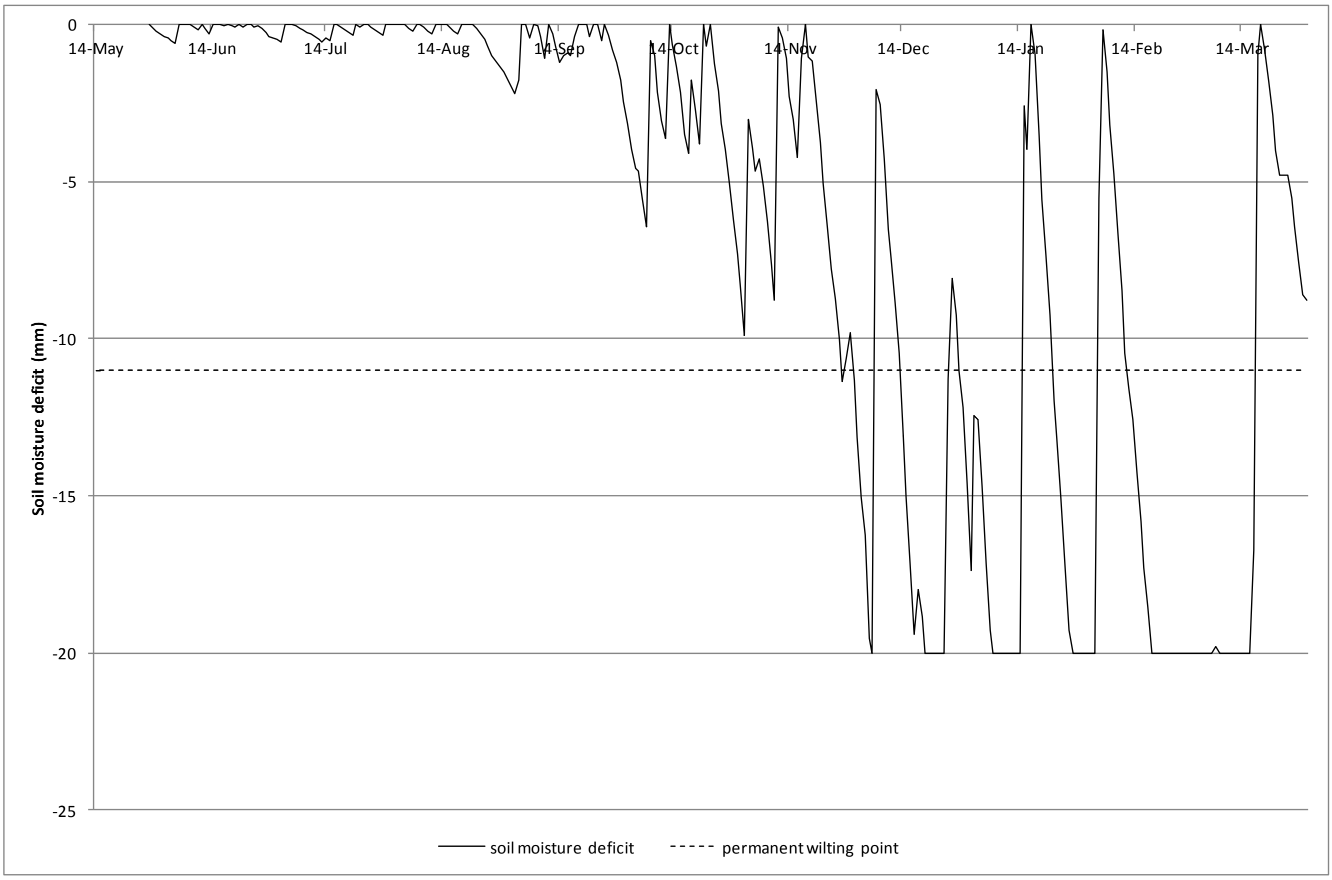


Figure 4 Soil moisture deficit for native grasses in 152 mm substrate May 2012-March 2013

While it is recommended to irrigate grassed green roof systems at times of prolonged dry periods, none of the pilot-scale systems in this study were irrigated. This was afforded by the experimental nature of the study where water deficit limits could be investigated in order to test how the systems would respond to such extreme conditions. Sedums by contrast, are able to reduce water losses because they can switch between C3 carbon fixation (which results in evapotranspiration during the day) and CAM photosynthesis (resulting in night time evapotranspiration and therefore less water losses). Using this strategy, sedums can tolerate dry periods for much longer and so would not likely require as much irrigation as grasses. Although sedums did incur some water stress, primarily in the form of loss of turgor pressure, this was not apparent until much later (March) by comparison to the stress incurred by grasses (December). Planting a green roof with several species may optimize water loss throughout the growing season (and potentially reduced irrigation needs) 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).

3.4 WATER QUALITY

Figure 5 presents precipitation and effluent pH from each green roof throughout the monitoring period. Effluent pH was consistently much lower than precipitation pH, which on an average was 5.94 (Figure 5). Concurrently, bench-top batch experiments of the same substrate blend show a rapid decline in pH to 5.37 within the first few minutes of mixing. This may be attributed to the Sphagnum peat that was used in the engineered substrate blend used for these pilot-scale experimental green roof systems. It is also possible that proton cations were displaced from the substrate during saturation assuming they were not strongly bound. As the systems become more established it would be expected that effluent pH could increase since Rowe (2011) collected effluent from green roof systems and found a pH of 5.2-5.6 S.U. early in the study which increased 7.2-8.3 S.U. as the system became more established, attributed to increased carbonate dissolution .

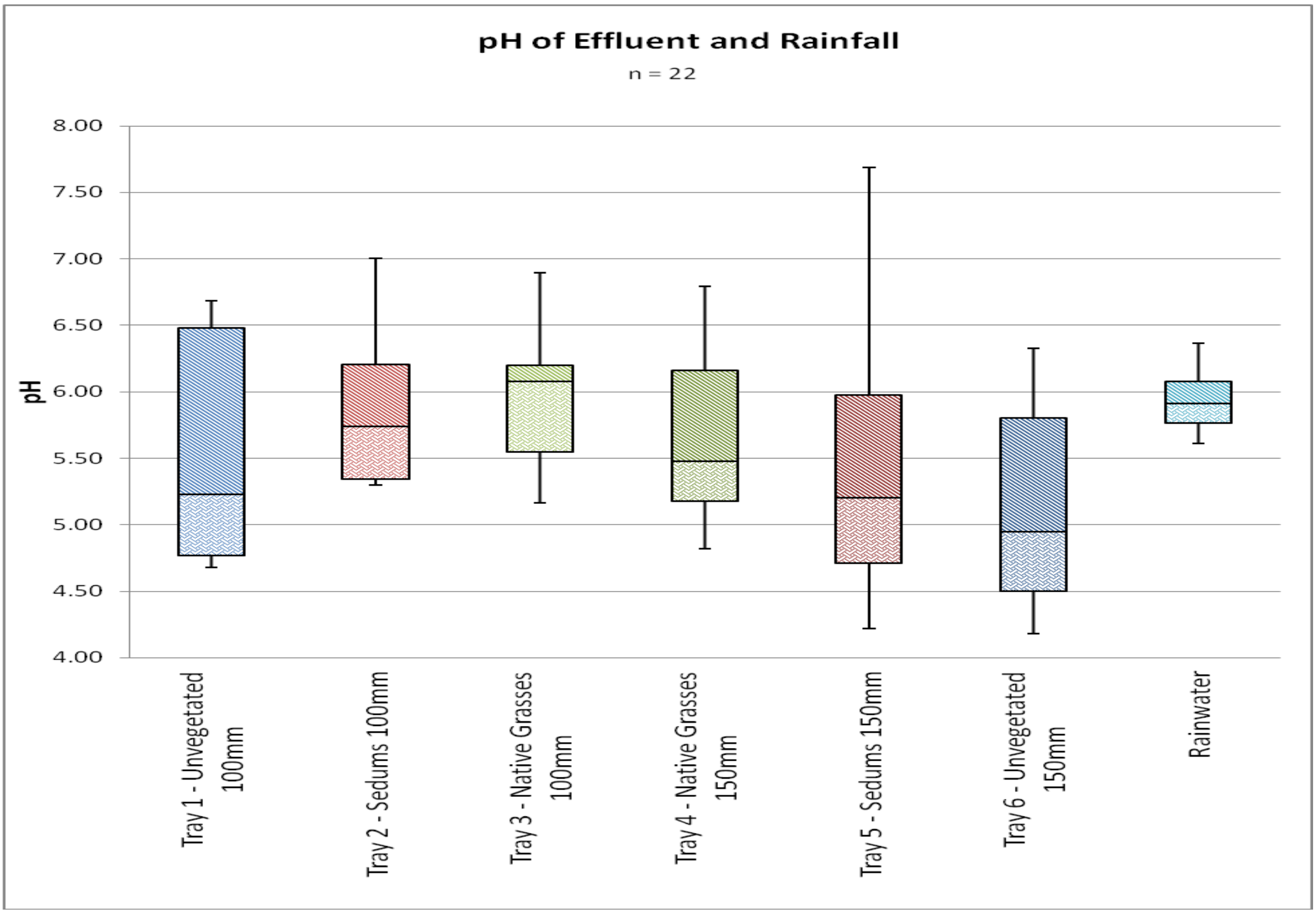
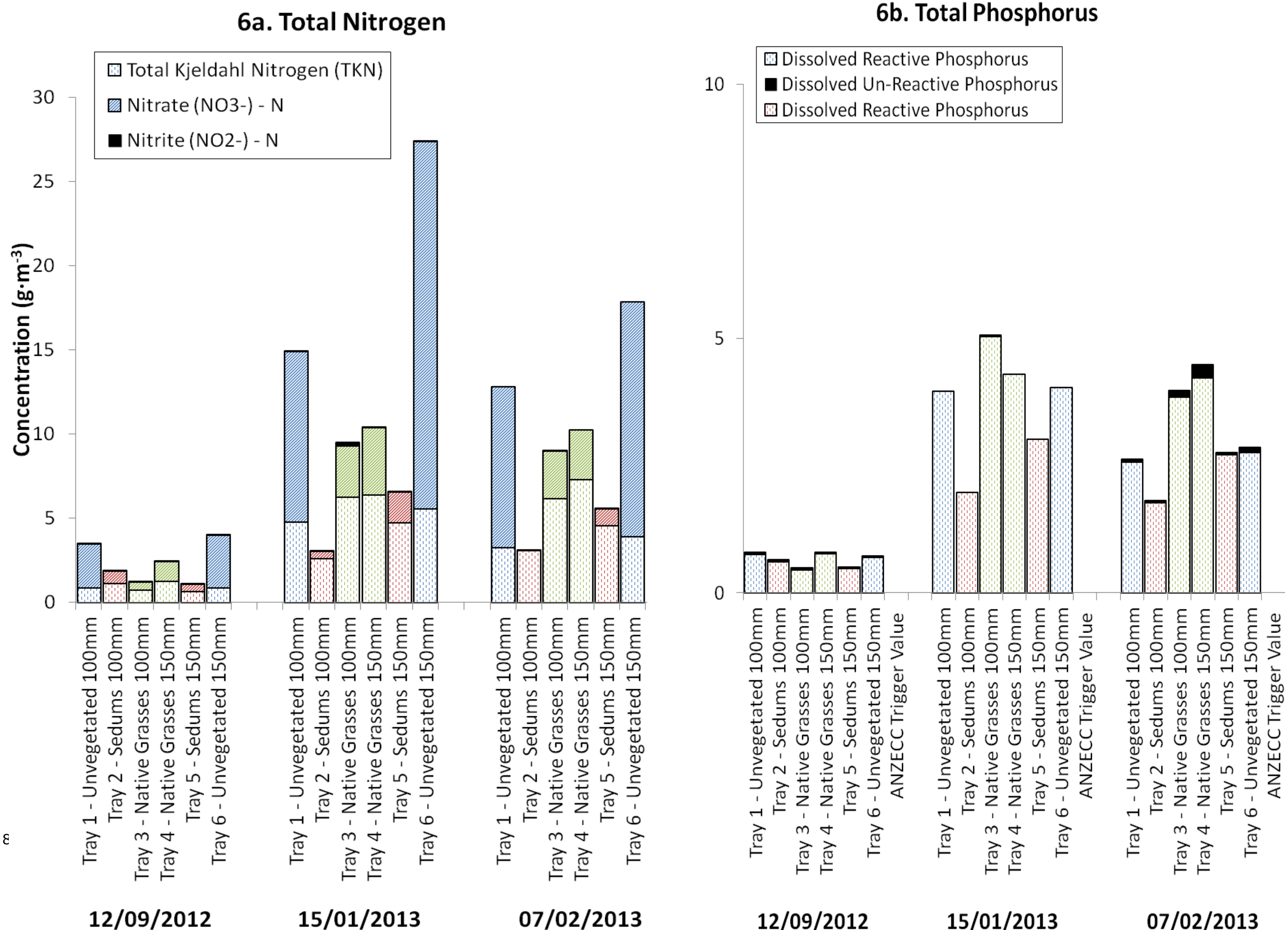


Figure 5: *pH of influent (precipitation) and effluent from all green roof systems since Jun 2012. The upper error bar corresponds to the 90th %ile, while the lower corresponds to the 10th%ile.*

During saturation of the green roof substrates, water can exchange readily-displaced cations (e.g. potassium) and anions (e.g. nitrate and phosphorus), which are released into the discharging water. It is important to have a good understanding of effluent water characteristics over time in order to ensure discharge water quality is not impairing receiving waterways from elevated nutrient concentrations released by substrate media. In order to accomplish this, it is necessary to quantify total nutrient export loads (a function of discharge and concentration), along with considerations of potential mixing (for dilution effects) in the receiving waterway. This has not yet been conducted for the study reported here since a number of non-point source pollution sources are conveyed into the same receiving stream resulting in a complex waterway. Since the ANZECC (Australian and New Zealand Environment and Conservation Council) water quality standards (0.295 g TN m^{-3} and 0.026 g TP m^{-3}) apply to ambient (i.e. in-stream concentrations), they are not directly comparable to effluent from the green roofs systems as they do not account for the effect of mixing. Nonetheless, nutrient speciation data for nitrogen (N) and phosphorus (P) measured in effluent from each green roof system are presented in Figure 6 to assess the potential nutrient export that might be possible (influent precipitation and roof runoff concentrations were below detection limits). The greatest component of N was nitrate and that of P was dissolved reactive phosphorus.


6a. Total Nitrogen
Total Kjeldahl Nitrogen (TKN)
Nitrate (NO3-) - N
Nitrite (NO2-) - N
Concentration (g·m-3)
0
5
10
15
20
25
30
Tray 1 - Unvegetated 100mm
Tray 2 - Sedums 100mm
Tray 3 - Native Grasses 100mm
Tray 4 - Native Grasses 150mm
Tray 5 - Sedums 150mm
Tray 6 - Unvegetated 150mm
12/09/2012
15/01/2013
07/02/2013
6b. Total Phosphorus
Dissolved Reactive Phosphorus
Dissolved Un-Reactive Phosphorus
Dissolved Reactive Phosphorus
0
5
10
Tray 1 - Unvegetated 100mm
Tray 2 - Sedums 100mm
Tray 3 - Native Grasses 100mm
Tray 4 - Native Grasses 150mm
Tray 5 - Sedums 150mm
Tray 6 - Unvegetated 150mm
ANZECC Trigger Value
12/09/2012
15/01/2013
07/02/2013

Elevated nutrient concentrations can be explained by two possible causes. Firstly, the systems in their first year were considered relatively new so would have incurred nutrient loss through effluent discharge (in excess of that incorporated into biomass during photosynthesis). Rowe (2011) found that phosphorus concentrations in green roof effluent decrease by approximately 26% after their first year and Köhler et al. (2002) suggested that by four years, an 80% reduction is expected attributed to initial decomposition of organic matter. Additionally, the engineered substrate in the Christchurch pilot systems contains a temperature controlled release fertilizer, which consistently reached the 'critical release temperature' of >21°C during the day, especially over the summer period. Due to an unusually sunnier summer in 2013, there has likely been an accelerated nutrient release from the fertiliser, which might result in an imminent decline in nutrient concentration. In New Zealand fresh waters, Abell et al. (2010) suggested that TN:TP (by mass) > 15:1 is indicative of potential P-limitation, TN:TP < 15:1 and >7:1 is indicative of potential N- and P co-limitation, and TN:TP < 7:1 is indicative of potential N-limitation, with an accepted TN:TP ratio for balanced growth of 7.2:1 by mass (16:1 by mole). Effluent nutrient concentrations in the Christchurch pilot-scale systems indicate that N limitation likely exists or is approaching.

Sedums showed lower nutrient release concentrations (Figure 6). It is possible that the ability of sedums to maintain the system cooler (due to a greater density of cover coupled with their succulent ability to store water) might slow the rate of fertiliser release due to a lower micro temperature prevailing. Substrate temperatures of the sedums were consistently lower than the grasses (data not presented). The results may also be explained by the faster sedum growth rates, which inherently consumed more available nutrients from the soil water leaving less for export in the discharge. However, greater sedum growth alone cannot explain the difference in effluent concentrations between systems since unvegetated systems showed lower concentrations than the grasses. Some (but not all) of the grasses reached wilting point so it is also possible some senescence from dead biomass released nutrients.

3.5 VEGETATION HEALTH

Although all systems generally coped well with the range of different seasonal conditions, the health of the native grasses in particular vegetation was most affected by the prolonged summer of 2013 since no system underwent any irrigation in the interest of the experiment (Figure 7). Nonetheless, the systems survived extremely well during the snow cover and bloomed extensively during Spring (Sept.) 2012.

An ideal green roof is self-sustaining requiring minimal maintenance, including irrigation (MacIvor and Lundholm, 2011 and Snodgrass and McIntyre, 2010). The biggest stressor for green roof systems is summer water deficit, exacerbated by extreme heat and high wind (Butler and Orians, 2011). Water deficit is often typical of Canterbury's climate, where temperatures can reach > 30 ˚C and wind speeds averages 15 km hr^{-1} (Table 2) that accelerate evapotranspiration. Drought conditions are also common due to roof exposure and the free draining nature of the engineered green roof substrate. Therefore, green roof vegetation must be able to survive frequent harsh conditions without frequent irrigation as the sedum systems in Christchurch have successfully demonstrated to-date. 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 to develop regional vegetation designs that optimize stormwater function (Schroll et al., 2011). Future experiments of this research will include planting mixed sedum and native grassed communities to ascertain their combined benefits across all climatic conditions experienced locally, along with controlled irrigation applications.

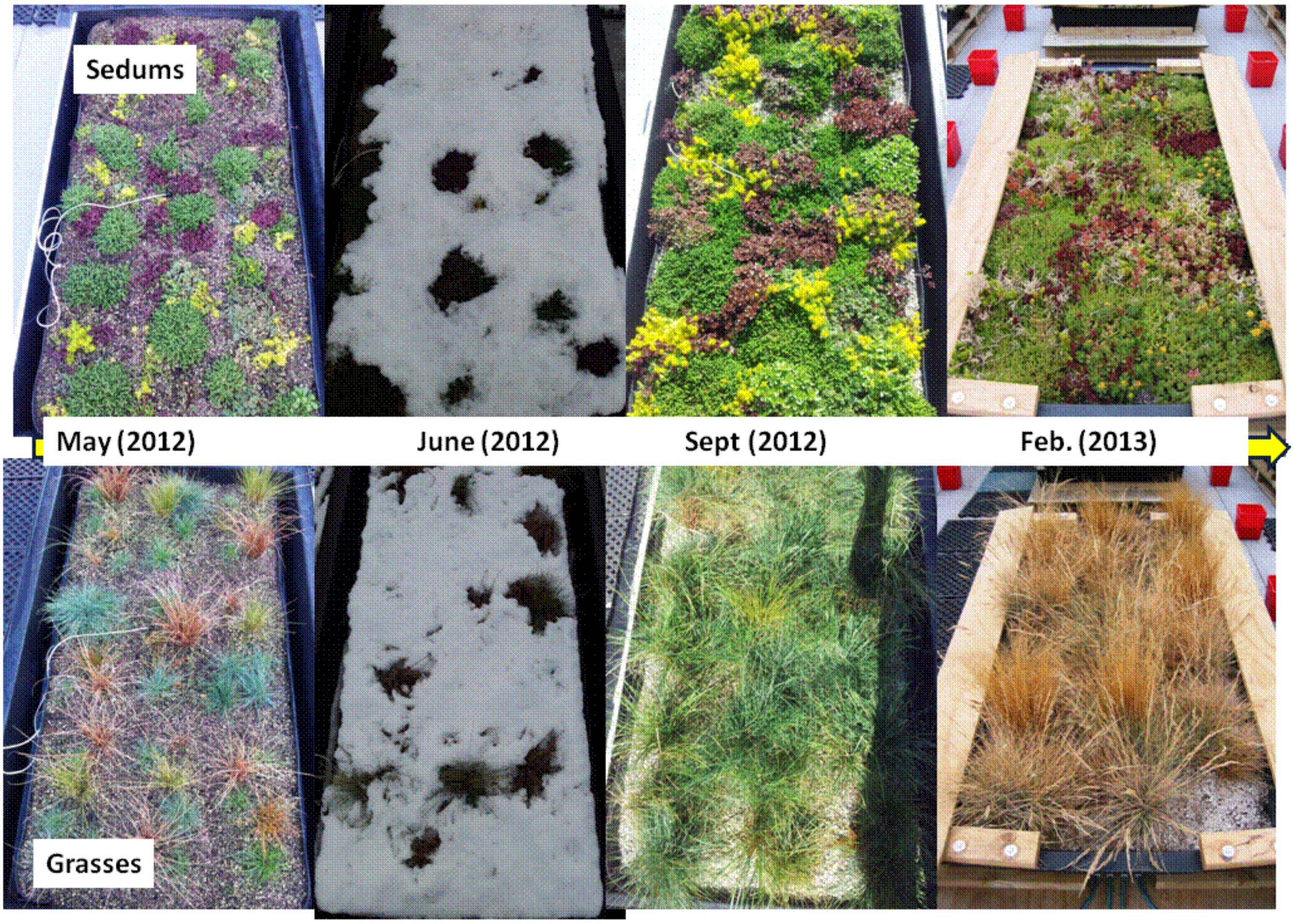


Figure 7: *Changes in vegetation health over seasons.*

CONCLUSIONS

The performance and hence sustainability of living systems such as green roofs can only be evaluated when they are monitored under prevailing climatic conditions. Preliminary data from the pilot-scale modular green roofs at the University of Canterbury indicate that systems consistently detained >50% of precipitation (typically more), which reduced potential stormwater runoff volumes by at least half. Substrates deeper by 50 mm offer slightly more water storage capacity, resulting in less effluent volumes. Systems planted with grasses produced lower effluent volumes than sedum systems, but plant health suffered in the summer as they were not irrigated. Soil moisture and available soil water conditions progressively declined reaching water-deficit conditions below the permanent wilting point in drier summer conditions, which were temporarily mitigated by moderate precipitation events. Limitations of available water for plant transpiration will ultimately dictate system longevity as vegetation health can suffer in periods of water deficit. Appropriate management of green roofs in periods of extended drought would require irrigation to maintain healthy living communities. Water quality in discharge leaving the systems needs to be adequately considered if it is conveyed into the receiving waterways. While observations from this study are only preliminary, they do indicate that green roofs are a feasible option for use in the rebuild of Christchurch and align with the best management practice of source control as an efficient stormwater management option.

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