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# Hydrology of a vegetable raingarden: implications for vegetable yield and stormwater management

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**Submitted in total fulfilment of the requirements of the degree of Master of Philosophy**

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**The University of Melbourne**

*Produced on archival quality paper*

## Abstract

Stormwater runs off the roofs and other impervious surfaces of cities at artificially high rates, and carries with it a range of contaminants. Raingardens, as biofiltration systems, are self-watering garden beds that are designed to capture and filter this urban runoff, using sandy soils and resilient plants. This improves the health of local waterways; reducing both pollution and erosion. Given these benefits, the construction of raingardens is being actively promoted in many cities, including Melbourne. However, raingardens might have another significant benefit; as sites of food production, at least on a small, non-commercial scale, using captured stormwater (urban runoff) for irrigation. The use of stormwater is an increasingly popular practice for overcoming water scarcity issues, which often constrain home vegetable gardening and other forms of urban agriculture. Nonetheless, the use of raingardens for food production has not been explored, and vegetables represent a significant departure from the types of plants that are conventionally used in these systems. As such, this thesis investigates the potential to produce vegetables in raingardens. The focus is on how water availability in a "vegetable raingarden" affects the yield of various common vegetables, as well as the role of raingardens in reducing urban runoff. These issues were explored through a 1.5-year field trial and a greenhouse (pot) experiment. This included an assessment of: 1) the merits of a sub-irrigated raingarden design relative to surface irrigation, 2) two soil types with different water-holding capacities (loamy sand, as used in conventional raingardens, and potting mix, as commonly used in vegetable gardens), and 3) reduction in both the frequency and volume of urban runoff. The results indicate that, if designed and managed effectively, it is possible to productively grow vegetables in raingardens, and the function of raingardens in reducing runoff can be retained. A wide range of common vegetables could be able to survive and produce yield in these systems. Furthermore, whether sub- or surface-irrigated, a vegetable raingarden has the potential to not require any back-up irrigation, particularly in the winter months under Melbourne conditions, and particularly if the sub-irrigated raingarden is fitted with waterproof lining so that it retains water. A lined raingarden would be reasonable for stormwater management; the system tested in the field trial reduced the volume of runoff by 63% and the frequency by 34%. However, an infiltration (unlined) raingarden type was even more effective, reducing both the volume and frequency of runoff by > 90%. Overall, sub-irrigation did not offer any clear advantages over surface irrigation in relation to vegetable growth and yield, or the efficient use of water. A traditional vegetable gardening soil or mix is the preferred soil type, because it provides relatively high water availability, and thereby greater vegetable growth and yield, compared to conventional raingarden media (loamy sand). The use of this vegetable gardening soil or mix precludes a uniform profile design for a raingarden, because a separate layer of "filter" media would be required.

**Declaration**

This is to certify that

(i) the thesis comprises only my original work towards the MPhil except where indicated in the preface,

(ii) due acknowledgement has been made in the text to all other material used,

(iii) the thesis is less than 50 000 words in length, exclusive of tables, maps, bibliographies and appendices

Signed: ______________________________________________ Date: 5th July 2013

## Preface

This thesis is a contribution to the project “Turning rain into food; the benefits and performance of vegetable raingardens.” It was a collaborative project funded by Melbourne Water, coordinated by Keysha Milenkovic. It was conducted by researchers at the University of Melbourne and Monash University.

In addition to myself, the research team was comprised of Tim Fletcher, Claire Farrell and Nick Williams (all of the University of Melbourne), and Minna Tom and David McCarthy of Monash University. Significant technical assistance was provided by Peter Poelsma, particularly during the construction of the “field trial” raingardens described in this thesis. Many aspects of the design of the field trial and the irrigation and monitoring protocols were established in meetings or other correspondence involving the whole research team. For most of its duration, however, the field trial was predominantly a partnership between me and Minna Tom, who was a Masters by Research student. Minna’s work was focused on contamination, whereas my work (as described in this thesis) was focused on hydrology and vegetable yield. The construction of the raingardens, which commenced in July 2011, as well as an initial period of data collection (most of the first summer growing season), took place in the few months immediately prior to my MPhil candidature enrolment in March 2012, during which time I was employed as a casual research assistant. The greenhouse experiment described in this thesis was conducted by me, under the supervision of Claire Farrell in particular. From initial planning to completion, it was conducted entirely during my MPhil candidature.

One of the outcomes of our project was an instruction sheet for building a vegetable raingarden, intended for members of the public and other interested parties. It was published by Melbourne Water, under the direction of Keysha Milenkovic, and is presented at the end of this thesis (Appendix I). I would also like to note the interesting work of an Honours student, Chris Porter. In affiliation with our project, Chris was investigating the likely social barriers and drivers that may influence the adoption of “vegetable raingardens” by the public.

## Acknowledgements

First, I must thank Claire Farrell in particular for her supervision. From considerable hands-on help with the field trial and in the lab, to countless meetings, Claire’s assistance with my work was always exceptional. I also gratefully acknowledge the supervision of Tim Fletcher, who advised on hydrology-related matters and administrative issues in particular. Additional advice and feedback was provided by Nick Williams (my third supervisor), which included comments on this thesis, and also by Steve Livesley and Chris Williams, as members of my Advisory Committee.

I also gratefully acknowledge the many contributions of Minna Tom to the field trial described in this thesis. Minna played a major role in its design and construction. Throughout the 1.5 years of monitoring, Minna also conducted one of the three irrigations per week (I conducted all others), and made significant contributions to planting and maintenance. While the vast majority of data collection for this thesis was conducted by me, the notable exception was downloading of soil moisture and temperature data, for which Minna assumed primary responsibility for most of the monitoring period. Minna also obtained the soil nutrient level and particle size data presented in Appendix A.

I would also like to express my sincere appreciation for the funding provided by Melbourne Water, which covered my studentship and research costs. Thank you to Keysha Milenkovic in particular for her support over the course of my candidature, especially during my work on the instruction sheet.

The field trial, the greenhouse experiment, and most associated laboratory work for this thesis was conducted at the University of Melbourne's Burnley campus. At Burnley, Nick Osborne and Sascha Marianna Andrusiak provided very frequent and outstanding technical support for the field trial and greenhouse experiment, and all related work in the Nursery. Sascha deserves particular mention for her assistance in the setup of the greenhouse experiment, including ordering some materials, amending the soils, and organizing an automatic irrigation system. Her "whatever you need" attitude made all the difference. Technical and/or administrative support was also provided by Ross Payne, Andrew Smith, Bhawana Bhatta, Ruth Hughes, Rob James, Rodger Young, Joanne Patton, Frank Prato, Jamie Pearson, and others at Burnley and Parkville. I would particularly like to thank Bhawana Bhatta and Ruth Hughes for taking the time to introduce me to the pH/EC and AFP procedures, respectively, that are described in this thesis.

A laboratory calibration of a soil moisture probe was conducted in the Civil Engineering department at Monash University's Clayton campus. Perrine Hamel advised on the calibration procedure and provided some technical assistance. Other technical and/or administrative assistance at Monash was provided by Frank Winston, Richard Williamson, Anthony Brosinsky and Mike Leach.

Finally, Antigone Vasilopoulos (Senior RHD Officer) was a great ally during a difficult time. I must also acknowledge the steadfast support of Chris Ives and the Richards family, and above all Dianita Carolina, who even enthusiastically assisted with some harvesting, buying plants, kitting out pots, and entering reams of numbers into Excel.

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# 1. Introduction: The potential to use raingardens for food production

## 1.1. Water in Australian cities

### 1.1.1. Water scarcity

Stormwater runs off the impervious surfaces of Australian cities in such large quantities that it requires concerted management to mitigate its effects on local waterways. In contrast, the traditional water supply networks of Australian cities are frequently under strain, and relatively low quantities of this water are available for home vegetable production. The water scarcity situation experienced by many Australian cities and towns, which has been described as a crisis, has resulted mainly from below-average runoff into urban water catchments (Edwards, 2011). Melbourne, for example, has been affected by substantial decreases in rainfall since 1960 and some exceptionally severe droughts, including a long-term drought that began in 1997 and ended in 2009 (see Barker-Reid et al., 2010). As a result, in mid-2009, Melbourne's largest reservoir (the Thomson, completed in 1984) reached a record low of 16.2% (Melbourne Water, 2011b). Melbourne's water scarcity problems are only going to worsen if climate change predictions for the city are accurate, as these predictions include reduced rainfall and higher temperatures (CSIRO, 2007; Howe et al., 2005; Maunsell Australia Pty Ltd., 2008). Compounding this problem, consumption is likely to increase given projected increases in population (Edwards, 2011).

Australian cities have responded to water scarcity with a range of strategies, such as the development of major new infrastructure projects (e.g. desalination plants and large-scale wastewater reuse projects), water restrictions, and water-efficiency incentives and education (Barker-Reid et al., 2010). Water reuse is a particularly critical component of Melbourne's response to the water crisis. It is especially important for vegetable production as commercial production now relies heavily on high quality reclaimed water, and many households use untreated greywater[1] for irrigation of backyard lawns and gardens (Barker-Reid et al., 2010; Hamilton et al., 2007; Misra et al., 2010; Peverill and Premier, 2006). Another increasingly popular technique for overcoming water shortages in Australian cities, and for sustainably satisfying demand for water more generally, is rainwater harvesting (Hatt et al., 2007; McQuire, 2008; Palla et al., 2011; Zhang et al., 2009b). For many Australian households, the adoption of both water reuse and rainwater harvesting techniques is at least partly driven by water restrictions, which require households to avoid or ration some uses of water, particularly outdoors. Such restrictions were in place in Melbourne for over ten years (Edwards, 2011), but were lifted in

[1] Greywater is the non-toilet component of household wastewater that originates predominantly in the laundries and bathrooms of residential buildings.

December 2012 with the possibility of reinstatement during future drought periods. The most severe stage (Stage 4) included a ban on all outside watering (therefore precluding any irrigation of vegetable gardens), although the use of rainwater and greywater was unrestricted.

### 1.1.2. Managing urban runoff

Another pressing issue is managing the considerable impacts of urban development on surface runoff, and on the hydrologic cycle more generally (Li et al., 2009). As noted by Akan and Houghtalen (2003), quantities and rates of runoff in the undeveloped, natural environment are affected by factors such as soil type, vegetative cover, and topography. In urban areas, infiltration is reduced and runoff quantities increase because of the creation of impervious surfaces, the removal of vegetation, and practices such as surface compaction. In addition, the rate of runoff is intensified due to extensive networks of gutters, pipes and man-made channels that move stormwater with artificially high efficiency. Ultimately, therefore, an increase in impervious surface cover within urban catchments alters the hydrology and geomorphology of streams (Paul and Meyer, 2001). Developed areas are also particularly vulnerable to flooding and, paradoxically, to drought. This is because the pulses of excess runoff are not contributing to groundwater recharge, leading to lower stream baseflows and urban water supply problems during dry periods (Heasom et al., 2006; Li et al., 2009). Flow modification following urbanization also affects biota and ecosystem processes (Paul and Meyer, 2001; Wheeler et al., 2005).

The quality of runoff is also significantly affected by urbanization. A wide range of pollutants can build up on urban surfaces and they are washed into waterways when it rains (Akan and Houghtalen, 2003). Even a typical roof can be a source of various contaminants, such as heavy metals, and pathogens from animal waste (Ahmed et al., 2009). Such “nonpoint source” pollution is a major cause of water quality deterioration throughout the world (e.g. Line and White, 2007). In Melbourne, stormwater is known to have a major impact on water quality throughout the urbanized portion of the Yarra River catchment (Allinson et al., 2011). Approximately 500 billion litres of runoff containing pollutants such as heavy metals, oil, litter, organic matter and excess nutrients enter Melbourne’s waterways via stormwater drains every year (Melbourne Water, 2011a). One well-publicised issue has been the detection of dangerously high levels of the bacteria *E. coli* along the Yarra River by the Environment Protection Authority (Gardiner, 2008; Wright, 2012). Stormwater flowing into the Yarra was identified as one of the leading causes. Reducing the amount of nitrogen entering Port Phillip is another important objective, particularly in light of the threat of artificial eutrophication to the bay (Denman et al., 2006; Harris and Crossland, 1999; Murray and Parslow, 1999; Taylor et al., 2005).

### 1.1.3. Water Sensitive Urban Design and the raingardens of Melbourne

To counter the environmental impacts of continuing urbanization, it is widely acknowledged that our cities need to become more environmentally sustainable. In Australia, Water Sensitive Urban Design (WSUD) is a way of incorporating stormwater treatment and water cycle management into urban landscapes (Denman et al., 2006; Lloyd et al., 2002). It is analogous to schemes such as Low Impact Development (LID) in the United States, and Sustainable Urban Drainage Systems (SUDS) in the United Kingdom (Bratieres et al., 2008; DeBusk et al., 2011; Elliott and Trowsdale, 2007). It has included the design and installation of a wide range of technologies such as rainwater tanks (Vaes and Berlamont, 2001), green roofs (Getter and Rowe, 2006; Mentens et al., 2006; Oberndorfer et al., 2007), and “biofiltration” or “bioretention” systems (Davis et al., 2009). These technologies enhance runoff management by intercepting stormwater flows, improving their quality, and restoring the flow regime closer to the pre-developed, natural level (Bratieres et al., 2008; DeBusk et al., 2011; Williams and Wise, 2006).

Raingardens in particular, as biofiltration systems, are self-watering garden beds that are engineered to capture and treat stormwater that runs off roofs and other impermeable surfaces. Raingardens typically comprise a shallow excavation or a raised garden bed, filled with sandy filter media and planted with resilient vegetation. Following “biofiltration”, outgoing water is delivered directly to a stormwater drainage network or waterway via an underlying perforated collection pipe, or left to infiltrate into underlying soil for groundwater recharge (Davis et al., 2001; Hatt et al., 2007; Read et al., 2008). Raingardens have two main benefits in relation to WSUD.

1. As filters of runoff; raingardens treat urban runoff by reproducing natural physical, chemical and biological processes (Hatt et al., 2007). Raingardens moderate quantities of runoff and, as such, have a role in channel protection and flood mitigation. They also remove various contaminants.
2. As attractive, low-maintenance features; raingardens can improve the appearance of an urban landscape or a residential garden whilst using little or no potable water and offering considerable flexibility in their design (Lloyd et al., 2002).

The development of raingardens and other biofiltration systems, which began in the United States in the 1990s, has integrated knowledge from a number of disciplines including engineering, hydrology, soil science, horticulture and landscape architecture (Davis et al., 2009). They have consistently met sustainable stormwater management objectives and, subsequently, they have rapidly become one of the most versatile and widely used stormwater management practices in many parts of the world (Davis et al., 2009; Trowsdale and Simcock, 2011). Raingardens have been actively promoted and enthusiastically adopted in the city of Melbourne. Melbourne Water[2] has been working with local councils to build raingardens in public and private spaces, and launched a "10,000 Raingardens" campaign in late 2008 to encourage the general public to build raingardens around their homes. It follows a similar initiative launched in late 2005 in Kansas City, Missouri. The long-term aims are to reduce the degradation of Melbourne's waterways associated with urban runoff and to provide passively irrigated green features throughout the city.

Raingardens could have a possible third benefit; they could be used to produce food in urban areas, at least on a small, non-commercial scale, by combining the functions of a traditional vegetable garden with those of a raingarden. This follows recent exploratory adaptations of green roofs for vegetable production (e.g. Whittinghill et al., 2013). While most vegetable production currently occurs in large-scale commercial settings, and backyard food production makes a relatively small contribution to national food consumption, it is predicted that the importance of urban agriculture will increase in the coming decades (Barker-Reid et al., 2010). Urban agriculture might become particularly important if it can be incorporated into WSUD. In the process of managing urban runoff and promoting the construction of raingardens, runoff might be used to overcome the limits that the water scarcity crisis has imposed on food production by providing an alternative source of water for irrigation.

## 1.2. Traditional vegetable gardening and modern urban agriculture

### 1.2.1. Backyard production

Growing vegetables in small "backyard" plots, commonly known as vegetable gardens, vegetable patches, and kitchen gardens, has been common practice in Australian cities for many decades. Historically, there have been many reasons why Australians choose to grow their own food, including economic motivations, the availability of space and other resources (e.g. water and free time), and as an expression of independence or as part of an "ecological lifestyle" (Gaynor, 2006). A tradition of vegetable gardening is particularly strong amongst some cultural groups, such as those of Macedonian and Vietnamese heritage (Head and Muir, 2007; Head et al., 2004), and migrants from rural areas of Italy (Gaynor, 2006). Home food production has also been divided along class lines in Australia, whereby vegetable gardening has tended to be primarily a middle class activity (Gaynor, 2006).

[2] Melbourne Water is a statutory authority that manages Melbourne's water supply catchments, sewage, and major waterways and drainage systems.

### 1.2.2. Victory gardens

In Australia, as in many other countries, vegetable gardens were used extensively during World War II, when the spectre of food shortages was an additional motivator for home food production (Gaynor, 2006). Urban spaces were transformed into remarkably productive areas during this time (Gorgolewski et al., 2011). The Australian government viewed home food production as a way to conserve scarce resources (Gaynor, 2006), and "Dig for Victory" and "Grow Your Own" campaigns successfully urged householders throughout Australia to grow their own vegetables (Figure 1.1). Similar campaigns led to the creation of more than a million allotments in the United Kingdom, during which easy-to-grow vegetables such as kale reached the height of their popularity (Poulter, 2007). Similarly, in the United States and Canada, early urban garden movements turned into or merged with initiatives that promoted "victory gardens" during the world wars (Brantz and Dumpelmann, 2011). While in Britain, the aim was to keep civilians from starving during the deprivations of war, the rhetoric in the United States enlisted gardeners into the fight more directly (Cockrall-King, 2011). As part of these initiatives, Eleanor Roosevelt installed a "victory garden" on the grounds of the White House. This was emulated by Michelle Obama in 2009, when a large "kitchen garden" was planted on the South Lawn of the White House to encourage healthy eating (Burros, 2009; Cockrall-King, 2011). Similarly, in Australia, the "Grow Your Own" campaign (Figure 1.1) strenuously encouraged home gardeners to grow their own vegetables as a patriotic duty, constantly reminding civilians that large amounts of commercial produce were required for the armed services, that there could be shortages, and that their health and bank balances would both benefit from home food production (Gaynor, 2006).

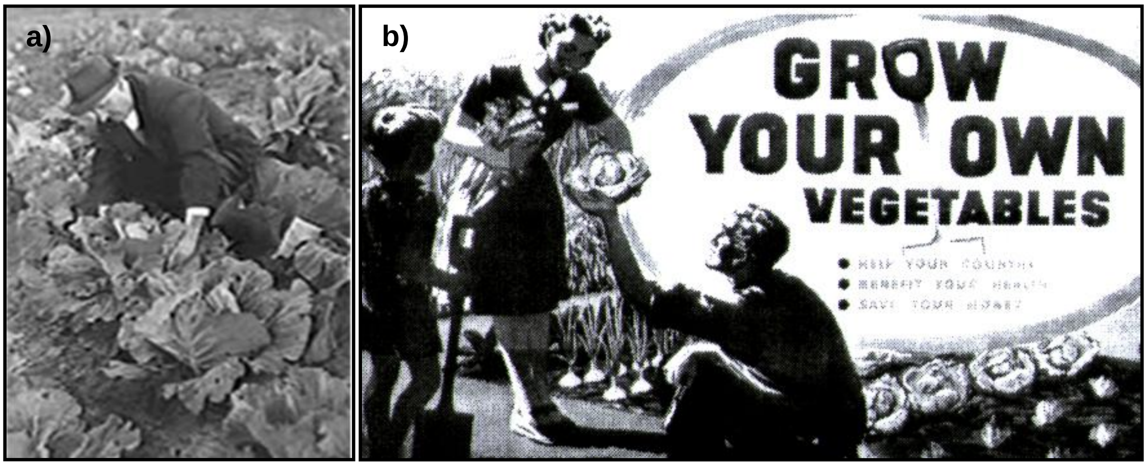


**Figure 1.1: Vegetable gardening during World War II: a) Cabbages being grown in a large "Dig for Victory" garden at Wattle Park, eastern Melbourne in September 1942 (from the Australian War Memorial collection), and b) An advertising campaign for home vegetable production (Gaynor, 2006).**

### 1.2.3. Urban agriculture revival

Although the concept of food production being integral to the functioning of cities quickly evaporated after World War II (Gorgolewski et al., 2011), home vegetable production remained reasonably popular in Australian cities in the “post-war boom” years and in the closing decades of the twentieth century (Gaynor, 2006).

Indeed, throughout the world, there has been a recent resurgence of interest in urban agriculture, driven primarily by issues of environmental sustainability and food security (Barker-Reid et al., 2010; Broadway, 2009; Dixon et al., 2009; Whittinghill and Rowe, 2011). In London, for example, there was a push to create more than two thousand “food gardens” in the city for the 2012 London Olympic Games (Cockrall-King, 2011). For North American cities, it has been suggested that urban farming, including the efforts of individuals for self-sufficiency, will be critical in the development of the future food system, even if it will never have the capacity to feed the entire population (Hanson and Marty, 2012; Vitiello, 2008). While the pace and scale of the urban agriculture movement is less in Australia than in North America and Europe, there are signs that backyard food production will continue to rise (Barker-Reid et al., 2010). At least, Gaynor (2006) predicts that, in the Australian cities of the future, the private production of food will continue to be important as an environmentally beneficial (or benign) expression of independence.

### 1.2.4. Environmental impacts of vegetable gardening

The perception of a low or neutral environmental footprint is now a major appeal of backyard vegetable production (Lavelle, 2011). Gaynor (2006) observes that home food production is often viewed through the lens of environmentalism, and associations with permaculture and “ecological lifestyles” contributed to the ongoing popularity of vegetable gardening in the second half of the twentieth century. In particular, home food production reduces the distance that food is transported from its place of production to the consumer (“food miles”) to an absolute minimum. In reducing pressure on the commercial food system, if only in a small way, various non-renewable resources used in the production and transportation of food have been preserved (Gaynor, 2006).

However, a vegetable garden also has the potential to cause adverse environmental impacts. One of the biggest threats that vegetable gardening poses to the environment is through the application of fertilizers and chemical treatments. Indeed, in Australia, home food production has historically contributed to suburban pollution, particularly through the use of toxic and persistent pesticides, and on occasion it has produced polluted food (Gaynor, 2006). At present, a particular threat posed by home food production is the incidental application of harmful chemicals when practicing wastewater reuse. As discussed in section 1.1, owing to Melbourne's water scarcity issues, many households in the city now rely on greywater to maintain their gardens (Barker-Reid et al., 2010). Re-using greywater has potential risks to both human health and the environment because, among other contaminants, greywater can contain surfactants[3] and enteric viral pathogens (Barker-Reid et al., 2010; Misra et al., 2010). Compared with large commercial water reuse schemes, greywater irrigation of vegetables in Melbourne's backyards is subject to a relatively low degree of regulation and control over water quality and use (Barker-Reid et al., 2010). As such, new options for safely irrigating backyard-grown vegetables would be valuable. Furthermore, particularly given the limited availability of land and space for food production in cities, it has been recognized that the new "urban vegetable farmer" needs to be able to grow food on the roofs and sides of buildings, and by other novel methods (Cribb, 2010; Gilmore, 2008).

### 1.2.5. Vegetable production on green roofs

Among the many novel approaches in modern urban agriculture, there is considerable potential for "green roofs" to supply vegetables and other crops (Oberndorfer et al., 2007) (Figure 1.2). This is in addition to the practice of rooftop farming, on a commercial scale, which is already popular in New York City in particular (see Foderaro, 2012; Gorgolewski et al., 2011). Currently, green roofs, like raingardens, are primarily used for various environmental benefits, including urban stormwater management (Czemiel Berndtsson, 2010; Farrell et al., 2012). Potential benefits of utilizing green roof space to produce food include improved economic and food security for the vegetable growers, and improved food safety through reducing the use of potentially contaminated urban land in agriculture (Whittinghill and Rowe, 2011).

Green roof vegetable production differs from the care of "aesthetic" green roofs in that it requires fertility amendments, irrigation, regular maintenance, and frequent harvesting of plant products (Elstein et al., 2008; Ouellette et al., 2012). One particular challenge is achieving adequate crop production in the relatively shallow substrate depths of "extensive" green roofs (those with < 15 cm of media), which are dictated by weight limits on most existing flat roofs (Whittinghill and Rowe, 2011; Whittinghill et al., 2012; Whittinghill et al., 2013). In this shallow growing media, water availability fluctuates dramatically and is often limiting between rain events (Farrell et al., 2013). Vegetables generally require deeper media and/or greater inputs of water and nutrients than more traditional green roof plants, which are usually ground cover or succulent species that require little maintenance after establishment (Whittinghill and Rowe, 2011; Whittinghill et al., 2013).

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[3] Surfactants are a class of synthetic compounds which may cause water repellency.

**Figure 1.2: Basil and tomato plants being grown on a green roof on a two-storey building at the University of Melbourne's Burnley campus.**

Insufficient moisture could be remedied by altering media composition and depth, or with irrigation if it is available; possibly using rainwater collected from another part of the roof (Whittinghill and Rowe, 2011). Cho et al. (2010) investigated irrigation methods for growing leafy vegetables such as lettuce in an extensive green roof system. They found that "wick irrigation" was more efficient than reservoir-drainage and drip irrigation. Only the wick irrigation method constantly maintained the water content in the substrate, and biomass and relative growth rate were comparatively high, at least in summer.

Following their examination of different growing systems in Michigan, Whittinghill et al. (2012; Whittinghill et al., 2013) concluded that, with proper management, cultivating vegetables and herbs in green roof systems is indeed possible, and potentially very productive. Of the tomatoes, green beans, cucumbers, peppers, basil and chives tested, only peppers didn't survive in their green roof system, which contained a typical green roof substrate, to a depth of 10.5 cm. Similarly, Ouellette et al. (2012) found that acceptable yields of tomatoes can be achieved using a 3-inch extensive green roof media comprised of clay aggregate with 4-5% organic matter, as long as adequate fertilizer is applied.

However, another challenge for "vegetable green roofs" is in applying irrigation and any required fertilizers without causing nutrient leaching; a balance must be achieved between meeting the nutritional needs of crops and adversely impacting the water quality of runoff, particularly given that positive impacts on runoff quality are a benefit of conventional green roofs (Whittinghill and Rowe, 2011; Whittinghill et al., 2012). The composition of the growing media is one aspect that requires consideration, particularly the organic matter that is contained in commercial green roof media, as this may leach nutrients when it decomposes (Whittinghill and Rowe, 2011). Other possible avenues for improving runoff quality include minimizing fertilizer and pesticide applications, using slow-release fertilizers, limiting runoff by optimizing irrigation, and managing soil moisture using various inorganic or organic mulches (Whittinghill and Rowe, 2011; Whittinghill et al., 2012).

Vegetable production in raingardens represents a very similar situation to green roofs, but this is an opportunity that is yet to be investigated. Furthermore, although many of the challenges are shared, such as the need to adequately retain runoff, raingardens will not be as restricted by substrate depth.

### 1.3. Biofiltration systems and raingardens: Design and performance

#### 1.3.1. Defining features

Biofiltration systems, which are also known as "bioretention" systems and "biofilters", are typically excavated trenches or basins containing vegetation, filter media of up to 1 m deep, and appurtenances for inflow and overflow, with outgoing water either delivered directly to a stormwater drainage network or waterway (usually via an underlying perforated collection pipe) or left to drain naturally for groundwater recharge (Davis et al., 2001; Hatt et al., 2007; Read et al., 2008). A biofiltration system should be located to capture runoff directly from an impervious area, as this maximizes recharge and water quality treatment performance (Davis et al., 2009).

The scale of biofiltration systems can range from small garden beds to large street-side biofiltration trenches (Read et al., 2008). Generally, though, a biofiltration system should be at least 2% of the size of the runoff catchment area (Bratieres et al., 2008), as recommended in current Melbourne Water guidelines for building a raingarden (e.g.

Melbourne Water, 2010a). This is primarily to reduce the proportion of inflow lost through overflow and to allow the system to drain effectively, which is also dependent on the properties of its soil. A biofiltration system is supposed to be wet only during and immediately after rainfall, so that the soil pore spaces are largely empty within 72–96 hours (Davis et al., 2009; Melbourne Water, 2010a), except in the cases where a saturated zone is in place to maintain soil moisture. Biofiltration systems are typically designed to receive runoff from a storm of several centimetres of rainfall over several hours (Davis et al., 2001), meaning that they will, in most cases, treat around 90-95% of the mean annual flow, with the remainder discharged as untreated overflow. The percentage of flow treated may decrease over time, as the filter media becomes clogged (McCarthy et al., 2008).

Ensuring that the biofiltration system is not too small is particularly important in a vegetable raingarden, in order to minimize the risk of waterlogging. However, it will be equally important that the system is not too large, because this situation could result in low water availability for at least some of the vegetables and necessitate supplemental irrigation. Ideally, a vegetable raingarden, like conventional raingardens, would not require any irrigation to supplemental rainfall, or any substantial maintenance. As noted by Davis et al. (2009), the only regular maintenance required of most conventional biofiltration systems is either aesthetic in nature or related to hydrologic performance, such as the removal of accumulated sediment from inlets.

A “raingarden”, specifically, is defined as a landscaped garden, usually forming a shallow depression 10–30 cm deep of relatively small area, that receives rainwater from a roof, car park or other impervious surface (Figure 1.3) (Dussaillant et al., 2005). Generally, all raingardens are biofiltration systems, but not all biofiltration systems are raingardens. For example, “swales” and “bioswales” are biofiltration systems that form a short water course or channel, conveying water from one point to another, and therefore they have a slightly different function to raingardens. However, “raingardens” can vary widely in design. Three types of raingarden are currently recommended by Melbourne Water.

#### 1.3.1.1. In-ground lined raingarden

The in-ground lined raingarden (Figure 1.4) is an excavated pit with a perforated pipe beneath the soil to take filtered rainwater to the stormwater drain (Melbourne Water, 2010a). This pipe is typically surrounded by gravel to improve drainage. There is also an overflow pipe on the surface to prevent flooding. The base and sides of this raingarden are fitted with waterproof (typically PVC) lining, separating the raingarden from the surrounding soil. As such, runoff can only leave this type of raingarden via the outflow or overflow pipe, or through evapotranspiration.

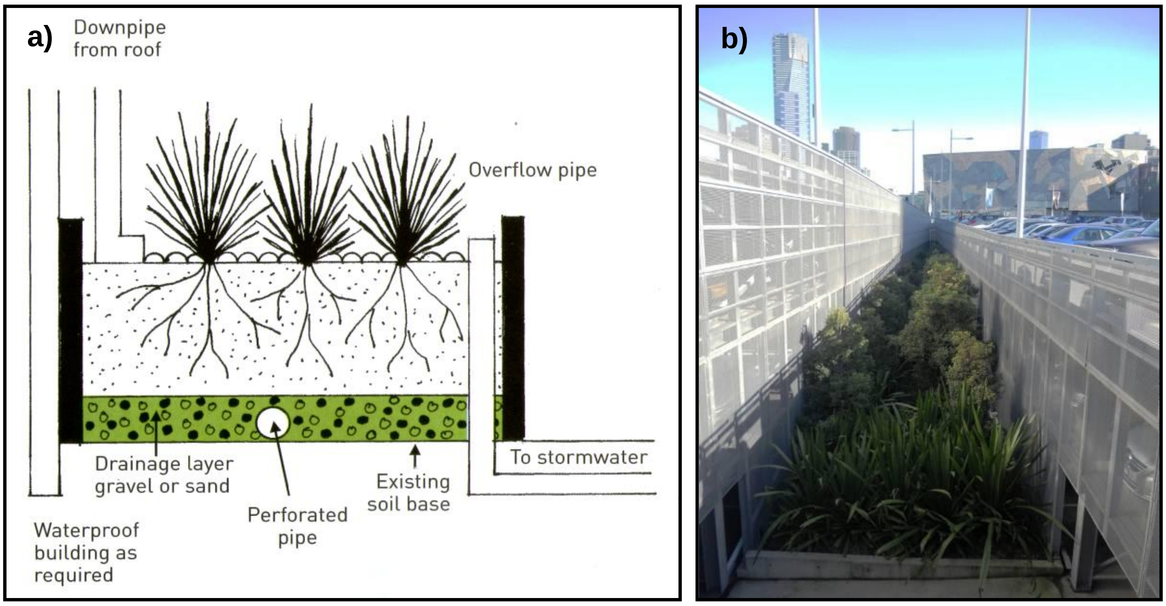



**Figure 1.3: a) Schematic section through a typical raingarden (McQuire, 2008), and b) A large raingarden at Federation Square in Melbourne's city centre, adjacent to the Yarra River.**

### 1.3.1.2. Infiltration raingarden

The infiltration raingarden (Figure 1.4) is an excavated pit, described as a gravel-filled trench (Melbourne Water, 2010c). There is no impermeable liner with this design. As such, outflow is allowed to infiltrate into the surrounding soil and to replenish groundwater, rather than being discharged to the stormwater drain. They are most effective in areas with sandy soils. An infiltration-style design is recommended for most biofiltration systems as long as the underlying soil drains well, if nonhazardous runoff is anticipated, and if the system is not close to a permanent structure (Davis, 2008; Davis et al., 2009). Because they inhibit infiltration into surrounding soils, lined systems are often regarded as having relatively poor hydrologic performance (Li et al., 2009).

### 1.3.1.3. Planter-box lined raingarden

The planter-box lined raingarden (Figure 1.4) is an above-ground variation of the in-ground lined raingarden, positioned to collect water from a disconnected downpipe or rainwater tank overflow (Melbourne Water, 2010b). An infiltration design, with no lining, is feasible. One advantage of planter-box types, and of raised garden beds more generally, is that drainage is promoted and the risk of waterlogging is reduced (Mason, 2005).

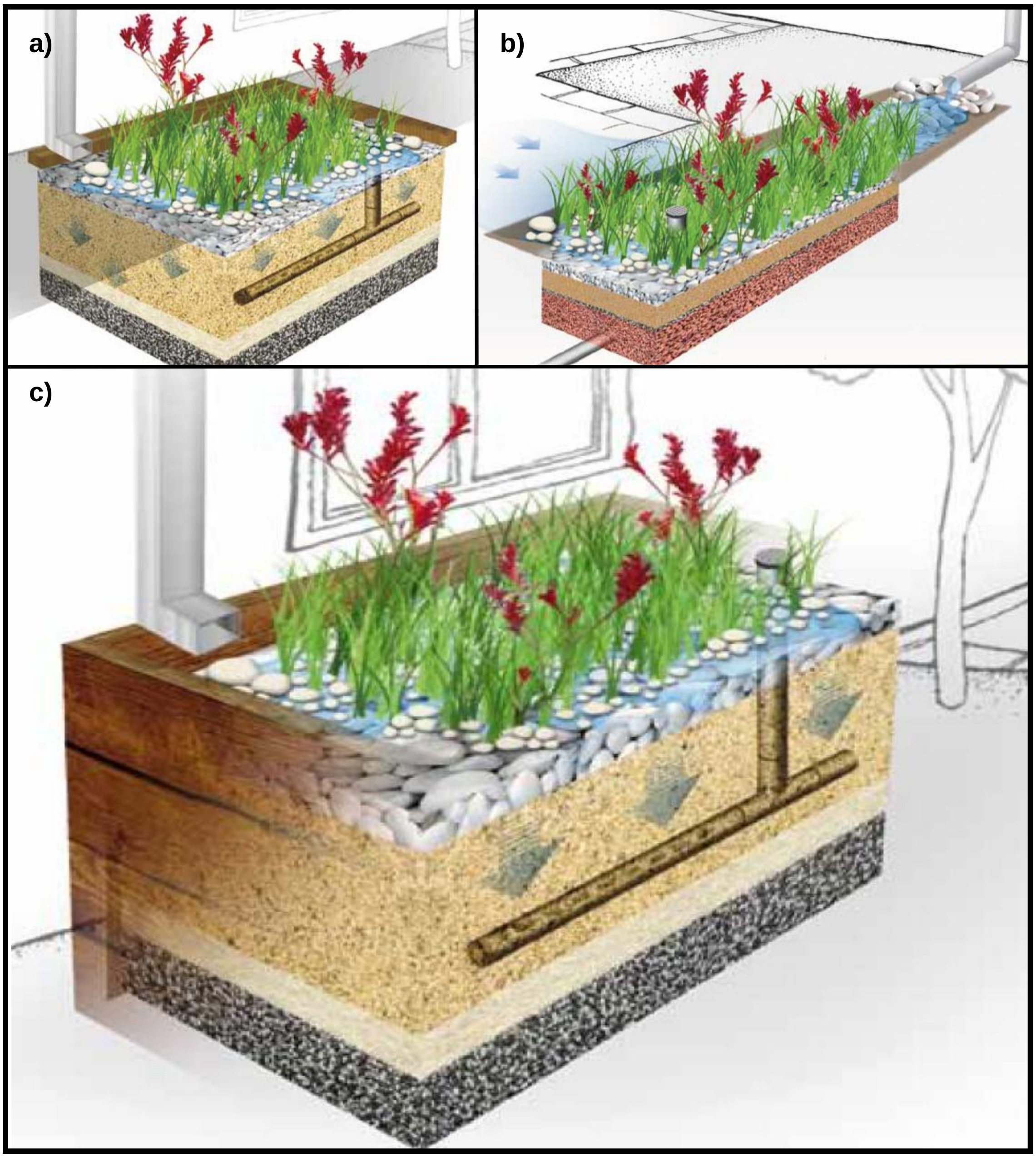



**Figure 1.4: a) In-ground lined raingarden (Melbourne Water, 2010a), b) Infiltration raingarden (Melbourne Water, 2010c), and c) Planter-box lined raingarden (Melbourne Water, 2010b).**

### 1.3.2. Water quality

The impacts of biofiltration systems on water quality have been particularly well studied, often based on laboratory simulations using “pots”, “boxes”, “columns” or “mesocosms” (e.g. Hatt et al., 2008; Hatt et al., 2006; Hsieh and Davis, 2005a, b; Hsieh et al., 2007; Kim et al., 2003; Rusciano and Obropta, 2007). These laboratory studies have reported effective removal of a wide range of pollutants, particularly sediments, heavy metals, hydrocarbons, pathogenic bacteria and, to a lesser extent, nutrients. Similar results have been reported through field tests of biofiltration systems, most notably a suite of studies conducted in the eastern United States; in Maryland (Davis, 2007, 2008; Davis et al., 2003; DiBlasi et al., 2009; Li et al., 2009), Washington DC (Li and Davis, 2008a; Li and Davis, 2008b), Connecticut (Dietz and Clausen, 2005, 2006) and North Carolina (Hunt et al., 2006; Hunt et al., 2008; Li et al., 2009). Effective removal of most pollutants has also been found in Australian field studies (e.g. Hatt et al., 2009), and biofiltration systems have been reported to be generally effective in treating heavily polluted runoff from urban roads in Trondheim, Norway (Muthanna et al., 2007) and Auckland, New Zealand (Trowsdale and Simcock, 2011). Even “street tree” biofiltration systems, which are a further development of the biofiltration concept, can effectively remove nitrogen in particular (Breen et al., 2004; Denman et al., 2006).

Overall, it seems that biofiltration systems built according to optimal specifications can be used to achieve a wide range of stormwater management objectives (Bratieres et al., 2008; Davis et al., 2009). Both the plants and soils play an important role in the removal of contaminants. As runoff infiltrates through the raingarden, fine particulates are trapped and dissolved pollutants are removed by adsorption to the filter media, or by adsorption or uptake by plants and microbial components of the plant–soil environment (Read et al., 2008). Generally, it seems that particulates and their associated pollutants (e.g. metals, phosphorus) are primarily removed by mechanical straining, while nutrients are removed by biological processes (Hatt et al., 2007). As such, Davis et al. (2009) suggest that the main reason biofiltration systems are relatively effective at improving water quality is their employment of multiple pollutant removal processes.

### 1.3.3. Water quantity

Davis et al. (2009) suggest that biofiltration systems are primarily regarded as tools for improving water quality, and that the effectiveness of these systems in controlling peak flows and providing management for channel erosion control and flood control is undervalued. As is the case for water quality, this effectiveness has been demonstrated through field studies in the eastern United States (Davis, 2008; DeBusk et al., 2011; Heasom et al., 2006; Hunt et al., 2006; Hunt et al., 2008; James and Dymond, 2011; Li et al., 2009). For example, Li et al. (2009) report field results for six biofiltration systems in Maryland and North Carolina, finding that the systems achieved such significant hydrologic benefits that they could mitigate the post-development hydrology caused by impervious surfaces. The systems decreased outflow runoff volumes and peak flows, thereby contributing to flood control and channel erosion protection. In promoting infiltration, they also promoted groundwater recharge. The potential benefits of raingardens for groundwater recharge in the United States have also been highlighted by Dussaillant et al. (2005; 2004).

In Australia, Hatt et al. (2009) studied three field-scale biofiltration systems; one at Monash University in Melbourne, and two in the northern suburbs of Brisbane. Generally, these systems substantially reduced total runoff volumes and flow peaks, attenuating peak runoff flow rates by at least 80%. Like most of the United States studies, it was suggested that biofiltration systems can play a role in restoring flow regimes to their pre-development levels; particularly where they can be built without lining, in order to promote infiltration into surrounding soils. Similarly, in New Zealand, Trowsdale and Simcock (2011) reported that a biofiltration system reduced peak flow and volume for all of the rainfall events that they monitored.

### 1.3.4. Infiltration, evapotranspiration and seasonal variability

Despite the important role of evapotranspiration and infiltration in the functioning of biofiltration systems, little is known about how these processes can be optimized for hydrologic benefits and pollutant removal (Davis et al., 2009). These processes are likely to be particularly important in retaining and attenuating runoff inflows. For example, the soil infiltration rate affects the ability of the biofiltration system to mitigate peak flow (Davis et al., 2009), while evapotranspiration between rainfall events creates a greater storage capacity in the soil for the next event (Dussaillant et al., 2005). Infiltration and evapotranspiration together might account for 50–90% of inflow, depending on soil type, media depth and type, and drainage configuration (Davis et al., 2009).

A critical aspect of infiltration and evapotranspiration processes is the seasonal variability that they might cause in the performance of biofiltration systems. Hunt et al. (2006) found that seasonal differences in the weather had statistically significant impacts on the outflow volume of a biofiltration system in North Carolina. In particular, there was a significantly higher ratio of outflow to inflow during the winter, when evapotranspiration rates were relatively low. Water that was normally lost from the system in the warm seasons would remain in the system. Furthermore, the surrounding water table was also higher during winter which, in turn, limited the amount of infiltration from the system.

The importance of seasonal variability has also been highlighted by studies in Pennsylvania (Emerson and Traver, 2008; Heasom et al., 2006). Following a four-year study of two biofiltration systems, Emerson and Traver (2008) found that the rate at which surface water infiltrated into the raingarden varied approximately twofold over the course of one year, and followed a cyclic pattern whereby maximum values occurred in late summer and minimum values in late winter. Emerson and Traver proposed that changes in hydraulic conductivity related to temperature are more significant in causing seasonal variation than changes in evaporation and biological processes such as plant transpiration and root uptake, mechanical root activity, and burrowing insects such as earthworms. It is unknown if this is applicable to the milder conditions of southeast Australia. In any case, seasonal variation is likely to be particularly significant in a vegetable raingarden, given the importance of seasonality in establishing and maintaining vegetable gardens.

### 1.4. Filter/growing media

#### 1.4.1. Conventional biofiltration media

Conventional biofiltration media is required to drain readily, support plant growth, and capture various stormwater pollutants, but these characteristics are sometimes in conflict (Bratieres et al., 2010). Fundamentally, there are two designs for the arrangement of filter/growing media in biofiltration systems; one is a uniform profile consisting of a combined filtration and vegetative layer, and the other separates the vegetation and filter layers (Hsieh and Davis, 2005a). In the latter design, the vegetation layer is optimized for vegetation survival, while the filter layer is optimized for pollutant removal; the filter layer backs up any deficiency of the vegetation layer in pollutant removal. An effective media arrangement is important because the media is expected to play a critical role in the system's performance, particularly in the removal of pollutants.

For example, previous laboratory and field studies have found that the removal of nutrients (e.g. phosphorus) is highly sensitive to media characteristics such as type and depth (Davis et al., 2001, 2006; Hatt et al., 2007; Hsieh and Davis, 2005a; Hunt et al., 2006). Media depth is also an important factor in the treatment of metals. Through controlled studies using laboratory boxes and existing facilities, Davis et al. (2003) found high metal removal (> 90%) in biofiltration media, with most of the metals being removed within just 20 cm of the surface. Subsequent field and laboratory-based studies produced comparable results (Li and Davis, 2008a; Li and Davis, 2008b, c; Sun and Davis, 2007), and Hatt et al. (2007) suggest that a relatively shallow filter bed could readily be used without sacrificing metal-removal performance. Similarly, based on modelling results, Li and Davis (2008c) recommend a shallow media depth. Nonetheless, a certain depth of soil, typically a minimum of 30 cm, is required to properly support plant growth (Davis et al., 2003; Hsieh and Davis, 2005a). Furthermore, deeper media depths can enhance the performance of the system by reducing outflow in large rainfall events (Li et al., 2009).

With regard to media type, a sandy media is typically used, because this allows effective interaction between the media and the solution passing through it (Henderson et al., 2007). Bratieres et al. (2008) suggest that a biofiltration system designed to optimally remove nutrients and sediment possesses a sandy loam media without any additional organic matter. Organic matter can result in the release of phosphate as it breaks down, which is then leached from the system and significantly increases phosphorus outflow concentrations. Sandy loam and other sandy filter media can adequately support plant growth in biofiltration systems without the addition of organic matter to the media, most likely because the stormwater influent provides adequate nutrients for plant growth (Henderson et al., 2007). However, this might only apply to the Australian native trees, shrubs, groundcovers, lilies and perennial grasses that have been tested, as these are generally well adapted to a low nutrient environment. The commonly used Facility for Advancing Water Biofiltration (FAWB) guidelines for filter media recommend that organic matter content be in the range 3-5% (w/w), so that the water holding capacity of the soil is high enough to support healthy plant growth (FAWB, 2009). These guidelines also specify the use of loamy sand (rather than sandy loam) and a maximum Total Nitrogen (TN) content of 1000 mg/kg, a maximum Orthophosphate ($PO_4^{3-}$) content of 80 mg/kg, a pH in the range 5.5 to 7.5, and electrical conductivity (EC) of < 1.2 dS/m (FAWB, 2009).

Fine sand might be a viable alternative to loamy sand. In a one-year column trial, Bratieres et al. (2009; 2010) found that fine sand-based filter media had similar pollutant removal performance and sustained the growth of a native sedge species, following an initial "amelioration" with organic matter, fertilizer and trace elements. However, the hydraulic conductivity (drainage rate) of the vegetated fine sand-based columns greatly deteriorated after one year, which could make it an inefficient system in the long-term.

### 1.4.2. Soil requirements of a vegetable raingarden

Whilst sandy soil might be suitable for some vegetables, the cultivation of leafy vegetables in sandy soil is generally considered unsuitable because of its low water holding capacity, relative to other soils (Nishihara et al., 2001). Many vegetables require a moisture-retentive and well-fertilized soil (Pollock, 2004), and there are commonly-available soils and "mixes" that are designed to achieve these needs. However, using these soils in a vegetable raingarden (as well as supplemental fertilizers) might offset its benefits as a biofiltration system. At worst, growing vegetables in raingardens using conventional methods of care might have a negative impact on surrounding waterways, particularly through the leaching of nutrients, resulting from the use of fertilizers and the breakdown of organic matter. The optimization of media to deliver appropriate water quality outcomes, while satisfying the water and nutrient requirements of vegetable crops, should therefore be a principal objective in the development of vegetable raingardens.

## 1.5. Plants and irrigation methods

### 1.5.1. Vegetation in conventional biofiltration systems

Plants in a biofiltration system need to be able to tolerate the soil going from periodically dry to very wet, which includes saturation for at least several hours and up to 30 cm of runoff pooling (Davis et al., 2009). This extreme wetting and drying regime is particularly prevalent in Australia (Read et al., 2008). As such, relatively drought-tolerant, native plants with extensive fibrous root systems are usually recommended (e.g. Melbourne Water, 2010c). Perennial types are also preferred, so that regular replanting is not required. Nonetheless, a wide variety of vegetation has been used in biofiltration systems, from monocot tussocks and forbs to woody shrubs and trees (Read et al., 2008).

An important role of plants in a conventional biofiltration system, in many cases, is to improve its appearance so that it becomes a "landscaping asset" (Henderson et al., 2007). However, plants also make a very significant contribution to the treatment efficiency of biofiltration systems (Read et al., 2008). As noted by Davis et al. (2009), the engineering benefits of vegetation in biofiltration systems have not been well quantified but, theoretically, plants promote hydrological performance in a number of ways. First, vegetation can be used to divert and slow surface flow (Davis et al., 2009). Second, the constant growth and death of roots helps to promote and maintain media permeability (Breen et al., 2004; Davis et al., 2009; Dussaillant et al., 2005; Read et al., 2008). A particular benefit of this is that the system becomes less prone to clogging (Hatt et al., 2009). Third, vegetation modifies water retention between storm events (Read et al., 2008). In particular, plant evapotranspiration between rainfall events provides a higher available storage capacity in the soil for the next event (Dussaillant et al., 2005).

As discussed above (section 1.3.2), vegetation also plays a major role in pollutant removal. For example, the above-ground parts of plants have a direct role in filtering sediments from runoff (Davis et al., 2009). Other pollutants can be removed through phytoremediation. In a biofiltration system, phytoremediation processes are beneficial in the uptake of non-biodegradable pollutants such as heavy metals, and in both the uptake and breakdown of carbon- and nutrient-based (organic) pollutants (Davis et al., 2009; Read et al., 2008). Plant cycles make direct use of nitrogen and phosphorus in particular (Read et al., 2008). Furthermore, vegetation supports soil microbial communities both within the rhizosphere and external to it, which further promotes pollutant degradation (Davis et al., 2009; Read et al., 2008).

The importance of vegetation in biofiltration systems has been highlighted by studies that have compared systems with plants to systems without. These studies have found notable differences in the removal of nutrients such as nitrogen and phosphorous, whereby vegetated systems remove substantially more nutrients from runoff (e.g. Henderson et al., 2007; Lucas and Greenway, 2008). Indeed, without plants, soil-based filter media may act as a source rather than a sink of some pollutants, particularly nitrogen (Hatt et al., 2007; Henderson et al., 2007).

Read et al. (2008) found that the choice of plant species can also have marked impacts on performance, with up to 420-fold variation in pollutant removal among 20 species. Similarly, Bratieres et al. (2008) found that all vegetation enhanced nutrient removal in biofiltration systems but some species, such as *Carex appressa* and *Melaleuca ericifolia*, performed significantly better than others. Further research is needed to identify the morphological or physiological factors that lead to such differences between species (Bratieres et al., 2008). These factors might include root mass, root architecture, and growth rate (Read et al., 2009; Read et al., 2008).

### 1.5.2. Irrigation methods for a vegetable raingarden

A wide range of vegetables and herbs can be cultivated in the temperate regions of Australia, and they are all viable candidates for a vegetable raingarden. However, growing vegetables and herbs in a raingarden is a significant departure from the plants that are conventionally used in biofiltration systems. It is currently unknown if vegetables can emulate the hydrological and pollutant removal benefits provided by those plants. A more immediate concern, however, is whether water availability in a raingarden can sustain the growth of vegetables, and whether yield is sufficient for a “vegetable raingarden” to be worthwhile.

One particular concern is the potential for over-watering in a saturated raingarden following significant rainfall. In the case of tomatoes, for example, over-watering reduces the amount of air available in the root zone and leads to problems such as plant disease, cracking of the fruit, and reduced flavour and biomass (Peet and Willits, 1995; Pollock, 2004; Qassim and Ashcroft, 2006). On the other hand, perhaps an even greater concern is the drought experienced by plants in a raingarden. Water deficiencies in vegetable production can lead to reduced yield and wilting. When plants wilt[4] they can no longer carry out certain physiological functions, such as cell expansion and to a lesser extent photosynthesis, and prolonged periods of wilting usually kill the plant (Lambers et al., 2008). Water deficiencies can also lead to problems such as bolting[5] in leaf crops (Tsabedze and Wahome, 2010).

[4] When plants wilt they lose turgor, which is the basic support mechanism in plants.
[5] Bolting is rapid, reproduction-based growth.

To date, Melbourne Water have advised the public that vegetables with high water requirements are not suitable for raingardens; recommending that stormwater is initially directed into a conventional raingarden and the outgoing, filtered runoff is directed into a traditional vegetable garden (Melbourne Water, 2010d). Among vegetable crops, tomatoes are one of the most demanding for water (Costa et al., 2007). A mature tomato plant can typically use 2-3 L of water per day when light levels are high (Peet, 2005), but this can range from 0.4 L to 5.6 L depending on the stage of growth and season (Peet and Welles, 2005). As such, irrigation is generally necessary where natural rainfall is insufficient (Csizinszky, 2005), and many studies have reported that the amount of water applied to tomato plants directly affects growth and yield (e.g. Deek et al., 1997; Harmanto et al., 2005; Tan, 1993). In their investigation into tomato, bean and cucumber production on green roofs, Whittinghill et al. (2012) found that supplemental irrigation enabled larger fruit, a greater number of fruit, and more biomass.

The effects of irrigation on the growth and yield of other vegetables, such as pepper (e.g. Sezen et al., 2006), cucumber (e.g. Yuan et al., 2006), lettuce (e.g. Gallardo et al., 1996; Sanchez, 2000), onion (e.g. Kadayifci et al., 2005; Pelter et al., 2004), leek (e.g. Sorensen et al., 1995), radish (e.g. Hegde, 1987; Wan and Kang, 2006), spinach (e.g. Nishihara et al., 2001), broccoli (e.g. Gutezeit, 2006; Lopez-Urrea et al., 2009), and broad bean (e.g. Husain et al., 1988; Xia, 1994) are reasonably well documented. These studies are variously field- and greenhouse-based investigations, and they relate to a wide range of climates and soil types; frequently sandy soils. Nonetheless, other than indicating plant water requirements, the results of such studies generally have limited applicability to growing conditions in a vegetable raingarden.

#### 1.5.2.1. Sub-irrigation for a vegetable raingarden

If a vegetable raingarden requires large quantities of back-up irrigation, the runoff management function of the system could be compromised. A key challenge in developing vegetable raingardens, therefore, is using inputs of water efficiently. One potential design is to invert the raingarden so that, rather than runoff being conveyed to the surface, the raingarden is sub-irrigated. Water would be delivered to below the plant root zone and then absorbed upwards through capillary rise. Garden beds that use capillary rise are commonly known as wicking beds in Australia, and as sub-irrigated planters in the United States. Sub-irrigation generally offers high water use efficiency relative to surface irrigation; particularly spray types, as demonstrated for tomato cultivation (Ahmed et al., 2000; Goodwin et al., 2003; Incrocci et al., 2006; Santamaria et al., 2003). Sub-irrigation might also help to limit pooling in a vegetable raingarden, which would reduce plant stress. However, sub-irrigation has not been widely adopted, at least partly because it is associated with problems such as algal growth (Goodwin et al., 2003).

#### 1.5.2.2. Irrigation scheduling for a vegetable raingarden

If a vegetable raingarden requires back-up irrigation, it will be important to schedule this appropriately, ideally using deficit irrigation. Deficit irrigation strategies deliberately allow crops to sustain some degree of water deficit, often associated with a minor reduction in yield but a significant reduction in irrigation water use (Costa et al., 2007; Fereres et al., 2003; Fereres and Soriano, 2007; Geerts and Raes, 2009). Deficit irrigation has been investigated in relation to a range of vegetable crops including tomato (e.g. Pulupol et al., 1996), onion (e.g. Leskovar et al., 2012), cucumber (e.g. Mao et al., 2003), and pepper (Dorji et al., 2005). The associated method of partial root-zone drying, which involves wetting only one half of the root zone at a time, has also been evaluated by a number of studies, particularly for tomato (e.g. Campos et al., 2009; Kirda et al., 2004; Mingo et al., 2004; Savic et al., 2009; Tahi et al., 2007; Wang et al., 2010; Zegbe et al., 2004). The findings generally indicate that deficit irrigation is effective for vegetable production, particularly if applied in conjunction with appropriate soil moisture measurements.

Soil moisture is often expressed as the volumetric soil water content, typically as a percentage, and measured using a neutron probe or, more recently, devices utilizing electrical properties such as time-domain reflectometry (TDR) (Fares and Polyakov, 2006; Fereres et al., 2003). The status of water in soils is also commonly described in terms of water potential, which is measured in units of pressure (Lambers et al., 2008; Thompson et al., 2007). The concept of soil water potential is based on the rule that, when two compartments are separated by a semi-permeable membrane, water will move from a high to a low water potential (Lambers et al., 2008). It is an expression of the amount of tension exerted by a plant to extract water from the soil, and is typically measured using tensiometers or resistance blocks (Fereres et al., 2003; Muñoz-Carpena et al., 2005). The term “matric potential” refers specifically to the force with which water is adsorbed onto surfaces such as soil particles, and this is the most important component of soil water potential in non-saline soils (Lambers et al., 2008). Very negative pressures[6], and thereby large suction tensions, are generated by clay and organic soils because they have small soil pores (Lambers et al., 2008).

Direct measurements of soil moisture status, in terms of either volumetric soil water content or soil water potential, can be used to determine the need for irrigation (Thompson et al., 2007). This involves selecting either a threshold value to ensure that crops do not

[6] The matric potential always has a negative value because the forces always hold some water in place, relative to pure water with no adsorptive surfaces, which would be at or near zero.

experience water stress or a loss in production, or a target soil moisture range for optimal plant growth (Muñoz-Carpena et al., 2005; Thompson et al., 2007). Many studies have used and evaluated thresholds or targets of soil water potential in particular to irrigate vegetables, including a number of studies on tomato (e.g. Coolong et al., 2011; Smajstrla and Locascio, 1996; Thompson et al., 2007).

For soil water content sensors, the concept of available water content (AWC) provides a practical framework for irrigation management (Thompson et al., 2007). AWC is the water that plants can actually use (Hanson et al., 2000). It is the difference between the soil water content at field capacity and that at -1.5 MPa, which is often referred to as the permanent wilting point[7] (Lambers et al., 2008). AWC is significantly affected by soil texture and organic matter. For example, the soil water content at field capacity, and thereby the amount of available water, will be higher in fine-textured soils with a high clay or organic matter content than in coarse-textured (sandy) soils (Lambers et al., 2008).

### 1.6. Conclusions: Opportunities and challenges for a vegetable raingarden

There is considerable potential for raingardens to be used in urban agriculture; at least on a small, non-commercial scale, as an extension of traditional home vegetable gardening. However, there is currently little or no information in the literature on how growing conditions in a raingarden affect vegetable yield, or how these growing conditions could be engineered to better suit vegetable production. Vegetables are generally much more sensitive to water stress than the plants that have previously been used in raingardens, which have usually been chosen based on their capacity to survive an extreme wetting-drying regime and their ability to contribute to the retention and treatment of urban runoff. Water availability is therefore a critical issue in a vegetable raingarden, and there are at least three key knowledge gaps and design issues that need to be considered.

First, one way of minimizing water stress is to ensure that a raingarden is appropriately sized relative to its catchment area. A raingarden that is too small will not function effectively from a stormwater management perspective and might become waterlogged. Conversely, a large raingarden might not be irrigated sufficiently. Both of these situations are likely to have adverse effects on the growth of vegetables. Second, vegetable growth and yield will be significantly affected by the choice of method for delivering water. Water usually enters raingardens at the surface, but it might be preferable for water to enter at the base of a "vegetable raingarden"; i.e. for the system to be sub-irrigated. The use of sub-irrigation might offer better water use efficiency, and it might also be beneficial for

[7] The permanent wilting point is the lowest water potential at which a plant can access water from soil. Field capacity is the water content after the soil becomes saturated, following gravitational drainage. At field capacity, the water potential of all non-saline soils is close to zero.

food safety, whereby some pollutants are filtered out of the runoff water as it moves upwards through the raingarden. Third, sandy soil is typically used in a raingarden, primarily to improve the quality of urban runoff. However, with its relatively low water holding capacity, sandy soil might not be suited to a vegetable raingarden. On the other hand, the moisture-retentive and well-fertilized soils that are used in traditional vegetable gardening might not be ideal either, as these soils might offset the benefits of the system for improving runoff quality.

There is also no information on how vegetable cultivation affects the ability of raingardens to provide their environmental benefits, such as their effects on local flow regimes and on the quality of runoff water emanating from an impervious surface. For example, a raingarden might be less able to regulate quantities and rates of urban runoff if it needs regular supplemental irrigation, or if the use of an impermeable liner is necessary. A liner is essential in some situations, such as if the raingarden is being constructed next to a permanent structure, and it might also help to promote soil moisture in a vegetable raingarden.

### 1.7. Research questions

To address these knowledge gaps and inform the design of vegetable raingardens, a field trial and a greenhouse experiment were conducted, and these are the subject of the following two chapters. In particular, the following research questions were evaluated:

1. Do reasonably-sized vegetable raingardens require irrigation to supplement rainfall, under Melbourne conditions?
2. Is a sub-irrigated vegetable raingarden design advantageous for water availability and the production of yield, relative to surface irrigation?
3. How does the growth and yield of vegetables differ between two soil types with different water-holding capacities; namely loamy sand, as used in a conventional raingarden, and a conventional containerised vegetable garden “mix”?
4. Do leaf, root, legume and fruit vegetable types respond differently to variations in water availability, as measured by yield and growth of roots and leaves?
5. Can the function of a raingarden in stormwater management be retained, if it is used and modified for vegetable production?

In relation to Research Questions 1 and 5 in particular, a focus was on the performance of a raingarden if it is constructed to be a) lined, or b) the infiltration (unlined) type. Seasonal or other temporal variations in raingarden performance were also considered in relation to the above questions, with the exception of Research Question 3.

## 2. Field trial

### 2.1. Introduction

A review of the literature (Chapter 1) identified significant knowledge gaps that need to be addressed to design effective vegetable raingardens. In particular, the availability of water to vegetables in a raingarden is critical, particularly in the summer months when water might be limited, and there are aspects of the raingarden design that might need to be modified to achieve optimal conditions. This could include making the raingarden sub-irrigated to ensure that water is always available. However, as discussed, these modifications may not be ideal for runoff management.

This chapter describes an assessment of two purpose-built, full-scale, sub-irrigated “vegetable raingardens”, which were designed to address those knowledge gaps. One of the raingardens was of the infiltration (unlined) type, and the other was lined with no infiltration. Over a 1.5-year period, performance was assessed based on the yield of various commonly grown vegetables, the ability of the raingardens to reduce urban stormwater runoff, and the irrigation requirements of the raingardens. Ideally, a vegetable raingarden would require no irrigation to supplement rainfall, as is typically the case for conventional raingardens. It was anticipated that this would not be the case for vegetable raingardens, particularly in Melbourne during summer months, and particularly if the raingarden is of the infiltration (unlined) type, which would be less able to retain water. To assess the gardens’ irrigation requirements, a form of deficit irrigation was used, based on a soil water content threshold (see section 1.5.2.2). Apart from having an impact on irrigation requirements, and potentially vegetable yield, the presence of waterproof lining in a raingarden was also expected to diminish the capability of the raingarden to reduce quantities and rates of runoff (see section 1.3.1.2.). To test this, the quantity of overflow from the two raingardens was measured, and compared to inflow. In summary, this study was used to investigate all but Research Question 3 of the thesis (see section 1.7).

### 2.2. Methods

#### 2.2.1. Study site

The study was conducted at the University of Melbourne’s Burnley campus, which is located approximately 5 km east of Melbourne’s city centre. The four gardens were constructed adjacent to an existing house, referred to as Building 909 hereafter (coordinates 37°49'44.22"S, 145°1'13.40"E), and rainwater was collected from the roof (catchment area 133 $m^2$). Building 909 resembles many houses in inner city and suburban Melbourne (Figure 2.1). Its exterior plumbing was overhauled during construction of the garden beds to feed all water from the four downpipes into a splitter box (Figure 2.1). According to principles for calculating rainwater harvest amounts (McQuire, 2008), up to 73.5 kL of rainwater per year could be harvested from the roof, given mean annual rainfall of 650.2 mm in Melbourne (Bureau of Meteorology, 2012).

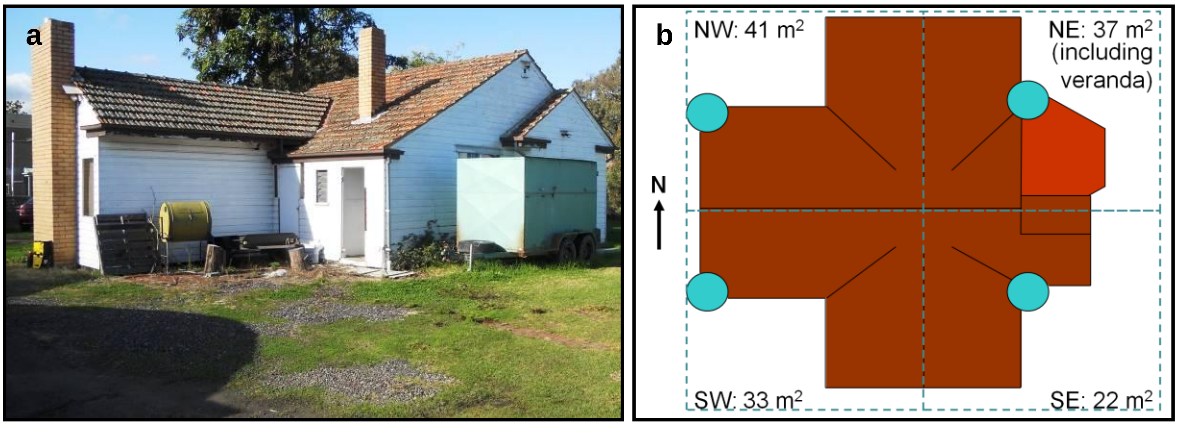



**Figure 2.1: a) Building 909 in June 2011, viewed from the northwest, prior to construction of the vegetable garden beds, and b) Plan view of the Building 909 roof, showing the positions of the four downpipes (blue circles) and their approximate catchment areas (NW, NE, SW, SE). These downpipes were modified to collectively feed into a splitter box on the northwest side of the house.**

### 2.2.2. Garden bed configuration

Of the four vegetable garden beds, two were "vegetable raingardens" (Figure 2.2); i.e., self-watering gardens fed directly with roof-water, with the inlet at the base. Being sub-irrigated, they were inverted relative to conventional raingardens, which typically receive inflow at the surface (see section 1.3.1). The only major difference between the two raingardens was the presence of waterproof lining. They were constructed as follows:

1. **Lined raingarden:** A vegetable raingarden with an internal sheet of impermeable, durable plastic (PVC) covering its base and sides, which prevented water infiltrating into the underlying soil.
2. **Unlined raingarden:** A vegetable raingarden identical to the Lined raingarden except it had no waterproof lining, making it an infiltration-type biofiltration system (see section 1.3.1.2). Unlike the Lined raingarden, it also had a surface drip-irrigation system for back-up watering when soil moisture was limiting.

The other two gardens were conventional raised bed vegetable gardens; both unlined and irrigated at the soil surface using micro-spray systems (Figure 2.3). They served as controls, particularly for Research Questions 1 and 2. Micro-spray was chosen, rather than a drip system, because it was expected to better represent watering methods used in domestic gardening, such as hand watering and common sprinklers. These two gardens were not raingardens, as they did not receive any runoff directly from the roof. The micro-spray systems were the sole source of water, other than rain falling directly on the garden beds (none of the four gardens were covered or sheltered). The raised bed gardens contained the same filter/growing media as the Lined and Unlined raingardens (see section 2.2.3). The only difference between the two control gardens was the source of irrigation water, which was primarily for analysis of chemical and microbial contamination (not described in this thesis; evaluated in a parallel study):

1. **<u>Tank control</u>:** Irrigated using rainwater from the roof, stored in a 3.44 kL tank.
2. **<u>Potable control</u>:** Irrigated using tap water; this garden was connected to an existing external tap on Building 909.

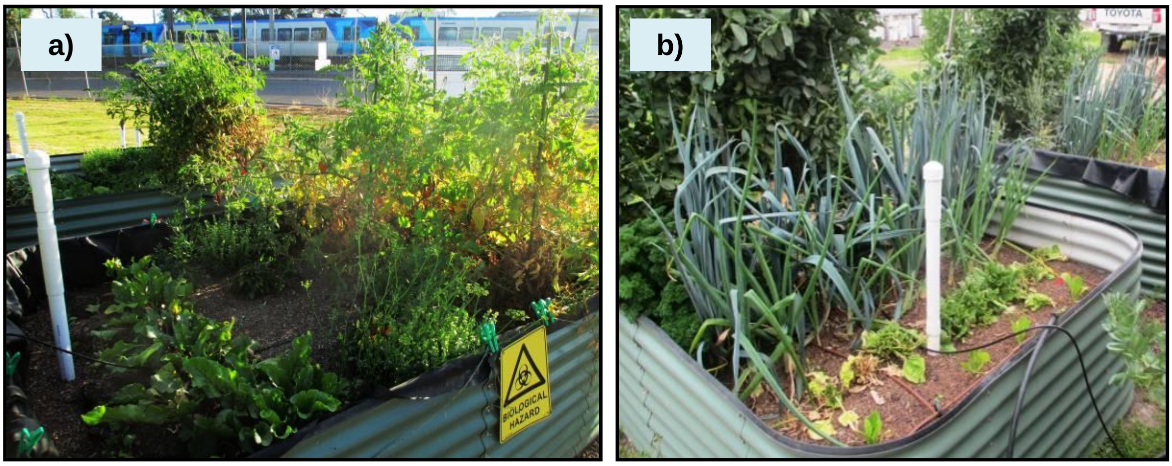



**Figure 2.2: The two raingardens: a) the Lined raingarden in February 2013, and b) the Unlined raingarden in October 2012.**


**Figure 2.3: The two control gardens: a) the Tank control in November 2011, and b) the Potable control in July 2012.**

The four gardens were installed in August 2011 in an area directly northwest of Building 909, where the gardens would receive maximum direct sunlight and where the ground surface was relatively even. Prior to site preparation, this area was mostly covered by an irregular grass lawn underlain by brick paving and gravel. The brick paving was removed, and the area was partially excavated to a depth of approximately 10-20 cm.

Each of the four gardens was constructed using a pre-fabricated modular raised garden bed made of corrugated steel (Birdies Original Garden Bed, sourced from Birdies Garden Supplies). As such, the raingardens were the “planter-box” type rather than the “in-ground” type (see section 1.3.1). Each garden bed had rim-to-rim dimensions of 218 cm (length) x 153 cm (width) x 82 cm (height), with a total area of approximately 3.34 $m^2$. Given that the two vegetable raingardens (Unlined and Lined) each received approximately one third of the total water from the roof, following division by a splitter box (see section 2.2.4), each raingarden was approximately 7.5% of its catchment area. This is well above the 2% minimum recommended size for a biofiltration system (see section 1.3.1), but within the likely size range for domestic applications of the vegetable raingarden. The maximum volume of each raised garden bed was approximately 2.74 $m^3$, although the gardens were not filled to capacity with filter/growing media. The soil surface was always at least 10 cm below the rim of the bed.

The gardens were arranged in a non-random quadrant formation, with the two raingardens in the western half and the two controls in the east. There was approximately 0.75 m between each of the gardens. The assignment of each treatment partly depended on proximity to the relevant water source; for example, the Tank control garden was close to the rainwater tank (see section 2.2.4). Site selection was also informed by the results of soil infiltration testing, using a single-ring infiltrometer. The Lined raingarden was allocated to the plot with the lowest infiltration rate (2 mm $hr^{-1}$). The Unlined raingarden was allocated to the plot with the highest rate (> 100 mm $hr^{-1}$), so that infiltration would be relatively unimpeded. Relative to the raingarden plots, the control garden plots had intermediate rates (16 mm $hr^{-1}$ for Potable and 45 mm $hr^{-1}$ for Tank).

### 2.2.3. Filter/growing media

Although a sandy filter media without any additional organic matter is optimal for the removal of pollutants from runoff (see section 1.4.1), a uniform sandy layer by itself was assumed to be not optimal for vegetable growth (this is investigated in Chapter 3). Therefore, the filter/growing media composition used in this study followed the separate vegetation and filter layer design recommended by Hsieh and Davis (2005a), in which the vegetation layer is employed to optimize vegetation survival, and the filter layer is optimized for pollutant removal.

All four gardens contained three layers of filter and growing media (Figure 2.4); a layer of gravel (20 mm scoria; a lightweight porous volcanic rock) at the base and a 350 mm-thick layer of vegetable garden soil at the top, separated by a relatively thin layer of fine sand. The sand was prevented from settling into the gravel layer by a sheet of geotextile, but there was no barrier between the sand layer and the overlying soil. Roof-water was delivered via a slotted pipe at the base of the raingarden, within the gravel layer (Figure 2.5). The gravel layer acted as a reservoir; at least on an intermittent basis, following significant rainfall. This sub-irrigation design was expected to promote water use efficiency (see section 1.5.2.1).

It was intended that the layer of fine sand would perform a treatment function. In particular, it was anticipated that the sand would remove some contaminants that may be present in the roof-water (e.g. lead), as the water moved upwards in the profile through capillary rise. By limiting the quantity of contaminants reaching the vegetable root zone, this would improve food safety. Conversely, the sand layer also had the potential to act as a buffer to minimize leaching of organic matter from the soil layer, limiting contamination of the underlying soil and groundwater. Fine sand can provide effective pollutant removal in a biofiltration system, as demonstrated by Bratieres et al. (2009; 2010; see section 1.4.1). However, in the field trial, the treatment performance of the vegetable raingardens was unlikely to be at the level of a conventional biofiltration system (contamination risks were assessed in a parallel study; see Tom et al., 2013). It is particularly unlikely that pollutant removal mechanisms specific to nitrogen would exist in the sand, given the absence of extensive root development in the sand layer.

At 350 mm, the depth of the soil layer was anticipated to be sufficient to support vegetable growth, and it is consistent with a minimum depth of 300 mm recommended for biofiltration systems (see section 1.4.1). The soil was a commercially available “Five Way Soil” sourced from C. Fulton Pty Ltd (Hawthorn, Melbourne); a blend of two soils and three manures. Its nutrient levels and particle size distributions are presented in Appendix A. Its water holding capacity (Table 2.1) was determined using an air-filled porosity procedure, based upon the Australian Standard for Potting Mixes (AS 3743), as described in Appendix B. With water holding capacity known, the matric potential of the soil (see section 1.5.2.2) was determined using the filter paper method, in which filter paper is used to absorb water from the soil (Doube et al., 1996; Greacen et al., 1989; Hamblin, 1981). The matric potential of the soil is then determined from the water content of the filter paper, as described in Appendix C. From this, soil moisture at permanent wilting point (PWP; -1.5 MPa) was found to be at 6.5% soil water content, or 18% soil water holding capacity. The electrical conductivity (EC) and pH of the soil (and of the underlying fine sand) were also measured (Table 2.1), using the methods described in Appendix D.

**Table 2.1: Properties of the vegetable garden soil and fine sand. Values in parentheses represent mean standard error (n = 3).**

| | WHC (%) | AFP (%) | Bulk density ($g/cm^3$) | pH | EC (uS/cm) |
|---|---|---|---|---|---|
| **Soil** | 56.9 (0.6) | 6.3 (0.3) | 0.64 (0.01) | 7.3 (0.00) | 2412.7 (19.50) |
| **Sand** | n/a | n/a | n/a | 4.0 (0.02) | 39.8 (0.67) |

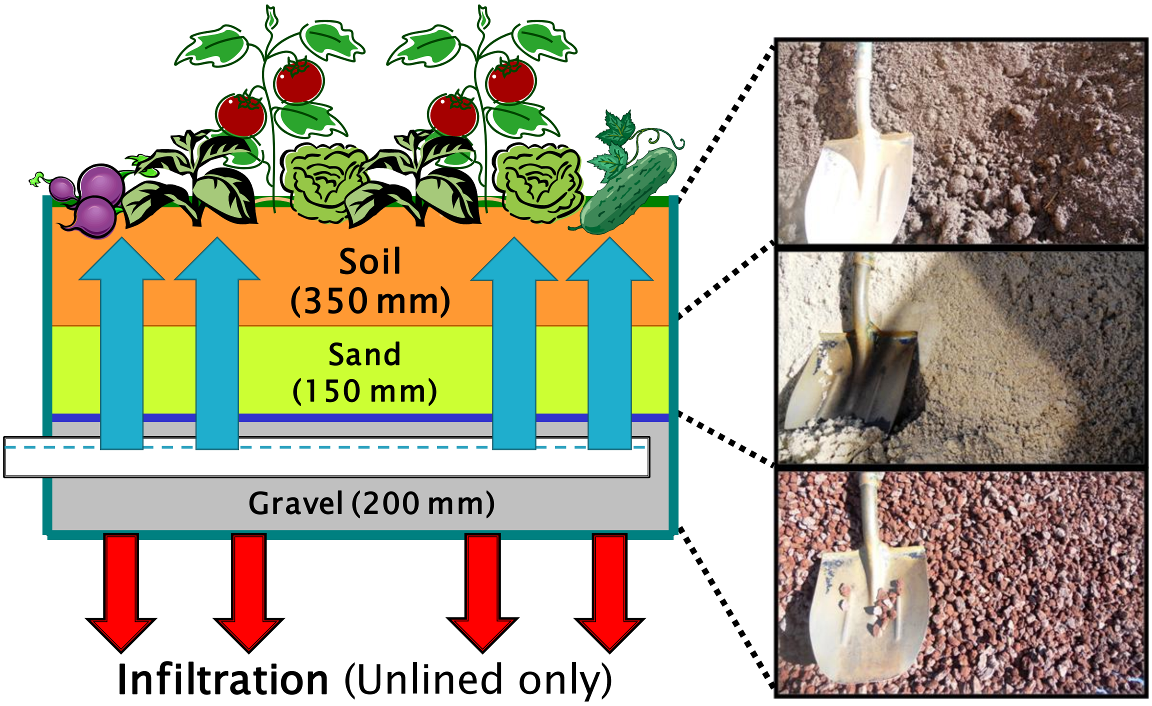



**Figure 2.4: Design of the two raingardens. Water enters via a slotted pipe in the gravel layer (bottom) and moves upwards, through a layer of sand (middle) and into a layer of soil (top). Blue arrows indicate upwards movement of water via capillary rise. Red arrows indicate infiltration into the underlying soil.**

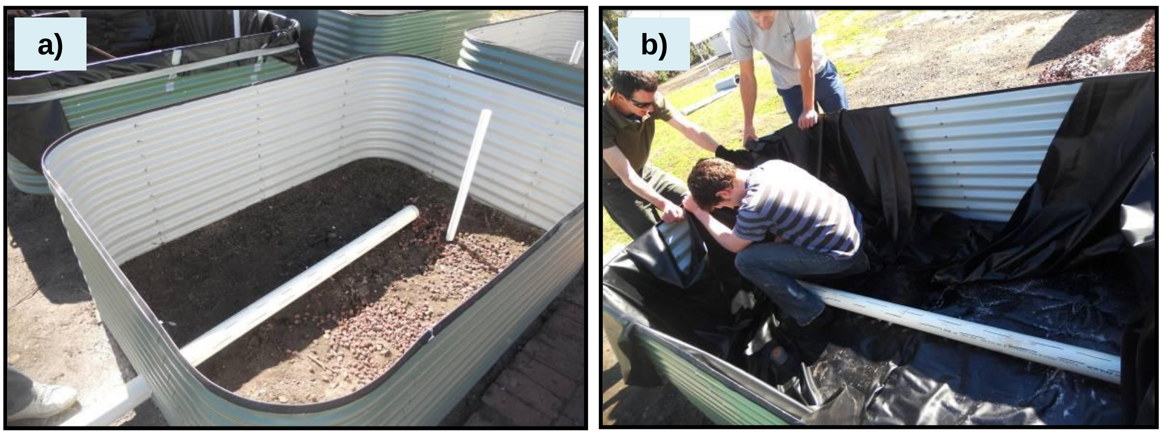



**Figure 2.5: The slotted pipe (inlet for roof-water) being installed in the Unlined raingarden (a) and Lined raingarden (b). The pipe was inserted through a hole that was made in the base of the western wall of the bed.**

### 2.2.4. Plumbing and monitoring system

Consistent with the common practice of downpipe disconnection or diversion (Melbourne Water, 2012), the existing downpipes on Building 909 were replaced with new, standard stormwater pipes and these conveyed roof-water to a purpose-built splitter box (Figure 2.6). The splitter box then conveyed one third of this roof-water to a specially-installed 3.44 kL (3440 litre) rainwater tank, and one third to each of the two raingardens (Figure 2.7). An Odyssey capacitance depth logger (1.5 m) was installed in the rainwater tank to record water level. The sensor was calibrated using a two-point calibration consistent with the manufacturer's guidelines (Dataflow Systems Pty Ltd, 2010). The roof-water that was collected in the tank was used for irrigation of all gardens except the Potable control (this was back-up irrigation in the case of the raingardens). The tank was connected directly to the micro-spray system in the Tank control garden and to the drip irrigation system in the Unlined raingarden, and there was also a free hosepipe that was used to recharge the overflow pit of the Lined raingarden (Figure 2.8; see also section 2.2.6).

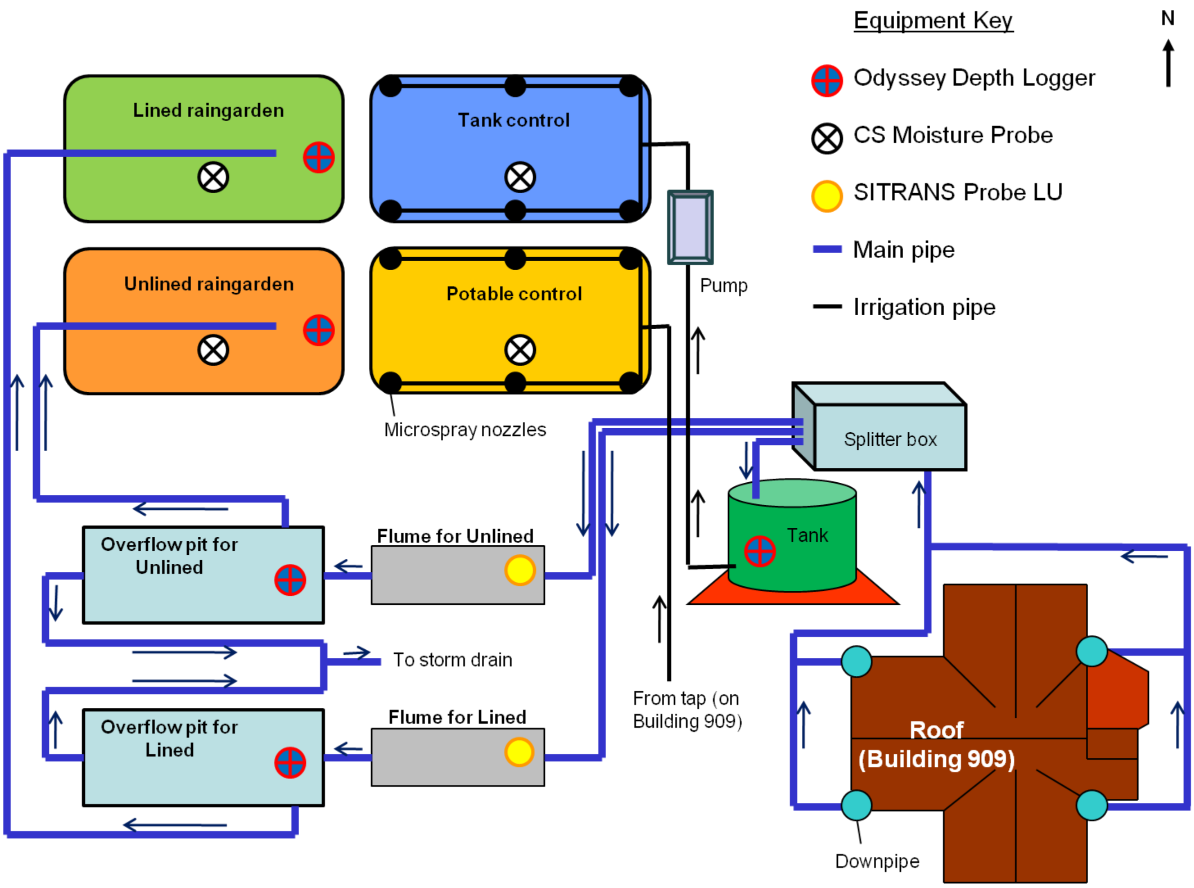



**Figure 2.6: Schematic diagram of the plumbing system, including monitoring equipment. For clarity, the drip irrigation system in the Unlined raingarden (connected to the tank) is not shown. Arrows indicate the direction of water flow through the system. The components of the system are not to scale.**

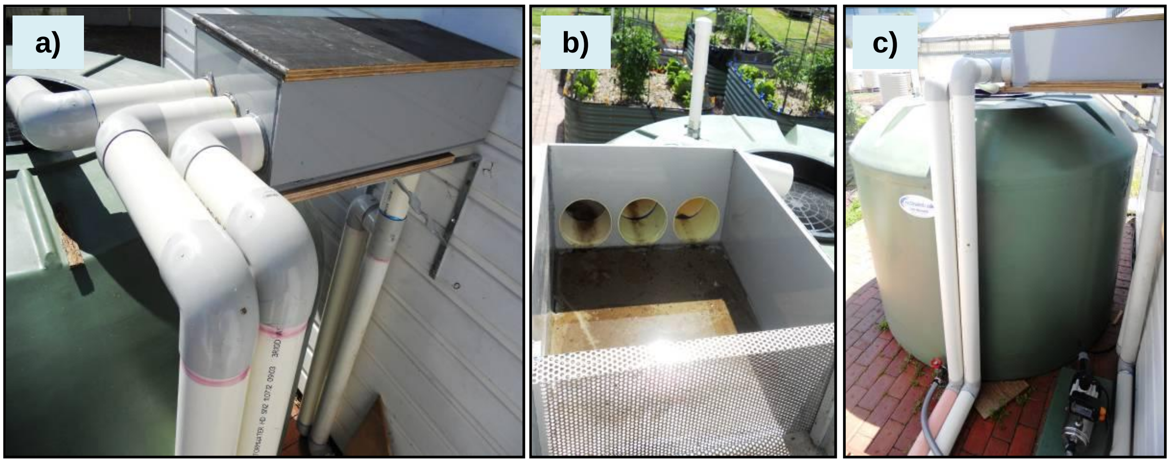



**Figure 2.7: An external (a) and internal (b) view of the splitter box, and its position on top of the rainwater tank (c).**

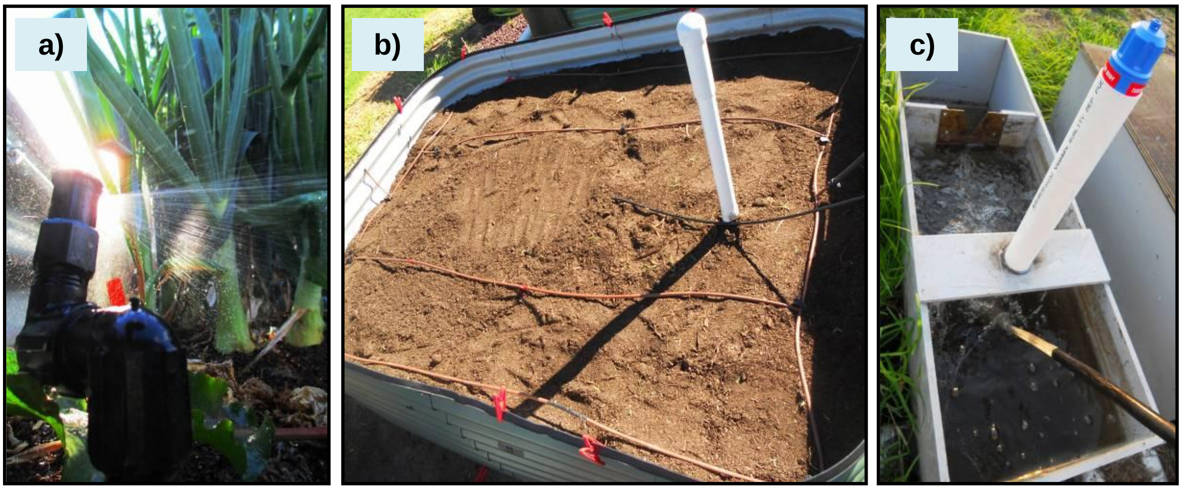



**Figure 2.8: The three outlets of the rainwater tank: a) one of the six micro-spray nozzles in the Tank control garden, b) the four lines of the drip irrigation system in the Unlined raingarden, and c) The free hosepipe being used to recharge the overflow pit of the Lined raingarden (see section 2.2.6).**

Positioned between the splitter box and the raingardens were two trapezoidal flumes and two purpose-built overflow pits; one flume and pit for each raingarden (Figure 2.6; Figure 2.9). The two flumes were used to measure inflow volumes and rates for their respective raingardens. The flumes were fitted with ultrasonic level monitors (Siemens SITRANS Probe LU; Figure 2.10), and connected to a data logger (dataTaker DT50) inside Building 909. The overflow pits, which were fitted with v-notch weirs (angle 40°; Figure 2.9), prevented water-logging of the raingardens by conveying excess inflow to the nearest stormwater drain. A maximum probable flow rate of 0.78 L $s^{-1}$ for each raingarden was allowed for in the design of the overflow pits, so that the system could cope with rainfall intensity of up to 63 mm $hour^{-1}$. In order to record the water level and calculate outflow to the stormwater drain (see section 2.2.7.2), a calibrated Odyssey depth logger (0.5 m) was installed in the eastern section of both overflow pits (Figure 2.9). There were also calibrated Odyssey capacitance depth loggers (1.0 m) within the two raingardens themselves, contained in a perforated PVC pipe (acting as a stilling well) (Figure 2.10).

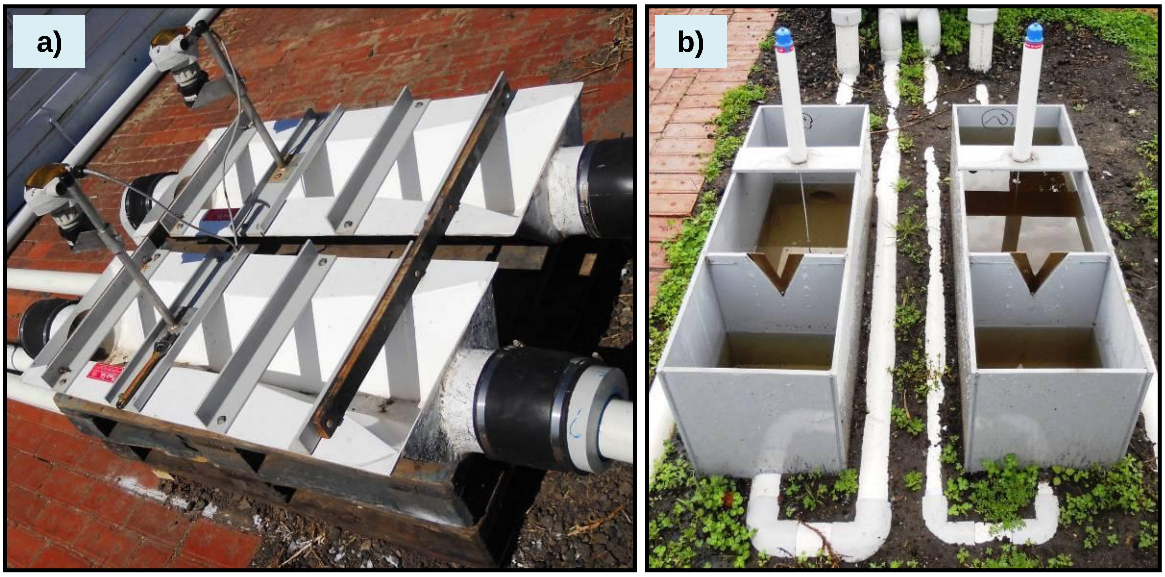



**Figure 2.9: The flumes (a) and overflow pits (b) of the two raingardens. During the monitoring period, the flumes and pits were fitted with waterproof covers (not pictured).**


**Figure 2.10: Monitoring equipment: a) The two ultrasonic level monitors (attached to the flumes) for measuring inflow to the raingardens, b) Data being downloaded from the Odyssey capacitance depth logger (in its PVC pipe) in the Lined raingarden, and c) a CS616 Water Content Reflectometer being installed in the soil.**

The water content of the soil layer of each of the four gardens was measured using soil moisture probes (Campbell Scientific CS616 Water Content Reflectometer), connected to a data logger (Campbell Scientific CR800). The soil moisture probes were buried in an inclined position (approximately 30° from horizontal) over a depth of approximately 3-10 cm from the soil surface (Figure 2.10), in order to give average soil moisture over approximately 10 cm depth. The probes were calibrated for the soil (Appendix E). In addition, soil temperature 5 cm below the surface was measured in each of the four gardens (Thermochron iButtons).

To record rainfall at the site, a tipping bucket rainfall recorder was fixed to the wooden cover of the flumes (Davis Rain Collector II with an Odyssey "rain gauge" data logger). Rainfall data was verified using two basic "rain cups", installed on either side of the main rainfall recorder. The data was also compared with records from the nearest Bureau of Meteorology weather station (Hawthorn Scotch College; 086304), approximately 1 km southeast of the study site. All of the monitoring apparatus logged data continuously at regular intervals for 1.5 years (Table 2.2).

**Table 2.2: The recording intervals of the monitoring equipment.**

| **Apparatus** | **Recording interval** |
|---|---|
| DT50 data logger (inflow data) | 1 minute |
| Odyssey depth loggers (water level) | 1 minute |
| CR800 data logger (soil moisture) | 6 minutes |
| Thermochron iButtons (soil temperature) | 2 hours |
| Tipping bucket rainfall recorder | Event-based |

### 2.2.5. Planting

There were three growing seasons; two summers and one winter (Table 2.3). A total of 14 species, and up to three varieties of each, were planted as either seeds or seedlings to test a range of plants commonly used in home vegetable gardens (Table 2.4).

**Table 2.3: The dates of the three growing seasons; the start and end months considered in the analysis, and the actual planting and final harvest dates. For further harvest details, see section 2.2.7.1 and Appendix F.**

| | Start month | End month | Planting date | Final harvest date |
|---|---|---|---|---|
| **Summer 1** | Nov 2011 | Mar 2012 | 20$^{th}$ Sep 2011* | 4$^{th}$ Apr 2012 |
| **Winter** | Apr 2012 | Oct 2012 | 12$^{th}$ Apr 2012 | 1$^{st}$ Nov 2012 |
| **Summer 2** | Nov 2012 | Mar 2013 | 15$^{th}$ Nov 2012 | 2$^{nd}$ Apr 2013 |

*September and October 2011 was a preliminary period before full monitoring commenced. This initial period is excluded from quantitative analysis (with due consideration), so that the first summer growing season formally began in November.

### 2.2.6. Irrigation scheduling

For the majority of the study period, irrigation followed a simple deficit irrigation strategy, whereby irrigation was applied when the soil water content of the soil layer was below 10% (as measured by the soil moisture probes). The two control gardens were irrigated according to the protocol in Table 2.5. This threshold (10%) was chosen based on the 6.5% permanent wilting point value calculated for the soil (see section 2.2.3). If one of the control gardens was below the threshold but the other was not, both were irrigated. The irrigation systems were operated manually and the soil water content was checked three times a week; i.e., the control gardens were irrigated approximately every other day, if needed. This irrigation schedule was compliant with the current Melbourne water restrictions, to represent a realistic watering regime for “backyard” vegetable gardening. In order to address Research Question 1, the same deficit irrigation strategy was used for the two raingardens. This was back-up irrigation in addition to the rainwater received from the roof following rainfall. When soil water content was below 10% (checked three times a week), the Unlined raingarden was irrigated according to the protocol in Table 2.5. The Lined raingarden, in the absence of a micro-spray or drip irrigation system, was irrigated by recharging its overflow pit to capacity with roof-water from the rainwater tank. As such, the Lined raingarden was entirely sub-irrigated when the deficit irrigation regime was in place, while the Unlined raingarden was surface-irrigated (via a drip system) to supplement sub-irrigation. The quantity of irrigation water applied to the Lined raingarden was always much lower than that applied to the Unlined, and varied between irrigations.

**Table 2.4: Plants evaluated in the field trial across the three growing seasons (2 summer and 1 winter seasons).**

| Type | Species | Common name | Variety | Seedling or Seed | Season(s) | Plants per bed |
|---|---|---|---|---|---|---|
| **Root & bulb** | *Beta vulgaris* | Beetroot | Crimson Globe | Both[a] | Summer 1 & 2 | ≥ 8 |
| | *Raphanus sativus*[b] | Radish | Scarlet Globe | Seed | Winter & Summer 2 | 9 |
| | *Allium cepa* | Onion | Brown | Seedling | Winter | ≥ 8 |
| | *Allium porrum* | Leek | None specified | Seedling | Winter | ≥ 18 |
| **Leafy & flower** | *Lactuca sativa*[b] | Lettuce | Cos | Seedling | All | 4 |
| | *Spinacia oleracea* | Spinach | Viking | Seed | Winter | ≥ 15 |
| | *Brassica oleracea*[c] | Broccoli | Magic Dwarf | Seedling | Winter | 3 |
| **Fruit & legume** | *Solanum lycopersicum* | Tomato | Mama's Delight (Round) | Seedling | Summer 1 | 1 |
| | | | Sweet Bite (Cherry) | Seedling | Summer 1 | 1 |
| | | | San Marzano (Plum) | Seedling | Summer 2 | 2 |
| | *Cucumis sativus* | Cucumber | Lebanese | Seed | Summer 1 | 2 |
| | *Capsicum annuum* | Pepper | Chilli Salsa | Seedling | Summer 2 | 2 |
| | *Vicia faba* | Broad bean | Early Long Pod | Seed | Winter | ≥ 5 |
| | *Phaseolus vulgaris* | Common bean | Butter (Yellow) | Seedling | Summer 2 | 5 |
| **Herb** | *Ocimum basilicum* | Basil | Sweet Basil | Seedling | Summer 1 | 4 |
| | | | Greek Basil | Seedling | Summer 2 | 2 |
| | *Petroselinum crispum* | Parsley | Afro (Curly-leaved) | Seedling | Summer 1 & Winter[d] | 4 |
| | | | Italian (Flat-leaved) | Seedling | Summer 2 | 4 |

[a]Beetroot was planted as seed in the first summer season but as seedlings (unspecified variety) in the second summer season.
[b]Radish and lettuce plants were used primarily for *E. coli* and trace metal (contamination) analysis, and the sampling strategy was not suitable for analysis of yield (yield was only measured for lettuce in the first summer season).
[c]Owing to pest damage, broccoli was not suitable for yield analysis.
[d]In the winter growing season only, parsley failed to establish in the Lined raingarden and Potable control, and was not suitable for yield analysis.

**Table 2.5: The irrigation protocol for each of the four gardens.**

| Garden | Water source | System | Duration | Volume |
|---|---|---|---|---|
| **Potable** | Tap | Micro-spray | 30 minutes | 138L (4.6L/min) |
| **Tank** | Rainwater tank | Micro-spray | 30 minutes | 138L (4.6L/min) |
| **Unlined** | Rainwater tank | Drip | 20 minutes | 138L (6.9L/min) |
| **Lined** | Rainwater tank | Recharge pit | As needed | As needed |

The deficit irrigation regime was in place from December 2011 onwards, although regular hand-watering (applied to the surface) was occasionally needed for all four gardens, and temporarily replaced the deficit irrigation strategy. Most notably, this was the case in the two to three weeks immediately following planting for seedling establishment. Hand watering was also required when the rainwater tank was empty, following an extended time of low rainfall and high frequency of irrigation (one two-week period in both of the summer growing seasons, specifically February 2012 and January 2013). Watering was conducted according to the soil water threshold, but the volume applied was significantly lower (approximately 40%) and only tap water was available. The Lined raingarden continued to be irrigated by recharging its overflow pit.

Other than irrigation, maintenance activity included regular cleaning of the splitter box and flumes to sustain hydrologic performance, as well as some of the practices associated with a traditional vegetable garden. No fertilizers, pesticides or herbicides were used at any time. A thin layer of pea-straw mulch was applied for the first summer growing season, but no mulch was applied in the winter and second summer growing seasons.

### 2.2.7. Data collection and analysis

#### 2.2.7.1. Yield

Plant measurements were focused entirely on yield. Tomatoes, beans and cucumbers were harvested as they ripened, based on consistent colour and size criteria. For these fruit vegetables, harvests were generally conducted on a weekly basis. The yield of other species was measured in a one-off harvest at the end of the growing season and/or as they ceased to be productive. An exception was the two herb species, parsley and basil, in the first summer growing season, for which weekly/fortnightly pruning and sampling was necessary. Further details on harvests are presented in Appendix F.

Yield measurements comprised fresh and dry weights of edible plant parts and, where applicable, the number of fruit. Dry weights were obtained by oven-drying at 80°C to a constant weight. For each species/variety, yield weights and numbers were pooled for each garden. However, for beetroot, onion and leek, the number of plants per garden was variable, so every plant was measured individually and both total and mean weights were calculated for each garden. For tomatoes, beans, cucumbers, and other species that required running harvests, weights were combined for growing season totals for each species in each garden. In the second summer season, the number of harvested tomatoes affected by blossom end rot and cracking/splitting was also recorded. For analysis, the four gardens were compared in relation to the various measures of yield, particularly total dry weight. The emphasis was on differences between the two raingardens and the two controls (Research Question 2; the advantages of sub-irrigation), and between the Unlined and Lined raingardens (Research Question 1; the supplemental irrigation needs of a vegetable raingarden, particularly given the presence or absence of waterproof lining). While greater yield relative to other gardens was regarded as an indicator of superior performance, the overall performance of the gardens was assessed based on the efficiency of water use under deficit irrigation (and therefore the effectiveness of irrigation method), and not the gardens' ability to maximize yields.

#### 2.2.7.2. Hydrology

Data was downloaded from the monitoring apparatus weekly. Continuous data were generally available for November 2011 onwards. In the first instance, the rainfall, irrigation, water level, soil moisture and inflow data were assessed on a monthly basis using descriptive statistics; particularly mean, minimum and maximum values, and totals where applicable. Consistent with the analysis of yield, the analysis of soil moisture and irrigation emphasised differences between the two raingardens and the two control gardens. Differences in water level between the Lined and Unlined raingardens were also a focus of initial analysis. Regressions were used to analyse irrigation requirements in relation to rainfall and temperature, and in the analysis of soil moisture in relation to water level (95.0% confidence level). Data were checked for normality prior to analysis and transformed where necessary. All data presented in figures and tables are non-transformed. Statistical analysis was conducted using Minitab 16 Statistical Software (2012, Minitab, Inc.). The ability of the two raingardens to retain/reduce stormwater runoff was evaluated based on inflow and overflow (to address Research Question 5). In particular, for both raingardens, the focus was on:

1. Frequency (days) of (i) inflow and (ii) overflow.

2. Volume of (i) inflow and (ii) overflow.

3. Flow statistics (particularly percentile flows)

In order to compare the inflow data recorded by the level monitors on the flumes to the overflow data, the depths of water in the overflow pits (as measured using the Odyssey capacitance depth loggers) had to be expressed as flows. This could be calculated using a weir equation as there was a v-notch weir in each of the overflow pits. For a v-notch weir the flow rate can be calculated as:

$$q = 8/15\ c_d\,(2g)^{1/2}\ \tan(\theta/2)\ h^{5/2}$$

Where $q$ is the flow rate ($m^3\ s^{-1}$), $\theta$ is the v-notch angle, $h$ is head on the weir (m), $g$ = 9.81 ($m\ s^{-2}$) (gravity), and $c_d$ is a discharge constant for the weir (0.583 Thompson's Weir). This equation was applied to every measurement of water level. The overall water balance for each raingarden was assessed according to the principles shown in Figure 2.11. The difference between total inflow and total overflow was assumed to equate to evapotranspiration for the Lined raingarden, and to both evapotranspiration and infiltration losses (not separable) for the Unlined. For the Lined raingarden, occasions of overflow that were directly the result of irrigation, involving "topping up" the pit (see section 2.2.6), were excluded from analysis.

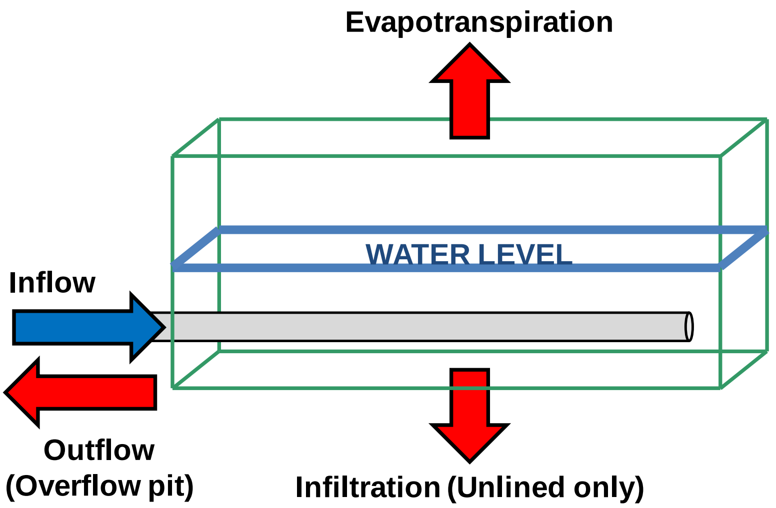



**Figure 2.11: Principles for evaluating the water balance of the raingardens.**

### 2.3. Results

#### 2.3.1. Vegetable yield

There were no consistent differences in the measures of yield between the two raingardens and the two control gardens (Table 2.6). Overall, the least productive of the four gardens was the Lined raingarden, but this was not the case for all species or varieties.

In the first summer growing season, yield by dry weight (Table 2.6; see Appendix F for fresh weight) was generally greater in the two control gardens for lettuce, tomato and cherry tomato. This was not the case for the number of cherry tomato fruit, however; fruit was generally larger in the Tank control (discussed below) but numbers were fewer (Table 2.7). For cucumber, yield (by all measures) was lowest in the Lined raingarden, but the Unlined was comparable to the controls. For the two herb species, the Tank control garden produced much greater yield of basil than any of the other three gardens, but there was little difference between the four gardens for parsley, with the Lined raingarden producing the greatest yield by a small margin. The only plant that showed greater yield in the two raingardens was beetroot.

In the winter growing season, the yields of spinach, leek and onion were lowest in the Lined raingarden, while the yield from the Unlined raingarden was generally comparable to the controls. However, the yield of broad beans was greatest in the Lined raingarden and lowest in the Tank control. The yield of broccoli was zero in all four gardens, owing to pest damage.

In the second summer growing season, tomato yield was greatest in the Tank control, followed by the Unlined raingarden, with the Lined raingarden and Potable control producing equally low yield. This was in contrast to the relatively high yield produced by the Potable control in the previous summer. Also unlike the previous year, beetroot yield was lowest in the Lined raingarden, but greatest in the Unlined, which produced the greatest yield for bean as well. However, for pepper, the Lined raingarden produced the greatest yield of the four gardens, while the Tank control produced the least. For basil, the two raingardens both produced more yield than the controls, but this situation was reversed for parsley.

The number of tomatoes affected by blossom end rot in the second summer season was greatest in the Lined raingarden (Table 2.8). This was also the case for the number of cracked tomatoes (Table 2.8). However, the Tank control garden was also significantly affected; much more so than the Unlined raingarden. In both summer growing seasons, and for all three varieties, it was also observed that the size of individual tomato fruit was generally greatest in the Tank control garden, and relatively low in the raingardens, particularly the Lined (Table 2.9).

**Table 2.6: Yield by dry weight. For root and bulb vegetables (with variable numbers of plants in each garden) the mean weights are presented. The total weights are presented for the remainder. The value in parentheses is the rank of the garden; 1 being the highest yield, 4 being the lowest.**

| | Yield: Dry weight (g) | | | | Summary | |
|---|---|---|---|---|---|---|
| | Control gardens | | Raingardens | | | |
| | Potable | Tank | Unlined | Lined | Highest | Lowest |
| **Root/bulb** | | | | | | |
| Beetroot* (S1) | 22.87 (3) | 20.33 (4) | 36.85 (1) | 35.65 (2) | *Unlined* | *Tank* |
| Beetroot* (S2) | 17.44 (2) | 16.40 (3) | 32.90 (1) | 10.39 (4) | *Unlined* | *Lined* |
| Onion (W) | 14.72 (2) | 40.63 (1) | 12.30 (3) | 4.29 (4) | *Tank* | *Lined* |
| Leek (W) | 26.58 (1) | 20.79 (3) | 22.29 (2) | 13.35 (4) | *Potable* | *Lined* |
| **Leaf** | | | | | | |
| Lettuce (S1) | 59.42 (2) | 68.34 (1) | 47.12 (4) | 49.27 (3) | *Tank* | *Unlined* |
| Spinach (W) | 138.32 (3) | 203.87 (1) | 175.13 (2) | 23.27 (4) | *Tank* | *Lined* |
| **Fruit/legume** | | | | | | |
| Tomato: Round (S1) | 603.91 (1) | 598.6 (2) | 267.53 (3) | 152.4 (4) | *Potable* | *Lined* |
| Tomato: Cherry (S1) | 349.83 (1) | 289.57 (2) | 197.95 (4) | 236.24 (3) | *Potable* | *Unlined* |
| Tomato: Plum (S2) | 805.25 (4) | 1864.19 (1) | 1277.59 (2) | 895.91 (3) | *Tank* | *Potable* |
| Cucumber (S1) | 688.99 (3) | 1078.69 (1) | 809.7 (2) | 239.89 (4) | *Tank* | *Lined* |
| Pepper (S2) | 21.74 (3) | 13.06 (4) | 22.27 (2) | 36.88 (1) | *Lined* | *Tank* |
| Broad bean (W) | 179.20 (2) | 97.81 (4) | 135.31 (3) | 199.43 (1) | *Lined* | *Tank* |
| Common bean (S2) | 10.95 (2) | 8.89 (3) | 27.60 (1) | 0 (4) | *Unlined* | *Lined* |
| **Herb** | | | | | | |
| Basil: Sweet (S1) | 643.77 (2) | 1236.84 (1) | 463.55 (4) | 569.23 (3) | *Tank* | *Unlined* |
| Basil: Greek (S2) | 42.86 (4) | 54.64 (3) | 95.22 (1) | 78.03 (2) | *Unlined* | *Potable* |
| Parsley: Afro (S1) | 500.00 (4) | 521.88 (2) | 521.26 (3) | 567.02 (1) | *Lined* | *Potable* |
| Parsley: Italian (S2) | 153.89 (1) | 134.66 (2) | 54.96 (4) | 63.39 (3) | *Potable* | *Unlined* |

***Edible root (tuber) only. See Appendix F for fresh leaf weights.**

**Table 2.7: The number of fruit/pods harvested from the four gardens, for the fruit and legume vegetables. The value in parentheses is the rank of the garden; 1 being the highest yield, 4 being the lowest.**

| | Number of fruit/pods | | | | Summary | |
|---|---|---|---|---|---|---|
| | Control gardens | | Raingardens | | | |
| | Potable | Tank | Unlined | Lined | Highest | Lowest |
| Tomato: Round (S1) | 113 (2) | 126 (1) | 61 (3) | 32 (4) | *Tank* | *Lined* |
| Tomato: Cherry (S1) | 1161 (1) | 507 (4) | 575 (3) | 716 (2) | *Potable* | *Tank* |
| Tomato: Plum (S2) | 422 (4) | 951 (1) | 810 (2) | 570 (3) | *Tank* | *Potable* |
| Cucumber (S1) | 55 (3) | 66 (1) | 56 (2) | 16 (4) | *Tank* | *Lined* |
| Pepper (S2) | 92 (3) | 66 (4) | 98 (2) | 173 (1) | *Lined* | *Tank* |
| Broad bean (W) | 170 (2) | 118 (4) | 147 (3) | 171 (1) | *Lined* | *Tank* |
| Common bean (S2) | 18 (2) | 12 (3) | 31 (1) | 0 (4) | *Unlined* | *Lined* |

**Table 2.8: The number of plum tomatoes affected by blossom end rot (B.E.R.) and cracking in each of the four gardens. The value in parentheses is the rank of the garden; 1 being the most affected, 4 being the least.**

| | **Number of affected fruit** | | | | **Summary** | |
|---|---|---|---|---|---|---|
| | **Control gardens** | | **Raingardens** | | | |
| | Potable | Tank | Unlined | Lined | Most | Least |
| B.E.R. | 55 (4) | 149 (2) | 95 (3) | 188 (1) | *Lined* | *Potable* |
| Cracking | 2 (4) | 11 (2) | 4 (3) | 12 (1) | *Lined* | *Potable* |

**Table 2.9: The average weight of individual fruit (total fresh weight / total count) for the three tomato varieties in each of the four gardens. The value in parentheses is the rank of the garden; 1 being the greatest weight, 4 being the lowest.**

| | **Average fresh weight (g)** | | | | **Summary** | |
|---|---|---|---|---|---|---|
| | **Control gardens** | | **Raingardens** | | | |
| | Potable | Tank | Unlined | Lined | Highest | Lowest |
| Round (S1) | 92.70 (2) | 99.15 (1) | 82.46 (3) | 77.48 (4) | *Tank* | *Lined* |
| Cherry (S1) | 3.68 (3) | 7.73 (1) | 4.56 (2) | 3.62 (4) | *Tank* | *Lined* |
| Plum (S2) | 31.87 (2) | 34.56 (1) | 25.69 (3) | 21.81 (4) | *Tank* | *Lined* |

### 2.3.2. Soil moisture and irrigation requirements

#### 2.3.2.1. Summary of growing seasons

Above average rainfall was recorded for four of the five months of the first summer growing season (Table 2.10). For this period (November 2011-March 2012), 344.7 mm of rainfall (total) was recorded at the site, with an average of 68.9 mm per month. There was exceptional November rain as well as multiple large storm events, which are reflected in some very high daily totals (e.g. 26$^{th}$ November and 25$^{th}$ December; Table 2.10). Under these conditions, all four gardens required minimal irrigation in late 2011 (Table 2.11). However, the subsequent January was very dry in comparison, and soil moisture in each of the four gardens reached one of its lowest points of the 1.5-year monitoring period (Figure 2.12 and Appendix G). Despite wetter conditions in February and March, all four gardens required irrigation regularly from the beginning of 2012 until the end of the growing season.

**Table 2.10: Total and highest daily rainfalls recorded by the vegetable raingarden site rain gauge for each month. Mean and historical highest daily rainfall data is for the Hawthorn BOM weather station (operational for the past 40 years). For the mean, arrows indicate whether the recorded total was higher (up) or lower (down) than average.**

| Month | Total (mm) | Days ≥ 1 mm | Days ≥ 10 mm | Highest daily (mm) | Mean (mm) | Highest daily since 1972 (mm) |
|---|---|---|---|---|---|---|
| **Sep 2011**[a] | 74.1 | n/m | n/m | 52.0 (28/29th) | *59.0* ↑ | *35.0 (1984)* |
| **Oct 2011**[a] | 53.2 | n/m | n/m | 19.0 (29/30th) | *66.2* ↓ | *41.4 (2000)* |
| **Nov 2011** | 125.0 | 11 | 3 | 52.2 (26th) | *67.7* ↑ | *100.0 (1988)* |
| **Dec 2011** | 75.8 | 6 | 3 | 35.0 (25th) | *58.9* ↑ | *75.0 (1999)* |
| **Jan 2012** | 30.2 | 7 | 1 | 14.6 (8th) | *49.1* ↓ | *79.2 (2004)* |
| **Feb 2012** | 67.2 | 7 | 2 | 34.4 (27th) | *47.8* ↑ | *109.0 (2005)* |
| **Mar 2012** | 63.4 | 7 | 3 | 17.8 (3rd) | *46.4* ↑ | *52.4 (1995)* |
| **Apr 2012** | 57.2 | 9 | 2 | 17.0 (25th) | *54.5* ↑ | *57.3 (2011)* |
| **May 2012** | 92.8 | 7 | 3 | 40.4 (25th) | *58.1* ↑ | *54.6 (1978)* |
| **Jun 2012** | 73.6 | 9 | 3 | 30.6 (21st) | *50.5* ↑ | *47.0 (1999)* |
| **Jul 2012** | 62.0 | 13 | 1 | 19.8 (27th) | *53.0* ↑ | *52.0 (1990)* |
| **Aug 2012** | 53.8 | 15 | 0 | 7.2 (31st) | *57.4* ↓ | *33.6 (1983)* |
| **Sep 2012** | 37.4 | 5 | 2 | 11.8 (6th) | *58.7* ↓ | *52.0 (2011)* |
| **Oct 2012** | 32.2 | 9 | 1 | 10.2 (9th) | *66.5* ↓ | *41.4 (2000)* |
| **Nov 2012** | 38.2 | 6 | 1 | 21.0 (27th) | *65.8* ↓ | *100.0 (1988)* |
| **Dec 2012** | 24.8 | 6 | 0 | 8.0 (1st) | *58.0* ↓ | *75.0 (1999)* |
| **Jan 2013** | 20.8 | 3 | 1 | 16.6 (31st) | *49.1* ↓ | *79.2 (2004)* |
| **Feb 2013** | 53.2 | 5 | 1 | 37.4 (26th) | *47.8* ↑ | *109.0 (2005)* |
| **Mar 2013** | 49.2 | 8 | 2 | 21.2 (16th) | *46.4* ↑ | *52.4 (1995)* |

[a]September and October 2011 was a preliminary period before full monitoring commenced (n/m = not measured). The data presented for these two months are as recorded by the Hawthorn BOM weather station.

Despite another wet start, the winter growing season (April 2012-October 2012) was drier than average in the final three months (Table 2.10). A total of 409 mm of rainfall was recorded at the site (note that the winter season was two months longer than the summer growing seasons). The average monthly rainfall was 58.4 mm for this period. May was the second wettest month of the entire study period, behind November 2011, with exceptional rainfall on 25th May. Between May and September 2012, rainfall totals steadily declined from month to month, culminating in only 32.2 mm in October, which was similar to the preceding January. Nonetheless, neither raingarden required any irrigation under the deficit regime, while the two control gardens required frequent irrigation by October. Soil temperatures were much lower than in summer (Figure 2.13 and Appendix G), and this was probably a major factor in the raingardens not requiring back-up irrigation.

**Table 2.11: Total irrigation volumes for each month. The value in parentheses is the number of times that irrigation was required under the deficit irrigation regime; i.e., not including any other watering, such as watering of newly planted seedlings.**

| | | Irrigation volumes (L) | | | |
|---|---|---|---|---|---|
| | | Control gardens | | Raingardens | |
| | | Potable | Tank | Unlined | Lined |
| | Sep 2011[a] | 9 | 99 | 99 | 99 |
| | Oct 2011[a] | 526 | 533 | 1392 | 521 |
| Summer 1 | Nov 2011 | 138 (1) | 138 (1) | 138 (1) | 6 (1) |
| | Dec 2011 | 138 (1) | 138 (1) | 138 (1) | 99 (4) |
| | Jan 2012 | 1802 (13) | 1802 (13) | 1664 (12) | 421 (13) |
| | Feb 2012[b] | 562 (7) | 562 (7) | 755 (9) | 280 (11) |
| | Mar 2012 | 832 (7) | 832 (7) | 792 (6) | 155 (3) |
| Winter | Apr 2012[c] | 633 (3) | 633 (3) | 722 (4) | 299 (4) |
| | May 2012 | 14 (0) | 9 (0) | 5 (0) | 9 (0) |
| | Jun 2012 | 0 (0) | 0 (0) | 0 (0) | 0 (0) |
| | Jul 2012 | 0 (0) | 0 (0) | 0 (0) | 0 (0) |
| | Aug 2012 | 2 (0) | 2 (0) | 2 (0) | 2 (0) |
| | Sep 2012 | 6 (0) | 6 (0) | 6 (0) | 6 (0) |
| | Oct 2012 | 702 (5) | 702 (5) | 16 (0) | 16 (0) |
| Summer 2 | Nov 2012 | 400 (2) | 400 (2) | 538 (3) | 124 (0) |
| | Dec 2012 | 604 (4) | 604 (4) | 1017 (7) | 17 (0) |
| | Jan 2013[b] | 923 (12) | 923 (12) | 1004 (12) | 0 (0) |
| | Feb 2013 | 1104 (8) | 1104 (8) | 966 (7) | 0 (0) |
| | Mar 2013 | 690 (5) | 690 (5) | 138 (1) | 0 (0) |
| | **TOTAL[d]** | **8552 (68)** | **8547 (68)** | **7901 (63)** | **1434 (36)** |

[a] Irrigation prior to the start of main irrigation regime; includes hand-watering and tests of the irrigation system. Note the large volume applied to the Unlined raingarden.
[b] February 2012 and January 2013 both include two weeks of hand-watering, according to the principles of the deficit irrigation strategy, when the rainwater tank was empty.
[c] Deficit irrigation in April 2012 was entirely conducted before the winter crop was planted (to maintain lettuce for contamination research), and is not considered part of the winter growing season. The planting was followed by one week of hand-watering.
[d] Total since the beginning of full monitoring in November 2011.

Following the dry close to the winter growing season, the second summer season was much drier than the first, with rainfall in three of the five months (November to January) well below average. Average monthly rainfall was only 37.2 mm in this period, and total rainfall was only 186.2 mm, which was 54% less than the first summer. Rainfall in November 2012 in particular was only 30.5% of that recorded in November 2011. January 2013 was the driest month of the entire 1.5-year study period; the site received only 20.8 mm of rain, and 80% of that total was received in the final eight hours of the month. This summer growing period was also exceptionally hot (Appendix G), including 14 days above 30°C in February and nine consecutive days above 30°C in March. Nonetheless, the Lined raingarden required no back-up irrigation, other than routine watering of new seedlings. The Unlined raingarden did require back-up irrigation, at a frequency comparable to the control gardens (Table 2.11).

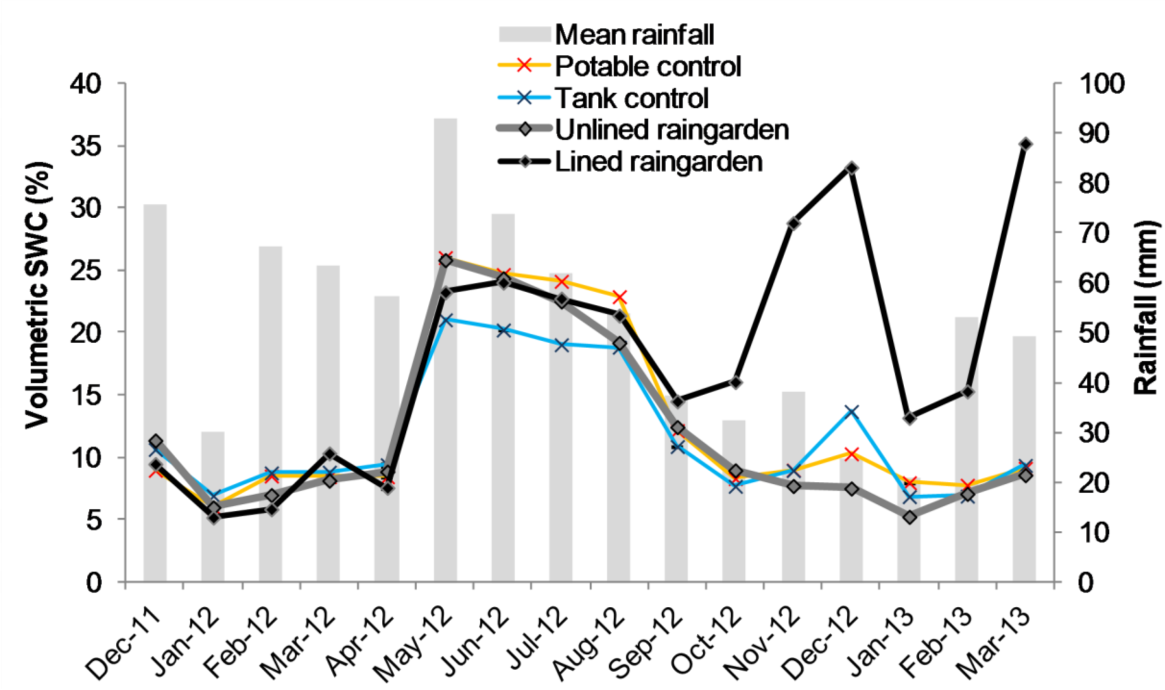



**Figure 2.12: Mean soil moisture (± SE) in the four garden beds in each month of the monitoring period (except November 2012, when probes were not calibrated), with rainfall totals for comparison. Further details are presented in Appendix G. CS616 probes are checked in standard media to ensure accuracy of ± 2% volumetric water content (Campbell Scientific Inc., 2002).**

### 2.3.2.2. Differences between gardens

In terms of total volume, the main source of water for both raingardens was the sub-irrigation system supplying rainwater from the roof (Table 2.12). The inflow hydrographs for this sub-irrigation water showed a series of peaks corresponding to rainfall, with no baseflow, which is typical for runoff from impervious surfaces. The total volume of water received by the control gardens, which received no roof-water via sub-irrigation, was much less than that received by the two raingardens; only 20-28% for the first two growing seasons, and 36% of the Unlined and 53% of the Lined in the second summer (Table 2.12).

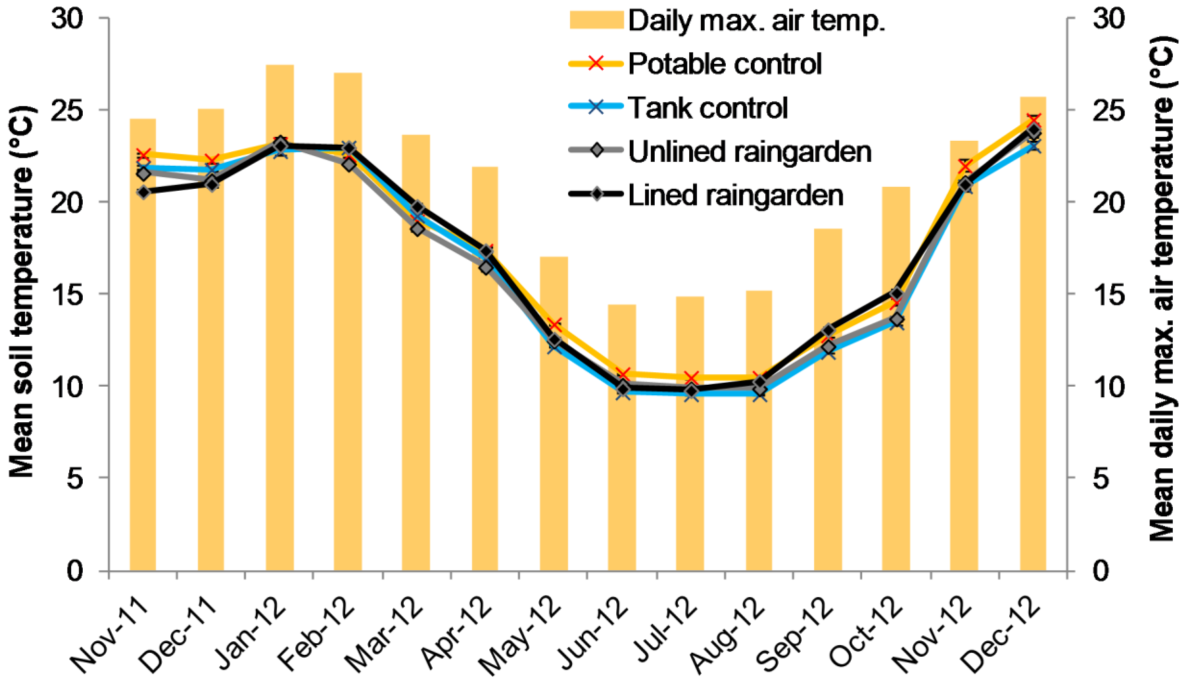



**Figure 2.13: Mean soil temperature (± SE) in the four garden beds in each month of the monitoring period (except January-March 2013; no data). Soil temperature was recorded to the nearest 0.5°C. Mean daily maximum air temperatures, as recorded by the Melbourne Regional Office station of the Bureau of Meteorology (station number 086071), are presented for comparison. Further details are presented in Appendix G.**

**Table 2.12: The total amount of water received by the two control gardens and the two raingardens over the three growing seasons.**

| | | Sub-irrigation (roof) (L) | Deficit irrigation (L) | Other watering[a] (L) | Direct rain[b] (L) | Total (L) |
|---|---|---|---|---|---|---|
| **Control gardens (both)** | Summer 1 | n/a | 3448 | 24 | 1206 | **4678** |
| | Winter | n/a | 1254 | 103 | 1364 | **2721** |
| | Summer 2 | n/a | 3580 | 141 | 621 | **4342** |
| **Unlined rain-garden** | Summer 1 | 15412 | 3462 | 25 | 1206 | **20105** |
| | Winter | 11099 | 552 | 94 | 1364 | **13109** |
| | Summer 2 | 7836 | 3523 | 141 | 621 | **12121** |
| **Lined rain-garden** | Summer 1 | 14758 | 936 | 25 | 1206 | **16925** |
| | Winter | 10930 | 184 | 98 | 1364 | **12576** |
| | Summer 2 | 7389 | 0 | 141 | 621 | **8151** |

[a] Mostly hand-watering of newly planted seedlings.
[b] Not measured directly; estimated based on rainfall data and area of garden bed.
[c] This includes deficit irrigation in early April, prior to the planting of the winter crop. For the entire period after the winter crop was planted, the total deficit irrigation volume was 702 L for the control gardens and zero for both raingardens.

The Lined raingarden required no irrigation to supplement rainfall throughout the final 12 months of the 1.5-year study; a period which included the exceptionally dry and hot second summer. When irrigation was required, in the first summer growing season, the Lined raingarden received only 27% of the volume of back-up irrigation water that the Unlined received, because of the different irrigation methods (see section 2.2.6). Consequently, the Lined raingarden had the lowest mean soil moisture of any of the four gardens in January and February 2011. However, the Lined raingarden began to show consistently greater soil moisture than the Unlined (and the controls) approximately mid-way through the winter growing season (August 2012), and from then on soil moisture diverged considerably between the two raingardens (Figure 2.12; Figure 2.14).

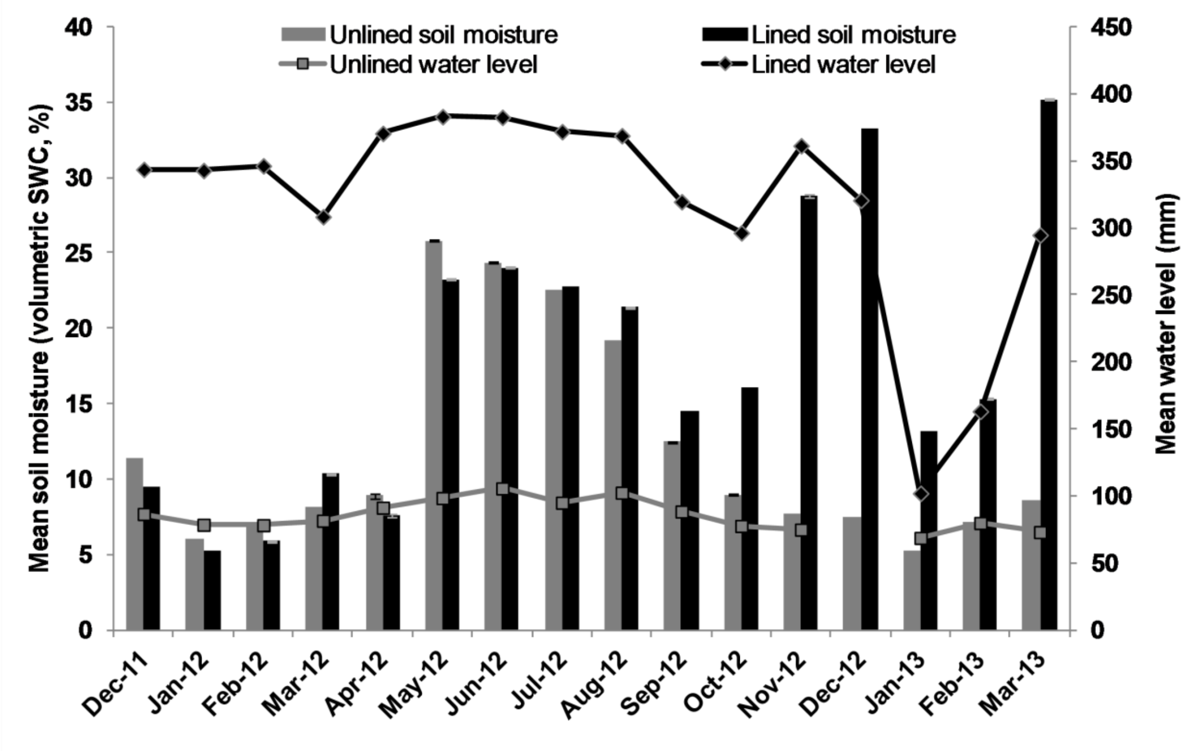



**Figure 2.14: Mean (± SE) soil moisture in the two raingardens, Unlined (grey bars) and Lined (black bars), and the relationship with mean (± SE) water level for each month. For the Unlined raingarden, there is no water level data for December 2012.**

The Unlined raingarden required irrigation to supplement rainfall in both summer growing seasons, but not in winter. Despite the large volume of roof-water received by the Unlined raingarden via sub-irrigation, there were generally no major differences in soil moisture between the Unlined raingarden and the control gardens (Figure 2.12). As such, in the summer growing seasons, the volume of back-up irrigation that the Unlined raingarden required was very similar to the volume of irrigation water applied to the control gardens (Table 2.12). However, in the winter growing season, the control gardens needed irrigation late in the season while the Unlined raingarden needed none. Generally, under the deficit irrigation regime, the volume of back-up irrigation water required for the Unlined raingarden was inversely proportional to rainfall in the summer months (Figure 2.15), although the relationship between rainfall and irrigation volumes was not statistically significant ($R^2$=20.1%, P=0.071). Irrigation requirements were better correlated with soil temperature ($R^2$=52.4%, P=0.003) (Figure 2.16).

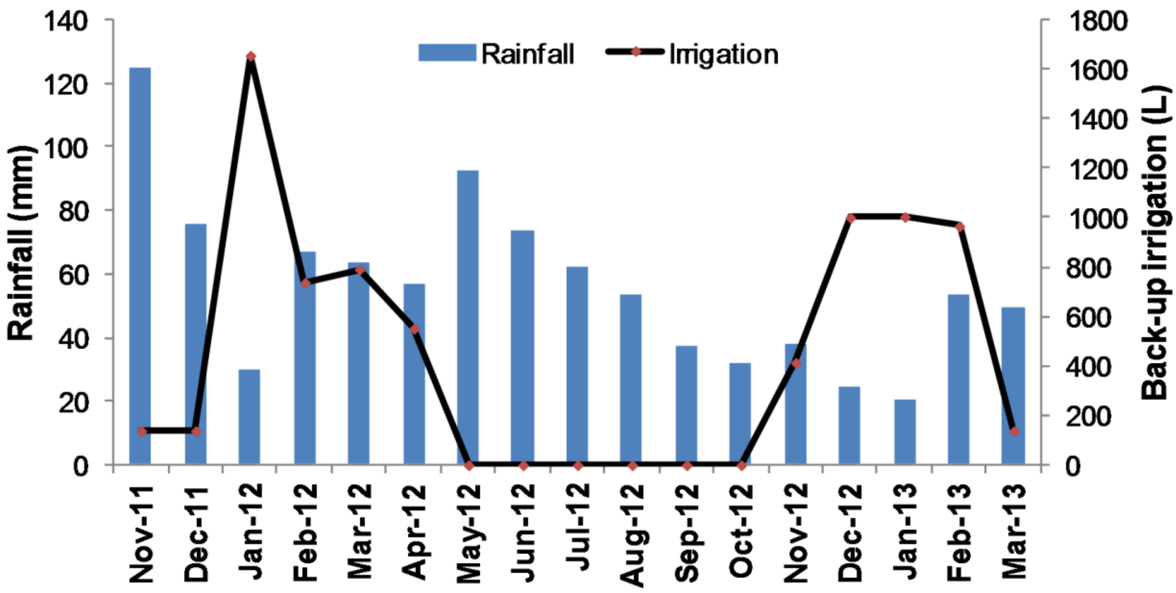



**Figure 2.15: Irrigation requirements for the Unlined raingarden under the deficit irrigation regime (black line), in relation to monthly rainfall totals (blue bars).**

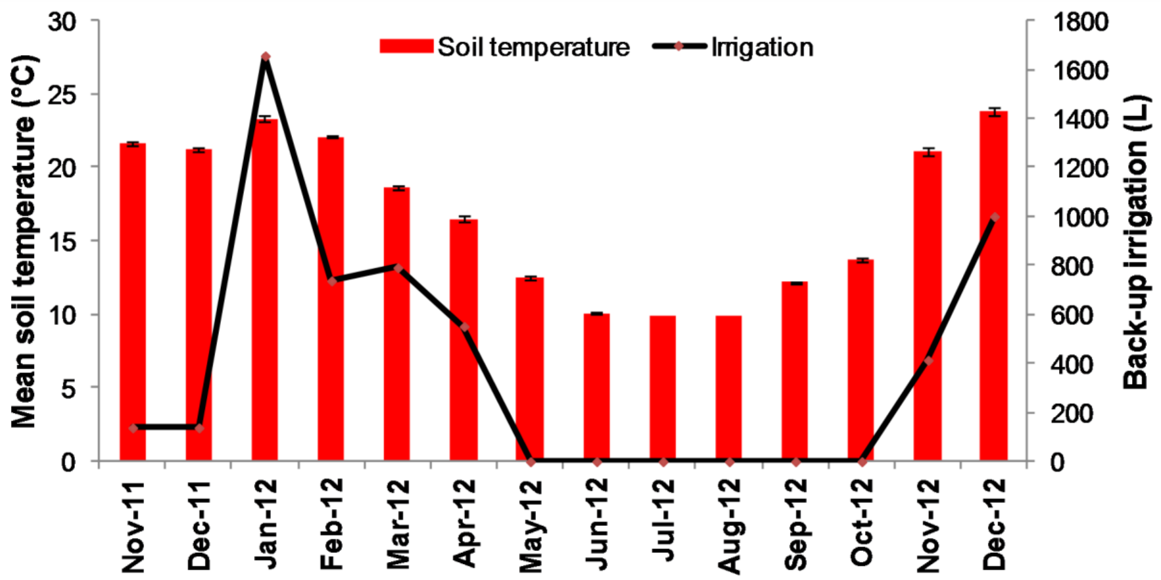



**Figure 2.16: Irrigation requirements for the Unlined raingarden under the deficit irrigation regime (black line), in relation to mean (± SE) soil temperature for each month (red bars). There is no soil temperature data for 2013.**

A key factor explaining the different irrigation requirements of the two raingardens was water level, measured by the Odyssey depth loggers (Table 2.13). The water level in the Lined raingarden, which could only lose water through evapotranspiration and not through infiltration into the underlying soil, was consistently much higher than in the Unlined. For most of the 1.5-year study period, it was typically 25-35 cm above ground level (Figure 2.14; Table 2.13), in either the upper part of the sand (middle) layer or in the lower part of the soil (top) layer. This would be expected to significantly assist capillary rise of water into the vegetable root zone. The maximum water level in the Lined raingarden over the monitoring period was 46.5 cm above ground level; this was recorded early in the study, on 26th November 2011. The maximum water level was limited by the height of the overflow pit.

In contrast, the mean water level in the Unlined raingarden, which could lose water through both evapotranspiration and infiltration into the underlying soil, was within the gravel layer in every growing season (Figure 2.14; Table 2.13). The water level temporarily rose into the sand layer in most months of the study, following significant rainfall events, but it did not rise into the soil layer during the drier periods (e.g. January to March 2012). Indeed, it reached a maximum of less than 250 mm in January 2012, and only 185 mm, which is not even as high as the gravel-sand boundary, in January 2013. Variations in the water level in the Unlined raingarden did seem to have some influence on soil moisture ($R^2$=78.0%, P<0.001). This was not the case for the Lined raingarden ($R^2$=1.6%, P=0.641). This is because the water level in the Lined was much more consistent over the monitoring period, with the exception of the dry second summer growing season, but soil moisture varied considerably (Figure 2.14).

A large storm on 28th September 2011, the first major rainfall event to affect the system, demonstrated the different responses of the two raingardens to rainfall. Approximately 50 mm of rainfall was received. Before the storm, at 3 pm, the depth of water in the two raingardens was very similar; well below the gravel-sand boundary in both (Figure 2.17). During the storm, the water level in the Lined raingarden increased by 27.5 cm by 5 pm, and stayed within the soil layer until shortly after 11 pm. In comparison, the water level in the Unlined raingarden increased by approximately 17.5 cm by 5 pm, which was 10 cm less than the Lined. Apart from a short-lived increase shortly before 8 pm, it stayed mostly within the sand layer and declined into the gravel layer before 11 pm.

**Table 2.13: Summary of water depth (mm) by month in the two raingardens. In all months, the minimum water level in the Unlined raingarden was at or close to zero depth, and is therefore not presented. Standard error is shown for the mean (±). For context, the gravel layer was at approximately 0-200 mm, the sand layer at 200-350 mm, and the soil layer at 350-700 mm (see section 2.2.3). The "Hours in soil" value is the number of hours for which the water level was above 350 mm.**

| | | Depth of water (cm) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Unlined raingarden | | | Lined raingarden | | | |
| | | Mean | Max | Hours in soil | Mean | Min | Max | Hours in soil |
| Summer 1 | Nov 2011 | 126.43 ± 0.3 | 441.7 (26th) | 14.4 | 390.5 ± 0.1 | 354.9 (26th) | 464.6 (26th) | 719.8 |
| | Dec 2011 | 86.56 ± 0.2 | 432.4 (25th) | 3.9 | 343.7 ± 0.1 | 264.6 (18th) | 444.6 (25th) | 284.2 |
| | Jan 2012 | 78.52 ± 0.1 | 248.7 (8th) | 0 | 342.9 ± 0.1 | 270.2 (30th) | 410.0 (8th) | 272.9 |
| | Feb 2012 | 78.23 ± 0.2 | 315.4 (27th) | 0 | 346.4 ± 0.1 | 261.3 (4th) | 425.1 (16th) [a] | 313.7 |
| | Mar 2012 | 81.55 ± 0.2 | 320.3 (3rd) | 0 | 308.4 ± 0.3 | 195.5 (15th) | 425.1 (16th) [a] | 194.3 |
| Winter | Apr 2012 | 91.30 ± 0.2 | 433.5 (25th) | 1.8 | 370.6 ± 0.1 | 289.7 (2nd) | 423.4 (6th) | 569.4 |
| | May 2012 | 98.45 ± 0.3 | 427.5 (25th) | 5.3 | 383.1 ± 0.03 | 364.9 (24th) | 421.7 (13th) | 743.8 |
| | Jun 2012 | 105.67 ± 0.3 | 425.8 (22nd) | 5.4 | 382.6 ± 0.03 | 365.5 (12th) | 403.3 (29th) | 719.8 |
| | Jul 2012 | 94.98 ± 0.2 | 390.3 (27th) | 1.5 | 371.9 ± 0.1 | 322.0 (25th) | 411.7 (1st) | 604.2 |
| | Aug 2012 | 102.47 ± 0.2 | 251.4 (10th) | 0 | 368.9 ± 0.1 | 298.6 (29th) | 417.8 (6th/31st) | 629.5 |
| | Sep 2012 | 88.42 ± 0.2 | 294.1 (6th) | 0 | 319.6 ± 0.2 | 230.6 (28th) | 420.1 (6th) | 157.4 |
| | Oct 2012 | 77.65 ± 0.2 | 215.3 (10th) | 0 | 296.4 ± 0.2 | 211.1 (6th) | 403.9 (16th/24th) | 105.9 |
| Summer 2 | Nov 2012 | 74.91 ± 0.2 | 403.4 (27th) | 1.6 | 361.4 ± 0.1 | 225.1 (1st) | 435.7 (29th) | 521.3 |
| | Dec 2012 | No data[b] | No data[b] | No data[b] | 320.7 ± 0.3 | 183.8 (31st) | 412.3 (15th) | 270.5 |
| | Jan 2013[b] | 68.69 ± 0.1 | 184.7 (31st) | 0 | 102.0 ± 0.2 | 71.9 (30th) | 271.3 (31st) | 0 |
| | Feb 2013 | 79.86 ± 0.2 | 433.5 (26th) | 1.4 | 163.2 ± 0.5 | 78.6 (28th) | 415.0 (26th) | 67.9 |
| | Mar 2013 | 73.06 ± 0.1 | 309.4 (28th) | 0 | 294.8 ± 0.3 | 184.4 (13th/16th) | 429.5 (28th) | 185.2 |

[a] Not an error: The maximum water levels for February and March 2012 were identical, and fell on the same day of the month (16th), at the same time of day (3.36 pm for February and 3.06 pm for March).
[b] Due to a technical fault, there was no data for the Unlined raingarden for the majority of December 2012, and no data for 1st-9th January 2013 (a time of very low rainfall).

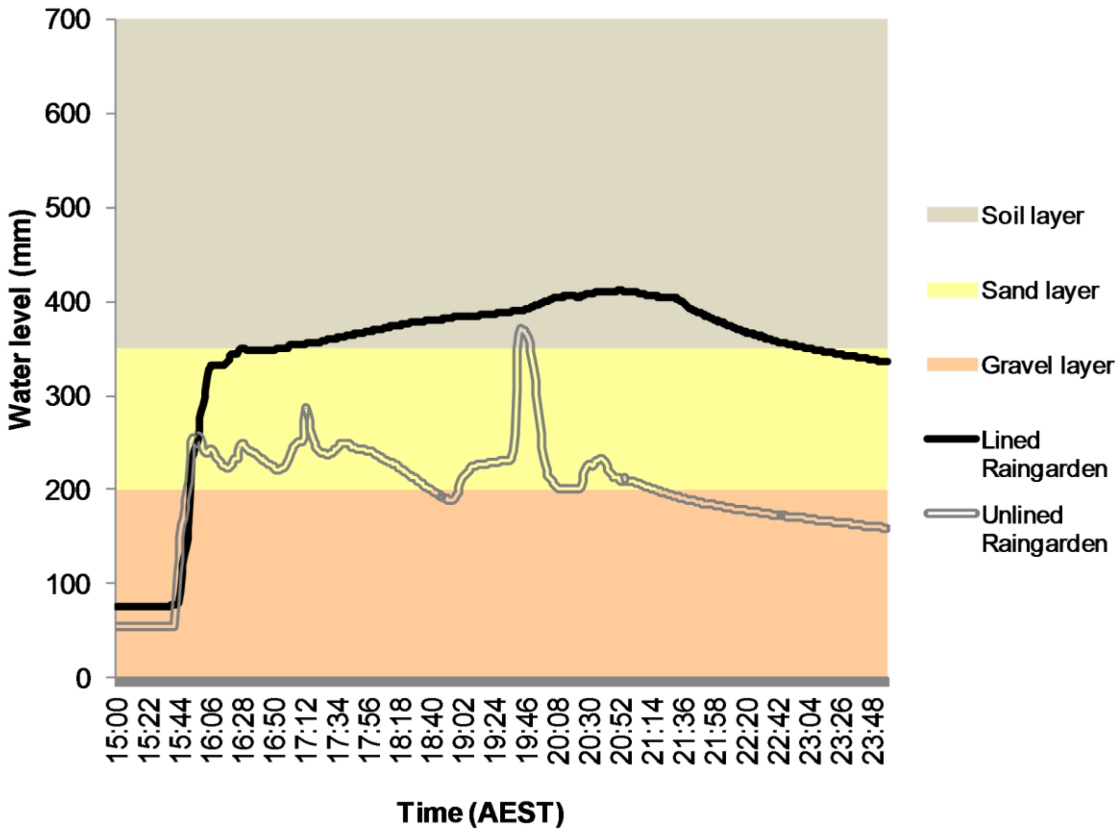



**Figure 2.17: Water level in the two raingardens between 3 pm and 11.59 pm (AEST) on 28th September 2011, following heavy rainfall. The approximate boundaries of the filter/growing media layers are presented for comparison.**

### 2.3.3. Runoff reduction

#### 2.3.3.1. Frequency

Overall, the hydrologic performance of the Unlined raingarden, which lost significant amounts of water through infiltration into the underlying soil, was better than the Lined. In terms of reducing the frequency of runoff, overflow to the stormwater drain from the Unlined raingarden occurred on 6.6% of days on which inflow occurred (Figure 2.18; further details in Appendix G). As such, the vast majority of rain events were entirely captured by the Unlined raingarden. This included 11 months (of 17) with no overflow at all, and overflow occurred on only one day (26th February 2013) between July 2012 and the end of the study in March 2013. The maximum number of days of overflow per month was two. In contrast, overflow from the Lined raingarden occurred on 66.0% of rain days (Figure 2.19), including three months in which overflow occurred on every day of inflow. There was only one month (January 2013) in which no overflow was recorded. In summary, the difference in runoff frequency reduction between the two raingardens was clear; 93% for the Unlined compared to 34% for the Lined.

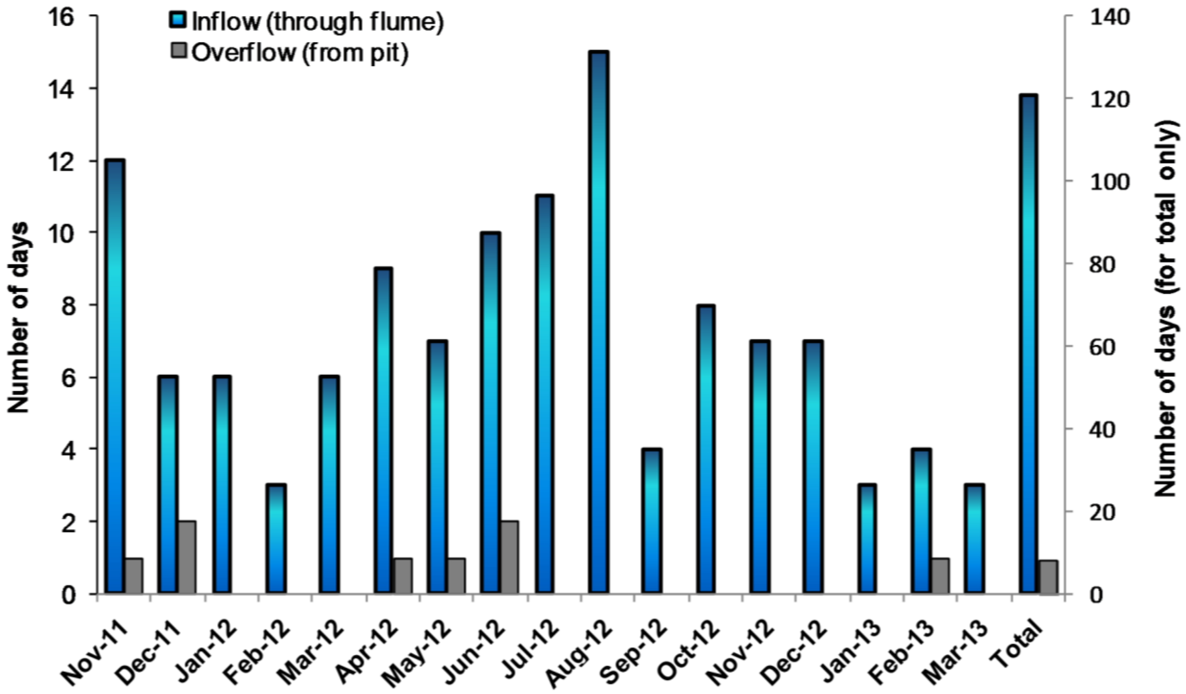



**Figure 2.18: Number of days per month of inflow (> 1 L m$^{-1}$) to the Unlined raingarden compared to the number of days of overflow.**

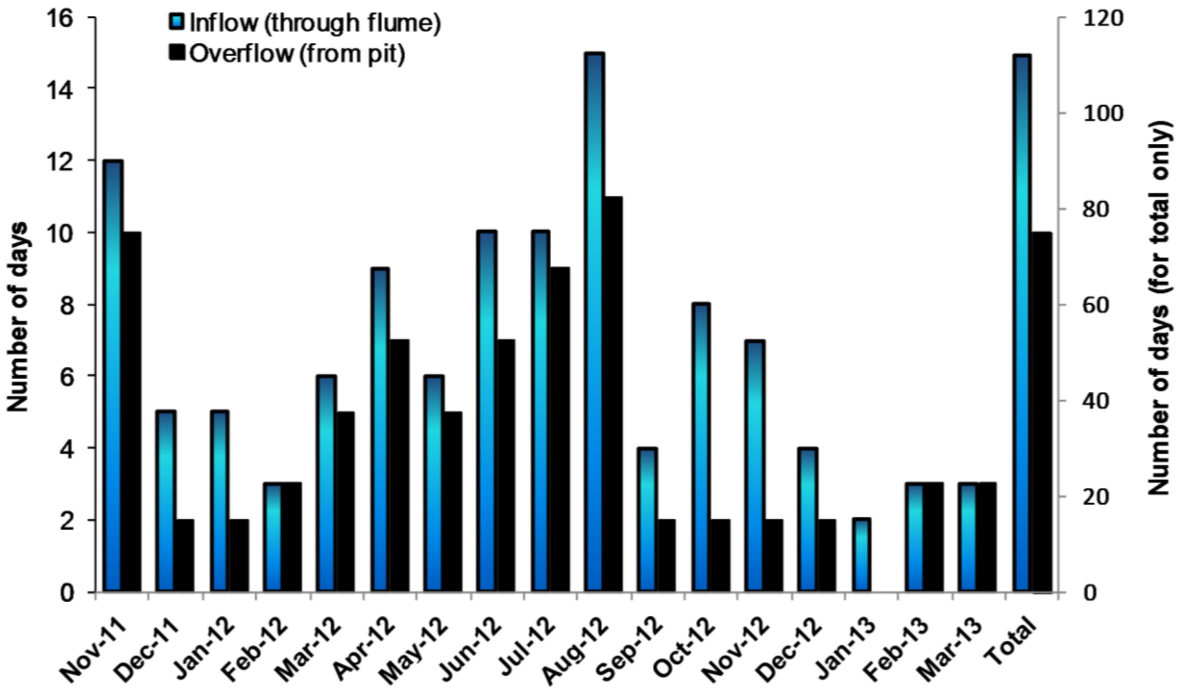



**Figure 2.19: Number of days per month of inflow (> 1 L m$^{-1}$) to the Lined raingarden compared to the number of days of overflow.**

#### 2.3.3.2. Volume

Both raingardens also reduced the volume of runoff and attenuated flow rates but, as was the case for frequency, the Unlined performed better than the Lined. For the Unlined raingarden (Figure 2.20), over the entire study period, 9% of the volume of inflow overflowed to the stormwater drain, compared to 37% for the Lined (Figure 2.21; further details in Appendix G). This indicates that almost two thirds (63%) of the inflow was used and lost through evapotranspiration in the Lined raingarden, while 91% of the inflow to the Unlined raingarden was lost through the combination of evapotranspiration and infiltration into the underlying soil.

For both raingardens, the quantity of overflow relative to inflow was highest in May 2012 (particularly following exceptionally high rainfall on the 25$^{th}$); 36% for the Unlined and 91% for the Lined. For the Unlined, overflow was otherwise between 0 and 17% of inflow in all months. The performance of the Lined raingarden was highly variable over the course of the study period, and it was generally effective in reducing runoff from rainfall events that were preceded by dry periods, particularly in October 2012 and January 2013.

For both raingardens, rates of overflow were less than rates of inflow up to the 99.9th percentile, with the Unlined particularly effective at attenuating peak flow (Table 2.14). However, for both raingardens, the maximum overflow rate was higher than the maximum inflow rate. This only occurred during high intensity rainfall events in December 2011. It indicates that, for periods of less than two minutes, the entire inflow to the raingardens was being discharged to the stormwater drain, probably together with some rainfall that had fallen directly onto the garden beds. It occurred on three occasions for the Lined raingarden in December 2011 (10$^{th}$, 11$^{th}$ and 25$^{th}$), but did not occur again during the monitoring period. For the Unlined raingarden, it occurred only once during the monitoring period; at 5.37 pm on 25$^{th}$ December 2011, during one of the most severe thunderstorms. The second highest overflow rate was 63.36 L m$^{-1}$, which was less than the corresponding inflow rate, on 11$^{th}$ December 2011.

**Table 2.14: Attenuation of peak flow; percentiles of inflow and overflow rates for the Unlined and Lined raingardens.**

| | | Percentile of flow rates (L m$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | **95.0** | **97.5** | **99.0** | **99.5** | **99.9** | **100.0** |
| **Unlined** | **Inflow** | 0.13 | 0.26 | 0.89 | 1.75 | 5.33 | 72.19 |
| | **Overflow** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 90.43 |
| **Lined** | **Inflow** | 0.12 | 0.20 | 0.70 | 1.65 | 5.14 | 74.90 |
| | **Overflow** | 0.00 | 0.00 | 0.05 | 0.38 | 3.95 | 83.66 |

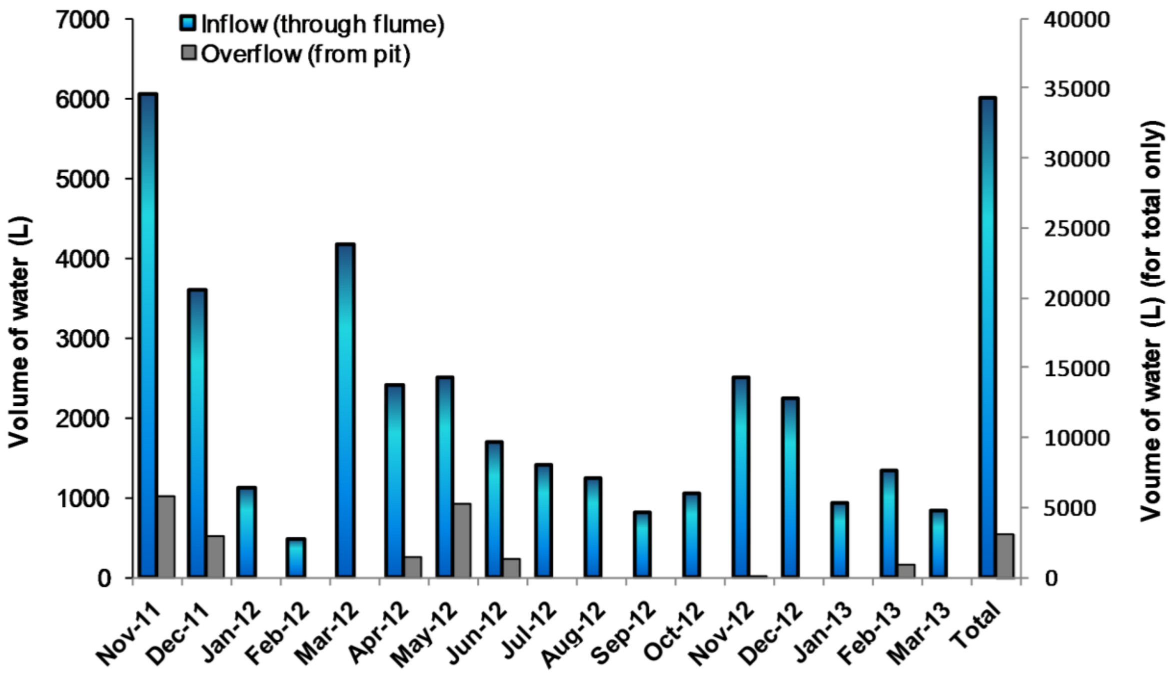



**Figure 2.20: Total volume of inflow (through the flume) in comparison to the total volume of overflow (to the stormwater drain) for the Unlined raingarden.**

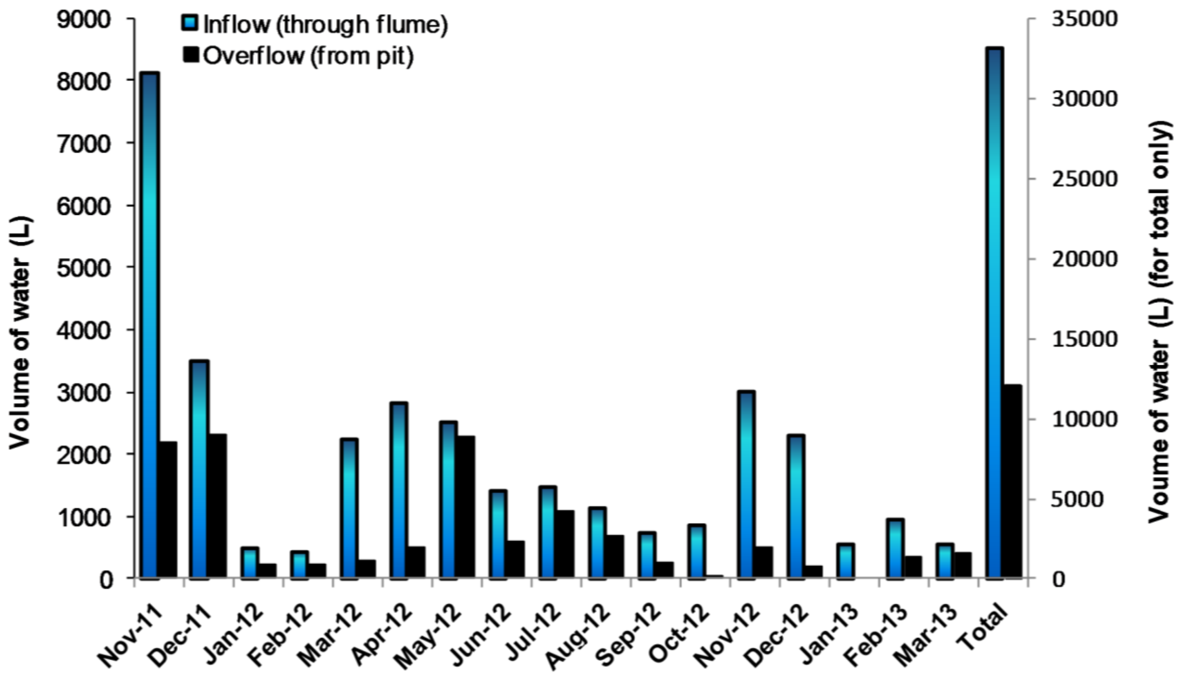



**Figure 2.21: Total volume of inflow (through the flume) in comparison to the total volume of overflow (to the stormwater drain) for the Lined raingarden.**

### 2.3.4. Analysis of Christmas Day (2011) storms

Given the intensity of the series of large thunderstorms on 25th December 2011 and the effects on inflow and overflow (see above; section 2.3.3.2.), this rain day warranted further analysis. Immediately prior to this day, from the 21st to 24th December 2011, the site received no measurable rainfall. In total, the site received 35 mm by midnight (AEST), which is equivalent to a total volume of 4655 L of roof-water. Therefore, approximately 1550 L would be expected to enter each of the two raingardens and the rainwater tank, assuming that no water was lost before it entered the plumbing system. In addition, approximately 117 L of rain water would have fallen directly on each garden bed. As shown in Figure 2.22, the thunderstorms began at approximately 2.50 pm AEST and ended at approximately 9.10 pm AEST.

The water level in the tank increased by 391 mm (0.39 m) over the course of the day, indicating an increase in volume of approximately 1030 L. This is approximately two thirds of the expected volume based on rainfall alone (1550 L), indicating an initial loss of 33%. Inflow totals to the two raingardens were consistent with this, although inflow was higher for the Unlined raingarden (1092 L) than the Lined (937 L).

The initial, smaller storms did not result in any overflow from the Unlined raingarden (Figure 2.22), but this was followed by a sudden increase in overflow at 5.37 pm, during the largest storm; this was the maximum recorded overflow rate for the Unlined raingarden in the entire 1.5-year monitoring period. Overflow was also high following the next storm, but became low relative to inflow in the later storms. In contrast, overflow from the Lined raingarden was much more responsive to inflow, even for the initial storms (Figure 2.22). In the bigger storms, the increases in overflow were greater than the increases in inflow, which was unusual for the study period. The additional estimated 117 L of rainfall that would have fallen directly onto the garden bed throughout the day might have contributed to this. Unlike the Unlined raingarden, the maximum overflow rate for the Lined raingarden occurred at 9 pm, during the final storm.

Corresponding to the pulses of heavy rainfall and inflow, there were clear increases in water level in both raingardens throughout the day (Figure 2.23). At the beginning of the day, the depth of water in the Unlined raingarden was at or close to zero, while the depth of water in the Lined raingarden was much higher, at 33.8 cm (slightly above the sand-soil boundary). The water level in the Lined raingarden reached a maximum of 44.5 cm during the largest storm, at 5.37 pm. The water level in the Unlined raingarden also reached the soil layer (from its zero starting point), which is demonstration of the ability of the Unlined raingarden to temporarily retain water. Like the Lined raingarden, the maximum depth of water (43.2 cm) was recorded at 5.37 pm, corresponding with the spike in overflow.

However, despite increasing with each subsequent storm, including another large increase at 9 pm, the water level declined to below 20 cm (into the gravel layer) by midnight, while the water level in the Lined raingarden remained in the soil layer.

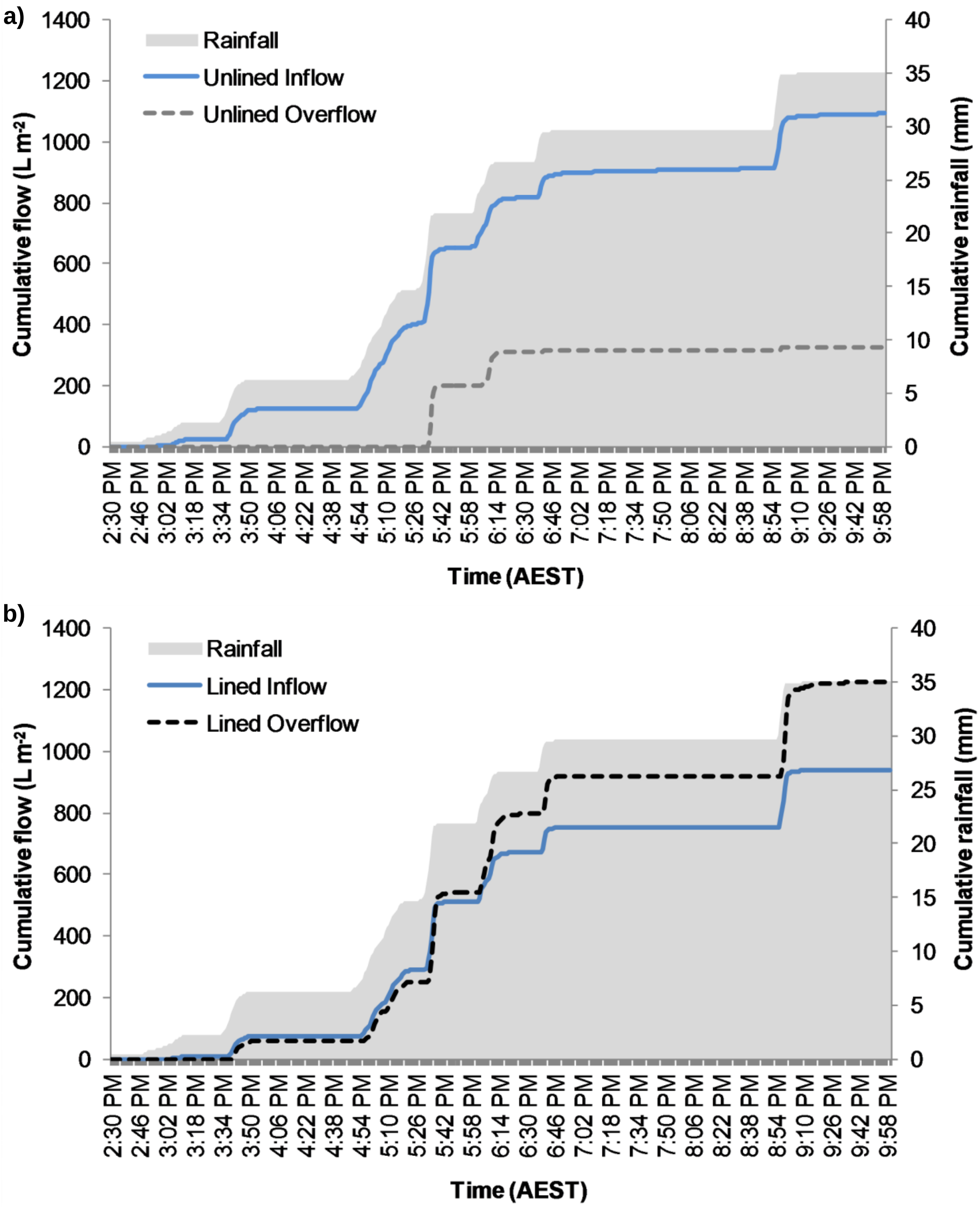



**Figure 2.22: Cumulative inflow and overflow hydrographs for the Unlined (a) and Lined (b) raingardens for the period 2.30 pm to 10 pm (AEST) on 25th December 2011, with total rainfall (cumulative) at the site for comparison.**

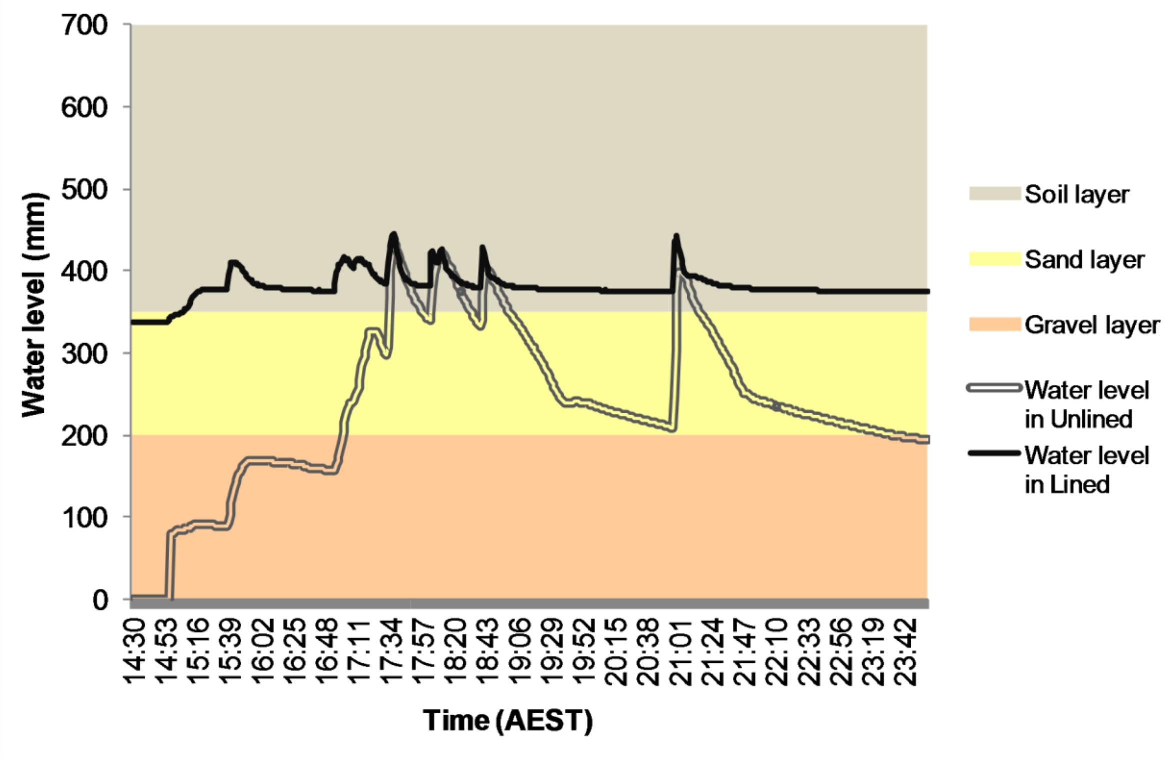



**Figure 2.23: Water level in the two raingardens between 2.30 pm and 11.59 pm (AEST) on 25th December 2011. The approximate boundaries of the filter/growing media layers are presented for comparison.**

The rainfall and the associated increases in water level in the raingardens caused clear but relatively low magnitude increases in soil moisture. The greatest increase was in the Potable control garden (Figure 2.24), indicating that the raingardens were not able to effectively convey roof-water to the soil layer, at least in the early stages of the 1.5-year monitoring period. It is in contrast to the performance of the Lined raingarden on another high rainfall day 14 months later, towards the end of the monitoring period. On this day, 26th February 2013, there was 36.6 mm of rainfall by noon (AEST), and 37.4 mm in total; i.e., similar to 25th December 2011. It began raining at 4.50 am, and significant inflow through the flume began after 6.40 am. Coinciding with this inflow, the soil moisture in the Lined raingarden began to increase and continued to rise considerably for the rest of the day (Figure 2.25), for a total increase of just over 10% (volumetric SWC) by midnight. The soil moisture in the Unlined raingarden increased by only 1.5% over this time, which was not much greater than the increase in the Tank control garden, and less than the increase in the Potable control.

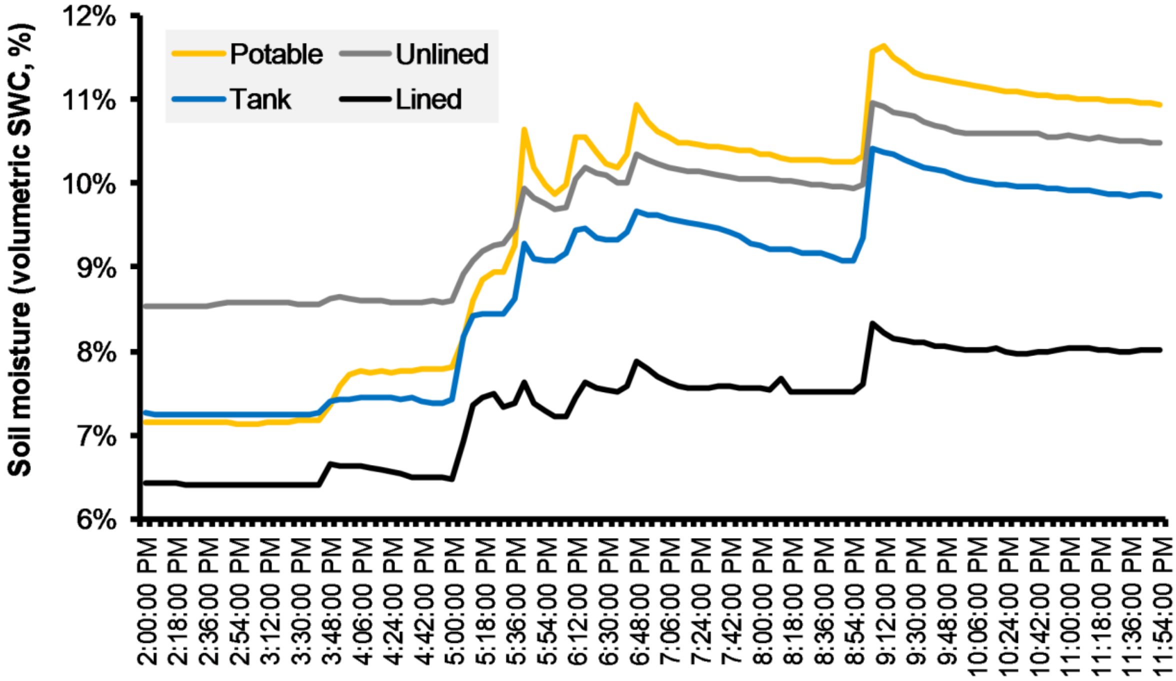



Figure 2.24: Soil moisture in each bed on 25th December 2011, between 2 pm and midnight (AEST).

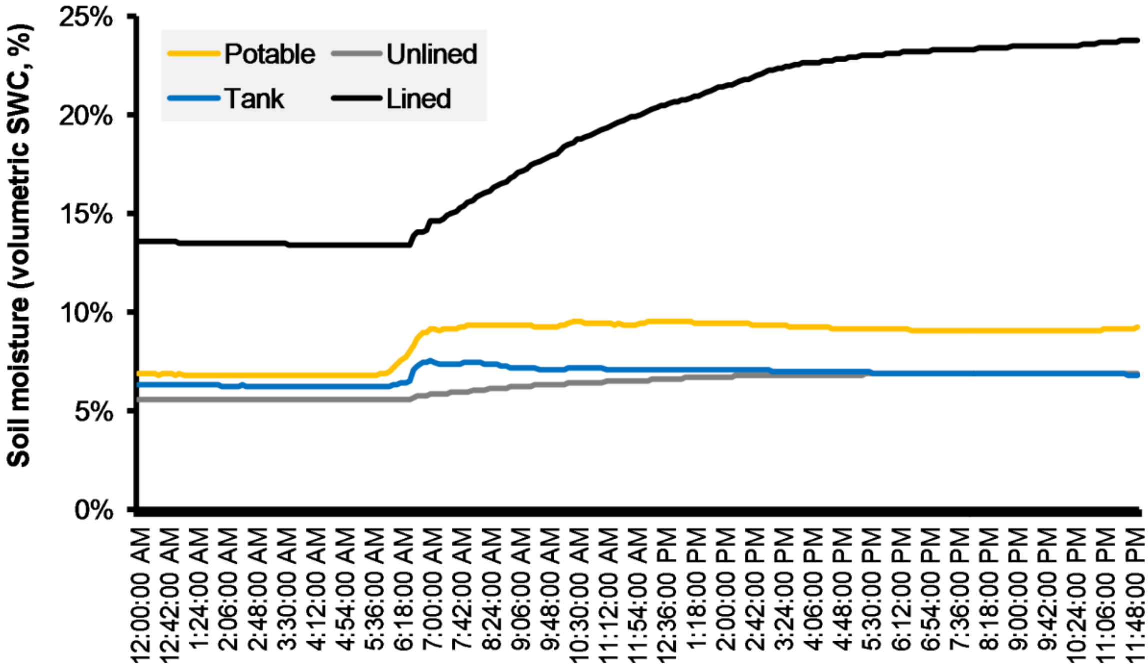



Figure 2.25: Soil moisture in each bed on 26th February 2013 (24 hours).

## 2.4. Discussion

### 2.4.1. Sub-irrigation and surface irrigation

Both raingardens received a relatively large volume of water from the roof, and it seems that Melbourne rainfall can be sufficient to sustain a raingarden sized 7.5% of its catchment area. However, additional irrigation might be required in the summer months and neither raingarden design evaluated in this study was optimal.

Indeed, for vegetable production, sub-irrigation appeared to be less effective and less efficient than the surface irrigation applied to the control gardens, contrary to previous reports (e.g. Ahmed et al., 2000; Goodwin et al., 2003). For many species, particularly onion, lettuce, tomato, parsley (Italian variety only) and basil (Sweet variety only), yield was greater in both control gardens than in the two raingardens. This is despite the much greater total volume of water that was received by the raingardens, which was predominantly roof-water conveyed via the sub-irrigation system. Incidentally, that yield was greater in the control gardens for those species is also at odds with the perceived advantages of drip irrigation (as used in the Unlined raingarden) over spray irrigation types (as used in the control gardens), which include more precise and uniform water distribution (Christen et al., 2006; Fereres et al., 2003; Locascio, 2005). These advantages of drip irrigation have frequently been verified by field studies reporting lower water use and higher yield (e.g. Raina et al., 1999; Singh et al., 2009).

Nonetheless, it is likely that the effectiveness of sub-irrigation for a vegetable raingarden could be improved by amending the raingarden design employed in this study, as discussed below (section 2.4.5). Further research is required, and the merits of surface irrigation relative to sub-irrigation are further explored in Chapter 3.

### 2.4.2. Advantages of the Unlined raingarden

Of the two raingardens, the Unlined raingarden generally performed better in relation to both yield and runoff retention. The latter finding is consistent with the view that the use of an impermeable liner in biofiltration systems should be avoided, unless hazardous runoff is anticipated or unless it is necessary for the protection of surrounding infrastructure (Davis, 2008; Davis et al., 2009; Li et al., 2009). The Unlined raingarden was more effective than the Lined at reducing both frequencies and volumes of runoff, and at attenuating flow rates. More than 90% of the inflow to the Unlined raingarden appears to have been lost to evapotranspiration and infiltration into the underlying soil, assisted by the relatively high infiltration rate of the plot (> 100 mm $hr^{-1}$). For comparison, in a study in the eastern United States, Li et al. (2009) found that only 20–50% of runoff entering conventional, surface-irrigated biofiltration systems was lost to infiltration and evapotranspiration.

However, the Unlined raingarden required a high volume of back-up surface irrigation in the summer months, at frequencies and volumes comparable to the control gardens. This might explain the greater yield of onion, leek, spinach, common bean, cucumber, beetroot (in the second summer), and the round and plum tomato varieties, relative to the Lined raingarden. As noted by Lambers et al. (2008), as long as the upper soil is fairly moist, plants tend to absorb most of their water from shallower soil regions, which is where roots are concentrated. Generally, only as the soil dries will relatively more water be absorbed from deeper layers.

The volume of irrigation water required by the Unlined raingarden under the deficit irrigation regime was at least partly related to rainfall, which is consistent with previous studies on vegetable production. For example, for tomato production in Florida, Smajstrla and Locascio (1996) applied irrigation according to soil water potential thresholds and found that seasonal irrigation requirements were inversely proportional to seasonal total rainfall. They also found that little irrigation was required while the plants were small and plant water use was low, but that it was increasingly required as plants grew and crop water use increased, which might have been an issue in the present study. As such, it might be beneficial to schedule irrigation to suit the life phase of plants in a vegetable raingarden. Overall, the relatively high irrigation requirements of the Unlined raingarden are a significant disadvantage, although this did not affect its runoff management performance, and it was no more demanding in water than a traditional vegetable garden.

### 2.4.3. Advantages of the Lined raingarden

Even though the relatively high soil moisture in the Lined raingarden did not lead to greater vegetable yield, this raingarden performed much better than the Unlined in terms of its irrigation requirements. Under the deficit irrigation strategy, the Lined raingarden did not need back-up irrigation during either the winter or second summer growing seasons, to maintain soil moisture above 10% soil water content. However, in the first summer growing season, back-up irrigation was needed. It is possible that the sand layer acted as a capillary break during this period. Such breaks or barriers can occur at the interface between two soil layers that have different hydraulic characteristics (Ityel et al., 2012). This might have been overcome in the second half of the monitoring period as the boundaries between the media layers became less discrete and/or as the sand became less hydrophobic (while it was not overcome at all in the Unlined raingarden). That the water level was at or above the sand-soil layer in the Lined raingarden also appears to have been an important factor in its relatively high soil moisture. Similarly, the presence of a relatively shallow water table has been found to reduce the irrigation needs of field-grown tomatoes, whereby the water table may supply water to the plants through upward flux or by deep rooting (Burgmans et al., 1998; Pitts et al., 1991).

Although the hydrologic performance of the Lined raingarden was not as good as the Unlined, because the lining of such systems restricts infiltration (Sharkey 2006; Davis 2008), it did significantly reduce frequencies and volumes of runoff. The Lined raingarden captured approximately 21 kL of runoff over the 1.5-year monitoring period. On 34% of rain (inflow) days there was no overflow at all from the Lined raingarden, as the entire inflow volume was captured. This compares favourably to the performance of lined conventional biofiltration systems in Maryland, in which the entire inflow volume was captured for 18% of rainfall events (Davis, 2008). However, outflow from an underdrain was being measured in that case, and it was reported that outflow occurred for many hours or even several days at very low rates (Davis, 2008).

Of the two raingardens, the Lined was particularly susceptible to temporal variation in magnitudes of overflow. This temporal variation, though considerable, showed no clear seasonal correlation. For example, the month of greatest overflow was November 2011 (late spring), while the only month of zero overflow was January 2013 (mid-summer). This might not be the case for vegetable raingardens constructed in other climates. For example, Hunt et al. (2006) found that seasonal differences in the weather had statistically significant impacts on the outflow volume of a conventional biofiltration system in North Carolina, whereby the ratio of outflow to inflow was highest in winter. Overall, the choice of lined or unlined depends on the primary objectives of the system; for runoff reduction, unlined systems appear to be most appropriate, but to use water efficiently (and thereby conserve water as a resource), lined systems are likely to perform best.

### 2.4.4. Causes of variation in yield between gardens

The differences in yield between the four gardens can only be partly explained by differences in irrigation method, which was the only independent variable. Factors such as soil, aspect, and plant arrangement (and therefore competition) were constant. For example, shade can have a particularly detrimental effect on vegetative growth in biofiltration systems (Mazer et al., 2001), but the gardens were specifically positioned to receive equal levels of direct sunlight.

However, a possible source of variation in vegetable yield is the activity of soil fauna. Many earthworms were observed in the gardens by the end of the first summer growing season. Earthworms increase the fertility of vegetable gardens by improving soil aeration and by redistributing and breaking down organic matter (Pollock, 2004). They might also have affected the flow of water through the gardens, given the tendency of bioturbation to increase soil porosity and infiltration (Wilkinson et al., 2009). It is possible that conditions in the sub-irrigated raingardens, particularly the Lined, were less favourable for beneficial forms of animal activity and/or more favourable for invertebrate species that have adverse effects on plant growth. The role of soil fauna in vegetable raingardens is worthy of investigation in future work. It might even affect the capability of the system to remove pollutants from runoff. For example, Tomar and Suthar (2011) found that an integrated “vermi-biofiltration” reactor containing earthworms was more efficient than a traditional biofiltration system in removing a key chemical pollutant from wastewater.

The availability of nutrients for plant growth is another important consideration. Apart from water, nutrients are the environmental factor that most strongly constrains all terrestrial productivity (Lambers et al., 2008). As nutrients are absorbed by growing roots (Lambers et al., 2008), reduced plant growth due to water stress may have reduced nutrient availability. This might have been an issue in the Lined raingarden in particular, in the absence of surface irrigation. Nutrient availability might also be influenced by water source. For example, Denman et al. (2006) found that applications of a model stormwater solution increased height, growth and root length density of trees compared with tap water applications, which was attributed to the nutrients in the stormwater. In the present study, the Tank control garden produced considerably greater yield than the Potable control for a few species; most notably cucumber, onion, plum tomato, and basil. Furthermore, for all three varieties of tomatoes, the Tank control produced the largest fruit. It is possible that the roof-water that was used to irrigate the Tank control contained a greater concentration of both macro- and micro-nutrients than the tap water that was used to irrigate the Potable control. However, given that the two raingardens were also irrigated with the roof-water, and that this was partly delivered through surface irrigation in the Unlined, the benefit of any additional nutrients from this source seems to be less important than other factors.

It also appears that the sub-irrigated raingardens were more susceptible to plant disease and physiological disorders. For example, the plum tomatoes in the Lined raingarden were the smallest and most affected by both blossom end rot and cracking, with the Potable control the least affected. Blossom end rot is usually attributed to a calcium deficiency, often associated with some kind of stress such as water deficit (Saure, 2001). Previous work has reported that blossom end rot incidence is higher under deficit irrigation than under full irrigation or partial root-zone drying (Obreza et al., 1996; Sun et al., 2013), and higher under less frequent irrigation (once per day compared to multiple times per day) (Pires et al., 2011). It is possible, therefore, that the soil moisture in the Lined raingarden, despite being relatively high, was too variable over the second summer season. Similarly, while there are various potential causes of cracking in tomatoes, cracks can develop if ripening fruit expands too rapidly, and a rapid influx of water can contribute to the occurence and severity of cracking (Saltveit, 2005). This might have been a factor in the Lined raingarden, which had the most extreme wetting-drying regime of the four gardens in the second summer season.

It is worth noting that many features of a plant's physiology respond directly to changes in water status in the plant tissues, rather than to changes in the bulk soil water content or potential. This is a potential problem with all soil water-based approaches to irrigation scheduling (Jones, 2004). Ultimately, a plant’s response to a given amount of soil moisture varies as a complex function of evaporative demand, and it can be difficult to successfully relate the soil-based data to plant performance (Fereres et al., 2003). Therefore, in future work, the effects of vegetable raingardens on yield might be further explored via plant stress measurements. Another important limitation of soil moisture monitoring is the difficulty in coping with the spatial variability of soil water properties and of irrigation water distribution (Fereres et al., 2003). Even in the relatively small area of the garden beds in the present study, this might have been an issue.

### 2.4.5. Alternative raingarden designs

The optimal design for a vegetable raingarden might be a partially lined system, as a compromise between the Lined and Unlined raingardens that were tested. For example, a semi-permeable layer, such as a layer of clay, could be installed at the base to separate the gravel layer from the underlying soil, especially on soil with a high infiltration rate. Another option for improving water use efficiency could be to introduce the water within the soil (top) layer. A risk of this design is that the vegetables would be more susceptible to contamination by pollutants in the runoff. However, in the present study, the chemical and microbial contamination risk associated with the two raingardens (irrigated only with roof-water) was low; and no higher than the Potable control garden (Tom et al., 2013).

Another alternative is to replace the soil and sand layers with a uniform layer of loamy sand, as used in many conventional raingardens (see section 1.4.1). This is investigated in Chapter 3. Sub-irrigation might also be more effective if the growing media is placed to a reduced depth (< 35 cm), as it seems likely that the large depth of media, sand and gravel reduced the efficiency of capillary rise. The research into using green roofs for vegetable production ( see section 1.2.5) demonstrates the potential to grow vegetables in shallow growing media, although this does tend to require the use of fertilizers (Ouellette et al., 2012; Whittinghill et al., 2012).

A more minor but important design amendment is to use “wicks” to assist capillary rise and overcome the capillary break that seems to be caused by the sand layer (Figure

2.26). The use of mulch to better conserve soil water could also be explored; mulch helps to maximize water use by plants through reducing evaporation (Kirnak and Demirtas, 2006). Mulch is commonly used in vegetable gardening, and various types of mulch have been reported to reduce evapotranspiration and/or increase yield in the production of crops such as Swiss chard (*Beta vulgaris*) (Zhang et al., 2009a; Zhang et al., 2008). Emerson and Traver (2008) also noted the likely importance of soil surface mulching in sustaining the functionality of biofiltration systems, and mulch can help to remove pollutants such as oil and grease from runoff (Hong et al., 2006). Furthermore, in the present study, the maximum water level was limited to near the base of the soil layer by the height of the overflow pit. This restriction could be adjusted, so that the water is allowed to rise closer to the soil surface following rainfall (Figure 2.26).

As an alternative to the planter box design, it might be possible to construct an "in-ground" vegetable raingarden (see section 1.3.1.1). Consideration of local soil contamination issues would be required, as these are common in urban areas (Bewley and Hockin, 2011). Related to this, future research might investigate whether vegetable raingardens are appropriate for locations where the runoff is more polluted, particularly where the runoff is from sources such as the heavily trafficked road reported on by Trowsdale and Simcock (2011). In that case, the runoff draining into a biofiltration system had particularly high concentrations of sediment, zinc, lead and copper. Some heavy metals (e.g. zinc) are essential micronutrients for plants but become toxic at elevated concentrations (Lambers et al., 2008). This might affect vegetable growth and yield in a vegetable raingarden, although food safety would be the foremost concern in that instance.

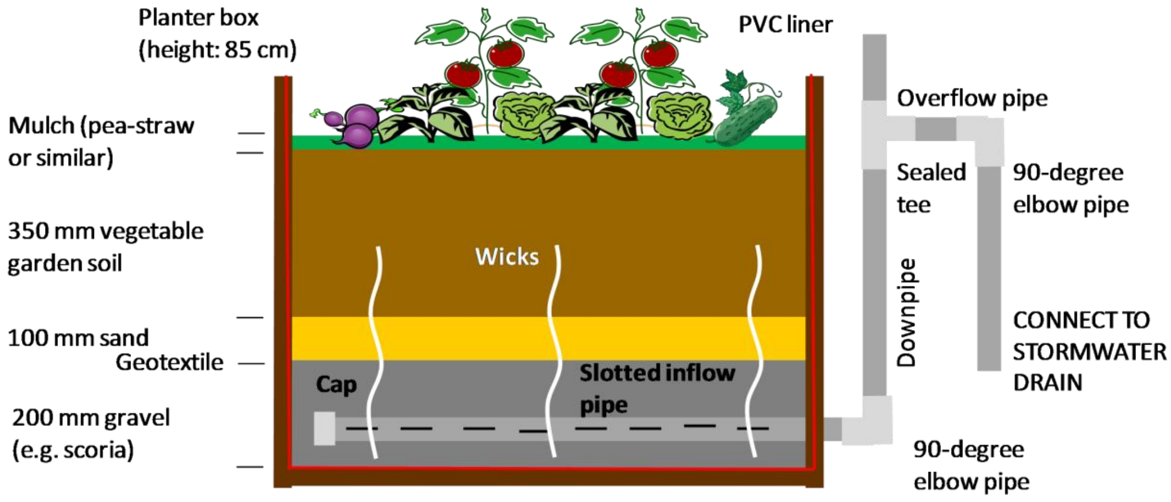



**Figure 2.26: Schematic diagram showing how wicks could be added to a sub-irrigated vegetable raingarden to promote capillary rise, and a simpler overflow design (replacing the pits in this study) that would allow a higher water level.**

The results of this study also have implications for vegetable production on green roofs. The Lined raingarden that was tested can be regarded as a green roof system, although only as the intensive type (as opposed to extensive); i.e. it could only be used on a building with structural reinforcement, given that the substrate depth was > 20 cm. As discussed in section 1.2.5., rainwater for irrigation could be collected and conveyed from another part of the building's roof. Effective runoff management, low irrigation requirements and reasonable yield are likely benefits of a "vegetable green roof" based on the Lined raingarden. However, relative to the tested raingarden, the system might be more exposed to the weather if it were positioned on a roof, to the extent that yield and irrigation requirements might be altered.

### 2.4.6. Choice of vegetables

While there was considerable variation in yield between plant species and varieties, there were no clear differences between the vegetable types. The results indicate that all vegetable and herb species tested are suited to production in raingardens under Melbourne conditions, with no or minimal fertilizer inputs required (given a "vegetable garden" soil or similar). The only exception is broccoli, and possibly other cultivars of *Brassica oleracea*, because severe pest damage could only have been avoided through the use of pesticides. There might also be some doubt over the plants that did particularly poorly in the Lined raingarden, in the absence of surface irrigation. A notable example was cucumber, which is a relatively shallow-rooted crop that is very sensitive to water stress (Janoudi and Widders, 1993; Kirnak and Demirtas, 2006; Yuan et al., 2006).

The only species in the first summer growing season that showed greater yield in the two raingardens was beetroot, which initially indicated that root/bulb crops, although shallow rooted, were the vegetable type best suited to sub-irrigation. However, this was not supported by the onion and leek yields in the winter season or by beetroot in the second summer, as the Lined raingarden produced the lowest yield for all.

The relatively deep-rooted species also appeared to have little or no advantage in the sub-irrigated raingardens. For tomato in particular, the most active zone of the root system is mostly within the top 30 cm of the soil, but tomatoes may root as deep as 2 m (Heuvelink, 2005). Furthermore, root production, depth and distribution can respond to conditions of water deficit and to areas of disparate soil moisture (Ben-Asher and Silberbush, 1992; Marouelli and Silva, 2007; Oliveira et al., 1996; Pitts et al., 1991; Reid and Renquist, 1997). Despite this, for all three varieties, tomato yield was low in the Lined raingarden relative to the other gardens, and this highlights the apparent benefit of surface irrigation. The effects of sub-irrigation and surface irrigation on root biomass are investigated in Chapter 3.

### 2.5. Conclusions

A variety of common vegetables may be suited to production in vegetable raingardens, but the design of the sub-irrigated beds appears critical. There were large volumes of runoff water delivered to the raingardens that were not able to reach the vegetable root zone; possibly because the sand (“filter”) layer was a barrier to capillary rise.  While the Unlined raingarden produced yield that was comparable to the surface-irrigated control gardens, it required considerable back-up irrigation in the summer months, even in a relatively wet summer. Only in winter did the Unlined raingarden not require back-up irrigation. On the other hand, the Lined raingarden required no back-up irrigation for the last 12 months of the monitoring period, which included a relatively dry and hot summer. During this time, soil moisture was generally much higher in the Lined raingarden than in the other three gardens, and it was also more responsive to rainfall. It seems that the consistently high water level in the Lined raingarden was a factor in this.

Raingardens can be used to grow vegetables without compromising the role that these systems play in reducing quantities and rates of urban runoff. The Unlined raingarden was particularly effective, reducing both frequencies and volumes of runoff by > 90%, but even the Lined raingarden captured approximately 21 kL of runoff over the 1.5-year monitoring period. However, like irrigation requirements, there might be considerable temporal variation in inflow to overflow ratios in response to variation in rainfall and evapotranspiration rates.

# 3. Greenhouse experiment

## 3.1. Introduction

For a vegetable raingarden to be effective, it must be designed so that water availability is suitable for plant growth. In the field trial (Chapter 2), it was clear that the design of the sub-irrigated raingardens was not optimal. While a very large volume of roof-water was available to the raingardens (> 33 kL in 1.5 years), this was not conveyed effectively to the root zone, leaving some doubt as to whether rainfall alone would be sufficient for irrigation of a vegetable raingarden. Furthermore, this raised the issue of whether a more conventionally designed, surface-irrigated raingarden would be better suited to vegetable production, and whether sub-irrigation is more effective than surface irrigation in backyard vegetable production in general. Despite its importance, and the common perception of better water use efficiency with sub-irrigation, this has rarely been investigated.

Also critical in the design of a vegetable raingarden is the choice of soil type. As discussed in section 1.4.1, the use of loamy sand is currently recommended for conventional raingardens, primarily to achieve water quality objectives (Bratieres et al., 2009; Bratieres et al., 2010; Bratieres et al., 2008; FAWB, 2009; Henderson et al., 2007). An advantage of the loamy sand is that it would allow a uniform profile in a vegetable raingarden, consisting of a combined filtration and vegetative layer, as opposed to a profile with separate vegetation and filter layers (Hsieh and Davis, 2005a). The latter design was used in the sub-irrigated raingardens in the field trial (Chapter 2), in which the sand ("filter") layer appeared to act as a capillary break, inhibiting the movement of water upwards to the vegetable root zone. However, particularly given the low water holding capacity of sandy soils, using loamy sand that meets current raingarden specifications might not be suitable for many vegetables, which typically require more moisture-retentive soils. In traditional vegetable gardening, these conditions are met through the use of purpose-made soils and mixes, as used in the field trial (Chapter 2).

This chapter describes a greenhouse pot experiment that was conducted to more rigorously investigate the merits of sub-irrigation and surface irrigation, and to inform the choice of soil type for a vegetable raingarden. It considers plant growth and yield of bean, beetroot, parsley and tomato, all of which were used in the field trial (Chapter 2). Irrigation was conducted at a frequency equivalent to Melbourne's mean rainfall. The greenhouse experiment addressed Research Questions 1-4 of the thesis. In particular, it complemented the field trial by investigating:

- Vegetable growth and yield in a treatment that represents a surface-irrigated raingarden, sized 7.5% of its catchment area (the same as the field trial), receiving rainfall at mean volumes and frequencies for Melbourne with no supplemental irrigation (Research Question 1).
- Differences in water availability, vegetable growth and vegetable yield between sub-irrigation and surface irrigation, given identical frequencies and volumes of irrigation (Research Question 2).
- Differences in water availability, vegetable growth and vegetable yield in two different soil types; a potting mix used in conventional containerised vegetable gardens, and a loamy sand used in conventional raingardens (Research Question 3).
- How leaf, root, legume and fruit vegetable types respond to these differences in irrigation method and soil type, with regard to vegetable growth, yield and water use (Research Question 4).

### 3.2. Methods

The experiment was conducted in an unheated poly-tunnel at the University of Melbourne's Burnley Campus (37°49'44.22"S, 145°1'13.40"E). The poly-tunnel is referred to as a greenhouse hereafter. The experiment was conducted from September 2012 to February 2013, concurrent with the second summer growing season of the field trial. As discussed in Chapter 2, this was a relatively hot spring-summer period. Greenhouse temperatures ranged from 10.5°C to 51.5°C (Table 3.1). The irrigation treatment phase of the experiment lasted 105 days, commencing on 16$^{th}$ November 2012 (late spring) and finishing on 28$^{th}$ February 2013 (end of summer).

**Table 3.1: Temperature data for the greenhouse and, for comparison, outdoor daily maximum temperature data for the same period, as recorded at the Melbourne Regional Office site (site number 086071) (Bureau of Meteorology, 2012). Values in parentheses are standard error.**

| | Greenhouse temp. (°C) | | | Outdoor: Daily maximum temp. (°C) | | | |
|---|---|---|---|---|---|---|---|
| | **Mean** | **Min** | **Max** | **Mean** | **Max** | **Days > 29** | **Days > 34** |
| ***November**** | *27.4 (1.30)* | *14.5* | *49.0* | *24.8 (1.52)* | *39.6* | *2* | *2* |
| **December** | 23.9 (0.47) | 10.5 | 49.5 | 25.7 (0.98) | 38.3 | 8 | 4 |
| **January** | 25.5 (0.50) | 10.5 | 51.5 | 27.3 (1.04) | 41.1 | 8 | 5 |
| **February** | 26.6 (0.53) | 12.5 | 50.5 | 29.2 (0.93) | 37.2 | 16 | 5 |

*For November, greenhouse temperature data is available only for the 26$^{th}$-30$^{th}$. Outdoor temperature data for November is for the 16$^{th}$ (the first day of the irrigation treatment phase) onwards.

The pots were all of the flower bucket type, with no drainage holes. Each pot had a capacity of 9 L, a rim diameter of 23 cm, and a height of 33 cm. A single drainage hole of approximately 15 mm in diameter was drilled into every pot between 10 cm and 12 cm from the base; which was just above the gravel-sand boundary when the pots were filled. In those pots that were used for the sub-irrigation treatment, a second hole of the same size was drilled close to the base of the pot (< 5 cm). The threaded end of a 15 mm micro-elbow was inserted through this hole. The elbow was secured using two brass flanged back nuts (15 mm); one on the inside of the pot and one on the outside. Teflon tape and silicone sealant were used to make this fitting watertight.

Each pot was filled with 1500 ± 1 g of 20 mm-size scoria gravel to a depth of ≤ 10 cm. This was intended to act as a reservoir in the sub-irrigated pots (Figure 3.1). It was hand-washed prior to potting in order to remove excess sediment. A single piece of geotextile with dimensions of approximately 250 x 250 mm was placed over the gravel layer. The geotextile helped to maintain soil volume by minimizing both downward migration of fines from the soil layer above and loss of soil through the drainage hole.

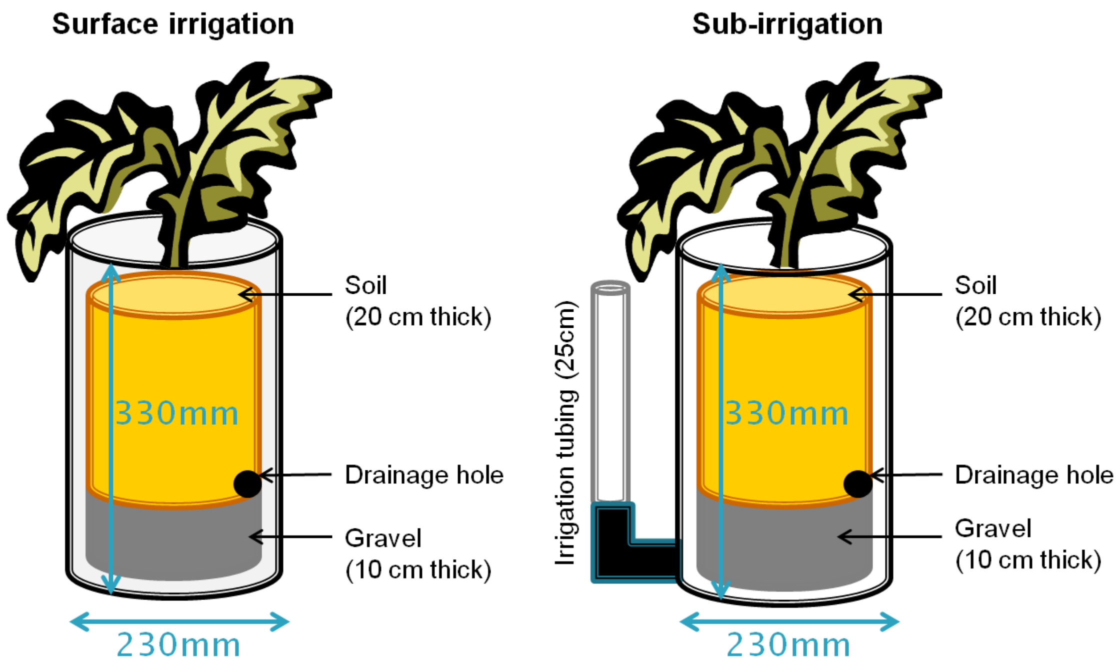



**Figure 3.1: Design of the surface-irrigated pots (left) and sub-irrigated pots (right).**

### 3.2.1. Soils: potting mix and loamy sand

Each pot was filled with one of two soil types (Figure 3.2). One of the soils was Burnley general potting mix, which consisted of medium pine bark and coarse mined sand in a ratio (by volume) of 4:1. It contained the fertilizer Debco Greenjacket No. 2 (N:P:K 16.5:4.1:9.6) (4000 g per $m^3$), the granular soil wetter SaturAid (1500 g per $m^3$), and dolomite (1000 g per $m^3$). The other soil was a loamy sand (sourced from Daisy's Garden Supplies), as recommended in current guidelines for biofiltration substrates (FAWB, 2009; see section 1.4.1). The same additives used in the potting mix, including the fertilizer Debco Greenjacket, were added to the loamy sand in the same concentrations. This ensured experimental control as the only difference between the soils was one of texture and composition, and therefore water availability, rather than nutrient availability. It is also similar to the amelioration approach for biofiltration media used by Bratieres et al. (2009; 2010) (see section 1.4.1).

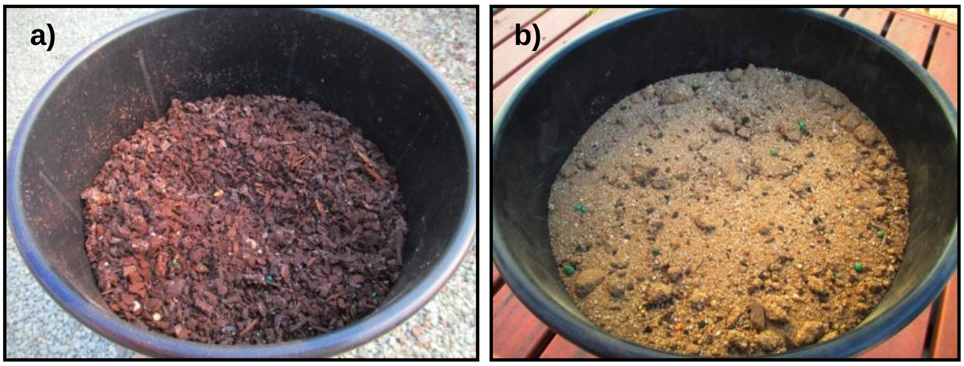



**Figure 3.2: Samples of the potting mix (a) and the loamy sand (b).**

For both soils, water holding capacity was determined via the air-filled porosity method described in Appendix B, soil matric potential via the filter paper method described in Appendix C, and EC and pH according to the method described in Appendix D (Table 3.2). With regard to soil matric potential, it was found that, when matric suction was -1.5 MPa, the water content of the potting mix was 7.9% of the water holding capacity, and 3.5% for the loamy sand.

The soil was added to each pot by weight; 4000 ± 1 g for the mix and 7000 ± 1 g for the loamy sand. The maximum height of the soil surface in any pot, from the base of the pot, was 30 cm. Sufficient space (> 5 cm) was left between the soil surface and the rim of the pot for pooling following applications of water to the surface-irrigated pots.

**Table 3.2: Mean (± SE) water holding capacity (WHC), air-filled porosity (AFP), bulk density, pH and electrical conductivity (EC) for the potting mix and loamy sand.**

| | WHC (%) | AFP (%) | Bulk density (g/cm$^3$) | pH | EC (uS/cm) |
|---|---|---|---|---|---|
| **Potting mix** | 54.0 ± 0.5 | 9.3 ± 0.3 | 0.47 ± 0.003 | 4.94 ± 0.04 | 1057.40 ± 16.34 |
| **Loamy sand** | 26.3 ± 0.1 | 0.6 ± 0.2 | 1.63 ± 0.007 | 6.68 ± 0.05 | 534.80 ± 10.50 |

### 3.2.2. Plant species

Four plant species representing four different vegetable types were used (Table 3.3; Figure 3.3). All were planted as seedlings, obtained from a commercial nursery, with one plant per pot to eliminate competition effects. All of the pots were planted at the beginning of October 2012, although the beetroot required replanting on 1st November 2012.

**Table 3.3: The four vegetable species used in the greenhouse experiment. Days to first and final harvest are counted from the start of the main irrigation treatment phase (16th November 2012).**

| Type | Species | Common name (and variety) | Days to first harvest | Days to final harvest |
|---|---|---|---|---|
| **Legume** | *Phaseolus vulgaris* | Bean (Dwarf Yellow) | 15 | 61 |
| **Root** | *Beta vulgaris* | Beetroot (no variety specified) | n/a | 105 |
| **Leaf/herb** | *Petroselinum hortense* | Parsley (Italian; flat leaf) | n/a | 46 |
| **Fruit** | *Solanum lycopersicum* | Tomato (San Marzano) | 24 | 77 |

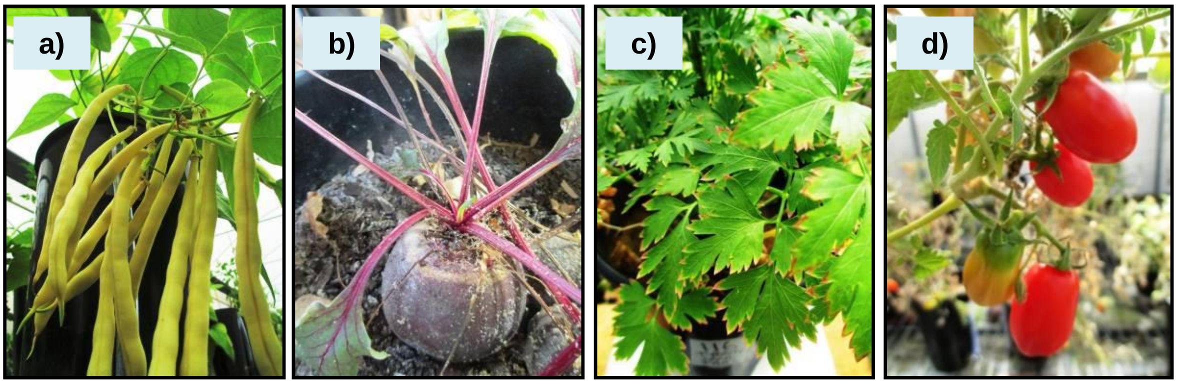



**Figure 3.3: The four plant species, photographed during the experiment; a) bean, b) beetroot, c) parsley, and d) tomato.**

### 3.2.3. Establishment phase and initial harvest

All pots were surface-irrigated with potable water according to a well-watered regime until mid-November 2012. At the end of this establishment phase, 40 pots (4 plant species × 2 soils × 5 replicates) were harvested to determine initial biomass and leaf area. Specifically, measurements comprised total shoot and root biomass, with the total shoot biomass further separated into total leaf and total stem. The exception to this was beetroot, for which the petioles were considered to be part of the leaves, with no separate stem; i.e. for beetroot only, total shoot was equivalent to total leaf. Both fresh and dry weights were measured for the shoots, including the separate leaf and stem components, and dry weights only for the roots. Root mass was determined by thoroughly washing soil from the roots prior to drying. All dry weights were obtained after drying in an oven at 80°C for one week, to a constant weight. Prior to drying, leaf area was measured for all four species (LI-3100 area meter, Lincoln NE).

### 3.2.4. Irrigation treatments

Irrigation treatments commenced on 16th November 2012. With 24 different treatments in total (4 plant species × 2 soils × 3 irrigation treatments) and five replicates for each, there were 120 planted pots. These were arranged in a randomized block design to allocate three different irrigation treatments randomly in each of eight blocks (4 plant species × 2 soils). There were additional bare (un-vegetated) pots for each soil type and irrigation treatment to determine evaporation separately from transpiration.

For all three irrigation treatments, the frequency of irrigation corresponded to the mean number of rain days with ≥ 1 mm of rainfall for each month. This quantity of rainfall (≥ 1 mm) was considered enough to generate runoff from an impervious surface. Rainfall statistics for the Melbourne Regional Office site were obtained from the Bureau of Meteorology (Bureau of Meteorology, 2012). The three treatments were as follows:

1. **T-Subs**: This was the sole sub-irrigation treatment. The irrigation tubing was filled with water in 250 ml increments until the reservoir was full (Figure 3.4). The reservoir was deemed full when excess water appeared at the drainage hole, and when the water level in the irrigation tubing became stable at approximately the height of the hole. The amount of water applied to each pot was recorded. The amount of water applied varied between the soils and between the plant species, whereby tomato in the loamy sand was the most demanding in water and beetroot in the potting mix the least (Table 3.4).
2. **T-Surf**: The mean volume of water applied with T-Subs was calculated for each treatment; i.e. the mean of the five replicates. This volume was applied to the corresponding pots in the T-Surf treatment, except it was applied to the soil surface (Figure 3.4).
3. **T-Rain**: This was also a surface irrigation treatment. The volume of water applied corresponded to mean monthly rainfall for Melbourne (Table 3.5), as if it was being received by a raingarden sized 7.5% of its catchment area. In November, for example, the equivalent of 7.55 mm of rainfall would be applied at each of the eight irrigations. Given that the area of each pot was 0.0415 $m^2$, the catchment area in this scenario would be 0.554 $m^2$. With 1 mm of rain equivalent to 1 L $m^{-2}$, 7.55 mm of rain would result in 3.14 L being conveyed to the “raingarden” (pot).

The T-Subs treatment represents a sub-irrigated raingarden being well-watered by every rainfall event, while T-Rain represents all available runoff being conveyed to the surface of a conventional raingarden. With T-Rain, this included substantial pooling on the soil surface (Figure 3.4), of short duration (< 1 hour), which is typical of a surface-irrigated raingarden (see section 1.3.1). Generally, the volume applied with T-Rain was more than double that required by the T-Subs pots; on average, the T-Subs irrigation volume was 35% of T-Rain for bean, 24% for beetroot, 32% for parsley, and 43% for tomato (Table 3.6). The T-Surf irrigation treatment was used primarily for a direct comparison between sub-irrigation and surface irrigation. Initially, roof-water from Building 909 (stored in the rainwater tank; see section 2.2.4) was used for irrigating all pots but, following below-average rainfall, potable water was used from December onwards. At all irrigations, water source was the same for all pots.


**Figure 3.4: The three irrigation treatments in the greenhouse experiment; a) a T-Subs pot being irrigated, b) a T-Surf pot being irrigated, and c) pooling in one of the T-Rain pots following irrigation.**

**Table 3.4: The mean volume of water (± SE) applied at irrigation for the T-Subs and T-Surf treatments.**

| | Mean volume of irrigation water applied (L) | | | |
|---|---|---|---|---|
| | **Bean** | **Beetroot** | **Parsley** | **Tomato** |
| **Potting mix** | 1.32 (0.09) | 0.92 (0.05) | 1.27 (0.06) | 1.64 (0.08) |
| **Loamy sand** | 1.48 (0.14) | 1.06 (0.07) | 1.33 (0.11) | 1.85 (0.14) |

**Table 3.5: Volume of water ($V_{Rain}$) applied with the T-Rain irrigation treatment at each application. T-Rain assumed a raingarden size of 7.5% of its catchment area, and volumes were based on long-term rainfall data for the Melbourne Regional Office site (site number 086071; latitude 37.81°S; longitude 144.97°E; elevation 31 m; commenced 1908; latest data from June 2012). All rainfall statistics were obtained from the Bureau of Meteorology website (Bureau of Meteorology, 2012).**

| | **Mean rainfall (mm)** | **Mean number of days of ≥ 1 mm rain [a]** | **Quantity of rain per day, $Rain_{Day}$ (mm)** | **$Rain_{Day}$ minus 1mm, $Rain_{Day-1}$ (mm)** | **$V_{Rain}$ (L)** |
|---|---|---|---|---|---|
| **Nov [b]** | 60.4 | 8.3 (8) | 7.6 | 6.6 | 3.62 |
| **Dec** | 59.5 | 7.2 (7) | 8.5 | 7.5 | 4.15 |
| **Jan** | 47.6 | 5.6 (6) | 7.9 | 6.9 | 3.83 |
| **Feb** | 48 | 5.1 (5) | 9.6 | 8.6 | 4.76 |

[a] Values in parentheses are the number of days per month that the pots were watered in the present study (rounded up or down from the mean value).
[b] In November, the irrigation treatment phase was in effect for the second half of the month only (it began on the 16th). Therefore, irrigation was conducted four times in a 15-day period, rather than eight times in a 30-day period.

**Table 3.6: Volume of water applied at each irrigation with the T-Subs and T-Surf irrigation treatments, as a percentage of that applied with T-Rain.**

| | | Percentage of T-Rain (%) | | | |
|---|---|---|---|---|---|
| **Month** | **Soil** | **Bean** | **Beetroot** | **Parsley** | **Tomato** |
| **November** | Potting mix | 36 | 25 | 35 | 45 |
| | Loamy sand | 41 | 29 | 37 | 51 |
| **December** | Potting mix | 32 | 22 | 31 | 40 |
| | Loamy sand | 36 | 26 | 32 | 45 |
| **January** | Potting mix | 34 | 24 | 33 | 43 |
| | Loamy sand | 39 | 28 | 35 | 48 |
| **February** | Potting mix | 28 | 19 | 27 | 34 |
| | Loamy sand | 31 | 22 | 28 | 39 |
| | ***Mean*** | ***35*** | ***24*** | ***32*** | ***43*** |

### 3.2.5. Yield, growth and evapotranspiration measurements

All pots were weighed immediately prior to each irrigation, and again at approximately 12 hours after irrigation. The weight of each pot was used to determine the net amount of irrigation water retained (i.e. water content), as well as the loss of water through evapotranspiration since the previous irrigation. Measurements of yield for beans and tomatoes were made weekly, as pods and fruit became ripe. Ripe bean pods were harvested once a week from 1st December until 15th January, and ripe tomato fruit from 10th December until 31st January, for a total of eight harvests in both cases. Yield measurements consisted of the number of fruit and pods, and fresh and dry weights. Dry weights were measured after drying samples in an oven at 80°C until constant weight. In addition, for tomatoes, the number of harvested fruit affected by blossom end rot was recorded from the third harvest (27th December) onwards. At the final harvest, measurements comprised:

1. Yield of edible parts; this was the fresh and dry weight of leaves for parsley and of the edible roots (tubers) for beetroot. The final harvest yield measurements for tomatoes and beans followed the same procedure as the weekly measurements.
2. Biomass of other plant parts; total shoot and total root, with total shoot further separated into total leaf and total stem for parsley, bean and tomato. This followed the same procedure as the initial harvest with the exception that, for bean, only the dry weight of leaves and stems was measured due to severe wilting.
3. Leaf area; parsley and beetroot only, primarily due to the severe wilting of many of the bean and tomato leaves. Leaf area could also be regarded as a measure of yield for parsley. For beetroot only, leaves in the final harvest were separated into “alive” and “dead”, and only the area of the former was measured. Leaves were considered dead if they were dry, shrivelled and had lost colour.

### 3.2.6. Data analysis

There were two phases to consider in the analysis. First, the establishment phase and initial harvest, for which any differences in the growth of the seedlings could be attributed to differences between the two soils. Second, for the irrigation treatment phase and final harvest, differences associated with the soils were juxtaposed with differences associated with irrigation methods and volumes. In the second phase only, yield and water use were considered, in addition to plant growth. “Dead” plants were included in the analysis because it is highly likely that death was a result of stress caused by the irrigation treatments. In any case, unequivocally dead plants were extremely few in number, and dry (rather than fresh) weights of plant parts were used in the analysis.

### 3.2.6.1. Yield, biomass allocation and leaf area

Yield was assessed based on total dry weight, as the sum of all pods for bean, fruit for tomato, leaves for parsley, and edible roots (tubers) for beetroot. The number of pods/fruit was also assessed for bean and tomato. In addition, for tomato only, the number of fruit affected by blossom end rot was expressed as a percentage of the total number, and the average fruit size was calculated by dividing the fresh weight of fruit per pot by the number of fruit per pot.

Total biomass at both the initial and final harvests was the sum of all plant mass (dry weights) other than the yield components (pods, fruit, or tubers), in order to assess the function of the rest of the plant. For all species, dry weights were also used to determine the leaf mass ratio (LMR), stem mass ratio (SMR; not applicable to beetroot), and root mass ratio (RMR). In these calculations, the dry weight of leaves, stems or roots, as applicable, was divided by the total biomass as of the final harvest, with units of g $g^{-1}$. The subdivision of biomass into these leaf, stem and root components is generally the preferred method for analysing allocation of biomass, as opposed to root:shoot ratios (Poorter and Nagel, 2000).

For both the initial and final harvests, total leaf area was also assessed. The area of the "dead" beetroot leaves at the final harvest was calculated as:

dry weight of dead leaves × (total area of alive leaves / total dry weight of leaves)

The total leaf area for beetroot was then the sum of the "alive" (measured) and "dead" (calculated) areas. At the final harvest, leaf area was not measured at all for bean and tomato, because most of the leaves could be considered dead in both cases. For both species, the ratio of leaf area to leaf weight at the initial harvest was used to estimate leaf area at final harvest. Dry weights and leaf areas together were used to determine specific leaf area (SLA; with units $cm^2$ leaf $kg^{-1}$ leaf). Given that total leaf area at the final harvest for both bean and tomato were inferred from the dry weight of the leaves, SLA could not be calculated for these two species.

### 3.2.6.2. Evapotranspiration and transpiration

Water losses from the pots through evapotranspiration were calculated from the difference in pre- and post-watering pot weights at each irrigation, according to the principles described by Farrell et al. (2013). First, total evapotranspiration (ET), equivalent to total water use, was calculated as:

pot weight 12 hours after watering - pot weight before next watering

This was calculated for every pot at every watering. The transpiration (E) component of ET for each treatment was then calculated by subtracting evaporation (determined from soil-only pots) from the total water lost from each pot at each weighing event.

Cumulative evapotranspiration was calculated as the sum of evapotranspiration from the beginning of the irrigation treatment phase to the final harvest. Cumulative transpiration was also calculated. Daily transpiration was calculated by dividing cumulative transpiration by the number of days. Additionally, in order to assess plant water use relative to the size of the plant, transpiration per unit biomass (g $H_2O$ $g^{-1}$ biomass) or per unit leaf area (g $H_2O$ $cm^{-2}$ leaf) was determined by dividing cumulative transpiration by the final above-ground biomass (fresh, including yield components and the tubers for the beetroot) or leaf area.

#### 3.2.6.3. Water use efficiency

Water-use efficiency (WUE) refers to the amount of water lost during the production of biomass or the fixation of $CO_2$ in photosynthesis (Lambers et al., 2008). Water-use efficiency of productivity is the ratio between above-ground gain in biomass and loss of water during the production of that biomass. The water loss may refer to total transpiration only, or include soil evaporation (Lambers et al., 2008). In this study, water use efficiency (g $kg^{-1}$) for the irrigation treatment phase (i.e. growth excluding establishment) was calculated in relation to cumulative transpiration.

#### 3.2.6.4. Water content

Soil water content (SWC), like evapotranspiration, was determined from pot weights pre- and post-irrigation, according to the principle described by Farrell et al. (2013). First, pot weight was corrected for the estimated plant weight (biomass, including yield components) at each weighing, which was calculated as:

$$\text{initial mean fresh weight} + (\text{daily biomass gain} \times \text{preceding days of experiment})$$

This was subtracted from the measured pot weight. The daily biomass gain can be regarded as an approximation of the relative growth rate (RGR), which is the rate of increase in plant mass per unit of plant mass already present (Lambers et al., 2008). The daily biomass gain was estimated as:

$$(\text{final fresh weight} - \text{initial mean fresh weight}) / \text{number of days in experiment}$$

The final fresh weight in this calculation was the “total shoot” fresh weight, although for beetroot the edible roots (tubers) was included. For tomato and bean, there were two separate daily biomass gain values; one for the relatively short phase before weekly harvesting of fruit/pods commenced, and one for the harvesting period, when the fresh weight of the fruit/pods were included in the total fresh weight. The weight of the pot itself and any attachments was also subtracted from the total pot weight, as were the weight of gravel in the base of the pot (1500 g) and the soil dry weight. The soil dry weight was determined by drying samples of the potting mix and loamy sand to a constant weight in an 80°C oven. This corrected pot weight was assumed to include the total water content of the pot and was used to determine gravimetric soil water content. In addition to gravimetric soil water content, the water content of each pot at each weighing was also expressed as a depth of water (in mm) by dividing pot water content by the pot area.

#### 3.2.6.5. Statistical analysis

For the initial harvest, one-way ANOVAs with Tukey post hoc tests (family error rate: 5) were used to determine differences in total biomass, root biomass, shoot biomass and leaf area between the two soils ($P<0.05$). For the final harvest, two-way ANOVAs within species were used to determine differences in yield, all measures of biomass and biomass allocation, blossom end rot occurrence (tomato only), and all measures of water use and water content; not only between the three irrigation treatments and the two soils, but in the interaction between them (irrigation treatment × soil type) ($P<0.05$). For grouping information, the Tukey method was used in the General Linear Model, with a confidence level of 95.0%. For pot water content only, one-way ANOVAs were used to assess differences over time; from the beginning of the irrigation treatments to the final harvest of that vegetable species. In all comparisons of the different irrigation treatments, the focus was on the differences between the T-Subs and T-Surf treatments, as a direct comparison between sub- and surface-irrigation, and also between T-Subs and T-Rain, representing sub- and surface-irrigated raingardens respectively. For water use efficiency and measures of transpiration in relation to plant growth, one-way ANOVAs were also used to determine differences between the four plant species ($P<0.05$). Data were checked for normality prior to analysis and transformed where necessary. All data presented in figures and tables are non-transformed. All statistical analyses were conducted using Minitab 16 Statistical Software (2012, Minitab, Inc.).

## 3.3. Results

### 3.3.1. Effects of soil on growth during establishment

At the initial harvest, prior to the start of the different irrigation treatments, the total biomass was significantly different between the two soil types for bean ($P=0.001$), parsley ($P=0.015$), and tomato ($P=0.011$). In all cases, biomass was greater in the potting mix than in the loamy sand; 55% greater for bean, 116% for parsley, and 27% for tomato

(Table 3.7). There was no significant difference in total biomass for beetroot, but the establishment phase for beetroot was shorter than for the other three species.

Differences were primarily driven by greater growth of the above-ground part of the plants in the potting mix, particularly the leaves. Consistent with the trend in total biomass, shoot biomass was significantly greater in the potting mix for bean ($P<0.001$), parsley ($P=0.004$) and tomato ($P=0.006$), but not for beetroot. Total leaf area was also significantly greater in the potting mix, with significant differences for bean ($P<0.001$), parsley ($P<0.001$) and tomato ($P=0.002$) (Table 3.7). However, for specific leaf area (SLA), there were no significant differences for any of the four species ($P>0.05$ in all cases; data not shown).

There were no significant differences in root mass between the soils for any of the four plant species ($P>0.05$ in all cases; data not shown). However, for both bean and parsley, a greater proportion of biomass was allocated to roots in the loamy sand than in the potting mix, and more biomass was allocated to leaves in the potting mix than in the loamy sand (Table 3.7). For bean, there was a significant difference in both RMR ($P<0.001$) and LMR ($P<0.001$) between the soils. For parsley, there was a significant difference in the RMR ($P=0.004$) and LMR ($P<0.001$) between the soils, and also in SMR ($P=0.028$), whereby the proportion of biomass allocated to stems was greater in the potting mix. There were no significant differences in mass ratios between the soils for beetroot or tomato (Table 3.7).

### 3.3.2. Effects of soil and irrigation on yield

There were significant differences in yield between the two soils for bean ($P<0.001$) and beetroot ($P<0.001$). In both cases, yield was greater in the potting mix than in the loamy sand (Figure 3.5). At 241% overall, the difference was most marked for beetroot, in comparison to 54% for bean. For bean, there was also a significant difference between the soils for the number (count) of pods ($P<0.001$), whereby overall yield was 68% greater in the potting mix than in the loamy sand (data not shown). For both bean and beetroot, there were no significant differences between irrigation treatments.

For parsley only, there was a significant interaction between the soils and irrigation treatments ($P=0.004$), whereby there was no difference between the irrigation treatments in the loamy sand, but there were differences in the potting mix (Figure 3.5). In particular, in the potting mix, the mean yield of parsley was greater with the two surface irrigation treatments; by 150% for T-Rain, and 118% for T-Surf. With the T-Subs treatment, yield was only 21% greater in the potting mix.

**Table 3.7: Effects of soil type on total biomass, total leaf area and the proportion of biomass allocated to roots (root mass ratio; RMR), stems (stem mass ratio; SMR), and leaves (leaf mass ratio; LMR) as of the initial harvest before irrigation treatments commenced. Means that do not share a lower-case letter are significantly different. Values in parentheses represent mean standard error (n = 5).**

| Species | Soil | Total biomass (g) | Leaf area ($cm^2$) | RMR ($g\ g^{-1}$) | SMR ($g\ g^{-1}$) | LMR ($g\ g^{-1}$) |
|---|---|---|---|---|---|---|
| **Bean** | Mix | 28.34 a<br>(1.15) | 3898 a<br>(220.31) | 0.14 b<br>(0.01) | 0.21 a<br>(0.01) | 0.66 a<br>(0.01) |
| | Sand | 18.24 b<br>(1.76) | 1833 b<br>(131.25) | 0.28 a<br>(0.02) | 0.19 a<br>(0.01) | 0.53 b<br>(0.02) |
| | *P-value* | *0.001* | *<0.001* | *<0.001* | *0.101* | *<0.001* |
| **Beetroot** | Mix | 0.48 a<br>(0.01) | 82 a<br>(3.32) | 0.25 a<br>(0.02) | - | 0.75 a<br>(0.02) |
| | Sand | 0.49 a<br>(0.04) | 80 a<br>(6.22) | 0.26 a<br>(0.02) | - | 0.74 a<br>(0.02) |
| | *P-value* | *0.766* | *0.695* | *0.782* | - | *0.782* |
| **Parsley** | Mix | 20.11 a<br>(2.96) | 2066 a<br>(221.55) | 0.10 b<br>(0.02) | 0.37 a<br>(0.02) | 0.53 a<br>(0.01) |
| | Sand | 9.31 b<br>(0.34) | 738 b<br>(55.97) | 0.31 a<br>(0.05) | 0.26 b<br>(0.04) | 0.44 b<br>(0.01) |
| | *P-value* | *0.015* | *<0.001* | *0.004* | *0.028* | *<0.001* |
| **Tomato** | Mix | 84.16 a<br>(4.85) | 7822 a<br>(484.82) | 0.10 a<br>(0.01) | 0.33 a<br>(0.03) | 0.56 a<br>(0.03) |
| | Sand | 61.52 b<br>(4.91) | 4836 b<br>(464.17) | 0.15 a<br>(0.03) | 0.36 a<br>(0.03) | 0.49 a<br>(0.02) |
| | *P-value* | *0.011* | *0.002* | *0.144* | *0.554* | *0.091* |

For tomato, there were no significant differences between the two soil types or between irrigation treatments (P>0.05 in both cases, and for interaction). This was the case for both dry weight (Figure 3.5) and the number of fruit (data not shown). However, there was significant interaction between soils and irrigation treatments for average fruit size (P = 0.014), whereby fruit was smaller by > 2 g in the potting mix than in the loamy sand with the T-Surf irrigation treatment only (data not shown). The only tomato plant that was clearly dead by the final harvest was also under the T-Surf irrigation treatment, in the potting mix. A large proportion of the tomato fruit were affected by blossom end rot; generally between one third and two thirds, depending on the treatment, but the differences between irrigation treatments were not significant (P=0.066), and neither were those between the soils (P=0.103) (data not shown).

### 3.3.3. Effects of soil and irrigation on growth

#### 3.3.3.1. Final total biomass

For bean, as was the case for yield, total biomass at the final harvest was significantly greater in the potting mix than in the loamy sand (P<0.001), by 45% overall (Figure 3.6), but there were no significant differences between the irrigation treatments. For beetroot, there was a significant difference in total biomass between the irrigation methods (P<0.001), but not between the two soils. Biomass was greatest with T-Surf but lowest with the other surface treatment, T-Rain. The mean value for T-Surf was 73% greater than that for T-Rain, and 25% greater than that for T-Subs.

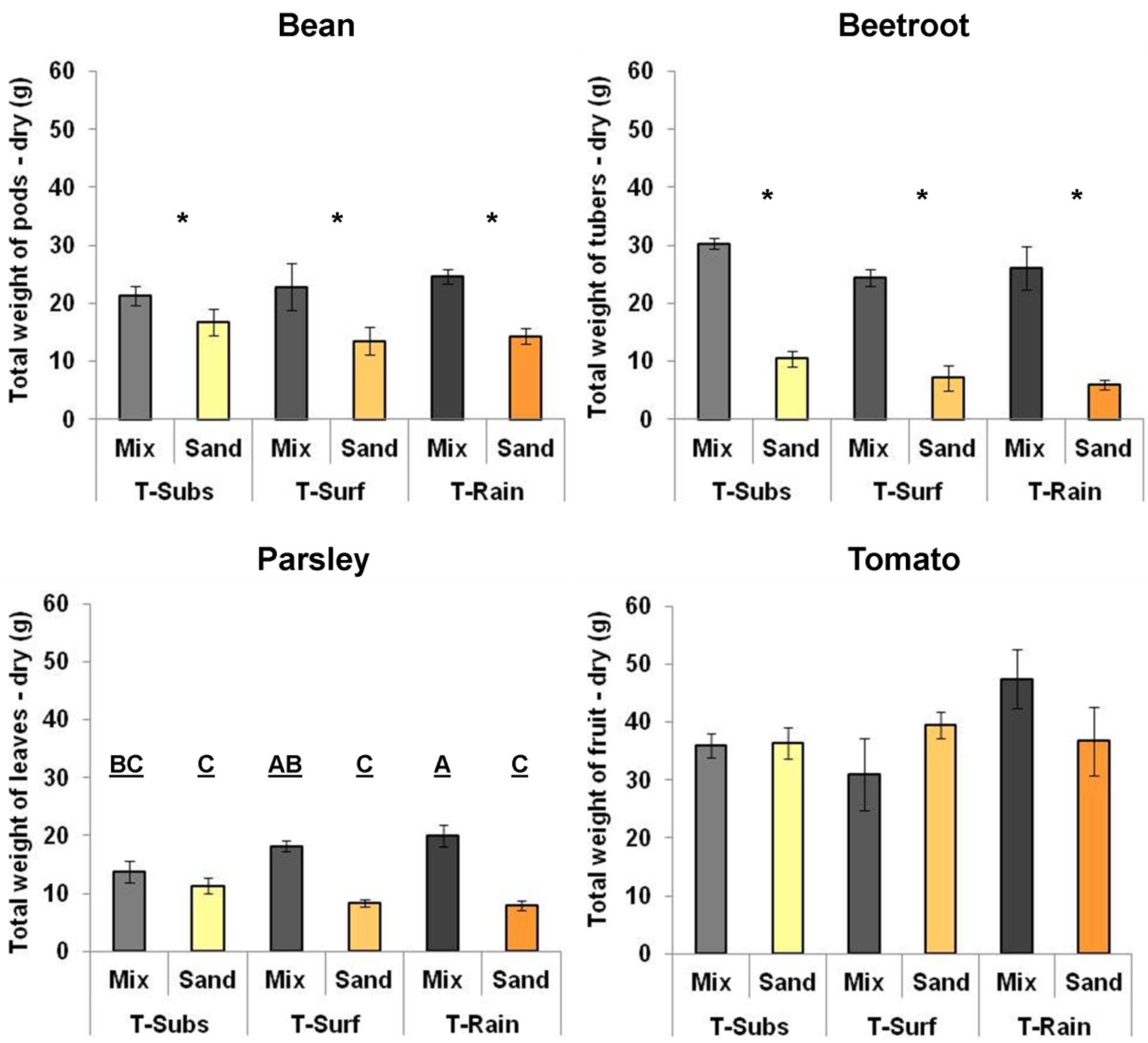



**Figure 3.5: Mean (± SE) yield by dry weight of bean (pods), beetroot (tuber), parsley (leaf) and tomato (fruit) in two soil types (potting mix and loamy sand) under three irrigation treatments (T-Subs – subsurface; T-Surf – surface irrigation same quantity as T-Subs; and T-Rain – surface irrigation as per mean rainfall). For parsley, there was significant interaction between the soils and irrigation treatments (P=0.004); means that do not share a letter are significantly different. For the other species, irrigation treatment had no significant effects on yield (bean, P=0.850; beetroot P=0.056; and tomato, P=0.261). Asterisks denote significant differences between soil types within irrigation treatments. There were no significant differences for tomato.**

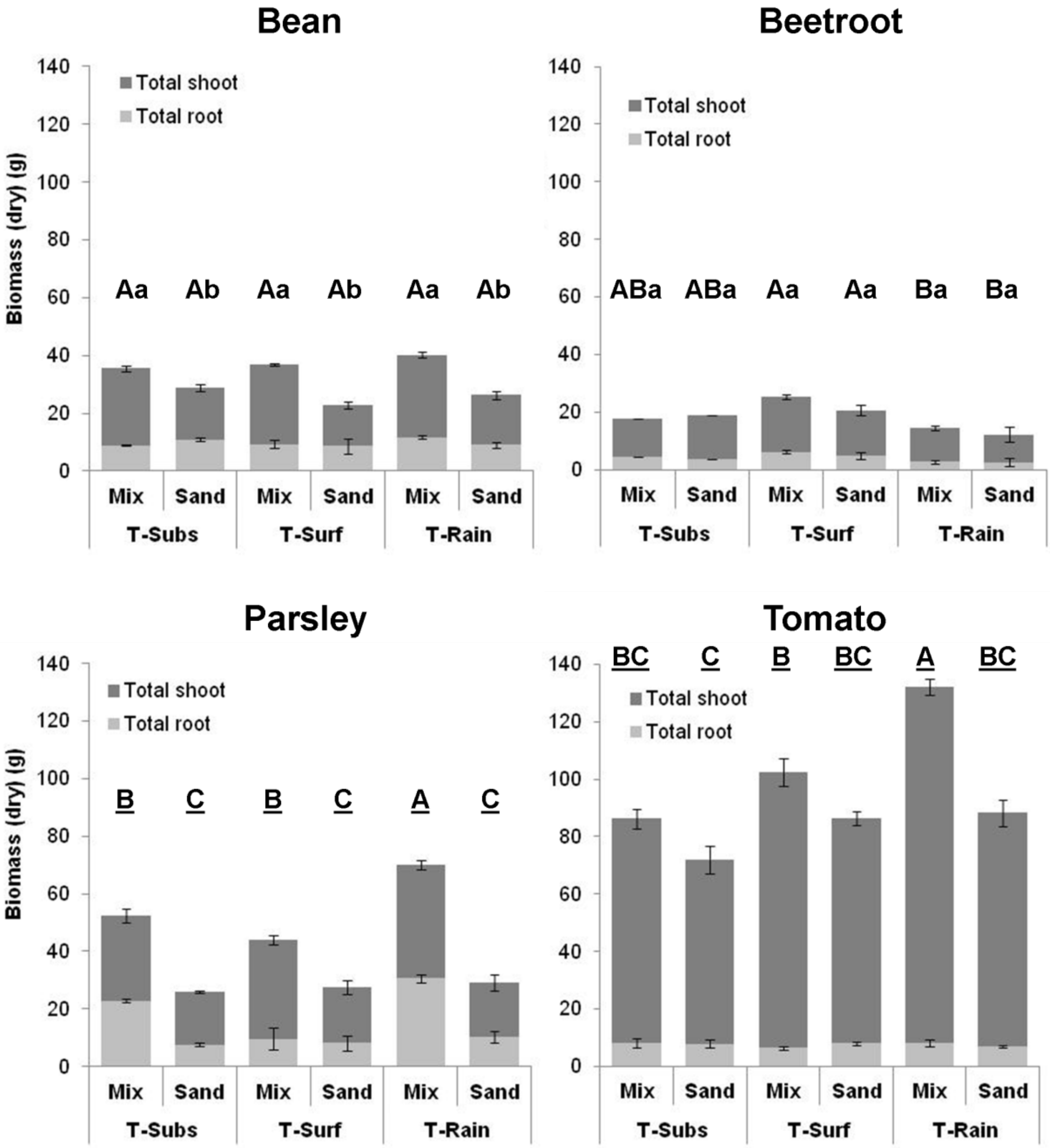



**Figure 3.6: Mean (± SE) total biomass by dry weight of bean, beetroot, parsley and tomato in two soil types (potting mix and loamy sand) under three irrigation treatments (T-Subs – subsurface; T-Surf – surface irrigation same quantity as T-Subs; and T-Rain – surface irrigation as per mean rainfall). Columns are partitioned into the total shoot (dark grey, top) and root (light grey, bottom) components of biomass. For beetroot, the total root weight and total biomass does not include the weight of the tuber; see results for yield. Biomass allocation is discussed in the text. Different letters denote significant differences for total biomass; means that do not share a letter (capital letters for irrigation treatments, unless underlined, lower-case letters for soils) are significantly different. Where letters are underlined, there was significant interaction between the soils and irrigation treatments.**

For both parsley and tomato, there was significant interaction between the soils and irrigation treatments (P=0.002 for parsley and P=0.001 for tomato). For parsley, the differences were similar to those in yield, whereby there was no difference between the irrigation treatments in the loamy sand, but there were differences in the potting mix, in which biomass was particularly great with T-Rain (Figure 3.6). Specifically, biomass with T-Rain was 140% greater in the potting mix than in the loamy sand. Unlike yield, however, in the potting mix, biomass with the T-Subs irrigation treatment was similar to T-Surf. That biomass was much greater (by 50%) in the potting mix than in the loamy sand with the T-Rain irrigation treatment was also the case for tomato. However, for tomato, biomass was similar between the two surface treatments (T-Surf and T-Rain) in the loamy sand and T-Subs in the potting mix (Figure 3.6). The lowest biomass was produced by the combination of T-Subs with the loamy sand.

#### 3.3.3.2. Final biomass allocation

For bean at the final harvest, there were no significant differences in root mass between treatments, but a significantly greater proportion of biomass was allocated to the roots in the loamy sand than in the potting mix (P=0.002) (Table 3.8), which was also the case at the initial harvest (see section 3.3.1). Correspondingly, the only significant differences in shoot mass were also between the two soils (P<0.001; 68% greater in the potting mix), with a significant difference in the proportion of biomass allocated to the stems (P<0.001; greater in the potting mix) but not to the leaves (Table 3.8).

For beetroot, there was a significant difference in both root and shoot mass only between the irrigation treatments (P=0.010 for root, P=0.001 for shoot), whereby both root and shoot mass (and thereby total biomass) were lowest with T-Rain but greatest with T-Surf. However, there were no significant differences in allocation to roots or shoots (Table 3.8).

For parsley root mass, there was significant interaction between the soils and irrigation treatments (P=0.002). Much more root mass was produced in the potting mix than in the loamy sand with both T-Subs (200%) and T-Rain (193%), but only 18% with T-Surf (Figure 3.6). This was also reflected in the proportion of biomass allocated to the roots, which was significantly greater with both T-Subs and T-Rain (P=0.030). There were also significant differences in shoot mass between the two soils (P<0.001; greater in the potting mix). Furthermore, there was significant interaction between the soils and irrigation treatments in the allocation of biomass to the leaves (P<0.001), whereby LMR was greatest in the loamy sand with T-Subs, but greater in the potting mix with T-Surf, and LMR was similar between the potting mix with T-Subs and both soils with T-Rain (Table 3.8). Unlike bean, there were no significant differences in the proportion of biomass allocated to stems (SMR) between the treatments.

**Table 3.8: Proportion of biomass allocated to roots (root mass ratio; RMR), stems (stem mass ratio; SMR), and leaves (leaf mass ratio; LMR) at the final harvest. Means that do not share a letter (capital letters for irrigation treatments, unless underlined, and lower case for soils) are significantly different. Underlined letters denote a significant interaction between soil and irrigation treatments. Where letters are absent, there are no significant differences. Values in parentheses represent mean standard error (n = 5).**

| | Irrigation treatment | Soil | Leaf area ($cm^2$) | RMR ($g\ g^{-1}$) | SMR ($g\ g^{-1}$) | LMR ($g\ g^{-1}$) |
|---|---|---|---|---|---|---|
| **Bean** | T-Subs | Mix | 2291 Aa (217) | 0.25 Ab (0.03) | 0.44 Aa (0.02) | 0.31 (0.04) |
| | | Sand | 1307 Ab (166) | 0.36 Aa (0.06) | 0.38 Ab (0.02) | 0.25 (0.05) |
| | T-Surf | Mix | 2121 Aa (250) | 0.25 Ab (0.01) | 0.47 Aa (0.02) | 0.27 (0.03) |
| | | Sand | 1009 Ab (160) | 0.38 Aa (0.04) | 0.39 Ab (0.01) | 0.23 (0.03) |
| | T-Rain | Mix | 2037 Aa (376) | 0.29 Ab (0.01) | 0.47 Aa (0.04) | 0.24 (0.04) |
| | | Sand | 1355 Ab (162) | 0.35 Aa (0.04) | 0.38 Ab (0.01) | 0.28 (0.04) |
| | *P-value* | *Soil* | *<0.001* | *0.002* | *<0.001* | *0.513* |
| | | *Irrig.* | *0.613* | *0.914* | *0.660* | *0.693* |
| | | *Inter.* | *0.648* | *0.534* | *0.771* | *0.407* |
| **Beetroot** | T-Subs | Mix | 1759 Ba (159) | 0.24 (0.02) | - | 0.76 (0.02) |
| | | Sand | 1725 Ba (210) | 0.18 (0.04) | - | 0.82 (0.04) |
| | T-Surf | Mix | 2550 Aa (140) | 0.24 (0.02) | - | 0.76 (0.02) |
| | | Sand | 2023 Aa (324) | 0.24 (0.04) | - | 0.76 (0.04) |
| | T-Rain | Mix | 1539 Ba (81) | 0.19 (0.01) | - | 0.81 (0.01) |
| | | Sand | 1190 Ba (211) | 0.23 (0.04) | - | 0.77 (0.04) |
| | *P-value* | *Soil* | *0.078* | *0.730* | - | *0.730* |
| | | *Irrig.* | *0.001* | *0.624* | - | *0.624* |
| | | *Inter.* | *0.476* | *0.316* | - | *0.316* |
| **Parsley** | T-Subs | Mix | 1357 Aa (155) | 0.43 ABa (0.05) | 0.31 (0.06) | 0.26 C (0.03) |
| | | Sand | 1261 Ab (202) | 0.26 ABa (0.07) | 0.27 (0.03) | 0.46 A (0.05) |
| | T-Surf | Mix | 1868 Aa (118) | 0.22 Ba (0.02) | 0.37 (0.01) | 0.42 AB (0.02) |
| | | Sand | 819 Ab (125) | 0.30 Ba (0.06) | 0.39 (0.08) | 0.31 BC (0.03) |
| | T-Rain | Mix | 2281 Aa (115) | 0.44 Aa (0.02) | 0.28 (0.02) | 0.28 C (0.02) |
| | | Sand | 900 Ab (128) | 0.35 Aa (0.05) | 0.38 (0.06) | 0.27 C (0.02) |
| | *P-value* | *Soil* | *<0.001* | *0.161* | *0.534* | *0.216* |
| | | *Irrig.* | *0.124* | *0.030* | *0.263* | *0.011* |
| | | *Inter.* | *<0.001* | *0.056* | *0.424* | *<0.001* |
| **Tomato** | T-Subs | Mix | 6515 Ca (309) | 0.10 Ab (0.01) | 0.45 Ba (0.02) | 0.46 Aa (0.01) |
| | | Sand | 5101 Cb (230) | 0.11 Aa (0.01) | 0.45 Ba (0.01) | 0.44 Ab (0.01) |
| | T-Surf | Mix | 8177 Ba (364) | 0.06 Bb (0.01) | 0.46 Ba (0.01) | 0.48 Aa (0.01) |
| | | Sand | 6194 Bb (398) | 0.09 Ba (0.00) | 0.46 Ba (0.01) | 0.45 Ab (0.01) |
| | T-Rain | Mix | 9779 Aa (144) | 0.06 Bb (0.00) | 0.49 Aa (0.00) | 0.45 Aa (0.00) |
| | | Sand | 6298 Ab (418) | 0.08 Ba (0.00) | 0.47 Aa (0.01) | 0.45 Ab (0.01) |
| | *P-value* | *Soil* | *>0.001* | *0.001* | *0.559* | *0.018* |
| | | *Irrig.* | *>0.001* | *<0.001* | *0.004* | *0.053* |
| | | *Inter.* | *0.012* | *0.427* | *0.560* | *0.104* |

There were no significant differences in root mass between treatments for tomato, but a significantly greater proportion of biomass was allocated to the roots with both the loamy sand (P=0.001) and with the T-Subs irrigation treatment (P<0.001) (Table 3.8). Given that root biomass was reasonably constant between treatments, variation in biomass allocation between treatments was driven by the significant differences in shoot biomass. For total shoot mass, there was a significant interaction between the soils and irrigation treatments (P=0.002). The proportion of total biomass allocated to the stems was significantly greater with the T-Rain irrigation treatment (P=0.004), and that allocated to the leaves was significantly greater in the potting mix (P=0.018).

#### 3.3.3.3. Final leaf area

For total leaf area, there were significant differences only between the two soils for bean (P<0.001; 76% greater in potting mix overall), and only between the irrigation treatments for beetroot (P=0.001; greatest with T-Surf, similar for T-Subs and T-Rain; Table 3.8). For beetroot only, SLA was significantly greater in the potting mix than in the loamy sand (P=0.033; data not shown). For both parsley and tomato, there was a significant interaction between the soils and irrigation treatments (P<0.001 for parsley and P=0.012 for tomato). For parsley, total leaf area was significantly greater in the potting mix than in the loamy sand with the two surface irrigation treatments (T-Surf and T-Rain), but not with T-Subs. There were no significant differences for SLA for parsley (P>0.05; data not shown). For tomato, total leaf area was significantly greater in the potting mix with all irrigation treatments, but this was particularly the case with T-Rain. Furthermore, the mean for the potting mix with T-Subs was relatively low, and similar to the mean for the loamy sand with both surface treatments (T-Surf and T-Rain) (Table 3.8).

### 3.3.4. Effects of soil and irrigation on water use and loss

#### 3.3.4.1. Cumulative evapotranspiration and transpiration

For both cumulative evapotranspiration (ET) and cumulative transpiration (E; evapotranspiration minus evaporation), there were significant interactions between the soils and irrigation treatments for bean (P<0.001 for both factors), parsley (P<0.001 for both factors), and tomato (P<0.001 for both factors). For all three species, ET and E were greatest with T-Rain in the potting mix, and also relatively high with T-Rain in the loamy sand, particularly for ET (Table 3.9). This was expected, given the greater volumes of irrigation water applied with T-Rain. ET and E were generally similar between the T-Subs and T-Surf irrigation treatments, but mostly greater in the potting mix with T-Subs, with E in particular lowest in the loamy sand with T-Subs for all three species (Table 3.9).

**Table 3.9: Cumulative evapotranspiration (ET) and transpiration (E) of vegetables growing in two soil types under three irrigation regimes. Means that do not share a letter (capital letters for irrigation treatments, unless underlined, and lower case for soils) are significantly different. Where letters are underlined, there was significant interaction between the soils and irrigation treatments. Values in parentheses represent mean standard error (n = 5).**

| | Irrigation treatment | Soil | Cumulative ET (kg) | Cumulative E (kg) |
|---|---|---|---|---|
| **Bean** | T-Subs | Mix | 14.15 BC (612.68) | 10.31 B (612.68) |
| | | Sand | 13.34 C (718.28) | 6.83 D (718.28) |
| | T-Surf | Mix | 15.45 BC (181.25) | 9.25 BC (181.25) |
| | | Sand | 14.77 BC (347.31) | 8.67 BCD (347.31) |
| | T-Rain | Mix | 23.14 A (400.91) | 14.56 A (400.91) |
| | | Sand | 16.10 B (475.93) | 7.58 CD (475.93) |
| | *P-value* | *Soil* | *<0.001* | *<0.001* |
| | | *Irrigation* | *<0.001* | *<0.001* |
| | | *Interaction* | *<0.001* | *<0.001* |
| **Beetroot** | T-Subs | Mix | 17.68 Aa (390.59) | 11.35 Aa (390.59) |
| | | Sand | 16.34 Ab (1396.20) | 4.72 Ab (1396.20) |
| | T-Surf | Mix | 19.41 Aa (126.24) | 9.97 Aa (126.24) |
| | | Sand | 17.47 Ab (1476.69) | 6.17 Ab (1476.69) |
| | T-Rain | Mix | 21.35 Aa (931.22) | 6.34 Ba (931.22) |
| | | Sand | 16.08 Ab (1130.87) | 0.52 Bb (1130.87) |
| | *P-value* | *Soil* | *0.003* | *<0.001* |
| | | *Irrigation* | *0.232* | *<0.001* |
| | | *Interaction* | *0.146* | *0.389* |
| **Parsley** | T-Subs | Mix | 10.84 BC (265.45) | 8.07 B (265.45) |
| | | Sand | 9.45 C (1251.40) | 5.08 C (1251.40) |
| | T-Surf | Mix | 11.81 BC (184.85) | 7.13 BC (184.85) |
| | | Sand | 10.48 BC (90.88) | 6.36 BC (90.88) |
| | T-Rain | Mix | 18.31 A (523.87) | 12.40 A (523.87) |
| | | Sand | 12.11 B (332.97) | 6.15 BC (332.97) |
| | *P-value* | *Soil* | *<0.001* | *<0.001* |
| | | *Irrigation* | *<0.001* | *<0.001* |
| | | *Interaction* | *<0.001* | *<0.001* |
| **Tomato** | T-Subs | Mix | 21.24 D (1136.23) | 16.41 B (1136.23) |
| | | Sand | 21.54 CD (896.51) | 12.97 C (896.51) |
| | T-Surf | Mix | 22.21 CD (975.14) | 14.74 BC (975.14) |
| | | Sand | 24.78 C (209.35) | 16.61 B (209.35) |
| | T-Rain | Mix | 38.78 A (376.00) | 27.27 A (376.00) |
| | | Sand | 29.54 B (495.14) | 17.89 B (495.14) |
| | *P-value* | *Soil* | *0.002* | *<0.001* |
| | | *Irrigation* | *<0.001* | *<0.001* |
| | | *Interaction* | *<0.001* | *<0.001* |

While there were no significant interactions for beetroot, both ET and E were significantly greater in the potting mix than in the loamy sand (P=0.003 for ET; P<0.001 for E). There was also a significant difference between the irrigation treatments in relation to E (but not ET) (P<0.001); overall, E was lowest with the T-Rain treatment, and it was exceptionally low (mean 0.52 kg) with the T-Rain and loamy sand combination. T-Subs and T-Surf were similar, however. Trends in cumulative ET and E over time are presented in Appendix H.

#### 3.3.4.2. WUE and transpiration in relation to growth

When transpiration was expressed on a biomass basis (Table 3.10), there was only a significant interaction between the soil and irrigation treatments for parsley (P=0.038). Of the six different treatments, transpiration per unit biomass was greatest in the loamy sand with the two surface irrigation treatments (T-Surf and T-Rain), while the other treatments were mostly similar to each other (Table 3.10). For beetroot, there was only a significant difference between irrigation treatments (P=0.006), whereby transpiration per unit biomass was significantly lower with T-Rain than with T-Subs or T-Surf, which corresponded with very low cumulative/daily transpiration (E) in the loamy sand in particular. There were no significant differences for bean or tomato (P>0.05). With regard to the differences between the vegetable species, transpiration per unit biomass was greatest for parsley, and lowest for beetroot and tomato (P<0.001) (Table 3.11).

For transpiration per unit leaf area, there were significant interactions between soil and irrigation treatments for bean (P=0.049), parsley (P=0.004), and tomato (P=0.016), but not for beetroot. For parsley, transpiration per unit leaf area was greatest in the loamy sand with T-Surf, but it was lowest in the loamy sand with T-Subs (Table 3.10). For tomato, five of the six treatments were similar, but transpiration per unit leaf area was significantly lower with the T-Surf and potting mix combination (Table 3.10). For beetroot, there were significant differences in transpiration per unit leaf area between the soils (P<0.001; greater in the potting mix) and between the irrigation treatments; overall, it was greatest with T-Subs and lowest with T-Rain (P=0.010). Similar to transpiration per unit biomass, transpiration per unit leaf area was significantly greater for bean and parsley than for beetroot and tomato (P<0.001) (Table 3.11).

For water use efficiency (WUE), there was only a significant interaction between soil and irrigation treatments for bean (P=0.001). WUE was greatest in the loamy sand than in the potting mix with T-Subs, but lowest in the loamy sand with T-Surf (Table 3.10). For tomato, there was a significant difference in WUE between soils only (P=0.031), whereby WUE was greater in the loamy sand. There were no significant differences in WUE between treatments for beetroot or parsley. Between the vegetable species, WUE was greater for beetroot than for the other three species (P<0.001) (Table 3.11).

**Table 3.10: Transpiration (E) in relation to plant growth (biomass and leaf area), and water use efficiency (WUE). Means that do not share a letter (capital letters for irrigation treatments, unless underlined, and lower case for soils) are significantly different. Where letters are underlined, there was significant interaction between the soil and irrigation treatments. Values in parentheses represent mean standard error (n = 5).**

| | Irrigation treatment | Soil | E per unit biomass (g $H_2O$ $g^{-1}$ biomass) | E per unit leaf area (g $H_2O$ $cm^{-2}$ leaf) | WUE (g biomass $kg^{-1}$ $H_2O$) |
|---|---|---|---|---|---|
| **Bean** | T-Subs | Mix | 49.55 Aa (2.63) | 4.71 $\underline{A}$ (0.63) | 2.79 $\underline{ABC}$ (0.25) |
| | | Sand | 41.87 Aa (2.58) | 5.74 $\underline{A}$ (1.10) | 3.90 $\underline{A}$ (0.29) |
| | T-Surf | Mix | 46.49 Aa (5.65) | 4.65 $\underline{A}$ (0.63) | 3.36 $\underline{AB}$ (0.37) |
| | | Sand | 63.39 Aa (9.01) | 9.82 $\underline{A}$ (2.08) | 2.08 $\underline{C}$ (0.29) |
| | T-Rain | Mix | 51.55 Aa (1.84) | 8.87 $\underline{A}$ (2.50) | 2.49 $\underline{BC}$ (0.14) |
| | | Sand | 58.34 Aa (7.51) | 6.11 $\underline{A}$ (1.09) | 2.98 $\underline{ABC}$ (0.22) |
| | *P-value* | *Soil* | *0.252* | *0.366* | *0.648* |
| | | *Irrigation* | *0.182* | *0.280* | *0.048* |
| | | *Interaction* | *0.107* | *0.049* | *0.001* |
| **Beetroot** | T-Subs | Mix | 25.96 Aa (1.27) | 6.58 Aa (0.36) | 4.20 Aa (0.15) |
| | | Sand | 22.11 Aa (6.82) | 2.53 Ab (0.58) | 9.74 Aa (3.17) |
| | T-Surf | Mix | 23.39 Aa (0.88) | 3.96 ABa (0.23) | 4.97 Aa (0.19) |
| | | Sand | 31.78 Aa (6.73) | 2.74 ABb (0.58) | 7.38 Aa (3.20) |
| | T-Rain | Mix | 15.25 Ba (1.09) | 4.08 Ba (0.47) | 6.53 Aa (0.42) |
| | | Sand | -1.18 Ba (12.85) | -0.78 Bb (1.86) | 18.45 Aa (9.68) |
| | *P-value* | *Soil* | *0.469* | *<0.001* | *0.075* |
| | | *Irrigation* | *0.010* | *0.010* | *0.306* |
| | | *Interaction* | *0.191* | *0.110* | *0.548* |
| **Parsley** | T-Subs | Mix | 74.93 $\underline{AB}$ (5.37) | 6.20 $\underline{ABC}$ (0.57) | 3.98 Aa (0.30) |
| | | Sand | 66.79 $\underline{AB}$ (14.06) | 3.61 $\underline{C}$ (0.81) | 4.63 Aa (1.43) |
| | T-Surf | Mix | 54.34 $\underline{B}$ (4.38) | 3.88 $\underline{BC}$ (0.30) | 3.38 Aa (0.40) |
| | | Sand | 102.51 $\underline{A}$ (14.75) | 8.31 $\underline{A}$ (0.91) | 2.88 Aa (0.43) |
| | T-Rain | Mix | 82.65 $\underline{AB}$ (2.08) | 5.45 $\underline{ABC}$ (0.18) | 4.02 Aa (0.18) |
| | | Sand | 101.16 $\underline{A}$ (12.83) | 7.91 $\underline{AB}$ (1.91) | 3.28 Aa (0.42) |
| | *P-value* | *Soil* | *0.029* | *0.082* | *0.727* |
| | | *Irrigation* | *0.138* | *0.193* | *0.236* |
| | | *Interaction* | *0.038* | *0.004* | *0.551* |
| **Tomato** | T-Subs | Mix | 28.55 Aa (1.94) | 2.55 $\underline{A}$ (0.26) | 1.50 Ab (0.27) |
| | | Sand | 23.12 Aa (1.87) | 2.55 $\underline{A}$ (0.15) | 4.10 Aa (0.27) |
| | T-Surf | Mix | 30.58 Aa (6.59) | 1.81 $\underline{B}$ (0.13) | 5.50 Ab (0.35) |
| | | Sand | 26.89 Aa (0.85) | 2.73 $\underline{A}$ (0.18) | 6.45 Aa (0.31) |
| | T-Rain | Mix | 29.44 Aa (1.30) | 2.79 $\underline{A}$ (0.04) | 5.49 Ab (0.07) |
| | | Sand | 30.51 Aa (2.96) | 2.87 $\underline{A}$ (0.13) | 8.31 Aa (0.16) |
| | *P-value* | *Soil* | *0.315* | *0.020* | *0.031* |
| | | *Irrigation* | *0.429* | *0.008* | *0.249* |
| | | *Interaction* | *0.585* | *0.016* | *0.214* |

### 3.3.4.3. Water content

In the analysis of water content, an emphasis was on differences between the T-Subs and T-Rain irrigation treatments, representing sub- and surface-irrigated raingardens respectively. For all four species and in both soils, water content was significantly greater with T-Rain following most irrigation events, with the exception of parsley in the loamy sand (Figure 3.7). However, for tomato in particular, even in the potting mix the water content with the T-Rain treatment was regularly depleted to be similar to the water content of the T-Subs pots prior to the next irrigation (Figure 3.7). This water content was frequently close to or beyond the permanent wilting point (Table 3.12). Indeed, for tomato in the potting mix, the water content of the T-Subs pots was significantly greater than that of the T-Rain pots prior to irrigation on multiple occasions, particularly in the second half of the irrigation treatment phase (Figure 3.7). The T-Rain pots reached permanent wilting point four times in the potting mix, and twice in the loamy sand, while the T-Subs pots only reached permanent wilting point once in both soils. For the other three species, permanent wilting point was not reached on any occasion with the T-Rain irrigation treatment. For T-Subs, the permanent wilting point was reached once for the bean in the potting mix, but not at all for beetroot or parsley (Table 3.12).

**Table 3.11: Differences in transpiration (E) in relation to plant growth, and water use efficiency (WUE), between vegetable species. Means that do not share a letter are significantly different. Values in parentheses represent mean standard error (n = 5).**

| | E per unit biomass ($g\ H_2O\ g^{-1}$ biomass) | E per unit leaf area ($g\ H_2O\ cm^{-2}$ leaf) | WUE ($g$ biomass $kg^{-1}\ H_2O$) |
|---|---|---|---|
| **Bean** | 51.86 B (2.46) | 6.65 A (0.67) | 2.93 B (0.15) |
| **Beetroot** | 19.55 C (3.13) | 3.18 B (0.52) | 8.55 A (1.85) |
| **Parsley** | 80.40 A (5.00) | 5.89 A (0.49) | 3.69 B (0.27) |
| **Tomato** | 28.18 C (1.29) | 2.55 B (0.09) | 3.36 B (0.16) |
| ***P-value*** | <0.001 | <0.001 | <0.001 |

The T-Subs irrigation treatment was also compared with T-Surf, as a comparison of sub- and surface irrigation given identical irrigation volumes. The most notable difference between these two irrigation treatments occurred with beetroot in the potting mix. From Day 35 of the treatments onwards, the water content with T-Subs became consistently and significantly greater ($P<0.05$) than with T-Surf, at both pre- and post-irrigation weighing (Figure 3.7). By the final weighing (Day 105), water content (as depth) with T-

Subs was 273% greater than with T-Surf (P<0.001), and the permanent wilting point had been reached twice with T-Surf but not at all with T-Subs (Table 3.12). For bean, parsley and tomato in the potting mix, there were no significant differences between T-Subs and T-Surf at any point during the experiment, with the exception of the final weighing (Day 62) for the bean (P=0.021; 33% greater with T-Subs), and the permanent wilting point for parsley being reached once with T-Surf but not with T-Subs.

There were a greater number of significant differences (P<0.05) between the T-Subs and T-Surf irrigation treatments in the loamy sand, for bean (Days 2 to 21, 25, 28, 31, 32, 42, 48, 62 of the experiment), parsley (Days 8, 12, 13, 14, 15), and tomato (Days 8, 13, 15, 21, 25, 28, 32, 35, 42 and 55). On the vast majority of these occasions, water content was greater in the T-Surf pots (Figure 3.7). This might be owed to a small proportion of the irrigation water drained from each T-Subs pot (as “overflow”) at each application, whereas a greater proportion was initially retained with T-Surf. For beetroot, there was only a significant difference on one occasion (Day 28; P=0.031; greater with T-Surf than with T-Subs).

Overall, for tomato, water content was 12% greater in the potting mix than in the loamy sand when expressed as a depth of water in the pot (P=0.039), and much greater (153%) when expressed as gravimetric soil water content (P<0.001) (data not shown). It was also significantly greater with the T-Rain irrigation treatment than with T-Subs or T-Surf (P=0.006 for gravimetric SWC and P=0.001 for water content as depth; data not shown). For the other three species, there was significant interaction between the soils and irrigation treatments (P<0.001 in all cases; data not shown), but in all cases the maximum water content occurred with the combination of potting mix and T-Rain irrigation treatment.

**Table 3.12: Number of days that soil water content (as water depth, mm) was below permanent wilting point (PWP; at -1.5 MPa) during the irrigation treatment phase. The number of days in this phase (to final harvest) varied between plant species.**

| | Soil | Number of days to final harvest | Number of days below PWP | | | Total |
|---|---|---|---|---|---|---|
| | | | T-Subs | T-Surf | T-Rain | |
| **Bean** | Mix | 61 | 1 | 0 | 0 | **1** |
| | Sand | 61 | 0 | 1 | 0 | **1** |
| **Beetroot** | Mix | 105 | 0 | 2 | 0 | **2** |
| | Sand | 105 | 0 | 0 | 0 | **0** |
| **Parsley** | Mix | 46 | 0 | 1 | 0 | **1** |
| | Sand | 46 | 0 | 0 | 0 | **0** |
| **Tomato** | Mix | 77 | 1 | 1 | 4 | **6** |
| | Sand | 77 | 1 | 1 | 2 | **4** |
| | | **Total** | **3** | **6** | **6** | |

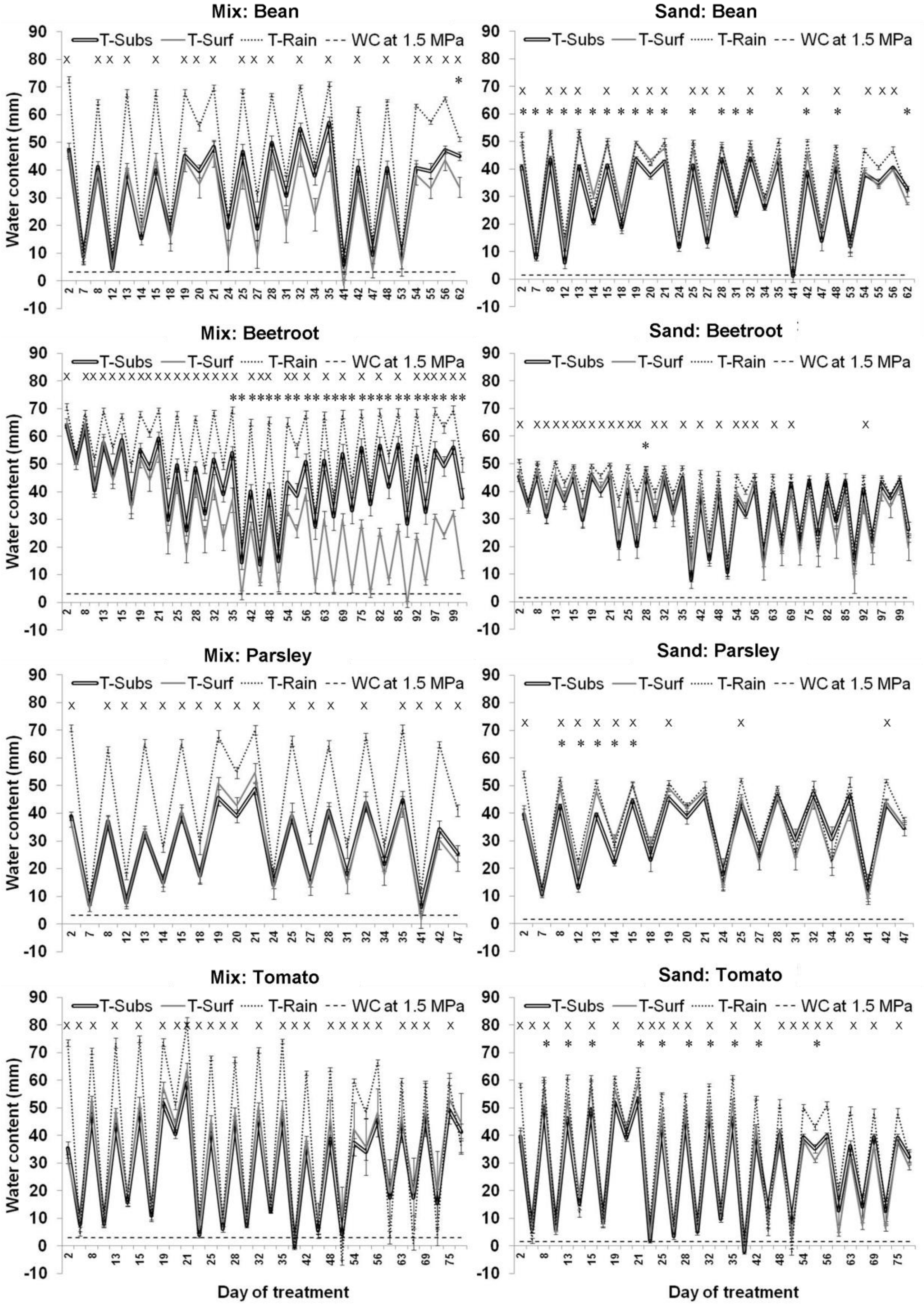



**Figure 3.7: Mean (± SE) water content expressed as depth of water. An asterisk (*) denotes a significant difference between the T-Subs and T-Surf irrigation treatments (P<0.05), and a cross (×) denotes a significant difference between the T-Subs and T-Rain irrigation treatments (P<0.05).**

### 3.4. Discussion

#### 3.4.1. Choice of soil type

The irrigation regime in this experiment was based on the average frequency of rainfall for Melbourne (and also the average volume, in the case of T-Rain), and the results indicate that vegetables are able to tolerate and produce substantial yield under these conditions without the need for supplemental watering. This is dependent, however, on a suitable soil being used in the raingarden.

There were some considerable differences in plant growth between the two soils that were tested, even following the establishment phase, when the pots were well watered. For bean, parsley and tomato, total biomass and leaf area at the initial harvest were significantly greater in the potting mix than in the loamy sand. Furthermore, for both bean and parsley, a greater proportion of biomass was allocated to the roots in the loamy sand than in the potting mix. This might have been a response to lower water availability in the loamy sand relative to the potting mix, consistent with the functional equilibrium model, in which plants respond to a decrease in below-ground resources such as water with increased allocation to roots (Poorter and Nagel, 2000). Drought avoidance through greater root growth, and greater extraction of soil moisture, has previously been reported to be an important drought tolerance mechanism for bean (Sponchiado et al., 1989). However, for all species, there were no differences in specific leaf area (SLA) between the soils after the establishment phase. This indicates that any differences between the soils did not cause differences in plant functioning, under the well-watered regime.

Differences in biomass and leaf area between the soils during establishment were mostly carried forward under the irrigation regime of the irrigation treatment phase, and were reflected in yield. For bean, for example, both yield and total biomass at the final harvest were significantly greater in the potting mix than in the loamy sand, and there was still a significantly greater proportion of biomass allocated to the roots in the loamy sand. A greater yield in the potting mix than in the loamy sand was particularly pronounced for beetroot. This is consistent with previous findings that the response of sugar beet yield to irrigation reflects the effects of soil type on the availability of water, and that sandy soils in particular can cause water stress even under “full” irrigation (Wright et al., 1997). The growth of the rest of the beetroot plant, including biomass allocation, was less affected by soil type, with the exception that there was significantly greater SLA (i.e. thinner leaves were produced) in the potting mix than in the loamy sand. There was no difference in SLA for parsley (and it could not be measured for bean or tomato).

The only species that did not respond to differences in soil type, with regard to yield, was tomato. Considerable quantities of fruit were produced in both soil types (> 240 g by fresh weight in all but 3 of the 30 pots). This lack of difference was unexpected to some extent given that, like beetroot, the hydraulic properties of the growing medium are considered to be critical in plant water uptake in tomatoes (De Swaef et al., 2012). That the tomato in the loamy sand could produce yield comparable to the potting mix might be owed to its low water use (transpiration) per unit biomass and per unit leaf area, relative to bean and parsley. Nonetheless, leaf area was significantly greater in the potting mix than in the loamy sand (as was also the case at the initial harvest), and soil type also had some affect on total biomass, through interaction with the irrigation treatments. Furthermore, a greater proportion of biomass was allocated to roots in the loamy sand, which is consistent with previous findings. For example, Mingo et al. (2004) found that partial root-zone drying (see section 1.5.2.2) applied to greenhouse-grown tomato plants increased root biomass by 55%, as resources were partitioned away from shoot organs. Similarly, McGiffen et al. (1992) reported that water stress (a reduced frequency of irrigation) caused a shift in biomass from shoots to roots in tomato.

Overall, the potting mix or a similar soil, such as the vegetable garden mix used in the field trial (Chapter 2), would be the preferred soil type for vegetable production. The greater water holding capacity of the potting mix generally resulted in greater water availability compared with the loamy sand, as evidenced by overall higher rates of evapotranspiration and greater soil water content following irrigation. In turn, greater water availability in the potting mix appears to have led to greater vegetable growth and yield than in the loamy sand, in general. A conventional raingarden growing media (loamy sand), as tested, is probably not viable for a vegetable raingarden (or “vegetable green roofs”), and therefore neither is a uniform profile design.

Traditional potting mix, containing slow-release organic fertilizer, also has the advantage of requiring no or minimal additional fertilizer inputs. This was demonstrated in the 1.5-year field trial (Chapter 2); no fertilizer was added to the gardens, other than in the process of topping up the soil, and adding mulch in the first growing season. While fertilizer was added to the loamy sand in the greenhouse experiment for purposes of control, the use of fertilizer in a raingarden cannot be advocated without further research, given the potential for negative impacts on the environment. Attempting to meet the nutritional needs of plants with minimal fertilizer applications is a challenge that is also faced in vegetable production on green roofs (see section 1.2.5).

However, a potting mix might also pose some risk to the environment if used in a raingarden, particularly an infiltration (unlined) type. The use of pine-bark potting mixes in particular could make the raingarden a source rather than a sink of nitrogen, which is even an issue for the media used in conventional biofiltration systems (Hatt et al., 2007; Henderson et al., 2007) (see section 1.5.1). This might be further reason to favour a lined design for a vegetable raingarden, in addition to its potentially low irrigation requirements (Chapter 2). However, in this case, it will be essential to construct the overflow of the system so that it discharges only "untreated" runoff water to the stormwater drain, rather than water that has been in contact with the nutrient-rich growing media (a suitable design is shown in Figure 2.26, and described in the Melbourne Water Instruction Sheet; Appendix I).

### 3.4.2. Choice of sub- or surface irrigation

The differences in plant growth and yield between the irrigation treatments were at least partly dependent on soil type. There was some significant interaction between the irrigation treatments and soils, most notably for the biomass and yield of parsley. The greatest differences between the irrigation treatments generally occurred in the potting mix. This might be attributed to greater water stress in the loamy sand masking any differences between irrigation treatments in that soil type, to some extent. However, even in the potting mix the differences between irrigation treatments might have been masked by stress caused by the infrequent application of irrigation according to Melbourne rainfall distribution, and by the high temperatures in the greenhouse (see section 3.2). A well-watered control for "optimal" growth might have demonstrated greater differences between the irrigation methods (this is further discussed below; section 3.4.3).

Considering the similar results between the T-Subs (sub-) and T-Surf (surface) irrigation treatments, which received the same volumes of irrigation water, sub-irrigation does not appear to offer significant benefits over surface irrigation in relation to vegetable growth or yield, or even in water use. In the potting mix, there was little difference in water content between the irrigation treatments other than for beetroot, and in the loamy sand, there was generally more water available to the plants with T-Surf than T-Subs. For both parsley and tomato, there was also a greater proportion of biomass allocated to roots with T-Subs than with T-Surf, indicative of lower water availability with T-Subs.

However, tomato plants appeared to be most stressed under the T-Surf irrigation treatment, particularly in the potting mix. Apart from producing the only dead plant by the final harvest, this particular treatment produced the lowest fruit size. Reductions in fruit size have been linked to water stress in previous studies (e.g. Nuruddin et al., 2003). Furthermore, if T-Subs is considered to represent a sub-irrigated raingarden being well-watered by each rainfall event, then there is some potential for more efficient water use than with surface irrigation, given that the relatively large volume of irrigation water applied with the T-Rain treatment (more than double; see section 3.2.4) did not lead to considerable benefits for yield. The yield of bean, for example, was not significantly different between these irrigation treatments, despite previous studies positively linking bean yield to irrigation volumes (e.g. Selen et al., 2008).

Also of note is that beetroot biomass and leaf area, but not yield, were significantly lower with T-Rain than T-Surf. With T-Rain, the total mass of both the roots (the non-edible component) and shoots was significantly reduced. This might be a consequence of the greater pooling that occurred on the soil surface at each application of the T-Rain treatment. If this problem was observed in a surface-irrigated vegetable raingarden, it could be overcome by increasing the size of the raingarden; i.e. to be > 7.5% of the size of its catchment area, or where this was not feasible, by installation of overflow ports, to prevent excessive ponding depths.

To evaluate how these four varieties of vegetables would perform in a sub-irrigated raingarden under field conditions, they were planted in the second summer growing season of the field trial (Chapter 2). The performance of Italian parsley was particularly similar between the two trials. In the greenhouse experiment, for the potting mix, the yield of the Italian parsley was lower with subirrigation than with the surface treatments. Similarly, in the field trial, in which the vegetable gardening mix had a similar water holding capacity to the potting mix, yield was 53-64% greater in the two surface-irrigated control gardens than the two sub-irrigated raingardens. Note, however, that surface irrigation was applied using micro-spray systems in the field trial, which represented traditional vegetable gardening rather than a surface-irrigated raingarden. The most notable difference between the results of the field trial and greenhouse experiment was for bean. There was no significant difference in yield between the irrigation treatments in the pot experiment, but irrigation method did seem to affect yield in the field trial; yield was nil in the entirely sub-irrigated Lined raingarden, indicating that this variety of bean required some surface irrigation (see section 2.3.1).

Overall, both sub-irrigation and surface irrigation appear to be viable options for a vegetable raingarden. A field study involving a conventionally-designed surface-irrigated raingarden is required to verify this, and to ensure that vegetables produced in a surface-irrigated system are safe for consumption.

### 3.4.3. Differences between plant species

There were no clear differences between the plant species tested in this experiment, in terms of their overall capacity to survive, function, and produce yield in a vegetable raingarden. Even for parsley, which had relatively high water use per unit biomass, growth and yield was reasonable. However, some plant species might be more affected by variations in raingarden design than others. For example, the results indicate that the yield of beetroot, and to a lesser extent bean, would be relatively low if loamy sand was used in a vegetable raingarden. On the other hand, tomato yield in a raingarden with loamy sand might be similar to a raingarden with potting mix. Furthermore, although all treatments were affected by a high incidence of blossom end rot in tomato fruit, which is indicative of water deficit or some other stress (Saure, 2001; Sun et al., 2013; Taylor et al., 2004), there were no significant differences in its occurrence between the soils or irrigation treatments. Overall, tomato was quite drought tolerant, with relatively low water use per unit biomass, similar to that of beetroot (although beetroot had higher WUE). The main concern with tomato would be the relatively large size of the plant, particularly as the plants mature and crop water use increases (Smajstrla and Locascio, 1996). Tomato depleted soil moisture more than the other three species, frequently to close to permanent wilting point, even in the potting mix, within the two to seven day intervals between irrigations. The water demands of the large plants were also reflected in higher cumulative evapotranspiration and transpiration rates.

Provided that the plants can survive any proceeding dryness, high water use might be a positive characteristic in the context of the runoff management function of a vegetable raingarden, which is also the case on green roofs (Farrell et al., 2013). One of the roles of vegetation in a conventional raingarden is to help retain and attenuate runoff. In particular, evapotranspiration between rainfall events provides a greater storage capacity in the soil for the next rainfall event (Dussaillant et al., 2005).

However, some assumptions are attached to the conclusion that average rainfall could be sufficient for an effective vegetable raingarden. First and foremost, it assumes that rainwater (runoff) can be conveyed effectively to the soil in the raingarden, which is an issue for sub-irrigation in particular, as highlighted in the field trial (Chapter 2). For example, the depth of soil in the greenhouse experiment was much shallower than in the field trial, so that the occurrence of capillary rise was not as critical. However, it is perhaps a realistic depth for a “vegetable green roof”, given that substrate depths on green roofs are limited by the structure of the building. Another assumption is that the vegetables are grown in a raingarden that it is approximately 7.5% of the size of its catchment area. Future research could assess vegetable production in relation to different catchment sizes. Such research should consider the probability that, with climate change, Melbourne will experience reduced rainfall and prolonged droughts, but also more frequent extreme storm events (CSIRO, 2007; Howe et al., 2005; Maunsell Australia Pty Ltd., 2008). Finally, even though maximum air temperatures in the greenhouse were much higher than maximum outdoor temperatures during this experiment (Table 3.1), evapotranspiration rates and thereby irrigation requirements might be higher in an outdoor vegetable raingarden, as the radiation balance and effect of air movement in a greenhouse is altered relative to the external environment (Fernandes et al., 2003).

In any case, yield is not likely to be optimal if the raingarden does not receive supplemental watering. There was no well-watered control in this experiment, because this was not directly relevant to raingarden design. Rather, all three irrigation treatments represented conditions of water deficit, applied to established plants. Previous studies have generally found that water deficit has an adverse impact on vegetable growth and/or yield, relative to well-watered plants. For example, this has been demonstrated in pot experiments for parsley (Petropoulos et al., 2008), tomato (McGiffen et al., 1992; Nuruddin et al., 2003; Torrecillas et al., 1995), and broad bean (*Vicia faba*) (Gallacher and Sprent, 1978; Xia, 1994), although at least one study has found that the water use efficiency of some genotypes of broad bean can increase markedly with increasing water deficit (Amede et al., 1999). There will also be differences in plant functioning. For example, it has been reported that the SLA of tomato can increase (i.e. thinner leaves are produced) in response to water deficit which, incidentally, is in contrast to the increased leaf thickness found in species adapted to water stress (McGiffen et al., 1992). Transpiration rates are likely to be reduced relative to well-watered plants. For example, Tahi et al. (2007) found that transpiration of tomato plants was reduced by about 50% by both partial root-zone drying and regulated deficit irrigation (see section 1.5.2.2), which led to a significant improvement in whole-plant WUE.

Less is known about beetroot, as the vast majority of studies on the water requirements and irrigation of *Beta vulgaris* have focused on the sugar beet variety. These studies are generally focused on sugar yield, but they frequently report that water deficit has a significant impact on other measures of growth and water use efficiency (Fabeiro et al., 2003; Kiziloglu et al., 2006; Monti et al., 2006; Rytter, 2005). This includes reductions in leaf and taproot growth, fibrous root distribution, and biomass allocation (Bloch and Hoffmann, 2005; Vamerali et al., 2009).

## 3.5. Conclusions

The yields of bean, beetroot, parsley and tomato were reasonable under a “rainfall” watering regime, in which irrigation was applied at intervals corresponding to the mean number of rain days for Melbourne during summer. As such, it is possible that little or no supplemental irrigation would be required for a vegetable raingarden, particularly if the raingarden is designed to maximise water availability for the plants. With regard to the choice of soil, a “mix” that is purpose-made for containerised vegetable gardening appears suitable. The potting mix tested in this study could not only hold more water, but water was generally more available, and this mostly led to greater growth and yield than the loamy sand. However, a critical issue in a vegetable raingarden is negotiating the conflict between providing adequate water and nutrients to support vegetable production and minimising the risk of nutrient release to the local environment. If loamy sand is required to meet runoff quality objectives (which assumes that fertilizer inputs to the loamy sand can be minimal), it might only be suitable for some vegetable species, such as tomato, for which there was no significant difference in yield between the two soils.

With regard to irrigation methods, sub-irrigation showed no clear advantage over surface irrigation in relation to yield and biomass, although there was also no clear disadvantage. For bean, beetroot and tomato, there was no significant difference in yield between the irrigation treatments. As such, both approaches could be regarded as viable options for a vegetable raingarden. However, the effects of the different irrigation treatments on growth and yield might have been masked by the effects of drought stress brought about by the frequency of irrigation, which was conducted according to the mean number of rain days for Melbourne for all pots. Ultimately, as for soil choice, the choice of irrigation method should also consider issues such as runoff quality objectives and food safety.

## 4. Thesis conclusions

The availability of water in a raingarden can be sufficient for the production of many common vegetables, and the role of the raingarden in reducing rates of urban runoff can be retained. However, the raingarden must be designed and managed effectively, and its performance is subject to considerable seasonal variation. Specifically, considering the results of both the field trial and greenhouse experiment, in response to the Research Questions stated at the outset of the thesis:

1. A vegetable raingarden sized ≤ 7.5% of its catchment area might not require irrigation to supplement rainfall to produce reasonable yield, under the current Melbourne climate. In the field trial, this was even the case in a drier than average summer, but only for the raingarden that was fitted with waterproof lining. Vegetables produced in infiltration-type (unlined) raingardens are more likely to require regular irrigation in summer, unless the raingarden can be designed to maximize the delivery of runoff water to the vegetable root zone. Nonetheless, supplemental irrigation could comply with all but the most severe of Melbourne's water restrictions, and is likely to have little or no impact on stormwater management. Indeed, if supplemental irrigation is applied using collected stormwater, rather than tap water, this increases the opportunity for reducing volumes of urban runoff. The vegetables tested in the greenhouse experiment were able to tolerate the frequency and volume of average summer rainfall, without supplemental irrigation.

2. A sub-irrigated raingarden design offered no clear advantages over surface irrigation in terms of yield or runoff management, but sub-irrigation appears to be a viable option provided that the raingarden is designed to maximize (or have limited dependency on) capillary rise. Sub-irrigation may also reduce the risk of contaminant transfer to some vegetables, which was tested in a parallel study. In the field trial, the two raingardens received a large volume of rainwater from the roof during the monitoring period (> 33 kL in 1.5 years), but the sub-irrigated raingarden design did not convey this water effectively to the vegetable root zone, at least in the infiltration-type (unlined) raingarden. Among the possible reasons for this, the sand ("filter") layer might have acted as a barrier to capillary rise. Consequently, for some vegetables, such as tomato and onion, yield was relatively low in at least one of the two raingardens, in comparison to two controls that represented traditional vegetable gardens. In the greenhouse experiment, even when identical volumes of irrigation water were applied, growth and yield with sub-irrigation was mostly similar to surface irrigation, even with regard to evapotranspiration rates and the efficient use of water. The only notable benefits of sub-irrigation were higher yield of parsley grown in loamy sand (but yield was lower with sub-irrigation in potting mix), and the avoidance of pooling, which appeared to be detrimental to the growth of beetroot.

3. The growth and yield of vegetables differed between the two soil types tested in the greenhouse experiment. The potting mix, as used in a conventional containerised vegetable garden, had a similar water holding capacity to the vegetable garden mix used in the field trial. More water was available for use by the plants in the potting mix than in ameliorated loamy sand, which represented conventional raingarden filter/growing media. This contributed to overall greater yield and biomass in the potting mix. The results indicated that conventional raingarden growing media (loamy sand) might not be viable for a vegetable raingarden. A vegetable raingarden is therefore likely to require separate vegetation and filter layers (as used in the field trial, and as recommended in the Melbourne Water Instruction Sheet; Appendix I), rather than a uniform profile design.

4. There was some variation in growth and yield between different vegetable species in both the field trial and greenhouse experiment. In the field trial, there was even variation within species; between varieties or growing seasons. Nonetheless, although some were more prone to pest damage, no vegetable species/variety performed particularly poorly, and it seems that many common vegetables can be effectively produced in vegetable raingardens. Even tomato produced reasonable yield, despite significant depletions in water content caused by the large size of the plant.

5. The results of the field trial indicated that a raingarden can be used to produce vegetables while maintaining its role in reducing quantities and rates of urban runoff. The infiltration-type (unlined) raingarden reduced both the frequency (number of days) and the volume of runoff by > 90%. Despite capturing approximately 21 kL of runoff over the 1.5-year monitoring period, the raingarden that was lined was less effective. It reduced the frequency of runoff by 34% and the volume of runoff by 63%; i.e. approximately two thirds of the inflow was used and lost through evapotranspiration. Its performance was also more variable over the monitoring period, being most effective for rainfall events that were preceded by dry periods. Overall, choosing between a lined or unlined system (in situations where lining is not essential) will depend on the primary objectives of the system; for runoff reduction, an unlined system would be ideal, but lined systems are able to use water more efficiently.

Finally, the results of this study are not only relevant to raingardens, but also to vegetable production on green roofs. "Vegetable green roofs" face many of the same challenges as vegetable raingardens; an issue that is particularly worthy of future research is meeting the nutritional needs of plants while minimizing negative impacts on runoff quality and the environment. Overcoming these challenges is likely to be worthwhile; vegetable raingardens and "vegetable green roofs" are opportunities for further expansion of stormwater reuse practices in urban food production, and for incorporation of urban food production into Water Sensitive Urban Design.

## References

Ahmed, A.K., Cresswell, G.C., and Haigh, A.M., 2000, Comparison of sub-irrigation and overhead irrigation of tomato and lettuce seedlings: Journal of Horticultural Science & Biotechnology, v. 75, p. 350-354.

Ahmed, W., Goonetilleke, A., and Gardner, T., 2009, Quantitative detection of pathogens in roof-harvested rainwater: Microbiology Australia, v. 30, p. 35-37.

Akan, A.O., and Houghtalen, R.J., 2003, Urban Hydrology, Hydraulics, and Stormwater Quality - Engineering Applications and Computer Modeling: Hoboken, John Wiley & Sons.

Allinson, M., Shiraishi, F., Kamata, R., Kageyama, S., Nakajima, D., Goto, S., and Allinson, G., 2011, A pilot study of the water quality of the Yarra River, Victoria, Australia, using in vitro techniques: Bulletin of Environmental Contamination and Toxicology, v. 87, p. 591–596.

Amede, T., Kittlitz, E.V., and Schubert, S., 1999, Differential drought responses of faba bean (*Vicia faba* L.) inbred lines: Journal of Agronomy and Crop Science, v. 183, p. 35-45.

Barker-Reid, F., Harper, G.A., and Hamilton, A.J., 2010, Affluent effluent: growing vegetables with wastewater in Melbourne, Australia—a wealthy but bone-dry city: Irrigation and Drainage Systems, v. 24, p. 79–94.

Ben-Asher, J., and Silberbush, M., 1992, Root distribution under trickle irrigation - factors affecting distribution and comparison among methods of determination: Journal of Plant Nutrition, v. 15, p. 783-794.

Bewley, R.J.F., and Hockin, S., 2011, Contaminated Soils and Bioremediation: Creation and Maintenance of Inner Space, *in* Ritz, K., and Young, I., eds., The Architecture and Biology of Soils: Life in Inner Space: Wallingford, CAB International, p. 196-215.

Bloch, D., and Hoffmann, C., 2005, Seasonal development of genotypic differences in sugar beet (*Beta vulgaris* L.) and their interaction with water supply: Journal of Agronomy and Crop Science, v. 191, p. 263-272.

Blonquist, J.M., Jones, S.B., and Robinson, D.A., 2005, Standardizing Characterization of Electromagnetic Water Content Sensors: Part 2. Evaluation of Seven Sensing Systems: Vadose Zone Journal, v. 4, p. 1059–1069.

Brantz, D., and Dumpelmann, S., 2011, Greening the City: Urban Landscapes in the Twentieth Century: Charlottesville, University of Virginia Press.

Bratieres, K., Fletcher, T.D., and Deletic, A., 2009, The advantages and disadvantages of a sand-based biofilter medium: results of a new laboratory trial, 6th International Water Sensitive Urban Design Conference and Hydropolis #3: Perth, Australia.

Bratieres, K., Fletcher, T.D., Deletic, A., Somes, N., and Woodcock, T., 2010, Hydraulic and pollutant treatment performance of sand based biofilters, Novatech 2010: 7th International Conference on Sustainable Techniques and Strategies in Urban Water Management: Lyon, France.

Bratieres, K., Fletcher, T.D., Deletic, A., and Zinger, Y., 2008, Nutrient and sediment removal by stormwater biofilters: a large-scale design optimisation study: Water Research, v. 42, p. 3930–3940.

Breen, P., Denman, L., May, P., and Leinster, S., 2004, Street trees as stormwater treatment measures, International Conference on WSUD: Adelaide.

Broadway, M., 2009, Growing urban agriculture in North American cities: The example of Milwaukee: Focus on Geography, v. 52, p. 23–30.

Bureau of Meteorology, 2012, Climate statistics for Australian locations (Melbourne Regional Office), Volume 2012: Melbourne, Bureau of Meteorology.

Burgmans, J.L., Watt, J.P.C., and Bussell, W.T., 1998, Lessons from processing tomato irrigation trials in Hawke's bay, New Zealand: New Zealand Journal of Crop and Horticultural Science, v. 26, p. 307-312.

Burros, M., 2009, Obamas to Plant Vegetable Garden at White House The New York Times: New York, Arthur Ochs Sulzberger, Jr.

Campbell Scientific Inc., 2002, CS616 Water Content Reflectometer Instruction Manual: Logan, Campbell Scientific Inc.

Campos, H., Trejo, C., Pena-Valdivia, C.B., Ramirez-Ayala, C., and Sanchez-Garcia, P., 2009, Effect of partial rootzone drying on growth, gas exchange, and yield of tomato (*Solanum lycopersicum* L.): Scientia Horticulturae, v. 120, p. 493-499.
Cho, Y.Y., Choi, K.Y., and Lee, Y.B., 2010, Effects of irrigation methods on the growth, water holding capacity of substrate and nutrient uptake of lettuce, chicory and endive grown in an extensive green roof system: Horticulture Environment and Biotechnology, v. 51, p. 348-354.
Christen, E.W., Ayars, J.E., Hornbuckle, J., and Hickey, M., 2006, Technology and practice for irrigation in vegetables, Volume Technical Report No.8.: Orange, NSW Deptartment of Primary Industries.
Cockrall-King, J., 2011, Food and the City: Urban Agriculture and the New Food Revolution: Amherst, Prometheus Books.
Coolong, T., Surendran, S., and Warner, R., 2011, Evaluation of irrigation threshold and duration for tomato grown in a silt loam soil: HortTechnology, v. 21, p. 466-473.
Costa, J.M., Ortuño, M.F., and Chaves, M.M., 2007, Deficit irrigation as a strategy to save water: physiology and potential application to horticulture: Journal of Integrative Plant Biology, v. 49, p. 1421–1434.
Cribb, J., 2010, The Coming Famine : The Global Food Crisis and What We Can Do to Avoid It: Berkeley, University of California Press.
CSIRO, 2007, Climate Change in Australia - Technical Report: Melbourne, CSIRO.
Csizinszky, A.A., 2005, Production in the open field, *in* Heuvelink, E., ed., Tomatoes: Wallingford, CABI, p. 237-256.
Czemiel Berndtsson, J., 2010, Green roof performance towards management of runoff water quantity and quality: A review: Ecological Engineering, v. 36, p. 351–360.
Dataflow Systems Pty Ltd, 2010, Technical Handbook for Odyssey Data Logger: Christchurch, Dataflow Systems Pty Ltd.
Davis, A.P., 2007, Field performance of bioretention: Water quality: Environmental Engineering Science, v. 24, p. 1048–1064.
Davis, A.P., 2008, Field performance of bioretention: Hydrology impact: Journal of Hydrologic Engineering, v. 13, p. 90–95.
Davis, A.P., Hunt, W.F., Traver, R.G., and Clar, M., 2009, Bioretention technology: overview of current practice and future needs: Journal of Environmental Engineering, v. 135, p. 109–117.
Davis, A.P., Shokouhian, M., Sharma, H., and Minami, C., 2001, Laboratory study of biological retention for urban storm water management: Water Environment Research, v. 73, p. 5-14.
Davis, A.P., Shokouhian, M., Sharma, H., and Minami, C., 2006, Water quality improvement through bioretention media: Nitrogen and phosphorus removal: Water Environment Research, v. 78, p. 284–293.
Davis, A.P., Shokouhian, M., Sharma, H., Minami, C., and Winogradoff, D., 2003, Water quality improvement through bioretention: Lead, copper, and zinc removal: Water Environment Research, v. 75, p. 73-82.
De Swaef, T., Verbist, K., Cornelis, W., and Steppe, K., 2012, Tomato sap flow, stem and fruit growth in relation to water availability in rockwool growing medium: Plant and Soil, v. 350, p. 237-252.
DeBusk, K., Hunt, W., and Line, D., 2011, Bioretention outflow: Does it mimic nonurban watershed shallow interflow?: Journal of Hydrologic Engineering, v. 16, p. 274–279.
Deek, I.M., Battikhi, A.M., and Khattari, S., 1997, Effect of irrigation and N-fertilization (fertigation) scheduling on tomato in the Jordan Valley: Journal of Agronomy and Crop Science, v. 178, p. 205-209.
Denman, L., May, P., and Breen, P.F., 2006, An investigation of the potential to use street trees and their root zone soils to remove nitrogen from urban stormwater: Australian Journal of Water Resources, v. 10, p. 303–311.
DiBlasi, C.J., Li, H., Davis, A.P., and Ghosh, U., 2009, Removal and fate of polycyclic aromatic hydrocarbon pollutants in an urban stormwater bioretention facility: Environmental Science and Technology, v. 43, p. 494–502.

Dietz, M.E., and Clausen, J.C., 2005, A field evaluation of rain garden flow and pollutant treatment: Water, Air and Soil Pollution, v. 167, p. 123–138.
Dietz, M.E., and Clausen, J.C., 2006, Saturation to improve pollutant retention in a rain garden flow: Environmental Science and Technology, v. 40, p. 1335–1340.
Dixon, J.M., Donati, K.J., Pike, L.L., and Hattersley, L., 2009, Functional foods and urban agriculture: two responses to climate change-related food insecurity: NSW Public Health Bulletin, v. 20, p. 14-18.
Dorji, K., Behboudian, M.H., and Zegbe-Dominguez, J.A., 2005, Water relations, yield, and fruit quality of hot pepper under deficit irrigation and partial rootzone drying: Scientia Horticulturae, v. 104, p. 137–149.
Doube, B.M., Williams, P.M.L., and Willmott, P.J., 1996, The influence of two species of earthworm (Aporrectodea trapezoides and Aporrectoedea rosea) on the growth of wheat, barley and faba beans in three soil types in the greenhouse: Soil Biology and Biochemistry, v. 29, p. 503-509.
Dussaillant, A.R., Cuevas, A., and Potter, K.W., 2005, Raingardens for stormwater infiltration and focused groundwater recharge: simulations for different world climates: Water Science & Technology: Water Supply, v. 5, p. 173-179.
Dussaillant, A.R., Wu, C.H., and Potter, K.W., 2004, Richards equation model of a raingarden: Journal of Hydrologic Engineering, v. 9, p. 219–225.
Edwards, G., 2011, Urban Water Management, *in* Crase, L., ed., Water Policy in Australia: The Impact of Change and Uncertainty: Washington, D.C., RFF Press, p. 144-165.
Elliott, A.H., and Trowsdale, S.A., 2007, A review of models for low impact urban stormwater drainage: Environmental Modelling & Software, v. 22, p. 394-405.
Elstein, J., Welbaum, G.E., Stewart, D.A., and Borys, D.R., 2008, Evaluating growing media for a shallow-rooted vegetable crop production system on a green roof, ISHS Acta Horticulturae 782: IV International Symposium on Seed, Transplant and Stand Establishment of Horticultural Crops; Translating Seed and Seedling Physiology into Technology.
Emerson, C.H., and Traver, R.G., 2008, Multi-year and seasonal variation of infiltration from stormwater best management practices: Journal of Irrigation and Drainage Engineering, v. 134, p. 598–605.
Fabeiro, C., Olalla, F.M.n.d.S., López, R., and Domínguez, A., 2003, Production and quality of the sugar beet (*Beta vulgaris* L.) cultivated under controlled deficit irrigation conditions in a semi-arid climate: Agricultural Water Management, v. 62, p. 215–227.
Fares, A., and Polyakov, V., 2006, Advances in crop water management using capacitance sensors: Advances in Agronomy, v. 90, p. 43–77.
Farrell, C., Mitchell, R.E., Szota, C., Rayner, J.P., and Williams, N.S.G., 2012, Green roofs for hot and dry climates: Interacting effects of plant water use, succulence and substrate: Ecological Engineering, v. 49, p. 270–276.
Farrell, C., Szota, C., Williams, N.S.G., and Arndt, S.K., 2013, High water users can be drought tolerant: using physiological traits for green roof plant selection: Plant and Soil.
FAWB, 2009, Adoption Guidelines for Stormwater Biofiltration Systems: Melbourne, Facility for Advancing Water Biofiltration, Monash University.
Fereres, E., Goldhamer, D.A., and Parsons, L.R., 2003, Irrigation water management of horticultural crops: HortScience, v. 38, p. 1036-1042.
Fereres, E., and Soriano, M.A., 2007, Deficit irrigation for reducing agricultural water use: Journal of Experimental Botany, v. 58, p. 147-159.
Fernandes, C., Cora, J.E., and Araujo, J.A.C.d., 2003, Reference evapotranspiration estimation inside greenhouses: Scientia Agricola, v. 60, p. 591-594.
Foderaro, L.W., 2012, To Find Fields to Farm in New York City, Just Look Up, The New York Times: New York, The New York Times Company.
Gallacher, A.E., and Sprent, J.I., 1978, The effect of different water regimes on growth and nodule development of greenhouse-grown *Vicia faba*: Journal of Experimental Botany, v. 29, p. 413-423.

Gallardo, M., Jackson, L.E., and Thompson, R.B., 1996, Shoot and root physiological responses to localized zones of soil moisture in cultivated and wild lettuce (Lactuca spp): Plant Cell and Environment, v. 19, p. 1169-1178.

Gardiner, A., 2008, E coli running riot in Yarra River, Herald Sun: Melbourne.

Gaynor, A., 2006, Harvest of the Suburbs: An Environmental History of Growing Food in Australian Cities Perth, University of Western Australia Press

Geerts, S., and Raes, D., 2009, Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas: Agricultural Water Management, v. 96, p. 1275–1284.

Getter, K.L., and Rowe, D.B., 2006, The role of extensive green roofs in sustainable development: HortScience, v. 41, p. 1276-1285.

Gilmore, H., 2008, Future farms over our heads, Sydney Morning Herald: Sydney, Fairfax Media.

Goodwin, P.B., Murphy, M., Melville, P., and Yiasoumi, W., 2003, Efficiency of water and nutrient use in containerised plants irrigated by overhead, drip or capillary irrigation: Australian Journal of Experimental Agriculture, v. 43, p. 189-194.

Gorgolewski, M., Komisar, J., and Nasr, J., 2011, Carrot City: Creating Places for Urban Agriculture: New York, Monacelli Press.

Greacen, E.L., Walker, G.R., and Cook, P.G., 1989, Procedure for filter paper method of measuring soil water suction, Volume Division of Soils Report No. 108, CSIRO, Australia.

Gutezeit, B., 2006, Plant mass and yield of broccoli as affected by soil moisture: HortScience, v. 41, p. 113-118.

Hamblin, A.P., 1981, Filter-paper method for routine measurement of field water potential: Journal of Hydrology, v. 53, p. 355-360.

Hamilton, A.J., Stagnitti, F., Xiong, X., Kreidl, S.L., Benke, K.K., and Maher, P., 2007, Wastewater irrigation: the state of play: Vadose Zone Journal, v. 6, p. 823–840.

Hanson, B.R., Orloff, S., and Peters, D., 2000, Monitoring soil moisture helps refine irrigation management: California Agriculture, v. 54, p. 38–42.

Hanson, D., and Marty, E., 2012, Breaking through concrete : building an urban farm revival: Berkeley, University of California Press.

Harmanto, Salokhe, V.M., Babel, M.S., and Tantau, H.J., 2005, Water requirement of drip irrigated tomatoes grown in greenhouse in tropical environment: Agricultural Water Management, v. 71, p. 225-242.

Harris, G.P., and Crossland, C.J., 1999, Introduction to the Port Phillip Bay Environmental Study: Marine Freshwater Research, v. 50, p. iii-iv.

Hatt, B.E., Deletic, A., and Fletcher, T.D., 2007, Stormwater reuse: designing biofiltration systems for reliable treatment: Water Science and Technology, v. 55, p. 201–209.

Hatt, B.E., Fletcher, T.D., and Deletic, A., 2008, Hydraulic and pollutant removal performance of fine media stormwater filtration systems: Environmental Science and Technology, v. 42, p. 2535–2541.

Hatt, B.E., Fletcher, T.D., and Deletic, A., 2009, Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale: Journal of Hydrology, v. 365, p. 310–321.

Hatt, B.E., Siriwardene, N., Deletic, A., and Fletcher, T.D., 2006, Filter media for stormwater treatment and recycling: the influence of hydraulic properties of flow on pollutant removal: Water Science and Technology, v. 54, p. 263–271.

Head, L., and Muir, P., 2007, Backyard: Nature and Culture in Suburban Australia: Wollongong, University of Wollongong Press.

Head, L., Muir, P., and Hampel, E., 2004, Australian backyard gardens and the journey of migration: Geographical Review, v. 94, p. 326–347.

Heasom, W., Traver, R., and Welker, A., 2006, Hydrologic modeling of a bioinfiltration best management practice: Journal of the American Water Resources Association, v. 42, p. 1329–1347.

Hegde, D.M., 1987, Effect of soil matric potential, method of irrigation and nitrogen fertilization on yield, quality, nutrient uptake and water use of radish (*Raphanus sativus* L.): Irrigation Science, v. 8, p. 13-22.

Henderson, C., Greenway, M., and Phillips, I., 2007, Removal of dissolved nitrogen, phosphorous and carbon from stormwater by biofiltration mesocosms: Water Science and Technology, v. 55, p. 183-191.
Heuvelink, E., 2005, Developmental processes, *in* Heuvelink, E., ed., Tomatoes: Wallingford, CABI, p. 53-83.
Hong, E., Seagren, E.A., and Davis, A.P., 2006, Sustainable oil and grease removal from synthetic storm water runoff using bench-scale bioretention studies: Water Environment Research, v. 78, p. 141-155.
Howe, C., Jones, R.N., Maheepala, S., and Rhodes, B., 2005, Melbourne Water climate change study: Implications of potential climate change for Melbourne's water resources: Melbourne, CSIRO.
Hsieh, C.-H., and Davis, A.P., 2005a, Evaluation and optimization of bioretention media for treatment of urban storm water runoff: Journal of Environmental Engineering, v. 131, p. 1521–1531.
Hsieh, C.-H., and Davis, A.P., 2005b, Multiple-event study of bioretention for treatment of urban storm water runoff: Water Science and Technology, v. 51, p. 177–181.
Hsieh, C.-H., Davis, A.P., and Needelman, B.A., 2007, Bioretention column studies of phosphorus removal from urban stormwater runoff: Water Environment Research, v. 79, p. 177–184.
Hunt, W.F., Jarrett, A.R., Smith, J.T., and Sharkey, L.J., 2006, Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina: Journal of Irrigation and Drainage Engineering, v. 132, p. 600–608.
Hunt, W.F., Smith, J.T., Jadlocki, S.J., Hathaway, J.M., and Eubanks, P.R., 2008, Pollutant removal and peak flow mitigation by a bioretention cell in urban Charlotte, NC: Journal of Environmental Engineering, v. 134, p. 403-408.
Husain, M.M., Hill, G.D., and Gallagher, J.N., 1988, The response of field beans (*Vicia faba* L.) to irrigation and sowing date: 1. Yield and yield components: Journal of Agricultural Science, v. 111, p. 221-232.
Incrocci, L., Malorgio, F., Bartola, A.D., and Pardossi, A., 2006, The influence of drip irrigation or subirrigation on tomato grown in closed-loop substrate culture with saline water: Scientia Horticulturae, v. 107, p. 365–372.
Ityel, E., Lazarovitch, N., Silberbush, M., and Ben-Gal, A., 2012, An artificial capillary barrier to improve root-zone conditions for horticultural crops: response of pepper, lettuce, melon, and tomato: Irrigation Science, v. 30, p. 293-301.
James, M.B., and Dymond, R.L., 2011, Case study: bioretention hydrologic performance in an urban stormwater network: Journal of Hydrologic Engineering v. doi:10.1061/(ASCE)HE.1943-5584.0000448.
Janoudi, A.K., and Widders, I.E., 1993, Water deficits and fruiting affect carbon assimilation and allocation in cucumber plants: HortScience, v. 28, p. 98-100.
Jones, H.G., 2004, Irrigation scheduling: advantages and pitfalls of plant-based methods: Journal of Experimental Botany, v. 55, p. 2427–2436.
Kadayifci, A., Tuylu, G.I., Ucar, Y., and Cakmak, B., 2005, Crop water use of onion (*Allium cepa* L.) in Turkey: Agricultural Water Management, v. 72, p. 59-68.
Kelleners, T.J., Seyfried, M.S., Blonquist, J.M., Bilskie, J., and Chandler, D.G., 2005, Improved interpretation of water content reflectometer measurements in soils: Soil Science Society of America Journal, v. 69, p. 1684-1690.
Kim, H., Seagren, E.A., and Davis, A.P., 2003, Engineered bioretention for removal of nitrate from stormwater runoff: Water Environment Research, v. 75, p. 355–367.
Kirda, C., Cetin, M., Dasgan, Y., Topcu, S., Kaman, H., Ekici, B., Derici, M.R., and Ozguven, A.I., 2004, Yield reponse of greenhouse grown tomato to partial root drying and conventional deficit irrigation: Agricultural Water Management, v. 69, p. 191–202.
Kirnak, H., and Demirtas, M.N., 2006, Effects of different irrigation regimes and mulches on yield and macronutrition levels of drip-irrigated cucumber under open field conditions: Journal of Plant Nutrition, v. 29, p. 1675–1690.
Kiziloglu, F.M., Sahin, U., Angin, I., and Anapali, O., 2006, The effect of deficit irrigation on water-yield relationship of sugar beet (*Beta vulgaris* L.) under cool season and semi-arid climatic conditions: International Sugar Journal, v. 108, p. 90-94.

Lambers, H., Chapin III, F.S., and Pons, T.L., 2008, Plant Physiological Ecology: New York, Springer.
Lavelle, M., 2011, Sustainable Gardening: Ramsbury, Crowood Press.
Leskovar, D.I., Agehara, S., Yoo, K., and Pascual-Seva, N., 2012, Crop coefficient-based deficit irrigation and planting density for onion: Growth, yield, and bulb quality: HortScience, v. 47, p. 31-37.
Li, H., and Davis, A.P., 2008a, Heavy metal capture and accumulation in bioretention media: Environmental Science and Technology, v. 42, p. 5247–5253.
Li, H., and Davis, A.P., 2008b, Urban particle capture in bioretention media. I: Laboratory and field studies: Journal of Environmental Engineering, v. 134, p. 409–418.
Li, H., and Davis, A.P., 2008c, Urban particle capture in bioretention media. II: Theory and model development: Journal of Environmental Engineering, v. 134, p. 419–432.
Li, H., Sharkey, L.J., Hunt, W.F., and Davis, A.P., 2009, Mitigation of impervious surface hydrology using bioretention in North Carolina and Maryland: Journal of Hydrologic Engineering, v. 14, p. 407–415.
Line, D.E., and White, N.M., 2007, Effects of development on runoff and pollutant export: Water Environment Research v. 79, p. 185–190.
Lloyd, S.D., Wong, T.H.F., and Porter, B., 2002, The planning and construction of an urban stormwater management scheme: Water Science and Technology, v. 45, p. 1–10.
Locascio, S.J., 2005, Management of irrigation for vegetables: past, present, and future: HortTechnology, v. 15, p. 482-485.
Lopez-Urrea, R., Montoro, A., Lopez-Fuster, P., and Fereres, E., 2009, Evapotranspiration and responses to irrigation of broccoli: Agricultural Water Management, v. 96, p. 1155-1161.
Lucas, W.C., and Greenway, M., 2008, Nutrient retention in vegetated and nonvegetated bioretention mesocosms: Journal of Irrigation and Drainage Engineering, v. 134, p. 613–623.
Mao, X., Liu, M., Wang, X., Liu, C., Hou, Z., and Shi, J., 2003, Effects of deficit irrigation on yield and water use of greenhouse grown cucumber in the North China Plain: Agricultural Water Management, v. 61, p. 219-228.
Marouelli, W., and Silva, W., 2007, Water tension thresholds for processing tomatoes under drip irrigation in Central Brazil: Irrigation Science, v. 25, p. 411–418.
Mason, J., 2005, Growing and Using Vegetables and Herbs: Sydney, Kangaroo Press.
Maunsell Australia Pty Ltd., 2008, Climate Change Adaptation Strategy: Melbourne, City of Melbourne.
Mazer, G., Booth, D., and Ewing, K., 2001, Limitations to vegetation establishment and growth in biofiltration swales: Ecological Engineering, v. 17, p. 429-443.
McCarthy, D., Deletic, A., and Fletcher, T., 2008, New technologies for mitigating risks of stormwater reuse, Volume Milestone Report: Melbourne, Monash University.
McGiffen, M.E., Masiunas, J.B., and Huck, M.G., 1992, Tomato and nightshade (*Solanum nigrum* L. and *S. ptycanthum* Dun.) effects on soil water content: Journal of the American Society for Horticultural Science, v. 117, p. 730-735.
McQuire, S., 2008, Water Not Down the Drain: A Guide to Using Rainwater and Greywater at Home: Melbourne, Alternative Technology Association.
Melbourne Water, 2010a, Instruction Sheet: Building a Raingarden, Inground (Lined): Melbourne, Melbourne Water.
Melbourne Water, 2010b, Instruction Sheet: Building a Raingarden, Planter Box (Lined): Melbourne, Melbourne Water.
Melbourne Water, 2010c, Instruction Sheet: Building an Infiltration Raingarden: Melbourne, Melbourne Water.
Melbourne Water, 2010d, What is a raingarden? - Frequently asked questions, Volume 2013: Melbourne, Melbourne Water.
Melbourne Water, 2011a, Stormwater, Volume 2012: Melbourne, Melbourne Water.
Melbourne Water, 2011b, Thomson passes 50% full, Volume 2011: Melbourne, Melbourne Water.

Melbourne Water, 2012, Instruction Sheet: Downpipe diversion: Melbourne, Melbourne Water.
Mentens, J., Raes, D., and Hermy, M., 2006, Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?: Landscape and Urban Planning, v. 77, p. 217–226.
Mingo, D.M., Theobald, J.C., Bacon, M.A., Davies, W.J., and Dodd, I.C., 2004, Biomass allocation in tomato (*Lycopersicum esculentum*) plants grown under partial rootzone drying: enhancement of root growth: Functional Plant Biology, v. 31, p. 971–978.
Misra, R.K., Patel, J.H., and Baxi, V.R., 2010, Reuse potential of laundry greywater for irrigation based on growth, water and nutrient use of tomato: Journal of Hydrology, v. 386, p. 95–102.
Monti, A., Brugnoli, E., Scartazza, A., and Amaducci, M.T., 2006, The effect of transient and continuous drought on yield, photosynthesis and carbon isotope discrimination in sugar beet (*Beta vulgaris* L.): Journal of Experimental Botany, v. 57, p. 1253-1262.
Muñoz-Carpena, R., Dukes, M.D., Li, Y.C., and Klassen, W., 2005, Field comparison of tensiometer and granular matrix sensor automatic drip irrigation of tomato: HortTechnology, v. 15, p. 584–590.
Murray, A.G., and Parslow, J.S., 1999, Modelling of nutrient impacts in Port Phillip Bay — a semi-enclosed marine Australian ecosystem: Marine and Freshwater Research, v. 50, p. 597 - 612.
Muthanna, T.M., Viklander, M., Blecken, G., and Thorolfsson, S.T., 2007, Snowmelt pollutant removal in bioretention areas: Water Research, v. 41, p. 4061–4072.
Nishihara, E., Inoue, M., Kondo, K., Takahashi, K., and Nakata, N., 2001, Spinach yield and nutritional quality affected by controlled soil water matric head: Agricultural Water Management, v. 51, p. 217-229.
Nuruddin, M.M., Madramootoo, C.A., and Dodds, G.T., 2003, Effects of water stress at different growth stages on greenhouse tomato yield and quality: HortScience, v. 38, p. 1389-1393.
Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R.R., Doshi, H., Dunnett, N., Gaffin, S., Kohler, M., Liu, K.K.Y., and Rowe, B., 2007, Green roofs as urban ecosystems: Ecological structures, functions, and services: BioScience, v. 57, p. 823-833.
Obreza, T.A., Pitts, D.J., McGovern, R.J., and Spreen, T.H., 1996, Deficit irrigation of micro-irrigated tomato affects yield, fruit quality, and disease severity: Journal of Production Agriculture, v. 9, p. 270-275.
Oliveira, M.D.G., Calado, A.M., and Portas, C.A.M., 1996, Tomato root distribution under drip irrigation: Journal of the American Society for Horticultural Science, v. 121, p. 644-648.
Ouellette, N.A., Walters, S.A., and Midden, K.S., 2012, Fertility management for vegetables on an extensive green roof, CitiesAlive!: 10th Annual Green Roof and Wall Conference: Chicago.
Palla, A., Gnecco, I., and Lanza, L.G., 2011, Non-dimensional design parameters and performance assessment of rainwater harvesting systems: Journal of Hydrology, v. 401, p. 65-76.
Paul, M.J., and Meyer, J.L., 2001, Streams in the urban landscape: Annual Review of Ecology and Systematics, v. 32, p. 333–365.
Peet, M.M., 2005, Irrigation and fertilization, *in* Heuvelink, E., ed., Tomatoes: Wallingford, CABI, p. 171-198.
Peet, M.M., and Welles, G., 2005, Greenhouse tomato production, *in* Heuvelink, E., ed., Tomatoes: Wallingford, CABI, p. 257-304.
Peet, M.M., and Willits, D.H., 1995, Role of excess water in tomato fruit cracking: HortScience, v. 30, p. 65-68.
Pelter, G.Q., Mittelstadt, R., Leib, B.G., and Redulla, C.A., 2004, Effects of water stress at specific growth stages on onion bulb yield and quality: Agricultural Water Management, v. 68, p. 107-115.
Petropoulos, S.A., Daferera, D., Polissiou, M.G., and Passam, H.C., 2008, The effect of water deficit stress on the growth, yield and composition of essential oils of parsley: Scientia Horticulturae, v. 115, p. 393–397.

Peverill, K., and Premier, R., 2006, Reclaimed Water Use in Victoria, *in* Stevens, D., ed., Growing Crops with Reclaimed Wastewater: Collingwood, CSIRO Publishing, p. 15-19.

Pires, R.C.D., Furlani, P.R., Ribeiro, R.V., Bodine, D., Sakai, E., Lourencao, A.L., and Neto, A.T., 2011, Irrigation frequency and substrate volume effects in the growth and yield of tomato plants under greenhouse conditions: Scientia Agricola, v. 68, p. 400-405.

Pitts, D.J., Tsai, Y.J., Myhre, D.L., and Obreza, T.A., 1991, Irrigation frequency and depth to the water table effects on drip irrigated tomatoes: Soil and Crop Science Society of Florida Proceedings, v. 50, p. 12-17.

Plauborg, F., Iversen, B.V., and Lærke, P.E., 2005, In Situ Comparison of Three Dielectric Soil Moisture Sensors in Drip Irrigated Sandy Soils: Vadose Zone Journal, v. 4, p. 1037-1047.

Pollock, M., 2004, Fruit and Vegetable Gardening in Australia: Camberwell, Dorling Kindersley.

Poorter, H., and Nagel, O., 2000, The role of biomass allocation in the growth response of plants to different levels of light, $CO_2$, nutrients and water: a quantitative review: Functional Plant Biology, v. 27, p. 595-607.

Poulter, S., 2007, World War Two vegetable comes back as 'superfood', The Daily Mail: London, Associated Newspapers Ltd.

Pulupol, L.U., Behboudian, M.H., and Fisher, K.J., 1996, Growth, yield, and postharvest attributes of glasshouse tomatoes produced under deficit irrigation: HortScience, v. 31, p. 926–929.

Qassim, A., and Ashcroft, B., 2006, Irrigation scheduling for vegetable crops, Agriculture Notes: Tatura, Department of Primary Industries.

Quinones, H., Ruelle, P., and Nemeth, I., 2003, Comparison of three calibration procedures for TDR soil moisture sensors: Irrigation and Drainage, v. 52, p. 203-217.

Raina, J.N., Thakur, B.C., and Verma, M.L., 1999, Effect of drip irrigation and polyethylene mulch on yield, quality and water-use efficiency of tomato (*Lycopersicon esculentum*): Indian Journal of Agricultural Sciences, v. 69, p. 430-433.

Raymont, G., and Lyons, D., 2010, Soil Chemical Methods – Australasia: Melbourne, CSIRO Publishing.

Read, J., Fletcher, T.D., Wevill, T., and Deletic, A., 2009, Plant traits that enhance pollutant removal from stormwater in biofiltration systems: International Journal of Phytoremediation, v. 12, p. 34-53.

Read, J., Wevill, T., Fletcher, T., and Deletic, A., 2008, Variation among plant species in pollutant removal from stormwater in biofiltration systems: Water Research, v. 42, p. 893-902.

Reid, J.B., and Renquist, A.R., 1997, Enhanced root production as a feed-forward response to soil water deficit in field-grown tomatoes: Australian Journal of Plant Physiology, v. 24, p. 685-692.

Rüdiger, C., Western, A.W., Walker, J.P., Smith, A.B., Kalma, J.D., and Willgoose, G.R., 2010, Towards a general equation for frequency domain reflectometers: Journal of Hydrology, v. 383, p. 319-329.

Rusciano, G.M., and Obropta, C.C., 2007, Bioretention column study: Fecal coliform and total suspended solids reduction: Transactions of the ASABE, v. 50, p. 1261–1269.

Rytter, R.M., 2005, Water use efficiency, carbon isotope discrimination and biomass production of two sugar beet varieties under well-watered and dry conditions: Journal of Agronomy and Crop Science, v. 191, p. 426-438.

Saltveit, M.E., 2005, Fruit ripening and fruit quality, *in* Heuvelink, E., ed., Tomatoes: Wallingford, CABI, p. 145-170.

Sanchez, C.A., 2000, Response of lettuce to water and nitrogen on sand and the potential for leaching of nitrate-N: HortScience, v. 35, p. 73-77.

Santamaria, P., Campanile, G., Parente, A., and Elia., A., 2003, Subirrigation vs drip-irrigation: effects on yield and quality of soilless grown cherry tomato: Journal of Horticultural Science and Biotechnology, v. 78, p. 290–296.

Saure, M.C., 2001, Blossom-end rot of tomato (Lycopersicon esculentum Mill.) — a calcium- or a stress-related disorder?: Scientia Horticulturae, v. 90, p. 193-208.
Savic, S., Liu, F., Stikic, R., Jacobsen, S.E., Jensen, C.R., and Jovanovic, Z., 2009, Comparative effects of partial rootzone drying and deficit irrigation on growth and physiology of tomato plants: Archives of Biological Sciences, v. 61, p. 801-810.
Selen, S.M., Akyildiz, A., Dasgan, H.Y., and Gencel, B., 2008, Yield and quality response of drip irrigated green beans under full and deficit irrigation: Scientia Horticulturae, v. 117, p. 95-102.
Sezen, S.M., Yazar, A., and Eker, S., 2006, Effect of drip irrigation regimes on yield and quality of field grown bell pepper: Agricultural Water Management, v. 81, p. 115-131.
Singh, R., Kumar, S., Nangare, D.D., and Meena, M.S., 2009, Drip irrigation and black polyethylene mulch influence on growth, yield and water-use efficiency of tomato: African Journal of Agricultural Research, v. 4, p. 1427-1430.
Smajstrla, A.G., and Locascio, S.J., 1996, Tensiometer-controlled drip irrigation scheduling of tomato: Applied Engineering in Agriculture, v. 12, p. 315-319.
Sorensen, J.N., Johansen, A.S., and Kaack, K., 1995, Marketable and nutritional quality of leeks as affected by water and nitrogen supply and plant-age at harvest: Journal of the Science of Food and Agriculture, v. 68, p. 367-373.
Sponchiado, B.N., White, J.W., Castillo, J.A., and Jones, P.G., 1989, Root growth of four common bean cultivars in relation to drought tolerance in environments with contrasting soil types: Experimental Agriculture, v. 25, p. 249-257.
Sun, X., and Davis, A.P., 2007, Heavy metal fates in laboratory bioretention systems: Chemosphere, v. 66, p. 1601–1609.
Sun, Y.Q., Feng, H., and Liu, F.L., 2013, Comparative effect of partial root-zone drying and deficit irrigation on incidence of blossom-end rot in tomato under varied calcium rates: Journal of Experimental Botany, v. 64, p. 2106-2116.
Tahi, H., Wahbi, S., Wakrim, R., Aganchich, B., Serraj, R., and Centritto, M., 2007, Water relations, photosynthesis, growth and water-use efficiency in tomato plants subjected to partial rootzone drying and regulated deficit irrigation: Plant Biosystems, v. 141, p. 265-274.
Tan, C.S., 1993, Tomato yield-evapotranspiration relationships, seasonal canopy temperature and stomatal conductance as affected by irrigation: Canadian Journal of Plant Science, v. 73, p. 257-264.
Taylor, G.D., Fletcher, T.D., Wong, T.H.F., Breen, P.F., and Duncan, H.P., 2005, Nitrogen composition in urban runoff—implications for stormwater management: Water Research, v. 39, p. 1982–1989.
Taylor, M.D., Locascio, S.J., and Alligood, M.R., 2004, Blossom-end rot incidence of tomato as affected by irrigation quantity, calcium source, and reduced potassium: Hortscience, v. 39, p. 1110-1115.
Thompson, R.B., Gallardo, M., Valdez, L.C., and Fernández, M.D., 2007, Using plant water status to define threshold values for irrigation management of vegetable crops using soil moisture sensors: Agricultural Water Management, v. 88, p. 147-158.
Tom, M., Richards, P.J., McCarthy, D.T., Fletcher, T.D., Farrell, C., Williams, N.S.G., and Milenkovic, K., 2013, Turning (storm)water into food; the benefits and risks of vegetable raingardens (*Evaluation des performances et des risques d'un jardin de pluie potager*), *in* Bertrand-Krajewski, J.-L., and Fletcher, T.D., eds., 8th International Novatech Conference, 23-27th June 2013: Lyon, France, GRAIE.
Tomar, P., and Suthar, S., 2011, Urban wastewater treatment using vermi-biofiltration system: Desalination, v. 282, p. 95–103.
Torrecillas, A., Guillaume, C., Alarcon, J.J., and Ruizsanchez, M.C., 1995, Water relations of two tomato species under water-stress and recovery: Plant Science, v. 105, p. 169-176.
Trowsdale, S.A., and Simcock, R., 2011, Urban stormwater treatment using bioretention: Journal of Hydrology, v. 397, p. 167-174.
Tsabedze, M.W., and Wahome, P.K., 2010, Influence of different irrigation regimes on production of lettuce (*Lactuca sativa* L.): American-Eurasian Journal of Agricultural and Environmental Sciences, v. 8, p. 233-238.

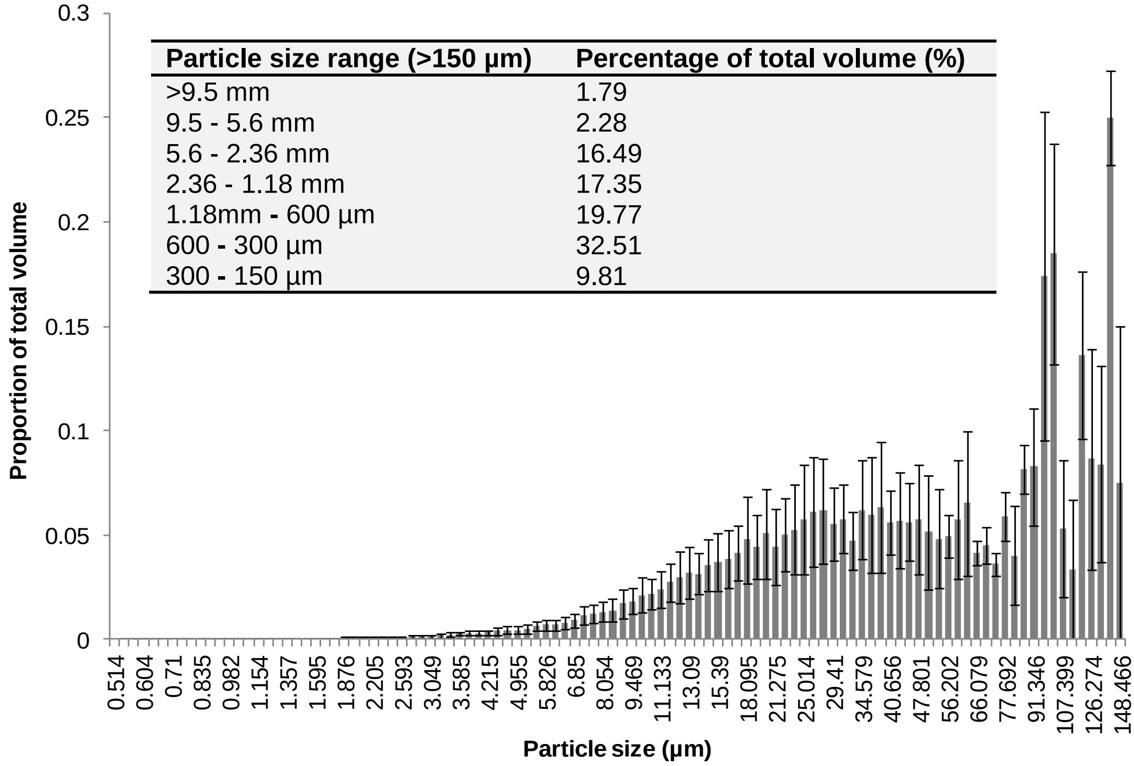
Vaes, G., and Berlamont, J., 2001, The effect of rainwater storage tanks on design storms: Urban Water, v. 3, p. 303–307.
Vamerali, T., Guarise, M., Ganis, A., and Mosca, G., 2009, Effects of water and nitrogen management on fibrous root distribution and turnover in sugar beet: European Journal of Agronomy, v. 31, p. 69-76.
Vitiello, D., 2008, Growing Edible Cities, *in* Birch, E.L., and Wachter, S.M., eds., Growing Greener Cities: Urban Sustainability in the Twenty-First Century: Philadelphia, University of Pennsylvania Press, p. 259-278.
Wan, S.Q., and Kang, Y.H., 2006, Effect of drip irrigation frequency on radish (*Raphanus sativus* L.) growth and water use: Irrigation Science, v. 24, p. 161-174.
Wang, Y.S., Liu, F.L., Andersen, M.N., and Jensen, C.R., 2010, Carbon retention in the soil-plant system under different irrigation regimes: Agricultural Water Management, v. 98, p. 419-424.
Western, A.W., and Seyfried, M.S., 2005, A calibration and temperature correction procedure for the water-content reflectometer: Hydrological Processes, v. 19, p. 3785-3793.
Wheeler, A.P., Angermeier, P.L., and Rosenberger, A.E., 2005, Impacts of new highways and subsequent landscape urbanization on stream habitat and biota: Reviews in Fisheries Science, v. 13, p. 141–164.
Whittinghill, L.J., and Rowe, D.B., 2011, The role of green roof technology in urban agriculture: Renewable Agriculture and Food Systems, v. 27, p. 314-322.
Whittinghill, L.J., Rowe, D.B., and Cregg, B.M., 2012, Vegetable production on extensive green roofs, CitiesAlive!: 10th Annual Green Roof and Wall Conference: Chicago.
Whittinghill, L.J., Rowe, D.B., and Cregg, B.M., 2013, Evaluation of vegetable production on extensive green roofs: Agroecology and Sustainable Food Systems, v. 37, p. 465-484.
Wilkinson, M.T., Richards, P.J., and Humphreys, G.S., 2009, Breaking ground: pedological, geological, and ecological implications of soil bioturbation: Earth-Science Reviews, v. 97, p. 257-272.
Williams, E.S., and Wise, W.R., 2006, Hydrologic impacts of alternative approaches to storm water management and land development: Journal of the American Water Resources Association, v. 42, p. 433–455.
Wright, A., 2012, Melbourne's Yarra River a filthy mess, Herald Sun: Melbourne, The Herald and Weekly Times.
Wright, E., Carr, M.K.V., and Hamer, P.J.C., 1997, Crop production and wateruse. IV. Yield functions for sugar beet: Journal of Agricultural Science, v. 129, p. 33–42.
Xia, M.Z., 1994, Effects of drought during the generative development phase of faba bean (*Vicia faba*) on photosynthetic characteristics and biomass production: Journal of Agricultural Science, v. 122, p. 67–72.
Yuan, B.Z., Sun, J., Kang, Y.H., and Nishiyama, S., 2006, Response of cucumber to drip irrigation water under a rainshelter: Agricultural Water Management, v. 81, p. 145-158.
Zegbe, J.A., Behboudiana, M.H., and Clothier, B.E., 2004, Partial rootzone drying is a feasible option for irrigating processing tomatoes: Agricultural Water Management, v. 68, p. 195-206.
Zhang, Q.T., Ahmed, O.A.B., Inoue, M., Saxena, M.C., Inosako, K., and Kondo, K., 2009a, Effects of mulching on evapotranspiration, yield and water use efficiency of Swiss chard (*Beta vulgaris* L. var. flavescens) irrigated with diluted seawater: Journal of Food Agriculture & Environment, v. 7, p. 650-654.
Zhang, Q.T., Inoue, M., Inosako, K., Irshad, M., Kondo, K., Qiu, G.Y., and Wang, S.P., 2008, Ameliorative effect of mulching on water use efficiency of Swiss chard and salt accumulation under saline irrigation: Journal of Food Agriculture & Environment, v. 6, p. 480-485.
Zhang, Y., Chen, D.H., Chen, L., and Ashbolt, S., 2009b, Potential for rainwater use in highrise buildings in Australian cities: Journal of Envionmental Management, v. 91, p. 222–226.

## APPENDICES

### Appendix A: Soil nutrient levels and particle size distribution (field trial)

**Table AA-1: Nutrient levels in a sample of the field trial ("Five Way") soil in 2012. The sample was collected by Minna Tom (Monash University) and measurements were made by ALS Limited.**

| Parameter | | Concentration (mg kg$^{-1}$) |
|---|---|---|
| Nitrogen oxides (NOx) | | 270 |
| Total Kjeldahl nitrogen (TKN) | | 4000 |
| Total nitrogen (TN) | | 4200 |
| Phosphorus (P) cations | | 1900 |
| Total petroleum hydrocarbon (TPH) | C6-C10 | <20 |
| | C10-C14 | 84 |
| | C15-C28 | 530 |
| | C29-C36 | 340 |
| Total recoverable hydrocarbons (TRH) | C10-C16 | <20 |
| | C16-C34 | 780 |
| | C34-C40 | 140 |
| Total phenols | | <30 |
| Total organic carbon | | 78000 |




| Particle size range (>150 µm) | Percentage of total volume (%) |
|---|---|
| >9.5 mm | 1.79 |
| 9.5 - 5.6 mm | 2.28 |
| 5.6 - 2.36 mm | 16.49 |
| 2.36 - 1.18 mm | 17.35 |
| 1.18mm - 600 µm | 19.77 |
| 600 - 300 µm | 32.51 |
| 300 - 150 µm | 9.81 |

**Figure AA-1: Particle size distribution in a <150 µm sample of the field trial ("Five Way") soil, measured using an AccuSizer Autodiluter AD. Error bars represent standard error (n = 3). INSET: Table showing particle size distribution for size ranges >150 µm, measured by sieving and weighing (Australian Standards AS 1289.3.6.1 2009). All measurements were made by Minna Tom (Monash University).**

## Appendix B: Method for measuring soil water holding capacity

Water holding capacity was determined by following the Air-Filled Porosity (AFP) procedure described in the Australian Standard for Potting Mixes (AS 3743-2003). In this procedure, a known volume of soil is immersed in water for a specified time and then removed and drained multiple times. The volume of water that drains from the soil is measured and expressed as a percentage of the total volume, to give air-filled porosity. The soil is then dried and the total water holding capacity is calculated as the difference between the wet and dry mass.

*Pre-treatment of soil*

The only pre-treatment required for this test is that the soil should be moistened, unless already in a moist condition, so that the water content is about 50% at 24 hours before testing. For the field trial, samples for measuring the water holding capacity of the soil were taken directly from each of the four gardens in October 2011 and then pooled. For the greenhouse experiment, both the potting mix and the loamy sand were tested using this procedure. The potting mix and loamy sand were watered to field capacity approximately 40 hours before testing. For all three soils, there were three replicates.

*Setup*

A purpose-made apparatus was prepared; three were required, for the procedure to be conducted for the three replicates simultaneously. This consisted of two 12 cm sections of stormwater pipe, with one of the sections (the top section) splayed so that it could be joined to the other. The base of the other section (the bottom section) was fitted with a watertight cap, into which four drainage holes were drilled. The volume of the bottom section was recorded, and this volume was assumed to be the “volume of soil” in the analysis.

A piece of nylon gauze was put in the base of the bottom section of the apparatus, so that it prevented soil loss from the drainage holes. The apparatus, with its top and bottom sections joined together, was completely filled with the soil (field trial soil, potting mix, or loamy sand), up to the top of the top section. Any excess soil was scraped off at the top. The apparatus was dropped from a height of approximately 5 cm, for a “free fall” under gravity. This was done five times, and the apparatus was refilled with soil until full. The top of the apparatus was then securely covered by nylon gauze, which was fixed with an elastic band. At the outset, the weight of a designated aluminium tray (for soil) and a 2 L container with four test tube lids (for drained water) was recorded for each replicate.

*Initial wetting and draining*

A bucket was filled with enough water to reach above the top of the *bottom section* of the apparatus, and the apparatus (both sections) was lowered into the bucket whilst being kept vertical. When the apparatus had taken up enough water to be able to stand vertically in the bucket unsupported, the water level in the bucket was raised so that it was in line with the very top of the apparatus, but no higher (Figure AB-1). The apparatus was left in the water for 30 minutes. Upon removal, it was allowed to drain for 5 minutes on a large rectangular plastic tray (Figure AB-1). This drained water was discarded. After this time, the apparatus was re-submerged in the water for 10 minutes, drained for 5 minutes, re-submerged for another 10 minutes, and then drained for another 5 minutes; i.e. there were three wetting and draining cycles. This procedure could be conducted on three replicates simultaneously, with a staggered start, at intervals of exactly 10 minutes.

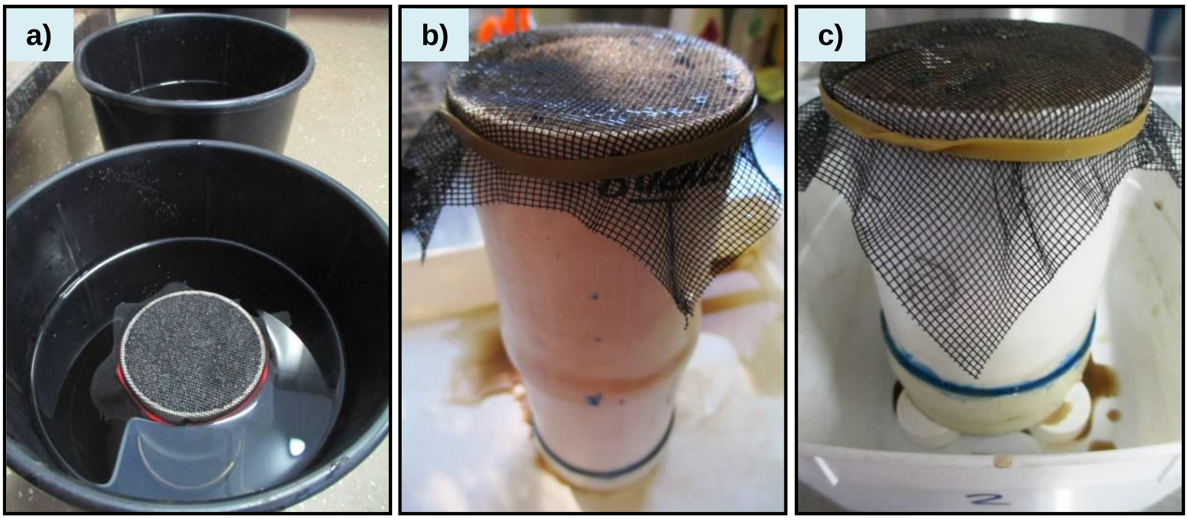



**Figure AB-1: The main stages of the AFP procedure: a) Soaking the apparatus, b) draining the apparatus (both sections, viewed from above), and c) draining the bottom section only.**

*Soaking and draining of bottom section only*

Subsequently, the upper half of the apparatus was removed, along with the upper section of the soil. This was done in a “slicing” motion, without exerting downward pressure on the bottom section. The soil in the upper section was discarded. The top of the bottom section of the apparatus was then covered with the nylon gauze and resubmerged, with the water level adjusted accordingly, to approximately half of the previous level. After two minutes, the apparatus was removed from the water for the final time, and on this occasion the drainage holes in the base were covered, using four fingers, so that no or minimal water was lost. The apparatus was held above the bucket for 20 seconds, and then allowed to drain into a 2 L container for 30 minutes (Figure AB-1). In this container, four test tube lids of equal size were used to elevate the apparatus

The base of the apparatus was removed from the container, and the drained water in the container was weighed. For verification, the volume of drained water was also measured using a measuring cylinder. The drained water was then discarded. All of the wet soil in the base of the apparatus was removed and weighed in a separate tin. The wet soil was dried in an oven at 105°C until it reached a constant mass (approximately 6 days), and then weighed immediately.

Using these weights of water and soil, it was possible to calculate water holding capacity (WHC), air-filled porosity (AFP), and bulk density for the field trial soil (Table AB-1). For the field trial soil, bulk density was verified in November 2011 by sampling the soil in each of the four gardens using a stainless steel ring of known volume (Table AB-2).

**Table AB-1: Calculations of field trial soil properties from the results of the AFP procedure (three replicates).**

| | | Sample number | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | Mean | Standard Error |
| **Field trial soil** | **WHC (%)[a]** | 55.8 | 58.8 | 56.1 | **56.9** | **0.6** |
| | **AFP (%)[b]** | 5.7 | 7.2 | 6.0 | **6.3** | **0.3** |
| | **BD ($g/cm^3$)[c]** | 0.54 | 0.63 | 0.57 | **0.58** | **0.015** |
| **Greenhouse potting mix** | **WHC (%)[a]** | 54.4 | 52.9 | 54.6 | **54.0** | **0.5** |
| | **AFP (%)[b]** | 7.8 | 10.6 | 9.5 | **9.3** | **0.3** |
| | **BD ($g/cm^3$)[c]** | 0.47 | 0.46 | 0.48 | **0.47** | **0.003** |
| **Greenhouse loamy sand** | **WHC (%)[a]** | 27.0 | 26.2 | 25.8 | **26.3** | **0.1** |
| | **AFP (%)[b]** | 0.4 | 0.7 | 0.8 | **0.6** | **0.2** |
| | **BD ($g/cm^3$)[c]** | 1.62 | 1.66 | 1.62 | **1.63** | **0.007** |

[a] WHC = (mass of drained(wet) soil – mass of dry soil) × 100 / volume of soil
[b] AFP = (weight of drained water / volume of soil) × 100
[c] Bulk Density = dry weight of soil / volume of soil

**Table AB-2: Results of separate bulk density analysis of the field trial soil in November 2011.**

| Sample (Garden) | Wet weight (g) | Dry weight (g) | Bulk density ($g/cm^3$) |
|---|---|---|---|
| **Potable control** | 333.6 | 199.7 | 0.62 |
| **Tank control** | 352.0 | 206.6 | 0.64 |
| **Unlined raingarden** | 329.4 | 200.8 | 0.62 |
| **Lined raingarden** | 340.6 | 211.8 | 0.66 |

**Appendix C: Method for measuring soil matric potential**

This procedure for measuring soil matric potential is based on the protocol described by Greacen et al (1989). In this method, filter paper is used to absorb water from the soil. The "matric potential" (see section 1.5.2.2) of the substrate is then determined from the water content of the filter paper.

For sample preparation, samples of the field trial soil and greenhouse experiment soils were oven-dried at 105°C to constant mass. The dried soil was separated into 42 tins, each containing 50 g (for the field trial soil and greenhouse experiment potting mix) or 100 g (for the greenhouse experiment loamy sand) of soil, and these tins were paired up (21 pairs). Additionally, 21 Whatman No.42 ashless filter papers (55 mm diameter) were oven-dried at 105°C for 30 minutes. Using the water holding capacity data (from the procedure described in Appendix B), distilled water was added to each pair of 50 g lots to make up different percentages of the water content (as Table AC-1), where 100% was the mean value for water holding capacity determined through the AFP procedure. For the field trial soil, for example, this was 56.9. Each sample was mixed well.

For each of the 21 samples, the first 50 g (field trial soil and potting mix) or 100 g (loamy sand) of soil was gently packed into a glass jar. A single filter paper was placed on top of this soil, so that it was not in contact with the sides of the jar, and the other 50 g or 100 g of soil was placed and packed on top (Figure AC-1). The jar was closed and sealed with electrical tape (field trial) or thermoplastic laboratory film (greenhouse experiment) to avoid water loss. All 21 jars were then placed into an insulated polystyrene box for one week to achieve equilibrium.

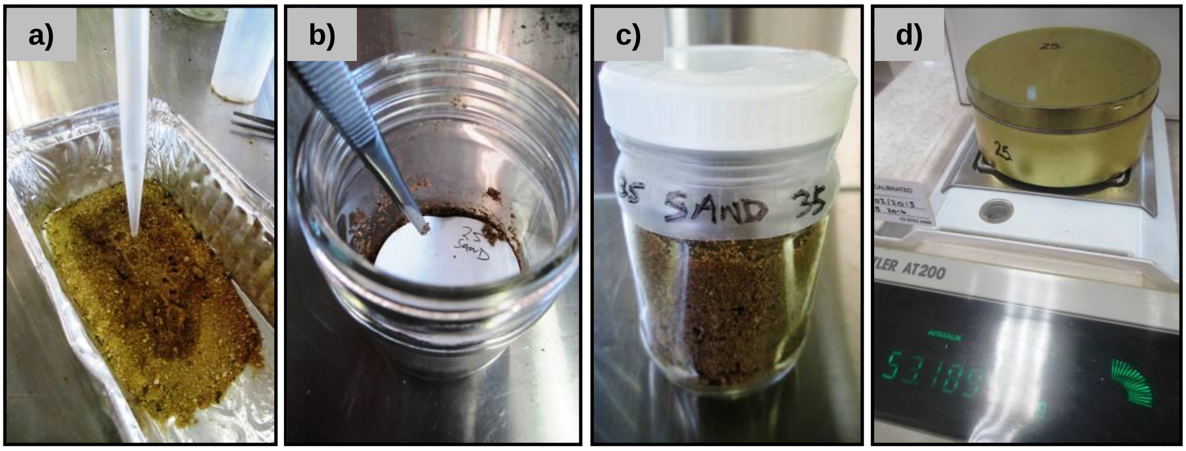



**Figure AC-1: Method for measuring soil matric potential: a) Adding water to the soil using a pipette, b) Placing filter paper over the bottom portion of soil, c) A fully-sealed jar containing the two portions of soil, separated by the filter paper, and d) Measuring the weight of a tin, containing the oven-dried filter paper.**

After one week, for each sample, the filter paper was removed using forceps and quickly cleaned with a 25 mm paint brush. Immediately, the filter paper was put into a sealed tin, which was weighed to ± 0.001 g. The filter paper was then dried in the tin, with its lid ajar, at 105°C for 60 minutes. Subsequently, the tin with the filter paper inside was weighed again, after several minutes inside a dessicator, to obtain its dry weight. Finally, the filter paper was removed from each tin, and the tins were weighed separately; this weight was then subtracted from all of the total tin weights measured previously. The gravimetric water content of each filter paper was determined using the formula:

*(wet weight – dry weight) / dry weight*

Matric suction was then determined using one of the two equations in Table AC-2.

**Table AC-1: Quantities of water added to 50g or 100 g (as applicable) soil samples for calculation of soil matric potential for all three soil types.**

| Sample number | Water content (%) | Water added (ml) | | |
|---|---|---|---|---|
| | | Field trial soil | Potting mix | Loamy sand |
| **1** | 0 | 0 | 0 | 0 |
| **2** | 5 | 2.845 | 2.70 | 1.32 |
| **3** | 10 | 5.690 | 5.40 | 2.63 |
| **4** | 15 | 8.535 | 8.10 | 3.95 |
| **5** | 20 | 11.380 | 10.80 | 5.26 |
| **6** | 25 | 14.225 | 13.49 | 6.58 |
| **7** | 30 | 17.070 | 16.19 | 7.89 |
| **8** | 35 | 19.915 | 18.89 | 9.21 |
| **9** | 40 | 22.760 | 21.59 | 10.52 |
| **10** | 45 | 25.605 | 24.29 | 11.84 |
| **11** | 50 | 28.450 | 26.99 | 13.15 |
| **12** | 55 | 31.295 | 29.69 | 14.47 |
| **13** | 60 | 34.140 | 32.39 | 15.78 |
| **14** | 65 | 36.985 | 35.09 | 17.10 |
| **15** | 70 | 39.830 | 37.78 | 18.41 |
| **16** | 75 | 42.675 | 40.48 | 19.73 |
| **17** | 80 | 45.520 | 43.18 | 21.04 |
| **18** | 85 | 48.365 | 45.88 | 22.36 |
| **19** | 90 | 51.210 | 48.58 | 23.67 |
| **20** | 95 | 54.055 | 51.28 | 24.99 |
| **21** | 100 | 56.900 | 53.98 | 26.30 |

**Table AC-2: Equations for calculating matric suction based on gravimetric water content (W).**

| Range of filter paper gravimetric water content (W) | Matric suction (kPa) |
|---|---|
| **0 – 0.453** | = exp (12.27–(17.93W)) |
| **0.453 – 1.784** | = exp (5.55–(3.11W)) |

Finally, the calculated matric suction values were plotted against soil water content (equivalent to the "water added"; Table AC-1), as shown for the field trial soil in Figure AC-2. From this, the wilting coefficient could be calculated, which is the percentage water content of a soil at which plants are first reduced to a wilted condition from which they cannot recover. Soil is considered to be at permanent wilting point (PWP) when the soil water potential is at or below -1.5 MPa (see section 1.5.2.2). For the field trial soil, for example, this was calculated to be 6.5%, which was 18% in terms of water holding capacity.

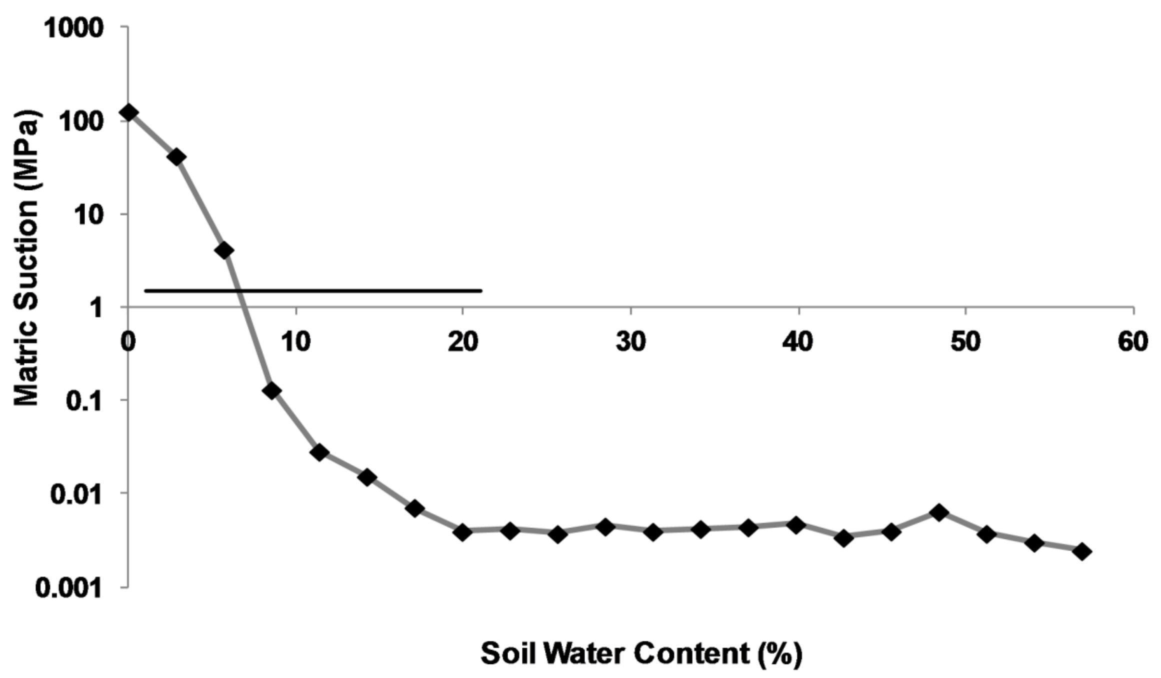



**Figure AC-2: Matric suction plotted against soil water content for the field trial soil. The horizontal line represents the permanent wilting point.**

**Appendix D: Method for measuring electrical conductivity (EC) and pH of soils**

The electrical conductivity (EC) and pH of soils were determined through the 1:5 soil/water suspension method, according to procedures described by Raymont and Lyons (2010) and the Australian Standard (AS 4419-2003). Electrical conductivity indicates the concentration level of dissolved salts (i.e. salinity) by measuring the ability of a solution to carry an electric current. High electrical conductivity (high salinity) will stress plants and reduce productivity. Soil pH is a measure of the acidity or alkalinity of soils, which affects chemical processes such as plant nutrient availability. The optimum pH range for most plants is between 5.5 and 7.0.

To prepare the soils, samples of approximately 200 g for each soil type were oven-dried at 40°C for at least 16 hours, until "air dry", and then sieved through a 2.36 mm aperture. A 1:5 weight-in-volume soil/water suspension ("supernatant") was prepared by putting 20 g of the dried soil into a 120 mL-capacity vial with a screw top lid and adding 100 ml of deionised water. There were three (field trial) or five (greenhouse experiment) replicates for each substrate. The vials were then mechanically shaken using an end-over-end shaker for 60 minutes to dissolve soluble salts, with a further 20-30 minutes allowed for the soil to settle, so that it formed an aqueous supernatant.

Prior to the start of the procedure, the EC and pH probes were calibrated in accordance with the manufacturer's instructions. For EC, the conductivity cell and meter were calibrated using a conductivity standard solution. For pH, a two-point calibration was conducted using a buffer of pH 6.88 with either a pH 4.00 (acidic) or pH 9.23 (alkaline) buffer solution, as necessary. Temperature was also measured during this procedure; readings were automatically adjusted to a standard temperature by the meter.

Two glass beakers (one for EC and one for pH) were filled with tap water and the probes were placed in the water. The probes would be returned to these beakers between each measurement. Each time the probes were removed from the beakers, before they were immersed in the supernatants, they were rinsed with deionised water and excess water was gently removed using lab ("delicate task") wipes.

To measure EC for the soil, the conductivity and temperature probes were dipped into the settled supernatant, and moved up and down slightly without disturbing the settled soil. The reading was recorded with the probe stationary, once the reading had stabilised, using the Automatic Stability Function on the meter. Between samples, the EC cell was removed from the supernatant, rinsed with deionised water, and returned to the tap water beaker. EC is reported in uS/cm (microsiemens per cm) (Table AD-1).

Measurements of pH were taken after those of EC. The pH and temperature probes were removed from the tap water beaker, rinsed with deionised water, well immersed in the supernatant (solution), and used to stir the supernatant gently (Figure AD-1). The pH value was recorded when the reading on the meter had stabilised, using the Automatic Stability Function on the meter. As for EC, between samples, the probes were removed from the supernatant, rinsed with deionised water, and returned to the tap water beaker.

**Figure AD-1: Measuring the pH of a potting mix supernatant.**

**Table AD-1: Results of pH and EC testing for all of the soils described in this thesis. The "Sand/loamy sand" is the fine sand in the field trial and the loamy sand in the greenhouse experiment, and the "Soil/mix" is the vegetable garden soil in the field trial and the potting mix in the greenhouse experiment (n/m: not measured).**

| | | Field trial | | Greenhouse experiment | |
|---|---|---|---|---|---|
| **Soil type** | **Replicate** | **pH** | **EC (uS/cm)** | **pH** | **EC (uS/cm)** |
| **Sand/ loamy sand** | ***1*** | 3.91 | 41.1 | 6.73 | 531 |
| | ***2*** | 4.03 | 40.9 | 6.63 | 504 |
| | ***3*** | 3.98 | 37.5 | 6.84 | 566 |
| | ***4*** | n/m | n/m | 6.59 | 525 |
| | ***5*** | n/m | n/m | 6.59 | 548 |
| | ***Mean (± SE)*** | 3.97 ± 0.035 | 39.83 ± 1.168 | 6.68 ± 0.048 | 534.80 ± 10.504 |
| **Soil/mix** | ***1*** | 7.30 | 2464 | 4.91 | 1066 |
| | ***2*** | 7.31 | 2349 | 4.91 | 1085 |
| | ***3*** | 7.31 | 2425 | 5.08 | 1042 |
| | ***4*** | n/m | n/m | 4.92 | 1092 |
| | ***5*** | n/m | n/m | 4.86 | 1002 |
| | ***Mean (± SE)*** | **7.31 ± 0.003** | **2412.67 ± 33.766** | **4.94 ± 0.037** | **1057.40 ± 16.339** |

**Appendix E: Laboratory calibration of soil moisture probes (field trial)**

The CS616 is a transmission line oscillator which operates in a similar way to time-domain reflectometry (TDR) systems; it measures changes in the bulk soil dielectric constant using multiple reflections of high frequency pulses travelling back and forth along a two-rod sensor (Blonquist et al., 2005; Kelleners et al., 2005; Plauborg et al., 2005; Western and Seyfried, 2005). All manufactured CS616s are checked in standard media to ensure accuracy of ± 2% volumetric water content (Campbell Scientific Inc., 2002). The calibration of CS616 moisture probes for the field trial soil was based on the manufacturer's instructions (Campbell Scientific Inc., 2002) and published methods for both the CS616 (Rüdiger et al., 2010) and its predecessor, the CS615 (Quinones et al., 2003; Western and Seyfried, 2005).

A transparent plexiglass cylinder was prepared with an opening at the top only. The diameter of the cylinder was 11 cm (radius 5.5 cm) and its total height 42 cm. This was large enough that, as required, the rods of the probe would be no closer than 2 cm from any surface of the container (Campbell Scientific Inc., 2002). The cylinder was stood vertically for the full duration of the calibration procedure.

A large sample of field trial soil (> 3 kg) was taken directly from the gardens in October 2011. A large sample size was required because the CS616 is configured to measure a relatively large quantity of soil (Rüdiger et al., 2010). The soil was oven-dried at 105°C for 48 hours (as Quinones et al., 2003), so that the volumetric water content was < 10% (Campbell Scientific Inc., 2002), and assumed to be zero.

The cylinder was filled with soil to a level of approximately 33 cm (a volume of 3136 $cm^3$), with a target bulk density of ≤ 0.8 $g/cm^3$, to be similar to field conditions. To achieve this, the soil was separated into three equal layers (as Campbell Scientific Inc., 2002), each of which had to be as close as possible to the target weights presented in Table AE-1. Prior to placing successive layers, the top of the existing compacted layer was scarified (as Campbell Scientific Inc., 2002).

**Table AE-1: Target weights for packing the calibration soil into the cylinder.**

| Layer number in cylinder | Height in cylinder (cm) | Target cumulative weight (g) |
|---|---|---|
| **1** | 0-11 | 844.33 |
| **2** | 11-22 | 1688.66 |
| **3** | 22-33 | 2532.99 |

A CS616 moisture probe was connected to a dataTaker DT85 logger, and the logger was connected to a computer. The output was recorded using the DeLogger software program. The frequency of measurement was set at 5 minutes. The CS616 was carefully inserted into the soil surface, through the top of the cylinder, ensuring that the measurement-sensitive volume around the probe rods was completely occupied by the calibration soil (as Campbell Scientific Inc., 2002).

With the soil and CS616 in place, the container was covered with cling film to minimize evaporation (Campbell Scientific Inc., 2002). A small funnel was inserted through the cling film to allow the regular addition of water. The cylinder was then placed on an electronic balance (0.1 g accuracy) to be continually weighed. The balance was connected to the same computer as the CS616 (as Quinones et al., 2003), and monitored using the RsCom program. As the CS616 output, the frequency of measurement was set at 5 minutes. Measuring the weight of the column facilitated calculation of the volumetric water content (Campbell Scientific Inc., 2002). The final setup is shown in Figure AE-1.

Water was then added to the top of the cylinder, via a measuring cylinder and the funnel, to make up 10% of the soil volume (i.e. 317 ml), which was the irrigation threshold for the four gardens (see section 2.2.6). Sufficient time was allowed for the soil moisture to equilibrate; the time required for equilibration depends on the amount of water added and the hydraulic properties of the soil (Campbell Scientific Inc., 2002). In the present study, it was typically two to three days. Equilibration was achieved when the CS616 period value was constant over a timeframe of approximately 4 hours (Campbell Scientific Inc., 2002; Rüdiger et al., 2010). With soil at equilibrium, the CS616 period value was recorded (as Campbell Scientific Inc., 2002). The weight of the cylinder was also recorded.

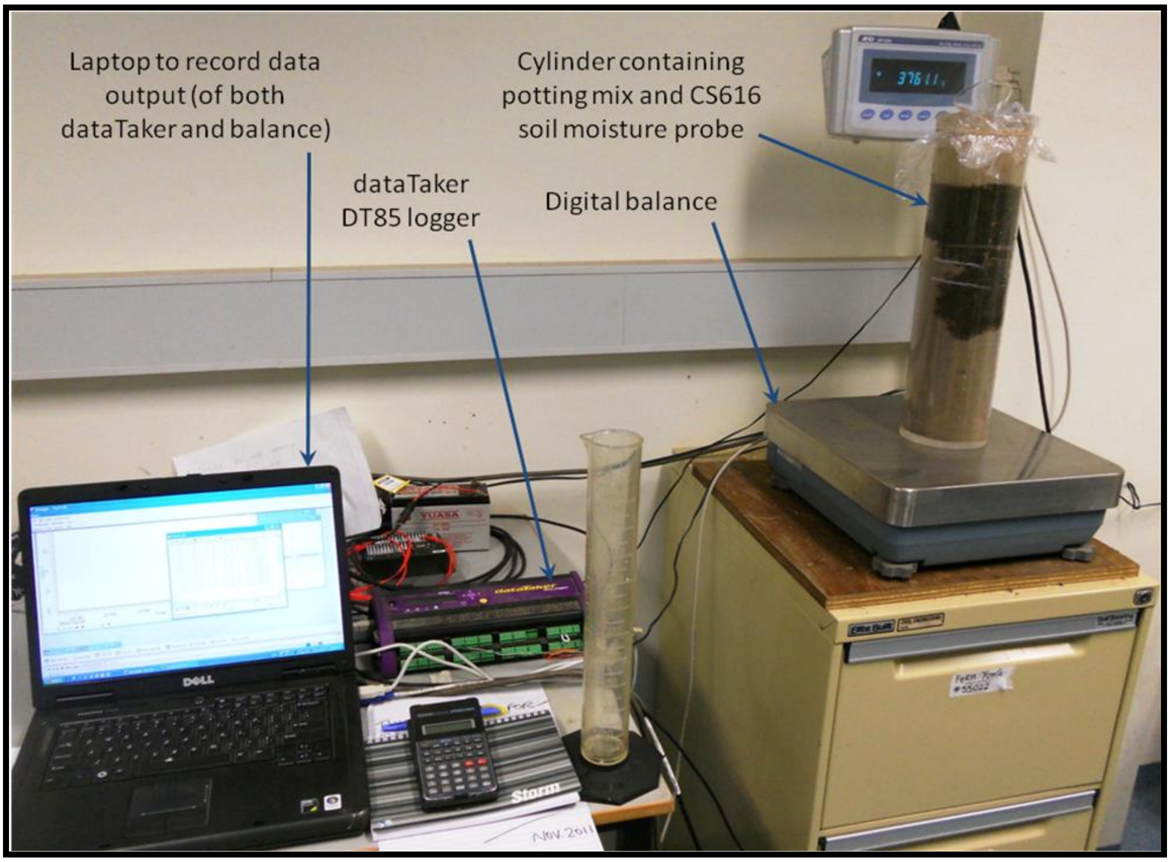



**Figure AE-1: Laboratory setup for calibration of the CS616 soil moisture probe.**

The soil moisture content was then increased by adding more water to the top of the cylinder (as Rüdiger et al., 2010). The soil water content was increased in 5% increments; i.e. 158.5 ml of water was added at each increment, plus however much water was lost through evaporation since the last increment, based on the change in weight of the cylinder (Table AE-2). CS616 period values (as a frequency, in seconds) and cylinder weights were again recorded as necessary, following sufficient time for equilibration. At each increment, gravimetric (i.e. by weight) and volumetric water contents were calculated (as Campbell Scientific Inc., 2002) to ensure that water was being added in the desired quantities. It was the volumetric water content (as a proportion) that was used in the analysis. Additions of water were conducted up to a target soil water content of 55%, which is the approximate water holding capacity of this soil (calculated through the method described in Appendix B). This method ensures that the soil density, pore structure, and sensor orientation are not changed throughout the experiment, and it is therefore favourable in comparison to increasing soil moisture content by removing the soil from the cylinder, oven drying, and adding a known quantity of water (Rüdiger et al., 2010). For the analysis, volumetric water content was plotted against the CS616 output (frequency) period (Figure AE-2).

**Table AE-2: Strategy for adding water to the calibration soil. 1 ml was assumed to equal 1 g. The CS616 output for zero water content was 1.56E-05.**

| *Target soil water content (%)* | *Date* | *Cylinder weight before water added (g)* | *Volume of water added (ml)* | *Cylinder weight after water added (g)* | *GWC** | *VWC*** | *CS616 reading (seconds)* |
|---|---|---|---|---|---|---|---|
| 10 | 10.11.11 | 3437.1 | 317 | 3760.8 | 0.13 | 0.10 | 2.09E-05 |
| 15 | 14.11.11 | 3756.8 | 163 | 3919.7 | 0.19 | 0.15 | 2.43E-05 |
| 20 | 16.11.11 | 3912.5 | 166 | 4075.5 | 0.25 | 0.20 | 2.76E-05 |
| 25 | 18.11.11 | 4055.2 | 179 | 4234.1 | 0.31 | 0.25 | 3.03E-05 |
| 30 | 21.11.11 | 4230.3 | 162 | 4390.3 | 0.38 | 0.30 | 3.22E-05 |
| 35 | 23.11.11 | 4389.8 | 159 | 4548.1 | 0.44 | 0.35 | 3.45E-05 |
| 40 | 25.11.11 | 4548.1 | 171 | 4705.2 | 0.50 | 0.40 | 3.68E-05 |
| 45 | 28.11.11 | 4702.5 | 161 | 4862.8 | 0.56 | 0.45 | 3.78E-05 |
| 50 | 30.11.11 | 4861.2 | 160 | 5019.3 | 0.62 | 0.50 | 3.85E-05 |
| 55 | 02.12.11 | 5018.5 | 159 | 5179.3 | 0.69 | 0.55 | 3.94E-05 |

*Gravimetric Water Content: (Mass wet – Mass dry) / Mass dry
**Volumetric Water Content is the product of the gravimetric water content and the bulk density: Gravimetric water content × Bulk density

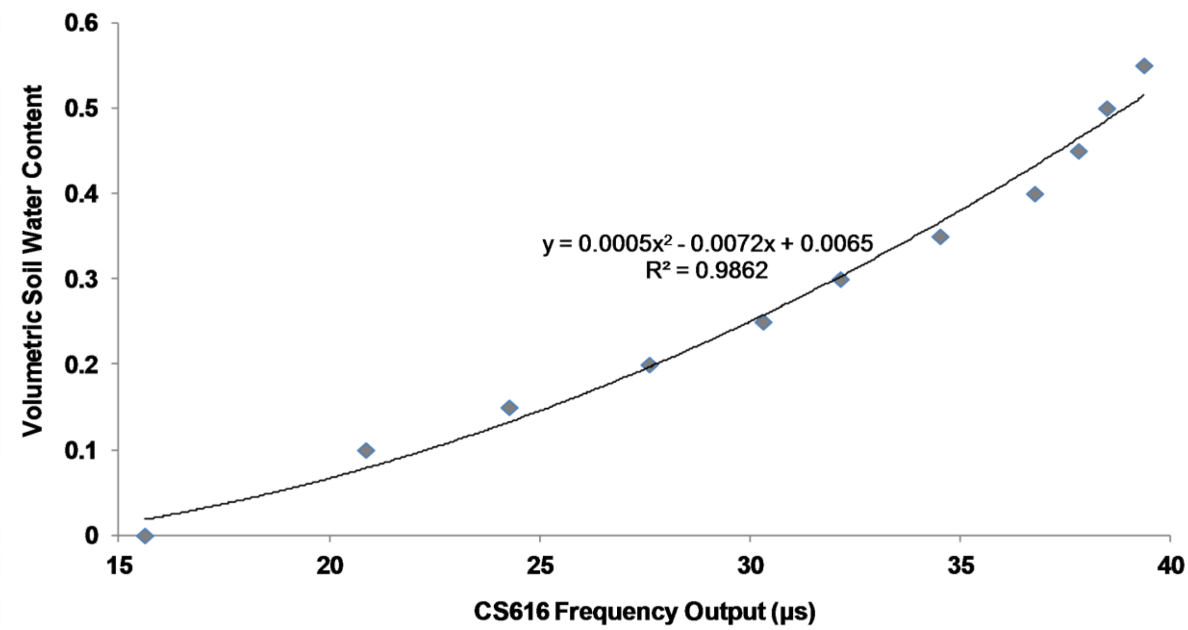
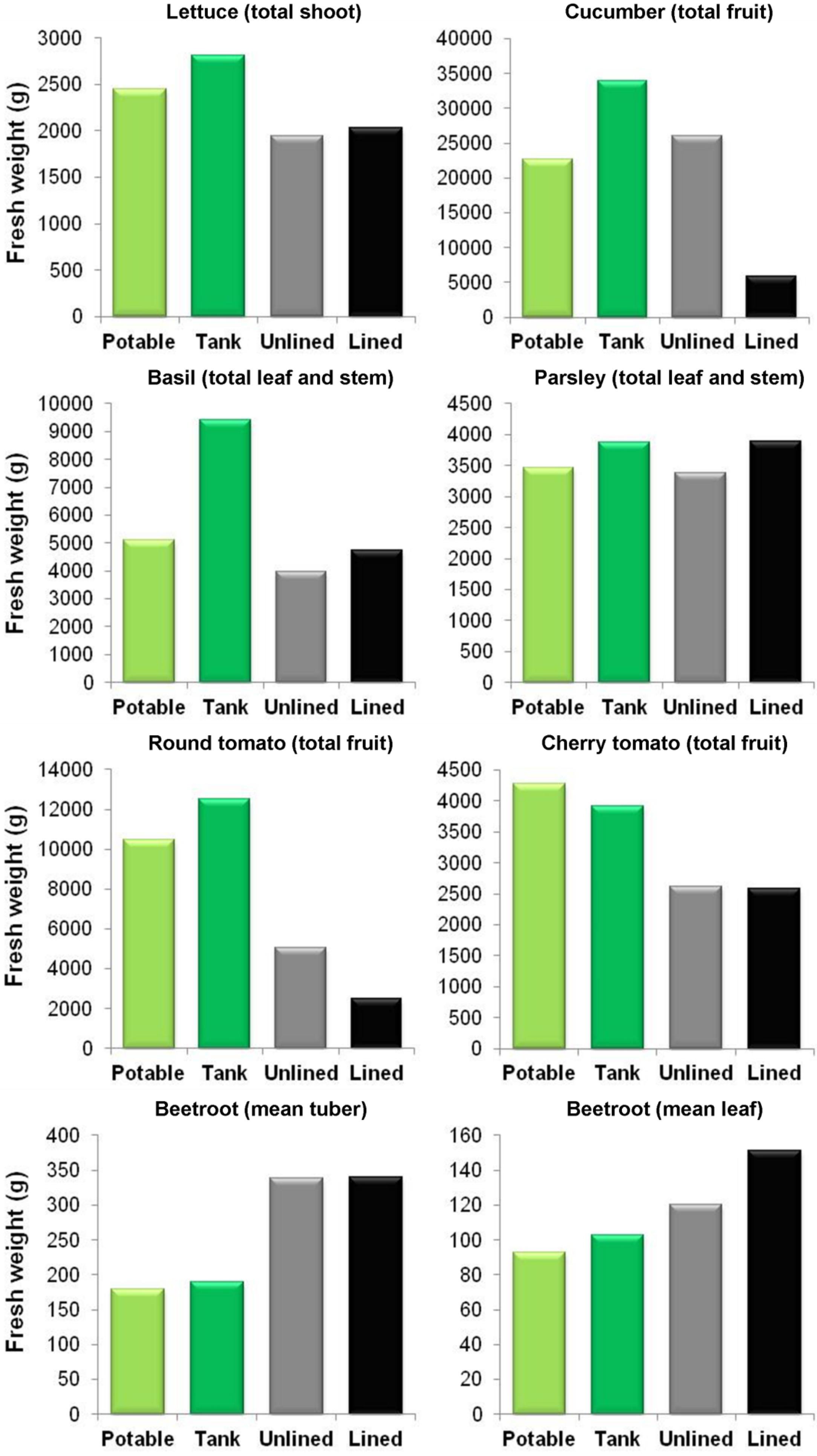


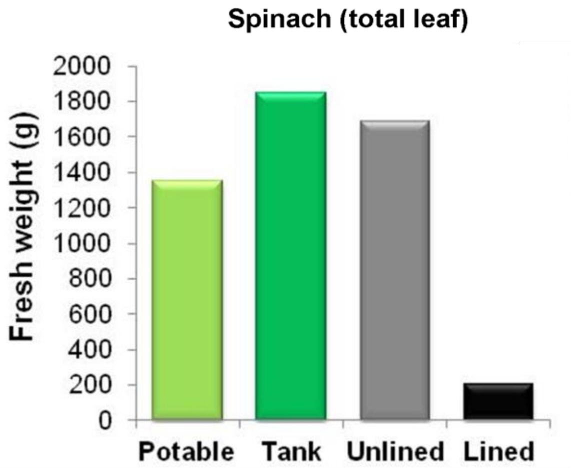

**Figure AE-2: Calibration of the CS616 soil moisture probe for the field trial soil; volumetric water content and corresponding CS616 output periods.**

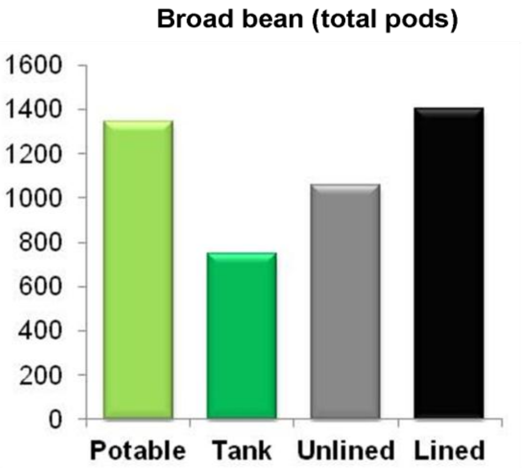
**Appendix F: Supplemental harvest information (field trial)**

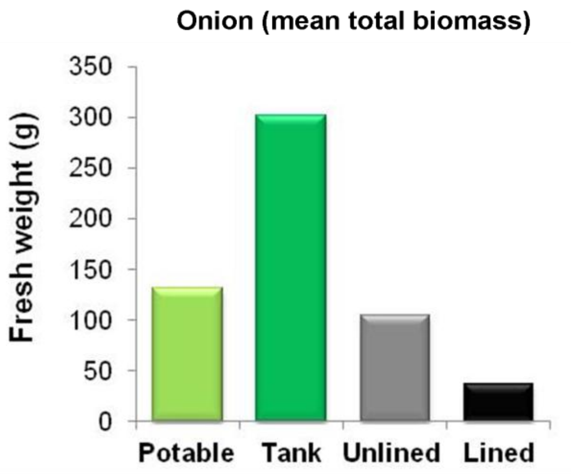
| SUMMER 1 | | | | | | |
|---|---|---|---|---|---|---|
| **Plant** | | **Plant part harvested** | **Typical harvest frequency** | **First harvest** | **Last harvest** | **Total harvests** |
| **Lettuce** |  | Leaf (total shoot) | n/a | 28th Nov 2011 | 28th Nov 2011 | 1 |
| **Basil** |  | Leaf and stem | Monthly | 28th Nov 2011 | 4th Apr 2012 | 7 |
| **Parsley** |  | Leaf and stem | Monthly | 15th Dec 2011 | 4th Apr 2012 | 5 |
| **Tomato: Cherry** |  | Fruit | Weekly | 15th Dec 2011 | 4th Apr 2012 | 15 |
| **Tomato: Round** |  | Fruit | Weekly | 4th Jan 2012 | 4th Apr 2012 | 11 |
| **Cucumber** |  | Fruit | Weekly/ fortnightly | 6th Jan 2012 | 4th Apr 2012 | 10 |
| **Beetroot** |  | Leaf (total shoot) and edible root | n/a | 31st Mar 2012 | 31st Mar 2012 | 1 |

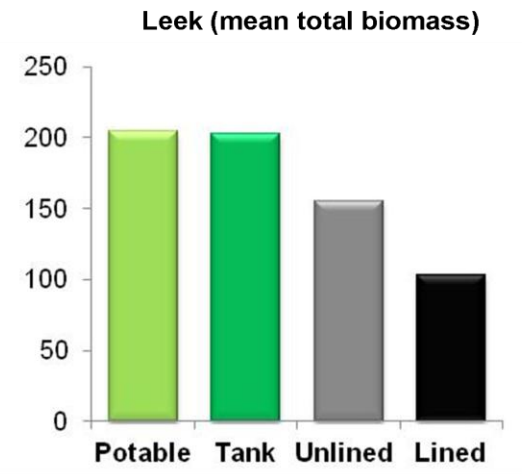

Lettuce (total shoot)
Cucumber (total fruit)
Basil (total leaf and stem)
Parsley (total leaf and stem)
Round tomato (total fruit)
Cherry tomato (total fruit)
Beetroot (mean tuber)
Beetroot (mean leaf)
Fresh weight (g)
Potable
Tank
Unlined
Lined

| WINTER | | | | | | |
|---|---|---|---|---|---|---|
| **Plant** | | **Plant part harvested** | **Harvest frequency** | **First harvest** | **Last harvest** | **Total harvests** |
| **Spinach** |  | Leaf (total shoot) | Monthly | 18th Jul 2012 | 31st Oct 2012 | 4 |
| **Broad bean** |  | Pods | Fortnightly | 22nd Sep 2012 | 1st Nov 2012 | 4 |
| **Onion** |  | Whole plant | n/a | 30th Oct 2012 | 30th Oct 2012 | 1 |
| **Leek** |  | Whole plant | n/a | 31st Oct 2012 | 31st Oct 2012 | 1 |

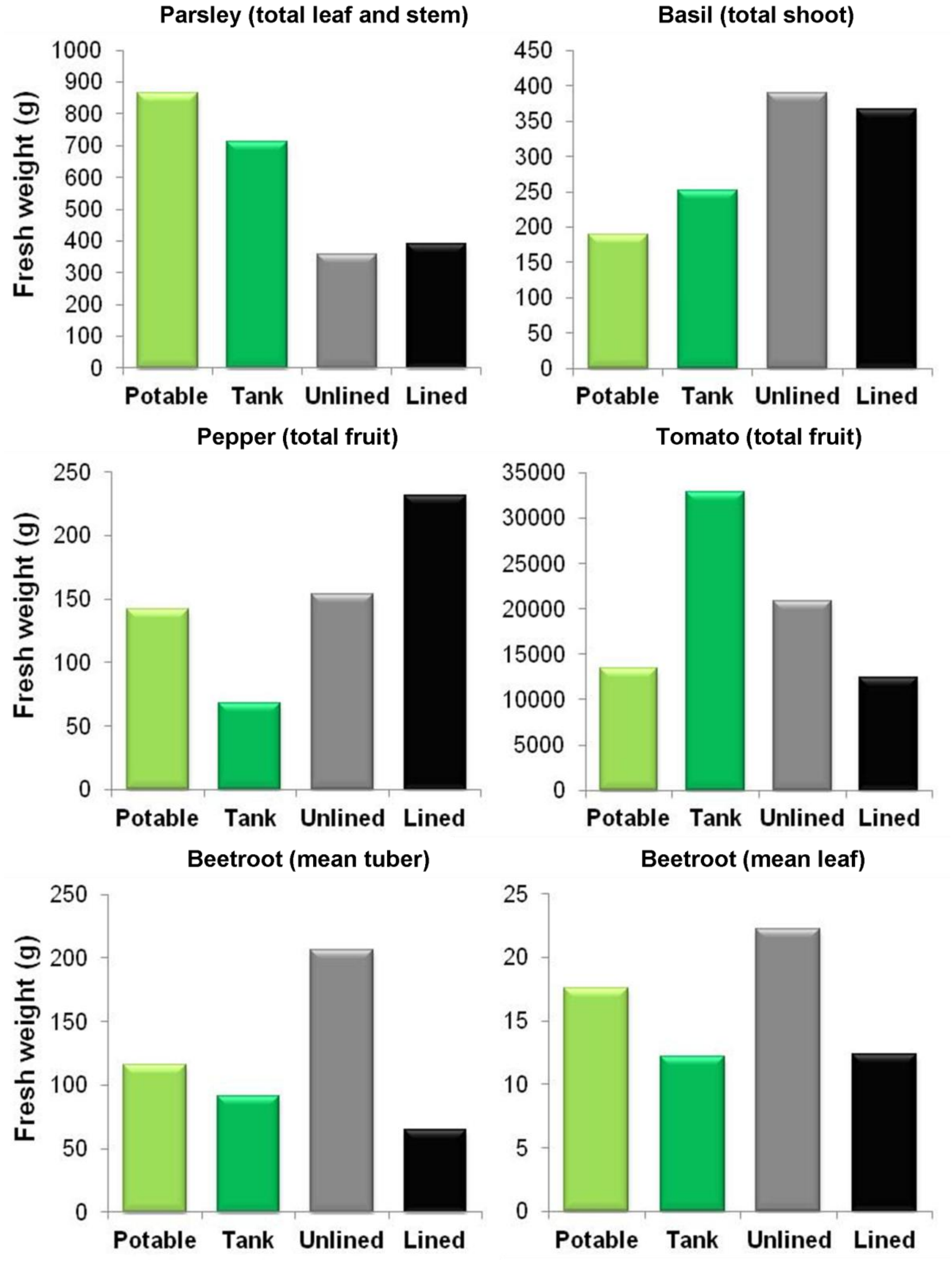


| SUMMER 2 | | | | | | |
|---|---|---|---|---|---|---|
| **Plant** | | **Plant part harvested** | **Typical harvest frequency** | **First harvest** | **Last harvest** | **Total harvests** |
| **Tomato: Plum** |  | Fruit | Weekly | 25th Jan 2013 | 2nd April 2013 | 11 |
| **Bean** |  | Pods | n/a | 27th Feb 2013 | 27th Feb 2013 | 1 |
| **Parsley** |  | Leaf and stem | n/a | 5th Mar 2013 | 5th Mar 2013 | 1 |
| **Basil** |  | Total shoot | n/a | 19th Mar 2013 | 19th Mar 2013 | 1 |
| **Pepper** |  | Fruit | n/a | 20th Mar 2013 | 20th Mar 2013 | 1 |
| **Beetroot** |  | Leaf (total shoot) and edible root | n/a | 21st Mar 2013 | 21st Mar 2013 | 1 |


Parsley (total leaf and stem)
Basil (total shoot)
Pepper (total fruit)
Tomato (total fruit)
Beetroot (mean tuber)
Beetroot (mean leaf)
Fresh weight (g)
Fresh weight (g)
Fresh weight (g)
Potable
Tank
Unlined
Lined
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400
450
0
50
100
150
200
250
0
5000
10000
15000
20000
25000
30000
35000
0
5
10
15
20
25

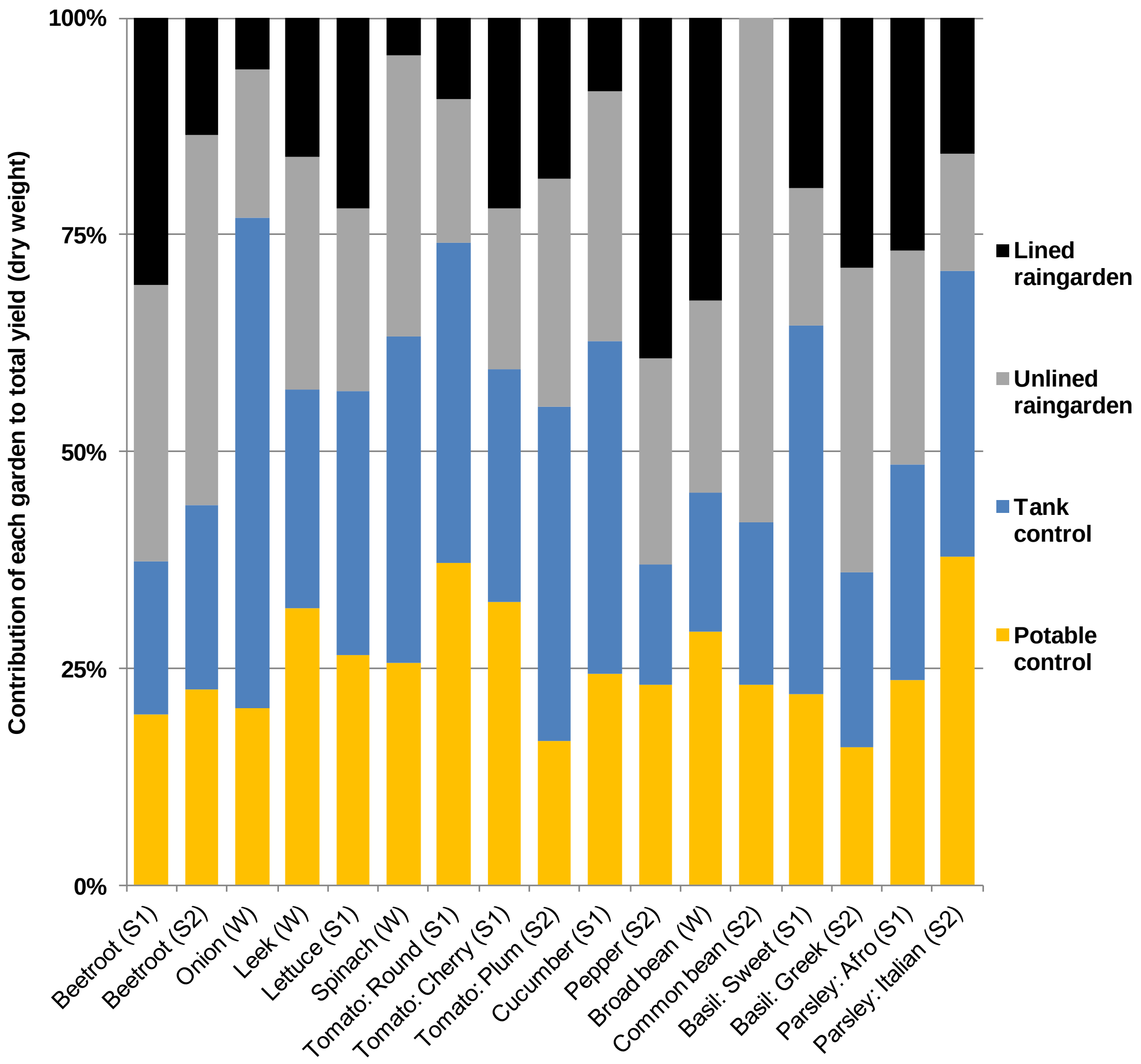



**Figure AF-1: Percentage contribution of each of the four gardens (two raingardens and two controls) to the total yield (by dry weight) of various species/varieties of vegetables/herbs over three growing seasons; Summer 1 (S1), Winter (W) and Summer 2 (S2). For root and bulb vegetables only (beetroot, onion and leek), which had variable numbers of plants in each garden, total yield is calculated according to the mean weight of individual plants. For beetroot, this does not include the weight of edible leaves; i.e. edible root (tuber) only.**

## Appendix G: Supplemental soil and hydrologic data (field trial)

**Table AG-1: Mean soil moisture as volumetric soil water content, with standard error (±), for each month of the monitoring period, with minimum and maximum values also presented. Data for November 2011 was not compatible with the subsequent data and is not presented here. All manufactured CS616 probes are checked in standard media to ensure accuracy of ± 2% volumetric water content (Campbell Scientific Inc., 2002).**

| | | | Soil moisture (volumetric SWC, %) | | | |
|---|---|---|---|---|---|---|
| | | | Control gardens | | Raingardens | |
| | | | Potable | Tank | Unlined | Lined |
| Summer 1 | **Nov 2011** | Mean | No data | No data | No data | No data |
| | | *Min-Max* | *No data* | *No data* | *No data* | *No data* |
| | **Dec 2011** | Mean | 8.99 ± 0.02 | 10.66 ± 0.04 | 11.38 ± 0.03 | 9.49 ± 0.04 |
| | | *Min-Max* | *6.93-13.46* | *7.04-18.87* | *8.33-17.42* | *6.33-17.25* |
| | **Jan 2012[a]** | Mean | 6.01 ± 0.01 | 6.94 ± 0.01 | 6.01 ± 0.01 | 5.21 ±0.01 |
| | | *Min-Max* | *4.94-7.91* | *5.97-7.76* | *4.36-8.47* | *4.02-6.38* |
| | **Feb 2012** | Mean | 8.53 ± 0.04 | 8.78 ± 0.03 | 7.00 ± 0.02 | 5.87 ± 0.03 |
| | | *Min-Max* | *4.84-18.78* | *5.60-18.62* | *4.19-11.85* | *3.76-16.70* |
| | **Mar 2012** | Mean | 8.48 ± 0.04 | 8.84 ± 0.03 | 8.16 ± 0.02 | 10.34 ± 0.04 |
| | | *Min-Max* | *5.80-20.91* | *6.08-17.07* | *5.92-15.84* | *6.12-22.35* |
| Winter | **Apr 2012[b]** | Mean | 8.47 ± 0.10 | 9.43 ± 0.12 | 8.88 ± 0.17 | 7.59 ± 0.11 |
| | | *Min-Max* | *5.51-61.28* | *5.71-58.58* | *5.19-61.89* | *5.38-49.32* |
| | **May 2012[c]** | Mean | 26.03 ± 0.03 | 21.05 ± 0.03 | 25.83 ± 0.03 | 23.25 ± 0.02 |
| | | *Min-Max* | *22.66-33.68* | *16.34-27.51* | *21.02-34.24* | *21.28-31.01* |
| | **Jun 2012[c]** | Mean | 24.68 ± 0.02 | 20.23 ± 0.02 | 24.37 ± 0.02 | 24.03 ± 0.02 |
| | | *Min-Max* | *23.24-28.54* | *17.42-24.58* | *22.02-28.17* | *22.15-28.05* |
| | **Jul 2012** | Mean | 24.13 ±0.02 | 19.05 ± 0.03 | 22.52 ± 0.02 | 22.75 ± 0.02 |
| | | *Min-Max* | *20.70-28.00* | *15.08-23.66* | *18.78-26.33* | *20.02-25.67* |
| | **Aug 2012** | Mean | 22.90 ± 0.03 | 18.85 ± 0.03 | 19.20 ± 0.02 | 21.38 ± 0.02 |
| | | *Min-Max* | *17.27-27.73* | *13.81-24.19* | *14.84-22.57* | *16.91-25.65* |
| | **Sep 2012** | Mean | 12.17 ± 0.03 | 10.89 ± 0.02 | 12.45 ± 0.02 | 14.51 ± 0.01 |
| | | *Min-Max* | *8.03-18.85* | *7.87-15.69* | *9.84-16.22* | *13.56-17.07* |
| | **Oct 2012** | Mean | 8.32 ± 0.01 | 7.71 ± 0.01 | 8.98 ± 0.01 | 16.06 ± 0.01 |
| | | *Min-Max* | *7.05-11.41* | *6.94-9.23* | *8.14-9.92* | *14.29-18.24* |
| Summer 2 | **Nov 2012** | Mean | 9.01 ± 0.01 | 8.97 ± 0.01 | 7.73 ± 0.01 | 28.80 ± 0.08 |
| | | *Min-Max* | *7.24-11.26* | *8.03-11.67* | *6.77-8.70* | *17.46-41.39* |
| | **Dec 2012[d]** | Mean | 10.31 ± 0.02 | 13.70 ± 0.02 | 7.53 ± 0.004 | 33.25 ± 0.03 |
| | | *Min-Max* | *8.67-13.78* | *11.03-15.94* | *7.17-8.07* | *30.42-38.36* |
| | **Jan 2013[d]** | Mean | 7.99 ± 0.02 | 6.88 ± 0.01 | 5.26 ± 0.01 | 13.19 ± 0.01 |
| | | *Min-Max* | *6.52-14.88* | *6.16-9.72* | *4.29-9.29* | *11.33-15.28* |
| | **Feb 2013** | Mean | 7.79 ± 0.02 | 6.92 ± 0.01 | 7.10 ± 0.01 | 15.31 ± 0.04 |
| | | *Min-Max* | *6.40-15.82* | *6.02-10.71* | *5.55-10.15* | *11.87-28.64* |
| | **Mar 2013** | Mean | 9.15 ± 0.02 | 9.38 ± 0.02 | 8.60 ± 0.01 | 35.17 ± 0.06 |
| | | *Min-Max* | *7.14-13.51* | *6.24-12.07* | *6.70-15.34* | *26.79-54.07* |

[a] No data for 6th to 13th January due to a technical fault.
[b] Up to 13th April only (one day after planting of winter crop), due to a technical fault.
[c] No data for 26th May to 6th June 2012 due to a technical fault.
[d] No data for 8th Nov 2012 (11.12 am) to 13th Jan 2012 (9.42 am) due to a technical fault.

**Table AG-2: Mean soil temperature (with standard error, ±) and minimum and maximum values for each month. Soil temperature was recorded to the nearest 0.5°C. Mean daily maximum air temperatures are as recorded by the Melbourne Regional Office station of the Bureau of Meteorology (station number 086071, opened in 1908) and compared to the long term mean (in parentheses).**

| | | | Soil temperature (°C) | | | | Daily max. air temp. (°C) |
|---|---|---|---|---|---|---|---|
| | | | Control gardens | | Raingardens | | |
| | | | **Potable** | **Tank** | **Unlined** | **Lined** | |
| **Summer 1** | **Nov** | Mean | 22.6 ± 0.10 | 21.9 ± 0.14 | 21.6 ± 0.12 | 20.6 ± 0.13 | 24.5 (>22.0) |
| | **2011[a]** | *Min-Max* | *19.0-27.5* | *18.0-28.0* | *17.0-29.0* | *16.5-29.0* | *15.8-35.0* |
| | **Dec** | Mean | 22.3 ± 0.13 | 21.8 ± 0.14 | 21.2 ± 0.15 | 21.0 ± 0.14 | 25.1 (>24.2) |
| | **2011** | *Min-Max* | *17.0-28.5* | *16.5-30.5* | *15.5-27.5* | *15.5-28.0* | *18.6-35.6* |
| | **Jan** | Mean | 23.2 ± 0.19 | 22.8 ± 0.21 | 23.3 ± 0.22 | 23.1 ± 0.18 | 27.4 (>25.9) |
| | **2012** | *Min-Max* | *16.0-33.5* | *15.0-35.0* | *15.0-36.0* | *16.0-31.0* | *19.0-40.0* |
| | **Feb** | Mean | 22.6 ± 0.11 | 23.0 ± 0.16 | 22.1 ± 0.12 | 23.0 ± 0.15 | 27.0 (>25.8) |
| | **2012** | *Min-Max* | *17.5-28.5* | *16.5-32.5* | *17.0-28.5* | *17.5-33.5* | *21.1-37.1* |
| | **Mar** | Mean | 19.0 ± 0.12 | 19.3 ± 0.14 | 18.6 ± 0.12 | 19.8 ± 0.14 | 23.7 (<23.9) |
| | **2012** | *Min-Max* | *13.5-24.5* | *13.0-28.0* | *13.0-25.5* | *14.0-27.5* | *18.0-31.6* |
| **Winter** | **Apr** | Mean | 17.4 ± 0.16 | 17.0 ± 0.15 | 16.5 ± 0.22 | 17.4 ± 0.18 | 21.9 (>20.3) |
| | **2012** | *Min-Max* | *10.5-26.0* | *11.0-24.5* | *7.5-35.0* | *10.5-29.0* | *15.1-28.5* |
| | **May** | Mean | 13.4 ± 0.07 | 12.2 ± 0.09 | 12.5 ± 0.08 | 12.6 ± 0.09 | 17.0 (>16.7) |
| | **2012** | *Min-Max* | *10.5-18.5* | *7.0-18.0* | *9.0-18.0* | *8.0-18.5* | *11.0-22.6* |
| | **Jun** | Mean | 10.7 ± 0.06 | 9.7 ± 0.07 | 10.1 ± 0.06 | 9.9 ± 0.08 | 14.4 (>14.1) |
| | **2012** | *Min-Max* | *8.0-13.0* | *6.0-13.0* | *7.5-12.5* | *6.0-13.0* | *10.5-17.7* |
| | **Jul** | Mean | 10.5 ± 0.06 | 9.6 ± 0.08 | 9.9 ± 0.06 | 9.8 ± 0.08 | 14.9 (>13.5) |
| | **2012** | *Min-Max* | *6.5-13.5* | *4.5-13.5* | *6.0-13.0* | *4.5-13.0* | *10.5-17.6* |
| | **Aug** | Mean | 10.5 ± 0.05 | 9.6 ± 0.08 | 9.9 ± 0.06 | 10.3 ± 0.08 | 15.2 (>15.0) |
| | **2012** | *Min-Max* | *8.0-13.5* | *5.5-14.5* | *7.0-13.5* | *6.5-17.0* | *10.8-21.2* |
| | **Sep** | Mean | 12.8 ± 0.09 | 11.9 ± 0.11 | 12.2 ± 0.08 | 13.1 ± 0.12 | 18.6 (>17.2) |
| | **2012** | *Min-Max* | *8.5-19.0* | *6.5-18.5* | *7.5-17.0* | *7.5-20.5* | *13.5-26.6* |
| | **Oct** | Mean | 14.6 ± 0.13 | 13.5 ± 0.13 | 13.7 ± 0.11 | 15.1 ± 0.16 | 20.8 (>19.7) |
| | **2012** | *Min-Max* | *10.5-22.5* | *9.0-21.0* | *10.0-20.0* | *10.5-27.5* | *13.4-32.0* |
| **Summer 2** | **Nov** | Mean | 22.0 ± 0.30 | 20.9 ± 0.29 | 21.1 ± 0.28 | 21.0 ± 0.26 | 23.3 (>22.0) |
| | **2012** | *Min-Max* | *9.0-45.5* | *6.0-51.0* | *10.0-38.0* | *11.5-37.0* | *16.0-39.6* |
| | **Dec** | Mean | 24.5 ± 0.23 | 23.1 ± 0.21 | 23.8 ± 0.26 | 24.0 ± 0.26 | 25.7 (>24.2) |
| | **2012** | *Min-Max* | *16.5-34.5* | *15.0-32.0* | *15.5-36.0* | *16.0-38.5* | *18.2-38.3* |
| | **Jan** | Mean | No data | No data | No data | No data | 27.3 (>25.9) |
| | **2013** | *Min-Max* | *No data* | *No data* | *No data* | *No data* | *20.8-41.1* |
| | **Feb** | Mean | No data | No data | No data | No data | 29.2 (>25.8) |
| | **2013** | *Min-Max* | *No data* | *No data* | *No data* | *No data* | *21.0-37.2* |
| | **Mar** | Mean | No data | No data | No data | No data | 27.6 (>23.9) |
| | **2013** | *Min-Max* | *No data* | *No data* | *No data* | *No data* | *18.5-37.1* |

[a] No data prior to 4 pm on 11th November 2011.

**Table AG-3: The number of days per month when some inflow (> 1 L $m^{-1}$) was recorded in the two flumes (i.e. inflow to the Unlined and Lined raingardens), and the number of days of overflow (> 1 L $m^{-1}$) to the stormwater drain. Flow that resulted directly from irrigation and maintenance activity has been excluded. For inflow, the number of days and dates are the same for both flumes (Unlined and Lined), unless stated otherwise.**

| | Number of days (and dates) | | |
|---|---|---|---|
| | **Inflow** | **Unlined Overflow** | **Lined Overflow** |
| **Nov 2011** | **12** (8th, 9th, 10th, 13th, 14th, 15th, 16th, 18th, 19th, 26th, 27th, 30th) | **1** (26th) | **10** (8th, 9th, 13th, 15th, 16th, 18th, 19th, 26th, 27th, 30th) |
| **Dec 2011** | **5/6** (10th, 11th, 12th, [a]19th, 25th, 26th) | **2** (11th, 25th) | **2** (10th, 11th) |
| **Jan 2012** | **5/6** (4th, [a]7th, 8th, 10th, 11th, [a]12th, [b]30th) | **0** | **2** (8th, *11th) |
| **Feb 2012** | **3** (5th, 11th, 16th) | **0** | **3** (5th, 11th, 16th, [[c] 27th, 28th]) |
| **Mar 2012** | **6** (1st, 3rd, 4th, 15th, 16th, 21st) | **0** | **5** (3rd, 4th, 15th, 16th, 21st) |
| **Apr 2012** | **9** (6th, 9th, 10th, 20th, 22nd, 23rd, 24th, 25th, 26th) | **1** (25th) | **7** (*6th, *9th, *20th, 22nd, 23rd 24th, 25th) |
| **May 2012** | **7** (3rd, [a]5th, 11th, 13th, 19th, 25th, 26th) | **1** (25th) | **5** ([[d]2nd], 11th, 13th, 19th, 25th, 26th) |
| **Jun 2012** | **10** (4th, 8th, 9th, 10th, 17th, 19th, 21st, 22nd, 29th, 30th) | **2** (21st, 22nd) | **7** (4th, 9th, 10th, 17th, 21st, 22nd, 29th) |
| **Jul 2012** | **10/11** (1st, 2nd, 4th, 12th, 14th, [a]18th, 25th, 26th, 27th, 28th, 29th) | **0** | **9** (1st, 2nd, 4th, 14th, 25th, 26th, 27th, 28th, 29th) |
| **Aug 2012** | **15** (4th, 6th, 8th, 9th, 10th, 11th, 14th, 15th, 16th, 17th, 18th, 23rd, 29th, 30th, 31st) | **0** | **11** (6th, 9th, 10th, 14th, 15th, 16th, 17th, 18th, 23rd, 30th, 31st) |
| **Sep 2012** | **4** (6th, 12th, 18th, 28th) | **0** | **2** (6th, 28th) |
| **Oct 2012** | **8** (6th, 9th, 11th, 13th, 16th, 19th, 22nd, 26th) | **0** | **2** (11th, 16th) |
| **Nov 2012** | **7** (1st, 8th, 9th, 10th, 18th, 27th, 30th) | **0** | **2** (9th, 27th) |
| **Dec 2012** | **4/7** (1st, 5th, [a]13the, [a]14th, 15th, 19th, [a]20th) | **0** | **2** (1st, 15th) |
| **Jan 2013** | **2/3** (9th, [a]27th, 31st) | **0** | **0** |
| **Feb 2013** | **3/4** (1st, 26th, 27th, [a] 28th) | **1** (26th) | **3** (1st, 26th, 27th) |
| **Mar 2013** | **3** (16th, 17th, 28th) | **0** | **3** (16th, 17th, 28th) |

[a] Some flow was recorded in the Unlined flume but no flow was recorded in the Lined flume following rain on 19th December 2011, 7th January 2012, 12th January 2012, 5th May 2012, 18th July 2012, three days in December 2012 (13th, 14th and 20th), 27th January 2013 and 28th February 2013.

[b] Some flow was recorded in the Lined flume but no flow was recorded in the Unlined flume following rain on 30th January 2012.

[c] 128.1 L of overflow (> 1 L $m^{-1}$) from the Lined raingarden was recorded on the 27th and 28th of February 2012, but inflow through the flume was not recorded due to a technical fault. This period of overflow was therefore excluded from analysis.

[d] Due to a technical fault, inflow through the flumes was not recorded for a rainfall event on 2nd May 2012. 180.3 L of overflow (> 1 L $m^{-1}$) from the Lined raingarden was recorded during this event, which is excluded from analysis.

* For days of overflow marked with an asterisk, both rainfall and irrigation directly resulted in overflow.

**Table AG-4: Total volume of inflow ($Q_{in}$) to the Unlined and Lined raingardens and total volume of overflow ($Q_{out}$) to the stormwater drain for each month of the field trial, where $\Delta Q = (Q_{out} - Q_{in}) / Q_{in}$.**

| | Inflow volume, $Q_{in}$ (flumes) (L) | | Outflow volume, $Q_{out}$ (overflow pits) (L) | | $\Delta Q$ | |
|---|---|---|---|---|---|---|
| | **Unlined** | **Lined** | **Unlined** | **Lined** | **Unlined** | **Lined** |
| **Nov 2011** | 6043 | 8122 | 1024 | 2204 | -0.830 | -0.729 |
| **Dec 2011** | 3610 | 3488 | 508 | 2304 | -0.859 | -0.339 |
| **Jan 2012** | 1110 | 503 | 0 | 225 | -1.000 | -0.551 |
| **Feb 2012** | 466 | 413 | 0 | 217 | -1.000 | -0.473 |
| **Mar 2012** | 4182 | 2230 | 0 | 275 | -1.000 | -0.876 |
| **Apr 2012** | 2399 | 2828 | 244 | 517 | -0.898 | -0.817 |
| **May 2012** | 2495 | 2502 | 922 | 2278 | -0.631 | -0.089 |
| **Jun 2012** | 1686 | 1398 | 221 | 606 | -0.868 | -0.567 |
| **Jul 2012** | 1403 | 1471 | 0 | 1081 | -1.000 | -0.265 |
| **Aug 2012** | 1249 | 1130 | 0 | 686 | -1.000 | -0.393 |
| **Sep 2012** | 811 | 729 | 0 | 250 | -1.000 | -0.657 |
| **Oct 2012** | 1053 | 867 | 0 | 28 | -1.000 | -0.968 |
| **Nov 2012** | 2511 | 3012 | 12 | 510 | -0.995 | -0.830 |
| **Dec 2012** | 2235 | 2307 | 0 | 186 | -1.000 | -0.919 |
| **Jan 2013** | 929 | 564 | 0 | 0 | -1.000 | -1.000 |
| **Feb 2013** | 1325 | 947 | 161 | 343 | -0.879 | -0.637 |
| **Mar 2013** | 833 | 556 | 0 | 403 | -1.000 | -0.275 |

**Appendix H: Transpiration and evapotranspiration graphs (greenhouse experiment)**

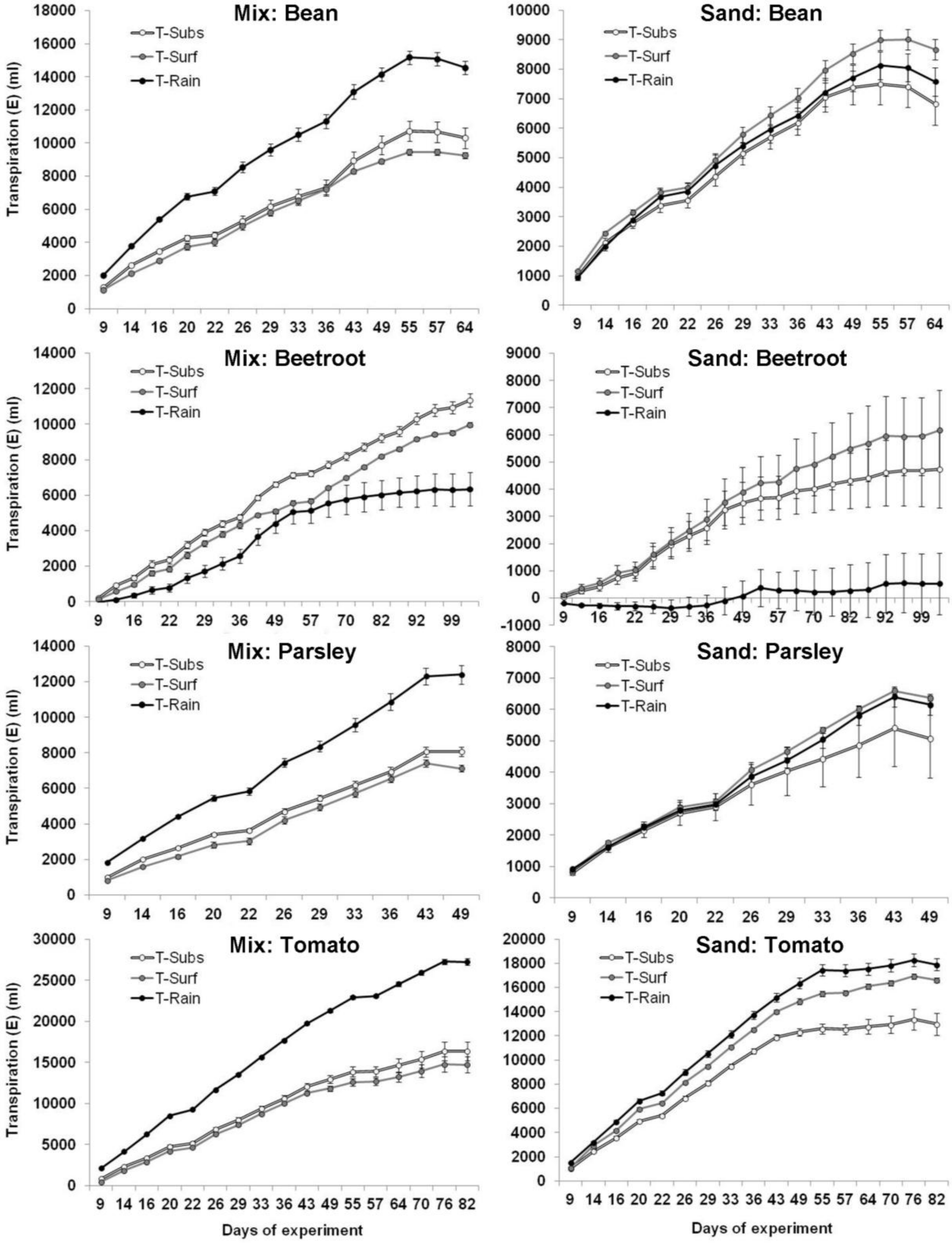



**Figure AH-1: The trend in cumulative transpiration (E) over time for the four species in the two soil types. Black bars denote mean standard error (n=5).**

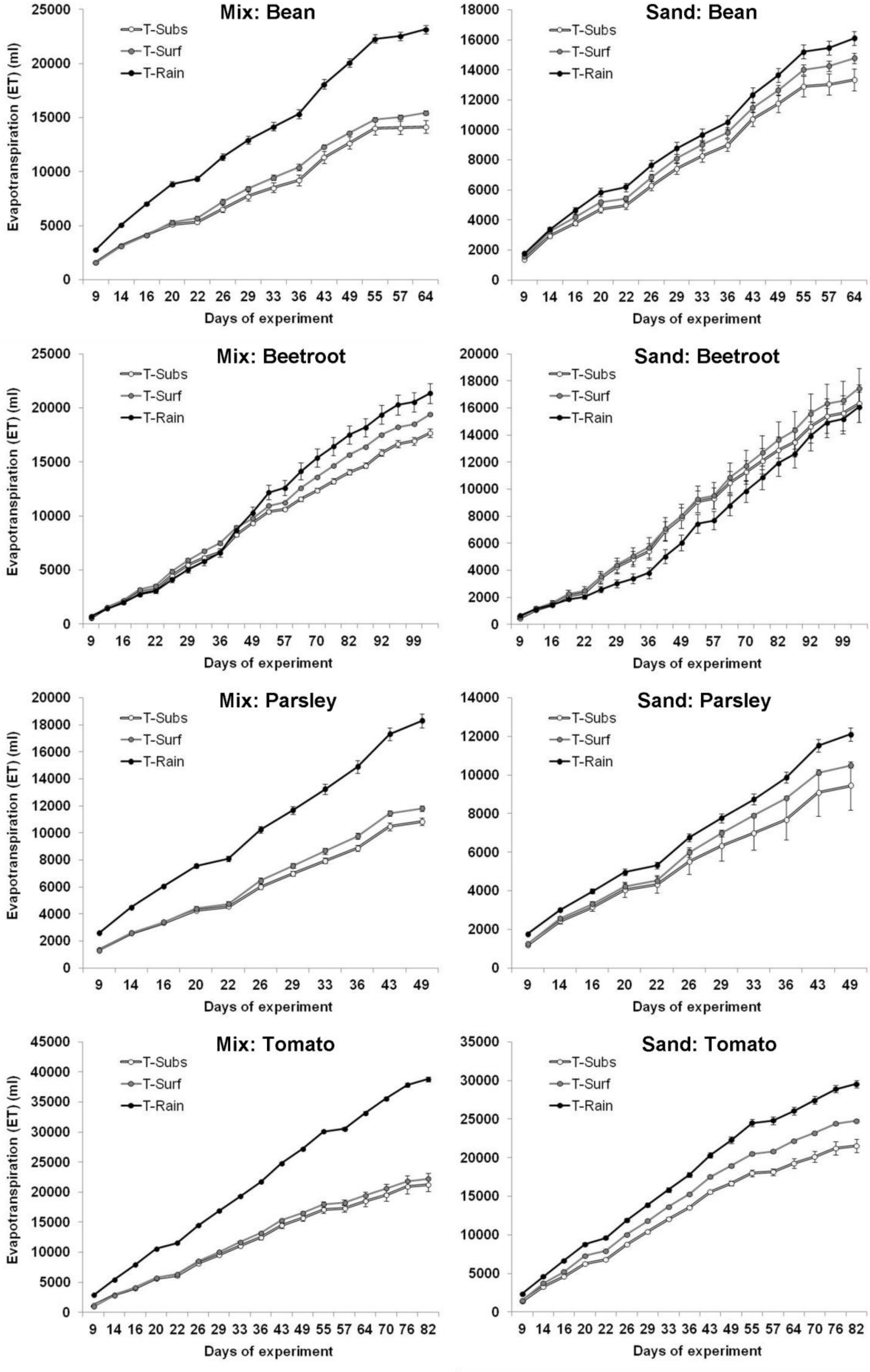



**Figure AH-2: The trend in cumulative evapotranspiration (ET) (transpiration and evapotranspiration) over time for the four species in the two soil types. Black bars denote mean standard error (n=5).**

**Appendix I: Melbourne Water Instruction Sheet**

INSTRUCTION SHEET

# Building a vegetable raingarden

healthy waterways Raingardens

## What is a vegetable raingarden?

Building a raingarden is a simple way to help the environment and the health of our local waterways while providing a self-watering garden for your backyard. A specially designed raingarden can even be used to grow vegetables.

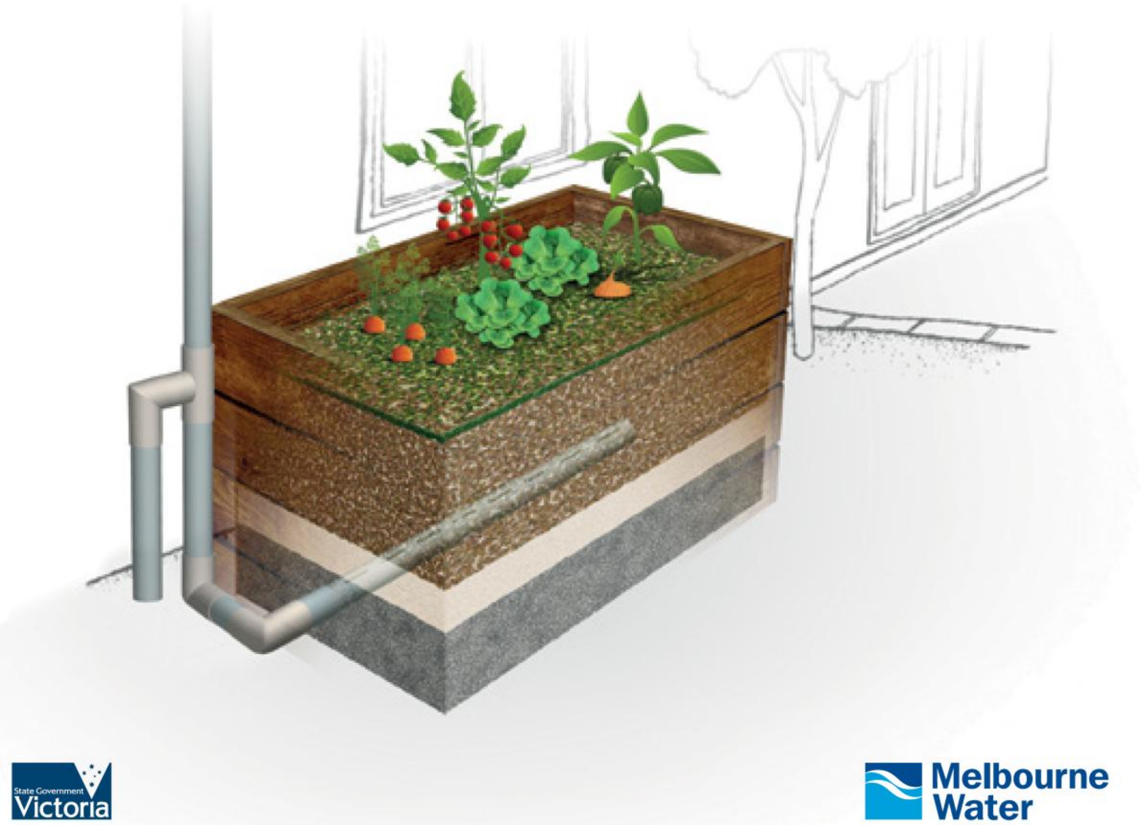
A vegetable raingarden is a specially prepared garden designed to receive and filter stormwater run-off from roofs. When built in a planter box, a vegetable raingarden can be positioned to collect roof water from a diverted downpipe.

While a traditional raingarden receives stormwater run-off on the surface, a vegetable raingarden is sub-irrigated, which means that water enters at the base of the raingarden. This helps to prevent the vegetables being submerged after heavy rain and allows water to be used more efficiently as there is less evaporation from the soil surface.

Featuring layers of soil and sand for filtration and gravel (e.g. scoria) for drainage, a vegetable raingarden helps to protect our rivers and creeks from stormwater pollutants and intense flows that can cause erosion.

*Please note: A certified plumber must be used for stormwater connections and modifications.*

*Did you know that a normal raingarden is only wet during and immediately after rain, leaving it dry most of the time? A vegetable raingarden is designed to use water more efficiently, however it is likely your raingarden will require some watering during dry periods.*



State Government Victoria

Melbourne Water

# Building your vegetable raingarden

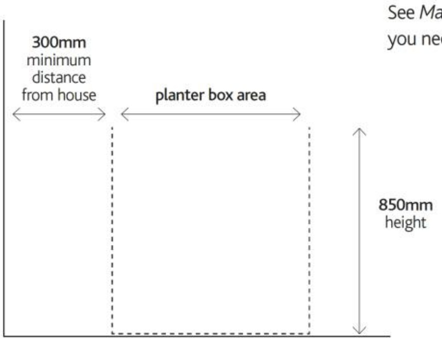
## Step 1 – getting started

### Location

Build your vegetable raingarden as close as possible to a source of stormwater such as a downpipe. This will help minimise the additional plumbing needed to bring water to the vegetable raingarden. The vegetable raingarden needs to sit at least 300mm away from any permanent structure (eg. a building). Any raingarden built within five metres from a permanent structure should be PVC lined to prevent the infiltration of water into the surrounding soils and building footings.

If the vegetable raingarden is not within five metres of a permanent structure, it should be built with an unlined base, to allow some of the water to infiltrate into the ground.

Remember that a vegetable raingarden should also be positioned to receive as much direct sunlight as possible.




Having decided on a location, it is important to determine the proximity of the existing stormwater, as the raingarden overflow pipe will need to be connected to it. Your local plumber can help with this process as well as diverting the downpipe.

### Stormwater reconnection

All connections or modifications to existing stormwater, need to be done by a licensed plumber. Your plumber will ensure that the stormwater is reconnected correctly and not connected to another service such as the sewer.

### Underground services

Be aware of any underground services (gas, electricity, water) that run near your house as this may determine where you can build your vegetable raingarden. A raingarden should not be built over or in close proximity to a septic system.

### Materials

See *Materials List* for information about what you need to build a vegetable raingarden.

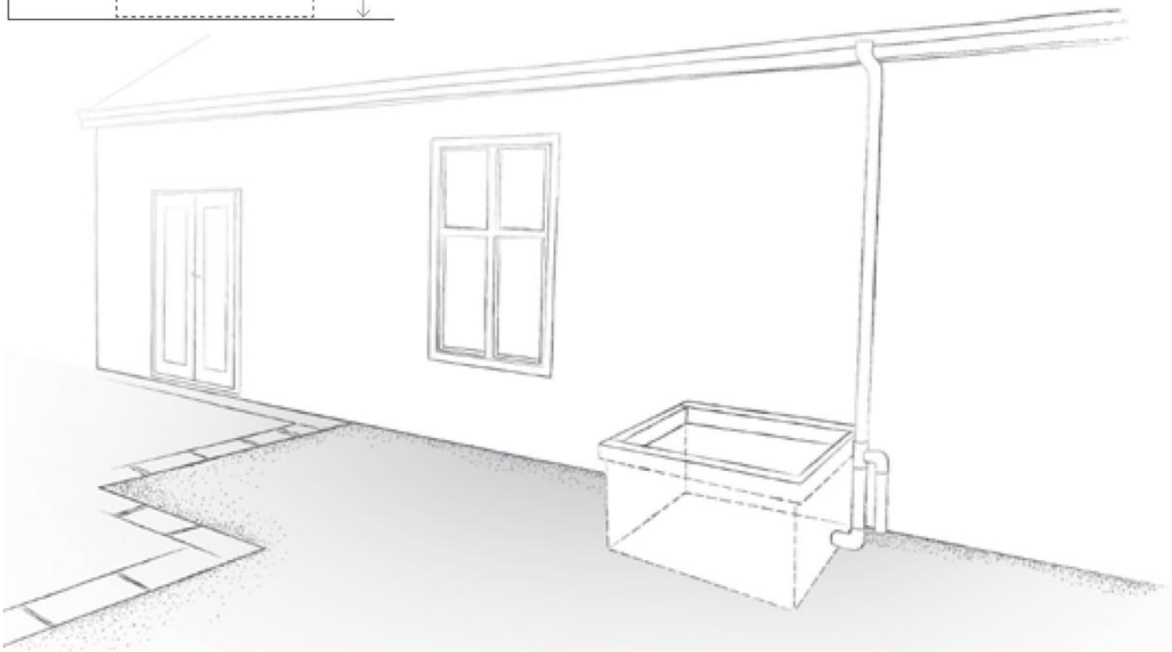
### Size

You need to make sure that your raingarden is large enough to manage the amount of stormwater it will receive. If your raingarden is going to capture run-off from the roof via a downpipe, measure the area of roof that drains to that downpipe. Generally, the size of the raingarden should be no less than 2% of the run-off area. But do not make the raingarden too large (>10%), as this may lead to "dry" zones in the vegetable raingarden which are not suitable for growing vegetables. Table 1 will help you work out the correct size.

Table 1 – Raingarden sizing chart*

| AREA OF RUN-OFF ($m^2$) | RAINGARDEN SIZE MINIMUM ($m^2$) |
|---|---|
| 50 | 1 |
| 100 | 2 |
| 150 | 3 |
| 200 | 4 |
| 250 | 5 |
| 300 | 6 |
| 350 | 7 |
| 400 | 8 |
| 450 | 9 |

* Please note raingarden size minimums. A vegetable raingarden can be built larger than these recommended minimums, however your raingarden should be no larger than 10% of the run-off area.



## Step 2 – planter box and pipe infrastructure

### Preparing your planter box

You can create a vegetable planter box out of any material as long as it is watertight and strong enough to hold saturated soil. This could be a corrugated iron 'tank' or you could build your own planter box using plantation hardwood or similar. If the raingarden is located within five metres of a permanent structure, the sides and base of the planter box will require a PVC liner. Overlap the sheets by 200mm and seal the joins with PVC tape.

Place the gravel (ie. scoria) (scoria to be 20mm in size) to a depth of 50mm. This will form a base for the slotted drainage pipe. Make sure the gravel is washed and free of excess dirt as this can create blockages in the inflow pipe (where water feeds the vegetable raingarden).

### Pipe infrastructure – to be completed by your plumber

Cut a section of 90mm diameter slotted drainage pipe. The drainage pipe's length needs to be slightly shorter than the length (internal) of the planter box. Lay the section of pipe horizontally along the centre of the planter box base - on top of the 50mm layer of scoria. Place a cap on one end of the pipe (internal). Your plumber will glue all plumbing pieces securely together.

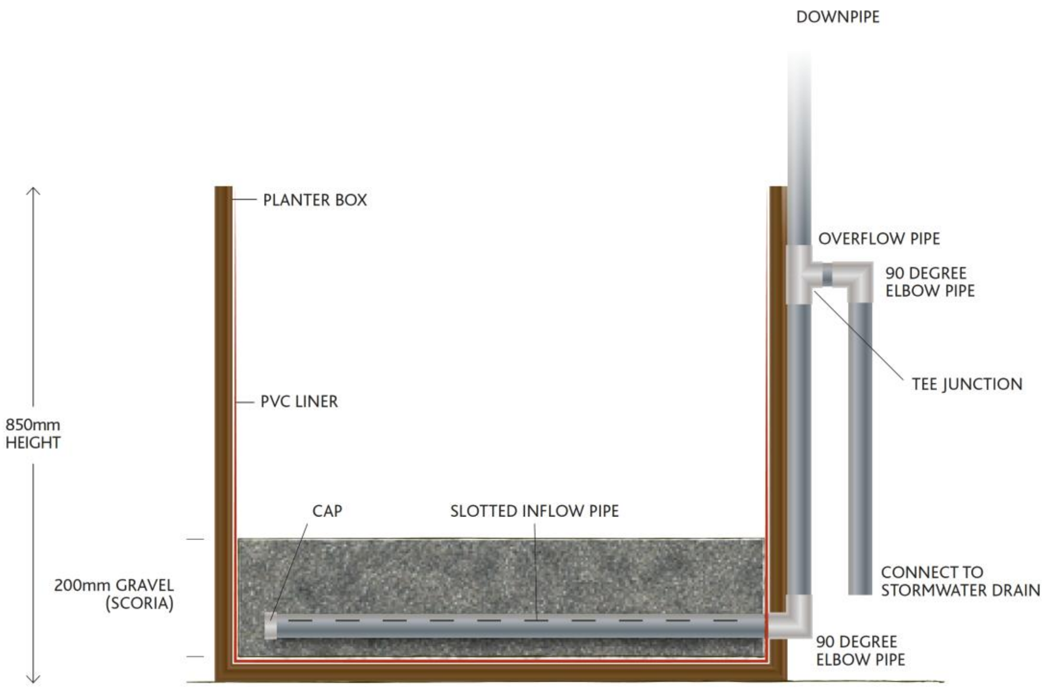
Make a 90mm diameter hole in the middle of one side of the planter box - 50mm from the base. Push the cap-free end of the inflow pipe through the hole, leaving the rest of the pipe lying across the middle of the planter box. You will need to fill gaps between the outside of the drainage pipe and the hole in the planter box with sealant.

The cap-free end of the drainage pipe then needs to be connected to the downpipe using additional pipe and pipe bends. The pipe infrastructure also needs to incorporate an overflow to pipe excess water back into the stormwater system.

Unlike a traditional planter box raingarden, the overflow for a vegetable raingarden is external to the planter box. This helps to limit contamination of any overflowing water going into stormwater. Excess nutrients from the vegetable mix need to be kept away from stormwater, as excess nutrients found in waterways can lead to algal blooms. To construct the overflow, connect a section of 90mm diameter PVC pipe to the downpipe using a tee joint/junction. The overflow pipe outside the planter box should be level with the soil surface of the finished planter box (or about 200mm from the top of the planter box).

The overflow pipe then needs to be connected into the stormwater by your plumber.

*Handy Hint – Mark the height of the overflow pipe connection (particularly the height of the bottom of the overflow pipe) on the inside of the planter box using a permanent marker. When filling the planter box with its layers this mark can be used as a guide for how much soil to add. The soil surface should be level with this mark.*



# Building your vegetable raingarden

## Step 3 – soil layers

### Gravel (scoria) layer

Add scoria to a depth of 150mm over the slotted drainage pipe to bring the total depth of gravel to 200mm. Take care not to dislodge or damage the pipe when adding the additional gravel.

### Sand layer and wicks

Place a layer of geotextile fabric on top of the gravel and then place white washed sand to a depth of 100mm. The geotextile will prevent the sand from settling downwards and will also act as a horizontal "wick", to move water to all corners of the vegetable raingarden. The use of vertical wicks is also recommended in order to assist capillary rise (upward movement) of water in the raingarden. This will help the plants to get water that would otherwise stay below the sand layer.

Wicks that are purpose-made for garden beds are commercially available, but you can use any kind of cloth as a wick, including old clothing and any leftover geotextile. The cloth should be rolled into a cylinder, or you can wrap the fabric around a small pipe or broom handle to help create a cylinderical shape. It should be long enough to comfortably span at least half of the height of the vegetable raingarden (i.e. approximately 500-700mm). Place the bottom end of the vertical wick in the gravel layer, as deep as possible. You may need to cut a small hole in the geotextile that separates the sand and gravel layers and pass the wick through it. Infill the sand and then the vegetable garden mix around the wick. Keep the wick reasonably vertical so that the top of the wick is well into the vegetable garden mix layer. Two to three wicks should be sufficient for a 2m$^2$ vegetable raingarden.

### Vegetable garden mix layer

Add vegetable garden mix to a depth of 350mm or to the height of the downpipe overflow connection. Vegetable garden mix is usually a blend of composted green waste and animal manures, with sand added for drainage. It is available from garden/ landscape suppliers. Potting mix can also be used, but you must ensure that it does not contain inorganic fertiliser, as this could harm local waterways if used in your vegetable raingarden.

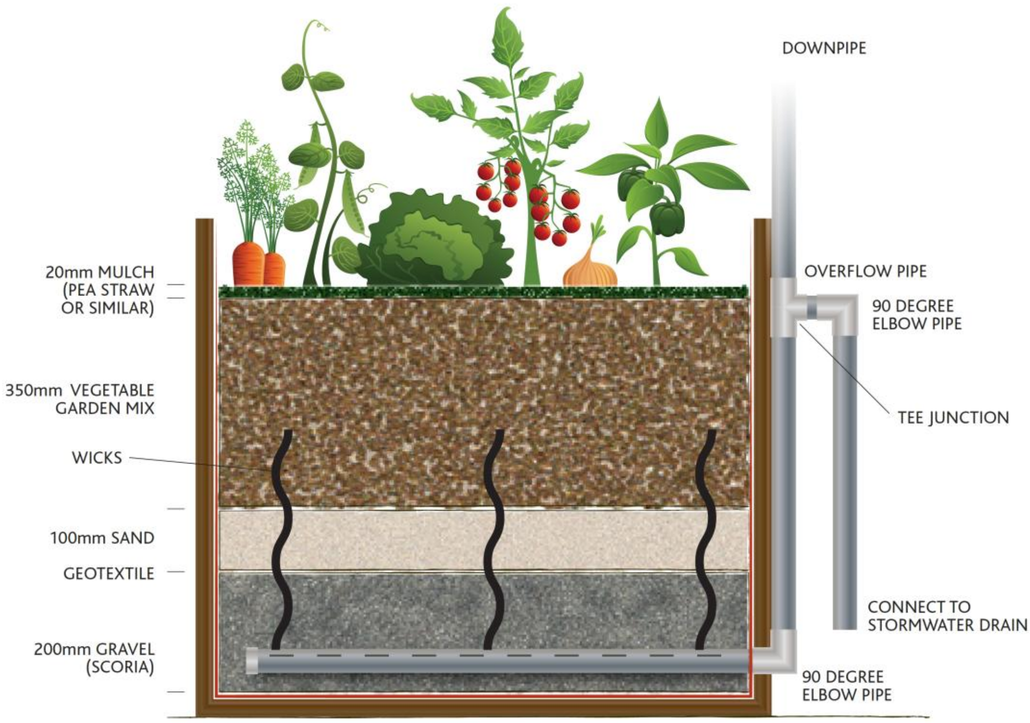
## Step 4 - plants and mulch

### Plants - vegetables

A wide range of vegetables can be grown in your vegetable raingarden including tomatoes, beans, lettuce, spinach, cucumber, beetroot, onions and leeks. Herbs such as basil and parsley should also grow well. While vegetables can be planted as either seeds or seedlings, seedlings generally need less hand watering to become established.

When selecting which vegetables to plant, remember to consider the time of year that your are planting. For example - it is best to plant tomatoes in Spring and broad beans in Autumn. Also be aware of the sun/shade and space requirements of individual plants. While a traditional raingarden is planted densely to cover the surface, individual vegetable plants generally require more space and will not grow well if crowded.

Note: fertilisers and chemical pesticides should not be used on your raingarden as the nutrients in the fertiliser and the compounds in chemical pesticides can have a detrimental effect on our aquatic flora and fauna.



# Looking after your vegetable raingarden

### Mulch

Spread mulch to a depth of 20mm around the plants. Pea straw mulch is ideal for a vegetable raingarden, as it provides nutrients for plants when it breaks down, which reduces the need for additional fertiliser. Lucerne and sugar cane mulch provide similar benefits. Avoid using gravel mulch in your vegetable raingarden, as it is likely to burn the vegetable plants during hot weather and does not add any nutrients to the soil.

Water the plants in line with your local water restrictions.

*Handy Hint – Ensure you firmly pat down each layer of soil when building your raingarden to help reduce the layers from sinking.*

Once established, a vegetable raingarden is low maintenance, however, a few simple tips can help your raingarden function well.

- Inspect your vegetable raingarden regularly - it is likely to need occasional watering in the summer months, during hot and dry periods. If the plants appear to be wilted or if the vegetable garden mix layer is very dry to touch, water the raingarden with a watering can, garden hose, or a spray/drip irrigation system. Your vegetable raingarden is unlikely to require additional water in the winter months.
- Do not water your vegetable raingarden excessively and avoid watering immediately before or after rainfall. This will allow the system to function more effectively as a vegetable raingarden.
- The use of fertilisers and pesticides should be avoided. If necessary, apply small amounts and ensure that the overflow has been set up accordingly and to avoid polluting stormwater, see pipe infrastructure
- Mulch such as pea straw will help retain moisture in your raingarden and prevent weeds from growing. However, some weeding may be necessary until plants have matured.
- Bird netting can be fitted to your vegetable raingarden to deter pests.
- Harvest and replace plants as necessary.
- The level of the vegetable garden mix needs to remain constant. If the level of the soil surface drops significantly below the height of the overflow, plants might become submerged following heavy rainfall affecting growth. Top up the vegetable garden mix layer as necessary.
- Ensure that the overflow pipe does not become blocked and remove any sediment or build up from the downpipe.

*Need help?*
*If you have questions about building a raingarden, your landscape gardener or local plumber may be able to help.*

## Materials List – what you need to build your vegetable raingarden

Table 2 – Details the materials required to create a 2m² vegetable raingarden. While item prices may vary depending on the materials you select, building a 2m² raingarden is likely to cost between $400 and $500 (plus the cost of a planter box and plumber).

| QUANTITY | MATERIAL |
|---|---|
| 2 l/m | 90mm diameter slotted pipe (Ag Pipe) |
| 2 l/m | 90mm diameter uPVC pipe* |
| 2 m² | Geotextile fabric |
| 3 | Wicks; any cloth, approximately 500-700 mm long |
| 0.4m³ | Gravel (20mm scoria) |
| 0.2m³ | Sand (white-washed) |
| 0.6m³ | Vegetable garden mix |
| 4-15 | Plants (as seedlings) |
| 0.1m³ | Mulch (e.g. pea-straw) |
| 3 | 90mm diameter uPVC 90 degree (elbow) bends |
| 1 | PVC 90mm tee |
| 1 | PVC 90mm cap |
| 10m² | PVC liner (if planter box is lined) |
| | PVC tape |
| | Silicone sealant |

**Costs per square meter will depend on the length of connections back to the existing stormwater drain.*

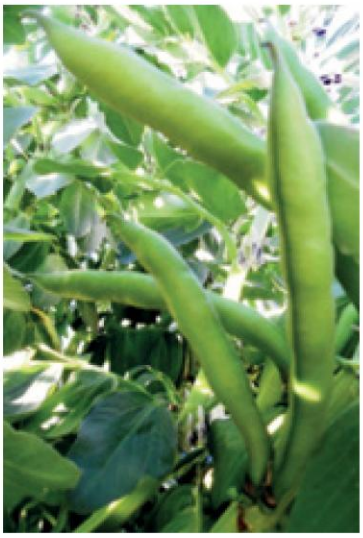
l/m = lineal metres  m² = square metres  m³ = cubic metres  mm = millimetres

*Handy Hint – You may decide to create your vegetable raingarden using a raised corrugated iron garden bed. Widely available at garden supply stores, the standard heights of these garden beds range from 400mm to 800mm. Once you have selected the garden bed, you will need to adjust the quantity of materials required to create your vegetable raingarden. Remember that the vegetable raingarden needs to be at least 2% of the size of the run-off area. Refer to Table 1 for more information.*

# Plant List – the best plants for your vegetable raingarden

The following common vegetables and herbs grow well in a vegetable raingarden.

| BOTANICAL NAME | COMMON NAME | PLANTING SEASON | MINIMUM SPACE AROUND EACH PLANT ($CM^2$) |
|---|---|---|---|
| *Allium cepa* | Onion | Autumn/Winter | 10 |
| *Allium porrum* | Leek | Winter/Spring/Summer | 15 |
| *Beta vulgaris* | Beetroot | Winter/Spring/Summer | 10 |
| *Capsicum annuum* | Capsicum/Chilli | Spring/Summer | 50 |
| *Cucumis sativus* | Cucumber | Spring/Summer | 100 |
| *Lactuca sativa* | Lettuce | All seasons | 30 |
| *Ocimum basilicum* | Basil | Spring/Summer | 20 |
| *Petroselinum crispum* | Parsley | Winter/Spring/Summer | 30 |
| *Phaseolus vulgaris* | Common bean | Spring/Summer | 15 |
| *Solanum lycopersicum* | Tomato | Spring/Summer | 60 |
| *Spinacia oleracea* | Spinach | Autumn | 20 |
| *Vicia faba* | Broad bean | Autumn | 20 |





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