University of Southern Queensland
Faculty of Health, Engineering and Sciences

Comparison of hand watering scheduling methods in domestic gardens

Final Dissertation
submitted by
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Abstract

This project aimed to determine a method of irrigation scheduling using affordable, simple to use technology for manual watering of domestic gardens. Literature shows the volume of hand watering is often inefficient, either water is applied in excess of or too little of what is required by plants (Singer and Munns 2006, p.115; Manning et al. (2013, p.4).

Four methods (M1, M2, M3 and M4) of scheduling hand irrigation were trialed on a vegetable patch in Toowoomba, Queensland during phase 1 of trials (December to February). M1 was a control for comparison - the gardener applied water when they intuitively thought it was required and in amounts they arbitrarily thought appropriate. An irrigation amount of 22mm per application was applied to all other methods. M2 utilised a 3in1 soil meter, which was calibrated by intuition during phase 1. At the end of the phase, the results were averaged on what value irrigation occurred on for 5, 10, and 15cm depths. From this it was determined irrigation should occur by the time a minimum value of 4 and 7 was indicated on the probe for the 5 and 10cm depths respectively. M3 was based on a theoretical landscape evapotranspiration calculation, however plants quickly deteriorated using this method and it was stopped due to insufficient water application and no further calibration of this method was used.

During phase 2 (February to June), M1 and M2 continued and a new method (M4) was introduced. This method assumed the weight loss in a pot plant was due to evapotranspiration, and irrigation occurred at 22mm. M2 was further adjusted, as the values didn't occur congruently and the 5cm value requirement was discontinued. M1 applied the most irrigation (1175mm), and M2 applied the least (603mm). M3 applied 932mm.

The results of M1, M2, and M4 were compared to theoretical irrigation schedules based on the estimated seasonal (M6) evapotranspiration rates. In all three trialed methods, over-watering was significant. Estimated amounts for each trial plot were 374mm, 286mm, and 374mm for plots associated with M1, M2, and M4 respectively. Gross over watering occurred in M1, with M2 almost doubling the amount of water applied during the trial compared to the estimated amount required.

Copious amounts of data were collected as part of this feasibility study. Further analysis needs to be conducted to make more detailed connections. Further suggested works include: a survey to gauge end user interest and attitudes, and a new trial should be conducted with a larger gardener sample, soil type, and/or seasonal variation.

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I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Caitlin Watson
Student Number: [redacted]

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Executive summary

The purpose of this project is to determine low cost and low technological methods to improve manual watering efficiency within domestic vegetable gardens. Current domestic hand watering is scheduled according to intuitive methods such as sight, time, and feel (Cubino, Subiros and Lozano 2014; Myers, Mohring and Anderson 2017). The efficiency of these methods is affected by the gardener's experience.

These methods commonly result in either over watering (Maheswari 2016; Syme et al. 2003) or under watering (Singer and Munns 2006; Syme et al. 2003). Both of these have adverse affects on plant health.

Over watering can cause soil saturation and resultant plant death from lack of oxygen at roots. In addition, over-watering can lead to leaching of nutrients which may enter municipal wastewater flows or natural water streams. Over-watering draws unnecessary volumes from water reservoirs, putting increased pressure on municipal water supplies.

Under watering can occur due to limitations on garden watering by water authorities when municipal water supplies are stressed (DEECA 2023; Toowoomba Region 2022). This can result in plant loss and decreased gardener enjoyment (ACIL Allen 2021), decrease available household food and/or increase household food costs (Athearn et al. 2021; Langellotto 2014), and lowering of mental and/or physical health across age groups (Dunnett and Qasim 2000; de Bell et al. 2020; Park et al. 2016).

To date there is limited published research to determine how to improve manual irrigation scheduling in domestic gardens. It is import to improved these practices, as it can decrease pressure on stressed town water supplies, improve plant health, and may allow for garden survival during water restrictions and drought periods when garden watering is limited.

This project drew on landscaping, agricultural, and horticultural irrigation scheduling methods to design and trial several methods of scheduling domestic manual watering. The methods were calibrated, trialed, and revised in effort to determine a design to improve efficiency. The water volume applied was compared to a water balance for the period of the trial. The trial results are also compared to Time Domain Reflectrometry (TDR) sensor data from the garden.

The results from Phase 1 of the trial roughly calibrated a low cost 3in1 soil meter (M2) and eliminated a landscaping method (WUCOLS evapotranspiration calculation method) (M3). It has been noticed that often significantly more water is applied arbitrarily by the gardener (M1) in a single watering than that advised by the local government water authority (Toowoomba Regional Council 2022b).

In Phase 2 a pot weight loss method (a method adapted from nursery lysimetry techniques) (M4) was designed and trialed. While M2 used the least amount of water, M4 also used significantly less than M1.

This research is a valuable start to finding tangible methods which can easily be implemented on a low budget by gardeners with limited scientific education regarding irrigation. This research is limited to the soil and plant types used in the trial, and therefore further research will be required to extend this trial across the broader gardening landscape within Toowoomba or outside of the soil and climate region.

Improving timing of irrigation and/or the volume applied will have a cumulative affect to decrease demand on potable water & municipal services, decrease nutrient leaching into waterways from urban points. Individual gardeners benefit by more cost effective watering methods for plant health and lessening of fertiliser loss (for those who over water).

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Nomenclature and acronyms

IoT -	Internet of Things
ET -	Evapotranspiration
ET_L -	Plant evapotranspiration
ET_o -	Reference Evapotranspiration
ETJ -	Garden evapotranspiration
FC -	Field Capacity
GWR -	Estimated garden water requirement
K_c -	Turf grass coefficient
K_L -	Landscape coefficient
K_{st} -	Crop stress factor
PAW -	Plant Available Water
PF -	Plant Factor
RAW -	Readily Available Water
SWB -	Soil Water Balance
WUCOLS -	Water Use Classification of Landscape plants

2. Introduction

“Gardening has always been an art, essentially” (Robert Irwin, n.d.). This is true for many domestic gardeners, who apply water at times and in volumes according to their intuition (Cubino, Subiros and Lozano 2014; Myers, Mohring and Anderson 2017). Domestic irrigation scheduling could potentially be scientifically developed, in light of the amount of research that has gone into irrigation science across the landscaping, horticultural and agricultural industries.

2.1. Study outline

This chapter provides an outline of the project. The literature review discusses the current research conducted into the irrigation scheduling from home gardens to irrigated crops. The research design and methodology chapter discusses the set up of the trial methods, how they were conducted and any assumptions used during the trial procedures. The results and discussion chapter provides the trial results, analysis and discussion of these results. The conclusion chapter provides any conclusions drawn from the trial analysis, and directions for future research.

2.2. Project specification

The current project specification can be viewed in Appendix A - Project Specification.

2.3. Problem background and need for research

Domestic garden irrigation is often inefficient due to low levels of experience, knowledge, and/or skills of the individual gardener (FAO 1995a; Myers, Mohring and Anderson 2017). Inefficiencies arise due to under or over wetting of the root zone. On the one hand, gardeners of standard patience do not apply sufficient water quantities for a long enough duration to appropriately wet a soil to worthwhile depth (Singer and Munns 2006, p.115). On the other hand, over-watering is a regular occurrence, as found by Manning et al. (2013, p.4) in their Townsville study. In support of this, Maheshwari (2016) found hand-watering resulted in significant excess volumes being applied in Sydney, New South Wales.

The bulk of urban potable water is used for green-spaces, aesthetic appearance, and municipal amenities (Nouri et al. 2013a). Effects on the garden soil include water logging and subsequent plant death. Excess water, which includes nutrients from the garden, may enter municipal wastewater lines increasing demand on wastewater treatment facilities. It may also enter waterways and contribute to their pollution.

Water use in excess of plant uptake results in unnecessary loss of urban potable water, and can have follow on effects to the garden soil and downstream water flows. Many urban potable water supplies are already stressed by current populations along with re-occurring droughts. Toowoomba recently increased water security for predicted population growth, along with drought proofing through the construction of the Wivenhoe Dam to Cressbrook Dam pipeline (Verdict Media 2023).

Significant research has gone into the efficiency improvement of domestic sprinkler and automated systems. Yet during high level (150L/p/d) water restrictions in the Toowoomba Regional Council (TRC) region, these efficient methods are not allowed while inefficient hand held watering devices remain in use (TRC 2022a).

2.4. Research aim

This project aims to improve water use efficiency for manual watering of domestic gardens by determining an affordable, low technological irrigation scheduling method.

2.5. Research objectives

1. Conduct a literature review to determine:
    a) the importance of home gardens and their irrigation,
    b) current hand-watering scheduling practices including determination of timing and application volumes,
    c) industry irrigation scheduling methods,
    d) factors affecting scheduling methods,
    e) Any case studies of hand watering scheduling by scientific methods.
    f) Evaluate the practicality of transferring industry irrigation scheduling methods to domestic hand watering.
2. Design trials for comparison of scheduling methods;
    a) Research crop characteristics to estimate plant water requirements,
    b) Conduct a soil water balance for trial site,
    c) Implement hand-watering trials.
3. Analyse trial data.
4. Design an improved manual watering schedule.

5. Make recommendations for future research.

2.6. Scope and limitations

Project resources are limited by a small student budget, and primarily use freely available or low cost items. The literature review was conducted using freely available sources, including those available to undergraduate students of the University of Southern Queensland's (UniSQ) library databases, along with Google and Google scholar. Some UniSQ equipment and laboratories were also available to undergraduate engineering students on request.

This is a student project, conducted from December 2022, with submission due in October 2023. Therefore amount of research and length of trials are limited by the time available including allowing time for dissertation writing.

This research focuses on the end users being domestic home gardeners. It is assumed the gardeners have limited irrigation, and soil-water dynamics education, along with limited irrigation technology skills. It assumes home gardeners are wanting to keep watering and other garden operation costs to a minimum, while still obtaining a crop of edible vegetables.

Domestic gardens are taken to incorporate both vegetable and ornamental plants for the purpose of the literature review, due to the limited research available. The garden trials used in this research were carried out using only vegetable plants available either by seed or seedling punnets through the local Bunnings Warehouse store.

The trials were limited to measuring water applied, and various methods of estimating and applying a value or indicator value to soil moisture. The plant nutrient uptake and growth were not considered in this project. Soil amendments such as fertiliser, compost, and mulch were added throughout the project trials, along with soil disturbances for weeding or new plantings, as deemed necessary by the gardener in their normal gardening practice. Changes in soil moisture were noticed from these actions, and are discussed in the analysis of the results.

The gardens used for the trial had a variety of plant species, and various growth stages at any time. The species were selected according to the gardener's normal practice. They were planted at such times as determined by the gardener, rather than to a horticultural or agricultural standard practice.

Plant health was observed by the researchers eye. It included noticeable wilting and/or yellowing of leaves, visually noticeable diseases (ie: mould and rust) and pests (ie: snail and tobacco beetle). Therefore the judgement of plant health can vary depending on the experience and knowledge base of the individual.

2.7. Risk management

The safety risk management plan developed for this project can be seen in Appendix B - Safety risk management plan

2.8. Resources

A full list of resources used for this project is provided in Appendix C - Resources required**.**

2.9. Project timeline

The current project plan is provided in Appendix D - Project Timeline.

2.10. Literature review outcomes

The literature review will investigate why home gardens are important, and why improving water use in them is needed. It will investigate how hand watering is currently scheduled by domestic gardeners, along with potential methods suitable for adaption from irrigation industries (agriculture, horticulture, and landscaping). The review will also determine what factors affect irrigation scheduling, particularly relating to what effects soil moisture content.

2.11. Research results and outcomes

This research work is expected to provide a more accurate and repeatable method of determining the timing of irrigation scheduling than that currently employed by domestic gardeners. It will determine affordable, low technological methods a home gardener could use to improve their manual watering schedule, in terms of application timing, and required volume, specifically for the trial site. The method should be intuitive without requiring specific education.

The outcomes of this research provide a baseline for further research into creating and improving manual watering schedules for domestic gardens. This research will provide a method for gardeners on other soil types, climate, and/or plant types to investigate suitable scheduling methods. It will provide a base for future research to be conducted regarding the potential of implementing these changes in the local government area. It may provide lead to tangible advise councils or water authorities can provide to users regarding garden water use.

3. Literature review

This section reviews the freely available literature regarding current research of hand watering domestic gardens, and industry irrigation methods. It describes the importance of home gardens and the issues related to watering of them, along with the current methods used to schedule hand watering. Industry irrigation scheduling methods from agriculture, horticulture and landscaping are investigated, including any factors which affect how these schedules are implemented or modified.

The literature review also evaluates the practicality of transferring industry irrigation scheduling methods to a domestic one. Finally a review of any case studies in which hand watering is scheduled by scientific methods will determine the research gap which this project aims to apply to generate better understanding of hand watering scheduling and water use.

3.1. Background

Urban water scarcity due to drought and strain on existing supplies from increasing urban populations is not a new issue in Australia (Nouri et al. 2013a; White, Noble, and Chong 2008). In particular Toowoomba experienced severe water shortages during the millennial drought with water reserves below 10% in 2009 (Verdict Media 2023). This prompted the immediate construction of the Toowoomba Pipeline project from Wivenhoe dam to Cressbrook dam to augment the bulk water supply (Verdict Media 2023). While this pipeline was first used in 2019/2020 (Engeny 2020), it is expected to be used in the future to provide for population growth, along with drought emergency supply (Engeny 2020).

The Water Vision 2050 Report is the Toowoomba Regional Council's water security strategy to guide their water planning over the next 30 years (Engeny 2020). It anticipates Equivalent Person demand on the Toowoomba bulk water supply system to increase approximately 80,000 (from 193,000 to 270,000) by 2050, with the average day demand primarily driven by population growth.

Strang (2004, cited in Head and Muir 2007) theorised domestic water users have become impervious to water conservation. Water is perceived by gardeners as a "precious resource that has been mismanaged by successive governments" and that government is responsible for the availability (or lack) of water (Head and Muir 2007). They found many gardeners did not connect their personal use of water to water in the greater environment.

Home gardeners need to become conscious soil water managers to optimise soil water inputs and minimise non-productive losses (Singer and Munns 2006, p. 113). The horticultural, agricultural and landscaping irrigation industries have been continually improving their soil water management to lower costs and improve profits, along with appeasing societal and political pressures for several decades now (Tian and Meyer 2009).

The urban landscape industry has been working on various methods to achieve the same goals. These improvements to water use efficiency across the industries include technology use and updates, along with increased water management education of water users from farm land to processing facilities in soil water movement relating to timing and application volume.

Improving irrigation efficiency has multiple benefits to the water user, local community and waterways as well as further downstream. By lowering water use, the user has decreased their immediate water cost, along with those of the municipal water provider. Less runoff and deep percolation results in decreased down-stream/ground water stresses such as turbidity and nutrients. Water demand on urban facilities is eased and increases future water security. Plant production is increased as stress from saturation or insufficient moisture is minimized.

Water efficiency in home gardens should consider user behaviour and influences to ensure the change of irrigation practice is to be taken up permanently (Manning et al. 2013). The millennial drought (1997 to 2010), as experienced in Melbourne, further proves consumer behaviors need to be considered, with majority of water reductions occurring through sustained behaviour change (Rowley 2016). The “Our Water, Our Future”, and other programs initiated during the drought, were based on behaviors researched by psychologists and in consultation with the communities and groups having to change water use behaviors (Rowley 2016). These behaviors have out-lasted the drought, with water use remaining approximately 166 L/c/d (target is 155 L/c/d), compared to 247 L/c/d prior to the drought (Rowley 2016).

Current research into improving garden watering efficiencies in Australia has primarily focused on sprinklers and automated systems. The research has shown how domestic water consumers are currently using water and highlighted areas for improvement (Maheswari 2016; Manning et al. 2013; Nouri et al. 2013a). Manning et al. (2013, p. 5-6) showed water consumers require a direct and active method to judge their water use against. This work seeks to determine if industrial irrigation scheduling methods can be transferred to a smaller scale in domestic gardens.

3.2. Importance of gardens

Gardening is more than a simple activity and place of growing plants (Dunnett and Qasim 2000, p. 40). It has long been recognised as providing a range of pantry, health, and social benefits. In particular, FAO (1995b) defines the home garden as 'a farming system which combines different physical, social and economic functions on the area of land around the family home.' Gardens are outdoor spaces used for food, display, social meetings, children's play, shade, animal rearing, and green waste disposal (FAO 1995b; Dunnett and Qasim 2000; Chalmin-Pui et al. 2021).

Urban gardens provide many psychological, physical, and health benefits to gardeners and visitors alike (Ward Thompson et al. 2016, p. 440, Chalmin-pui et al. 2021, Rosalund et al, 2020). Dunnett and Qasim (2000, p. 42, pp. 3) found more than 75% of gardeners felt they received mental benefits such as satisfaction and relaxation from their gardens. Gardeners use watering time for 'time out' pleasure (Head and Muir 2007). Physical activity is increased in gardeners (de Bell et al, 2020), with physical benefits of gardening for elderly residents including more muscle mass, aerobic endurance and hand dexterity (Park et al, 2016). Rosalund et al. (2020) found gardening can also reduce immune-mediated disease risk.

Children also gain significant benefits from gardens. Richard Louv (2005, cited in Watts 2011) found regular exposure of children to natural environments improved mental health conditions. This included reduced attention deficit hyperactivity disorder (ADHD) as well as anxiety and depression, while self-esteem increased. Furthermore, gardening and natural ecosystem exposure in childhood to increases stewardship later on (Watts 2011; Langemeyer et al. 2018, p.79).

Gardens have an increasing important environmental benefit. Private gardens provide the most frequent contact with nature for the majority of the urban population (Dunnett and Qasim 2000, p. 40). Gardens increase urban biodiversity as a provision of habitat and resources (Chalmin-Pui et al, 2021). They create permeable area which reducing flood risk by lowering surface water run-off. Furthermore, gardens can create their own microclimate, therefore working to reduce urban heat (Van den Bosch and Sang 2017).

Gardens also play an economic role. Houses with gardens have higher sale price, with the bigger the garden the higher the increase (Lake, Lovett, Bateman and Day 2000, cited in de Bell et al. 2020).

3.2.1. Concerns from inefficient watering of gardens

Gardening has become an increased past time for Australians, with over 2 billion plants purchased in 2020 (ACIL Allen 2021). This figure has been increasing since 2016, with 49% of businesses experiencing higher sales since COVID-19 in Australia (ACIL Allen 2021). More plants means in increased water usage to maintain plant vigor and production. Water use is higher by residents who perceive and receive more benefits from their gardens (Syme et al, 2003). Water use is also influenced by socio-demographic variables such as block size, lifestyle, garden interest and garden recreation activities (Syme et al, 2004).

Water is applied to gardens when the gardener believes there has been insufficient rainfall to maintain soil water requirements for their desired plant outcome (Lewis 2014). This varies from plant survival to active growth and production, or for establishment of new plants and seeds. The water volume applied changes with seasons and increases with larger block size, garden interest and recreational use (Jacobs, Du PLessis, and Knox 2020; Syme et al, 2004).

Commonly water is arbitrarily applied via individual intuition which varies with experience. This can lead to either under watering or over watering. The latter leads to water lost as it passes the root zone. It can also result in soil saturation, preventing oxygen transfer between roots and soil atmosphere which decreases nutrient absorption and root growth. The excess water can be considered as wasted and incurs immediate financial cost in water rates, leached nutrients and chemical controls degrading the receiving water quality (Singer and Munns 2006, p.111). Conversely, under watering causes plant wilt and death, along with limited soil nutrient transfer to the plant.

In their Sydney based study, Maheshwari (2016) found garden spaces use two thirds of domestic irrigation water while lawns account for the remainder. When this water consumption was compared to ET estimates for the time and place of study, gardens were over irrigated up to four times the amount required per unit area. Hand watering and microjet irrigation systems accounted for majority of garden watering methods (Maheshwari 2016).

The QLD Department of Primary Industries and Fisheries investigation into water use efficiency of hand watering in production nurseries and retail business also concurs gross over watering (McMahon 2009). This covered a variety of nursery water experience levels, from apprentice to “experienced”, which is concerning considering 55% of production nurseries and 94% of retail businesses in Australia hand water (McMahon 2009).

3.3. Current domestic garden irrigation timing and application methods

Experience and knowledge levels of home gardeners vary, from beginner to professional (ie: landscape gardeners). Current literature shows that in general a typical home garden manager uses low tech monitoring and watering technology in the plot, and is not well trained in irrigation science principles (Gardening Australia 2022; Yates Garden Guide 2006), or plant water needs (Costello and Jones 2014;Yates Garden Guide 2006).

When to water the garden, and how much to apply, is generally an arbitrary decision made by the gardener (Cubino, Subiros and Lozano 2014; Myers, Mohring and Anderson 2017). It is typically based on either sight or time (Gardening Australia 2022; Myers, Mohring and Anderson 2017). It will depend on the plant/area goals of the gardener, ie: plant maintenance vs vigorous growth or edible crops.

Gauging of time to water by sight includes eyeballing plant appearance, checking soil moisture with a finger or wooden dowel, or soil moisture hygrometer available from local garden centers (Gardening Australia 2022). Commonly gardeners are encouraged to water once the soil is dry when finger is dug into the top 2-5cm, or the soil visually looks dry (Gardening Australia 2022; TRC 2022b; Yates Garden Guide 2006), provided the plants are not showing signs of water stress such as wilting.

The use of time to decide irrigation timing is an individual judgement based on time since last watering. It can be a set schedule; ie: water every 3 days, or it may have other influencing factors, such as seasonal considerations including watering everyday in summer and watering once a week in winter (Costello and Jones 2014).

3.3.1. Influencing factors

There are many factors which influence the decision to water. These can include the climate and season of area, perceived wetness of soil, plant type and life stage, plant performance, demographics, commodification of water, current water use policy and restrictions, and to some extent the chosen watering apparatus. Social pressure may also affect watering times and amounts, particularly if it can be seen by the surrounding community (Manning et al. 2013, p. 8). Examples include limited watering of plants visible from the roadside, while regularly watering plants inside screening (such as privacy fences and hedges) which cannot be seen from the roadside; or long term changes in water use such as those seen post Melbourne millennial drought (Rowley 2016).

Income can influence watering practices. Domene, Sauri, and Pares (2013) discovered a preference for lower income households to cultivate climate adapted species for the local area. In comparison, they found higher income households choose plants and watering schedules with higher water use. In addition, Inman and Jeffrey (2006) showed low income households are more likely to implement behavioral changes or water saving technology with no cost. Cultural norms can also influence water use (Inman and Jeffrey (2006).

Water restriction policies have varying effects on users. Renwick and Archibald (1998) found they have largest effect on high garden water users with little change in small users. Potentially small users are already under-watering or have predominantly rain-fed gardens. Their research also found steep increases in water block prices reduced water consumption.

Inman and Jeffrey (2006) found water restrictions lower water use through changing consumer behaviour in regards to watering times and amounts. Once lifted, these policies did not see any lasting change in water use. This contradicts the finding from Rowley (2016) of sustained long term change in water use after the millennial drought in Melbourne. The reason for this may be long term psychological changes were made by water consumers in Melbourne, rather than only obeying short-term enforced water use practices. Inman and Jeffrey (2006) also state long term behaviour changes stem from education of efficient methods and tools, compared to public awareness campaigns which only have a short period of lowering water consumption.

Metering can initially lower water use by almost up to 20% (Maddus 2001, cited in Inman and Jeffrey 2006). They found this effect dissipates over time and water use increases again. Chesnutt and McSpadden (1991 cited in Inman and Jeffrey 2006) found automatically timed irrigation methods used more water (11.2% on average) than hand watering. Therefore providing households with engineered devices is not effective in the long-term, although (Inman and Jeffrey 2006) suggested this was due to users offsetting behaviour from awareness of their water-savings in one area and increasing use in another.

Manning et al. (2013, p.4) found consumers believed changing their water schedules to match seasonal and landscape needs was more achievable than soil amendments to retain moisture. Watering implements should be tested and/or calibrated for the local climate as well as end user requirements (Manning et al. (2013, p.9).

3.4. Water authority hand watering guidance

Common water advice to gardeners is often broad without provision of specific scheduling times and volumes. Gardeners receive tips and advice from a variety of sources including Word of Mouth, blogs, TV shows, books, magazines, YouTube and other video sharing platforms, and podcasts. These primarily offer simple advice such as to plant a "water wise" garden (ie: drought tolerant/local native plants, or group plants with similar water needs together), use water wisely ie: water early in the morning or later afternoon, or use mulch to retain soil moisture among (Orica 2006 p.81-97; Stewart and Bishop 2019, p. 147-149, TRC 2022b). This advice does not provide specific water volumes, application timings and rates for their soil and plants for their local climate.

Historically, governments increase the intensity of water saving messages during times of supply drought. For example, the millennial drought saw significant advertising in Melbourne and Sydney in particular on how households could lower water use. The Greenlife industry recognizes that any water restrictions can impact gardeners by lower rates of plant success with reduced enjoyment (ACIL Allen 2021).

Several ongoing water wise urban and domestic policies have been put into place, such as state government water efficiency rebates and offers (Department of Climate Change, Energy, the Environment and Water 2023) in efforts to lower water consumption. In July 2023, the Western Australian Government was the only state government with current incentives to improve water efficiency in the garden.

While all levels of Australian government provide garden water saving advice through their websites for the general public, these are primarily the standard advice listed above. The Western Australian government however clearly demonstrates a commitment to educating the general public on specific changes and improvements. The Western Australian Water Corporation has developed a very comprehensive *Waterwise* program to promote water conservation across the state (Water Corporation 2023). The program includes an endorsement for local governments who demonstrate leadership in sustainable water management (currently 64 out of 139 (Water Corporation 2023)), along with an online tool to determine which plants are low water use based on the locality of the user.

The University of California Davis (UCDavis) California Center for Urban Horticulture has a much more in-depth plant water calculator than that of the *Waterwise* online tool. It has created an online portal for Water Use Classificaton of Landscape Species (WUCOLS) which provides irrigation water needs for 3500 taxonomic plant groups based on the local region. (UCDavis 2023). This method is discussed in depth in section 6.4.2.WUCOLS method (M3).

Local governments and water suppliers are in a great position to provide specific watering advise related to the local region to their customers. While the TRC website lists standard general water wise practices, it also specifies a maximum water application for a sand, loam, and clay soil (TRC 2022b). These are 12, 42, and 28mm respectively per 20mm depth. It should be noted the website does not detail how these values were determined.

The Phoenix area of the United States of America goes further by providing detailed landscape watering requirements for their residents (Figure 2:1). This lists plant category, water category (desser adapted or high water use), the seasonal frequency of irrigation and how deeply to water. It is part of the *Water - Use it Wisely* campaign which was initiated in 1999 and is still ongoing. The primary operating principle has been "Don't tell us to save water. Show us how" (Arizona Department of Water Resources 2018).

WATER USE IT WISELY

LANDSCAPE WATERING GUIDELINES

How Much & How Often Water to the outer edge of the plant's canopy and to the depth indicated. Watering frequency will vary depending on season, plant type, weather and soil.		Seasonal Frequency — Days Between Waterings				Water This Deeply (Typical Root Depth)
		Spring Mar - May	Summer May - Oct	Fall Oct - Dec	Winter Dec - Mar	
Trees	Desert adapted	14-30 days	7-21 days	14-30 days	30-60 days	24-36 inches
	High water use	7-12 days	7-10 days	7-12 days	14-30 days	24-36 inches
Shrubs	Desert adapted	14-30 days	7-21 days	14-30 days	30-45 days	18-24 inches
	High water use	7-10 days	5-7 days	7-10 days	10-14 days	18-24 inches
Groundcovers & Vines	Desert adapted	14-30 days	7-21 days	14-30 days	21-45 days	8-12 inches
	High water use	7-10 days	2-5 days	7-10 days	10-14 days	8-12 inches
Cacti and Succulents		21-45 days	14-30 days	21-45 days	if needed	8-12 inches
Annuals		3-7 days	2-5 days	3-7 days	5-10 days	8-12 inches
Warm Season Grass		4-14 days	3-6 days	6-21 days	15-30 days	6-10 inches
Cool Season Grass		3-7 days	none	3-10 days	7-14 days	6-10 inches

These guidelines are for established plants (1 year for shrubs, 3 years for trees). Additional water is needed for new plantings or unusually hot or dry weather. Less water is needed during cool or rainy weather. Drip run times are typically 2 hours or more for each watering.

Figure 2:1: A screenshot of the plant watering guide detailing water requirements specific to the Phoenix metro area in the United States of America (Water - Use It Wisely 2022).

Majority of suburbs and regions serviced by the Toowoomba Bulk Water Supply are currently on low level water restrictions (200L/p/d target) (TRC 2022a). The details of how each water restriction level affects garden watering scheduling is detailed in Table 2-1. Interestingly it allows for different watering requirements for newly established gardens, which is only excluded in extreme restriction level.

Table 2-1: Toowoomba water restriction level regarding garden watering (Toowoomba Regional Council 2022a)

Restriction level	**Target water use (L/p/d)**	**Allowed watering times**	
		Established gardens	**Newly established gardens**
Low	200	Using a watering container, hand-held hose with nozzle, or efficient irrigation system before 10am and after 4pm any day except Monday.	Newly established gardens have the same restrictions as established, with the exception of watering any time on the day of establishment.
Medium	175	Using hand-held hose with nozzle or efficient irrigation system on the below times: Odd numbered premises Tues, Thurs & Sat. Even numbered premises Wed, Fri & Sun Summer (1st Oct to 31 March 5:30pm to 6:30pm) Winter: (1 April to 30 Sept) 4:30pm to 5:30pm	Exception of 1hr anytime on day of establishment and 1hr daily for the following 14days before following established garden timings.
High	150	Using hand-held hose with nozzle Odd numbered premises Tues & Sat. Even numbered premises Wed & Sun Use summer and winter times as above. If using watering container, all properties can water before 8am and after 4pm any day except Monday.	Exception of 1hr anytime on day of establishment and 1hr daily for the following 14days before following established garden timings.
Extreme	125	Using watering container Odd number premises - Sat Even numbered premises Sun Use summer and winter times as	No new garden watering permitted

		above.	

3.5. Industry irrigation scheduling

Urban water conservation is necessary from a utilities perspective (Syme et al, 2004). Lowering of water demand is considered more sustainable than other methods of increasing water supply (Inman and Jeffrey 2006). Various irrigation industries have proved water demand can be lowered through the educated use of irrigation schedules which consider soil properties, crop type and life cycle, as well as evapotranspiration. This section will investigate some of the various irrigation methods developed by industry

The Cooperative Research Centre for Irrigation Futures, and Irrigation Association of Australia are two national bodies which have formed for the education of irrigators across agriculture and horticulture industries. Numerous more irrigation education, research and development is carried out by industry or crop specific entities, such as Cotton Research and Development Corporation, Grains Research and Development Corporation, and Horticulture Innovation Australia.

Primarily industry methods of irrigation scheduling rely on on some estimation of evapotranspiration (ET) and a soil water balance (SWB). ET and SWB are discussed in detail in the following sections. Following this, specific industry scheduling methods are discussed.

3.5.1. Soil Water Balance and ET estimation

Historically soil water balance (SWB) has been the conventional method of monitoring ET (Nouri et al. 2016; O'Connor 2017). It monitors all water inflows [Precipitation (P), irrigation (I) and water table upward flows (W)], outflows [ET, runoff (R) and drainage (D)], and determines change in soil water content (ΔSWC)] (Equation 2-1). SWB errs when applied to large areas, as samples need to be representative of soil water properties (ie: drainage, bulk density, water holding capacity, and saturated hydraulic conductivity) (Nouri et al. 2016). This is further complicated in garden settings, as vegetation types, soil, water and microclimate can vary significantly within the same garden plots.

$$\mathrm{P} + \mathrm{I} + \mathrm{W} - \mathrm{ET} - \mathrm{R} - \mathrm{D} \ = \pm \ [\Delta\mathrm{SWC}]$$

Equation 2-1

3.5.2. Evapotranspiration

ET is the total water lost via evaporation (moisture moving from soil, vegetation interception, and water sources) and plant transpiration (vapour released from leaf stomata). While difficult to calculate, ET is an essential part of crop irrigation requirements and SWB calculation. ET can be calculated at various scales, ie: leaf, individual plant, field, or landscape (Verstraeten, Veroustraete and Feyen 2008). For the rest of this research work only field scale is considered.

The FAO-56 ET estimation method described by Allen et al. (1998) is most commonly used (Raza et al. 2021; Verstraeten, Veroustraete and Feyen 2008). Potential ET (ET_{pot}) of a crop is the maximum volume transferred to the atmosphere which corresponds to a reference crop ET (ET_O) by use of a crop coefficient (K_c) (Equation 2-2) (Verstraeten, Veroustraete and Feyen 2008; Allen et al. 1998). Globally a uniform alfalfa (or grass) field of significant area under standard meteorological and agronomic conditions is used to determine ET_O (Allen et al. 1998; Raza et al. 2021). The soil properties are also included in this reference. There are a variety of methods to determine K_C across industries and these are described in following sections.

$$ET_{pot} = K_C \cdot ET_O$$

Equation 2-2

A lysimeter can directly measure actual evapotranspiration however is expensive and time consuming (Raza et al. 2021). Weighing lysimeters measure soil water content by determining the mass change of a soil volume over time (Howell, 2005). Nouri et al. (2013b) concluded lysimeter measurements are not practical for determining landscape ET for a variety of reasons, particularly the due to the prevalence of heterogeneous plantings, geometries and maintenance requirements within landscape gardens.

Similarly sap flow measurements are not suitable for landscape ET measurements as they only measure a single point (Nouri et al. 2013b).

Remote sensing ET estimation

Remote sensing of soil moisture is relatively new, and cost depends on which sensors and satellites are used (Nouri et al. 2016). Imagergy has been used in agriculture and natural ecosystems using vegetation index methods. Optical bands are used to approximate canopy greenness which is directly related to transpiration (Nouri et al. 2016). The sophistication of the estimation method depends on funds available and time to digitize individual plant classes along with resolution size. Landscape areas measured using remote sensing also need to be large enough for the sensors. Nouri et al. (2016) found Moderate Resolution Imaging Spectrometer (MODIS) sensors based on the Enhanced Vegetation Index (EVI) on an annual time-step to be very close to the SWB estimate in their comparison study in Adelaide, South Australia. However the monthly time-step produced errors in estimations, and was not appropriate for irrigation scheduling.

3.5.3. Soil water content

The SWC is located within the top 1-2m of the profile, and therefore prone to evaporation (Verstraeten, Veroustraete and Feyen 2008). SWC varies over time due to inputs and outputs, and is directly related to ET as seen in Equation 2-1. It is heavily influenced by soil texture and structure, due to the size and tortuosity of pore spaces. The hydraulic conductivity, sub-soil constraints (acidity/hardpans), and bulk density also influence the SWC.

Soil texture is difficult to change, although the existing soil can be covered, or dug out and replaced, with a soil with better properties for soil water retention and flow. Amendments can also be applied, such as compost, to increase water holding capacity along with other soil properties.

The other properties affecting SWC are easily altered by soil disturbances. Annual or seasonal gardens are regularly turned over and weeded, therefore these properties are not considered further in this research project.

SWC can be measured a variety of ways in the field, including ceramic suction plate, pressure plate, or filter paper methods, as described in McKenzie, Coughlan, and Cresswell (2002 , p. 59-84). The gravimetric method is the simplest. A field sample is weighed (W_1), oven dried for 24hr at 105°C and weighed again (W_2). The gravimetric water content (GWC) can then be easily calculated as the water removed divided by the oven dry weight:

$$Gravimetric\ water\ content = \frac{(W_1\ - W_2)}{W_2}$$

Equation 2-3

This method only provides the GWC at that point in time. To continuously monitor a soil's moisture content, multiple samples must be taken over the period of drying and/or wetting.

This method is not practical for home gardeners, as there is a minimum 24hr delay in results, as well as having to send samples to a soil laboratory.

The GWC method is commonly used to calibrate all other SWC methods (Verstraeten, Veroustraete and Feyen 2008). Other methods can directly measure the SWC, and include tensiometers, soil moisture blocks, time domain reflectrometry sensors (TDRS), neutron probes, and remote sensing.

Tensiometers measure the negative pressure (suction) of water held by the soil. The plants extract the more readily available water from large pore spaces first, which is low tension. This occurs at field capacity (FC) (8-10kPa generally) (Agriculture Victoria n.d.). As the plants continue to extract the water, the tension increases as the more tightly held moisture is extracted. The tensiometer works by being partially buried at the required depths for the crop. Water flows freely in and out of the ceramic tip as the soil dries and wets. The outflow creates a partial vacuum between the tensiometer and soil, the value of which is indicated on the gauge. In extremely dry soils, the vacuum seal can be broken which is why the gauges are recommended for use up to 75kPa, after which their accuracy is questionable. Manual read devices may cost a few hundred dollars compared to screen read devices ranging up to thousands (Agriculture Victoria 2017).

Soil moisture blocks indirectly measure the field SWC by measuring the electrical resistance of a buried porous block. The gypsum block can absorb water which increases the electrical conductance of the block. When the soil dries, the water leaves the block and the electrical conductance decreases again. Agriculture Victoria (n.d.) report the gypsum blocks are capable of measuring soil water tension from 30-1500kPa, limiting their ability to measure moisture near FC. Schwankl et al. (2002) agree that this method is not suitable for high soil moisture content due to frequent irrigation, however it does provide a wider range of moisture level compared to a tensiometer. Device cost again ranges in price from a couple hundred to thousands depending on manual or screen read capabilities and the number installed (Agriculture Victoria 2017).

Time domain reflectometry sensors are another method. Two or three parallel rods are placed into the soil and a voltage applied. The velocity of the electromagnetic pulse is measured, with velocity decreasing as soil water content increases. This pulse is converted into percent SWC. Good soil contact is required to prevent errors from air gaps. This potential for error increases with depth. TDR is not recommended for soils with high electrical conductivity levels, as this causes the measurement to not be recorded as the pulse is prevented from being reflected back on the rods. The information is recorded on a data log device. Typically traditional TDRS range from $500 to thousands of dollars, depending on brand, number, data log device, etc, however low cost versions are undergoing research (Blonquist, Jones and Robinson 2005). There is also a time delay in the data, which varies depending on the spacing through the profile, as the wetting and drying front must reach the sensor (Hagenau, Kaufmann, Borg 2020).

Neutron probes indicate soil moisture based on measurements of thermal neutrons. An access tube is placed in the soil at the sample site and the probe inserted which emits fast neutrons. The probe measures the neutrons which slow due to interactions within the soil (Fayer and Gee 2005). These neutrons form a cloud of thermal neutrons, which depend on soil water along with other soil properties such as bulk density, bound water, soil-water elements and organic matter content (Fayer and Gee 2005). Of these, hydrogen has the greatest potential to affect the thermal neutron density, and water is the major source of these. The probe should be calibrated to each site by taking undisturbed soil samples at same depth directly adjacent to tubes for laboratory measurement to prevent error occurring from soil conditions and properties. Overall, the neutron probe is considered to give accurate soil water content values. It has comparatively large sample spherical volumes (15-30cm radius) (Fayer and Gee 2005). These probes are expensive and less reliable at shallow depths (ie: <30cm) due to air samples being included in the measurement. They also require radioactive precautions and are labour intensive.

Remote sensing is a relatively new method of observing moisture levels of the top centimeter of soil at a global level (Robock 2015). This near-surface moisture can then be used to estimate soil moisture at increased depths through models and data assimilation (Mohanty et al. 2017; Robock 2015). Resolution of this measurement is variable depending on the instrument and satellite platform used, anywhere from 0.003 to 156km (Mohanty et al. 2017). This scale means the surface soil characteristics, properties, topography, etc, are not uniform as they are for the ground-based methods discussed earlier. Therefore this method is not suitable for small scale, particular point in time applications. This was confirmed by the previously discussed study by Nouri et al. (2016).

Overall, these methods and apparatus are not practical for home garden use due to expense, not applicable for small scale, or don't give data close enough to real time to be usable. The next sections describe methods of calculating ET or SWC for irrigation scheduling across agricultural, horticultural and landscape industries. It is anticipated some of these methods may be able to transfer to a small scale home garden irrigation schedule.

3.5.4. Agricultural irrigation scheduling methods

Irrigation quantity can be estimated either by soil moisture measurement or SWB accounting. The field soil moisture measurement requires regular soil moisture measurements to predict when irrigation is required to prevent the soil moisture level going below a desired depletion point. SWB accounting requires calculation of a daily water balance equation to schedule irrigation from crop evaporation calculations. The soil water storage at the end of the day (or time period) is a summation of daily water inputs (rain, irrigation, and upwards groundwater movement) minus the outputs (deep percolation, actual evapotranspiration, and runoff) plus the daily initial soil water depth. It is difficult to calculate deep percolation and upward ground water movement, resulting in them being ignored or assumed negligible.

Both methods require a maximum allowable depletion point to be decided, typically based on end requirement of the crop and or crop growth stage. The field capacity (FC) also needs to be measured. The irrigation event then applies sufficient water to recharge the soil moisture level from the depletion point back to FC. The soil moisture measurement method of scheduling is considered to be the most accurate schedule method to date and provides an accurate estimation of water application quantity.

Agricultural irrigation schedules can be directly determined by SWC measurements. As discussed in previous sections, SWC can be scientifically measured via several apparatus. These measurements can be used to calibrate and determine accuracy of the various programs utilised by farm managers, or may feed directly into the calculations for the irrigation schedule.

The Agriculture Victoria website <https://www.agriculture.vic.gov.au> provides numerous comprehensive technical papers on the installation and use of tensiometers and soil moisture blocks to determine when to irrigate. The irrigator determines the appropriate root zone depth for the crop, and places at least 1 meter in the active root zone of the crop and 1 at the bottom of the zone to determine subsoil moisture and deep percolation. Other meters may be spread through the root zone, depending on the depth to monitor water infiltration and retention throughout the profile. The data is presented as tension (kPa), and the irrigator simply needs to know the tension limit for FC (typically 8-10kPa) and the refill point (the maximum tension point for the crop to draw water to, past this point the crop will become stressed). The refill point may change throughout the life stage of the crop, and for crop type.

Volumetric methods are also employed, which includes TDRS. Volumetric data allows for the timing irrigation and the amount of water to be applied to be determined. Aside from initial installation, this is a non-destructive method of determining SWC. Commonly multiple sensors are placed at varying depths, depending on the root zone of the crop, and often consist of 3 (one in high, middle and low zones) (Hagenau, Kaufmann and Borg 2020). Similar to use of tensiometers, the FC of the soil is determined along with refill point. Once the refill point is reached, irrigation occurs and the application volume is known to reach the FC of the field. TDRS are point based measurements and therefore errors can arise when the value is extended across fields.

Alternatively, the ET_{pot} of a crop can be estimated prior to the season based on historical ET_O and rainfall. From this a predictive irrigation schedule can be developed, where the ET_{pot} minus the rainfall is subtracted over daily (or other appropriate intervals) from the estimated RAW (O'Connor 2017). Irrigation is then scheduled based on the estimated RAW nearing/reaching 0. Alternatively the same calculations can be made using the seasonal ET_O during the crop growth for a more accurate ET_{pot} (denoted as ET_a for actual crop ET, or ET_c).

There are many methods to calculate ET_a, however the FAO56 Penman Montheith approach is still standard in agriculture (Zeleke and Wade 2012; Raza et al. 2021). Crop water required for a given period depends on the amount of evapotranspiration (ET) (Gabr 2021), which in turn depends on weather parameters and crop characteristics, as well as management and environmental aspects (Allen et al, 1998). Allen et al. (1998) provides comprehensive detail on calculating K_C for Equation 2-4.

$$ET_C = K_C \cdot ET_O$$

Equation 2-4

There are numerous computer programs to provide educated estimates and advice, and research is currently investigating how internet of things (IoT) can assist in automating and optimizing in-field water applications for irrigators (Gabr 2021; Mohammed, Riad, Alqahtani 2021; Myers, Mohring and Anderson 2017). A list of some Australian programs and apps which can be used to assist in ET estimation, SWB calculation, and/or work towards creating an irrigation schedule include:

- Computer models and programs - APSIM, SoilMapp, APSoil, Yeild Prophet, MySoil, (Hall and Summers 2021), Agriculture Victoria soil moisture monitoring site portal

- Plant Available Water (PAW) maps & estimation- Australian export grain innovation centre (AEGIC), CSIRO, DPIRD Seasonal Climate information, SoilWaterApp (SWApp) (Hall and Summers 2021)
- CliMate - weather data and simulates soil water for bare soil (Hall and Summers 2021)
- CosmOz - Cosmic ray probes in a national network to measure average soil moisture 10-50cm deep over 30ha (GRDC and UniSQ 2023)
- Irrigrow
- ASRIS - L5 ASC soil order
- Acclime snap view

3.5.5. Horticultural and nursery methods

Henderson (2006) provides four broad categories of irrigation scheduling methods used by vegetable growers. These are intuition, weather-based, simple soil based, and electronic systems. Henderson (2006) reports producers often initially utilising electronic systems to develop their intuition and experience before switching to a simpler method such as tensiometer or intuition.

An intuitive method is generated by historic experience intuitively allowing for climate factors (ie: rainfall and evaporative demand), crop growth stage, and water quality and availability (Henderson 2006). This method is used due any of the following:

- low priority of water management due to competing farm issues,
- Producer belief the cost and time investment of an objective measurement system is too small to be justified and/or give better results,
- Bad experience from previously used scheduling equipment,
- Producer believes they no longer need to invest in ongoing objective measures as they have gained enough instinctual knowledge and experience.

Weather and water budget approaches are limited in stand-alone use to simple rainfall and irrigation application records which are compared to intuitive or historical guesses of water requirements (Henderson 2006). Simple tools such as handheld manual moisture probes or tensiometers are widely used (Henderson 2006). These are relatively inexpensive for commercial growers (Henderson 2006, Hunt 2022).

Electronic irrigation scheduling systems use SWC measuring technology combined with manual or electronic logging and data storage (Henderson 2006). These systems are frequently used with associated software or irrigation management programs, and may also incorporate linked irrigation controllers to become fully automated (Henderson 2006). Hunt (2022) points out SWC technology is only as efficient as the irrigation system in use, with SWC sensors only assisting to manage an inefficient system more efficiently. Producer interest and uptake of electronic systems is usually influenced by either locally accessible consultancy firm, technical support from equipment suppliers, or from government and NRM program initiatives (ie: extension agents and demonstrations).

Rolfe (2006) provides a simplistic weighing lysimeter method for determining plant water use for nursery pots. This requires selection of a pot and plant representative of the plants to be watered under the regime. The FC of the pot is determined by weighing the sample pot/s once all free draining water has left the pot. The same pots are then weighed again prior to irrigation. The volume required to replenish the pot is determined based on the size of the pot and the weight loss. Rolfe (2006, p.3) provides a table of various container size and the associated weight loss (g)/mm refill required.

3.5.6. Landscaping methods

A significant difference between gardens and crops is that gardens generally contain a wide variety of plants and water needs, compared to a large mono-crop. The ideal water efficient garden would consist of seasonal and/or perennial plants that are suitable for the expected natural soil water schedule of the local region, however this is often not the case for many professional (or home) gardeners. Additional irrigation water is applied to plants to maintain plant survival at a minimum, with increased growth, flowering, and/or fruiting being the main goals of the gardener.

ET can be estimated via observations combined into a landscape coefficient (Nouri et al. 2013a; Saher, Stephen and Ahmad 2021). Saher, Stephen and Ahmad (2021) note there are two main categories driving ET in urban spaces, the type and size of green space and the microclimate and climate effects. Climate parameters include surface heat flux changes and complex wind profiles while green space factors include oasis style advection from xeric and mesic greenscapes (Saher, Stephen and Ahmad 2021). This complexity in modelling of urban ET distinguish it considerably from agricultural mono-crop calculations.

Various landscape coefficient methods (LCM) have been developed (Nouri et al. 2013a; Saher, Stephen and Ahmad 2021). The Water Use Classification of Landscape Species (WUCOLS) ET calculation method (Equation 2-5) is widely used in California. This method was developed via expert opinion from a panel of 36 landscape horticulturists instead of measured landscape properties. Therefore it may not be applicable or accurate outside of the landscape it was validated in.

The WUCOLS method calculates a landscape ET (ET_L) similar to the agricultural ET_C, however the coefficient used (K_L) is calculated by 3 factors, species factor (K_s), density factor (K_d) and micro-climate factor (K_{mc}). Costello, Matheny and Clark (2000) provide a guide on how to estimate these factors and acknowledge the accuracy improves with experience.

$$ET_L = ET_o \cdot K_L$$

Equation 2-5

Where: $K_L = K_s \cdot K_d \cdot K_{mc}$

The determination of K_s, K_d and K_{mc} is discussed in further detail in section 3.2.3 WUCOLS method (M3): .

Nouri et al. (2013a) compared three LCM in park lands in Adelaide, South Australia. They found the WUCOLS method of calculating ET_o to be more accurate compared to plant water use factor (PF) or irrigated public open space (IPOS-2008) methods. IPOS-2008 is primarily used for turf, and determines plant ET (ET_L) from the relationship between ET_o, the turf grass coefficient (K_c) and crop stress factor (K_{st}). K_{st} ranges from 0.4 (passive recreational turf) to 1.0 (elite sporting turf) (Nouri et al. 2016).

$$ET_L = ET_o \cdot K_c \cdot K_{st}$$

Equation 2-6

PF method determines ET_L via a relationship with ET_o. This is a coefficient for minimum irrigation required for acceptable aesthetics of the garden plants (Nouri et al. 2013a)

$$ET_L = ET_o \cdot PF$$

Equation 2-7

Nouri et al. (2013a) found Water Use Classifications of Landscape Species (WUCOLS) landscape plant coefficient for water consumption estimation the closest match to actual water use when trialed in Adelaide Parklands, South Australia. Soil water balance or similar in-situ methods should be compared to the estimated water requirements (Nouri et al. 2013a).

Domene, Sauri and Pares (2005) use Costello, Matheny and Clark 1992 method:

$$GWR = (ETJ - P)/IE^{8}$$

Equation 2-8

Where - GWR = Estimated garden water requirement

ETJ = Garden evapotranspiration

P = Precipitation

IE = Irrigation system efficiency

3.6. Feasibility of industry methods in domestic gardens

The main difficulty in transferring industry methods to home gardens is the non-heterogeneity of home gardens, particularly compared the crop uniformity of broad-acre cropping and horticulture fields. Agricultural cropping practices allow for relatively straight forward calculation of ET in comparison to home gardens (Nouri et al. 2013a). ET can be a complicated and time consuming method to calculate daily, particularly for a home gardener who's education level varies. While sensors such as TDRS or tensiometers could be employed in a home garden, the purchase cost, technology requirements and/or maintenance of such can present a barrier for home garden use.

Nursery pot plants see more variation in plant types and growth stage, and are therefore potentially similar to home gardens in their non-heterogeneity. However these plants are in pots with much smaller soil water storage available than a garden bed and therefore their water requirements could vary quite significantly.

It seems that any of the above methods would need to be trialed to determine if:

1) they can transfer to home garden use,
2) they actually improve water efficiency while achieving the gardener's goals, and
3) if future research could improve the practicality for home use.

3.7. Plant water requirements

Plant water requirements vary depending on species, soil, and climate. It can also vary depending on if the irrigator is maintaining a full profile of water or using deficit watering techniques. Theoretically, vegetable gardens should be able to follow irrigation requirements for each crop. Garden plant water use could vary greatly to agricultural crops however due to a variety of factors, including small and/or overlapping plantings, as well as numerous factors affecting microclimate.

Ornamental water requirements will depend on life stage and desired growth performance - ie: freshly planted will desire high growth rate. Mature plants only need to maintain vigor and flower flushes (or any other special properties of the plant throughout the season/lifespan). Plants that go dormant seasonally or for other reasons will require less water during these periods.

How much water to apply to vegetation will depend on when the irrigation is scheduled in relation to the SWC of the area. SWC is largely determined by the soil texture, which is discussed in the following section. The rate of infiltration will also affect the irrigation discharge rate, and is discussed in the subsequent section. A method to determine irrigation volume is discussed in the final subsection.

3.7.1. Soil texture

Soil texture is widely recognised as affecting plant water requirements (Lacey 2019; GM Bowman and J Hutka in McKenzie, Cresswell and Coughlan (2002)). This determines the hydraulic conductivity, and soil water holding capacity along with other soil properties (GM Bowman and J Hutka in McKenzie, Cresswell and Coughlan (2002)). Table 2:2 provides RAW requirements at specific tensions for water sensitive crops (including vegetables), fruit crops, perennial pastures, annual pastures, and various grain crops for a variety of soil textures.

An approximation of soil texture can be determined using the bolus and ribbon hand method in the field. Accurate results from this method rely on the person conducting the method to have considerable experience. This is because the method is subjective, with organic matter, clay mineralogy and cation composition, among other components, influencing the process (GM Bowman and J Hutka in McKenzie, Cresswell and Coughlan (2002)). Laboratory methods are also available, such as Australian Standard 1289.3.6.1 and 1289.3.6.3. These methods involve sieving the soil and using a hydrometer.

Table 2:2: Readily available water requirements for plants and requirement based on soil texture (reproduced from Lacey 2019)

Water Tension	To -20kPa	To -40kPa	To -60kPa	To -100kPa
	Water sensitive crops (ie: vegetables and some tropical fruits)	Most fruit crops (including tropical) and table grapes	Perennial pastures (including lucerne), maize, soybeans, wine grapes	Annual pastures, winter and hardy crops (ie: cotton, sorghum)
Soil Texture	Readily Available Water			
Sand	30	35	35	40
Loamy sand	45	50	55	60
Sandy loam	45	60	65	70
Loam	50	70	85	90
Sandy clay loam	40	60	70	80
Clay loam	30	55	65	80
Light clay	25	45	55	70

3.7.2. Infiltration

The ability of a set water volume to wet a soil depends on the soils initial water content and holding capacity (Singer and Munns 2006, p.115). It is desirable to have an application rate lower than soil infiltration rate to prevent ponding/runoff and thus uneven infiltration (Singer and Munns 2006, p.115). Once application rate is higher than infiltration rate, the soil's hydraulic conductivity and time of application affect the infiltration rate. Large soil pores, cracks, and/or dry soils with strong structure under wetting have highest initial infiltration rate. Over time this decreases as the water front extends and the water has to travel longer. Eventually the hydraulic gradient eventually reaches a near steady state where the infiltration rate equals the saturated hydraulic conductivity. The relationship between the infiltration water volume in m^3 (Q), infiltration soil surface area (A) in m^2 , and time (t) in seconds to determine infiltration capacity (I) in m/s is shown in Equation 2-9.

$$I = \frac{Q}{At}$$

Equation 2-9

A soil's pore structure has a significant effect on I, and this is reflected in the bulk density. Table 2-3 lists general values for both ideal bulk density for plant root growth and values above which are restrictive across soil types. As previously mentioned, in a garden setting, these values can change many times over a seasonal or annual planting due to soil regularly being turned over for planting, weed removal, and/or amendment additions.

Table 2-3: General ideal and restrictive soil bulk density for root growth based on soil texture (reproduced from USDA 2008)

Soil Texture	**Ideal bulk densities for plant growth (g/cm^3)**	**Bulk densities that restrict plant growth (g/cm^3)**
Sandy	< 1.60	> 1.80
Silty	< 1.40	> 1.65
Clayey	< 1.10	> 1.47

Mulches affect infiltration of water. It is commonly applied in efforts to retain SWC by lowering soil evaporation by slowing and hindering the water and energy exchange from the soil to the atmosphere (Liao et al. 2021; Wang et al. 2021). Wang et al. (2021) found soil water content decreased with increased organic mulch. Liao et al. (2021) similarly found at low irrigation/rain volumes, infiltration was reduced. However they also found following heaving irrigation/rain events, the mulch increased infiltration. This is particularly relevant for regions with heavy rainfall (or irrigation application). Allen et al. (1998) provides adjustments for K_C calculations if mulch is applied, as does the WUCOLS method.

3.7.3. Irrigation volume

Regardless of how the irrigation is applied, the discharge rate should not exceed the soils infiltration rate. This prevents water loss due to runoff.

To water according to RAW needs, Lacey (2019) recommends the following steps:

1. Determine effective root zone depth (generally within top 30cm).

2. Determine the number of soil layers in effective root zone and depth of each layer.
3. Identify soil texture and calculate gravel percentage for each layer.
4. Adjust RAW by gravel percentage.
5. Multiply depth of each layer by adjusted RAW.
6. Total the RAW values to determine total root zone RAW value (in mm).
7. Convert to liters (Lacey 2020a): depends if watering is overlapping or not.
   a) Overlapping volume stored (L): Assumption of wetted strip width (m) multiplied by wetted strip length (or spacing length to calculate volume per plant) (m) multiplied by root zone RAW (mm).
   b) Non-overlapping (assumption of wetted cylinder) (L): pi multiplied by radius (m) squared multiplied by root zone RAW (mm).
8. Convert to irrigation time (Lacey 2020b): Irrigation time (hr) = volume of RAW (L) divided by discharge rate (L/hr).

3.8. Determination of irrigation efficiency

Irrigation efficiency can be calculated several ways, depending on what factors are being measured. Various traditional methods are described in Wang, Zerihun and Feyen (1995), which include application efficiency (E_a), storage efficiency (E_s) (Equation 2-11), and Christiansen's coefficient of uniformity (U_c) (Equation 2-12) . E_a (Equation 2-10) examines the efficiency of the utilisation of the water application without indicating the irrigation adequacy or uniformity. The wetting adequacy of the root zone is measured by E_s (Equation 2-11), however as noted by Wang, Zerihun and Feyen (1995), it does not take into account deep percolation past the root zone. The uniformity is determined by U_c (Equation 2-12) and indicates the final infiltration profile uniformity without considering E_a or E_s. Terms in Equation 2-12 are defined by Wang, Zerihun and Feyen (1995) as "*M* is the mean of *N* single observations of water depth infiltrated at X_i" where X_i is an equal area of the wetted field.

$$E_a = \frac{water\ stored\ in\ the\ soil\ root\ zone}{irrigation\ +\ rainfall}$$

Equation 2-10

$$E_s = \frac{water\ stored\ in\ the\ soil\ root\ zone}{water\ needed\ in\ the\ root\ zone}$$

Equation 2-11

$$U_c = 1 - \frac{\sum_{i-1}^{N} |X_i - M|}{NM}$$

Equation 2-12

At 100% E_a, water is commonly under applied. At 100% E_s, deep percolation commonly occurs due to too much water being applied. Equation 2-10 to Equation 2-12 can be used together to form a more complete description of irrigation efficiency.

Another assessment is to determine the change in SWC (ΔSWC) (Liao et al. 2021). This is simply calculated by Equation 2-13, where SWC1 represents the SWC after irrigation (or rainfall) and SWC0 is the SWC prior to irrigation.

$$\Delta \mathrm{SWC} = \mathrm{SWC}_1 - \mathrm{SWC}_1$$

Equation 2-13

Methods involving the crop yield have also been developed, such as water use efficiency (WUE) and irrigation WUE (IWUE). These methods are calculated as the yield over the ET or water application respectively, and have been reviewed twice, by Zwart et al. (2010 as cited in Corbari and Mancini 2022) and Bastiaaansen and Steduto (2017 as cited in Corbari and Mancini 2022).

Knox, Kay and Weatherhead (2011) argue for calculating efficiency based on economical criteria, which is also advocated in McMahon (2009) for commercial nurseries.

In summary, there have been many attempts over the decades at developing irrigation efficiency further. The variety of methods are best categorized by Pereira and Marques (2017), and include: technical, allocative, economic, overall technical, pure technical, scale, sub-vector, water use, irrigation water use, and irrigation water technical cost.

3.9. Summary

Gardens provide a multitude of benefits to urban populations. The inefficient watering of gardens can cause issues to down-stream water-way health, and has implications on water security. Gardeners who hand water are not regularly using scientific or accurate scheduling methods to determine water application specific to their soil type, with numerous detrimental effects.

Agriculture and horticulture industries have significant research already conducted into crop water requirements and irrigation scheduling. Agriculture crop water needs are less complex due to generally being a mono or dual crop compared to domestic gardens with several plant species at varying growth stages. Never the less, the principles of agriculture scheduling methods could be applied to domestic gardens. Some of the programs used in the determination of the ET and soil water balance calculations can be utilised for home gardens, such as SoilMAPP.

Calculation of evapotranspiration and irrigation schedules appropriate to the differing water goals and vegetation water requirements of landscape gardens have been initiated by landscaping bodies. These take into account mixed plantings and microclimates created in urban spaces.

There is potential for this research to be adapted for domestic garden application. This would help home gardeners to limit plant mortality, lowering plant purchasing expense, and in some cases lowering watering costs, along with improving the ability of water authorities to provide more specific watering guides to service customers. More accurate watering reduces the potential of harmful down stream effects of over-watering, such as nutrients entering waterways, causing algae blooms or increasing the load on municipal water treatment systems.

4. Phase 1 - Research design and methodology

Water savings designs which are aimed at general public use need to consider the consumer behaviour and demographics (Manning et al. 2013). This project considers the use of low cost, low technology education, easily accessible items available to the average home gardener which can be utilised in scheduling hand watering of small urban gardens.

The project was broken down into the following steps:

1. Project preparation: This consisted of the literature review which researched current home and professional methods of irrigation scheduling, affecting factors, and any previous work relating to the research gap.
2. Trial creation and preparation: preparing the garden beds, determining trial methodology.
3. Conducting initial trial phase to allows for any calibration and adjustment of methods.
4. Conduct final trial phase for extended period.
5. Prepare water balance for comparison to trial results.
6. Evaluation of the trial results.

4.1. Trial preparation

4.1.1. Definition and preparation of trial garden site

There is no standard backyard garden, as the heterogeneity of plant species and density are dependent on the individual gardener/home owner. New estate housing is less likely to have established canopy trees, shrubs and bushes compared to older housing areas. The soil and microclimate of all gardens vary spatially. Therefore a garden in the front yard will have different characteristics to one in the back yard, or to the neighbor's garden. The base soil may be the natural soil of the area, however will almost certainly have man-made changes to various degrees. Man-made changes include regular addition of mulch or other soil amendments, imported soils, increased compaction from foot or vehicle traffic, or soil may be regularly turned for annual or seasonal plantings.

The garden areas used for this trial are located in Toowoomba, Queensland. The regional climate is classified as warm temperate, with wet summers and dry winters (Bureau of Meteorology 2016). Average annual rainfall is 952.4mm (Bureau of Meteorology 2022). Higher average rainfall occurs during the summer months (Bureau of Meteorology 2022) (see Figure 3-1). The mean maximum temperature from November to March is 25^{o}C and above for each month (Figure 3-1).

Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Years	
Temperature															
Mean maximum temperature (°C)	27.6	26.6	25.5	22.9	19.6	16.9	16.3	17.9	20.9	23.7	26.0	27.5	22.6	67	1931 1998
Mean minimum temperature (°C)	16.7	16.6	15.4	12.3	9.1	6.3	5.3	6.0	8.5	11.5	13.8	15.7	11.4	67	1931 1998
Rainfall															
Mean rainfall (mm)	132.1	121.1	94.6	61.9	58.4	56.8	52.0	39.5	46.7	72.2	89.5	120.0	952.4	130	1869 2007
Decile 5 (median) rainfall (mm)	115.4	90.4	84.6	49.9	43.5	39.2	41.4	31.0	42.3	59.5	80.0	109.5	917.6	120	1869 2007
Mean number of days of rain ≥ 1 mm	8.2	7.9	7.5	5.3	5.3	4.8	4.7	4.2	4.6	5.8	6.6	7.8	72.7	120	1875 2007
Other daily elements															
Mean daily sunshine (hours)															
Mean number of clear days	5.2	3.7	6.8	8.7	9.7	11.7	14.8	15.0	13.5	10.2	7.5	6.9	113.7	41	1957 1998
Mean number of cloudy days	12.0	11.7	10.5	8.0	10.4	8.2	7.8	6.6	5.8	9.1	9.4	11.4	110.9	41	1957 1998
9 am conditions															
Mean 9am temperature (°C)	21.7	21.1	20.1	17.9	14.8	11.7	11.0	12.3	15.2	18.0	20.2	21.6	17.1	67	1931 1998
Mean 9am relative humidity (%)	75	79	77	73	75	76	73	68	65	66	66	70	72	56	1938 1998
Mean 9am wind speed (km/h)	19.0	20.4	20.8	18.8	18.1	18.0	18.6	19.3	20.3	20.2	19.4	18.2	19.3	41	1957 1998
9am wind speed vs direction plot	PDF	PDF	PDF	PDF	PDF	PDF	PDF	PDF	PDF	PDF	PDF	PDF	PDF		
3 pm conditions															
Mean 3pm temperature (°C)	26.1	25.5	24.3	22.0	18.3	15.8	15.3	16.9	19.8	22.4	24.8	26.3	21.5	49	1949 1998
Mean 3pm relative humidity (%)	57	61	58	56	57	57	53	47	44	49	49	51	53	45	1949 1998
Mean 3pm wind speed (km/h)	17.7	19.1	19.3	18.0	19.5	20.5	21.0	21.4	20.9	19.4	18.7	17.4	19.4	41	1957 1998
3pm wind speed vs direction plot	PDF	PDF	PDF	PDF	PDF	PDF	PDF	PDF	PDF	PDF	PDF	PDF	PDF		

Figure 3-1: Climate statistics for Toowoomba, Queensland (Bureau of Meteorology 2022).

An image of the garden layout in relation to local features (house, impervious features such as footpaths and roads, fences, etc) is provided in Figure 3-2. The garden beds used are noted at M1, M2, and M3, for the 3 scheduling methods trialled. All of the garden beds were created between July 2022 and November 2022. Garden beds consisted of mixed seasonal vegetable plantings. The planting schedule is listed in Appendix F - Garden bed planting schedule.

Garden beds were created by turning over the parent soil to a depth 2/3 of the shovel, applying a 2-4cm thick layer of enriched compost (Seasol and Searles 5in1 organic fertiliser) prior to planting. Up to 7cm thick sugarcane mulch layer was applied surrounding plants after planting. Some sections also had a single layer of cardboard applied to assist with weed suppression during the summer months. It should be noted that while digging the garden beds, particularly M1 and M3, large roots from the hedge were found throughout (approximately 1.5cm diameter).

Prior to beginning of trials a single layer of cardboard and approximately 5cm layer of pine bark mulch was laid in-between garden beds M2 and M3, as well as between the hedges and garden beds, to suppress weeds.

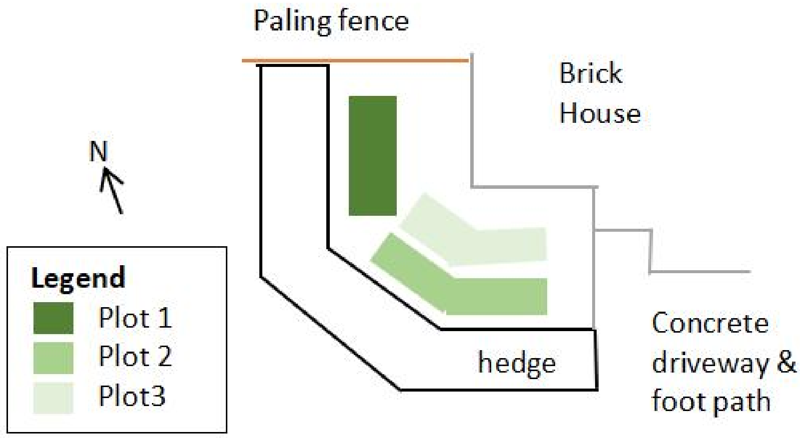


Figure 3-2: Trial site layout.

The goals of the gardener for garden beds with vegetables is to provide fresh produce for the family, while the ornamentals are for privacy and aesthetics, along with reducing grass maintenance. Images of the gardens from the start of the trial are provided in Appendix E - Trial plot photos.

The native soil of the garden area is a vertosol, based on the location inputted into the SoilMapp app provided by CSIRO 2019. Vertosols have clay content 35% and above with strong cracking when dry due to the shrink/swell property (CSIRO 2021). They have very high fertility and water holding capacity (CSIRO 2021). Soil property values were estimated using the ASRIS online soil map tool found at
<http://www.asris.csiro.au/mapping/viewer.htm>, with details displayed in Table 3-1.

It should be noted the soil at the site has had significant human interference within the past 15-20 years as it is located on a relatively new housing estate. Due to the natural slope of the land, the allotment had to be leveled for house construction which resulted in some sections being excavated and others being filled. When digging up the garden beds, decomposing parent material was found approximately 15cm below the surface, particularly in the south west corner. The soil was deeper on the eastern side of the trial site, with the garden fork not digging into parent material. This difficultly is why the garden beds where not dug to significant depth.

Table 3-1: Estimated soil properties

Soil property	Value
Bulk density (top soil)	1.0-1.2g/cm^3
Bulk density (sub soil)	1.2-1.4g/cm^3
Clay (top soil)	20-40%
Clay (sub soil)	40-60%
Silt (top soil)	20-40%
Silt (sub soil)	20-40%
Sand (top soil)	20-40%
Sand (sub soil)	20-40%
Texture (top soil)	Clay loam
Texture (sub soil)	Clay
pH (top soil)	5.6-7.0
pH (sub soil)	4.9-5.6

4.1.2. Soil characteristics methodology:

To increase water use efficiency, need to determine soil characteristics which affect water flow and retention. These include field texture and soil water capacity, the dispersiveness of the soil, organic matter content, and bulk density.

From owner knowledge, the house was built approximately 2009, and from viewing surroundings, it appears the ground was modified for the housing lot. The trial site soil may be Vertosolic Spolic using the Australian Soil Classification (Isbell 2016). Some manufactured items (such as PVC offcuts) were found while constructing the garden beds, but not enough to quantify as an urbic soil.

4. 1. 2. 1. Field texture

Bolus and ribbon method as described in the Australian Soil and Land Survey Field Handbook (National Committee on Soil and Terrain 2009, pp.133). A golf ball sized soil sample moistened with water and kneaded into a ball which just begins to stick to the fingers. At this point, the soil is approximately at field capacity. The wetting and kneading of the bolus is continued until there is no apparent change. The bolus is then pressed out between the thumb and forefinger in a shearing motion to form a ribbon approximately 1cm wide and

2mm deep which is used to characterise the field texture. The field texture grade provided in National Committee on Soil and Terrain (2009, pp.134) was used to determine the field texture.

It should be noted this reading can vary depending on the experience of the person conducting the grading. MacDonald (1990) notes this method is subjective, requiring extensive experience for good results, as it can be influenced by organic matter, clay mineralogy, cation composition and other soil components.

4. 1. 2. 2. **Laboratory texture**

The Australian Standards 1289.3.6.1 and AS 1289.3.6.3 will be followed to determine soil texture at the beginning and end of the trial period. Compost and other soil amendments have been added throughout the trial as per gardener discretion, and it is anticipated this may change the texture of the top 15-20cm of soil profile.

This method will be compared against the field method results in effort to see if the field method provided an accurate estimate.

4. 1. 2. 3. **Bulk density**

While bulk density plays a significant role in soil water movement and retention, it was decided this property should not be measured, as the results would vary every time the garden was weeded, dug over for re-planting, and time since last disturbance.

4.2. Phase 1 methodology

The garden area was divided into 3 plots and labeled as P1, P2, and P3. Each plot was hand watered by one of the below methods (M1-M3). Two trial phases were conducted to allow for adjustments to be made to the methods as needed. The planting layout of each plot is shown in Appendix G - Plot diagrams.

4.2.1. Control method (M1):

Method 1 (M1) was to assume current practice, schedule water timing and volume as per the gardener's normal practice in P1. The timing and application amount is arbitrarily decided by sight (personal judgement of plant turgor), length of time since last watering, plant life stage, and judgement of daily temperature. This schedule changed regularly at the whim of the gardener, and was documented for reference.

The water volume meter was attached to the nozzle end of the hose. This way the volume measured did not include any loses between the tap and hose end. The screen was blocked out during use to prevent unconscious bias from viewing the volume while still applying.

The application volume, any antecedent climatic conditions, and/or plant appearance which factor into decision were recorded. Any runoff was also noted.

4.2.2. Garden probe & pot weight method (M2):

M2 used indications from soil moisture probe (Brunnings 3in1 Soil Meter available at garden centers) to assist in scheduling for P2. The probe was calibrated prior to use, as per method described in section 8.4.6 3in1 soil meter calibration. The moisture indication from probe was checked daily as per manufacturer instructions on packet. Initially in phase 1 the reading was compared to the suggested moisture level on packet (moist), and water only applied when the reading had dropped to the minimum recommended level. Plants quickly appeared stressed (wilted and no noticeable growth). For the remainder of phase 1 probe measurements were taken at 5, 10 and 15cm depths to determine optimum value for initiating water when it was judged that leaving longer would induce water stress.

4.2.3. WUCOLS method (M3):

Method 3 (M3) trialed the calculation of ET_L (Equation 2-5), using the WUCOLS coefficient (K_L) combined with ASCE-Penman-Monteith ET_o for tall crop method in P3 during phase 1. Nouri (et al., 2013) found this method more accurate than other landscape coefficients in determining an irrigation schedule for landscape plants. It is aimed at ornamental landscape plantings, thus the vegetable plants in this trial will needed observing to determine if this method is suitable for production. As this method accounts for mixed species planting, micro-climate of urban spaces, and the density of the planting, it is expected to be highly efficient, particularly compared to M1. This method requires some education, and time to complete calculations, and therefore may not be appropriate for home use outside of further research for mobile app development.

The K_s, K_d, and K_{mc} were estimated using Costello, Matheny and Clark (2000) as a guide. A similar California regional climate to the trial area was researched for K_s estimations.

$$ET_L = ET_o \cdot K_L$$

Equation 3-1

Definitions: ET_L = landscape evapotranspiration

ET_o = Reference evapotranspiration

K_L = landscape coefficient

K_S = species factor

K_d = density factor

K_{mc} = microclimate factor

Data for ET_o was downloaded from <https://www.longpaddock.qld.gov.au/silo/point-data/#responseTab1> in the ASCE-Penman-Monteith tall crop format for the Toowoomba Airport. This removed any human error in calculating the ET_o, and only left any inherent errors from the downloaded data. It should be noted this site sets wind speed to the standard 2m/s (Zajaczkowski and Jeffrey 2020, p.12), in comparison Toowoomba's annual average wind speed of 5.4m/s (BOM 2022a).

K_S accounts for the water needs of species, which is separated into 4 categories. The values are determined from Costello, Matheny and Clark (2000). These authors recommend using the K_s value provided if single species planting. When multiple species plantings have varying water requirements, the highest water need category should be used to determine the K_s value. This is to prevent water stress to the highest water need planting, however those with a lower water need may experience damage due to over-watering. For given ranges of K_s, experience in watering the plant can be utilised to determine the more correct value, however in the case of having low experience, Costello, Matheny and Clark (2000) recommend using the middle value. As this was the first time using this method, the middle value of each range was selected.

Table 3-2: Species factor (K_s) relating to water needs (Costello, Matheny and Clark 2000, p.12).

Category	**Water need**
Very low (VL)	<0.1

Low	0.1-0.3
Moderate	0.4-0.6
High (H)	0.7-0.9

K_d is a factor for the vegetative (leaf area) density of plantings. This is not a standardised evaluation system and thus can vary between user discretion and experience.

Table 3-3: Density factors (K_d) (Costello, Matheny and Clark 2000).

Category	**Water need**	**Planting type**
Low	0.5-0.9	Immature/sparsley planted (less than 90% of ground covered by single vegetation type (shrubs and ground covers), or less than 70% shaded by tree canopy.
average	1.0	Full planting (90-100% ground covered) - predominently of 1 vegetation type., or 70-100% tree canopy cover.
High (H)	1.1-1.13	Established vegetation mixture (trees, shrubs and ground cover), 2-3 vegetation tiers & complete canopy cover

K_{mc} accounts for the micro-climate of the landscape and is selected from Table 3-4. At the beginning of the trial (01.12.2022), the garden bed was deemed to have a K_{mc} of 1.0. It was considered the surrounding hedging shielded the low growing/young plants from the wind tunnel created by the residential street. The garden bed experienced all day sunlight, with late afternoon shading from the hedge at the very end of the bed, so the hedges are not considered in the garden bed tiers.

In determining Kd, only a single tier was present (vegetables) initially and considered as low density planting at this early stage. A Kd of 0.7 was given (some plantings are very dense, however others are less dense in the garden bed). This was expected to change as the plants matured, and vine plants grow up the trellis and shade plants below creating a second canopy tier.

Table 3-4: K_{ms} (Costello, Matheny and Clark 2000).

Category	**Water need**	**Condition description**
Low	0.5-0.9	Increased shade or decreased wind conditions. Eg: south of walls, under building overhangs.
Average	1.0	Similar to ET_o conditions (open field, no heat or wind inputs extraordinary to the location), not affected by nearby structures, slopes, etc. Eg. Parkland gardens
High	1.1-1.4	Increased evaporation due to site features (increased wind, heat absorbing or reflective surfaces) - street plantings, North-West facing walls.

Vegetables are not listed on the WUCOLS species factor list, however given in general leafy green vegetables require a high water intake, a high water requirement was decided on (K_s = 0.7).

Therefore an initial K_L value of 0.49 was adopted.

4. 2. 3. 1. Defining WUCOLS climatic region

WUCOLS climatic regions are based on California areas. These were compared to Toowoomba to determine the most suitable region for the WUCOLS ET calculations.

Monthly Average Reference Evapotranspiration by ETo Zone (inches/month)

Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1	0.93	1.40	2.48	3.30	4.03	4.50	4.65	4.03	3.30	2.48	1.20	0.62	33.0
2	1.24	1.68	3.10	3.90	4.65	5.10	4.96	4.65	3.90	2.79	1.80	1.24	39.0
3	1.86	2.24	3.72	4.80	5.27	5.70	5.58	5.27	4.20	3.41	2.40	1.86	46.3
4	1.86	2.24	3.41	4.50	5.27	5.70	5.89	5.58	4.50	3.41	2.40	1.86	46.6
5	0.93	1.68	2.79	4.20	5.58	6.30	6.51	5.89	4.50	3.10	1.50	0.93	43.9
6	1.86	2.24	3.41	4.80	5.58	6.30	6.51	6.20	4.80	3.72	2.40	1.86	49.7
7	0.62	1.40	2.48	3.90	5.27	6.30	7.44	6.51	4.80	2.79	1.20	0.62	43.4
8	1.24	1.68	3.41	4.80	6.20	6.90	7.44	6.51	5.10	3.41	1.80	0.93	49.4
9	2.17	2.80	4.03	5.10	5.89	6.60	7.44	6.82	5.70	4.03	2.70	1.86	55.1
10	0.93	1.68	3.10	4.50	5.89	7.20	8.06	7.13	5.10	3.10	1.50	0.93	49.1
11	1.55	2.24	3.10	4.50	5.89	7.20	8.06	7.44	5.70	3.72	2.10	1.55	53.0
12	1.24	1.96	3.41	5.10	6.82	7.80	8.06	7.13	5.40	3.72	1.80	0.93	53.3
13	1.24	1.96	3.10	4.80	6.51	7.80	8.99	7.75	5.70	3.72	1.80	0.93	54.3
14	1.55	2.24	3.72	5.10	6.82	7.80	8.68	7.75	5.70	4.03	2.10	1.55	57.0
15	1.24	2.24	3.72	5.70	7.44	8.10	8.68	7.75	5.70	4.03	2.10	1.24	57.9
16	1.55	2.52	4.03	5.70	7.75	8.70	9.30	8.37	6.30	4.34	2.40	1.55	62.5
17	1.86	2.80	4.65	6.00	8.06	9.00	9.92	8.68	6.60	4.34	2.70	1.86	66.5
18	2.48	3.36	5.27	6.90	8.68	9.60	9.61	8.68	6.90	4.96	3.00	2.17	71.6

Variablity between stations within single zones is as high as 0.02 inches per day for zone 1 and during winter months in zone 13. The average standard deviation of the ETo between estimation sites within a zone for all months is about 0.01 inches per day for all 200 sites.

(https://cimis.water.ca.gov/App_Themes/images/etozonemap.jpg) CIMIS ET0 zones

Toowoomba airport coordinates used : (-27.54o, 151.91^{o}) to determine aeral point grid ET. (BOM 2022b). Determined by the average of the 151.85^{o} and 151.95^{o} longitudes on the grid for -27.5^{o} latitude.

Table 3-5: Toowoomba ET (BOM 2022b)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
175	134	138.5	102	74.5	64	66.5	82	105	141.5	159.5	174.5	1424

The annual long term (30/11/1950 to 05/12/2022) average ET_o using Silo ASCE Penman-Monteith Tall crop is 1616.2mm, which converts to 63.63in. Comparing to the CIMIS table, the closest zone is 16. Comparing this to the WUCOLS regions provided in Costello and Jones (2014, p.13), the ET_o is similar to the Central Valley. This relates to the USDA plant hardiness zones as well, with Toowoomba classified as zone 9b (Gardenia 2022). Costello and Jones (2014) list several reference cities within each WUCOLS region, with Bakersfield, Fresno, Modesto and Sacramento representative of the central valley. These have the same USDA plant hardiness zoning as Toowoomba according to the USDA Plant Hardiness Zone Map (https://planthardiness.ars.usda.gov/).

Measured rain from gauge on site will be used in water balance equation.

4.3. Trial procedure

1. Determine FC of garden bed soil
2. Determine refill point
3. Ensure all trial plots have edging gutters to prevent runoff.
4. Calibrate flow meter.
5. On first day (t=0), water each garden section to FC. This allows all sections to start at the same moisture content. Or, preferably, start trial after significant rainfall when can assume the soil is at FC.
6. Apply water to each section as indicated by the individual method for that section using a handheld hose with water flow meter attached to measure the volume applied.
7. Record pertinent details to water application and timing, along with plant and/or soil appearance.
8. Note any outside disturbances to the garden as they occur (ie: animals, weeding).

4.4. Points to note:

To prevent runoff, water was applied within the visible infiltration rate of the soil. Gutters were also dug around the plots to capture any runoff and keep it within the plot area.

Gardena Water Smart Flow Meter (available from Bunnings Warehouse stores) was used to measure applied volumes. Flow meter was installed on the open end of hose to prevent any errors in measurement due to tap or hose leakages.

Gardens were weeded intermittently by the gardener as part of their standard practice, thus soil disturbances may occur during the trial that would normally occur. Dates and sections any significant disturbance occurs were recorded.

Scheduling methods were adjusted as necessary when plants appeared significantly water distressed during trial, to prevent permanent wilting and death. All adjustments were recorded.

4.4.1. Watering depth

The Toowoomba Regional Council (TRC) recommends a generic 28mm maximum watering depth for clay soils, and 42mm for loam soils, with any more being lost to deep percolation

(Toowoomba Regional Council 2022b). It does not detail how regularly this should be applied. The values from this website were chosen as they are readily available values specifically recommended for the local area for gardeners. Initial soil texture was determined using *SoilMapp* app produced by CSIRO (2019) as it is easily accessible to gardeners for a quick reference. The app indicated a vertosol soil with high clay content, and therefore 28mm was chosen as the initial refill depth.

This refill value is confirmed in the following sections by calculating several soil water parameters used for irrigation management.

4.4.2. Determination of effective root zone depth

Determining effective root zone depth (RZD) for a mixed planting such as vegetable patch is difficult due to the variety of plants having differing root systems. Roots may be extensive with depth or laterally, with some plants being more opportunistic than others (Connellan 2013, p. 214). In addition soil type affects root growth, direction and area. Heavy, compacted soils have shallower roots (Connellan 2013). Soil samples or destructive digging can conclusively show exact root depths, however this is excessive testing for a small household vegetable patch.

Average effective RZDs were determined from Allen et al. (1998), who provide a comprehensive list of the effective root depths of commonly planted vegetables and fruits. The average for all expected plants in this trial was 0.51m, varying between 0.3m and 1.0m.

It should be noted the soil in the plot was visually heavily compacted underneath the top 15cm layer which was turned over and amendments added during plot creation. This meant roots and water could freely move through the top 15-20cm layer, until reaching the compacted layer below which impeded movement. This was visually seen during plot creation, when 40mm was applied to a freshly prepared 1m^2 section. While the surface did not appear water logged, on digging down, the 10-15cm layer was over-saturated and sloshy.

Table 4-6: Effective root depth

Crop	effective root depth (m)
a. small veg	**0.3**
Carrots	0.5
Cauliflower	0.4
Celery	0.3
Garlic	0.3
Lettuce	0.3
Onions Green	0.3
Spinach	0.3
Raddish	0.3
b. Solanum vegetables	**0.6**
Sweet peppers	0.5
tomatoes	0.7
c. Vegetables - cucumber	**0.8**
cantaloupe	0.9
cucumber	0.7
pumpkin	1.0
zuchini/squash	0.6
sweet melons	0.8
watermellon	0.8
d. roots and tubers	**0.6**
beets	0.6
parsnip	0.5
e. Legume	**0.5**
green beans	0.5
f. Perennial veg	**0.3**
mint	0.4
strawberries	0.2
Average	**0.51**

4.4.3. Determination of FC, PAW, RAW and refill depth

Generic field capacity (FC) values are provided for a vertosol by CSIRO (2019). These values are reproduced in Table 2-1. Note that as generic values they will not be the same as the trial plot, however are indicative of what could be expected. Figure 3-3 shows how the plant available water (PAW) can be calculated by subtracting the wilting point from the PAW. Using the values from Table 3-6, the PAW is: 0.22, -, 0.19, and 0.14 mm/mm for layer 1, 3 and 4 respectively, and the average of the three layers is 0.183mm/mm. This is more similar to the range found by Connellan (2013) of a clay loam as seen in , as it is 0.23 above the maximum range they suggest for clay. Due to the ease of accessibility for a gardener, the CSIRO (2019) value was chosen to guide this trial.

Table 3-7: Summary data for vertosol soils (CSIRO 2019).

Layer	Depth (cm)	Electrical conductivity (dS/m)	pH	Organic Carbon (%)	Bulk density (Mg/m3)	FC (mm/mm)	Wilting point (mm/mm)	Clay (%)
1	0-6	0	6.5	2.70	1.01	0.54	0.32	43.0
2	-	-	-	-	-	-	-	
3	6.0-32	0	7.0	0.93	1.00	0.56	0.37	50.0
4	32-66	0	7.5	0.66	1.09	0.47	0.33	50.0
5	66-87	-	8.0	-	-	-	-	43.0

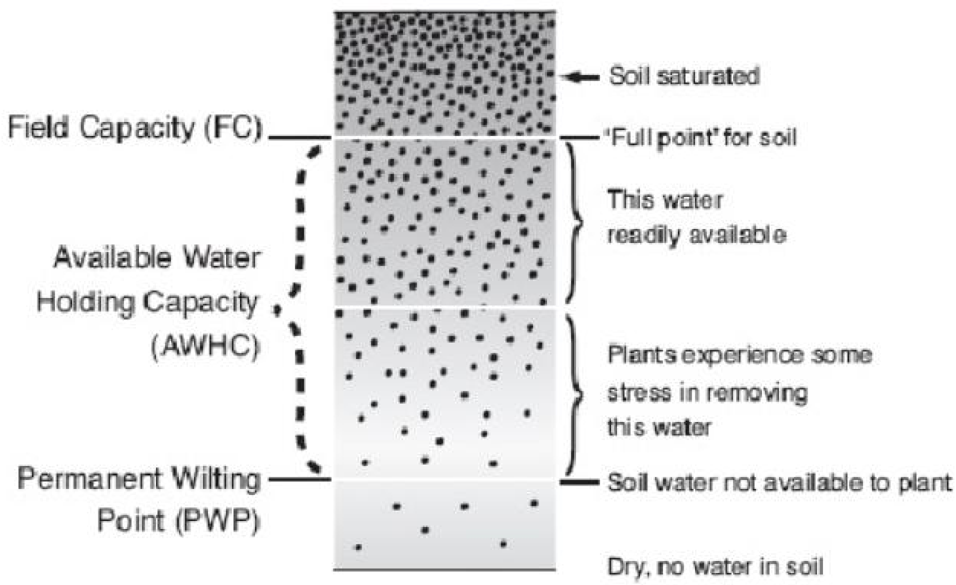


Figure 3-3: Soil water properties and terms (Connellan 2013). Note: AWHC is used by Connellan (2019) instead of PAW.

Table 3-8: Guide to soil water properties (Connellan 2013)

Soil type	**FC (mm/m)**	**PWP (mm/m)**	**Range PAW (mm/m)**	**Average Paw (mm/m)**	**Infiltration rate (mm/h)**
Loam	34	100	180-220	200	10-15
Silt loam			160-180	170	8-12
Clay loam	300	160	120-180	150	5-10
Clay	380	240	120-160	140	1-5

While the PAW provides the full amount available to plants, the water at greatest depth requires more energy from the plant to extract. The readily available water (RAW) for plants can be determined from the PAW and RZD value using Equation 3-2 from Connellan (2013).

$$\mathrm{RAW} = \mathrm{RZD} \cdot \mathrm{PAW}$$

Equation 3-2

Refill depth (RD) is determined by Equation 3-3 from Connellan (2013), where MAD is the management allowable depletion. MAD varies between plants, therefore a low MAD value of 30% was selected to prevent water stress in the vegetables with lower tolerance levels, such as lettuce and capsicums. This was based on values provided in Allen e al. (1998). RD is the acceptable RAW depletion amount before irrigation commences.

$$\mathrm{RD} = \mathrm{RAW} \cdot \mathrm{MAD}$$

Equation 3-3

Table 3-9: Final soil water values utilised for trial

FC (mm/mm)	**Wilting point (mm/mm)**	**PAW (mm/mm)**	**RZD (mm)**	**RAW (mm)**	**MAD (%)**	**RD (mm)**
0.56	0.37	0.18	500	90	30	27

4.5. Flow meter calibration

The accuracy of the flow meter was determined by attaching it to the end of the hose, as would be for use in the trials. A known volume (10L) was marked on the side of a large bucket. The bucket was filled to the mark using a low flow rate. The time taken was noted.

This was repeated 3 times, and the flow meter flow rate and volume recorded to the test results were compared to determine the accuracy of the meter. This was repeated for medium, and high flow rates.

4.6. 3in1 soil meter calibration

It is difficult to determine the accuracy of a cheap garden soil moisture meter, as the indicator shows a value from 1 (dry) to 10 (wet). The instructions state its moisture accuracy range is ±1, however not what actual units these numbers relate to. It also makes no mention of what soil types it is suited to. Peer reviewed literature on this was not found, so some of the methods used in the blog of Pavlis (2022) were used.

This blog tested the meter in the extremes of moisture limits; FC vs a dry soil, disturbed vs. compacted, fertilised vs unfertilised. To replicate the conditions the probe will experience in the trial plots, a soil sample large enough to fill a 17mm pot was spread out and sun dried for 3 weeks. The weight was recorded. The moisture of the disturbed, dry soil was measured on the meter before the pot was submerged in a bucket of water for 48hr. It was then allowed to drain until no more water was in the drainage receptacle. This was assumed to be FC, and the moisture reading was taken, along with the pot weight. The pot was weighed and the moisture reading taken daily until the pot weight reached the initial dry weight.

5. Phase 1 Results & analysis

5.1. Soil Texture

The field texture for all 3 plots was found to be a sandy clay loam to light clay. The individual site results summarized in Table 4-1. Several ribbons were made for each of the sites, and the average is presented below. Some of the ribbons were over 7cm, and all formed unbroken rods, indicating the soil could also be a medium clay.

Table 4-1: Field texture results

Field Texture - Ribbon and Bolus results										
Properties	**Undisturbed soil**		**M1**		**M2**		**M3 - Site 1**		**M3 Site 2**	
	5cm	**15cm**	**5cm**	**15cm**	**5cm**	**15cm**	**5cm**	**15cm**	**5cm**	**15cm**
Soil feel	G	G	G	G	G	G			G	G
Ribon length (cm)			7.5	6.5	4	6.5	Too much organic matter to be coherent		5.5	7
Cylinder	yes	yes	yes	yes	yes	yes			yes	yes
Horse Shoe	yes	yes	No	yes	no	yes			yes	yes
Over hand			No	No	No	No			SC	yes
Field texture			MC	LC	SCL	LC			CLS	LC

Note: G = Gritty; SC = slight cracking; CLS = clay loam sandy; LC = light clay; MC = Medium clay.

The laboratory texture analysis was not completed.

5.2.Pot test

The pot test measured the weight difference in the pot of garden soil and also was used to determine accuracy/calibration of the Brunnings 3in1 soil meter. The pot remained in a fully shaded outdoor position for the duration of the experiment. The pot used for the experiment was 17cm high and 17cm diameter. The soil was sun dried for 3 weeks, until its weight did not change further, and then the pot was filled up to 10.5cm. Two sheets of paper towel were placed on the bottom of the pot to prevent any soil loss from the drainage holes during the experiment. A 3cm compost layer was placed on top of this to replicate the plot conditions.

The pot was then dropped 3 times from 10cm height to consolidate the material. The top of the soil after this was 12.8cm (ie: had compacted 0.7cm). The initial dry weight of the filled pot was 1830g.

The pot was placed in a bucket of water (with 2 pieces of paper towel over the soil surface to prevent soil loss) with the water covering the pot. It was left overnight to ensure it was fully saturated. The saturated pot was placed on a raised surface inside a bowl to freely drain and the entire apparatus placed inside a bag to prevent evaporation. The pot was weighed daily to determine field capacity (ie: no water in bowl), then the bag was removed for the remainder of the experiment. The 3in1 meter was inserted daily at depths of 5cm, 10cm and 12.5cm, marked on the meter, to determine a moisture reading on an analogue scale of 1-10. For simplification, any readings partway between whole numbers were recorded using .5 after the smaller number.

The resulting measurements can be seen in full in Appendix H- Pot test results.

5.2.1. Pot weight

On the 3rd day (21/12/2022) there was no water was in the bowl, and the wet pot weighed 2753g. This was taken to be the field capacity of the soil, and the gravimetric content (θ_g) was calculated as 50.5% by Equation 4-1.

$$\mathrm{FC}\ (\theta_g) = \frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}} = \frac{2753 - 1830}{1830} = 0.5044$$

Equation 4-1

Initially the pot was weighed daily, however after the first 3 weeks daily weight loss was generally 20g or less and it was decided the need for daily weighing was not required. The days not weighed have been linearly interpolated for Figure 4-1, and Figure 4-2.

The initial dry soil pot weight was 1830g (including pot) and the final dry soil pot weight was 1826g. This small decrease in total weight could be accounted for by small bits of wet soil clinging to the probes on the first days when it was very moist.

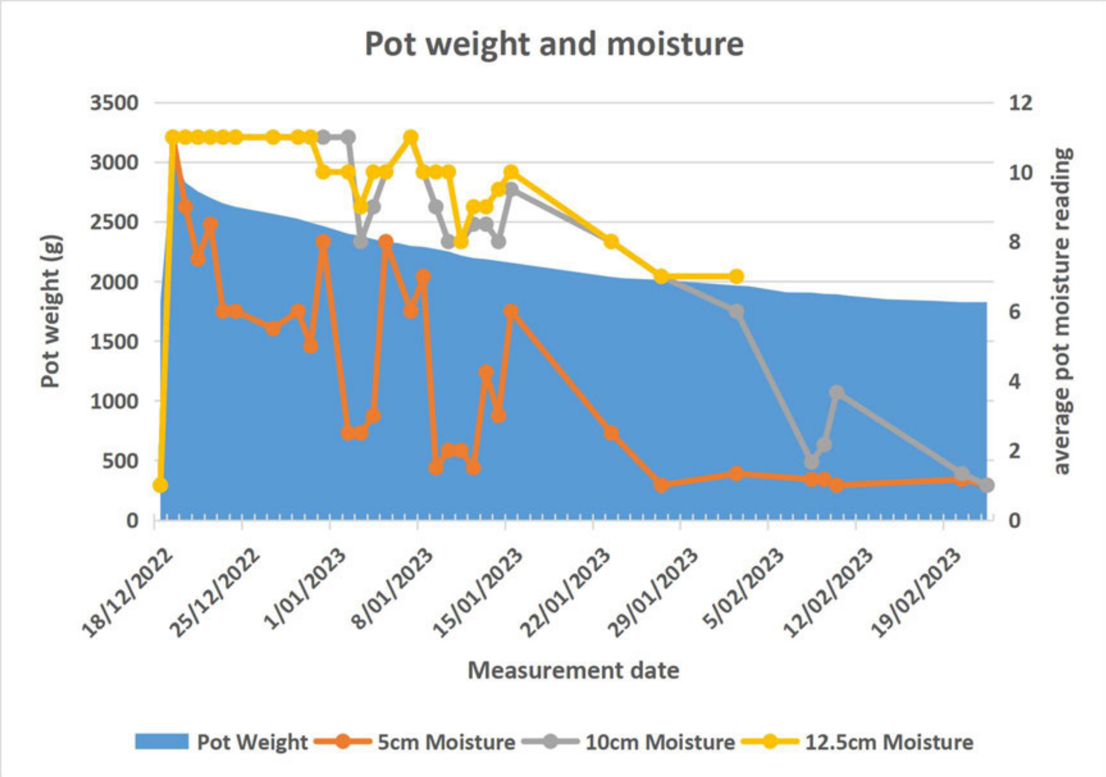


Figure 4-1: Pot weight and soil meter moisture reading

Once reaching field capacity, the daily weight loss amount trended down as expected (Figure 4-2). Highest amounts were recorded during the first 15 days (27g to 75g recorded daily). The daily weight loss fluctuates as it trended down, this is expected due to different climatic conditions resulting in different soil evaporation. The downward trend was also expected, as the soil chemical bonds hold tighter to the remaining water as the water content is evaporated.

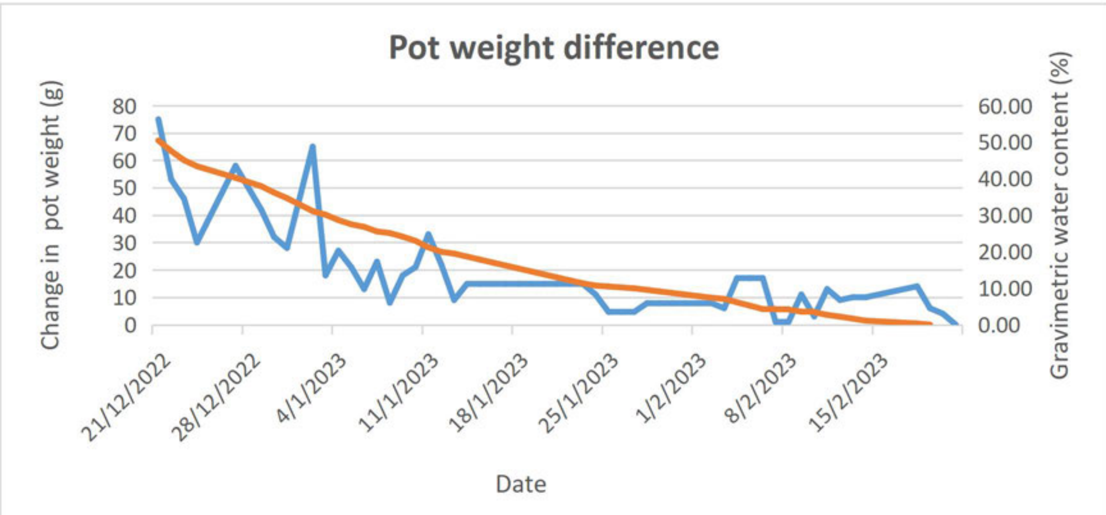


Figure 4-2: Pot weight difference

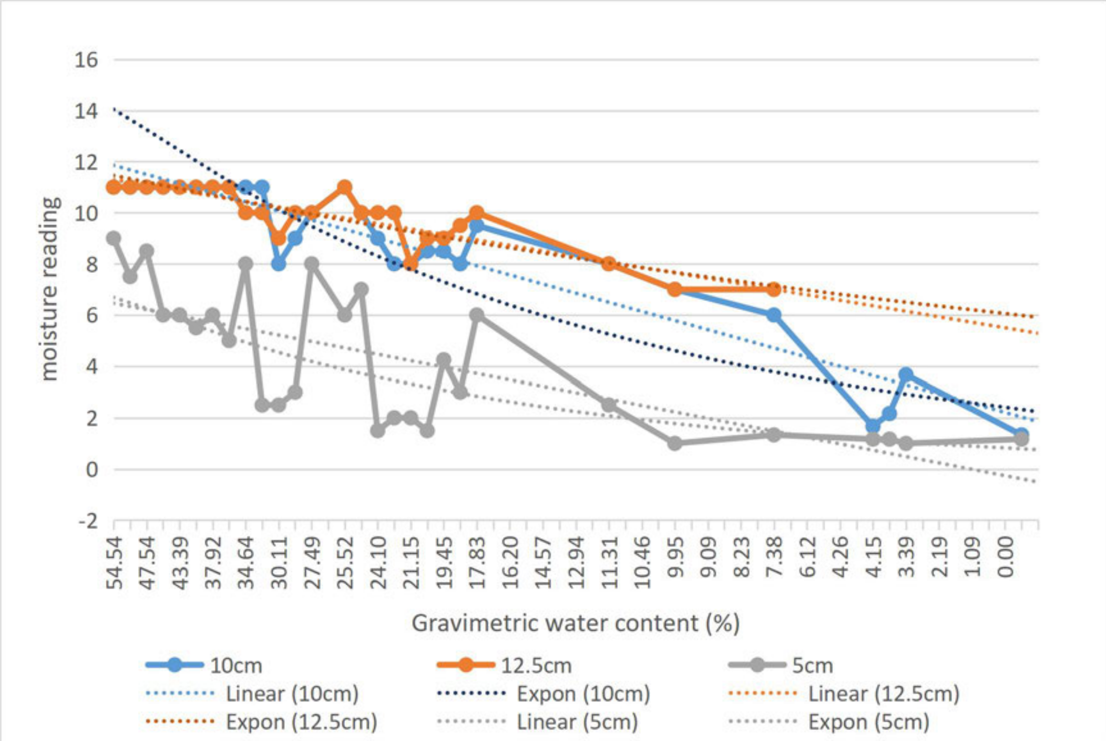


Figure 4-3: Gravimetric water content comparison

5.2.2. Pot moisture and meter accuracy

The pot moisture was taken as the average of the 3in1 meter probes being used in the garden at the time. A single probe was in use until 13/01/2023 and a third started on 23/01/2023. 0.5 was used to indicate when readings were in-between exact numbers.

The average moisture reading of the 3in1 meter fluctuates significantly for the 5cm depth as seen in Figure 4-1. The 10cm and 15cm readings have less variance, however also fluctuate visibly as the reading begins to drop. The fluctuation for all 3 heights is less at lower end of the scale, as the soil becomes completely dry. This could also be because the readings were no longer taken daily and therefore it appears as though there is less variance in-between readings. After approximately 6 weeks, the probe was no longer able to reach the bottom of the pot, as the soil was too dry to push into without potentially damaging the probe.

Initial readings prior to reaching field capacity showed as above 10 on the meter for all depths. Readings over 10 are indicated by 11 in the results to distinguish between an actual reading of 10 and a reading over 10. The top 5cm averaged 7.5 moisture reading on reaching field capacity, while the subsequent layers remained at 11.

The top 5cm (which consisted of half compost material) dried out the quickest, and was only displaying over 10 for the first day of wet readings. In comparison the 10cm layer remained over 10 for 11 days and the 12.5cm layer for 9 days. This is expected for pot moisture, as the surface followed by the base would dry first due to moisture travelling downwards and the surface exposure to evaporation.

Two anomaly were experienced. On 27th January, one section of soil had a significantly lower reading of 4 at both 10cm and 12.5cm depths, while the other 2 meters recorded 8 and 9 (Figure 4-4 and Figure 4-5). When the same spot was probed with the other meters, similar readings were made, therefore it was assumed there was something in the soil at this section causing interference with the measurement.

Similarly, on 9th February at the 10cm depth in one particular point of the pot all probes had a significantly higher reading of 7, while in other points at same depth the reading recorded was 1.5 and 3 (Figure 4-4). It is unknown what caused this reading to be so high, as the soil could not be broken down otherwise it would change the conditions for the subsequent readings. This anomaly was not experienced again, so unsure if a beetle or other item containing significant moisture was within the soil, or a soil constituent interfering with the measurement.

A comparison of the cumulative percentage weight loss with moisture reading is shown for each measurement depth in Figure 4-6 and Figure 4-7. An exponential trend line best fits the 5cm moisture readings (Figure 4-6), while a linear trend line appears to fit both the 10cm and 12.5cm readings better (Figure 4-7).

The 3in1 meter packet advises that the readings are within +-1. This was inconsistent with the data collected for this experiment. Figure 4-4, Figure 4-5, and Figure 4-6 show the readings for the 3 different probes, along with Table 16-2 from Appendix H- Pot test results. The figures show several days where the measurements are more than +-1 from each other. Initially two probes were used to determine consistency, however the first week of readings revealed they showed more than +-1 difference. A third was purchased to compare against. This generally provided 2 readings consistent with +-1 difference, while the 3rd reading may or may not have fallen within the accepted accuracy range.

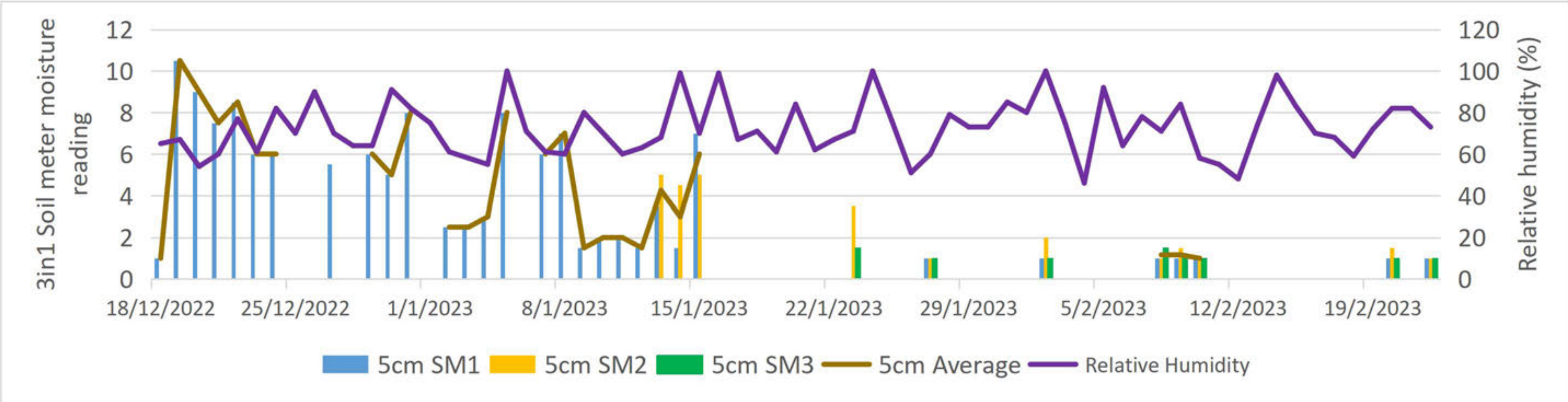


Figure 4-4: 3in1 soil meter readings for 5cm level compared to relative humidity

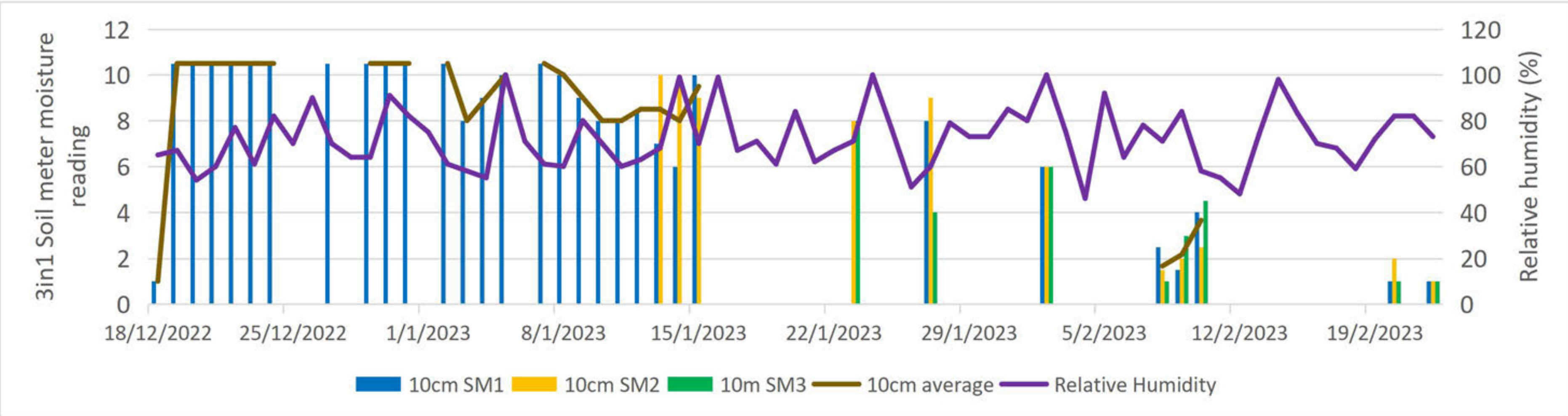


Figure 4-5: 3in1 soil meter readings for 10cm level compared to relative humidity

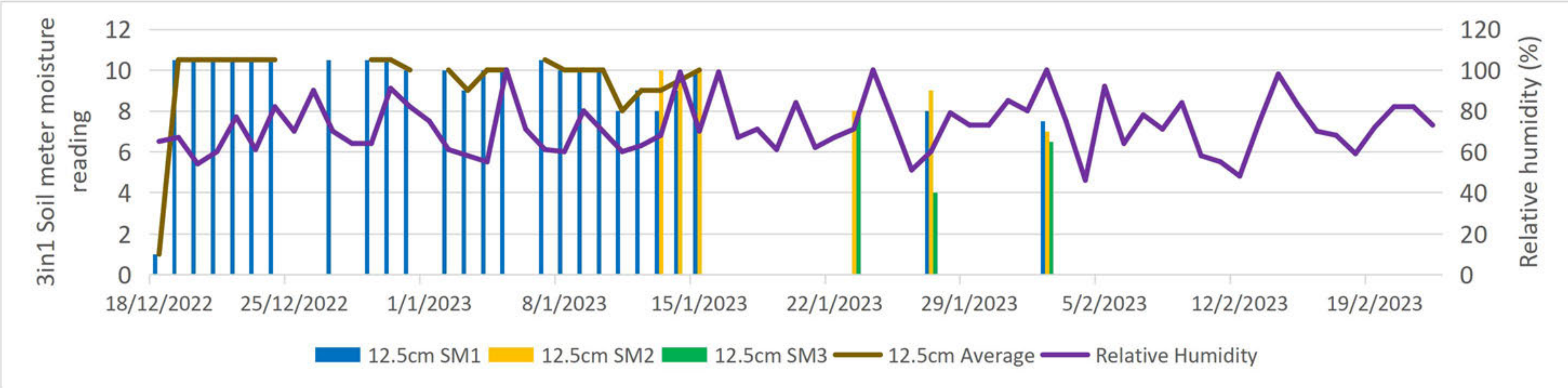


Figure 4-6: 3in1 soil meter readings for 12.5cm level compared to relative humidity

Figure 4-4 shows the 3in1 soil meter readings for the 5cm depth varied with the relative humidity (RH). The monthly RH data was downloaded for Toowoomba from <http://www.bom.gov.au/climate/dwo/202306/html/IDCJDW4126.202306.shtml>. This is consistent with the 3in1 soil meter reading not matching the percentage weight loss in Figure 4-7. Both the 10cm and 12.5cm depth readings also appear to have been influenced by the RH (Figure 4-5 and Figure 4-6), and again this is reflected in the comparison with the percentage moisture loss (Figure 4-7 and Figure 4-8).

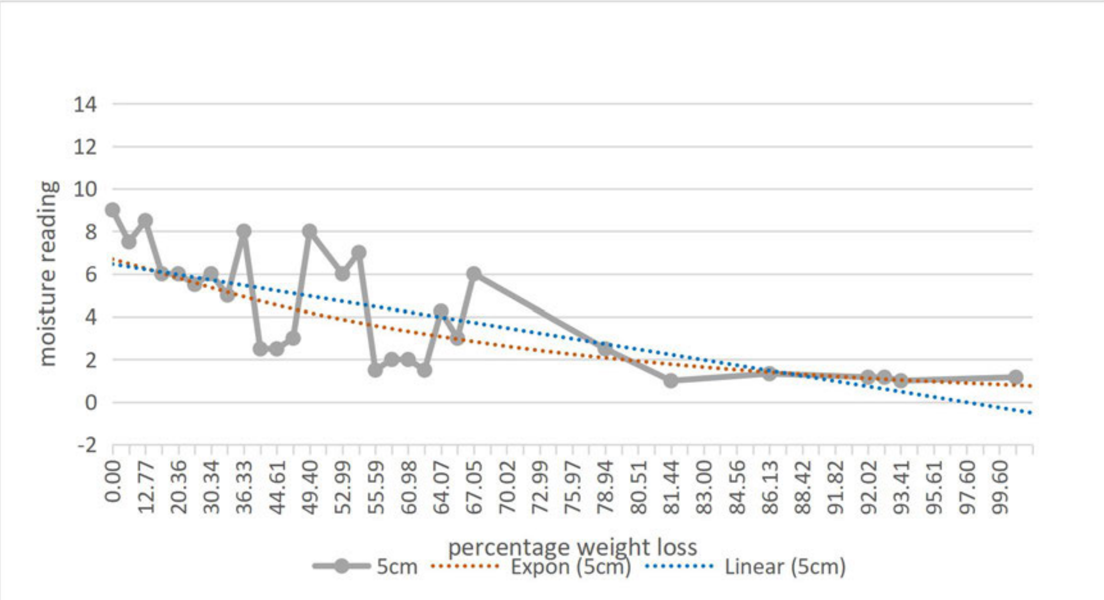


Figure 4-7: Moisture reading at 5cm depth compared to cumulative percent of pot weight loss

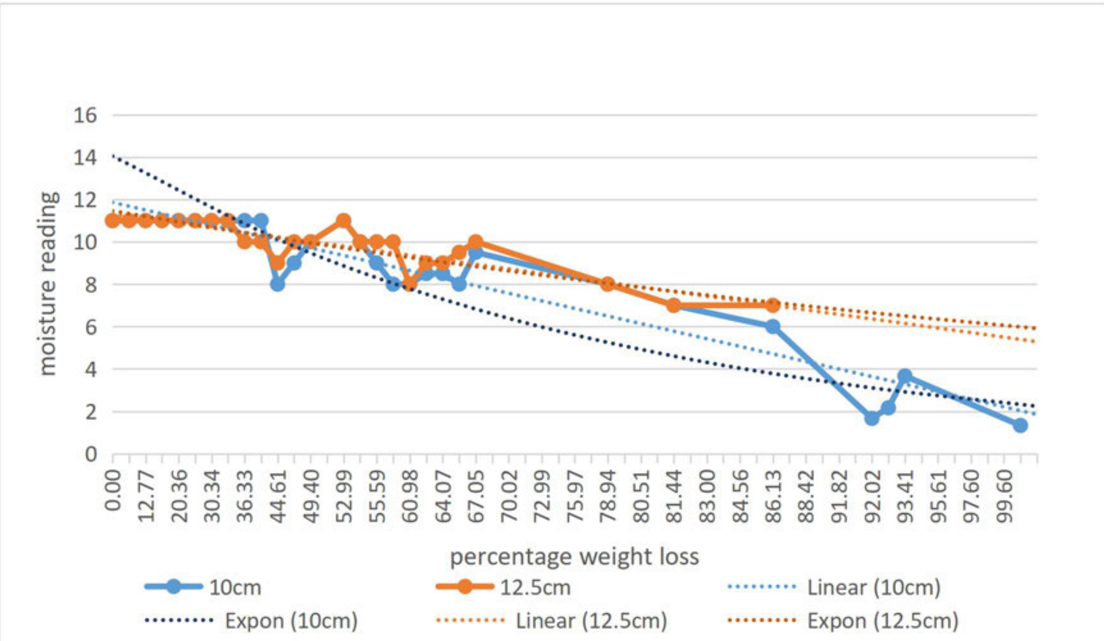


Figure 4-8: Moisture reading at 10cm and 12.5cm depth compared to cumulative percent of pot weight loss.

5.3. Precipitation

Rainfall for December 2022 was taken from the Bureau of Meteorology's Toowoomba Airport records. A rain gauge was set up in the garden, and measurements taken from this during 01/01/2023 to 28/02/2023.

5.4. Trial method water use

A significant rainfall event was recorded on 1st December, and the plots were assumed to be at field capacity on the 2nd December. Records of water application amounts commenced on this date. Phase 1 ended on 30th January 2023, to ensure enough data had been gathered to guide the methodology for the next trial phase.

The highest water application during phase 1 was M1, which used 636.4mm applied over 19 days (Table 4-2). Over half of this water was applied in the final week (30/01/2023) (Figure 4-9). M2 used the least amount of water (264.3mm) over 13 application days. M3 was stopped on the 20th December 2022, less than 4 weeks into the trial. The 7 day comparison results can be seen in Appendix K.

Table 4-2: Phase 1 trial water use

	Trial methods		
Method	**M1**	**M2**	**M3**
Total No. application days	19.0	13.0	2.0
Total irrigation per plot (L)	2456.4	1083.5	115.5
Total irrigation per m^2 (mm)	636.4	264.3	25.0
Minimum irrigation per m^2 (mm)	0.0	0.0	0.0
Median irrigation per m^2 (mm)	43.3	22.0	22.0
Average irrigation irrigation per m^2 (mm)	70.7	29.4	28.0
Maximum irrigation per m^2 (mm)	321.6	74.0	87.3

Table 4-2 shows the median and average irrigation for M1 per m^2 is double that of M2. The maximum value of M1 is over three times that of M2. In Figure 4-9, it can be seen this value is applied during the week of 30/01/2023. There is also a noticeable rain event during this week with the and M2 has less water in this week than the preceding weeks which did not have rain.

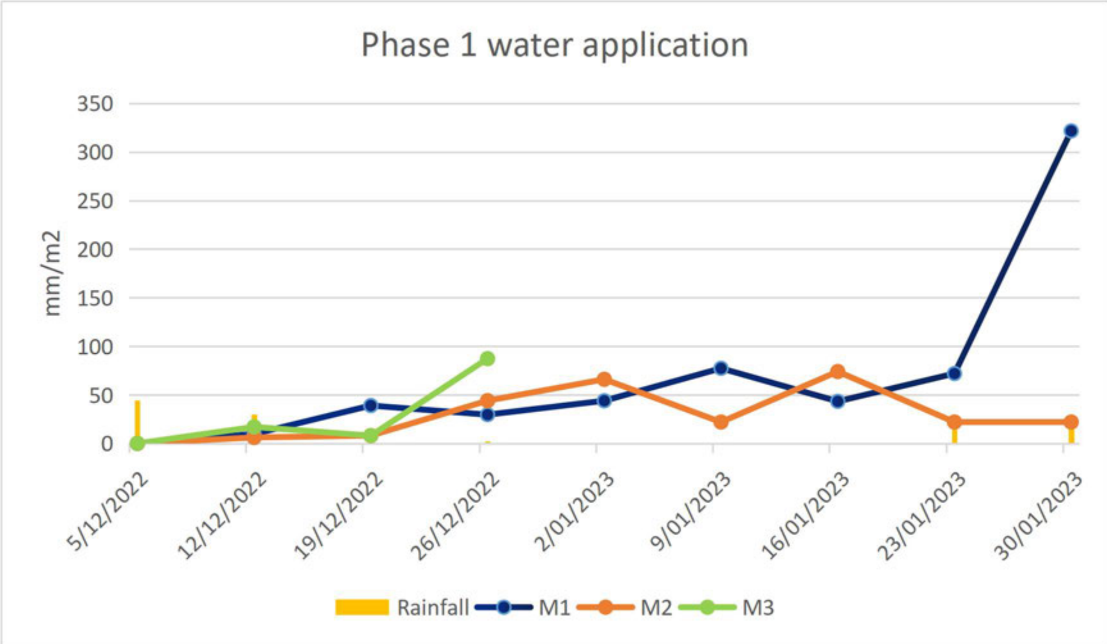


Figure 4-9: Seven day irrigation application depths.

During Phase 1, 8 different points in the plot were measured using the 3in1 soil moisture probe. Each point had a different vegetable planting. The spread of results are shown in Figure 4-10, Figure 4-11, and Figure 4-12 for the 5cm, 10cm and 15cm depth readings respectively. Between 02/12/2023 and 11/12/2023 the measurements were not taken at consistent depths, and the results have not been included for comparison.

The meter read beyond the maximum point (10) on several occasions, and these are marked as 11. Since the measurement dial only had whole numbers, readings that were not on whole numbers were represented by recording the midway point (ie: 3.5 when the needle was between 3 and 4).

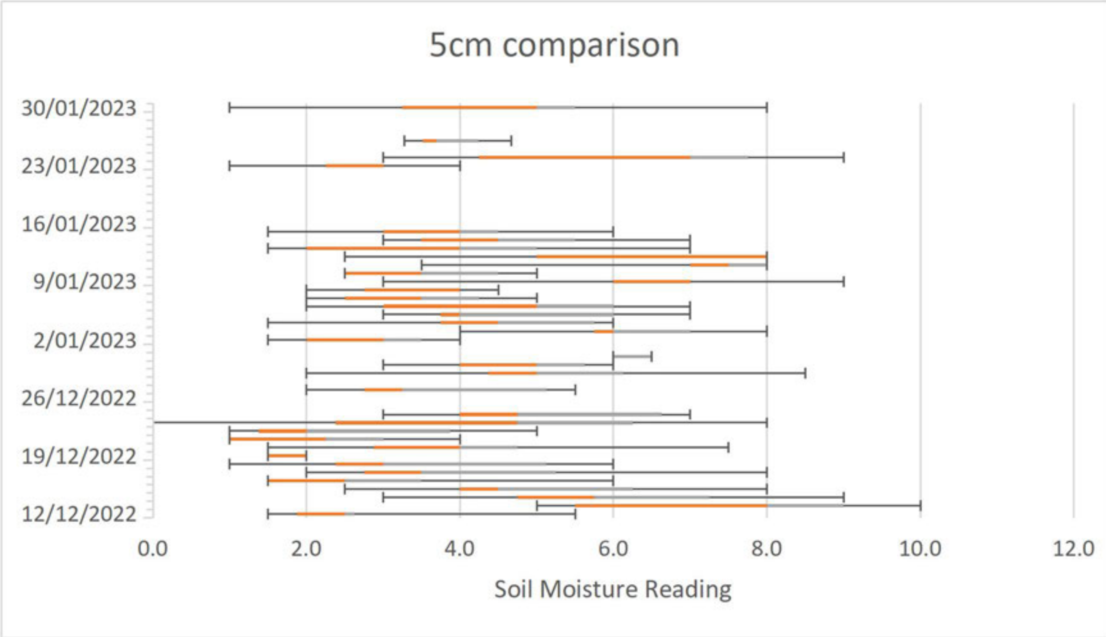


Figure 4-10: Phase 1 5cm depth 3in1 soil meter results

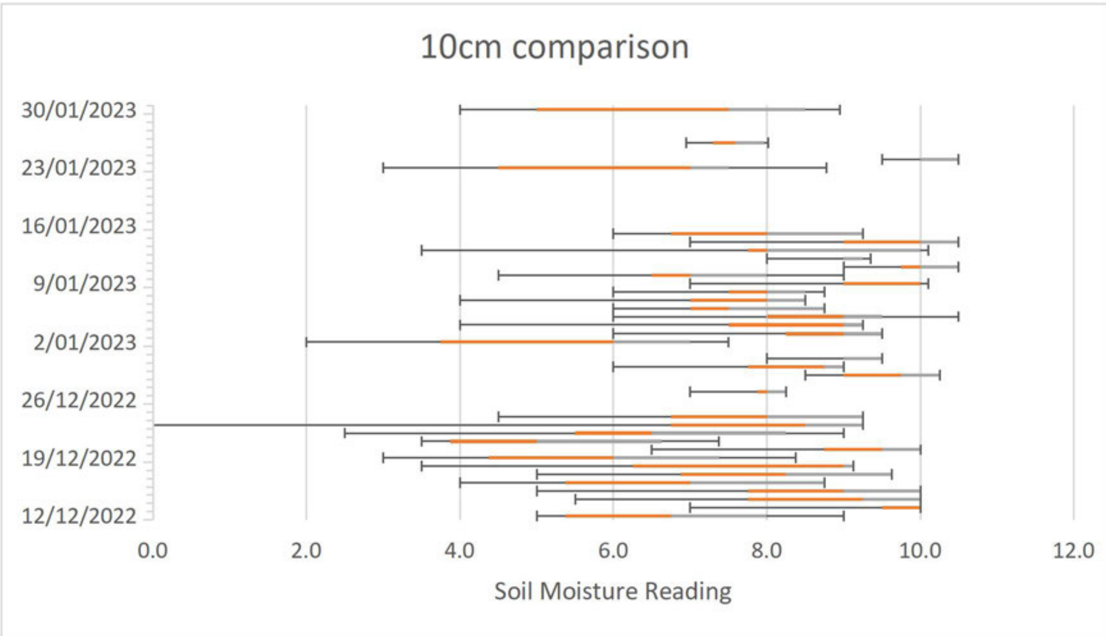


Figure 4-11: Phase 1 10cm depth 3in1 soil meter results.

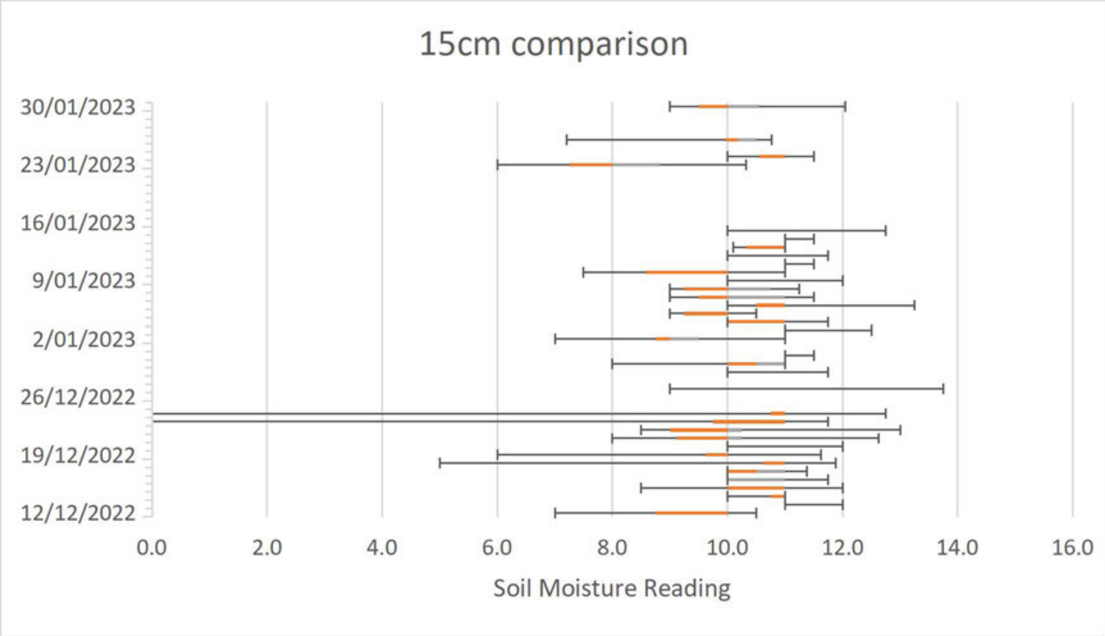


Figure 4-12: Phase 1 15cm depth 3in1 soil meter results

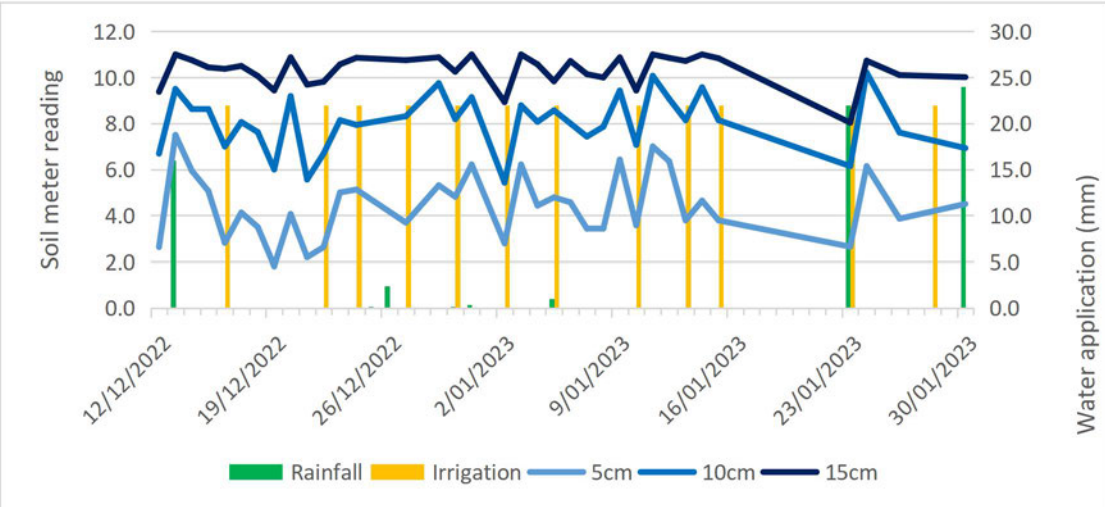


Figure 5-13: Phase 1 3in1 soil meter average measurements comparison with water application.

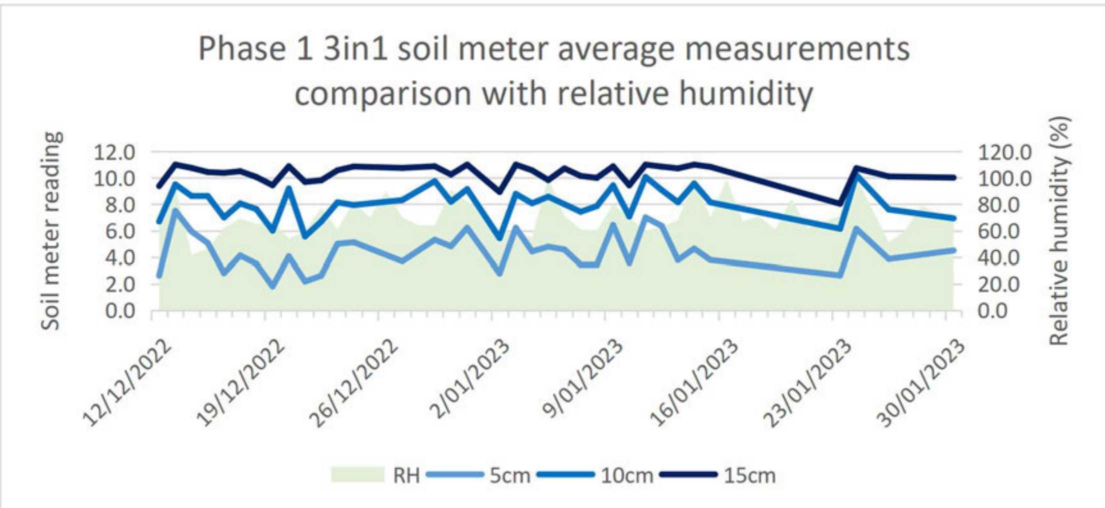


Figure 5-14: Phase 1 3in1 soil meter average measurements comparison with relative humidity.

Under the M3 irrigation regime, plants constantly appeared wilted and stressed, along with the produce taking on a bitter and unpalatable taste. The results of the 20 days of this trial are displayed in Table 4-3, and weekly results can be seen in Appendix K.

ET_L was calculated using Equation 3-1, with a K_L value of 0.49 as determined in the methodology. ET_0 values were downloaded from <https://www.longpaddock.qld.gov.au/silo/point-data/> using the decimal latitude -27.55 and longitude 151.90, and selecting the ASCE Penman Monteith for tall crop. The plot FC was assumed to occur on 01/12/2022 due to significant rainfall recorded on 01/12/2022 at 9am. The arbitrary value of 100mm was given to FC to make the calculations simple. In the following days, soil water is estimated by subtracting the ET_L of the current day and adding any precipitation and irrigation to the previous day's soil water value. If the value was over 100, it was assumed the extra was lost to deep percolation, and the soil water remained at FC. The following calculations for the 2/12/2022 demonstrate this procedure.

$$ET_L = K_L \cdot ET_O = 0.49 \cdot 3.4 = 1.66mm$$

$$SW_2 = SW_1 - ET_L + P + I = 100 - 1.66 + 13.3 + 0 = 111.634$$

Where: SW_1 is the initial soil water and SW_2 is the soil water at the end of the period, P is precipitation and I is irrigation.

In this calculation, SW_2 is over 100, and it is reduced to 100 with the additional value assumed to be lost to deep percolation.

Initially in the methodology irrigation was to be applied when estimated cumulative evapotranspiration reached 28mm. Due to the constantly stressed appearance of the plants in M3, and consistently dry feeling of the top 5cm of soil, this value was changed to an arbitrary 15mm for plot 3 only. As seen in Table 4-3, even with this smaller value, the estimate soil water loss did not exceed this amount due to the rainfall received. Water was applied on 11/12/2022 and 16/12/2022 due to the assumption the plants distressed appearance (wilting and yellowing of leaves) was due to insufficient water. Further water was applied on 20/12/2022 and the trial was canceled.

Table 4-3: ET_L Results (M3)

Date	ET_0 (mm/d)	P (mm/d)	I (mm/d)	ET_L (mm/d)	Soil Water (mm)	Refill required	Required Irrigation (mm)
1/12/2022	2	30	-	0.98	100	-	-
2/12/2022	3.4	13.3		1.666	100	no	0
3/12/2022	5.5	0.4		2.695	97.705	no	0
4/12/2022	5.4	0		2.646	95.059	no	0
5/12/2022	6.5	0		3.185	91.874	no	0
6/12/2022	8.4	0		4.116	87.758	no	0
7/12/2022	8.9	0		4.361	83.397	Yes	16.6
8/12/2022	6.9	32.8		3.381	100	no	0
9/12/2022	5.3	0		2.597	97.403	no	0
10/12/2022	4.2	0		2.058	95.345	no	0
11/12/2022	5.5	0.1	17	2.695	100	no	0
12/12/2022	5.7	0		2.793	97.207	no	0
13/12/2022	2.9	12.6		1.421	100	no	0
14/12/2022	7.4	0		3.626	96.374	no	0
15/12/2022	7.2	0.5		3.528	93.346	no	0
16/12/2022	6.5	0	8	3.185	98.161	no	0
17/12/2022	6.4	0		3.136	95.025	no	0
18/12/2022	6.3	0		3.087	91.938	no	0
19/12/2022	5.3	0		2.597	89.341	no	0
20/12/2022	7.2	0	43	3.528	100	no	0

5.5. Phase 1 discussion

Using average root zone depth means that some plants have smaller root zone than the average. This may result in distress for them as water evaporates from this shallower depth first. Using average values when the top 15cm of soil has been recently disturbed, therefore has different bulk density and hydraulic conductivity/infiltration rate compare to 15cm and deeper layer, as evidenced while saturating $1m^2$ with 40mm.

The trial assumed application efficiency of 100%. The main reason being runoff was limited/negligible due to the gutters surrounding the plots, keeping any runoff within the trial plot. Deep percolation was not measured and therefore was not accounted for.

While taking M2 measurements, there were occasions that the meter was on the wrong mode, and therefore gave unusually low readings for several points before the issue was realised. This is potentially an issue for a gardener who is not taking daily measurements.

The high water application for M1 during the week ending 30/01/2023 was a decision made to increase water application on return from travel.

M3 appeared to have failed very quickly. This may be due to the inexperience in determining the K_L value. This method was also designed for lowering water consumption in landscape plantings, not for productive vegetables. The plot may also not have been at FC following the initial rain on 01/12/2022. On examining the seven day comparison data in Appendix K, it would seem lack of water was not the reason for the distressed appearance, as M3 applied almost double the water of M2, which had thriving, vigorous plants.

Other factors not considered in M3 may have been the hedge drawing water from the bed, as several large lateral roots from it were disturbed when creating the plot. The distressed appearance may have also been related to nutrient deficiency, however this was not monitored or measured during this trial.

6. Phase 1 conclusion

The 3in1 meters are subject to inconsistencies within the soil. Abnormal readings should be redone in a new location due to this. The three probes used within this experiment did not always read within the same +-1 accuracy described by the manufacturer, although it should be noted the meters were not inserted in the exact same spot, and therefore the inaccuracy may be due to the soil inconsistency, even over such a small distance as a couple of centimeters.

With the exception of the discussed anomalies, the readings over time indicate moisture loss consistent with the weight loss of the pot. The meters may be useful in indicating a moisture level in the soil. Repeating the trial may yield more results which generate more accurate averages. For field use, multiple probing sites is recommended to develop a good overview and make obvious any anomalies in readings, as was experienced in this trial.

In general, more water is applied to wilted appearing plants, regular (daily or twice daily depending on heat) misting of seeds and seedlings (in 2 leaf phase). Daily or every second day watering of young produce plants, then 2-4 day watering of established produce plants.

WUCOLS ET_L was too low to keep up with moisture demand of the vegetables. The K_L value was significantly less than the K_c values recommended for agricultural crops in FAO56. Therefore it may be more appropriate to estimate using a cropping method such as the Penman Monteith described by Allen et al. (1998).

Using the 3in1 soil meter did significantly lower water use, and warrants further investigation.

7. Phase 2 Methodology

In Phase 2, M1 continued without change. M2 continued, with irrigation volumes of 22mm occurring when the 3in1 Soil Meter reached 4 and 7 at 5cm and 10cm depths respectively. Due to the significant failure of M3, it was decided not to attempt to re-calibrate the method, and instead M4 was employed, as discussed in the following section.

7.1. Pot weight method (M4)

Method 4 (M4) was applied to P3 during phase 2 and is adapted from the one outlined in Rolfe (2006). This method requires a seed/seedling to be planted into a pot plant (containing the same dirt as the plot), concurrently with the plot planting. A 170mm plastic garden pot using same soil and amendments as the plot received was used. The pot was fully saturated and allowed to drain until water stops dripping (overnight to ensure minimal evapotranspiration loss), with the pot and basin enclosed in a plastic bag to prevent evaporative loss. Once water stopped being collected in the basin and pot weight did not change, the pot was then weighed to determine FC. Following planting, the pot was weighed daily to record water loss, which was attributed wholly to ET. Once the recharge point was reached, enough water to just surpass FC was applied. The water application needed to surpass FC slightly to prevent salt build up, but not be so excessive as to waste water and create excessive nutrient losses. This same value was applied to the garden, with the assumption the ET of the pot was equivalent to that of the plot.

It was assumed the pot would experience more ET than the garden bed, as it is fully exposed to the sun, wind, etc on all sides while the garden only has the surface exposed. No adjustments were made to this value however as it was not known what the difference factor may be or how to calculate this. The garden bed was visually monitored to check for water-logging over time. If it was to occur, the timing/volume of the water applied to the garden bed would need to be adjusted by an unknown factor to prevent serious damage to plants..

Equation 6-1 shows how the water volume required in pot (or pot ET (ET_p) is determined using the pot weight loss method provided by Rolfe (2006). For a 170mm pot used in the trial, the change in weight recorded divided by 25g weight loss per mm water depth (Table 6-1) provides the estimated ET_p.

$$ET_p = \frac{\Delta weight}{25g/mm}$$

Equation 6-1

Table 6-1: Container size weight loss evapotranspiration (Rolfe 2006)

Container diameter size (mm)	**Weight loss (g) per mm water required**
80	5
100	10
150	20
170	25
200	30
250	50
300	70

$$\text{water loss} = [(\text{Field capacity weight}) - (\text{weight at last reading})]/\text{weight loss from table}$$

Rolfe (2006) suggests the water loss can be converted into a crop factor using evaporation from a class A pan or automatic weather station. These instruments were considered to be outside the budget for the trial, in addition to the logistics of a class A pan in a home garden not being realistic. It could be compared to the seasonal ET calculated in section 8.

Rolfe (2006) does not state what soil type is in the pots, however it is assumed the soil would be a good quality potting mix as it is a nursery technical paper. Therefore the water holding capacity is potentially different to any garden soils. This means using the above diameter sizes and weight losses may have errors as the g/mm water required factor could be incorrect.

7.2. TDR Sensors

Acclima Time domain reflectrometry sensors were placed in each of the trial plots during phase 2 to compare the soil moisture recorded on these to the estimated water balance and trial methods. The sensors were placed at 15cm and 30cm horizontal levels. A 3rd sensor was placed in each bed vertically from the surface, to emulate the 3in1 soil meter placement.

7.3. Trial procedure

1. Place TDR sensors in effective root zone area within RAW depth and in area considered to be deep percolation.

2. Ensure all plants in garden bed to be used for trial have furrows to prevent any runoff.
3. On first day (t=0), water each garden section to FC. This allows all sections to start at the same moisture content. Or, preferably, start trial after significant rainfall when it can be assumed the soil is at FC.
4. Apply water to each section as indicated by the individual method for that section using a handheld hose with water flow meter attached to measure the volume applied.
5. Record pertinent details to water application and timing, along with plant and/or soil appearance.
6. Note any outside disturbances to the garden as they occur (ie: animals, weeding).

8. Phase 2 Results and analysis

8.1. Trial methods

Phase 2 setup occurred over the week ending 06/02/2023, although watering continued from Phase 1 methods. Measurements from Phase 2 were taken from 07/02/2023 to 20/06/2023. The most water in total was applied using M1 and the least using M2 (Table 7-1). M2 also had the lowest median, average, and maximum application per m^2. M4 had the highest median application, with M1 using 82.1% of this and M2 using only 33% in comparison. M1 had the highest average and maximum values. In comparison the maximum individual M2 and M4 applications were one quarter and one third respectively of the M1 result comparison.

Table 7-1: Phase 2 overall comparison

	Trial methods		
Method	**M1**	**M2**	**M4**
Total No. application days	44.0	29.0	50.0
Total irrigation per plot (L)	4535.2	1443.2	1321.3
Total irrigation per m^2 (mm)	1174.9	603.0	932.0
Minimum	0.0	0.0	0.0
Median	54.2	22	66
Average irrigation	61.8	31.7	49.1
Maximum	264.2	66	88

M1 has a significantly higher water application amount for the first week of the phase (13/02/2023) compared to M2 and M4 for the same week, or any other week, as seen in Figure 7-1. The seven day water application amounts for M1 and M4 become very similar from approximately 24/04/23 until the 12/06/23 (Figure 7-1). The three methods do follow a similar rise and fall pattern.

M2 is the only method with no water applied for the fortnight of weeks ending 01/05/2023 and 08/05/2023 (Figure 7-1). No water is applied to all three methods for the week ending 12/06/2023.

The full table of results is available in Appendix K and J.

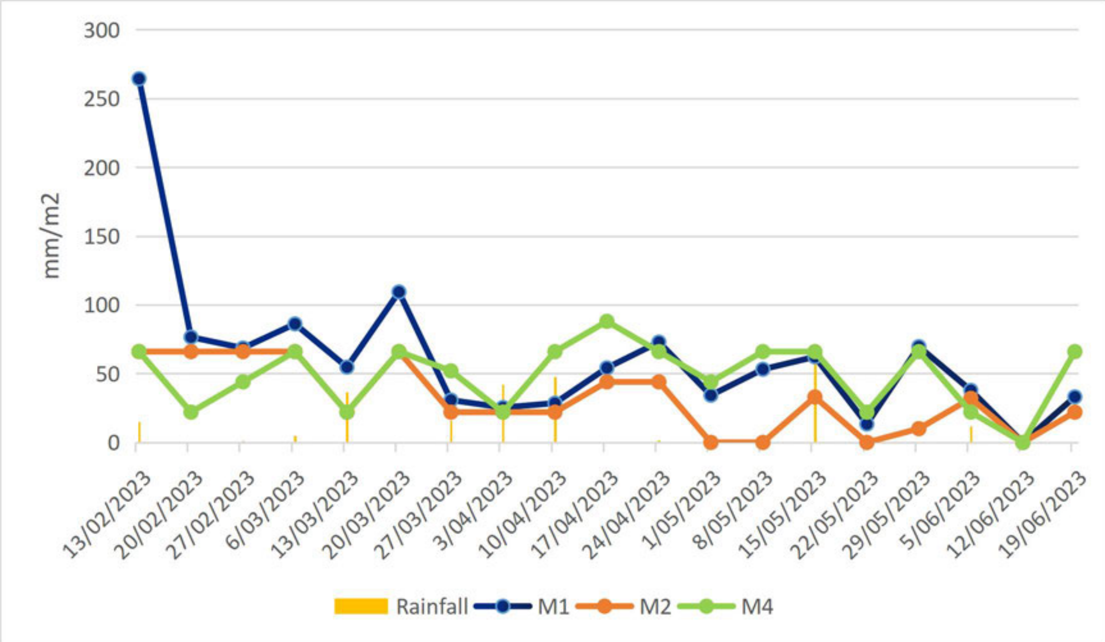


Figure 7-1: Phase 2 seven day water application totals

8.1.1. M2 results

Figure 7-2 to Figure 7-4 show that under the watering regime used for M2, different values could be expected for each depth. The 5cm depth measurements have a large spread and tend to be in low to mid moisture readings. The 10cm depth measurements also show a spread of results around the upper middle values, although there are some outliers. One of these occurs on 05/03/2023 when a minimum value of 1.5 is recorded. The 15cm depth measurements have less spread in results, and are primarily between 8 and 11. Five outlying results have been recorded on 11/02/23, 18/02/23, 28/02/23 16/04/23, and 11/05/23. Three of these occurred in the same measurement area (planted with beetroot).

The methodology was altered slightly during Phase 2. It became apparent by 20/02/2023 that the soil moisture readings were not reaching the irrigation points congruently. It was decided to initiate irrigation once the readings were within ± 1 of the refill readings.

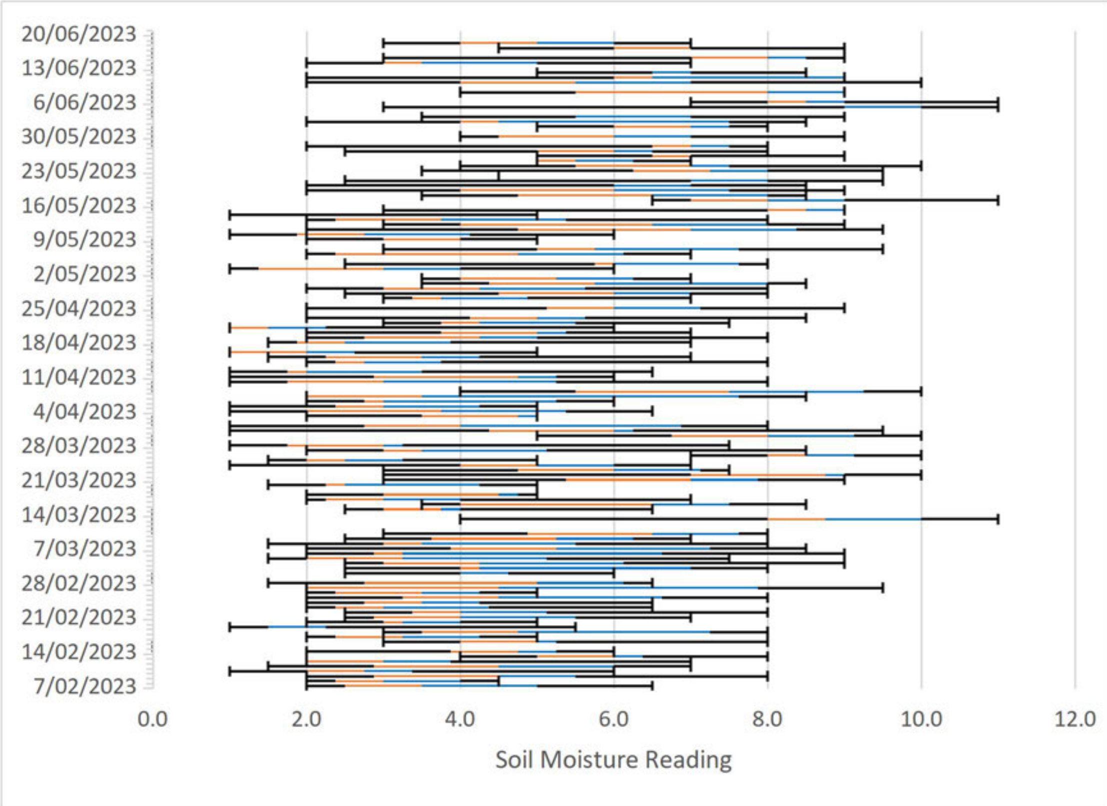


Figure 7-2: Phase 2 M2 - 5cm measurement comparison

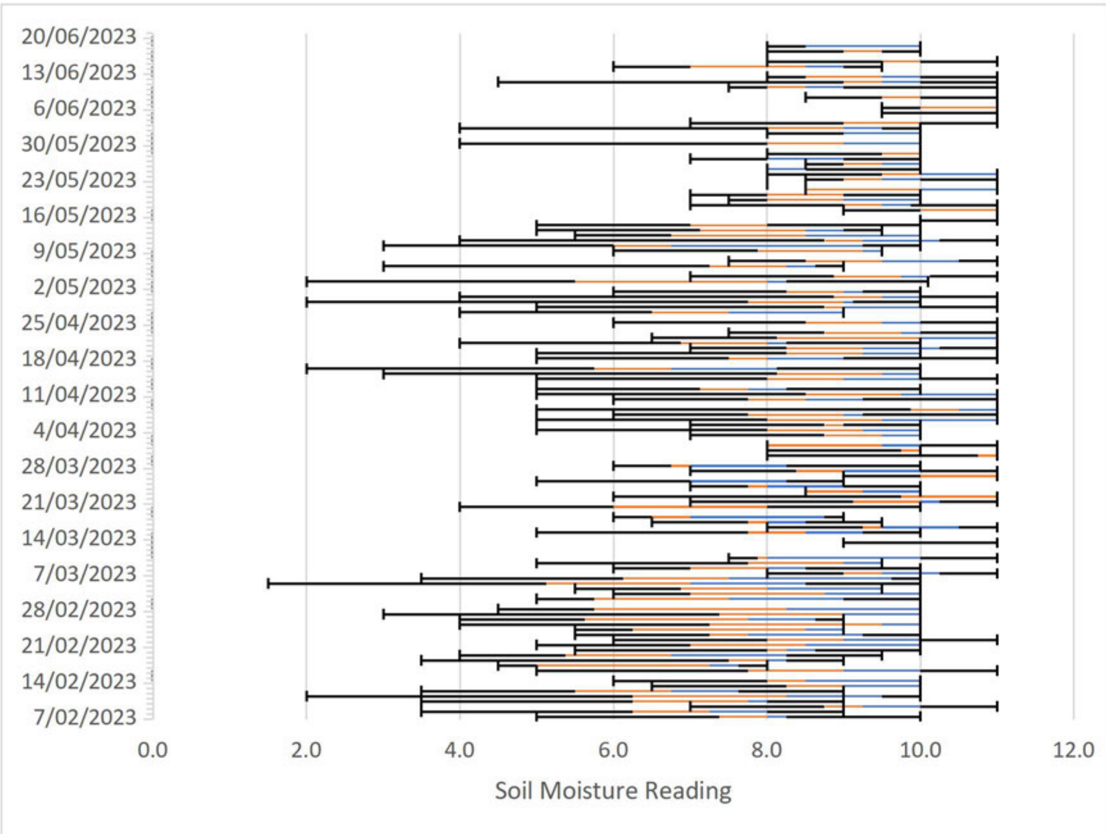


Figure 7-3: Phase 2 M2 - 10cm measurement comparison

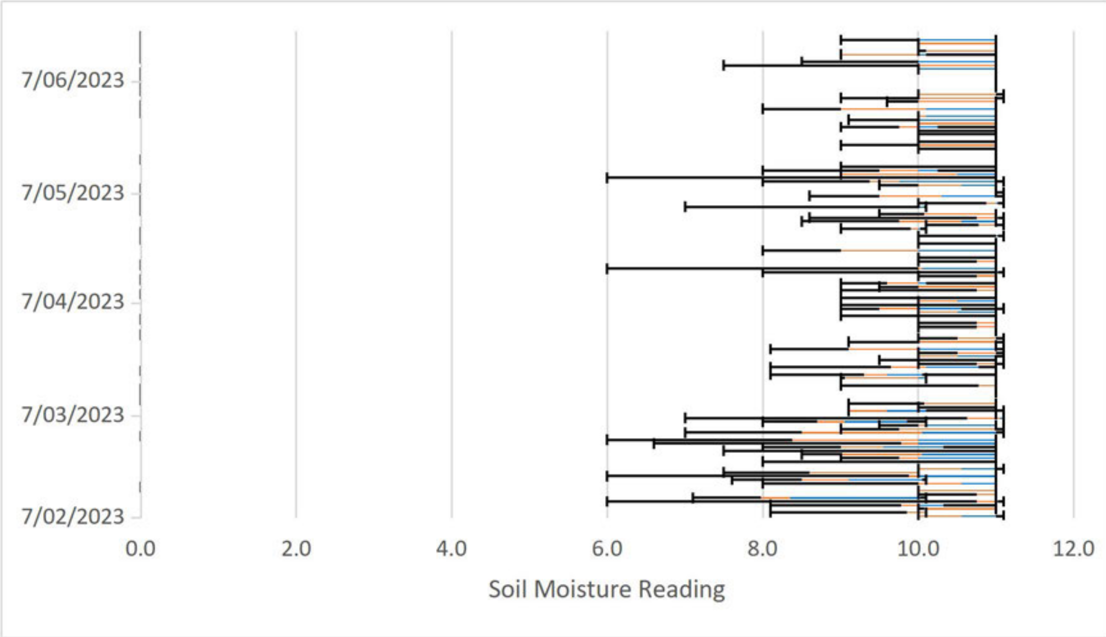


Figure 7-4: Phase 2 M2 - 15cm measurement comparison

Figure 7-5 shows the average measurements for all three measurement depths under M2 compared to rainfall and irrigation depths. The moisture measurements show an increase in moisture value the same day as the rainfall, and a one day lag in measurement increase after irrigation.

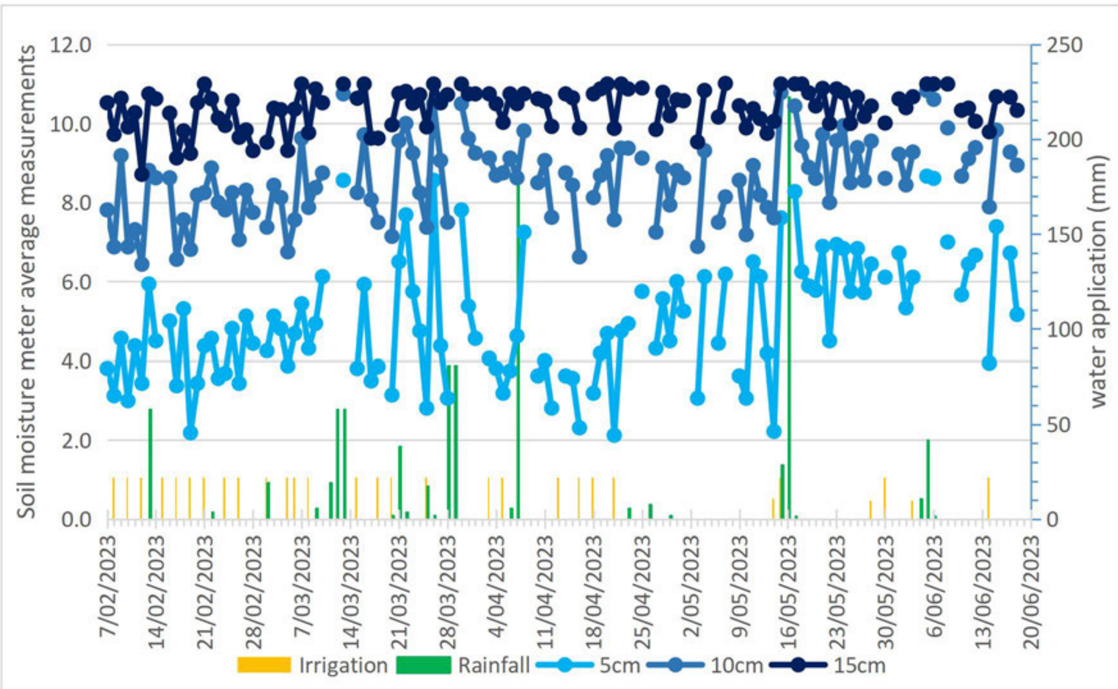


Figure 7-5: Phase 2 M2 - average moisture measurements compared to water inputs

Figure 7-6 shows the M2 average soil moisture measurements compared to the relative humidity.

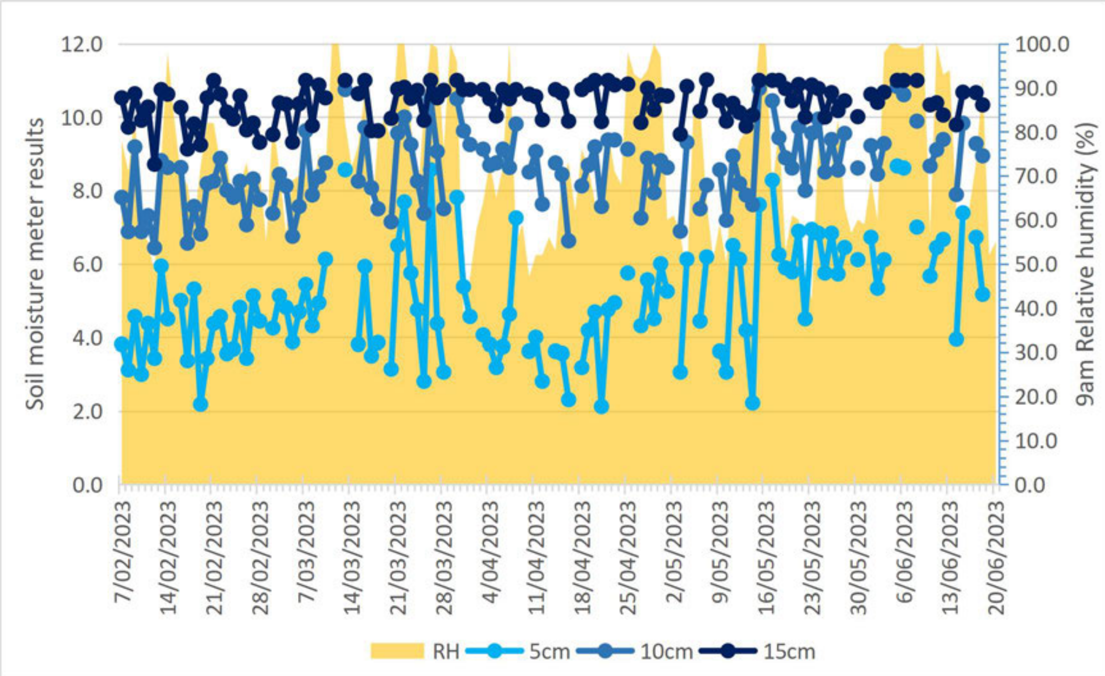


Figure 7-6: M2 results compared to 9am relative humidity

8.1.2. M4 results

A 170mm diameter pot was filled with soil from plot 3. The initial field capacity was 2018g at the time of planting (12/12/22) Chia seedlings (approximately 15cm tall). This value was used reassessed on 07/02/23, by submerging the pot in water until no bubbles were visible then allowing to freely drain for 1 hour until no water was visibly dripping from the pot. The pot weight of the new assumed FC was 2238g. The FC weight was not remeasured again, however when measurements exceeded this value, the higher value was assumed to be the new FC. These changes in value can be seen in Figure 7-7.

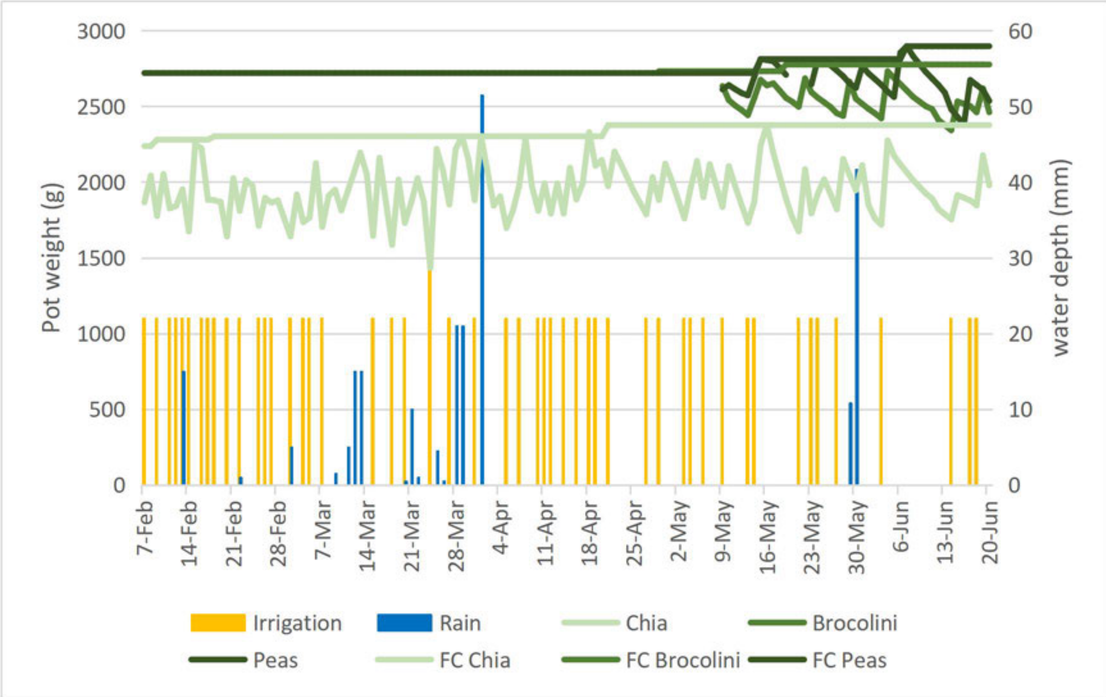


Figure 7-7: M4 Phase 2 pot weight and water application

The equivalent 22mm depth for the pot surface area was calculated as 0.506mm for the pot using Equation 7-1 and Equation 7-2.

$$Area_{pot} = \frac{\pi D^2}{4} = \frac{\pi \cdot 0.17^2}{4} = 0.023m^2$$

Equation 7-1

$$Irrigation_{pot} = Irrigation_{plot} \cdot Area_{pot} = 22mm/m^2 \cdot 0.023m^2 = 0.506mm$$

Equation 7-2

During the trial, the pot area was incorrectly calculated using 170mm as the radius. The results are summarized in Table 7-2.

The refill point in weight can be calculated by rearranging Equation 6-1, as below.

$$\Delta weight = ET_p \cdot 25g/mm = 22mm \cdot 25g/mm = 550g$$

Two more pots were set up when the winter season plants were sown. Broccolini and snow peas were planted in 200mm pots, with an initial FC weight of 2732g and 2720g respectively. Equation 7-1, Equation 7-2, and Equation 7-3 were calculated with these values. The value of

30g/mm weight loss per mm water from Table 6-1 was used. The results are shown in Table 7-2.

Table 7-2: M4 Pot details

Pot size	**170mm pot**		**200mm pot**
	Trial	Actual	Actual
Area (m^2)	0.091	0.023	0.031
Irrigation (mm)	1.997	0.499	0.691
Δweight (22mm) (g)	550		660
Δweight (10mm) (g)	250		300

During the trial, irrigation was prompted by the ET value reaching, or anticipated to reach, 22mm cumulative total on the day of measurement. The plot was watered based on the readings from the chia pot for the full length of the Trial.

There were various days when data could not be recorded, and this has been linearly interpolated from the proceeding measurement and the one following.

The chia pot went to seed before the plot chia plants, and also did not grow as high. It regularly appeared under severe stress with the end of the soft green stems and leaves often wilted and limp in appearance.

Broccolini seedlings and snow pea seeds were planted on 29/04/2023 in 200mm pots. At planting time it was noted that the plot at these points was moist on the top 2-3cm, and then dry. Due to this an additional 22mm was applied to ensure the seeds/seedling had moisture, even though 22mm had been applied the morning of.

The estimated ET_p fell below the RP 19 times for the chia pot (Figure 7-8). The broccolini and snow peas did not go past the RP, as seen in Figure 7-9 and Figure 7-10. The 200mm pots were in the initial and development growth stages for the trial period. The dates of this can be seen in Appendix F. The initial stage can be compared to a lower RP of 10mm (RP_{10}). Figure 7-9 and Figure 7-10 show the RP_{10} point is exceeded 5 and 3 times for broccolini and snow peas respectively. The RP would increase from RP_{10} to RP_{22} over the development stage (20/05/23 and 16/05/23 for snow peas and broccolini respectively). Figure 7-9 and Figure 7-10 show that the RP_{10} is only surpassed during development stage.

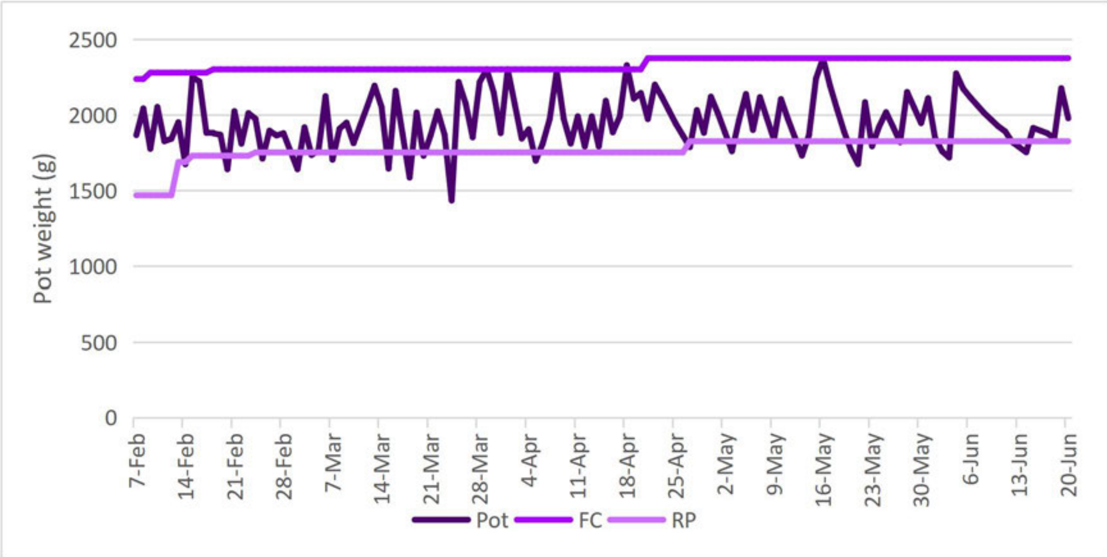


Figure 7-8: Chia pot weight

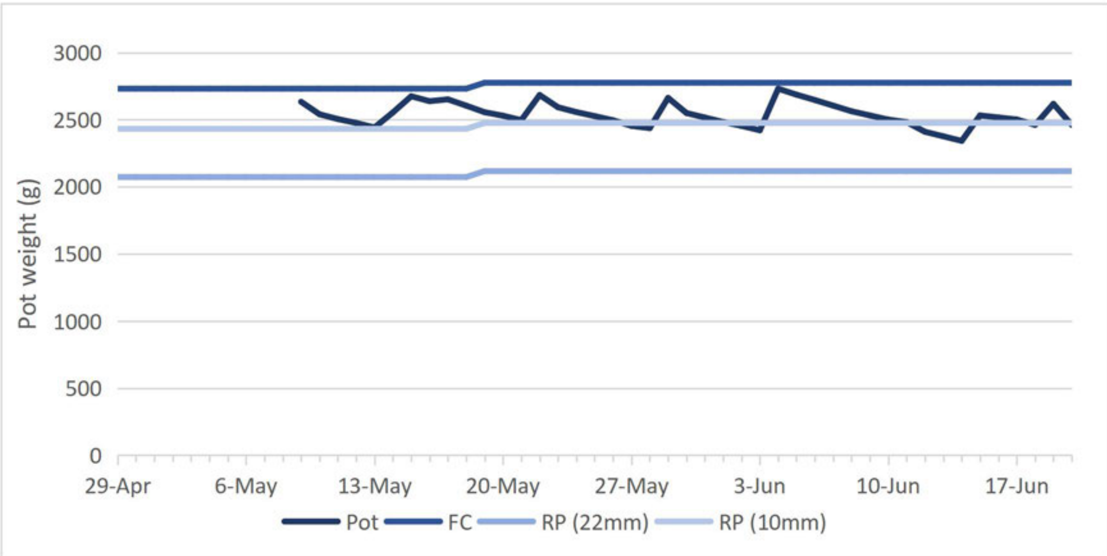


Figure 7-9: Brocolini pot

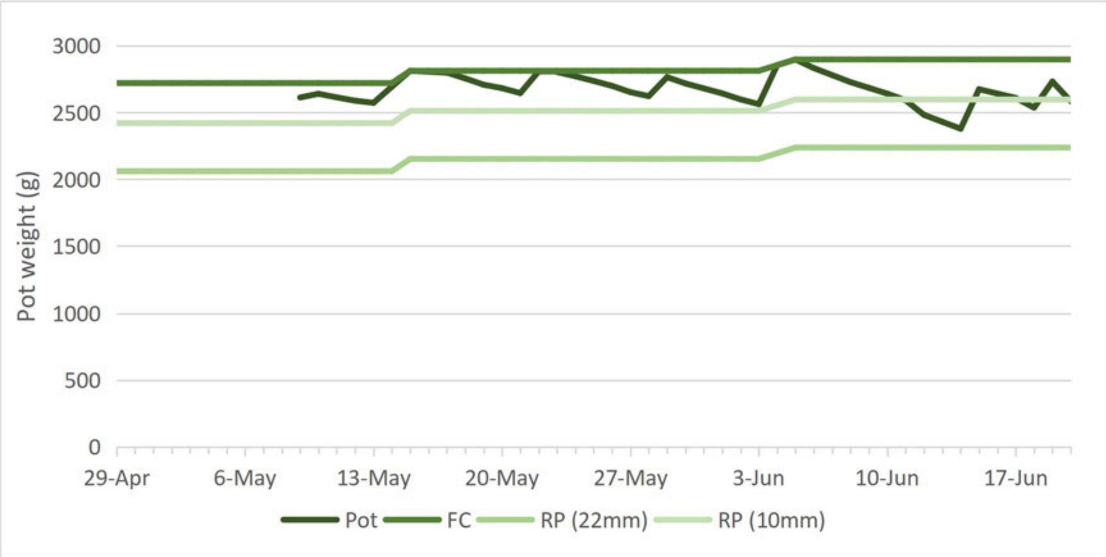


Figure 7-10: Snow pea pot

8.2. TDRS

The TDR sensors were initially installed in the plots on 01/02/2023. One was installed vertically from the plot surface, and then horizontally at 15cm and 30cm depths in each plot. In P3 the sensor could not be installed at 30cm depth as the degrading parent material was too hard to penetrate.

The TDRS had ongoing setup and recording issues, which has resulted in limited data for analysis. The batteries went flat extremely quickly and was not checked regularly enough. Data recording periods can be seen in Table 7-1.

Table 7-3: TDRS recording periods

Date start	**Date end**
01/02/2023	02/02/2023
14/02/2023	19/02/2023
08/03/2023	29/03/2023
14/04/2023	18/04/2023
06/05/2023	10/05/2023

The period from 08/03/2023 to 29/03/2023 was chosen for analysis as it has the longest span of data collected. The results are displayed in Figure 7-11, Figure 7-12, and Figure 7-13 for P1, P2, and P3 respectively. From these figures it can be seen that P1 had distinct differences between the volumetric water content (VWC) of all three probes, whereas the 15cm and 30cm depth probes of P2 had similar VWC to each other. The results displayed for P2 and P3 from 28/03/2023 to 29/03/2023 are markedly different to those of the preceding days.

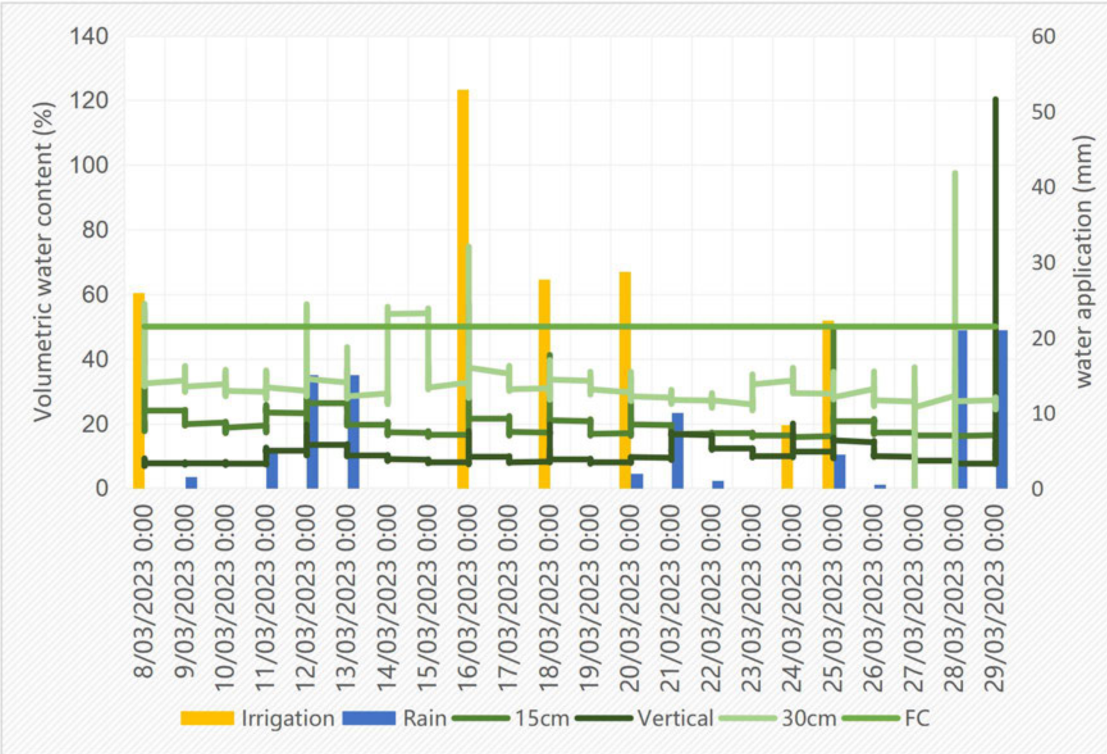


Figure 7-11: Plot 1 TDRS volumetric water content from 08/03/2023 to 29/03/2023.

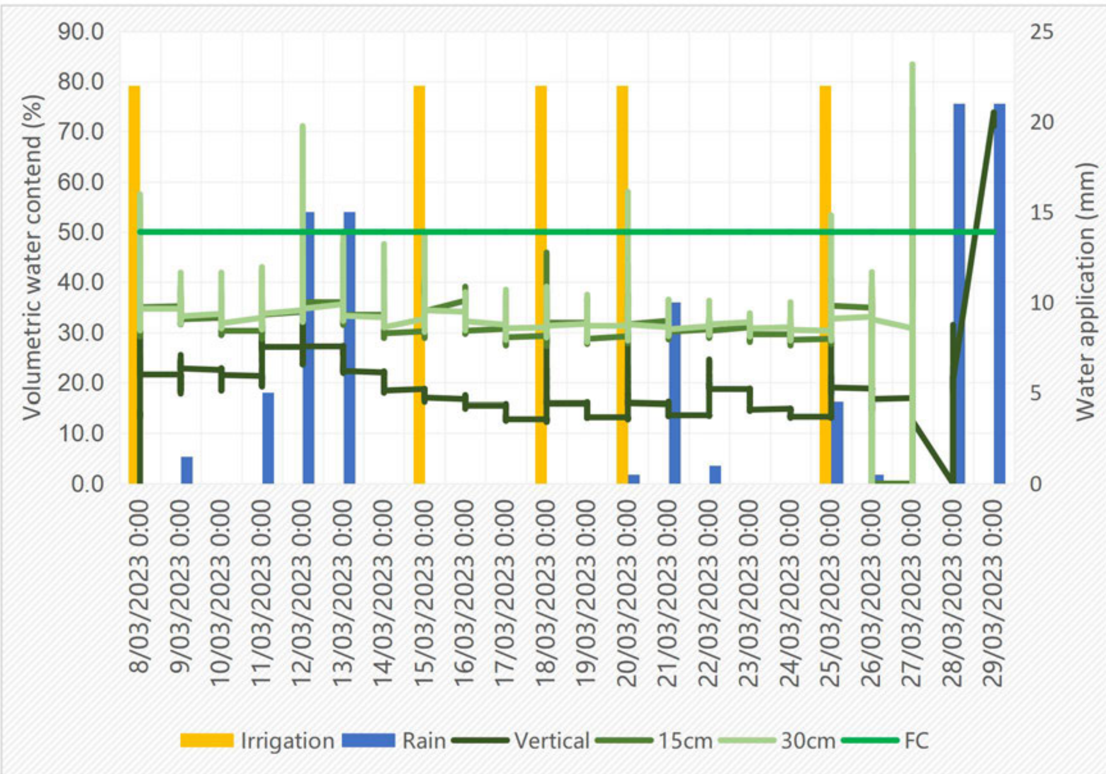


Figure 7-12: Plot 2 TDRS volumetric water content from 08/03/2023 to 29/03/2023.

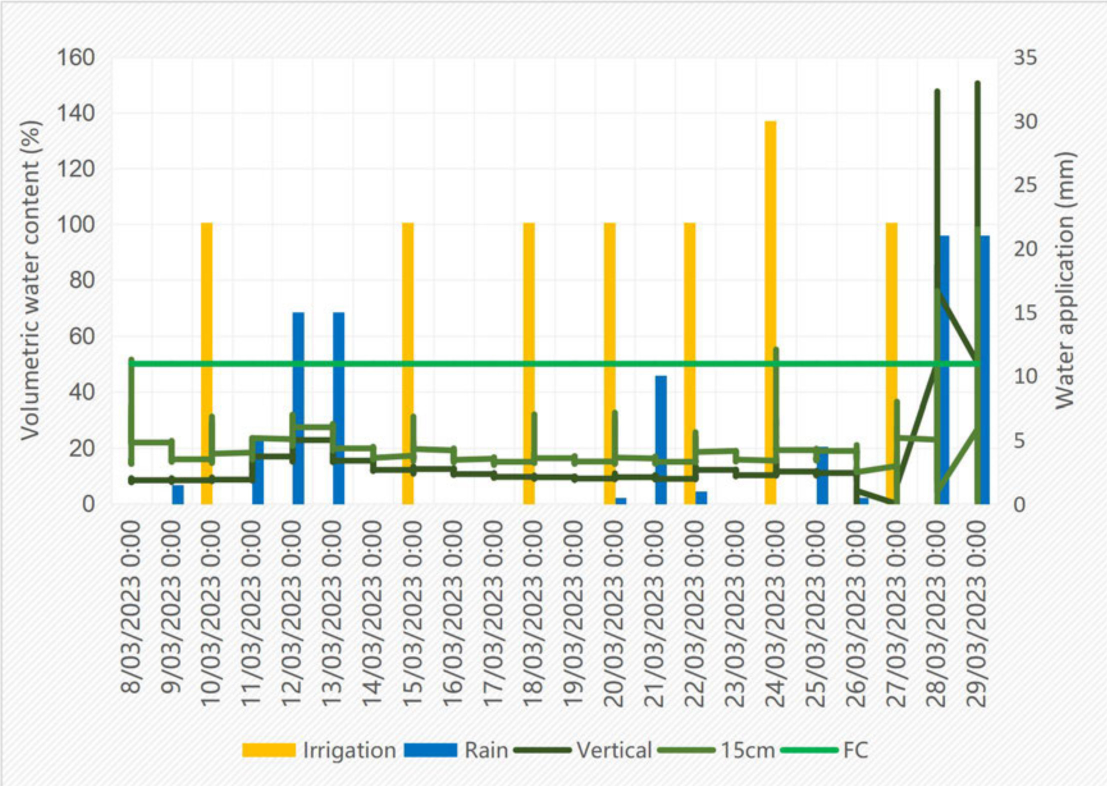


Figure 7-13: Plot 3 TDRS volumetric water content from 08/03/2023 to 29/03/2023.

9. Phase 2 discussion and conclusions

From the results, it can be seen that both M2 and M3 resulted in water savings compared to M1. M2 had the highest savings. A noticeable lowering of water use can be seen during May and June, when the summer vegetables have reached the end growth stage, or already been removed and been replanted with winter vegetables in their initial and development phases. All three methods resulted in vegetable produce which was utilised in the home kitchen.

M2 used the least amount of water, and part of this could be attributed to the change in sun position between seasons resulting in less ET. In summer P2 was in direct sunlight at the same time as P3, however in winter, only the western end of the P2 received direct sunlight while P3 was in full sun majority of the day still. P1 received shading from the house in winter until mid to late morning, and shading from the western hedge from mid-afternoon onwards, giving it a small window of mid-day sun, however the actual length of time was not recorded.

The summer shading was not noted, however by the time 9am measurements occurred all 3 plots were in full sun. Plot 1 did receive some late afternoon shade from the hedge.

M2 results show the moisture increasing with depth. This is expected as it is well established soil water is evaporated from the surface layers first, and plants also utilise the surface first as it requires less energy (Allen, et al 1998).

P3 had roots from the surrounding hedge drawing water from it, as noted in Phase 1. This most like attributed to the regular dry feel to the soil and plant stress. This method should be repeated in a different plot to see if there is a difference in results.

Under M4, the FC appears to change as the development growth phase starts for the broccolini pot. This supports the theory of the pot weight increasing due to plant growth and weight increasing. The first change in FC of the pea pot occurred 5 days prior to the estimated start of development growth stage based on the estimated meditteranean time frames provided by Allen, et al (1998). The different date may be due to the climate difference, or different water and nutrient regime experienced in the trial.

A larger pot for M4 could better represent the soil water movements. The 170mm pot was selected as it was estimated this was the depth of the loose garden bed to the compacted, undisturbed soil level below when the bed was created. The plant roots quickly filled this pot, and by the time the plant had flowered roots were visible on the surface.

There were also concerns the watering method of the pot was not wetting the soil fully, and instead was taking preferential path between the pot wall and the soil edge. Initially a small period was trialed by allowing the pot to sit in a saucer for 10min before removing until the next irrigation. There was a lot of human error in leaving the pot sitting in the saucer overnight, and this was abandoned as it was not thought to be simulating the soil water experience in the plot.

Using a separate pot for each planting allows the user to apply better targeted water. In P3 there was the opportunity to water the snow peas and broccolini with different amounts. Figure 7-9 and Figure 7-10 show that the 22mm water application would have had significant over watering, as approximately only 10mm (broccolini) or less (snow peas) had been lost to ET when irrigation was applied due to the chia pot reaching/exceeding 22mm ET.

The TDR sensors had ongoing recording issues, and due to this the results for P2 and P3 on 28/03/23 and 29/03/23 are most likely not correct due to how markedly different the results are to the rest of the graph.

The rain data has been added to the TDR plots at the time of 9am reading. Due to this the graph appears to rise in VWC before the water input, however this would be because most of the rainfall events occurred in the afternoon/evening.

Using the estimated 50% FC, the plots do not appear to have reached/surpassed FC often. This could be due to the value being over-estimated, or not enough water being applied to completely fill the soil profile. A third explanation could also be attributed to the mulch hindering infiltration through to the soil, and the moisture is retained in the mulch. Previous work by Liao, et al (2021) found straw mulch reduced soil infiltration for light rain events. Observation several times during the trial noted the soil only feeling damp on the top 2-3cm of soil.

It would appear there are errors in the P1 30cm results. On 14/03/23 and 15/03/23 the VWC increases from approximately 30% to 55%. The other probes do not measure a similar change, and there is no water input recorded for these days.

10. Water balance comparison

10.1.1. Residential water use

The total residential water use was collected along with the main garden tap from 13th March to 19th June. A 2nd garden tap was metered for 2 weeks before the tap water meter was broken and was unable to be replaced.

Figure 8-1 compares the total allotment use (read from the water main meter), outdoor use (based on 1 out of 2 taps) and rainfall over 7 day increments. The data was incomplete (ie: water main and tap meter were read on 6 -12 day increments), and linear interpolation was used to complete the data set. The two data sets (original and interpolated) are listed in Appendix I - Allotment, tap and rainfall water.

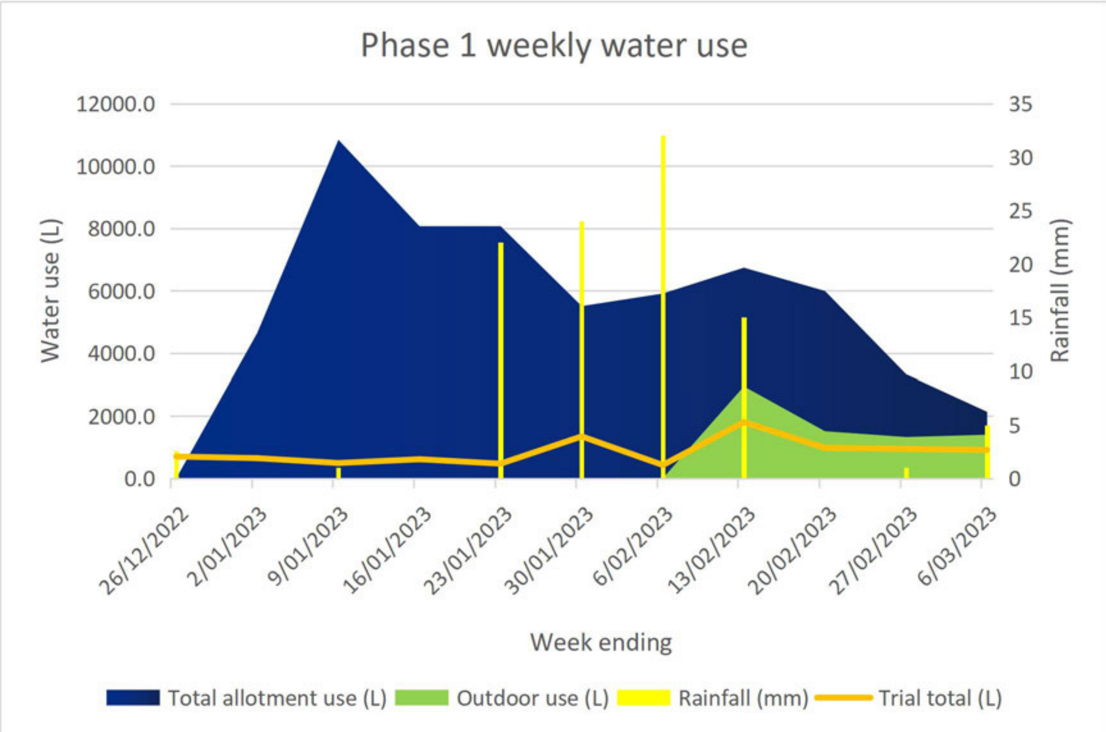


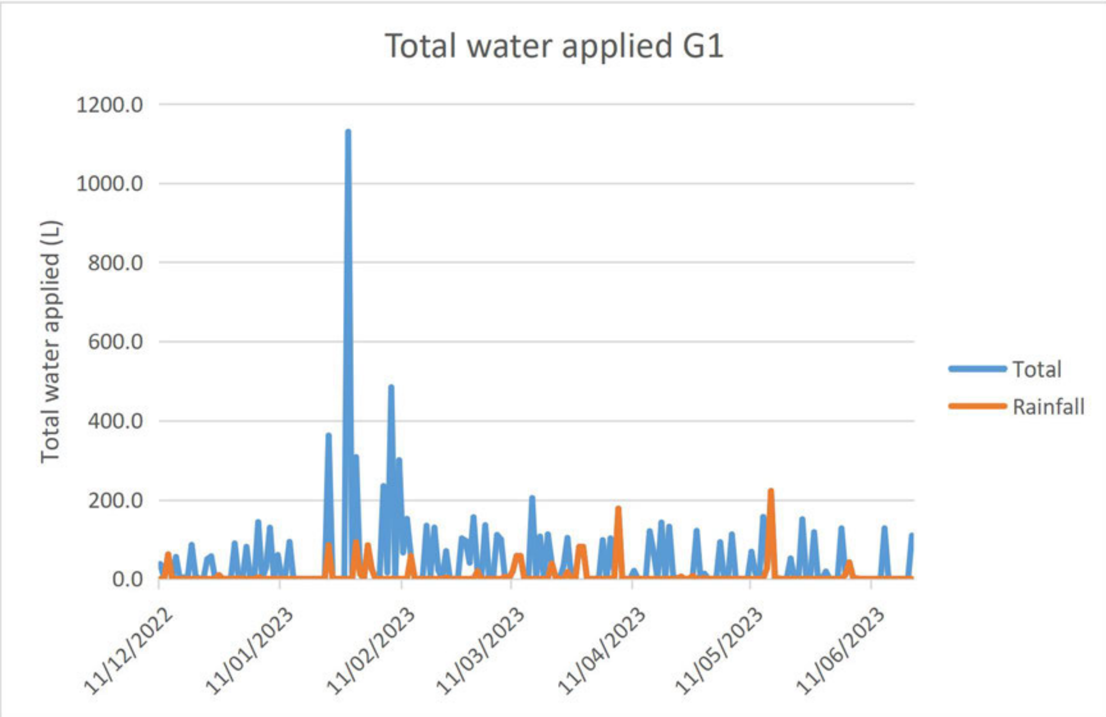
Figure 8-1: Weekly water use comparison

It is interesting to note for the week of 15/05/23, outdoor use peaks and the highest rainfall is recorded. It would be expected that outdoor water use would be at a minimum when significant rainfall is recorded, as plants and lawns would require less.

On three separate occasions the total total trial water use is higher than the outdoor use. These weeks (24/04/2023, 29/05/2023 and 05/06/2023) have all been interpolated to determine the outdoor use, which shows that the linear interpolation is not completely accurate.

10.1.2. Garden 1 water use

The rainfall was recorded in the garden from 01/01/2023 to 20/06/2023. Rainfall for December 2022 was taken from the Bureau of Meteorology's Toowoomba Airport records.



10.2. ET_c water balance (M5)

Irrigation can be scheduled using Equation 2-4 and the procedure outlined in O'Connor (2017). This method was selected out of the numerous options (see literature review) due to its widespread acceptance within the agricultural industry (Allen et al 1998; O'Connor 2017). The irrigation is set to occur when the crop water uptake has utilised all/majority of the RAW. This procedure requires the calculation of ET_C and the water inputs (rain and irrigation). Once the RAW plus inputs minus cumulative ET_C closely equates to zero, irrigation can then be scheduled to refill the RAW.

The daily ET_O was determined by downloading the monthly Toowoomba airport point potential ET from BOM (2022b), as the airport location was closest to the trial site. The monthly ET_O was divided by days to determine average daily ET_O for the ET_C calculations

(Table 10-1). The historical ET_O was calculated using the historical average values while the seasonal ET_O was calculated using the actual values experienced during the trial period.

Point potential was selected as it is representative of ET from small irrigated fields surrounded by unirrigated land. Of the three options, this was deemed most similar to the urban garden used in this project which is surrounded by unirrigated surfaces (non-watered grassed areas, house, driveway and roadway). This method assumes latent and sensible heat transfer occurs only via convection with the over passing air not affected by the actual ET (Wang et al. 2009).

Table 10-1: Toowoomba Airport potential point evapotranspiration (BOM 2022b)

	ET (mm)	
	Monthly	**Daily**
Jan	216	6.97
Feb	170	6.07
Mar	175	6.97
Apr	131	6.07
May	98	6.97
Jun	87	6.07
Jul	95	3.06
Aug	117	3.77
Sept	146	4.87
Oct	184	5.94
Nov	204	6.80
Dec	221	7.13
Summer	607	6.74
Autumn	404	4.39
Winter	299	3.25
Spring	534	5.87
Annual	1844	5.07

It is noted BOM ET_o calculations have several inherent errors. These include measurement error of data used, sample size errors, spatial coverage of available stations, interpolation and mapping techniques, model error of ET estimation, and professional judgments used within the modeling (BOM 2022b).

K_c values were drawn on from Allen (1998) and Pereira (2021) and adjusted for the trial location and setup, as detailed in following subsections.

The value of RAW was set to 22mm the same as Phase 2 trial.

The actual rainfall experienced throughout the trial was used as the rainfall amounts for calculations. Recordings of 2mm or less were considered ineffective and were excluded from the calculations. In addition, the initial 2mm of each rainfall event was removed as ineffective.

No consideration was given to intensity of rainfall due to it not being measured, and as a result, runoff volumes have not been excluded from the calculations. The infiltrating rainfall amount may be overestimated in the calculations as a result, giving rise to a larger RAW value than is actually experienced in the plot.

10.2.1. Determination of K_c

K_c is the crop factor applied to the ET_o to determine the ET_a. It is separated into an initial, mid and end season value to construct a K_c curve for the duration of the crop life. Several parameters affect the value of K_c, such as growth stage, planting date, species, surface mulching, and inter-cropping.

Over the course of the trial, 31 different species were planted (Appendix F - Garden bed planting schedule). Using the definitions from Allen (1998), these were inter-cropped in non-pristine conditions in small spaces (ie: $1m^2$ or less in most cases). Primarily contiguous vegetation was used (ie: the crucifers planted in plots 1 and 2 had intermingled canopies, while the canopy of the pumpkin vine on the trellis extended down to the capsicums on the ground in plot 2). In addition, there were also separately planted crops, such as the capsicum, silver beet and kankong in plot 3.

Allen (1998, p.199) provides a weighted method for determing the field K_c value ($K_{c\ field}$) when the ground cover fraction is different for each crop. This is shown in Equation 8-1.

$$K_{c\,field} = \frac{f_1 h_1 K_{c1} + f_2 h_2 K_{c2}}{f_1 h_1 + f_2 h_2}$$

Equation 10-1

Where: f = fraction of field surface planted to that crop

h = crop height

K_c is reduced by organic mulching. Sugar cane mulch was applied across the full soil surface of all three plots. For each 10% of covered surface, Allen (1998, p.197) suggests reducing soil water evaporation by 5%. Therefore $K_{c\ ini}$ is reduced by the full reduction percentage (50%) as it is primarily soil water evaporation, whereas $K_{c\ mid}$ and $K_{c\ end}$ are reduced by 50% difference between ($K_{c\ mid}$ - $K_{cb\ mid}$) and ($K_{c\ end}$ - $K_{cb\ end}$) using tables 12 and 17 from Allen (1998).

$K_{c\ ini}$ is further affected by the time interval between wetting events, atmosphere evaporation power, and wetting event magnitude. To simplify the determination of values, those from table 12 of Allen (1998, p. 110-113) were used. A more accurate method can be calculated from equation 59 of Allen (1998, p.117) which utilises the ET_o, however due to the large differences in planting date, the daily ET could vary from 2.13 to 5.71mm/d and a significant number of calculations would have to be completed.

Allen et al. (1998, p.117-118) suggest more accurate $K_{c\ ini}$ values can be obtained via use of graphs within the publication for irrigation depths below 10mm or above 40mm. For depths between 10 and 40mm, $K_{c\ ini}$ can be estimated using Equation 8-2.

$$K_{cini} = K_{cini(p.117)} + \frac{I-10}{40-10}\left[K_{cini(p.118)} - K_{cini(p.117)}\right]$$

Equation 10-2

Where: $K_{c\ ini\ (p.117)}$ refers to the value obtained from Allen et al. (1998, p.117)

$K_{c\ ini\ (p.118)}$ refers to the value obtained from Allen et al. (1998, p.118)

I = average infiltration depth (mm)

$K_{c\ ini}$ depends on the average interval between irrigation events and ET_o along with irrigation depth. For the purposes of calculating the water balance and schedule, it was assumed watering during the initial plant growth period would occur daily at 10mm during summer, and 7mm during autumn (reflecting the decreasing ET_o values). Therefore only the $K_{c\ ini\ (p.117)}$ value was required. This schedule and depth was selected to ensure seedlings received regular and sufficient water to replenish water lost according to the estimated $ET_{o.}$ From this, $K_{c\ ini}$ for summer was 1.06 and 1.14 for Autumn. It was assumed the full soil surface would be wetted, and therefore no further adjustment was required.

The $K_{c\ mid}$ values provided by Allen et al (1998) were adjusted using Equation 8-3. This adjustment was required as the average wind speed recorded at the Toowoomba airport was greater than 2.0m/s throughout the year (annual average 5.4m/s at both 9am and 3pm).

$$K_{c(mid)adj} = K_{c(mid)} + \left[0.04(u_2 - 2) - 0.004(RH_{\min} - 45)\right]\left(\frac{h}{3}\right)^{0.3}$$

Equation 10-3

Where: RH_{min} = minimum Relative humidity

The length of growth stages also needed to be determined. According to Allen (1998, p. 104-106) the length of growth varies by 115 days for the planted species. A decision needed to be made regarding how plant specific the ET_c estimation should be, as 31 different species were planted over the course of the trial. In addition, plants were inter-cropped in non-pristine conditions with in small spaces (ie: $1m^2$ or less in most cases). Primarily contiguous vegetation was used (ie: the crucifers planted in plots 1 and 2 had intermingled canopies, while the canopy of the pumpkin vine on the trellis extended down to the capsicums on the ground in plot 2. In addition, there were also separately planted crops, such as the capsicum, silver beet and kankong in plot 3.

All three of the plots were mulched, which also affects K_c. Allen et al. (1998) recommends when using organic mulch to reduce K_C by 5% for every 10% of ground covered. All three plot surfaces were 100% mulched, therefore a 50% reduction was applied.

Finally Allen et al. (1998) provides an adjustment equation for an intercropped field with varying fractions of crop ground cover. This is shown in Equation 10-4.

$$K_{Cfield} = \frac{f_1 h_1 K_{C1} + f_2 h_2 K_{C2}}{f_1 h_1 + f_2 h_2}$$

Equation 10-4

Where: f_1 and f_2 refer to field surface fractions planted to crops 1 and 2; h_1 and h_2 are their heights.

K_c errors

The assumption that the full soil surface was wetted caused error, as not every plant species required the this. For example the zucchini and pumpkin plants were only watered in the small section the seeds were planted until they reached the development stage when water was applied across the full surface. In comparison the lettuce and carrots were simply spread across the full garden surface, and therefore the full surface was wetted.

The K_c values do not appear realistic for P3 for two periods. From 24/01/23 to 27/02/23 K_c ranged from 2.12 to 3.63. From 20/03/23 to 01/04/2023 K_c ranged from 2.03 to 3.63. K_c values are not expected to exceed 1.9. With more time, the spreadsheet calculations could be further investigated to improve these values to be more realistic.

10.3. ET_c results

The results for Phase 2 time period (07/02/203 to 20/06/2023) are displayed in Figure 9-2 for the recorded seasonal ET_O and rainfall. Table 10-2 shows the summary of the number of irrigation days estimated for each plot, and the irrigation amount applied. This estimates that M2 would use the least amount of water and M1 and M3 the same amount per m^2.

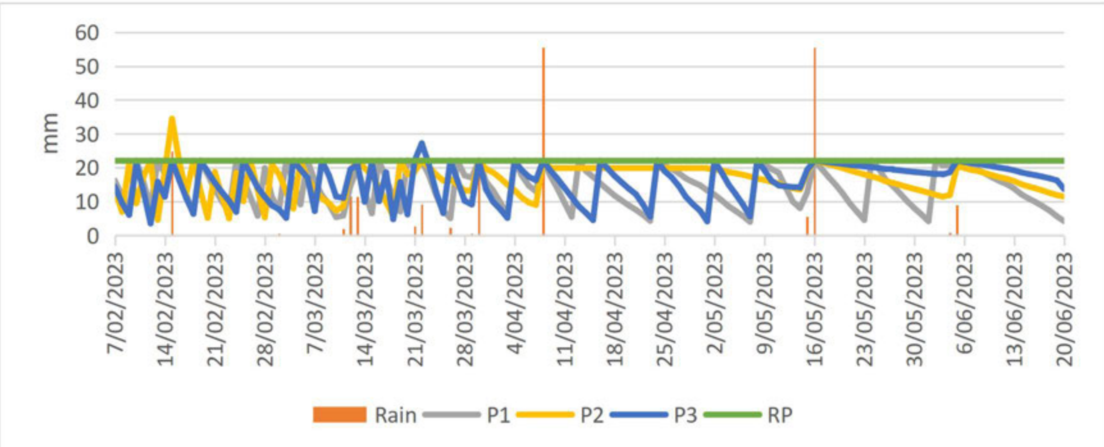


Figure 10-2: Seasonal irrigation schedule showing the RAW value for trial plots 1-3, including rainfall.

Table 10-2: Seasonal ET_C summary

Plot	RAW (mm)	effective rain (mm)	Number of irrigation days	total irrigation volume (mm)	Total water volume per plot (L)

1	22	2	17	374	1541
2			13	286	1187
3			17	374	1728

The K_C calculation results can be seen in Appendix O - K_c tables. This includes the adjustment for the Toowoomba airport wind speed and relative humidity, mulch, and field weighting in separate tables.

Time did not allow for calculation of the historical ET_C.

Table 10-3 shows the results of the trial methods compared to the irrgiation schedule created using the seasonal ET_C.

Table 10-3: Comparison of trial methods and seasonal ET_C schedule.

	Trial methods			**Seasonal irrigation schedule**		
Method	**M1**	**M2**	**M4**	**P1**	**P2**	**P3**
Total No. application days	44.0	29.0	50.0	17.0	13.0	17.0
Total irrigation (L)	4535.2	1443.2	1321.3	1541	1187.0	1728.0
Total irrigation (mm)	1174.9	603.0	932.0	374.0	286.0	374.0

10.4. ET_C discussion and conclusion

The excessive weighted $K_{c\ field}$ values may be due to the calculation exceeding the upper limit of ET for the cropped surface. Allen, et al. (1998) refers to this upper limit as $K_{c\ max}$ and provides an estimation calculation.

It is interesting to note that the estimate for P2 shows less water than P1 and P3. This result reflects what occurred in the trial of M1, M2, and M4, where M2 used significantly less. The trial noted M1 and M4 had similar average and median values, yet very different overall use as M1 had 2 irrigation dates with extremely high water use. It would be interesting to remove or adjust these values to the average, and reassess the water use to compare to these values, however time does not allow.

The higher water use of P1 and P3 is reflected in a higher number of irrigation events

The RAW did exceed 22mm on several occasions in the estimation calculations. This was assumed to be lost to deep percolation and ignored by setting the maximum RAW after irrigation to 22mm. This assumption may create an error, as the water may or may not have moved through the profile in the space of 24hr.

From Table 10-3 it would appear M1 significantly over-watered, which aligns with the findings of the literature review. The estimation also suggests both M2 and M3 over watered, however as discussed in the methodology, the ET_C estimation is subject to errors. Also noted in the phase 2 discussion is that M4 (in P3) also had hedge roots traversing the plot at the time the garden bed was formed.

11. Survey development

While the trial period has demonstrated that affordable, low technology scheduling methods can lower water consumption, it is unclear if these methods would be utilised by the general public. The literature review demonstrated that psychological change needs to occur in water users for long term changes in water consumption (Manning et al. 2013; Rowley 2016). A survey can give insight into the the willingness of a the audience to uptake these methods.

An online survey was developed to gain this insight, however did not pass the Human Research Ethics Committee in time to provide to participants. The survey is attached in Appendix J- Survey. The survey was designed in the UniSQ online survey tool to ensure it was presented professionally, and to utilise the software, storage, and analytical options freely available as a UniSQ student.

The survey was intended to be distributed across the UniSQ email newsletter network via the assistance of the project supervisor - Dr Malcolm Gilles. It was also intended to be distributed through the Toowoomba Regional Council employees social network and Toowoomba Buy Swap and Sell Facebook group. By distributing primarily to Toowoomba and surrounds area, the local perceptions and watering behaviour could be surveyed.

The introductory text was developed using the template participant information sheet (PIS) provided by the UniSQ Human Ethics department. On reading this, participants would have to click a policy link to show their consent to the survey before the survey opened.

There were then 2 screening questions (A1 and A2 of Appendix K - Survey). A1 was designed to eliminate respondents under 18 to remove any potential issues arising from surveys of minors. A2 was designed to ensure respondents were from the target audience - people who hand water their garden.

The next set of questions (B1 to B12) were designed to find out more about the current watering behaviour, education, awareness, and goals of the gardener. This was due to the limited amount of data currently available for hand watering of domestic gardens.

The final set of questions (C1 to C3) were designed to find out how likely respondents were to change their current hand irrigation scheduling practices, and if any practices were perceived to be more acceptable than others.

12. Future research

This project has been a feasibility study into the use of low cost, low tech methods of hand irrigation scheduling. The follow on research is broad and numerous. The trial results have proved the methods used do reduce water consumption and still produce a productive domestic vegetable patch. Therefore the trial should be repeated across a larger number of gardeners to see if repeatable results can be obtained. Further trials could be undertaken to determine other scheduling methods which could also be used.

Further work is needed in analysing the large amount of data collected from this trial.

More work could be undertaken in accurately determining the ET of a domestic vegetable garden. From this a mobile phone app could be created to assist in irrigation scheduling of domestic gardens based on evapotranspiration data.

The survey should also be conducted, to determine which methods are most likely to be taken up and therefore research can then focus on these methods. It could also investigate how to change peoples perceptions on permanently modifying their behaviour, or how general public education could be most effective on changing domestic gardeners watering methods.

13. Conclusion

Many methods have been developed by industry to develop irrigation schedules. This project has determined that two methods are transferable and feasible in lowering water application and maintaining a productive domestic vegetable patch. Both the home made weighing lysimeter and 3in1 soil meter resulted in significant lowering of water application for the trial period. The ET_L method was not successful and significantly under watered the plot resulting in significant wilting and some plant loss. The theoretical irrigation schedules developed for the trial based on FAO56 methods also proved the trial gardener significantly over watered.

The methods in this trial also proved the 22mm application depth, which was guided by the Toowoomba Regional Council (2022b) amount of 28mm, was sufficient with the scheduling methods. TDRS data showed this value limited over-watering.

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Appendix A - Project Specification

For: Caitlin Paige Watson

Title: Comparison of hand watering scheduling methods in domestic gardens

Major: Environmental engineering

Supervisor: Dr Malcolm Gillies

Enrolment: ENG4111 - ONL S1, 2023

ENG4112 - ONL S2, 2023

Project Aim: To determine an affordable, low technological irrigation scheduling method for manual watering of domestic gardens to improve water use efficiency.

Programme: **Version 1, 21st February 2022**

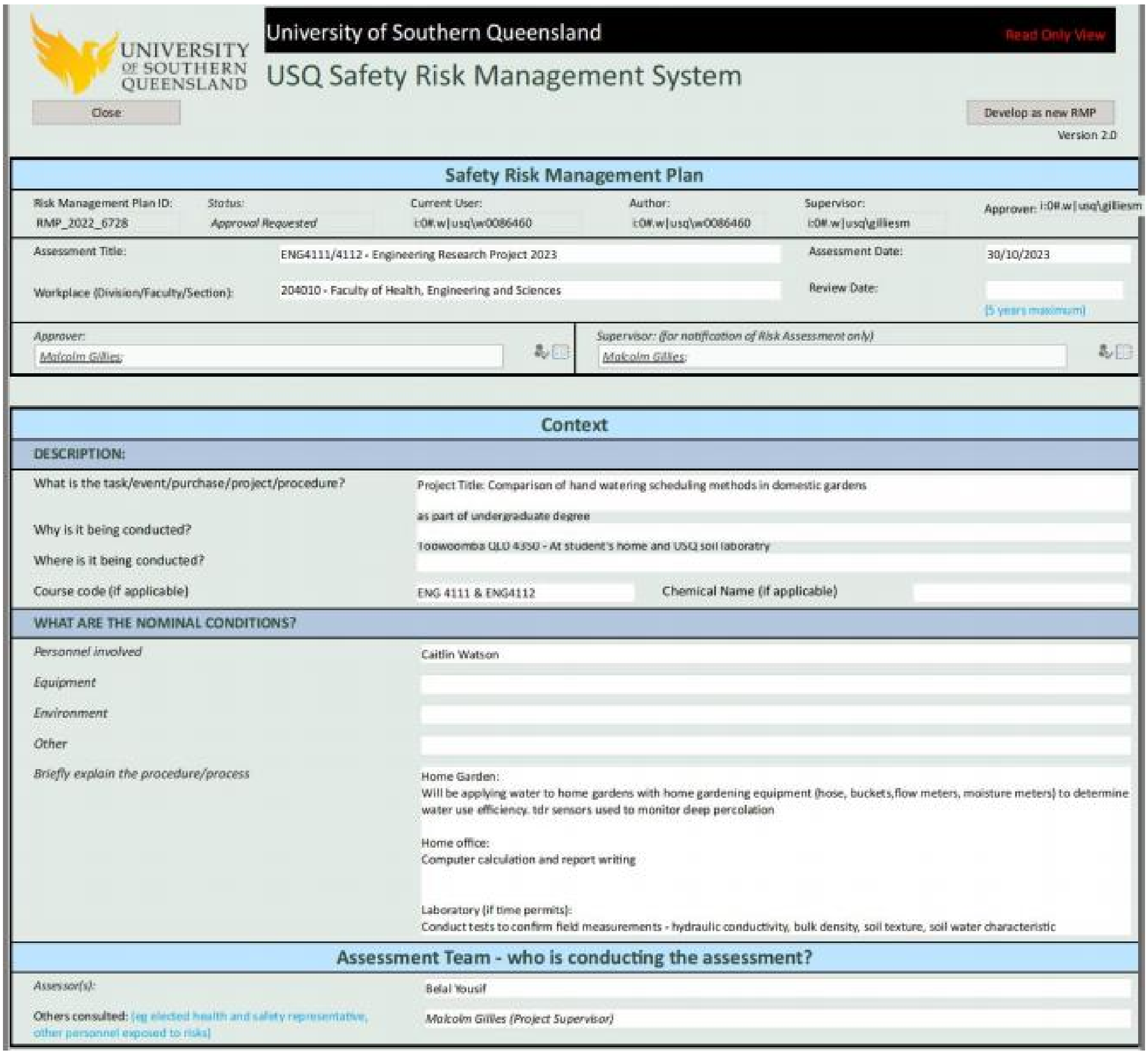
1. Research background of water use in urban gardens relating to scheduling methods and application rates.
2. Review existing professional irrigation scheduling methods and evaluate them based on their practicality and limitations within domestic gardens.
3. Research mixed vegetable crop characteristics to estimate plant water requirements.
4. Design trials to compare scheduling methods and application volume for manual watering in a domestic garden site.
5. Calculate an expected water balance for urban garden based on available soil and water data from location/s of experiment for control purposes.
6. Implement hand watering trials and record results.
7. Analyse trial measurement data and factors affecting the results.
8. Design an improved manual irrigation schedule for domestic garden based on analysis of trials.

If time and resources permit:

9. Trial the improved design and analyse the results.

Appendix B - Safety risk management plan

This is a screenshot of the Safety Risk Management Plan for this project from the online USQ Safety Risk Management System. The ID number is RMP_2022_6728.



University of Southern Queensland — Read Only View

USQ Safety Risk Management System

Close | Develop as new RMP

Version 2.0

Safety Risk Management Plan

Risk Management Plan ID:	Status:	Current User:	Author:	Supervisor:	Approver:
RMP_2022_6728	*Approval Requested*	i:0#.w|usq\w0086460	i:0#.w|usq\w0086460	i:0#.w|usq\gilliesm	i:0#.w|usq\gilliesm

Assessment Title:	ENG4111/4112 - Engineering Research Project 2023	Assessment Date:	30/10/2023
Workplace (Division/Faculty/Section):	204010 - Faculty of Health, Engineering and Sciences	Review Date:	(5 years maximum)

Approver: Malcolm Gillies;

Supervisor: (for notification of Risk Assessment only) Malcolm Gillies;

Context

DESCRIPTION:

What is the task/event/purchase/project/procedure?	Project Title: Comparison of hand watering scheduling methods in domestic gardens
Why is it being conducted?	as part of undergraduate degree
Where is it being conducted?	Toowoomba QLD 4350 - At student's home and USQ soil laboratry
Course code (if applicable)	ENG 4111 & ENG4112 — Chemical Name (if applicable):

WHAT ARE THE NOMINAL CONDITIONS?

Personnel involved	Caitlin Watson
Equipment	
Environment	
Other	
Briefly explain the procedure/process	Home Garden: Will be applying water to home gardens with home gardening equipment (hose, buckets,flow meters, moisture meters) to determine water use efficiency. tdr sensors used to monitor deep percolation Home office: Computer calculation and report writing Laboratory (if time permits): Conduct tests to confirm field measurements - hydraulic conductivity, bulk density, soil texture, soil water characteristic

Assessment Team - who is conducting the assessment?

Assessor(s):	Belal Yousif
Others consulted: (eg elected health and safety representative, other personnel exposed to risks)	*Malcolm Gillies (Project Supervisor)*

Risk Matrix

Probability	Consequence				
	Insignificant No Injury 0-$5K	**Minor** First Aid $5K-$50K	**Moderate** Med Treatment $50K-$100K	**Major** Serious Injury $100K-$250K	**Catastrophic** Death More than $250K
Almost Certain 1 in 2	M	H	E	E	E
Likely 1 in 100	M	H	H	E	E
Possible 1 in 1,000	L	M	H	H	H
Unlikely 1 in 10,000	L	L	M	M	M
Rare 1 in 1,000,000	L	L	L	L	L

Recommended Action Guide

Extreme:	E= Extreme Risk – Task ***MUST NOT*** proceed
High:	H = High Risk – Special Procedures Required (Contact USQSafe) Approval by VC only
Medium:	M= Medium Risk - A Risk Management Plan/Safe Work Method Statement is required
Low:	L= Low Risk - Manage by routine procedures.

Risk Register and Analysis

	Step 1	Step 2	Step 2a	Step 2b	Step 3			Step 4				
	Hazards: From step 1 or more if identified	*The Risk:* What can happen if exposed to the hazard without existing controls in place?	*Consequence:* What is the harm that can be caused by the hazard without existing controls in place?	*Existing Controls:* What are the existing controls that are already in place?	*Risk Assessment:* Consequence x Probability = Risk Level			*Additional Controls:* Enter additional controls if required to reduce the risk level	*Risk assessment with additional controls:* Has the consequence or probability changed?			
					Probability	*Risk Level*	*ALARP*		*Consequence*	*Probability*	*Risk Level*	*ALARP*
	Example											
	Working in temperatures over 35° C	*Heat stress/heat stroke/exhaustion leading to serious personal injury/death*	*catastrophic*	*Regular breaks, chilled water available, loose clothing, fatigue management policy.*	*possible*	*high*	*No*	*temporary shade shelters, essential tasks only, close supervision, buddy system*	*catastrophic*	*unlikely*	*mod*	*Yes*
1	Computer work for long periods	muscle soreness, bad posture	Moderate	Regular breaks, stretch as needed, use appropriate equipment for better posture	Rare	Low						
2	Working in garden environments	Insect/creepy crawly bites and stings	Major	Be aware of environment, eyes on hands, PPE (Long sleeves, gloves, long pants and closed in footware	Rare	Low						
3	Working in garden environments	Sunburn and heatstroke	Major	PPE (hat, sunscreen, long sleeves & pants), regualar breaks in shade, drink water regularly	Rare	Low						
4	Working in garden environments	Splinters	Insignifica	Wear gloves, check equipment	Rare	Low						
5	Soil & waterborn pathogen	illness	Minor	work with damp soil when possible, use a face mask, wear gloves, wash hands, don't drink or splash water on face	Rare	Low						
6	Use of garden tools	Blisters, scrapes & cuts	Minor	Wear PPE - gloves, long sleeves and pants, eyes on task, check equipment regularly	Rare	Low						
7	Garden environmen	slips trips and falls	Moderate	Be aware of ground surface, non-slip foot ware, keep work area clean and tidy	Rare	Low						
8	biological material from plants	transfer of seeds/weeds	Major	Clean and wash footware and garden equipment after use	Rare	Low						
9	biological material from plants	poisonous plants	Moderate	don't touch unknown plants, wear PPE (gloves, long sleeves and pants, closed in footware) if around,appropriate tooling to handle, wash any tooling which has touched poisonous plants	Rare	Low						
10	Travel (to field and laboratory)	car accident	Major	follow USQ Motor vehicles and travel fatigue procedure	Rare	Low						
11					Rare	Low						
12	Manual handling	strains, sprains, blisters	Moderate	Ensure correct posture, PPE, lifting equipment (ie: trolleys), are used as necessary	Rare	Low						

Step 5 - Action Plan (for controls not already in place)

Additional Controls:	*Exclude from Action Plan: (repeated control)*	*Resources:*	*Persons Responsible:*	*Proposed Implementation Date:*

Supporting Attachments

View Attachments

Click here to attach a file

Step 6 – Request Approval

Drafters Name:	*Caitlin Watson*	*Draft Date:*	*08/02/2023*
Drafters Comments:			

Assessment Approval: **All risks are marked as ALARP**

Maximum Residual Risk Level: **Low - Manager/Supervisor Approval Required**

Document Status: *Approval Requested*

Step 6 – Approval

Approvers Name:	*Malcolm Gillies*	*Approvers Position Title:*	
Approvers Comments:			

I am satisfied that the risks are as low as reasonably practicable and that the resources required will be provided.

Approval Decision:	*Approve / Reject Date:*	*Document Status:*	*Approval Requested*

Appendix C - Resources required

A variety of resources will be used for this project. They are divided below by their intended area of use. Any access restraints, contingencies, and associated extra costs are noted beside the resources.

General resources for literature review, data recording, & dissertation writing:

- Computer with internet connection & word processing program - already have access. Can use the Toowoomba USQ campus as backup.
- Cloud storage for collected data, research notes, and dissertation writing back up - already have access via student email and WPS.
- USQ online library and databases, particularly Scopus - access via student portal.
- Notebook and pen - already have.

Resources for trials:

The currently anticipated tools and equipment are listed below. Further resources may be required for soil testing and trials pending further research and development.

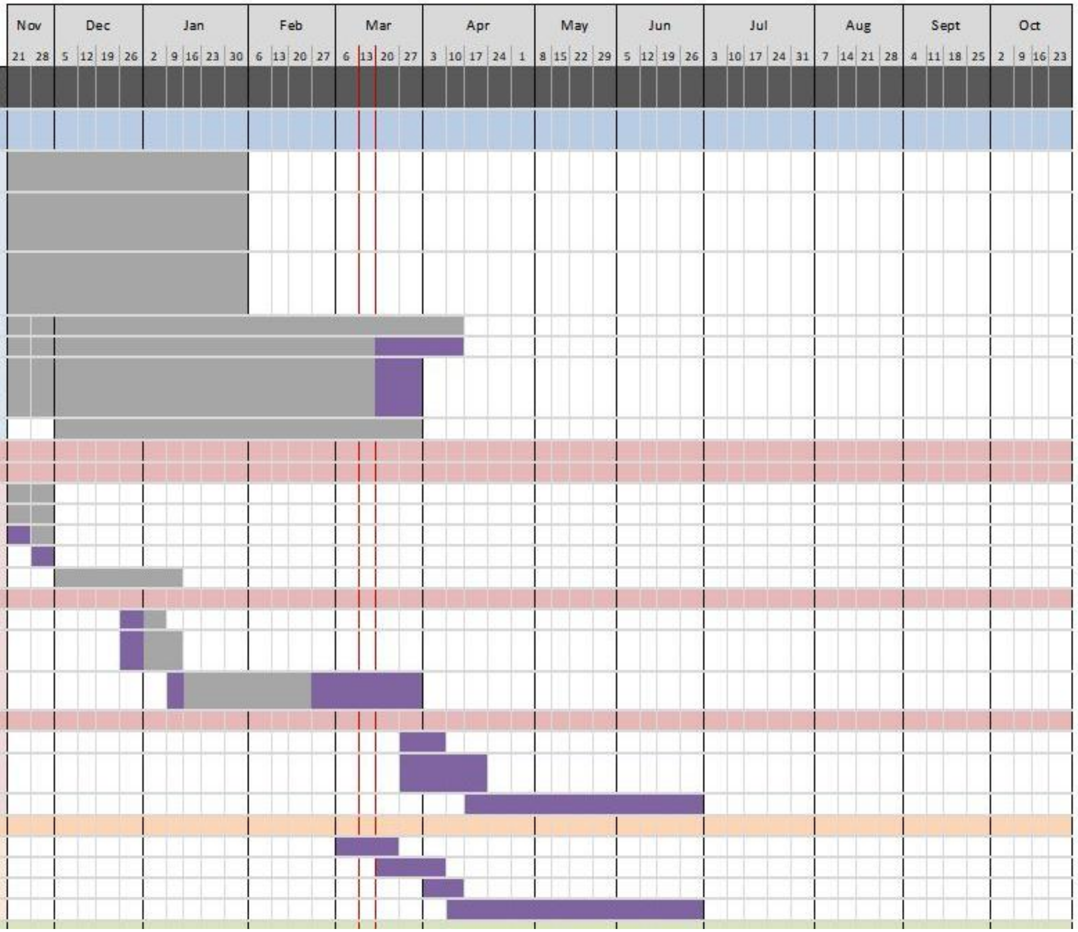
Resource	Location	Cost	Obtained
Garden plots for experiment/trial	home	-	yes
Garden hose and associated tap/hose/nozzle fittings	home	-	yes
3x Garden tap flow monitor	Bunnings/Mitre 10	$50ea	yes
3xSoil moisture probe	Bunnings/Mitre 10	$16.60	yes
Bucket/watering can with litre markings	home	-	yes
Water for garden	Home - rainwater and town mains	council water rates	yes
Garden equipment: mattock, fork, PPE, wash-down area for weed spread prevention	home	-	yes
Garden pots	Bunnings/mitre 10	$10ea	yes
Scales - able to weigh up to 5kg.	home	-	yes
TDR sensors - borrowed from USQ.	USQ	-	yes
Soil oven, oven proof containers - USQ labs	USQ	-	no

Appendix D - Project timeline

Project Plan Version 2 - 15th March 2023

Start Date: 15 November 2022
Highlighted week: 15
Todays date: 15/03/2023

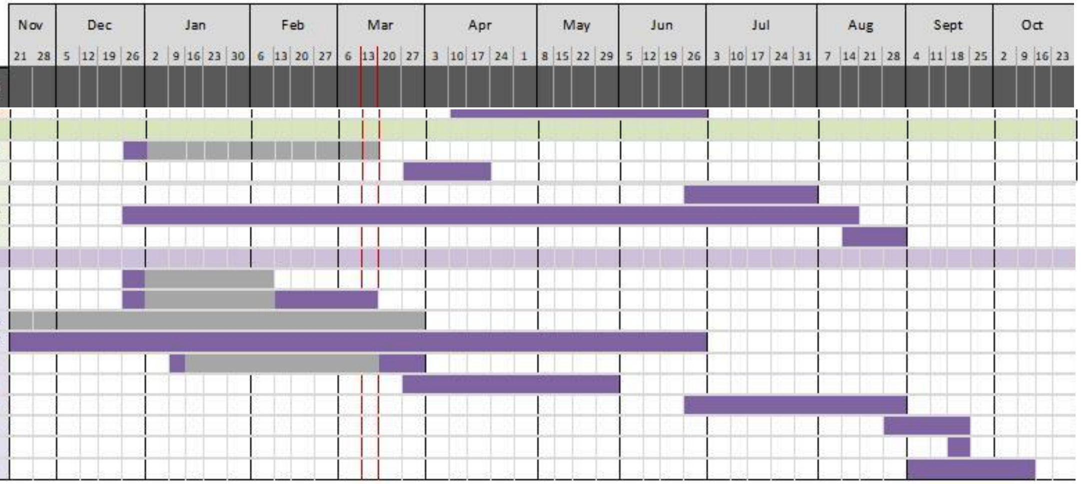
TASK	ACTUAL START	ACTUAL END	PROGRESS	ANTICIPATED START	ANTICIPATED END	DAYS
Literature Research						
Research the importance of home gardens and their irrigation	15/11/2022	12/12/2022	100%	15/11/2022	30/01/2023	77
Research current hand-watering scheduling practices including determination of timing and application	15/11/2022	12/12/2022	100%	15/11/2022	30/01/2023	77
Research industry irrigation scheduling methods	15/11/2022	12/12/2022	100%	15/11/2022	30/01/2023	77
Research factors affecting scheduling	15/11/2022	12/12/2022	100%	1/03/2022	11/04/2023	407
Research case studies of hand watering	30/03/2022		94%	4/04/2022	11/04/2023	373
Evaluate the practicality of transferring industry irrigation scheduling methods to domestic hand watering	15/11/2022		88%	15/11/2022	30/03/2023	136
Research vegetable crop water	15/11/2022		100%	1/12/2022	30/03/2023	120
Field testing						
Phase 1 - start up						
Create draft pre-trial	15/11/2022	29/11/2022	100%	15/11/2022	29/11/2022	15
Determine experimental site/s	15/11/2022	29/11/2022	100%	15/11/2022	29/11/2022	15
Resource check	22/11/2022	29/11/2022	100%	22/11/2022	29/11/2022	8
Finalise Phase 1 pre-trial	29/11/2022	1/12/2022	100%	29/11/2022	1/12/2022	3
Site Testing	1/12/2022	14/01/2023	100%	1/12/2022	13/01/2023	44
Phase 2 - review and adjust						
Review trial progress	30/12/2022	14/01/2023	100%	30/12/2022	6/01/2023	7
draft alterations to existing trial method as required, or create new method,	14/01/2023	3/02/2023	100%	30/12/2022	13/01/2023	14
Continue trials with amendments as required	3/02/2023		52%	13/01/2023	31/03/2023	77
Phase 3- review and adjust						
Review trial progress			0%	31/03/2023	7/04/2023	7
draft alterations to existing trial method as required, or create new method,			0%	31/03/2023	21/04/2023	21
Continue trials with amendments as			0%	21/04/2023	30/06/2023	70
Laboratory testing						
Determine stndard laboratory testing			0%	6/03/2023	20/03/2023	14
Resource check			0%	20/03/2023	3/04/2023	14
Collect soil samples for laboratory			0%	3/04/2023	10/04/2023	7
Conduct lab testing			0%	10/04/2023	30/06/2023	81



Highlighted week: 15

Todays date: 15/03/2023

TASK	ACTUAL START	ACTUAL END	PROGRESS	ANTICIPATED START	ANTICIPATED END	DAYS
[illegible]			[illegible]	[illegible]	[illegible]	[illegible]
Data analysis						
Analyse Phase 1	30/12/2022		536%	30/12/2022	13/01/2023	14
Analyse Phase 2			0%	31/03/2023	21/04/2023	21
Analyse Phase 3			0%	30/06/2023	31/07/2023	31
Comparison to anticipated water			0%	30/12/2022	14/08/2023	227
Comparison to any researched results			0%	14/08/2023	28/08/2023	14
Write up						
Project proposal	1/01/2023	3/02/2023	100%	1/01/2023	12/02/2023	42
Project specification	1/02/2023		58%	1/01/2023	15/03/2023	73
Draft dissertation template and outline	28/02/2022	13/03/2023	100%	7/03/2022	30/03/2023	388
Draft literature review chapter	28/02/2022			28/02/2022	30/06/2023	487
Phase 1 write up	13/01/2023		80%	13/01/2023	30/03/2023	76
Phase 2 write up			0%	31/03/2023	30/05/2023	60
Phase 3 write up			0%	30/06/2023	29/08/2023	60
ENG4903 Seminar preparation			0%	29/08/2023	22/09/2023	24
ENG4903 Conference Seminar			0%	18/09/2023	22/09/2023	4
Finalise & submit dissertation			0%	7/09/2023	15/10/2023	38



14. Appendix E - Trial plot photos

Image 1: Trial area showing view to the west of plots 2 and 3 during establishment (September 2022)

Image 2: Trial area showing view to the south of plot 1 during establishment (September 2022).

15. Appendix F - Garden bed planting schedule

Date	Plant	Plot	Growth Stage	Survival	Fraction of plot planted (f)	Vegetable classification	Init start	Init end	dev. end	Mid end	late end	total days
29/10/2022	Basil (Genovese)	1	seed	Y	0.05	j. unknown	29/10/2022	23/11/2022	23/11/2022	18/12/2022	7/01/2023	70
29/10/2022	Tomatoes	1	seed	Y	0.10	b. Solanum vegetables	29/10/2022	28/11/2022	7/01/2023	21/02/2023	23/03/2023	145
5/11/2022	raddish	2	seed	Y	0.08	a. small veg	5/11/2022	10/11/2022	20/11/2022	5/12/2022	10/12/2022	35
18/10/2022	Zuchini	2	seed	y	0.19	c. Vegetables - cucumber	18/10/2022	7/11/2022	7/12/2022	1/01/2023	16/01/2023	90
5/11/2022	pumpkin	2	seed	Y	0.13	c. Vegetables - cucumber	5/11/2022	25/11/2022	25/12/2022	24/01/2023	13/02/2023	100
10/11/2022	Celery	1	punnet	Y	0.20	a. small veg	10/11/2022	5/12/2022	14/01/2023	28/02/2023	15/03/2023	125
11/11/2022	oregano	1	punnet	Y	0.10	f. perenial vegetable	11/11/2022	7/12/2022	29/01/2023	3/03/2023	1/06/2023	202
27/11/2022	stevia	3	punnet	Y	0.03	j. unknown	27/11/2022	22/12/2022	22/12/2022	16/01/2023	5/02/2023	70
29/10/2022	Leek	3	seed	Y	0.02	a. small veg	29/10/2022	23/11/2022	23/12/2022	2/01/2023	7/01/2023	70
20/11/2022	goosebery	1	punnet	Y	0.15	b. Solanum vegetables	20/11/2022	20/12/2022	29/01/2023	15/03/2023	14/04/2023	145

14/11/2022	silverbeet	3	punnet	Y	0.11	a. small veg	14/11/2022	4/12/2022	24/12/2022	18/01/2023	23/01/2023	70
27/11/2022	apple cucumber	3	punnet	Y	0.03	c. Vegetables - cucumber	27/11/2022	17/12/2022	16/01/2023	25/02/2023	12/03/2023	105
27/11/2022	mousemellon 1	3	punnet	Y	0.03	c. Vegetables - cucumber	27/11/2022	17/12/2022	16/01/2023	25/02/2023	12/03/2023	105
5/11/2022	beetroot	2	seed	Y	0.05	d. roots and tubers	5/11/2022	30/11/2022	30/12/2022	24/01/2023	3/02/2023	90
11/12/2022	Beans	1	punnet	Y	0.24	e. Legume	11/12/2022	31/12/2022	30/01/2023	1/03/2023	11/03/2023	90
27/11/2022	mousemellon 2	3	punnet	Y	0.13	c. Vegetables - cucumber	27/11/2022	17/12/2022	16/01/2023	25/02/2023	12/03/2023	105
12/12/2022	climbing spinach	1	punnet	Y	0.03	e. Legume	12/12/2022	1/01/2023	31/01/2023	2/03/2023	12/03/2023	90
12/12/2022	Chia	1	punnet	Y	0.03	i. Cereals	12/12/2022	1/01/2023	31/01/2023	1/04/2023	11/05/2023	150
10/12/2022	Chives	1	punnet	Y	0.05	a. small veg	10/12/2022	4/01/2023	3/02/2023	13/02/2023	18/02/2023	70
14/11/2022	capsicum	3	punnet	Y	0.11	b. Solanum vegetables	14/11/2022	14/12/2022	18/01/2023	27/02/2023	19/03/2023	125
16/12/2022	corn	2	seed	Y	0.12	i. Cereals	16/12/2022	5/01/2023	30/01/2023	24/02/2023	6/03/2023	80
9/12/2022	corn	3	seed	y	0.14	i. Cereals	9/12/2022	29/12/2022	23/01/2023	17/02/2023	27/02/2023	80
11/12/2022	Beans	2	punnet	Y	0.07	e. Legume	11/12/2022	31/12/2022	30/01/2023	1/03/2023	11/03/2023	90
9/12/2022	carrots	1	seed	Y	0.07	a. small veg	9/12/2022	8/01/2023	17/02/2023	18/04/2023	8/05/2023	150
20/01/2023	Jerusalem	1	punnet	Y	0.03	f. perenial	20/01/2023	9/02/2023	6/03/2023	11/11/2023	11/12/2023	325

	Artichoke					vegetable						
12/12/2022	Chia	3	punnet	Y	0.16	i. Cereals	12/12/2022	1/01/2023	31/01/2023	1/04/2023	11/05/2023	150
21/12/2022	corn	3	emerge nc	N	0.14	i. Cereals	21/12/2022	10/01/2023	4/02/2023	1/03/2023	11/03/2023	80
21/01/2023	squash	1	punnet	N	0.24	c. Vegetables - cucumber	21/01/2023	10/02/2023	12/03/2023	6/04/2023	21/04/2023	90
6/04/2023	kale	1	seed	N	0.13	a. small veg	6/04/2023	6/05/2023	10/06/2023	8/09/2023	18/10/2023	195
21/01/2023	squash	3	punnet	N	0.16	c. Vegetables - cucumber	21/01/2023	10/02/2023	12/03/2023	6/04/2023	21/04/2023	90
11/05/2023	parsley	3	seedling	y	0.03	j. unknown	11/05/2023	5/06/2023	5/06/2023	30/06/2023	20/07/2023	70
20/12/2022	corn	2	emerge nce	Y	0.12	i. Cereals	20/12/2022	9/01/2023	3/02/2023	28/02/2023	10/03/2023	80
15/04/2023	Spring onion	3	punnet	Y	0.02	a. small veg	15/04/2023	10/05/2023	9/06/2023	19/06/2023	24/06/2023	70
5/12/2022	capsicum	2	punnet	Y	0.16	b. Solanum vegetables	5/12/2022	4/01/2023	8/02/2023	20/03/2023	9/04/2023	125
11/05/2023	parsley	2	seedling	y	0.05	j. unknown	11/05/2023	5/06/2023	5/06/2023	30/06/2023	20/07/2023	70
11/05/2023	Wombook	2	seedling	y	0.11	a. small veg	11/05/2023	10/06/2023	20/07/2023	14/08/2023	24/08/2023	105
11/05/2023	lettuce	2	seedling	y	0.11	a. small veg	11/05/2023	10/06/2023	20/07/2023	14/08/2023	24/08/2023	105
30/04/2023	**peas**	**3**	**seed**	**Y**	**0.12**	**e. Legume**	**30/04/2023**	**20/05/2023**	**19/06/2023**	**24/07/2023**	**8/08/2023**	**100**
14/05/2023	Wombook	2	seedling	y	0.11	a. small veg	14/05/2023	13/06/2023	23/07/2023	17/08/2023	27/08/2023	105
14/05/2023	lettuce	2	seedling	y	0.11	a. small veg	14/05/2023	13/06/2023	23/07/2023	17/08/2023	27/08/2023	105
12/04/2023	Kale	1	emerge	N	0.13	a. small veg	12/04/2023	12/05/2023	16/06/2023	14/09/2023	24/10/2023	195

			nce									
14/05/2023	lettuce	1	punnet	Y	0.13	a. small veg	14/05/2023	13/06/2023	23/07/2023	17/08/2023	27/08/2023	105
14/05/2023	Wombook	1	punnet	Y	0.13	a. small veg	14/05/2023	13/06/2023	23/07/2023	17/08/2023	27/08/2023	105
12/05/2023	Brussels sprouts	1	punnet	Y	0.13	a. small veg	12/05/2023	21/06/2023	20/08/2023	9/10/2023	24/10/2023	165
11/04/2023	**brocolini**	**3**	**emergence**	**Y**	**0.14**	**a. small veg**	**11/04/2023**	**16/05/2023**	**30/06/2023**	**9/08/2023**	**24/08/2023**	**135**
11/05/2023	**peas**	**3**	**emergence**	**Y**	**0.12**	**e. Legume**	**11/05/2023**	**31/05/2023**	**30/06/2023**	**4/08/2023**	**19/08/2023**	**100**
11/05/2023	cauliflower	2	seedling	y	0.11	a. small veg	11/05/2023	15/06/2023	4/08/2023	13/09/2023	28/09/2023	140
14/05/2023	cabbage	1	punnet	Y	0.13	a. small veg	14/05/2023	23/06/2023	22/08/2023	11/10/2023	26/10/2023	165
11/05/2023	Brussels sprouts	2	seedling	y	0.19	a. small veg	11/05/2023	20/06/2023	19/08/2023	8/10/2023	23/10/2023	165
14/11/2022	**Society Garlic initial**	**3**	**Punnet**	**Y**	**0.01**	**j. unknown**	**14/11/2022**	**9/12/2022**	**8/01/2023**	**7/02/2023**	**28/02/2023**	**106**
1/03/2023	**Society Garlic perenial**	**3**	**New growth**	**y**	**0.02**	**j. unknown**	**1/03/2023**	**1/03/2023**	**1/03/2023**	**9/06/2023**	**17/09/2023**	**200**

16. Appendix G - Plot diagrams

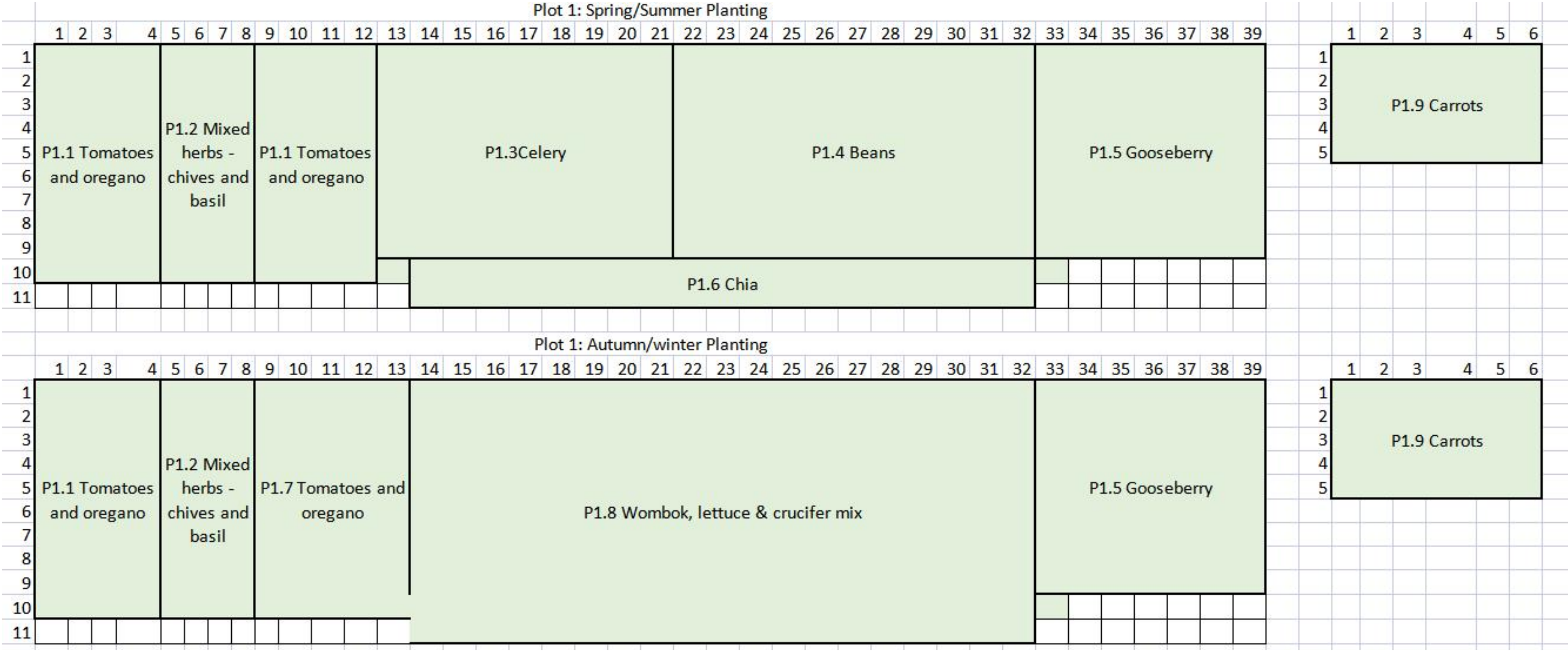


Figure 15-1: Plot 1 (method 1) planting scheme.

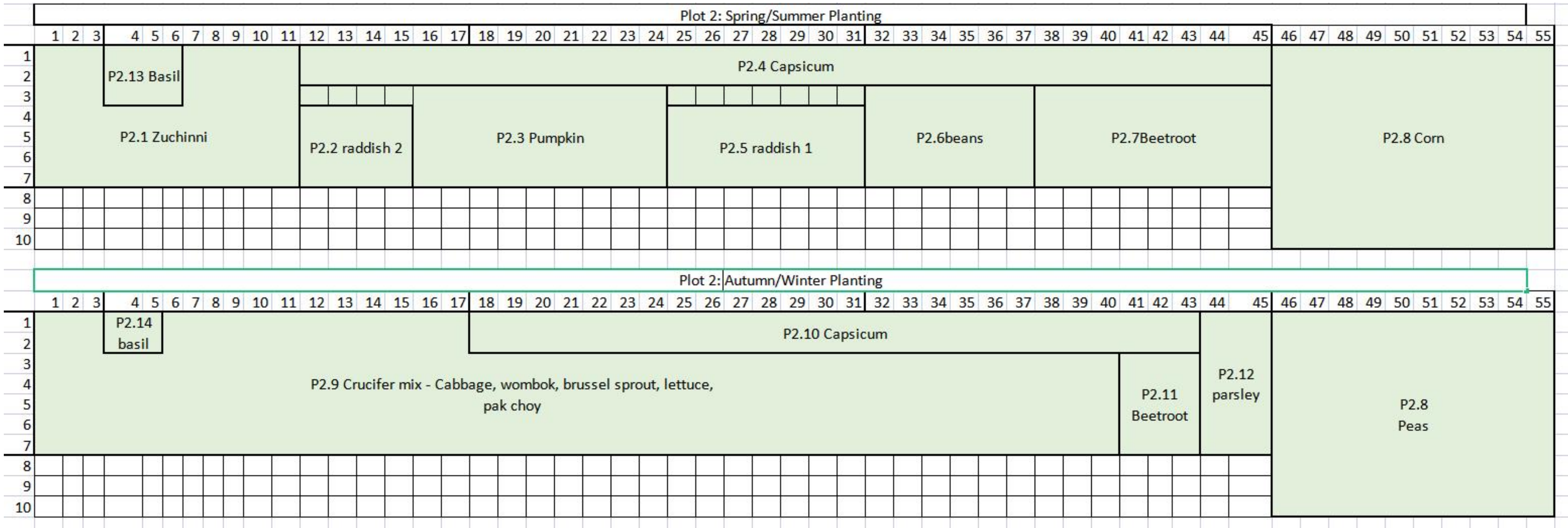


Figure 15-2: Plot 2 (Method 2) planting scheme.

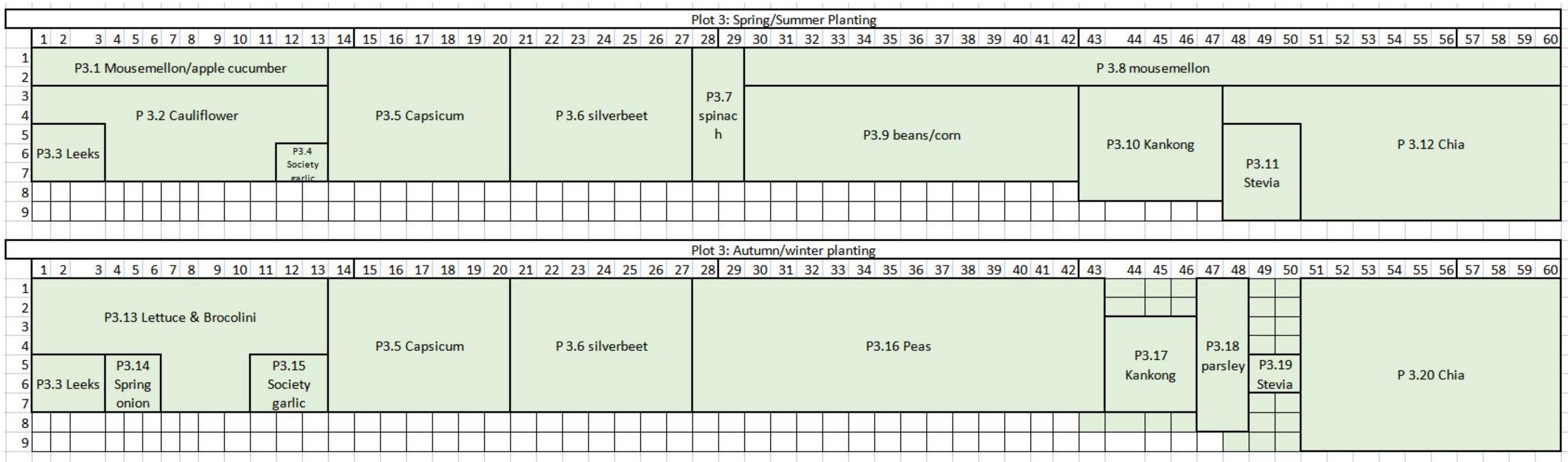


Figure 15-3: Plot 3 planting scheme (method 3 and 4).

17. Appendix H- Pot test results

Table 16-1: Pot test weight and average moisture reading results

Date	Pot Weight (g)	Average moisture reading			Weight difference (g)
		5cm	10cm	12.5cm	
18/12/2022	1830	1	1	1	
19/12/2022	3074	11	11	11	-1244
20/12/2022	2828	9	11	11	246
21/12/2022	2753	7.5	11	11	75
22/12/2022	2700	8.5	11	11	53
23/12/2022	2654	6	11	11	46
24/12/2022	2624	6	11	11	30
27/12/2022	2566	5.5	11	11	58
29/12/2022	2524	6	11	11	42
30/12/2022	2492	5	11	11	32
31/12/2022	2464	8	11	10	28
2/1/2023	2399	2.5	11	10	65
3/1/2023	2381	2.5	8	9	18
4/1/2023	2354	3	9	10	27
5/1/2023	2333	8	10	10	21
6/1/2023	2320				13
7/1/2023	2297	6	11	11	23
8/1/2023	2289	7	10	10	8
9/1/2023	2271	1.5	9	10	18
10/1/2023	2250	2	8	10	21
11/1/2023	2217	2	8	8	33
12/1/2023	2195	1.5	8.5	9	22
13/1/2023	2186	4.25	8.5	9	9
14/1/2023	2171	3	8	9.5	15
15/1/2023	2156	6	9.5	10	15
16/1/2023	2141				15

17/1/2023	2126				15
18/1/2023	2112				15
19/1/2023	2097				15
20/1/2023	2082				15
21/1/2023	2067				15
22/1/2023	2052				15
23/1/2023	2037	2.5	8	8	15
24/1/2023	2026				11
25/1/2023	2021				5
26/1/2023	2017				5
27/1/2023	2012	1	7	7	5
28/1/2023	2004				8
29/1/2023	1996				8
30/1/2023	1989				8
31/1/2023	1981				8
1/2/2023	1973				8
2/2/2023	1965	1.3	6	7	8
3/2/2023	1959				6
4/2/2023	1942				17
5/2/2023	1925				17
6/2/2023	1908				17
7/2/2023	1907				1
8/2/2023	1906	1.2	1.7		1
9/2/2023	1895	1.2	2.2		11
10/2/2023	1892	1.0	3.7		3
11/2/2023	1879				13
12/2/2023	1870				9
13/2/2023	1860				10
14/2/2023	1850				10
18/2/2023	1836				14
19/2/2023	1830				6
20/2/2023	1826	1.2	1.3		4

21/2/2023	1826				0
22/2/2023	1826	1	1		0

Note: The coloured cells have been linearly interpolated.

Table 16-2: Pot test measurement record

Date	Pot Weight (g)	Moisture probe 1			Probe 2			Probe 3		
		5cm	10cm	12.5cm	5cm	10cm	12.5cm	5cm	10cm	12.5cm
18/12/2022	1830	1	1	1	Not in operation			Not in operation		
19/12/2022	3074	10+	10+	10+						
20/12/2022	2828	9	10+	10+						
21/12/2022	2753	7.5	10+	10+						
22/12/2022	2700	8.5	10+	10+						
23/12/2022	2654	6	10+	10+						
24/12/2022	2624	6	10+	10+						
27/12/2022	2566	5.5	10+	10+						
29/12/2022	2524	6	10+	10+						
30/12/2022	2492	5	10+	10+						
31/12/2022	2464	8	10+	10						
2/01/2023	2399	2.5	10+	10						
3/01/2023	2381	2.5	8	9						
4/01/2023	2354	3	9	10						
5/01/2023	2333	8	10	10						
6/01/2023	2320									
7/01/2023	2297	6	10+	10+						
8/01/2023	2289	7	10	10						
9/01/2023	2271	1.5	9	10						
10/01/2023	2250	2	8	10						
11/01/2023	2217	2	8	8						
12/01/2023	2195	1.5	8.5	9						
13/01/2023	2186	3.5	7	8	5	10	10			

14/01/2023		1.5	6	9	4.5	10	10		
15/01/2023		7	10	10	5	9	10		
16/01/2023									
17/01/2023									
18/01/2023									
19/01/2023									
20/01/2023									
21/01/2023									
22/01/2023									
23/01/2023	2037				3.5	8	8	1.5	8	8
24/01/2023	2026									
25/01/2023										
26/01/2023										
27/01/2023	2012	1	8	8	1	9	9	1	4	4
28/01/2023										
29/01/2023										
30/01/2023										
31/01/2023										
1/02/2023										
2/02/2023	1965	1	6	7.5	2	6	7	1	6	6.5
3/02/2023	1959									
4/02/2023										
5/02/2023										
6/02/2023	1908									
7/02/2023										
8/02/2023	1906	1	2.5		1	1.5		1.5	1	
9/02/2023	1895	1	1.5		1.5	7		1	3	
10/02/2023	1892	1	4		1	2.5		1	4.5	
11/02/2023	1879									
12/02/2023	1870									
13/02/2023										

14/02/2023	1850									
18/02/2023	1836									
19/02/2023	1830									
20-Feb	1826	1	1		1.5	2		1	1	
21/02/2023	1826									
22/02/2023	1826	1	1		1	1		1	1	

18. Appendix I - Allotment, tap and rainfall water

Table 17-1: Original allotment and tap water meter values.

Original data		
Date	**Total allotment use (L)**	**Tap 1 total**
21/12/2022	2125992	
2/01/2022	2133958	
9/01/2023	2144796	
25/01/2023	2163231	
30/01/2023		
6/02/2023		
13/02/2023		
20/02/2023		
27/02/2023		
6/03/2023		
13/03/2023	2195142	8542.9
20/03/2023	2197341	9536.9
20/03/2023	219734.1	0
27/03/2023	220142.6	426.3
3/04/2023	220619.1	0
10/04/2023		
18/04/2023	221095.5	1905
22/04/2023	221225	
1/05/2023	221480	3050.4
7/05/2023	221743.5	4026.1
15/05/2023	222059.9	5496.6
23/05/2023	222349	
30/05/2023	222566.5	6364.6
5/06/2023	222800.8	6534.6
12/06/2023		
19/06/2023		

20/06/2023	2234561	7466.5
Total	**108569**	**16497.8**

Table 17-2: Modified allotment and tap water values

	Allotment water use		Garden tap use		Site rainfall
Modified date	**Total allotment accumulative (L)**	**7day use (L)**	**Accumulative (L)**	**7day use (L)**	**7day total (mm)**
26/12/2022	**2129311.2**	0.0	0.0	0.0	
2/01/2023	2133958.0	4646.8	0.0	0.0	0
9/01/2023	2144796.0	10838.0	0.0	0.0	1
16/01/2023	**2149759.3**	4963.3	0.0	0.0	0
23/01/2023	**2157824.6**	8065.3	0.0	0.0	22
30/01/2023	**2167789.7**	9965.1	0.0	0.0	24
6/02/2023	**2172348.4**	4558.7	0.0	0.0	32
13/02/2023	**2176907.1**	4558.7	0.0	0.0	15
20/02/2023	**2181465.9**	4558.7	0.0	0.0	0
27/02/2023	**2186024.6**	4558.7	0.0	0.0	1
6/03/2023	**2190583.3**	4558.7	0.0	0.0	5
13/03/2023	2195142.0	4558.7	8542.9	0.0	36.5
20/03/2023	2197341.0	2199.0	9536.9	994.0	0.5
27/03/2023	2201426.0	4085.0	9963.2	426.3	16
3/04/2023	2206191.0	4765.0	**10407.7**	444.5	42
10/04/2023	2208573.0	2382.0	10852.2	444.5	47.5
17/04/2023	**2210657.3**	2084.3	**11741.2**	889.0	0
24/04/2023	**2213100.0**	2442.8	**12396.8**	655.6	1.5
1/05/2023	2214800.0	1700.0	13013.6	616.8	2.5
8/05/2023	**2217830.5**	3030.5	**14173.1**	1159.5	0
15/05/2023	2220599.0	2768.5	15459.8	1286.7	70
22/05/2023	**2223128.6**	2529.6	**15864.9**	405.1	1
29/05/2023	**2225354.3**	2225.7	**16269.9**	405.1	0
5/06/2023	2228008.0	2653.7	16497.8	227.9	12
12/06/2023	2230192.3	2184.3	16932.7	434.9	0
19/06/2023	2232376.7	2184.3	17367.6	434.9	0

Total	**103065.5**	**103065.5**	**8824.7**	**8824.7**	**329.5**

Note: values in bold have been linearly interpolated from the original data (Table 17-1).

19. Appendix J - Field texture photo results

Image 18-1: Plot 1 - 5cm depth

Image 18-2: Plot 1 - 15cm

Image 18-3: Plot 2, 5cm depth

Image 18-4: Plot 2, 15cm depth

Image 18-5: Plot 3 site 1 5cm depth after pressing slightly with finger.

Image 18-6: Plot 3, site 2 5cm depth.

Image 18-7: plot 3, site 2 15cm depth

20. Appendix K - 7 day trial comparisons

Table 19-1: 7 day trial comparisons

Modified date	Allotment water use		Garden tap 1 use		Site rainfall	Total irrigation (L)				Total irrigation(mm/m^2)				No. of days applied		
	Total allotment accumulative (L)	7day use (L)	Accumulative (L)	7day use (L)	7day total	G1	G2	G3	Trial total (L)	G1	G2	G3	Trial total	G1	G2	G3
5/12/2022	-	-	-	-	**44.4**	0.0	**0**	0.0	**0.0**	0.0	**0**	**0**	0.0	**0**	**0**	**0**
12/12/2022	-	-	-	-	**30**	37.6	**25.256**	78.5	**141.4**	9.7	6.16	**17**	32.9	**1**	**1**	**1**
19/12/2022	-	-	-	-	**0.2**	150.5	**33.21**	37.0	**220.7**	39.0	8.1	**8**	55.1	**4**	**1**	**1**
26/12/2022	2129311.2	0.0	0.0	**0.0**	2.6	114.3	**180.4**	403.3	**698.0**	29.6	44	87.3	160.9	**3**	**2**	**3**
2/01/2023	2133958.0	4646.8	0.0	**0.0**	0	169.6	**270.6**	203.3	**643.5**	43.9	66	44	153.9	**2**	**3**	**1**
9/01/2023	2144796.0	10838.0	0.0	**0.0**	1	298.4	**90.2**	101.6	**490.2**	77.3	22	22	121.3	**3**	**1**	**2**
16/01/2023	2152861.3	8065.3	0.0	**0.0**	0	167.1	**303.4**	138.6	**609.1**	43.3	74	30	147.3	**3**	**3**	**1**
23/01/2023	2160926.6	8065.3	0.0	**0.0**	22	277.6	**90.2**	101.6	**469.4**	71.9	22	22	115.9	**1**	**1**	**0**
30/01/2023	2166429.0	5502.4	0.0	**0.0**	24	1241.3	**90.2**	101.6	**1433.2**	321.6	22	22	365.6	**2**	**1**	**2**
6/02/2023	2172335.0	5906.0	33.2	**33.2**	32	234.7	**90.2**	101.6	**426.5**	60.8	22	22	104.8	**1**	**1**	**1**
13/02/2023	2179070.0	6735.0	2978.8	**2945.6**	15	1020.0	**270.6**	304.9	**1595.5**	264.2	66	66	396.2	**5**	**3**	**5**
20/02/2023	2185059.0	5989.0	4489.3	**1510.5**	0	295.4	**270.6**	101.6	**667.6**	76.5	66	22	164.5	**4**	**3**	**5**
27/02/2023	2188383.0	3324.0	5813.7	**1324.4**	1	264.8	**270.6**	203.3	**738.7**	68.6	66	44	178.6	**3**	**3**	**4**
6/03/2023	2190514.0	2131.0	7212.8	**1399.1**	5	332.4	**270.6**	304.9	**907.9**	86.1	66	66	218.1	**3**	**3**	**3**
13/03/2023	2195142.0	4628.0	8542.9	**1330.1**	36.5	211.2	**90.2**	101.6	**403.0**	54.7	22	22	98.7	**2**	**1**	**1**
20/03/2023	2197341.0	2199.0	9536.9	**994.0**	0.5	422.0	**270.6**	304.9	**997.5**	109.3	66	66	241.3	**3**	**3**	**3**
27/03/2023	2201426.0	4085.0	9963.2	**426.3**	16	118.7	**90.2**	240.2	**449.1**	30.8	22	52	104.8	**2**	**1**	**2**
3/04/2023	2206191.0	4765.0	10407.7	**444.5**	42	98.0	**90.2**	101.6	**289.8**	25.4	22	22	69.4	**1**	**1**	**1**
10/04/2023	2208573.0	2382.0	10852.2	**444.5**	47.5	110.2	**90.2**	304.9	**505.3**	28.5	22	66	116.5	**2**	**1**	**3**
17/04/2023	2210657.3	2084.3	11741.2	**889.0**	0	209.1	**180.4**	406.6	**796.1**	54.2	44	88	186.2	**3**	**2**	**4**
24/04/2023	2213100.0	2442.8	12396.8	**655.6**	1.5	281.4	**180.4**	304.9	**766.7**	72.9	44	66	182.9	**3**	**2**	**3**
1/05/2023	2214800.0	1700.0	13013.6	**616.8**	2.5	132.4	**0**	203.3	**335.7**	34.3	0	44	78.3	**2**	**0**	**2**
8/05/2023	2217830.5	3030.5	14173.1	**1159.5**	0	205.2	**0**	304.9	**510.1**	53.2	0	66	119.2	**2**	**0**	**3**
15/05/2023	2220599.0	2768.5	15459.8	**1286.7**	70	240.1	**135.3**	304.9	**680.3**	62.2	33	66	161.2	**3**	**2**	**3**
22/05/2023	2223128.6	2529.6	15864.9	**405.1**	1	51.6	**0**	101.6	**153.2**	13.4	0	22	35.4	**1**	**0**	**1**
29/05/2023	2224992.9	1864.3	16327.8	**462.9**	0	268.8	**41**	304.9	**614.7**	69.6	10	66	145.6	**2**	**1**	**3**
5/06/2023	2228008.0	3015.1	16497.8	**170.0**	12	146.1	**131.2**	101.6	**378.9**	37.8	32	22	91.8	**2**	**2**	**1**
12/06/2023	2230192.3	2184.3	16932.7	**434.9**	0	0.0	**0**	0.0	**0.0**	0.0	0	0	0.0	**0**	**0**	**0**
19/06/2023	2232376.7	2184.3	17367.6	**434.9**	0	127.8	**90.2**	304.9	**522.9**	33.1	22	66	121.1	**1**	**1**	**3**
Total	**103065.5**	**103065.5**	**8824.7**	**17367.6**	**406.7**	**7226.3**	**3646.0**	**5573.1**	**16445.4**	**1872.1**	**889.3**	**1206.3**	**3967.7**	**64**	**43**	**62**

21. Appendix L - daily results M1

Table 20-1: Irrigation applied in Plot 1. Column headings: 1 - Tomato, 2 - Herbs, 3- Celery, 4- Kale, 5- Brassica (1), 6- Chia, 7- Brassica (2), 8- Spinach, 9- Beans, 10- Gooseberry, 11- Carrot, 12- Climbing spinach, 13-Chia, 14- Total irrigation applied (L), 15- Irrigation applied (L/m^2). Note: columns 8,12 and 13 were initially watered separately before being combined into column 6.

Soil surface area watered (m2)	**0.85**	**0.35**	**0.765**	**0.765**	**0.765**	**0.285**	**0.969**	**0.969**	**0.765**	**0.603**	**0.2**	**0.214**	**0.071**	**Total plot area:**	**3.9**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15.0**
11/12/2022	9.5	1.7	13.4						8			2.1	2.9	37.6	9.7
15/12/2022	13.2	2.1	23.9						5.6		9	0	1.7	55.5	14.4
17/12/2022	0	0	0						0		4	0	0	4	1.0
18/12/2022	0	0	0						0		5.2	0	0	5.2	1.3
19/12/2022	23.7	7.1	35.9						10.4		6.9	0	1.8	85.8	22.2
20/12/2022	0	0	0						0		7.3	0	0	7.3	1.9
23/12/2022	15	4	15			9.1			0		7			50.1	13.0
24/12/2022	13	5	21			5.7			9.7		2.5			56.9	14.7
30/12/2022	27	10	20			15			12		4.7			88.7	23.0
2/01/2023	15.9	10.7	25			12			14.3		3			80.9	21.0
5/01/2023	46.7	14.2	56			7.1			15.7		0			139.7	36.2
7/01/2023	21.5	7.8	0			0			0		0			29.3	7.6
8/01/2023	38	8.9	50			12.5			20		0			129.4	33.5
10/01/2023	0	0	60.2			0			0		0			60.2	15.6

12/01/2023	13.3	0	0			0			0		0			13.3	3.4
13/01/2023	20.2	6.5	28.5			14.5			23.9		0			93.6	24.2
23/01/2023	54	0	119			12			75	17.6	0			277.6	71.9
28/01/2023	147.9	103.5	226.3			84.3			226.3	178.4	59.2			1026.0	265.8
30/01/2023	46	4.8	56			14			28.5	44	22			215.3	55.8
6/02/2023	34.6	13.2	78.3			19.9			50.4	22	16.3			234.7	60.8
7/02/2023	0	0	0			0			0	0	16.3			16.3	4.2
8/02/2023	25.5	12.3	353			11.1			45.8	20.6	16.3			484.6	125.5
10/02/2023	58.2	15.8	123.2			12.9			42	35.3	13			300.4	77.8
11/02/2023	0	0	56.3			0			0	0	10.6			66.9	17.3
12/02/2023	43.9	10.6	24			12.2			23.6	26.2	11.3			151.8	39.3
17/02/2023	25.6	10	26.2			15			30.9	12.9	13.7			134.3	34.8
18/02/2023	0	0	0			0			0	0	9.2			9.2	2.4
19/02/2023	18	9.8	34.3			12.2			29.6	12.2	13.6			129.7	33.6
20/02/2023	0	0	0			0			0	9.1	13.1			22.2	5.8
22/02/2023	21	6	0			5			20.5	6	7.6			66.1	17.1
26/02/2023	33.4	10				8.1			21.1	12.8	16.9			102.3	26.5
27/02/2023	22.4	10.7				0			30.1	17.1	16.1			96.4	25.0
28/02/2023	0	0				0			40.9	0	0			40.9	10.6
1/03/2023	59	12.6				18.7			0	26.4	39.1			155.8	40.4
4/03/2023	59.8	7.1				13.1			27.8	11.8	16.1			135.7	35.2
7/03/2023	24.2	0				27.9			21.1	17.9	20.1			111.2	28.8
8/03/2023	19.1	8.3				16.3			23.1	20.1	13.1			100	25.9
16/03/2023	63.5	18.6				19			55.7	28	19.5			204.3	52.9

18/03/2023	27.3	8.6				12			26.7	15.2	17.3			107.1	27.7
20/03/2023	49.3	0				16.1			12.6	11.3	21.3			110.6	28.7
24/03/2023	26.8	5.8				0			0	0	0			32.6	8.4
25/03/2023	0	0				24.4			16.8	17.3	27.6			86.1	22.3
3/04/2023	23	17.1		0		13.3		8.5	0	23	13.1			98	25.4
5/04/2023	25.6	8.9		8		15.8		7.7		18.4	18.1			102.5	26.6
6/04/2023	0	0		3.1		0		4.6		0	0			7.7	2.0
11/04/2023	0	0		4.6		0		5.9		0	9.9			20.4	5.3
15/04/2023	26.5	8.3		5.2		20.6		9.7		27.7	22.5			120.5	31.2
16/04/2023	13	0		3.7		22.6		3.8		25.1	0			68.2	17.7
18/04/2023	28.2	11.4		7.6		22.8		5.6		20.3	46.5			142.4	36.9
20/04/2023	31.7	16.6		7.4		18.9		6.7		24.7	26			132	34.2
21/04/2023	0	0		3.6		0		3.4		0	0			7	1.8
27/04/2023	26.9	15.7		5.3		15.3		8.9		17.9	31.3			121.3	31.4
29/04/2023	0	0		6		0		5.1		0	0			11.1	2.9
3/05/2023	28.9	10.9		6.8		12.9		4.6		16.2	12.5			92.8	24.0
6/05/2023	25.5	18.2		0		14		3.5		28	23.2			112.4	29.1
11/05/2023	0	0			0	14	0	0		30.2	24.4			68.6	17.8
12/05/2023	0	0			6.9	0	8			0	0			14.9	3.9
14/05/2023	56.6	13.6			7.1	10.4	24.2			25.8	18.9			156.6	40.6
21/05/2023	0	0			7.6	0	24.3			0	19.7			51.6	13.4
24/05/2023	44.5	10.6			14.7	15.9	27.4			18.1	19.5			150.7	39.0
27/05/2023	13.4	8.5			14	9.8	32.4			16.9	23.1			118.1	30.6
30/05/2023	0	0			0	0	0			0	18.5			18.5	4.8

3/06/2023	27	13.6			8.6	17	19.4			20.3	21.7			127.6	33.1
14/06/2023	25.2	9.9			15.3	21.5	14.2			21.7	20			127.8	33.1
21/06/2023	35.4	9.2			8.3	10.6	20.8			10.1	15.3			109.7	28.4
Total	**1547.9**	**518.2**	**1445.5**	**61.3**	**82.5**	**685.5**	**170.7**	**78.0**	**968.1**	**906.6**	**863.1**	**2.1**	**6.4**	**7336.0**	**1900.5**
Average	7.6	2.5	16.9	1.2	1.6	3.6	3.3	1.7	7.8	5.7	4.3	0.6	0.8	36.0	9.4
Median	26.8	10.0	35.9	5.3	8.5	14.0	22.5	5.6	23.6	20.1	16.3	2.1	1.8	96.4	25.0
# days water	49	44	23	13	10	44	10	15	31	39	52	3	5	66	65

22. Appendix O - K_c tables

Table 23-1: K_C values unadjusted (Allen, et al (1998)) and adjusted for summer, autumn and winter relative humidity and wind speed using Toowoomba Airport values.

	Allen et al (1998)			summer adjustment				Autumn adjustment				Winter adjustment			
Crop	**Kc ini**	**Kc mid**	**Kc end**	**Kc mid (adj)**	**ETmid (mm/d)**	**Kc end (adj)**	**ETend (mm/d)**	**Kc mid (adj)**	**ETmid (mm/d)**	**Kc end (adj)**	**ETend (mm/d)**	**Kc mid (adj)**	**ETmid (mm/d)**	**Kc end (adj)**	**ETend (mm/d)**
a. small veg	0.7	1.05	0.95	1.16	6.36	1.06	5.815495152	1.16	4.13	1.06	3.77	1.16	4.14	1.06	3.78
b. Solanum vegetables	0.6	1.15	0.8	1.26	6.91	0.91	4.993023242	1.26	4.49	0.91	3.24	1.26	4.50	0.91	3.25
c. Vegetables - cucumber	0.5	1	0.8	1.11	6.09	0.91	4.993023242	1.11	3.95	0.91	3.24	1.11	3.96	0.91	3.25
d. roots and tubers	0.5	1.1	0.95	1.21	6.64	1.06	5.815495152	1.21	4.31	1.06	3.77	1.21	4.32	1.06	3.78
e. Legume	0.4	1.15	0.55	1.26	6.91	0.66	3.622236725	1.26	4.49	0.66	2.35	1.26	4.50	0.66	2.36
f. perenial vegetable	0.5	1	0.8	1.11	6.09	0.91	4.993023242	1.11	3.95	0.91	3.24	1.11	3.96	0.91	3.25
i. Cereals	0.3	1.15	0.4	1.26	6.91	0.51	2.799764815	1.26	4.49	0.51	1.82	1.26	4.50	0.51	1.82
j. unknown	0.46	0.59	0.42	0.70	3.84	0.53	2.909427737	0.70	2.49	0.53	1.89	0.70	2.50	0.53	1.90

Table 23-2: K_{CB} values unadjusted (Allen, et al (1998)) and adjusted for summer, autumn and winter relative humidity and wind speed using Toowoomba Airport values.

	Allen et al (1998)			summer				Autumn				Winter			
Crop	**K_{CB} ini**	**K_{CB} mid**	**K_{CB} end**	**K_{CB} mid (adj)**	**ETmid (mm/d)**	**K_{CB} end (adj)**	**ETend (mm/d)**	**K_{CB} mid (adj)**	**ETmid (mm/d)**	**K_{CB} end (adj)**	**ETend (mm/d)**	**K_{CB} mid (adj)**	**ETmid (mm/d)**	**K_{CB} end (adj)**	**ETend (mm/d)**
a. small veg	0.15	0.95	0.85	1.06	5.82	0.96	5.267180546	1.06	3.77	0.96	3.42	1.06	3.78	0.96	3.43
b. Solanum vegetables	0.15	1.1	0.7	1.21	6.64	0.81	4.444708636	1.21	4.31	0.81	2.88	1.21	4.32	0.81	2.89
c. Vegetables - cucumber	0.15	0.95	0.7	1.06	5.82	0.81	4.444708636	1.06	3.77	0.81	2.88	1.06	3.78	0.81	2.89
d. roots and tubers	0.15	1	0.85	1.11	6.09	0.96	5.267180546	1.11	3.95	0.96	3.42	1.11	3.96	0.96	3.43
e. Legume	0.15	1.1	0.5	1.21	6.64	0.61	3.348079422	1.21	4.31	0.61	2.17	1.21	4.32	0.61	2.18
f. perenial vegetable	0.15	0.95	0.9	1.06	5.82	1.01	5.541337849	1.06	3.77	1.01	3.60	1.06	3.78	1.01	3.61
i. Cereals	0.15	1.1	0.25	1.21	6.64	0.36	1.977292905	1.21	4.31	0.36	1.28	1.21	4.32	0.36	1.29
j. unknown	0.46	0.59	0.4	0.70	3.84	0.51	2.799764815	0.70	2.49	0.51	1.82	0.70	2.50	0.51	1.82

Table 23-3: Kc after adjustments for Toowoomba location and mulch application.

Plant	Subplot	FAO56 plant name	initial height (m)	max height (m)	total growth (m)	Growth fraction (m/d)	total days	ini	mid adj(summer)	Mid adj (autumn)	Mid adj (winter)	end adj (summer)	end adj (autumn)	end adj (winter)
Basil (Genovese)	P1.2	Basil	0	0.50	0.50	0.02	70	0.23	0.70	0.70	0.70	0.52	0.52	0.52
Tomatoes	P1.1	Tomatoes	0	0.60	0.60	0.01	145	0.3	1.24	1.23	1.06	0.86	0.86	0.86
Celery	P1.3	Celery	0.05	0.60	0.55	0.01	125	0.35	1.11	1.11	1.06	1.01	1.01	1.01
oregano	P1.1	mint	0.03	0.15	0.12	0.00	202	0.25	1.09	1.08	0.99	0.96	0.96	0.96
goosebery	P1.5	tomatoes	0.2	0.60	0.40	0.01	145	0.3	1.24	1.23	1.06	0.86	0.86	0.86
Beans	P1.4	green beans	0.15	0.40	0.25	0.01	90	0.2	1.24	1.23	0.94	0.64	0.63	0.64
climbing spinach	P1.6	green beans	0.15	0.40	0.25	0.01	90	0.2	1.24	1.23	0.94	0.64	0.63	0.64
Chia	P1.6	Grains (small)	0.15	1.50	1.35	0.03	150	0.15	1.24	1.23	0.86	0.44	0.43	0.44
Chives	P1.2	Onions Green	0.1	0.30	0.20	0.00	70	0.35	1.11	1.11	1.06	1.01	1.01	1.01
carrots	P1.9	Carrots	0	0.30	0.30	0.00	150	0.35	1.11	1.11	1.06	1.01	1.01	1.01
Jerusalem Artichoke	P1.6	artichokes	0.15	0.70	0.55	0.01	325	0.25	1.09	1.08	0.99	0.96	0.96	0.96
lettuce	P1.8	Lettuce	0.1	0.30	0.20	0.00	105	0.35	1.11	1.11	1.06	1.01	1.01	1.01
Wombook	P1.8	Lettuce	0.1	0.30	0.20	0.00	105	0.35	1.11	1.11	1.06	1.01	1.01	1.01
Brussels	P1.8	Cabbage	0.13	0.40	0.27	0.00	165	0.35	1.11	1.11	1.06	1.01	1.01	1.01

sprouts														
cabbage	P1.8	Cabbage	0.1	0.40	0.30	0.00	165	0.35	1.11	1.11	1.06	1.01	1.01	1.01
raddish	P2.5	raddish	0	0.30	0.30	0.02	35	0.35	1.11	1.11	1.06	1.01	1.01	1.01
Zuchini	P2.1	zuchini/squash	0	0.30	0.30	0.01	90	0.25	1.09	1.08	0.99	0.86	0.86	0.86
pumpkin	P2.3	pumpkin	0	0.40	0.40	0.01	100	0.25	1.09	1.08	0.99	0.86	0.86	0.86
beetroot	P2.7	beets	0	0.40	0.40	0.01	90	0.25	1.16	1.16	1.09	1.01	1.01	1.01
corn	P2.8	Sweet corn	0	1.50	1.50	0.03	80	0.15	1.24	1.23	0.86	0.44	0.43	0.44
Beans	P2.6	green beans	0.15	0.40	0.25	0.01	90	0.2	1.24	1.23	0.94	0.64	0.63	0.64
corn	P2.8	Sweet corn	0	1.50	1.50	0.03	80	0.15	1.24	1.23	0.86	0.44	0.43	0.44
capsicum	P2.4	Sweet peppers	0.1	0.70	0.60	0.01	125	0.3	1.24	1.23	1.06	0.86	0.86	0.86
parsley	P2.7	Basil	0.1	0.50	0.40	0.02	70	0.23	0.70	0.70	0.62	0.52	0.52	0.52
Wombook	P2.9	Lettuce	0.1	0.30	0.20	0.00	105	0.35	1.11	1.11	1.06	1.01	1.01	1.01
lettuce	P2.9	Lettuce	0.1	0.30	0.20	0.00	105	0.35	1.11	1.11	1.06	1.01	1.01	1.01
Wombook	P2.9	Lettuce	0.1	0.30	0.20	0.00	105	0.35	1.11	1.11	1.06	1.01	1.01	1.01
lettuce	P2.9	Lettuce	0.1	0.30	0.20	0.00	105	0.35	1.11	1.11	1.06	1.01	1.01	1.01
cauliflower	P2.9	Cauliflower	0.1	0.40	0.30	0.00	140	0.35	1.11	1.11	1.06	1.01	1.01	1.01
Brussels sprouts	P2.1	Cabbage	0.13	0.40	0.27	0.00	165	0.35	1.11	1.11	1.06	1.01	1.01	1.01
stevia	P3.11	Basil	0.15	0.50	0.35	0.01	70	0.23	0.70	0.70	0.62	0.52	0.52	0.52
Leek	P3.3	Onions Green	0	0.30	0.30	0.01	70	0.35	1.11	1.11	1.06	1.01	1.01	1.01
silverbeet	P3.6	Spinach	0.05	0.30	0.25	0.01	70	0.35	1.11	1.11	1.06	1.01	1.01	1.01
apple cucumber	P3.1	cucumber	0.1	0.30	0.20	0.00	105	0.25	1.09	1.08	0.99	0.86	0.86	0.86

mousemellon 1	P3.1	cucumber	0.1	0.30	0.20	0.00	105	0.25	1.09	1.08	0.99	0.86	0.86	0.86
mousemellon 2	P3.8	cucumber	0.1	0.30	0.20	0.00	105	0.25	1.09	1.08	0.99	0.86	0.86	0.86
capsicum	P3.5	Sweet peppers	0.07	0.70	0.63	0.01	125	0.3	1.24	1.23	1.06	0.86	0.86	0.86
corn	P3.9	Sweet corn	0	1.50	1.50	0.03	80	0.15	1.24	1.23	0.86	0.44	0.43	0.44
Chia	P3.12	Grains (small)	0.15	1.00	0.85	0.02	150	0.15	1.24	1.23	0.86	0.44	0.43	0.44
parsley	P3.18	Basil	0.1	0.50	0.40	0.02	70	0.23	0.70	0.70	0.62	0.52	0.52	0.52
Spring onion	P3.14	Onions Green	0.1	0.30	0.20	0.00	70	0.35	1.11	1.11	1.06	1.01	1.01	1.01
peas	P3.16	Peas	0	1.00	1.00	0.02	100	0.2	1.24	1.23	0.94	0.64	0.63	0.64
brocolini	P3.13	Broccoli	0	0.40	0.40	0.01	135	0.35	1.11	1.11	1.06	1.01	1.01	1.01
peas	P3.16	Peas	0	1.00	1.00	0.02	100	0.2	1.24	1.23	0.94	0.64	0.63	0.64
Society Garlic initial	P3.4	Society Garlic initial	0.15	0.40	0.25	0.00	106	0.23	0.70	0.70	0.62	0.52	0.52	0.52
Society Garlic perenial	P3.15	Society Garlic perenial	0.4	0.40	0.00	0.00	200	0.23	0.70	0.70	0.62	0.52	0.52	0.52

Table 23-4: fhKc values for weighted K_c calculations

Plant	**Subplot**	**FAO56 plant name**	**ini**	**mid adj(summer)**	**Mid adj (autumn)**	**mid adj (winter)**	**end adj (summer)**	**end adj (autumn)**	**end adj (winter)**	**fh (mid and end)**
Basil (Genovese)	**P1.2**	**Basil**	**0.01**	**0.02**	**0.02**	0.02	**0.01**	**0.01**	**0.01**	0.03

Tomatoes	P1.1	Tomatoes	0.03	0.07	0.07	0.06	0.05	0.05	0.05	0.06
Celery	P1.3	Celery	0.07	0.13	0.13	0.13	0.12	0.12	0.12	0.12
oregano	P1.1	mint	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.02
goosebery	P1.5	tomatoes	0.05	0.11	0.11	0.10	0.08	0.08	0.08	0.09
Beans	P1.4	green beans	0.05	0.12	0.12	0.09	0.06	0.06	0.06	0.10
climbing spinach	P1.6	green beans	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01
Chia	P1.6	Grains (small)	0.01	0.06	0.06	0.04	0.02	0.02	0.02	**0.05**
Chives	P1.2	Onions Green	0.02	0.02	0.02	0.02	0.02	0.02	0.02	**0.02**
carrots	P1.9	Carrots	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Jerusalem Artichoke	P1.6	artichokes	0.01	0.03	0.03	0.02	0.02	0.02	0.02	**0.02**
lettuce	P1.8	Lettuce	0.04	0.04	0.04	0.04	0.04	0.04	0.04	**0.04**
Wombook	P1.8	Lettuce	0.04	0.04	0.04	0.04	0.04	0.04	0.04	**0.04**
Brussels sprouts	P1.8	Cabbage	0.04	0.06	0.06	0.05	0.05	0.05	0.05	0.05
cabbage	P1.8	Cabbage	0.04	0.06	0.06	0.05	0.05	0.05	0.05	0.05
raddish	P2.5	raddish	0.03	0.03	0.03	0.03	0.02	0.02	0.02	**0.02**
Zuchini	P2.1	zuchini/squash	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.03
pumpkin	P2.3	pumpkin	0.03	0.06	0.06	0.05	**0.04**	0.04	0.04	0.05
beetroot	P2.7	beets	0.01	0.02	0.02	0.02	**0.02**	0.02	0.02	0.02
corn	P2.8	Sweet corn	0.02	**0.22**	0.22	0.16	0.08	0.08	0.08	**0.18**
Beans	P2.6	green beans	0.01	**0.03**	0.03	0.03	0.02	0.02	0.02	0.03

corn	P2.8	Sweet corn	0.02	0.22	0.22	0.16	0.08	0.08	0.08	**0.18**
capsicum	P2.4	Sweet peppers	0.05	0.14	0.14	0.12	0.10	0.10	0.10	0.11
parsley	P2.7	Basil	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.03
Wombook	P2.9	Lettuce	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03
lettuce	P2.9	Lettuce	0.04	0.04	0.04	0.04	0.03	0.03	0.03	**0.03**
Wombook	P2.9	Lettuce	0.04	0.04	0.04	0.04	0.03	0.03	0.03	**0.03**
lettuce	P2.9	Lettuce	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03
cauliflower	P2.9	Cauliflower	0.04	0.05	0.05	0.05	0.04	0.04	0.04	**0.04**
Brussels sprouts	P2.1	Cabbage	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04
stevia	**P3.11**	**Basil**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	0.02
Leek	**P3.3**	**Onions Green**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	0.01
silverbeet	**P3.6**	**Spinach**	**0.04**	**0.04**	**0.04**	**0.04**	**0.03**	**0.03**	**0.03**	0.03
apple cucumber	**P3.1**	**cucumber**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
mousemellon 1	**P3.1**	**cucumber**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	0.01
mousemellon 2	**P3.8**	**cucumber**	**0.03**	**0.04**	**0.04**	**0.04**	**0.03**	**0.03**	**0.03**	0.04
capsicum	**P3.5**	**Sweet peppers**	**0.03**	**0.10**	**0.10**	**0.08**	**0.07**	**0.07**	**0.07**	0.08
corn	**P3.9**	**Sweet corn**	**0.02**	**0.26**	**0.26**	**0.18**	**0.09**	**0.09**	**0.09**	0.21
Chia	**P3.12**	**Grains (small)**	**0.02**	**0.20**	**0.20**	**0.14**	**0.07**	**0.07**	**0.07**	0.16
parsley	**P3.18**	**Basil**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.02**

Spring onion	**P3.14**	**Onions Green**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
peas	**P3.16**	**Peas**	**0.05**	**0.30**	**0.30**	**0.22**	**0.15**	**0.15**	**0.15**	0.24
brocolini	**P3.13**	**Broccoli**	**0.05**	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**	0.06
peas	**P3.16**	**Peas**	**0.05**	**0.30**	**0.30**	**0.22**	**0.15**	**0.15**	**0.15**	0.24
Society Garlic initial	**P3.4**	**Society Garlic initial**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Society Garlic perenial	**P3.15**	**Society Garlic perenial**	**0.00**	**0.01**	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**	**0.01**

Table 22-5: $K_{c\ field}$

Date	Plot 1	Plot 2	PLot 3
7/02/2023	0.81	1.53	0.87
8/02/2023	0.81	1.17	0.86
9/02/2023	0.81	1.82	0.84
10/02/2023	0.81	1.82	1.05
11/02/2023	0.81	1.82	1.04
12/02/2023	0.81	1.82	1.02
13/02/2023	0.81	1.82	1.01
14/02/2023	0.87	1.69	0.98
15/02/2023	0.87	1.69	0.97
16/02/2023	0.87	1.69	0.96
17/02/2023	0.84	1.69	0.95
18/02/2023	0.89	1.69	0.69
19/02/2023	0.87	1.69	0.69
20/02/2023	0.87	1.69	0.68
21/02/2023	0.87	1.69	0.67
22/02/2023	0.84	1.69	0.66
23/02/2023	0.84	1.69	0.65
24/02/2023	0.84	1.69	0.64
25/02/2023	0.84	1.30	0.64
26/02/2023	0.84	1.30	0.61
27/02/2023	0.84	1.30	0.61
28/02/2023	1.25	1.30	0.44
1/03/2023	1.22	0.90	0.36
2/03/2023	1.08	0.86	0.43
3/03/2023	1.06	0.86	0.43
4/03/2023	1.06	0.86	0.42
5/03/2023	1.06	0.86	0.41
6/03/2023	1.06	0.86	0.40
7/03/2023	1.12	0.64	1.86
8/03/2023	1.12	0.64	1.86
9/03/2023	1.12	0.64	1.83
10/03/2023	1.12	0.64	1.83
11/03/2023	1.12	0.43	1.81
12/03/2023	1.26	0.41	1.43
13/03/2023	1.28	0.41	2.04
14/03/2023	1.28	0.41	2.04
15/03/2023	1.28	0.41	2.04
16/03/2023	0.80	0.64	2.04
17/03/2023	0.80	0.64	2.04
18/03/2023	0.80	0.64	2.04
19/03/2023	0.80	0.64	2.04
20/03/2023	1.05	0.64	1.54
21/03/2023	1.05	0.44	1.54
22/03/2023	1.05	0.44	1.54
23/03/2023	1.05	0.44	1.54
24/03/2023	1.12	0.44	1.54
25/03/2023	1.12	0.44	1.54
26/03/2023	1.12	0.44	1.54
27/03/2023	1.12	0.44	1.54
28/03/2023	1.12	0.44	1.54
29/03/2023	1.12	0.44	1.54
30/03/2023	1.12	0.44	1.54
31/03/2023	1.12	0.44	1.54
1/04/2023	1.12	0.44	1.54
2/04/2023	0.90	0.44	0.58
3/04/2023	0.90	0.44	0.58

4/04/2023	0.90	0.44	0.58
5/04/2023	0.90	0.44	0.58
6/04/2023	0.90	0.44	0.58
7/04/2023	0.90	0.44	0.58
8/04/2023	0.90	0.44	0.58
9/04/2023	0.90	0.44	0.58
10/04/2023	0.90	0.00	0.58
11/04/2023	0.90	0.00	0.58
12/04/2023	0.89	0.00	0.58
13/04/2023	0.89	0.00	0.58
14/04/2023	0.89	0.00	0.58
15/04/2023	0.47	0.00	0.58
16/04/2023	0.47	0.00	0.58
17/04/2023	0.47	0.00	0.58
18/04/2023	0.46	0.00	0.58
19/04/2023	0.45	0.00	0.58
20/04/2023	0.45	0.00	0.58
21/04/2023	0.45	0.00	0.58
22/04/2023	0.45	0.00	0.92
23/04/2023	0.45	0.00	0.92

24/04/2023	0.45	0.00	0.92
25/04/2023	0.45	0.00	0.92
26/04/2023	0.45	0.00	0.92
27/04/2023	0.45	0.00	0.92
28/04/2023	0.45	0.00	0.92
29/04/2023	0.45	0.00	0.92
30/04/2023	0.45	0.00	0.92
1/05/2023	0.45	0.05	0.92
2/05/2023	0.45	0.08	0.92
3/05/2023	0.45	0.10	0.92
4/05/2023	0.45	0.11	0.92
5/05/2023	0.45	0.12	0.92
6/05/2023	0.45	0.13	0.92
7/05/2023	0.45	0.14	0.92
8/05/2023	0.45	0.14	0.92
9/05/2023	0.38	0.15	0.92
10/05/2023	0.38	0.15	0.92
11/05/2023	0.37	0.19	0.47
12/05/2023	**1.34**	0.21	0.08
13/05/2023	1.30	0.21	0.08

14/05/2023	1.04	0.21	0.10
15/05/2023	1.03	0.21	0.10
16/05/2023	0.99	0.21	0.10
17/05/2023	0.97	0.21	0.09
18/05/2023	0.95	0.21	0.09
19/05/2023	0.93	0.21	0.09
20/05/2023	0.90	0.21	0.09
21/05/2023	0.89	0.21	0.09
22/05/2023	0.87	0.21	0.08
23/05/2023	0.86	0.21	0.08
24/05/2023	0.83	0.21	0.08
25/05/2023	0.83	0.21	0.08
26/05/2023	0.81	0.21	0.08
27/05/2023	0.79	0.21	0.08
28/05/2023	0.78	0.21	0.08
29/05/2023	0.77	0.21	0.08
30/05/2023	0.76	0.21	0.08
31/05/2023	0.75	0.21	0.08
1/06/2023	0.72	0.21	0.07
2/06/2023	0.56	0.22	0.07

3/06/2023	0.55	0.22	0.07
4/06/2023	0.55	0.22	0.07
5/06/2023	0.44	0.22	0.07
6/06/2023	0.49	0.26	0.16
7/06/2023	0.48	0.26	0.16
8/06/2023	0.48	0.26	0.16
9/06/2023	0.48	0.26	0.16
10/06/2023	0.48	0.26	0.17
11/06/2023	0.48	0.26	0.17
12/06/2023	0.48	0.26	0.17
13/06/2023	0.47	0.25	0.17
14/06/2023	0.47	0.25	0.17
15/06/2023	0.47	0.25	0.17
16/06/2023	0.47	0.25	0.17
17/06/2023	0.47	0.25	0.17
18/06/2023	0.47	0.25	0.17
19/06/2023	0.47	0.17	0.17
20/06/2023	0.47	0.15	0.85
21/06/2023	0.46	0.15	0.85
22/06/2023	0.46	0.15	0.84

23/06/2023	0.46	0.15	0.84
24/06/2023	0.46	0.15	0.81
25/06/2023	0.46	0.15	0.79
26/06/2023	0.46	0.15	0.79
27/06/2023	0.46	0.15	0.77
28/06/2023	0.45	0.15	0.77
29/06/2023	0.45	0.16	0.77
30/06/2023	0.32	0.11	0.76

23. Appendix P- Survey

Project Title Scheduling methods of domestic garden hand watering

Description This project is being undertaken as part of an Honours (Bachelor of Engineering) program through the University of Southern Queensland. The purpose of this project is to determine if low cost and low technological methods can be employed to improve manual watering efficiency within domestic gardens, specifically vegetables. The research objectives are to:

Outline the importance of home gardens and the impacts of their irrigation; Determine current hand-watering scheduling practices, particularly how timing and application volumes are decided; Industry irrigation scheduling methods which may be scaled down for domestic use; Scientific factors affecting scheduling methods; Review any case studies of hand watering scheduling by scientific methods; and Trial several methods which could be implemented in domestic gardens to determine their water use effectiveness.

Participation Your participation will involve completion of an online questionnaire that will take approximately 10 minutes of your time. Questions will include: What factors influence your decision on when and how much to water your garden; Do you currently use any tools or calculators to assist in this decision making; How likely you believe you are to implement various tools or calculators.

Your participation in this project is entirely voluntary. If you do not wish to take part, you are not obliged to. If you decide to take part and later change your mind, you are free to withdraw from the project at any stage. You will be unable to withdraw data collected about yourself after you have participated in the questionnaire.

If you do wish to withdraw from this project or withdraw data collected about yourself, please contact the Research Team (contact details at the bottom of this form).

Your decision whether you take part, do not take part, or take part and then withdraw, will in no way impact your current or future relationship with the University of Southern Queensland.

Expected benefits It is expected that this project will not directly benefit you and no incentives are offered to participants. However, it will benefit the researchers in providing a base level of current hand watering practices used by domestic gardeners, as well as providing guidance for research directions on methods that are perceived as serviceable and beneficial for domestic gardeners.

Risks In participating in the questionnaire, there are no anticipated risks beyond normal day-to-day living.

A1. **Are you over 18 years of age?**

Yes ☐

No ☐

A2. **Do you hand water any sections of your house garden (excluding pots)?**

Yes ☐

No ☐

B1. **2) Please select the answer which is your main priority when watering your garden by:**

	Conserving water	Maintaining vigourous plant growth	Keeping plants alive in dry conditions	I enjoy hand watering	Other
hand (ie: hand held hose, watering can)	☐	☐	☐	☐	☐
other irrigation methods (ie: sprinkler)	☐	☐	☐	☐	☐

B2. **3a) Please select all of the plant types (excluding pot plants) that you typically water by hand:**

Vegetables/seasonal edibles ☐

Fruiting trees ☐

Seasonal ornamentals ☐

Perenial ornamentals ☐

Lawn ☐

Other ☐

Other

B3. **3b) Please select all of the plant types (excluding pot plants) that you typically water by other irrigation methods (ie: sprinkler):**

Vegetables/seasonal edibles ☐

Fruiting trees ☐

Seasonal ornamentals ☐

Perenial ornamentals ☐

Lawn ☐

Other

B4. **4a) Please select how often you use each of the methods when deciding when to water by hand:**

	Never	Rarely	Sometimes	Very Often	Always
Use finger to judge the moistness of soil	☐	☐	☐	☐	☐
A specific number of days since last watered/rained	☐	☐	☐	☐	☐
Climate factors such as temperature or rain	☐	☐	☐	☐	☐
Plant appearance (ie: leaf wilt)	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐

B5. **4b) Please select how often you use each of the methods when deciding when to water by other irrigation methods (ie: sprinklers):**

	Never	Rarely	Sometimes	Very Often	Always
use finger to judge the moistness of soil	☐	☐	☐	☐	☐
a specific number of days since last watered/rained	☐	☐	☐	☐	☐
Climate factors such as temperature or rain	☐	☐	☐	☐	☐
Plant appearance (ie: leaf wilt)	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐

B6. **5a) How do you decide how much water to apply when watering by hand?**

	Never	Rarely	Sometimes	Very often	Always
Timer/set amount of time	☐	☐	☐	☐	☐
Until water runs off/ponded	☐	☐	☐	☐	☐
Apply water until intuitively judged as suitable	☐	☐	☐	☐	☐
Flow meter	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐

B7. **5b) How do you decide how much water to apply when using other irrigation methods (ie: sprinklers):**

	Never	Rarely	Sometimes	Very often	Always
Timer/set amount of time	☐	☐	☐	☐	☐
Until water runs off/ponded	☐	☐	☐	☐	☐

	Never	Rarely	Sometimes	Very often	Always
Apply water until intuitively judged as suitable	☐	☐	☐	☐	☐
Flow meter	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐

B8. 6a) What factors influence your decision on when to water by hand:

	Never	Rarely	Sometimes	Often	Always
weather conditions (rain, temperature, etc)	☐	☐	☐	☐	☐
calendar events such as travel and holidays	☐	☐	☐	☐	☐
amount of time since last water	☐	☐	☐	☐	☐
other	☐	☐	☐	☐	☐

B9. 6b) What factors influence your decision on when to water by other irrigation methods:

	Never	Rarely	Sometimes	Often	Always
weather conditions (rain, temperature, etc)	☐	☐	☐	☐	☐
calendar events such as travel and holidays	☐	☐	☐	☐	☐
amount of time since last water	☐	☐	☐	☐	☐
other	☐	☐	☐	☐	☐

B10. 7) Do you use any tools or calculators to guide when to water or how much water you apply:

	I don't use any	Moisture meter	Evapotranspiration calculator	Pot plant weight loss	Other
by hand	☐	☐	☐	☐	☐
by other irrigation methods	☐	☐	☐	☐	☐

B11. 8) On average, do your plants appear healthy majority of the time, or stressed from either under watering (ie: wilted with dry ground), and/or over watering (ie: poor growth with sodden ground).

- Dry and very stressed/plant death ☐
- Dry stress but quickly recovers with water ☐
- No stress evident - plants mostly vigorous and healthy ☐
- Wet stress evident due to poor plant growth, ground often wet ☐
- Sodden ground and very stressed/plant death ☐

B12. 9) Do you know how much water you currently apply to your garden annually? If yes, you may use the comment box to detail the amount used.

- Yes ☐
- No ☐

C1. **10) Please select how likely are you to implement a low cost (up to $50) tool to assist you in maximising your water efficiency, (where 1 is highly unlikey and 5 is highly likely)?**

- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- 5 ☐

C2. **11) Please indicate how likely are you to implement each of the following methods, where 1 is highly unlikely and 5 is highly likely.**

	1	2	3	4	5
Use a watering can to apply a known volume	☐	☐	☐	☐	☐
Use a water flow meter attached to a hose to apply a known volume	☐	☐	☐	☐	☐
Measure weight changes in a pot plant to indicate when and how much water to apply.	☐	☐	☐	☐	☐
Use a soil moisture meter inserted into ground to a specific depth with a calibrated value to indicate when water is required. This may need to be calibrated to each garden bed to determine what value prompts watering. A pre-determined amount of water would then be applied.	☐	☐	☐	☐	☐
Use a online tool (computer or phone) which would require you to enter details such as location, soil type (clay, loam, or sand), type of plants etc. It would then predict a watering schedule for you including days and volume to be applied.	☐	☐	☐	☐	☐

C3. **12) Would you be more likely to use one or more of the previous methods if the equipment was subsidised? Please add any comments you may have.**

- Yes ☐
- No ☐

D1. 13) Do you have any further comments?

Thank you kindly for taking the time to participate in this research.

If you have any questions regrding the survey please email Caitlin Watson at W0086460@umail.usq.edu.au