EXPLORATION OF METHODS WHICH INCREASE THE PRODUCTIVITY OF WATER IN URBAN AGRICULTURE

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 2018

DECLARATION

I declare that this research report is my own, unaided work. It is submitted for the Degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

(Signature of candidate)

13th day of August 2018

ABSTRACT

South Africa is stricken by erratic rainfall patterns which, combined with technical and socio-economic challenges, have given rise to food insecurity. Urban agriculture (UA) is considered as one of the promising agricultural practices that can address food insecurity in urban areas. However, if UA is successfully implemented at a large scale it will potentially trigger a drastic increase in potable water demands if it is the preferred source of water for irrigation. Considering that South Africa's fresh water resources are almost fully utilised it will therefore not be able to support this increase in potable water demands, the challenge is how to obtain alternative fit-for-purpose water for irrigation that will promote urban agriculture and thereby increase food production and enhance food security in urban and peri-urban environments.

This study identified three alternative sources of water that can be exploited for irrigated urban agriculture. These sources are wastewater, greywater, and rainwater. A desktop review of the literature showed that rainwater is the most suitable source of fit-for-purpose irrigation water that can be used to meet the demands of UA. This conclusion was based on the fact that rainwater offers various advantages (such as a lower salinity, sodicity, and heavy metal concentrations) over wastewater and greywater.

Field investigations of four in-field rainwater harvesting (RWH) techniques were implemented at the Siyakhana Food Garden which is an urban garden that serves the residents of Johannesburg. The four techniques, which included in-field RWH with catchment area covered with plastic sheeting (RWH 1), in-field RWH with hand compacted catchment area (RWH 2), ridge and furrow RWH with hand compacted catchment area (RWH 3) and ridge and furrow RWH with ridges covered with plastic sheeting (RWH 4). RWH 4 gave the highest water productivity values in terms of fresh produce yield and biomass of Broccoli.

DEDICATION

I dedicate this report to my family and friends for their support and motivation throughout this grueling process.

ACKNOWLEDGEMENTS

I am forever indebted to my MSc supervisor Professor A.E Taigbenu for his guidance, support, and inspiration throughout the process of preparation of this research report.

I am also indebted to my employer Arup (Pty) ltd for funding my studies.

I would also like to thank Professor M. Rudolph and the staff of Siyakhana Food garden for their assistance with my field experiment.

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LIST OF ABBREVIATIONS

DAFF - Department of Agriculture, Fisheries and Forestry

DWS - Department of Water Affairs and Sanitation

FAO - Food and Agriculture Organization

IFSS - Integrated food security strategy

LEPA - Low-energy precision application

LESA - Low-elevation spray application

MDG - Millennium development goals

MESA - Mid-elevation spray application

RAW - Readily available water

RWH - Rainwater harvesting

SAWS - South African weather stations

TAW - Total available water

UA - Urban agriculture

WHO - World Health Organization

WP - Water productivit

CHAPTER ONE: INTRODUCTION

Southern Africa is a beautiful country, tucked away in the semi-arid region of Africa. The country is blessed with natural resources. A walk through some of the affluent streets in urban centres could paint a picture of nonexistence of poverty and hunger. Unfortunately, this is not the case; in fact, approximately 7.37 million persons of the country's population of 57 million are food insecure (Stats SA, 2017). However, the works of numerous scholars strongly point to the huge potential of urban agriculture to alleviate food insecurity this among South Africa's urban population (Poulsen, *et al.*, 2015; Warren, *et al.*, 2015). It is therefore of utmost importance to determine how irrigated urban agriculture can be developed to improve food production without depleting the current freshwater resources (Viala, 2008; DWS, 2013).

An attempt will be made in the following introductory sections to give the reader background information on the basis of this study. The reader is also introduced to the problem that this study addresses. In addition, the reader is introduced to the aim and objectives that are accomplished in this study.

1.1 Background

Water in both frozen and liquid states is perhaps the most striking feature of the Earth. A pair of authors, who studied the morphology of the Earth, described it as a 'blue marble' (Ward, 2003; Graham, *et al.*, 2010). Water has been in existence on the Earth for over 3.8 billion years and is believed to have been formed on the Earth's surface through the emissions of prehistoric volcanoes. Water appears to be the fundamental ingredient required for the development of all life forms that walk the Earth.

The Earth has an abundance of this precious resource called water; to be exact it constitutes approximately 75% of the Earth's surface area that amounts to 1.39 billion cubic kilometres. 97.5% of this amount is saline and the remaining 2.5% exists as fresh water. The vast majority of fresh water (68.7%) is stored in the Arctic and Antarctic's permanent snow cover. A third of the fresh water is stored in groundwater. The remaining minority of fresh water (0.26%) is stored in lakes and rivers (Graham, *et al.*, 2010). This represents the Earth's natural static water storage which is the long-term average volume of water stored simultaneously in aquifers, water bodies and the atmosphere. For shorter time periods (years to months), the volume of water stored on the Earth's surface permanently varies as water is exchanged between the land, ocean and the atmosphere. This is referred to as the water cycle (Shiklomanov, 2000).

The water cycle is a gigantic system fueled by the energy of the sun. The water cycle can be simplified to three phases: evaporation, condensation and precipitation. Precipitation is of particular importance to humanity because surface runoff replenishes both rivers and streams which is the major source of water for socio-economic development globally and especially in South Africa. Therefore it is of utmost importance to South Africans that these resources are constantly replenished with little variation during the year or from year to year. However, surface runoff has alternate cyclic variations resulting in wet and dry years (Shiklomanov, 2000). To add further challenges to the security of South Africa's water supply, the country receives an average rainfall of approximately 450 mm/year which is well below the global average of 860 mm/year. The clear cut implication of these challenges is that by the year 2025, South Africa's water demand will exceed the available volume of freshwater that is renewed annually by the water cycle (DWS 2004). South Africa's fresh water resources should therefore be used prudently to support the growing economy and associated needs in full (DWS, 2013).

In the midst of South Africa's water security woes, the country has committed itself to achieve 17 goals which includes, to name but a few, combating poverty, hunger, disease, illiteracy, environmental degradation and all forms of discrimination. These goals are termed the Sustainable Development Goals (SDGs) which have superseded the Millennium Development Goals (MDGs). SDG 2 (to end hunger, achieve food security, improve nutrition and promote sustainable agriculture) is of particular importance to this research report as it places the emphasis that South Africa has put on eradicating hunger. Another positive step towards eradicating hunger was the development of the National Food and Nutrition Security Plan (NFNSP). These positive moves have resulted in a 50% reduction in the prevalence of hunger however, a staggering 13.4% of the country's population are still vulnerable to hunger (Stats SA, 2015; Stats SA, 2017). Freedom from hunger remains a fundamental human right in South Africa's constitution and many scholars believe that UA has the potential to secure a city's food supply and increase access to complex food items for poor communities at a relatively low cost (Smit & Nasr, 1992; Grewal & Grewal, 2012).

Various definitions of UA exist, conceived by scholars in the 1980s and consistently modified through the passage of time. According to Hoornweg & Faure (2008) UA can be defined as "an industry located within (intra-urban) or on the fringe (peri-urban) of a town, city, or metropolis, which grows and raises, processes and distributes a diversity of agricultural products, using largely human, land and water resources, products and services found in or around that urban area." While Poulsen *et al.* (2015) defined UA as "increased access to food through production of one's own food or through the income earned by selling one's UA produce". Drawing on the ideas expressed by these authors, UA can be defined as the process of growing food in vacant plots of land, situated in urban cities, for the purpose of consumption or as an additional source of income through the sale of agricultural products.

UA can take many forms, including urban farms, rooftop and school gardens, community and home gardens. UA has the advantages of reducing man's impact on the environment (Doron, 2005; Flores, 2006), supporting local economies (Moustier, 2006; Masi, 2008), and the potential to increase access to healthy and nutritious food in poor communities (Blaine, *et al.*, 2010; Grewal & Grewal, 2012).

UA is essentially a branch of agriculture and therefore, in order to be productive and sustainable, UA requires irrigation. Irrigation secures and increases crop yield but at the cost of increasing fresh water consumption (Shiklomanov, 2000). The irrigated agriculture sector is the largest fresh water consumer in Southern Africa, accounting for approximately 60% of the country's freshwater use (DWS, 2013).

In an urban city, there are often many competing demands for water (Xu, et al., 2013). The prevailing demand for water in cities belongs to the domestic sector and water is therefore treated to potable status by processes that are quite expensive. In addition, treating water to potable status removes the macronutrients which plants require to grow. This is noteworthy because it indicates that potable water is not a fit-for-purpose source of water for irrigated UA. The concept of 'fit-for-purpose water' carries various definitions by different farmers making the concept difficult to quantity. For the purpose of this study the concept of fit-for-purpose irrigation water can be defined as a source of water that is rich in plant macronutrients, does not cause harm to the receiving environment, does not pose a risk to public health and is freely available at a low cost (van Lier & Huibers, 2010).

1.2 Problem statement

Southern Africa is currently home to approximately 55 million people of which 7.37 million of the country's population struggle with the effects of food insecurity on a daily basis (Stats SA, 2017). South Africa has taken a giant leap forward by combating food insecurity with the augmentation of policies which support small food production interventions such as UA. Two such policies, the Integrated Food Security Strategy (IFSS) and the National Policy of Food and Nutrition Security, place an emphasis on increasing the participation of food insecure households in agriculture activities such as UA. In addition, an emphasis is also placed on promoting the use of rainwater harnessing technologies by both aforementioned policies (DAFF, 2002; DAFF, 2013). These policies are noteworthy because they reflect the consensus between the South African government and numerous scholars who believe that UA is a potential solution to food insecurity in urban areas (Poulsen, *et al.*, 2015; Warren, *et al.*, 2015).

The success of UA as a solution to food insecurity in South Africa is intertwined with overcoming the access to fit-for-purpose irrigation water barrier. The issue with this barrier that concerns the South African government and most scholars is that potable water is the main source of water for irrigation in UA. If UA is successfully implemented within urban cities there is potential for a drastic increase in potable water demands. Most of South Africa's fresh water resources are already committed and therefore cannot support this increased water demand. To support UA, alternative sources of fit-for-purpose irrigation water have to be explored (Viala, 2008; DWS, 2013).

The challenge that South Africa now faces is to determine how the irrigated urban agriculture can be developed to improve food production without depleting current freshwater resources (Viala, 2008; DWS, 2013).

1.3 Research aim:

This study aims to identify alternative sources of water for irrigated urban agriculture whilst exploring methods which can be used to increase water productivity using the Siyakhana Food Garden as a case study.

1.4 Specific objectives

- Identify and evaluate alternative sources of water for irrigated urban agriculture;
- Identify and evaluate methods which increase the productivity of water in urban agriculture.

CHAPTER TWO: LITERATURE REVIEW

2.1 Background

Southern Africa is a developing country that has come a long way in terms of food security, however, much is still to be done to completely eradicate food insecurity in urban cities. The South African government has taken proactive steps towards dealing with food insecurity by augmenting policies which support initiatives such as UA. This is significant because it shows that policy makers are in consensus with numerous scholars regarding the potential of UA to give poor South Africans living in urban and peri-urban environments the tools to produce nutritious foods and even earn an income through the sale of agricultural products (Labadarios, *et al.*, 2011; FAO, *et al.*, 2014; Poulsen, *et al.*, 2015; Warren, *et al.*, 2015). However, access to water is seen as the major limiting factor constraining UA (Poulsen , et al., 2015).

2.2 Urban agriculture

A linkage between food security and UA was identified by two groups of scholars who meticulously reviewed a wide range of studies that investigated the association between UA and food security (Poulsen, *et al.*, 2015; Warren, *et al.*, 2015). Although Poulsen *et al.* and Warren *et al.* reviewed different journal articles they found several similar key findings in their research. Their findings included convergence on key points such as food security, income and dietary diversity, thus providing support for the conclusions drawn by both studies. In addition, Poulsen *et al.* identified several barriers, such as access to land and water that may inhibit the success of UA. All of the aforementioned key points and barriers are discussed in the sections that follow.

2.2.1 Food security

A household has achieved food security when all residents have physical and economic access to sufficient nutritious foods that meet their dietary requirements for an active and healthy life. UA has the potential to ensure food security for poor urban households. However, Poulsen *et al.* (2015) and Warren *et al.* (2015) reported that the evidence regarding UA's association with food security was mixed with some studies indicating a positive association and others indicating no association whatsoever.

The quality of the various studies included in the review conducted by both Poulsen *et al.* (2015) and Warren *et al.* (2015) has made it difficult to draw any firm conclusions about the association between UA and food security. However, numerous urban dwellers perceive UA as a solution to their inability to procure nutritious foods. This perception is noteworthy because it reflects the prominent value that urban dwellers place on UA as a vital contributer to their households food security (Poulsen , *et al.*, 2015; Warren, *et al.*, 2015).

2.2.2 Income

Financial motivations materialized as the second most important driver for urban residents engaging in UA. Studies have shown that UA can provide an additional and, in some cases, the only source of household income. Urban residents skilled in agriculture can sometimes earn more than the minimum wage through the sale of agricultural products cultivated from their food gardens. UA therefore has the potential to be profitable (Poulsen , *et al.*, 2015; Warren, *et al.*, 2015).

2.2.3 Dietary Diversity

According to Ruel (2003) the concept of dietary diversity is defined as "the number of different food or food groups eaten during a pre-determined time frame". Poulsen *et al.* (2015) and Warren *et al.* (2015) reported that their findings indicated a positive association between UA and dietary diversity. Urban residents participating in UA have the opportunity to cultivate and consume specific food items, such as fruits and vegetables, which they would not be able to afford due to exorbitant food prices in local supermarkets.

2.2.4 Barriers faced in urban agriculture

UA does not appear to fully eliminate the pressure that urban residents face in obtaining nutritionally rich foods, but evidence has shown that UA may contribute towards an urban resident's food security. However, various barriers constrain UA's potential, such as access to land and fit-for-purpose irrigation water, distribution of agricultural products, and the high costs of inputs (fertilizer and equipment) (Poulsen , et al., 2015). This research report will only focus on the access to fit-for-purpose irrigation water barrier which is discussed in the following section.

Access to fit-for-purpose irrigation water barrier

The quality of water supplied to urban cities is dictated by the domestic sector which requires water to be treated to drinking quality standard (potable water). Potable water is a prohibitively expensive source of water for UA (van Lier & Huibers, 2010; Moglia, 2014). Numerous scholars believe that investigating alternative sources of fit-for-purpose water will contribute to the feasibility of UA by ensuring that it does not use the potable water supply (van Lier & Huibers, 2010; Moglia, 2014; Lupia & Pulighe, 2015).

2.3 Alternative water sources for urban agriculture

In many cases, access to fit-for-purpose irrigation water is the limiting factor that determines the sustainability of UA. There are various alternatives such as wastewater, greywater, and rainwater which could serve as fit-for-purpose irrigation water in UA.

2.3.1 Wastewater

Wastewater in the current context refers to treated, partially treated, or untreated sewage effluent. Treated wastewater refers to sewage effluent that has undergone some of the numerous treatment processes that render the effluent safe for discharge into freshwater resources. Partially treated wastewater refers to sewage effluent that has only undergone limited treatment, thereby rendering the effluent unsafe for discharge into a freshwater resource. Wastewater can be further treated to potable water quality, however at an additional cost (Elgallal, et al., 2016).

Irrigation with treated, partially treated, and in some cases raw wastewater is a frequent practice in many semi-arid and arid countries. It is estimated that 10% of the global population consume agricultural products that were irrigated with wastewater. On a commercial scale, wastewater has been recognised as a valuable source of irrigation water due to its reliability and nutrient properties (Elgallal, et al., 2016).

2.3.2 Greywater

Greywater in the current context refers to untreated household effluent from bath tubs, showers, hand-wash basins, kitchen sinks and the laundry. Greywater effluent from bath tubs and showers is referred to as light greywater (Friedler & Hadari, 2006), while that from laundry facilities, dishwashers and kitchen sinks is referred to as dark greywater. Greywater excludes household effluent from toilets (brown water) and urinals (yellow water) (Birks & Hills, 2007).

Greywater quality varies from source to source and depends on the quality of the water source, the quality of the distribution system and the activities of the water user. Greywater quality can be improved by filtration and disinfection at an additional cost (Li, et al., 2010). Typically, from a high-income household, greywater effluent amounts to approximately 65% of the wastewater effluent (Ghaitidak & Yadav, 2013). This is noteworthy because it shows that greywater is a promising and stable source of fit-for-purpose irrigation water which could be exploited on a continuous basis.

2.3.3 Rainwater

Earth's water is always in constant movement, changing states between vapour, liquid and ice. This process is described by the Earth's natural water cycle which is also known as the hydrological cycle. Water vapour is evaporated from the oceans and rivers which then condenses and returns to the Earth as precipitation or as it is more commonly known as, rainwater. Rainwater is a renewable resource that has been the primary source of water for agriculture since the beginning of time but its amount varies significantly over space and time that impacts on its reliability for UA, particularly in South Africa where rainfall is highly erratic (Perlman, 2016).

2.4 Water productivity improvement methods

Water productivity (WP) is a term that could mean different things to different people. To an economist, it refers to the financial gains earned from yield increases coupled with the reduction in inputs to farming. To an engineer, it is used to define the relationship between the volume of water used for crop production and the overall crop yield (Ali & Talukder, 2008).

Drawing on the ideas of Ali & Talukder (2008), WP can be thought of having three dimensions which are listed below:

- A reduction in water consumption for crop production;
- An increase in crop yield with no reduction in water consumption;
- An increase in yield coupled with a decrease in water consumption.

The literature scan identified two methods which focuses on improving WP namely watershed management and rainwater harvesting (RWH). This study will only focus on RWH which is an inexpensive WP improvement method that can be implemented by semi-skilled South Africans.

2.4.1 Rainwater harvesting

RWH is a technique that aims to significantly increase rainfall productivity ('more yield per drop'), thus mitigating against agricultural water scarcity (Biazin, et al., 2012). The concept of RWH in general describes the process of collection, storage and use of stormwater runoff for both agricultural and domestic use (Hatibu & Mahoo, 1999; Kahinda & Taigbenu, 2011). RWH techniques can be broken down into five categories (Kahinda & Taigbenu, 2011; Biazin, *et al.*, 2012):

1. Domestic RWH systems which collect and store water for household use.
2. Micro-catchment RWH systems which collect and store stormwater runoff in the soil;
3. Ex–situ RWH systems which collect and store stormwater runoff for supplementary irrigation during months of drought;
4. In–situ RWH systems which aim to maximise soil infiltration, reduce stormwater runoff, reduce evaporation and improve soil water availability.
5. In-field RWH systems which are a combination of the in-situ and ex-situ RWH systems.

Domestic rainwater harvesting systems

Domestic RWH systems are engineered to collect and store rainwater from small catchment areas such as rooftops. Rainwater is stored in either above ground or below ground tanks. Domestic RWH has the potential to provide a sustainable source of water for household use which includes drinking, garden watering, and UA. A sustainable domestic RWH system is one that is implemented after considering the socio-economic attributes, physical attributes (location, catchment characteristics, and rainfall), and water quality (Kahinda, et al., 2007a).

Micro-catchment rainwater harvesting systems

Micro–catchment RWH systems are engineered to collect stormwater runoff from a small catchment area (10 – 500 m^2). In most cases the farm constitutes the catchment area and the farmer has complete control over the quality of the rainwater that is harvested. Stormwater runoff is directed and diverted into a type of infiltration enhancement structure that is used to grow plants. Most micro–catchment RWH systems are indigenous structures that have been used by generations to increase rainwater productivity. Micro–catchment RWH systems include pitting, contouring and micro–basins (Biazin, *et al.*, 2012; Yosef & Asmamaw, 2015).

Ex–situ RWH systems

Ex–situ or macro-catchment RWH techniques are two terms that are used interchangeably by the literature (Biazin, *et al.*, 2012; Yosef & Asmamaw, 2015). The sole purpose of ex–situ RWH systems is to generate, collect and store stormwater runoff which can then be used for supplemental irrigation during dry-spells or for domestic uses. Stormwater runoff is collected from natural or paved surfaces and stored in above or belowground tanks. The quantity and quality of the harvested rainwater depends on the rainfall intensity and the catchment characteristics such soil type and levels of land pollution (Biazin, et al., 2012). The most common ex–situ RWH systems used throughout Africa consist of traditional open ponds, cisterns, micro-dams, sand dams and spate-irrigation systems.

In–situ rainwater harvesting systems

In–situ RWH techniques are designed to enhance infiltration, reduce stormwater runoff, reduce evaporation and improve soil moisture storage in the crop rooting zone (Ngigi, 2003). This system works best in areas where the rainfall intensity closely matches the crop water requirement (Hatibu & Mahoo, 1999). The most effective in–situ RWH systems are tillage and mulched ridge and furrow systems (Biazin, et al., 2012).

Tillage

Tillage is aimed at increasing infiltration and soil moisture storage while simultaneously conserving labour and energy (Kahlon *et al.*, 2013; Liu *et al.*, 2013). Tillage also reduces stormwater runoff which is then made available for plant uptake (Salem, et al., 2015). Tillage encompasses a range of techniques such as minimum tillage, reservoir tillage, and conventional tillage.

Minimum tillage is an agricultural RWH practice that involves a single pass of a chisel plough and spiked-tooth harrow which is then followed by manual spreading of seeds. The chisel plough enhances the soil's ability to store water for longer periods of time and the spike-tooth harrow crushes and sorts soil aggregates, thus effectively bringing larger soil aggregates to the surface. The process of shattering and sorting soil of aggregates is important because it reduces soil erosion during high intensity storms (Salem, et al., 2015).

Reservoir tillage is a modern pitting RWH system in which numerous small surface pits (approximate capacity of 1 litre) are formed to collect and store rainwater during rainfall events (Hackwell, *et al.*, 1991; Rochester, *et al.*, 1994; Patrick, *et al.*, 2007; Salem, *et al.*, 2014). Reservoir tillage creates increased levels of surface storage which in turn reduces stormwater runoff and soil erosion (Salem, et al., 2015).

Tillage RWH techniques are expected to increase infiltration and allow rainwater to percolate deeper into the soil profile. A group of scholars investigated the relationship between the aforementioned tillage practices and infiltration rates (Salem, et al., 2015). They reported that reservoir tillage produced the highest infiltration rate of 10.69 cm h^{-1}, followed by minimum tillage with an infiltration rate of 7.85 cm h^{-1}, followed by conventional tillage with an infiltration rate of 5.99 cm h^{-1}. Reservoir tillage's superiority can be found in its ability to create numerous small pits which aggregated to a large infiltration area that allowed rainwater to percolate into the soil profile.

Mulched ridge and furrow technique

The ridge and furrow RWH technique typically consists of alternate parallel ridges and planting furrows (as illustrated in Figure 2-1 on the following page). The planting furrow collects and stores stormwater runoff harvested from the ridges. Storage of stormwater runoff leads to an increase in water pressure which in turn increases infiltration in the planting furrow (Deng, *et al.*, 2006).

The technique's ridges are usually treated with some form of mulch; this is commonly referred to as the mulched ridge and furrow RWH technique. Mulch is used to decrease evaporation, increase yield and water use efficiency. Mulch can consist of various materials such as biodegradable or organic film, gravel, stone, and straw. The mulched ridge and furrow

RWH technique is one of the most efficient technical applications for maximizing rainfall productivity in semi-arid Chinese countries (Boers, *et al.*, 1986; Li & Gong, 2002; Deng, *et al.*, 2006; Wang, *et al.*, 2009; Qi, *et al.*, 2015). The advantages of the mulched ridge and furrow RWH system are that it is cheap, efficient, simple, adaptable and replicable. In addition, the system has the potential to increase stormwater runoff rates, improve infiltration in the planting furrow, reduce evaporation with mulching, increase transpiration and yield (Gupta, 1995; Li, *et al.*, 2000).

Two groups of scholars carried out field experiments to examine the links between three ridge treatments (biodegradable mulching, plastic sheeting and in-situ ridge compaction) and stormwater runoff rates, infiltration in the planting furrow, evapotranspiration and yield. Their experiments consisted of three ridge and furrow plots (as illustrated in Figure 2-1, in plot 1 the ridges were mulched with a biodegradable film, in plot 2 the ridges were covered with plastic sheeting, in plot 3 the ridges where hand compacted) and a fourth flat cultivation plot (Hu, *et al.*, 2014; Qi, *et al.*, 2015). Their results are discussed in the paragraphs that follow.

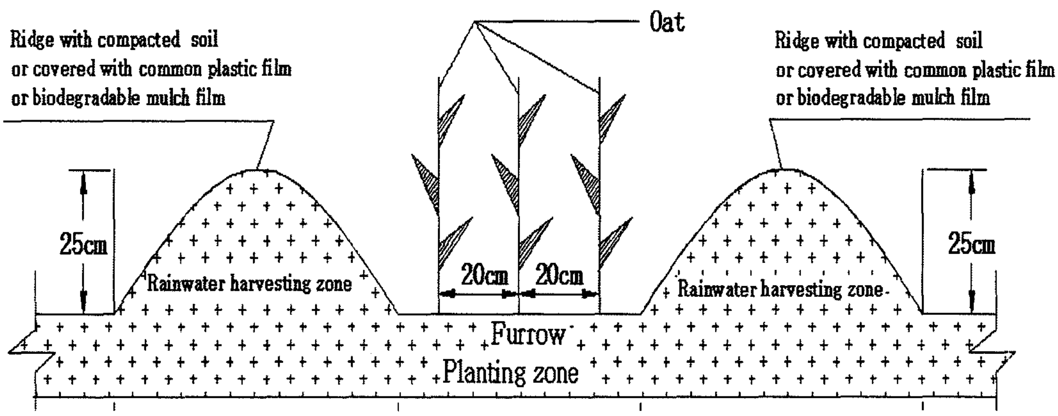


Figure 2-1 - Mulched ridge and furrow cross section (Qi, et al., 2015)

The scholars began by investigating the relationship between stormwater runoff rates and the three ridge treatments. They showed that plastic sheeting and biodegradable mulching produced a higher stormwater runoff rate than in-situ ridge compaction. This result was attributed to the fact that the plastic sheeting and biodegradable mulching had an impermeable surface that did not allow precipitation to infiltrate into ridges and thus almost a 100% of the stormwater runoff was harvested and stored in the planting furrow. The scholars noted that the biodegradable mulch performed on par with the plastic sheeting at the beginning of their experiments, but the latter outperformed the former towards the end of their experiments when the performance of the biodegradable mulch decreased and became comparable to in-situ ridge compaction. This result can be expected because the biodegradable mulch was decomposed by micro-organisms in the soil profile (Hu, *et al.*, 2014; Qi, *et al.*, 2015).

Next the scholars investigated the relationship between evapotranspiration and the three ridge treatments. They reported that the plastic sheeting and biodegradable mulch reduced evapotranspiration and presumably increased the rainwater passing through the crop in transpiration. Plastic sheeting provided the greatest reduction in evapotranspiration followed by biodegradable mulch (Hu, *et al.*, 2014; Qi, *et al.*, 2015).

They also investigated the relationship between yield and the ridge and furrow RWH method. They reported that the three ridge and furrow plots produced a higher grain yield than that of the flat cultivation plot. However, there was a decrease in the total grain yield cultivated from the experimental field because the cropping area was reduced as part of the land was used to create ridges (Hu, *et al.*, 2014; Qi, *et al.*, 2015). There is therefore a trade-off between the positive effects of the mulched ridge and furrow RWH technique and the reduction in overall grain yield. The trade-off depends on factors such the soil characteristics, the amount and intensity of rainfall, plant species, and mulched ridge and furrow ratios (Boers & Ben-Asher, 1982)

In-field rainwater harvesting

The in-field RWH system was developed for soils which, in the semi-arid regions of South Africa, produce high stormwater runoff and losses due to evaporation under conventional tillage systems (Hensley, et al., 2000). As of 2004 the system has been effectively adopted by over 1000 South African households (Kundhlande, et al., 2004).

The in-field RWH system typically consists of two distinct areas, a 2m wide catchment area and 1m wide basin strip which are illustrated in Figure 2-2 below. The catchment area is used to increase stormwater runoff which is discharged and stored in the basin strips until the infiltration process is completed. Stormwater runoff is increased by creating and maintaining a steep, uncultivated (no-tillage) and bare catchment surface (Bothma, et al., 2012). This allows the system to create rainfall wetting fronts that infiltrate into the crop rooting zone which contributes to higher transpiration rates and lower evaporation rates (van Rensburg, et al., 2012).

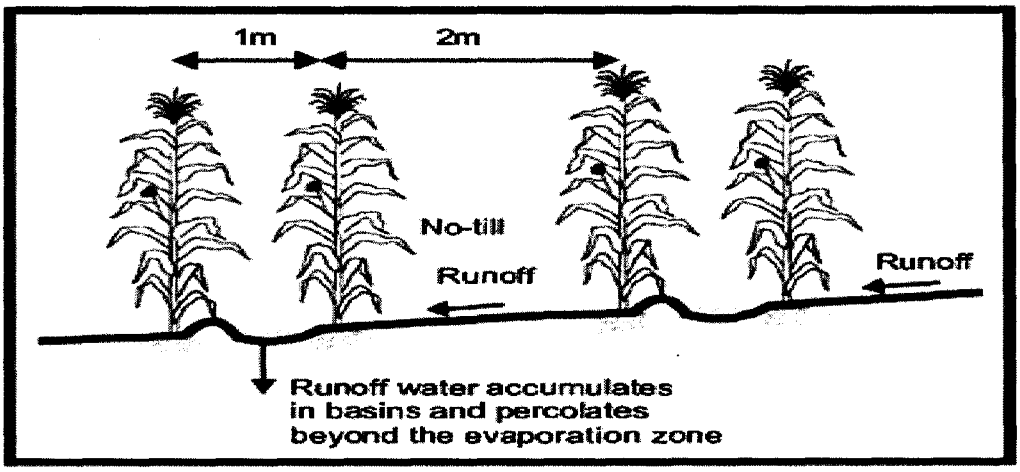


Figure 2-2 - Diagrammatic representation of the in-field RWH system (van Rensburg, et al., 2012)

Over the past 18 years numerous modifications and enhancements of the original in-field RWH technique developed by Hensley *et al.* (2000) have been carried out. The modifications include the reduction of the catchment area width from 2 to 1m (Mavimbela & van Rensburg, 2012), and the addition of mulches to both the catchment area and basin strips which improves grain yield and water use efficiency (van Rensburg, *et al.*, 2012; Botha, *et al.*, 2015). These modifications and enhancements are discussed in the paragraphs that follow.

Mavimbela & van Rensburg (2012) investigated the relationship between catchment area width and yield. Their experiments consisted of three in-field RWH plots with a catchment area width of 1, 2 and 3m. They found that a 1m wide catchment area produced an evaporation rate that was 22% and 31% lower than the respective 2m and 3m wide catchment areas. This result can be attributed to the fact that the increased catchment area promotes evaporation due to an increase in surface area exposed to direct sunlight (Acciaresi & Zulunga, 2006; Onyango, 2009). In contrast, reducing the catchment area implied that much of the surface area became shaded by the crop canopy and hence more sunlight got intercepted to promote photosynthesis rather than evaporation (Eberbach & Pala, 2005). Mavimbela & van Rensburg found that the 1 m wide catchment area produced a grain yield that was 21 and 45% higher than the respective 2 and 3 m wide catchment areas.

Mulches are commonly added to the catchment area to increase stormwater runoff rates and in addition, the basin strips are also commonly mulched to reduce evaporation. Two groups of scholars investigated the effects of organic mulches, stone mulches, compaction and conventional tillage practices on the catchment area's runoff generation potential and grain yield. Their field experiments incorporated mulching both the catchment area and basin strips. They reported that compaction of the catchment area generated the most runoff when compared to organic and stone mulches. This result can be expected as the stone and organic mulching would reduce runoff velocity and increase infiltration into the catchment area. They also reported that the combination of an organic mulched basin and stone mulched catchment area resulted in the highest grain yield when compared to the other mulching treatments. They concluded that once the generated surface rainwater runoff exceeds an infiltration threshold, most of the stored rainwater is lost to evaporation rather than transpiration (van Rensburg, *et al.*, 2012; Botha, *et al.*, 2015).

Semi-arid countries such as South Africa experience erratic rainfall patterns and frequent dry spells. In-field RWH can be used in conjunction with supplemental irrigation to secure crop yields during dry spells. Irrigation increases water availability for transpiration however, if not applied properly evaporation could be exacerbated (Mavimbela & van Rensburg, 2012). Pilbeam *et al.* (1995) reported a scenario where supplemental irrigation on bean crops increased evaporation rates by more than 55% while only 10–19% of the applied water was transpired by the crop. On the other hand, Mavimbela & van Rensburg concluded that supplemental irrigation has the potential to increase grain yields by almost 200%.

Selection of In-field RWH sites

Although governmental organisations and research groups promote the use of in-field RWH, its adoption rate is slow among residents who practice UA (Kahinda, et al., 2008). One of the reasons for this might be that there is a lack of guidelines which can be used by urban and rural dwellers to identify suitable sites for in-field RWH (Mati, et al., 2006). Scholars have therefore identified six key factors to be evaluated when determining the suitability of in-field RWH sites. These factors include rainfall, the rainfall-runoff relationship, soil structure and texture, slopes, crop characteristics and the socio-economic environment (FAO, 2003).

Kahinda *et al.* (2008) developed a GIS-based model which combined the physical, ecological, and socio-economic data layers to map out favourable and suitable in-field RWH sites across South Africa. The physical layers encapsulated aridity zones, rainfall, soil texture and depth. The ecological layer is associated with maintaining ecological diversity. Finally, the socio-economic layer encapsulated the percentage of households below the poverty datum, percentage of the population whom are not economically active, and the percentage of the population without access to piped water (Kahinda, et al., 2008).

Favourable and suitable areas to implement RWH include sites underlain by a deep sandy clay loam strata which are located in semi-arid or dry sub-humid areas that receive an annual rainfall that is less than 100mm. In addition, households with an annual income of less than R9600 are most suitable to benefit from in-field RWH. Gauteng has a high to moderate suitability for the adoption of in-field RWH which can be seen from the in-field RWH suitability map developed by Kahinda *et al.* (2008) that is illustrated in Figure 2-3.

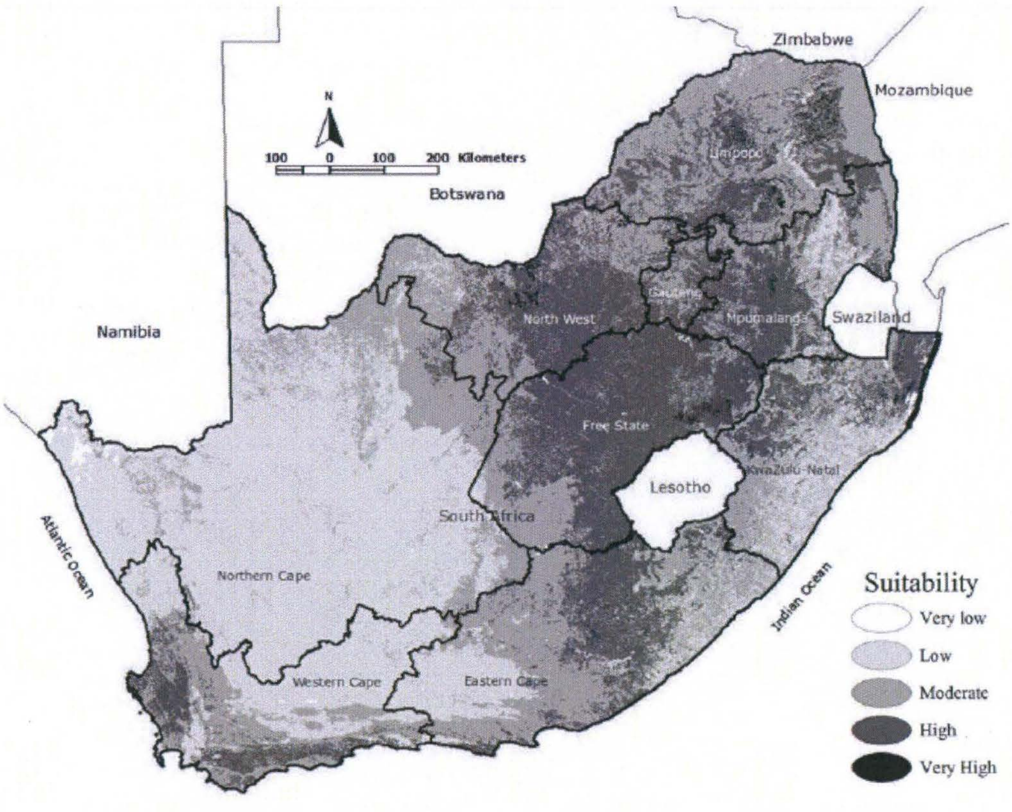


Figure 2-3 - In-field RWH suitability map (Kahinda, et al., 2008)

In-field RWH vs. tillage

Both in-field RWH and tillage aim to increase rainwater productivity by increasing grain yields, increasing infiltration rates, increasing transpiration and reducing evaporation. Botha, *et al.* (2015) tested the impact of in-field RWH on grain yield when compared to conventional tillage practices and Mavimbela & van Rensburg (2012) investigated the impact of supplemental irrigation on grain yield. Their results are discussed below.

Botha *et al.* (2015) found that in-field RWH increased maize yields on average by 12% when compared to conventional tillage. The ability of the in-field RWH system to induce surface rainwater runoff explains the superiority of the system over conventional tillage. This result is noteworthy because in semi-arid countries, every drop of rainwater has to be optimally utilised to produce food. Botha *et al.* concluded that the use of an appropriate RWH system could have a significant positive impact on food security in urban areas.

Mavimbela & van Rensburg (2012) concluded that the combination of in-field RWH and supplemental irrigation increased grain yields by 200% when compared to conventional flat cultivation. In summary, the combination of in-field RWH and supplemental irrigation can dramatically increase grain yield, however the questions that now remain are the choice of irrigation method, when to irrigate and the correct volume of water to irrigate, all of which are discussed in the sections that follow.

2.5 Irrigation Methods

Semi-arid countries such as South Africa receive erratic rainfall patterns and prolonged periods of drought which can lead to crop damage and a loss of grain yield. Statistically in semi-arid countries, severe crop reductions caused by prolonged dry spells occur once or twice in five years, and total crop failure caused by droughts occurs once in ten years. Erratic, insufficient, and unreliable rainfall patterns make supplementary irrigation an attractive option to assure grain yield in semi-arid countries (Kahinda, et al., 2007b).

If applied properly the combination of RWH and supplemental irrigation has the potential to further increase grain yields. Kahinda *et al.* (2007b) noted that supplementary rainwater irrigation increased and stabilised crop yield thus assuring a minimum yield even in cases when no fertlizer was added. Kahinda *et al.* found that supplementary rainwater irrigation resulted in a 13% reduction of the risks associated with crop failure that occurs due to drought and dry spells. This is noteworthy because it shows the importance of adopting supplementary irrigation. There are various irrigation methods available to urban farmers such as furrow irrigation, alternate furrow irrigation, sprinkler, and drip irrigation, all of which are discussed in the sections that follow.

2.5.1 Furrow irrigation

Furrow irrigation is a form of surface irrigation. A cross section of the furrow irrigation system is illustrated in Figure 2-4. Rainwater is discharged at the top of each furrow and allowed to flow down the furrow under the influence of gravity. The velocity of the rainwater flow down the furrow is determined by numerous factors such as inflow rate, infiltration rates, surface roughness, and slope. As rainwater flows down the furrow its velocity gradually decreases, thus taking a significant period of time to flow from the top of the furrow to the bottom. This results in a poor uniformity and distribution of the infiltrated rainwater in the soil (Emdad, et al., 2004).

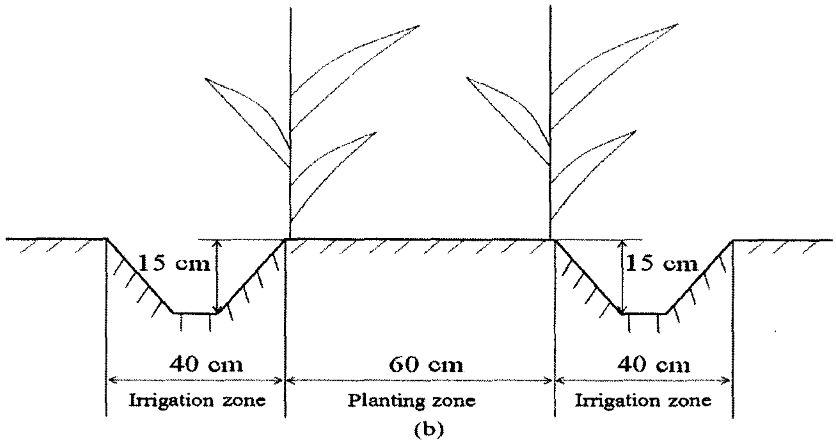


Figure 2-4 - Furrow Irrigation (Wu, et al., 2015)

The performance of furrow irrigation systems is closely related to the infiltration function of the soil (Walker & Skogerboe, 1987). The soil infiltration function has been reported to vary throughout the year and is dependent on surface sealing, soil moisture content prior to the start of irrigation, and the presence of mulch (Elliott, *et al.*, 1983; Raine, *et al.*, 1998). Irrigated soils are subjected to sequential periods of rapid wetting followed by periods of drying which can reduce aggregate stability resulting in the release of aggregates and scouring of the furrow (Caron, et al., 1992; Rasiah, *et al.*, 1992). The quality of the applied irrigation water will also affect the soil chemical properties which influence soil dispersion and aggregate breakdown, surface sealing, crust formation and changes in the infiltration function (Shainberg & Letey, 1984).

Emdad *et al.* (2004) investigated the effect of irrigation water quality on the soil structural properties. They reported that the infiltration rate at the end of 12 weeks of furrow irrigation was lower than the infiltration rate at the beginning of the irrigation operations, and they concluded that the reduction in infiltration rates was due to the formation of a 5cm thick apedal layer in week 4. The apedal layer was formed by the collapse of the soil structure during wetting and soil hardening without restructuring during drying (Emdad, et al., 2004).

2.5.2 Alternate furrow irrigation

Alternate furrow irrigation operates on the same basis as conventional furrow irrigation with the exception that furrows are alternatively irrigated. The advantages of alternate furrow irrigation include a reduction of surface water evaporation, a decrease in water loss to deep percolation and better utilization of nutrients. In addition, alternate furrow irrigation increases crop water use efficiency as more water is taken up by crops than those subjected to conventional furrow irrigation. Alternate furrow irrigation reduces the water required for crop growth however at the expense of grain yield. This is caused by reduced leaf transpiration which in turn inhibits photosynthesis (Kang, et al., 2000).

2.5.3 Sprinkler irrigation

Sprinkler irrigation is a form of overhead irrigation that allows water to be either sprayed at a high or a low velocity onto plants. Advantages of sprinkler irrigation systems include fertigation, automation, increased crop yield, improved water distribution and crop quality. Disadvantages of sprinkler irrigation systems include emitter clogging, high capital costs, depreciating assets, maintenance problems, high running costs (fuel and electricity), operational skill shortages and wheel rutting (Smith, et al., 2015). Centre pivot (Figure 2-5) and lateral move (Figure 2-6) are the two main sprinkler irrigation systems. Both irrigation systems consist of distribution piping and sprinklers supported by trusses that are mounted on a wheeled tower base.

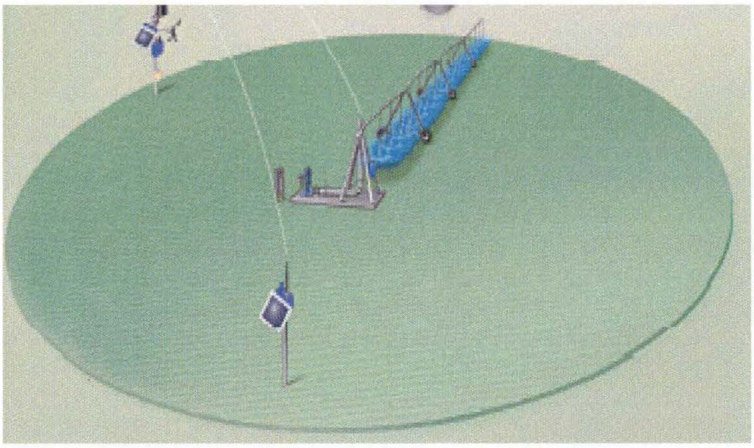


Figure 2-5 - Centre Pivot (Reinke, 2017)

Figure 2-6 - Lateral Move (Reinke, 2017)

Centre pivot sprinkler irrigation systems rotate along a centre pivot which supplies water to the system. The system can be fitted with different types of emitters which include low-energy precision application emitters (LEPA), low-elevation spray application emitters (LESA) and mid-elevation spray application emitters (MESA). LEPA emitters are positioned on the surface which allows water to be directly discharged on the soil. LESA emitters are positioned less than 1m above natural ground level and MESA emitters are position at a proximately 1m above the natural ground level (Rajan, et al., 2015).

A group of scholars investigated the efficiencies of LEPA, MESA and LESA emitters (Tolk, *et al.*, 1995; Schneider, 2000; Rajan, *et al.*, 2015). They found that LEPA emitters produce efficiencies greater than 90%, LESA emitter's efficiencies range between 70-80% and MESA emitter's efficiencies range between 60-70%. This result can be explained by first understanding the discharge regimes of the emitters. LEPA emitters discharge water directly onto the soil surface whereas LESA and MESA emitters discharge water out horizontally. A proportion of the LESA and MESA emitters discharge is therefore intercepted by the plant canopy which could evaporate without reaching the soil surface. This results in lower irrigation efficiency for the LESA and MESA emitters when compared to LEPA emitters.

Lateral move sprinkler irrigation system is generally used to irrigate oddly shaped fields. The system moves in either a north to south or west to east direction and generally draws water from open supply channels which are expensive to construct and maintain. Channel maintenance includes algae control, desilting, weed control and grading (Smith, et al., 2015).

2.5.4 Drip irrigation

Drip irrigation is a form of micro-irrigation that allows water to drip slowly onto the plant roots. Some of the advantages of drip irrigation include improved nutrient and water management, a reduction of water requirements, and a greater control on irrigation watering rates resulting in reduced water and fertilizer wastage to leaching and deep percolation. Drip irrigation can either be implemented on-surface or sub-surface. On-surface drip irrigation is not widely adopted by farmers because the drip tubing interferes with the cultivation and ploughing operation. Sub-surface drip irrigation is therefore more commonly adopted by farmers. Sub-surface drip irrigation is however subjected to damage from crop root intrusion, and tubing damage from burrowing animals (Ayars, et al., 1999).

The primary driver for the adoption of drip irrigation is the potential increase in grain yield with a reduction in water use. Ayars *et al.* (1999) reported that drip irrigation dramatically increased tomatoes and corn yields when compared to conventional surface irrigation. This result can be attributed to both improved fertilizer and water management which was achieved using the drip irrigation method. Ayars *et al.* identified several factors which influence the sustainability of drip irrigation which placement depth of emitters and preventing clogging of the emitter.

The placement depth of drip emitters is linked to the soil type, porosity and capillary action. Soil porosity describes the pore spacing in the soil structure, sandy soils are said to have large pore spacing and clayly soils are said to have small pore spacing. The pores allow irrigation water to enter the soil structure through infiltration, where it moves laterally and vertically. Water molecules upward flow is governed by capillary action. A smaller pore structure will exert a greater capillary force on the water molecules thus allowing it to travel further upwards than that off a large pore structured soil. Therefore Ayars *et al.* (1999) found that drip emitters can be placed deeper in clay soils than in sandy soils. Another important factor is the quality of the water used for drip irrigation as heavily sedimented water can lead to emitter clogging (Ayars, et al., 1999).

Clogging of drip emitters is considered by the practical and academic world as a major maintenance problem that is influenced by water quality (Capra & Scicolone, 1998; Bounoua, *et al.*, 2016). Complete or even partial clogging of drip emitters reduces drip emission uniformity and consequently decreases irrigation efficiency and increases the water volume required for crop growth (Capra & Scicolone, 1998; Bounoua, *et al.*, 2016). The table on the following page can be used to classify the potential risk of clogging based on water quality.

Table 2-1 - Water quality hazard risk rating (Bucks, et al., 1979)

Clogging factors		Hazard Rating		
		Minor	Moderate	Severe
Physical	Suspended Solids (mg/l)	<50	50-100	>100
Chemical	pH	<7.0	7.0-8.0	>8.0
	Dissolved solids (mg/l)	<500	500-2000	>2000
	Manganese (mg/l)	<0.1	0.1-1.5	>1.5
	Total iron (mg/l)	<0.2	0.2-1.5	>1.5
	Hydrogen sulphide (mg/l)	<0.2	0.2-2.0	>2.0
Biological	Bacterial Number (mg/l)	<10 000	10 000-50 000	50 000

The clogging of drip emitters can be caused by physical, chemical, or biological contaminants and is often the result of a combination of contaminants. Physical clogging is usually caused by suspended organic materials (such as faeces) and inorganic particles (such as sand, silt and clay). Filtration is proposed as a possible solution to physical clogging. Chemical clogging is usually caused by waters with a high concentration of hydrogen sulphide anions which react with and cause precipitation of iron and manganese. Biological clogging is usually caused by algae, bacteria, fungi, iron, and sulphur slimes (Bucks, et al., 1979; Capra & Scicolone, 1998; Bounoua, *et al.*, 2016).

Bounoua *et al.* (2016) investigated the underlying causes behind emitter clogging. They concluded that the emitters clog after two weeks of use with harvested rainwater and after six weeks of use with filtered harvested rainwater. This result can be explained by the fact that small particles pass through the filter and agglomerate into larger particles downstream of the filter which clog the emitters. In general, the risk of clogging increases as the suspended solids, total iron, electrical conductivity, calcium, manganese and magnesium content increase (Bounoua, et al., 2016).

2.5.5 Evaluation of irrigation systems

There are a number of irrigation techniques available namely furrow irrigation, alternative furrow irrigation, sprinkler irrigation, and drip irrigation. Sprinkler and drip irrigation's superiority over the other irrigation systems is found in their ability to increase grain yields while using considerably less volume of water when compared to furrow and alternate furrow irrigation. However, sprinkler and drip irrigation is susceptible to clogging and therefore requires high quality potable water. This is noteworthy because filtered rainwater is unsuitable for both sprinkler and drip irrigation. Alternate furrow irrigation reduces the volume of water required for crop growth when compared to traditional furrow irrigation however, at the expense of grain yield. In summary, the choice of irrigation method would depend on funding, maintenance, water conservation, grain yield and is therefore site and situation specific.

2.6 Irrigation design and scheduling

Irrigation is an indispensable technique which can be used by urban farmers to assure high crop yields during periods of drought and also increase crop productivity. However, if not applied correctly irrigation can cause waterlogging or crop water stress which can be detrimental to crops. The field water balance is an essential tool that can be used by urban dwellers to determine the correct volume of water that must be applied to the soil at the correct time. The concepts of crop water stress and the field water balance are explained in the sections that follow (Burger, *et al.*, 2003; Ali, 2010).

2.6.1 Crop water stress

In wet soils, water molecules are not strongly bonded by capillary forces which make it easy for the crop to extract water from the soil matrix. As the soil begins to dry out the remaining water molecules in the soil matrix becomes strongly bonded to the soil structure making it difficult for the crop to extract water from the soil. In the absence of a wetting event the potential energy of the soil water molecules will drop below a threshold value, at this point in time the crop is said to be water stressed. The crop water stress is commonly described by the Total Available Water (TAW) and Readily Available Water (RAW) relationships which are described in detail in the sections that follow (Allen, et al., 1998).

Total available water

Crops extract water from the soil to meet their transpiration requirements. In the absence of rainfall or irrigation, the soil water content in the crop root zone decreases as a result of the water extraction process. Eventually, a point in time is reached whereby the crops can no longer extract water from the soil matrix. This point is referred to as the wilting point (Allen, et al., 1998).

After heavy irrigation or a heavy rainfall event, the soil will drain until field capacity is reached. Field capacity refers to the volume of water that a well-drained soil should hold against gravitational forces. The relationship between the field capacity and the wilting point is commonly referred to as TAW. This relationship is born from the fact that water content above field capacity cannot be held in the soil matrix and water content below the wilting point cannot be extracted by plant roots. Therefore, the TAW is equal to the difference between the field capacity and the wilting point (Allen, et al., 1998).

$$\text{TAW} = (\theta_{FC} - \theta_{WP})Z_R \quad \text{......} \quad 2\text{-}1$$

Where: $\text{TAW} = \text{Total available water}$

$\theta_{FC} = \text{field capacity } (m^3/m^3)$

$\theta_{WP} = \text{wilting point } (m^3/m^3)$

$Z_R = \text{root zone (mm)}$

Readily available water

Water is theoretically available for plant extraction until the wilting point is reached but extraction rates are greatly reduced before the wilting point is reached. When the soil is wet the plant is able to extract water quick enough to meet its transpiration requirements. As the soil dries out the water extraction process slows down and the crop can no longer extract water to meet its transpiration demands. This results in the crop experiencing water stress. Therefore, the plant can only extract a fraction of the TAW without suffering water stress which is referred to as the readily available water (RAW) (Allen, et al., 1998).

$$\text{RAW} = p(\text{TAW}) \quad \text{......} \quad 2\text{-}2$$

Where: $\text{RAW} = \text{Readily Available Water (mm)}$

$p = \text{stress coefficient}$

$\text{TAW} = \text{Total Available Water (mm)}$

2.6.2 Field Water Balance

At the field level, the crop's water requirements are met by the water stored within the soil structure. Water stored within the soil structure is defined by the field water balance and is influenced by water additions and water losses at a given point in time. Using a time period of a day, the field water balance is described by the following equation and its components are discussed in the sections that follow (Allen, *et al.*, 1998; Burger, *et al.*, 2003; Ali, 2010):

$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_i - CR_i + ET_{c,i} + DP_i \qquad \text{2-3}$$

Where: $D_{r,i}$ = root zone depletion at the end of day i (mm)

$D_{r,i-1}$ = water content in the root zone at the end of the previous day (mm)

P_i = Rainfall on day i (mm)

RO_i = surface runoff on day i (mm)

I_i = net irrigation depth on day i (mm)

CR_i = Capillary rise on day i (mm)

$ET_{c,i}$ = Crop evapotranspiration on day i (mm)

DP_i = deep percolation on day i (mm)

Root zone depletion (D_R)

Root zone depletion refers to water shortage in the root zone relative to field capacity. Expressing the field water balance in terms of root zone depletion is particularly helpful because it makes adding and subtracting the field water components simple.

Root zone depletion can be assumed to equal zero at field capacity after irrigation or heavy rain. Thereafter, as a result of crop water uptake and percolation, the root zone depletion gradually increases as the soil water content gradually reduces. In the absence of irrigation or rainfall, the soil water content will gradually reach RAW and the crop begins to experience water stress. The root zone depletion will continue until the soil water content reaches the wilting point. At that point in time, the crop can no longer extract water for evapotranspiration and therefore the root zone depletion has reached its maximum, TAW. Consequently, the limits imposed on the root zone depletion are defined by the equation below (Allen, et al., 1998):

$$0 < D_{r,i} < TAW \quad \text{2-5}$$

Capillary rise (CR)

The phenomenon known as capillary rise describes the upward movement of water from the water table to the root zone. Capillary rise depends on the depth of the water table, wetness of the zone and the soil type. If the water table is more than 1m below the bottom of the root, capillary rise is generally assumed to be zero (Allen, *et al.*, 1998; Burger, *et al.*, 2003; Ali, 2010).

Evapotranspiration (ETc)

Water influences the metabolism and growth of plants. Water also functions as a medium in which gases, minerals and organic solutions are transported from one part of the plant to another. More than 90% of the water absorbed by the plant's roots is transpired into the atmosphere as water vapor through a process called transpiration. Transpiration occurs through the plant's leaves and has a twofold function, namely plant cooling and assists in carbon dioxide entry into the plant. Plants transpire water for cooling purposes and also to assist in carbon dioxide absorbation which is an essential ingredient of photosynthesis. Photosynthesis is a process that is used to manufacture food for the plant and requires water, sunlight and carbon dioxide (Allen, *et al.*, 1998; Burger, *et al.*, 2003; Ali, 2010).

The process of evapotranspiration can therefore be defined as the combination of evaporation from the ground and plant leaves, and transpiration from the plant which occurs simultaneously (Ali, 2010).

Deep percolation (DP)

The process of deep percolation is the downward flow of water through the soil until it reaches the water table. After irrigation or a heavy rainfall event it is generally assumed that the water above field capacity is lost to deep percolation in that day.

2.7 Summary

This literature review identified alternative sources of fit-for-purpose irrigation water for UA. Three potential sources of fit-for-purpose irrigation water were identified namely wastewater, greywater, and rainwater. This literature review also identified methods which can be used to increase the productivity of our valuable water resource. It was found that RWH proved quite successful in increasing the productivity of the resource. It was also identified that there are numerous RWH methods however no comparison was made between them. Lastly this literature survey reviewed different irrigation methods and irrigation scheduling techniques.

CHAPTER THREE: RESEARCH METHODOLOGY

In this chapter, an attempt will be made to give the reader a holistic view of the research methodology used to achieve this study's specific objectives. This methodology is encapsulated into two unique tasks. Each task addressed one of the specific objectives that were identified in Chapter One. Research task one is based on a desktop study and addressed specific objective 1. Research task two is based on a field experiment that addressed specific objective number 2. In addition, the reader is given a holistic view of the research philosophy adopted in this study.

3.1 Research philosophy

Research philosophy is an overarching term which relates to the development of knowledge. It encompasses four aspects namely positivism, interpretivism, pragmatism and realism. Positivism follows a quantitative research approach and dictates that only phenomenon which can be observed will result in the production of reliable and credible data. Interpretivism opposes the positivist philosophy and follows a qualitative rather than a quantitative research approach. Pragmatism argues that the researcher need not choose between the positivism and the interpretivism ideologies but rather adopt a hybrid of both to enable the researcher to better answer the research question. Realism dictates that what our senses show us is the truth. The selection of an appropriate philosophy is related to the research question and practical factors (Saunders, et al., 2009).

The study's research objective 2 leads one to believe that a positivist research philosophy is required but with adoption of pragmatism due to constrainsts such as timeframes, while the pursuance of research objective 1 adopted a interprevitist stance.

3.2 Research task 1

Research task 1 was used to address specific objective 1 which dealt with the identification and investigation of an alternative source of fit-for-purpose water that can be used by urban dwellers for irrigation. Following the interpretivist philosophy, this task was based on a desktop study in which the author investigated articles that met a set of predefined inclusion criteria which were relevant to specific objective 1.

The set of predefined inclusion criteria included the following:

- Only peer-reviewed articles published in reputable journals were included;
- The article must have examined the impacts that the fit-for-purpose water has on the environment or the threats that the fit-for-purpose water poses to public health;
- The article must have reported primary data; and
- Only articles published between 1998 and 2016 were considered.

Eligible journal articles were identified by searching the databases from Google Scholar, the Journal of Agricultural Water Management and the Journal of Irrigation Sciences. From the initial Google Scholar search, wastewater, grey water, and rainwater were identified as possible sources of fit-for-purpose water which can be used by urban dwellers for irrigation. Boolean operators were used to pair the primary keyword ("urban agriculture") with each of the three secondary keywords ("wastewater", "grey water" and "rainwater"). Articles were screened by title and then abstracted to eliminate the articles that clearly did not meet the inclusion criteria. Finally, the full text of all the remaining articles was reviewed to determine if they met the inclusion criteria.

Data that met the inclusion criteria were extracted from the journal articles and recorded on an Excel spreadsheet. The recorded data included the title and year of the article, author, research question, aims and objectives, study methodology, limitations noted by the study author, limitations noted by the reviewer, discrepancies, key results and key conclusions. The results were then analysed and conclusions were drawn on the source of 'fit-for-purpose water' for UA.

3.3 Research task 2

Research task 2 addressed specific objective 2 which dealt with evaluating methods that increase WP in an UA context. RWH was identified in the literature review as a WP improvement method that has already been implemented by many urban dwellers. Numerous RWH methods were identified in the literature review however, it is not known which method is the most productive. Thus, the purpose of this task is to determine which method is the most productive. Following the positivist philosophy, this task will employ a field experiment to investigate four RWH systems (which are listed below) to determine which one is the most productive.

1. In-field RWH (catchment area covered with plastic sheeting)
2. In-field RWH (hand compacted catchment area)
3. Ridge and furrow RWH (hand compacted ridges)
4. Ridge and furrow RWH (ridges covered with plastic sheeting)

3.3.1 Identification of variables

The most productive RWH method (independent variable) will be determined by the following dependent variables:

- The method that uses the least volume of irrigation water;
- The method that produces the highest fresh vegetable yield;
- The method that produces the greatest volume of biomass; and
- The method that has the highest water productivity.

The experimental site was located at the foot of a downslope and therefore runoff emanating from the higher lying areas naturally flowed into the experimental site. This runoff was therefore identified as an extraneous variable that was controlled during the experiment.

3.3.2 Field experiment

A field experiment was conducted in the Siyakhana Food Garden which RWH method is the productive. Descriptions of the experimental site, planting practices, experimental design and layout, irrigation design and scheduling are provided in the sections that follow.

Experimental site

Siyakhana Food Garden is situated in Bezuidenhout Park, Johannesburg. The coordinates of the study area are 26°11'00.3"S and 28°05'33.4"E, and it is at an elevation of 1753m above mean sea level. There are four South African weather stations (SAWS) within a 4 km radius of the study area. The closest SAWS (JHB-Republiek Stek - SAWS Number 0476101_W) is located 1.8 km away from the study area and has recorded a mean annual precipitation of 780mm over the past 86 years. The study area receives the bulk of its rainfall during the spring and summer seasons with a maximum and minimum range of air temperatures of 32°C and 15°C respectively (Smithers & Schulze, 2002). In addition, the site is underlain by a homogenous silt clay loam strata (Rudolph, 2016).

Over the past 10 years, Siyakhana has provided a range of fresh fruits and vegetables to the under-privileged community of Johannesburg. Some of the fruits and vegetables that are organically grown in the garden include lettuce, celery, green pepper, tomatoes, brinjal, beans, peas, beetroot, broccoli, cabbage and carrots. The ridge and furrow agronomic method is used in Siyakhana. Crops are planted in the furrows and during a rainfall event, surface runoff collected in the furrows drains to a traditional unlined open pond for storage. Potable water is currently used in Siyakhana for irrigation. Potable water is obtained from the local municipality at an excessive price which is considered as the major limiting factor constraining Siyakhana's success (Rudolph, 2016).

Planting practices

Broccoli (*brassica oleracea var. italica*) was chosen for this study because it is considered to be one of the most nutritious vegetables in the world. Broccoli contains a high concentration of iron, magnesium, calcium, vitamin A and C. Broccoli belongs to the *Cruciferae* family, which includes cauliflower, cabbage and kale. The most common cultivar of broccoli forms thick green stalks and a green head with diameter range of 10 to 20 cm (Starke Ayres, 2014).

Broccoli can be grown all year round but grows best in a relatively cool temperature. Optimum growth temperatures range between 15.5 °C to 17 °C. The crop is also resistant to frost and can survive temperatures as low as 0 °C. Broccoli can be grown on almost any soil type but the crop thrives on well-drained, moisture-retentive loamy soils supplied with organic matter. Optimum growth occurs in a soil pH range of 6 to 6.8 (Starke Ayres, 2014).

Broccoli is a heavy feeder of nitrogen, potassium, and phosphorus which has to be added to the soil as fertilizer. Adequate nitrogen supplementation ensures that the leaves are a dark green colour and also prevents shedding of leaves. Phosphorus assists plant root development and a deficiency of the macronutrient can lead to slow growth and delayed maturity. Potassium improves vegetable colour, sugar content, taste and also strengthens plant cells. Nitrogen, phosphorus and potassium should be added as follows (Starke Ayres, 2014):

- Nitrogen: A minimum of 200 kg/ha should be applied as follows:
  - 60 kg/ha should be broadcasted into the soil before transplanting;
  - The remainder should be applied as side dressing at 7, 14, 21 and 28 days after transplantation.
- Phosphorus: A minimum of 50 kg/ha should be broadcasted into the soil before transplanting.
- Potassium: A minimum of 250 kg/ha applied as follows:
  - 125 kg/ha should be broadcasted into the soil before transplanting;
  - The remainder should be applied as side dressing 28 days after transplantation.

Broccoli with a 90 day growing season was used in the field experiments. The broccoli seeds were sowed and raised in seedbeds located in Siyakhana's plant nursery. After sowing, the seed beds were irrigated with 15mm of water once a week for four weeks.

Experimental design and layout

A portion of Siyakhana Food Garden was cordoned off to conduct the field experiments. The total size of the cordoned off area amounted to 43.05 m^2 (10.5m x 4.1m). The field experiments consisted of four experimental groups which was assigned a unique plot within the cordoned off area as illustrated in Figure 3-1. The total area per plot amounted to 5.85 m^2 (4.5m x 1.3m). It was noted that all plots were underlain by a homogenous silt clay loam stratum. The four experimental groups are listed below:

1. In-field RWH (catchment area covered with plastic sheeting)
2. In-field RWH (hand compacted catchment area)
3. Ridge and furrow RWH (hand compacted ridges)
4. Ridge and furrow RWH (ridges covered with plastic sheeting)

Tillage was applied in each planting furrow to increase infiltration. Each planting furrow was also mulched with dried grass to reduce evaporation. Supplemental rainwater irrigation was applied to all the plots to safeguard grain yield.

Stormwater runoff emanating from the higher lying areas was identified as an extraneous variable which had to be controlled during the experiment. This was accomplished by constructing a stormwater cut off drain along the northern, western and eastern flanks of the experimental site. This allowed the drain to collect and convey stormwater to the southern flank of the experimental site where it was discharged. The cut off drain was also lined with plastic to prevent groundwater seepage. Canopy cover from nearby trees was also avoided by ensuring that none of the plots fell underneath any trees.

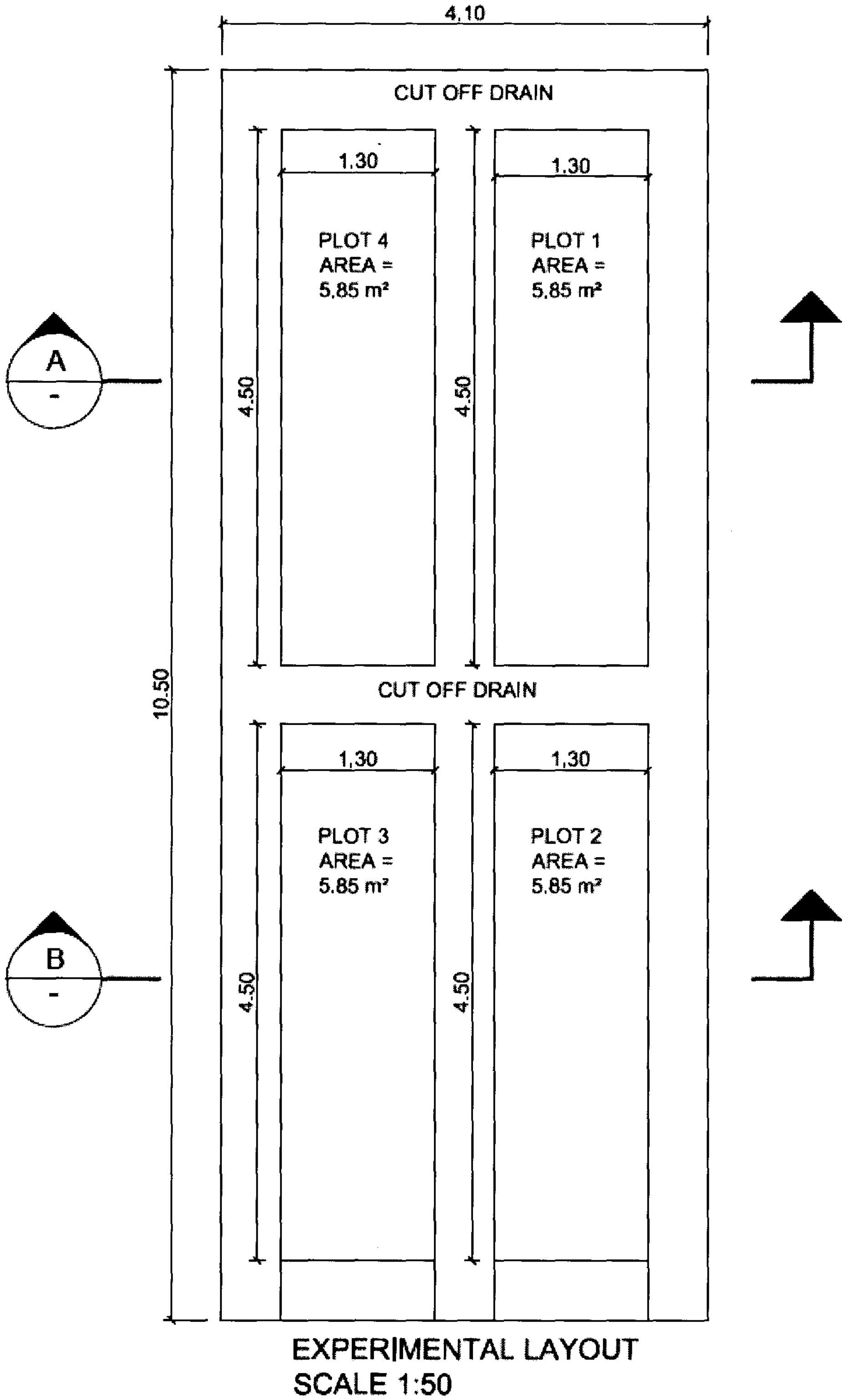
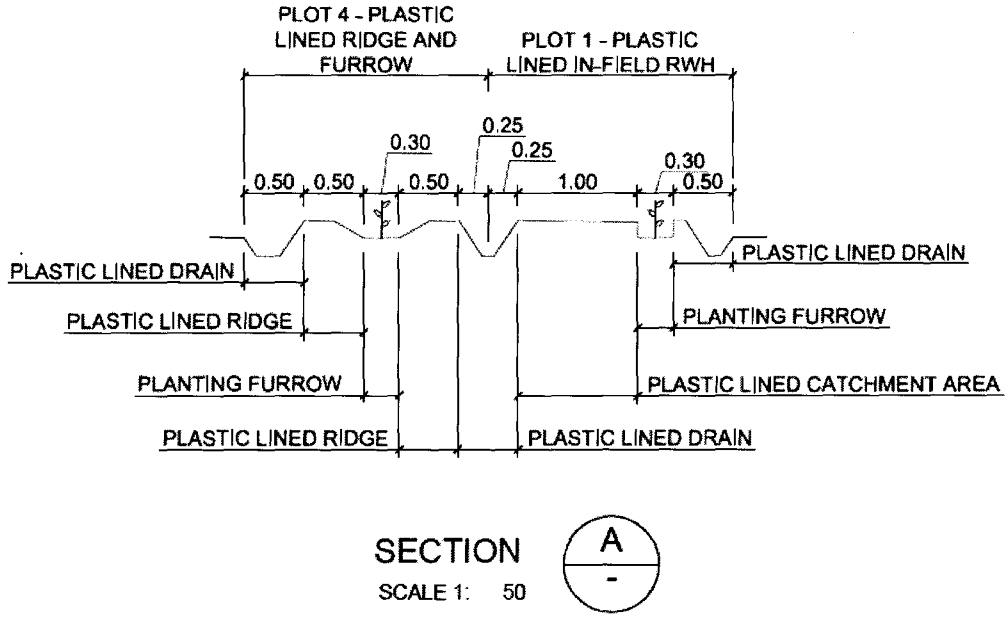


Figure 3-1 - Experimental layout



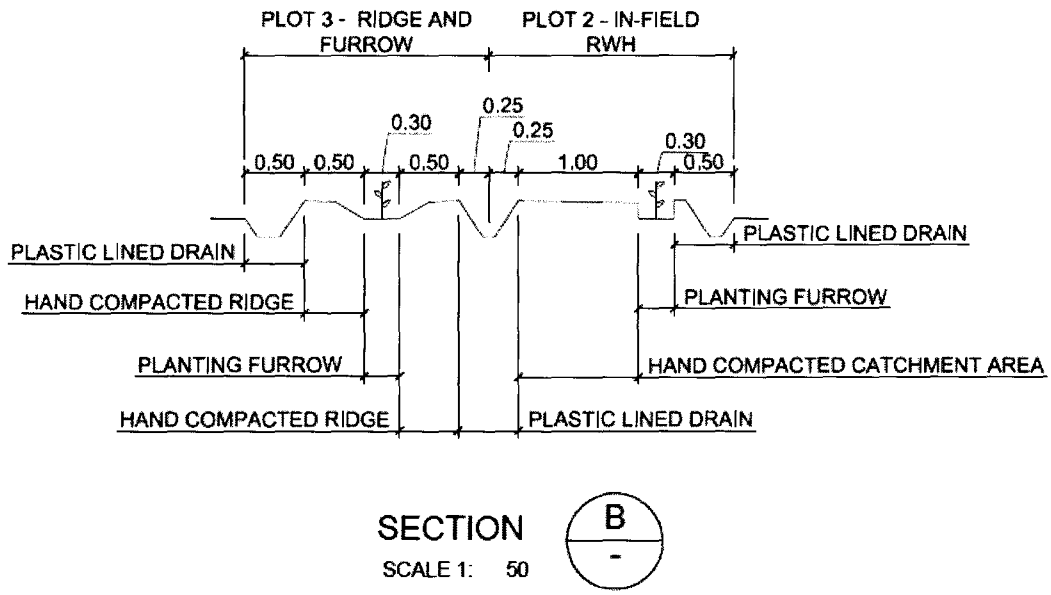


Figure 3-2 - Section A and B – Experimental group layouts

Nitrogen, potassium and a full dose of phosphorus fertilizer were incorporated into the planting furrows, after which four week old broccoli seedlings were hand transplanted followed by light irrigation to ensure seedling establishment. A plant to plant spacing of 40 cm was used which amounted to 10 plants per experimental plot. Nitrogen side dressing was added to the planting furrows in the form of fertilizer in equal splits once every week for four weeks. 28 days after transplantation, potassium side dressing was added to the planting furrows. Manual weeding was conducted during the crop growing cycle to control weeds. KangroShield 100 was sprayed onto the planting furrows to control insects such as thrips and aphids.

Irrigation design and scheduling

The irrigation design was based on the method proposed by Allen, *et al.* (1998) which states that irrigation is only required once the water content in the root zone dropped below the RAW. The step by step procedure is detailed below.

a) Calculate the TAW

$\text{TAW} = (\theta_{FC} - \theta_{WP})Z_R$..from 2-1

For a soil type of Silt clay loam: $\theta_{FC} = 0.37\ \text{m}^3/\text{m}^3$

$\theta_{WP} = 0.24\ \text{m}^3/\text{m}^3$

$Z_R = 550\ \text{mm}$

Therefore $\text{TAW} = (\theta_{FC} - \theta_{WP})Z_R$......................................from 2-1

$= (0.37 - 0.24)550 = 71.5\text{mm}$

b) Calculate the RAW

$\text{RAW} = p(\text{TAW})$...from 2-2

$= 0.45(71.5) = 32.18\text{mm}$

c) Calculate the root zone water content

Water content in the root zone was obtained by measuring the soil water storage using a soil moisture probe and recorded using a data logger. Measurements were taken at three positions: that is at the start, middle and end of the planting furrow, and these were at a depth of 55 cm. The soil water content in the root zone was then obtained using the following formula:

$$D_{r,i} = (\theta_{FC} - \theta_i)Z_R \qquad \text{3-1}$$

Where: θ_{FC} = field capacity (m^3/m^3)

θ_i = moisture content measured at depth x (m^3/m^3)

θ_{WP} = wilting point (m^3/m^3)

Z_R = root zone (mm)

The root zone water content in each plot was monitored every second day with the soil moisture probe. Once the root zone water content dropped below the RAW storage the respective plot was irrigated with 32mm of rainwater obtained from the traditional open unlined pond located onsite.

3.3.3 Data collection methods

The broccolis were harvested and plant samples were collected at the end of the crop growing cycle to investigate the links between the dependent variables (irrigation water applied, yield, biomass and water productivity) and the independent variable (RWH method).

Irrigation water applied

All irrigations were logged during the experiment and summed per site at the end of the experiment.

Yield

Five broccolis were randomly harvested from each experimental plot to measure fresh yield. To remove any dust or sand particles that may have settled on the vegetables, they were washed and hand dried with a cloth. The fresh broccoli weight was obtained by weighing the cleaned vegetables. Once the fresh yield readings were taken, the broccoli samples were then oven dried at 60°C for 48 hours. The dry broccoli weight was obtained by weighing the vegetables at the end of the oven drying process.

Plant biomass

Plant biomass was measured after the broccoli harvest. Five plant samples were collected from each group by cutting the plants at the base of its stem thus separating the roots from the plants. To remove any dirt or dust particles that may have settled on the samples they were thereafter washed and dried with a cloth. The plant biomass readings were obtained by weighing the clean plants. After which the plants were oven dried at 60°C for 48 hours. The weight of the dry matter was obtained by weighing the plants after the oven drying process was completed.

Water productivity

Water productivity is defined as the quantity of products produced per unit of water consumed.

$$WP = {}^{Y}/_{(P + I)} \qquad \text{3-2}$$

Where: $Y = \text{Yield (g)}$

$P = \text{Precipitation (mm)}$

$I = \text{Irrigation (mm)}$

Precipitation can be assumed to have been uniform in all four plot plots because they were all located next to each other, equation 3-2 can therefore be approximated to the following:

$$WP = {}^{Y}/_{I} \qquad (3\text{-}3)$$

In this study water productivity will be measured in two instances that is, in terms of yield and biomass. Water productivity in terms of yield was calculated as the ratio of the oven dried broccoli weight and net irrigated water applied over the growing season. Water productivity in terms of biomass was calculated as the ratio of the oven dried biomass weight and net irrigated water applied per experimental plot.

3.3.4 Research programme and execution plan

This study was based on a highly structured methodology to enhance its credibility and reliability therefore a detailed research programme and execution plan was developed which is listed on Table 3-1.

Table 3-1 - Research programme and execution plan

Date	Description
Monday, Week 1	Prepare seedbeds with fertilizer
Monday, Week 1	Sow seedlings
Monday, Week 1 to Monday, Week 4	Irrigate seedlings with 15mm of rainwater
Monday, Week 4	Construct the experimental plots as per Figure 4 and 5
	Fertilize the planting furrows (N = 60 kg/ha, K = 125 kg/ha , P = 50 kg/ha)
Tuesday, Week 4	Transplant the seedlings into the experimental plots.

Date	Description
	Irrigate with 15mm of water to ensure seedling establishment
Thursday, Week 4	Take soil moisture content readings as indicated in the research design
	Compute RAW (equation 2.1 and 2.2) and moisture content in the root zone (equation 3.1)
	If Dr < RAW then irrigate with 32mm of rainwater
Monday, Wednesday, Friday, Weeks 5 - 12	Take soil moisture content readings as indicated in the research design
	Compute RAW (equation 2.1 and 2.2) and moisture content in the root zone (equation 3.1)
	If Dr < RAW then irrigate with 32mm of rainwater
Monday, Week 13	Harvest broccoli heads and plants from the experimental plots
	Oven dry broccoli heads for 48 hours
	Oven dry broccoli plants for 48 hours
Wednesday, Week 13	Weigh and record oven dried broccoli weight
	Weigh and record oven dried broccoli plant mass

3.4 Research integrity

This study has been written in conjunction with the University of Witwatersrand academic integrity guidelines which, in broad terms, state that no student may act dishonestly to improve one's grade. Academic dishonesty includes cheating and plagiarism (Roosevelt University, n.d). The integrity of this study was ensured by simply avoiding the temptation to copy and paste another's work. Instead academic material was paraphrased and citations were included to give credit to the original author. The integrity of this study was further enhanced with the inclusion of a full reference list.

Another principle that is of utmost importance is maintenance of the author's objectivity because it is directly related to this study's credibility and validity. In addition, lack of objectivity will distort the conclusions drawn by the study and any associated recommendations (Saunders, et al., 2009). Recorded data were verified by Siyakhana's staff members to ensure that the data was recorded accurately. Data fabrication, subjective and selective data recordings were also avoided.

3.5 Summary

This study followed a structured research methodology which encapsulated two unique tasks. The first research task was based on a desktop study. The search strategy, inclusion criteria, data recording procedures and the basis of all conclusions were clearly indicated. The second research task was based on an experimental procedure. An in-depth description of the field experiment, irrigation design, data collection methods and the research program were provided to the reader.

CHAPTER FOUR: RESULTS AND DISCUSSION

In this chapter, the reader will be presented with the results of research tasks 1 and 2 which addressed specific objectives 1 and 2, respectively. Further, all results were analysed and explained in the discussion part of this chapter. The results and discussion are presented in the sections that follow.

4.1 Results: Objective 1 - Evaluation of the possible sources of water for UA

In many cases, access to fit-for-purpose water for irrigation is the limiting factor that determines the sustainability of UA. The literature review identified various sources of water such as wastewater, greywater, and rainwater which could form the basis of fit-for-purpose irrigation water. The viability of the same sources is determined by their impact on the receiving environment and the risks they pose to public health.

4.1.1 Wastewater

Over the past decade, there has been an increase in the volume of wastewater generated which can be attributed to the rising domestic water consumption. Approximately 80% of the domestic water supply is converted into wastewater (Kurian, et al., 2013). Wastewater can therefore be considered as a reliable source of nutrient-rich water which makes it an attractive source of water for UA (WHO, 2006; Elgallal, *et al.*, 2016).

Wastewater irrigation may cause negative impacts on the soil properties, groundwater and surface water quality, crop yields and also pose a threat to public health (WHO, 2006; Belhaj, *et al.*, 2016; Elgallal, *et al.*, 2016). Depending on the source and treatment of wastewater, it could contain excessive levels of pollutants such as salts, heavy metals, organic material and nutrients which are discussed below. The severity of the negative impacts will depend on the concentration and solubility of the pollutants. Additional important factors are the frequency of wastewater irrigation, the type of crops being grown, in-situ soil properties and climatic conditions (Belhaj, et al., 2016).

Excessive levels of salt

Untreated wastewater generally contains higher concentrations of total dissolved solids and soluble salts than freshwater. Wastewater treatment processes are unable to remove 100% of the excess sodium and salt (Bahri, 1998). Therefore, wastewater irrigation might promote soil sodification (an increase of sodium ions) and/or soil salinization (an increase in the concentration of soluble salts) which in turn can increase the soil's electrical conductivity. Excessive soil salinity creates oxidative and hyperosmotic stress which inhibits plant growth and productivity (Ngara, *et al.*, 2012; Levy & Tai, 2013). Soil sodification negatively affects the soil structure by increasing soil compaction and reducing soil permeability (Castro, et al., 2015).

Irrigation with untreated wastewater can increase salt content by over 337.5% when compared to freshwater water irrigation. Similarly, partially and treated wastewater irrigation can increase salt content by 225% and 175%, respectively, when compared to fresh water irrigation (Kiziloglu, et al., 2008).

Soil pH and Heavy metals

Soil pH influences the availability of nutrients and mobility of heavy metals for plant uptake. In general, heavy metals are more available for plant uptake from acidic soils than from neutral or alkaline soils (WHO, 2006). The pH of the applied wastewater affects soil pH levels. Irrigation with a low pH wastewater could decrease soil pH and consequently increase the mobility of heavy metals which would then become available for plant uptake (Xu, et al., 2013).

Wastewater may contain trace concentrations of heavy metals such as iron (Fe), nickel (Ni), cadmium (Cd), copper (Cu), manganese (Mn), and lead (Pb) (Belhaj, et al., 2016). It has been found that irrigation with untreated wastewater increased Fe content by 100%, Ni content by 380%, Cd content by 160%, Cu content by 70%, Mn content by 24% and Pb content by 160% when compared to freshwater irrigation (Kiziloglu, et al., 2008).

Plant uptake of heavy metals may damage their roots which in-turn inhibits their ability to uptake nutrients, therefore inhibiting normal plant growth. Heavy metals accumulation rate in plants depends on the plant species (Elgallal, et al., 2016). In general, leafy vegetables accumulate high amounts of Cd, Ni, and Pb because of their large leaf area, fast growth rates, and high transpiration rates (Belhaj, et al., 2016). Consumption of crops that have high levels of Cd and Pb poses significant public health risks (Elgallal, et al., 2016).

Organic matter

Wastewater contains a high concentration of organic matter. Organic matter acts as a reservoir for the essential macronutrients (nitrogen (N), phosphorus (P), and potassium (K)) that is required for plant growth. Application of untreated wastewater irrigation can potentially have a 4-fold increase in N content, a 10-fold increase in P content and an 8-fold increase in K content. An increase in soil organic matter content can also enhance soil structure, increase soil moisture content, reduce the mobility of heavy metals, increase soil fertility and reduce the use of fertilizers. However, an oversupply of organic matter can lead to excessive vegetative growth, create anaerobic conditions in the plant root zone, and have a negative impact on soil porosity (Castro, *et al.*, 2015; Elgallal, *et al.*, 2016).

Public health risks

Wastewater often contains a wide range of contaminants such as skin irritants, excreta-related pathogens and toxic chemicals. Contaminants accumulate in plants by first plant uptake through the roots and then retention on the surface. These contaminants pose a severe threat to public health. Exposure to these contaminants can lead to bacterial, viral, and protozoan diseases such as shigellosis, salmonellosis, cholera, amoebiasis, giardiasis, hepatitis A, viral enteritis, and other diarrheal diseases (WHO, 2006; Dickin, *et al.*, 2016).

Summary

Wastewater's reliability and high macronutrient content make it an attractive source of fit-for-purpose irrigation water for UA. However, low rainfall and high evaporation rates that are prevalent in South Africa will promote excessive salt accumulation in soils when wastewater is used for irrigation. Therefore, the critical environmental issue with regards to wastewater irrigation would be soil salinity and sodicity. Accumulation of salts causes soil salinity and/or sodification which contribute to soil infertility and crop yield reductions. Oversupply of macronutrients is also an important issue, which could lead to groundwater pollution and crop yield reductions. Long-term accumulation of heavy metals pose a further environmental concern, which could lead to soil and crop degradation and can cause public health risks through consumption of agricultural products.

4.1.2 Greywater

Greywater discharge amounts to 52% of potable water consumption and is therefore another potential source of irrigation water which could be continuously exploited for UA. Greywater potentially can provide the macronutrients (nitrogen and phosphorus) required for plant growth thus alleviating the need for fertilizers. Also, greywater has pest repellent properties due to its soapy nature (Pinto, *et al.*, 2010; Rodda, *et al.*, 2011).

Greywater may negatively affect soil pH and may also contain excessive levels of pollutants such soluble salts and nutrients (Pinto, *et al.*, 2010; Rodda, *et al.*, 2011; Albalawneh, *et al.*, 2016). The sustainability of greywater irrigation is based on the receiving soil's ability to absorb the aforementioned pollutants without causing degradation. An additional factor affecting the sustainability of greywater irrigation is public health risks associated with consumption of agricultural produce irrigated with greywater. All of these factors are discussed below.

Soil pH

Soil pH ranging between 6 and 7.5 is considered to be the optimal range for plant growth and to sustain the microbial health of the soil. Soil pH is directly related to the pH of the applied greywater. Greywater pH is influenced by its source. Greywater sourced from laundry effluent has a pH range between 8.0 and 10.0. Greywater extracted from other domestic sources has a pH range between 5.0 and 8.7. Depending on the greywater source, long term greywater irrigation could lead to an increased soil alkalinity (Pinto, *et al.*, 2010; Rodda, *et al.*, 2011).

Excessive salt levels

Greywater may contain high concentrations of substances which can negatively affect soil characteristics and crop growth. These substances include salts, sodium and boron. Excessive levels of salts and sodium will lead to soil salinization, soil sodicity and an increase in soil electrical conductivity. The concentrations of the aforementioned substances are determined by the greywater quality which is site specific. The volume of laundry effluent and detergents present in the greywater largely influence soil salt levels (Rodda, *et al.*, 2011; Albalawneh, *et al.*, 2016).

Nutrients

Phosphorus, nitrogen, and potassium are essential macronutrients that are required for plant growth and are usually added to the soil as fertilizer. Greywater irrigation could increase the aforementioned soil macronutrient content (Pinto, *et al.*, 2010; Rodda, *et al.*, 2011; Albalawneh, *et al.*, 2016). However, Pinto *et al.* found no increases in the concentration of the aforementioned macronutrients while conducting their glasshouse experiments. Pinto *et al.* reported that their results could be attributed to the volume of laundry effluent in the greywater used in their experiments. They concluded that laundry water and degetergents can negatively affect the concentration of nitrogen and phosporus that has accumulated in the greywater.

Public health risks

Brown and yellow waters are excluded from greywater however it does contain trace amounts of faeces and urine (from hand washing after use of the toilet). Greywater also contains dirt, and micro-organisms from skin surfaces. Storage of greywater creates an environment in which micro-organisms can survive and multiply (WHO, 2006). Greywater may therefore contain relatively high numbers of micro-organisms. Some of these micro-organisms can cause diseases to those who come into contact with greywater or those who consume greywater irrigated agricultural products (WHO, 2006; Rodda, *et al.*, 2011).

Summary

Greywater's reliability and high macronutrient content make it an attractive source of fit-for-purpose irrigation water for UA. Greywater's high macronutrient content has been reported to increase and secure crop yields (Pinto, *et al.*, 2010; Albalawneh, *et al.*, 2016). However low and unpredictable rainfall patterns combined with extended periods of drought that are prevalent in South Africa will promote excessive salt accumulation in soils when greywater is used for irrigation.

4.1.3 Rainwater

Rainwater has been the primary source of water for agriculture since the beginning of time. Rainwater is referred to as white water because it is said to be a source of biologically and chemically low risk water, however it does contain trace concentrations of pollutants (Gwenzi, et al., 2015).

The atmosphere may become polluted with dust particles, heavy metals, nitrates and sulphates. The same pollutants are captured by rainwater droplets and transferred to the soil via the process of wet deposition (Amodio, et al., 2014). The presence of the aforementioned pollutants in the atmosphere is spatially and temporally variable which is influenced by human activities and meteorological factors. These factors include temperature, humidity, and wind velocity (Sánchez, et al., 2015). The sustainability of rainwater irrigation is based on the receiving soil's ability to absorb the aforementioned pollutants without causing degradation. Additional factors affecting the sustainability of rainwater irrigation are rainwater pH, concentration of heavy metals and nutrients, and public health risks which are discussed below.

Rainwater pH

Rainwater pH is spatially variable and is influenced by human activities. Rainwater pH in urban areas ranges from 4.5 to 10.4 which is influenced by traffic emissions and the degree of industrial activities present (Sánchez, et al., 2015). Rainwater pH is also influenced by its standing time in storage tanks. Sánchez *et al.* (2015) reported an increase in rainwater pH that is allowed to stand in storage tanks.

Heavy metals

Heavy metal contamination occurs when rainwater comes into contact with urban surfaces. Urban surfaces may become polluted with trace metal compounds via the process of dry deposition. During a rainfall event, the same compounds are released into the stormwater runoff causing pollution. This process is commonly referred to as washout of urban surfaces. Washout of urban surfaces can occur within seconds or minutes which is dependent on the solubility of the heavy metal compound and rainwater pH (Chester, *et al.*, 1997; Sánchez, *et al.*, 2015).

Nutrients

Plant macronutrients (nitrogen and phosphorus) are added to the atmosphere by human activities. During a rainfall event, these pollutants are 'washed' out of the atmosphere and transferred to the soil by precipitation. This process is referred to as wet deposition. Additionally, nitrogen and phosphorus is added to runoff during a rainfall event by natural sources such as bird faeces (Sánchez, et al., 2015). Duncan (1995) reported that the typical nitrogen concentration (varies between 1.0

to 2.0 mg/L) and phosphorus concentration (varies between 1.0 to 2.0 mg/L) of urban rainfall exceeds the minimum threshold for algal blooms during storage

Public health risks

Faecal and microbial contamination of runoff occurs during a rainfall event. The process of contamination occurs when surface rainwater runoff comes into contact with bird and animal faeces. Consumption of agricultural products irrigated with contaminated rainwater can lead to gastrointestinal illnesses, nausea, vomiting and diarrhoea (Gwenzi, et al., 2015). Additionally, rainwater harvesting tanks are excellent sites for the dengue virus and mosquito breeding (WHO, 1997).

Summary

Rainwater is referred to as white water because it is said to be a biologically and chemically low risk water, however it does contain trace concentrations of pollutants such as dust particles, heavy metals, nitrates and sulphates (Gwenzi, et al., 2015). Most of the aforementioned pollutants are released into the atmosphere by human activities. During a rainfall event, these pollutants are washed out of the atmosphere and transferred to the soil by precipitation. Additionally, pollutants are transferred from urban surfaces to runoff during a rainfall event. Although there are trace elements of pollutants and pathogens present in rainwater, the study of Mavimbela & van Rensburg (2012) reported a 32% increase in maize grain yield using rainwater harvesting techniques.

4.2 Discussion: Objective 1 - Selection of fit-for-purpose irrigation water

This review investigated three sources of irrigation water namely wastewater, greywater, and rainwater. Wastewater and greywater irrigation can promote soil salinization, soil sodicity, and groundwater pollution. In addition, consumption of agricultural produce that is irrigated with wastewater or greywater can cause severe public health risks. Rainwater offers various advantages such as a lower salinity, sodicity and heavy metals concentration over wastewater and greywater. In conclusion rainwater has been identified as a suitable fit-for-purpose source of irrigation water for UA.

4.3 Results: Objective 2 - Evaluation of methods which increase the productivity of water in UA

As alluded in Chapter 3, four RWH methods were tested to identify the most productive method. Four plots were constructed in accordance with Section 3.3.2 and as listed below.

- Plot 1: RWH method 1
  : In-field RWH (catchment area covered with plastic sheeting)
- Plot 2: RWH method 2
  : In-field RWH (hand compacted catchment area)
- Plot 3: RWH method 3
  : Ridge and furrow RWH (hand compacted ridges)
- Plot 4: RWH method 4
  : Ridge and furrow RWH (ridges covered with plastic sheeting)

A total of 10, four week old, broccoli seedlings were transplanted into the each plot. This amounted to a plant to plant spacing of 40cm. The following sections describe the data recorded during the experiment.

4.3.1 Irrigation water applied

The methodology proposed in Section 3.3.2 was used to determine when to irrigate each plot and the volume of water to be applied. Prior to transplantation the field was saturated to ensure that each plot was at field capacity. The soil moisture content was recorded and the corresponding root zone water content was then calculated. It was assumed that any soil moisture above the field capacity level was lost to deep percolation during the course of the day. Irrigation was applied only once the root zone water content dropped below the readily available water content. The depth of water applied equalled the difference between the Field Capacity and the Root Zone Water Content. As per the field water balance, all water losses (root zone water depletion) were noted as negative and all water additions (irrigation and precipitation) were noted as positive values. The soil moisture content readings, root zone water content and irrigation recordings are provided in Appendix A. The root zone water content in each plot is illustrated in Figures 4-1, 4-2, 4-3 and 4-4 and is later discussed. In addition, the total irrigation water applied in each plot is illustrated on Figure 4-5.

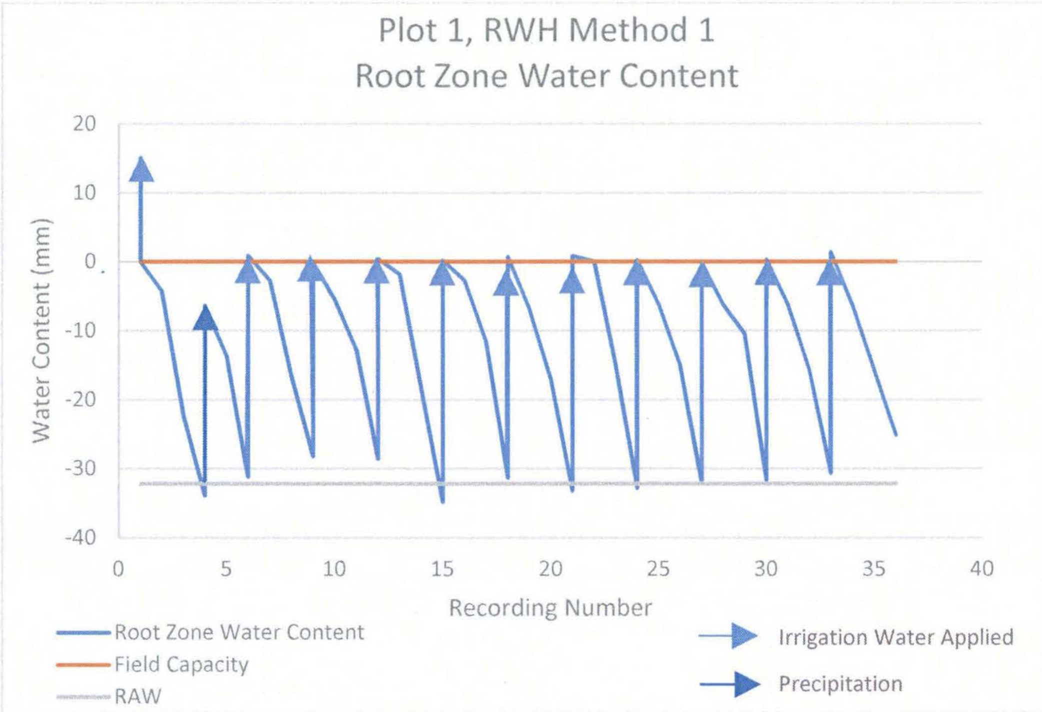


Figure 4-1 - Plot one root zone water content

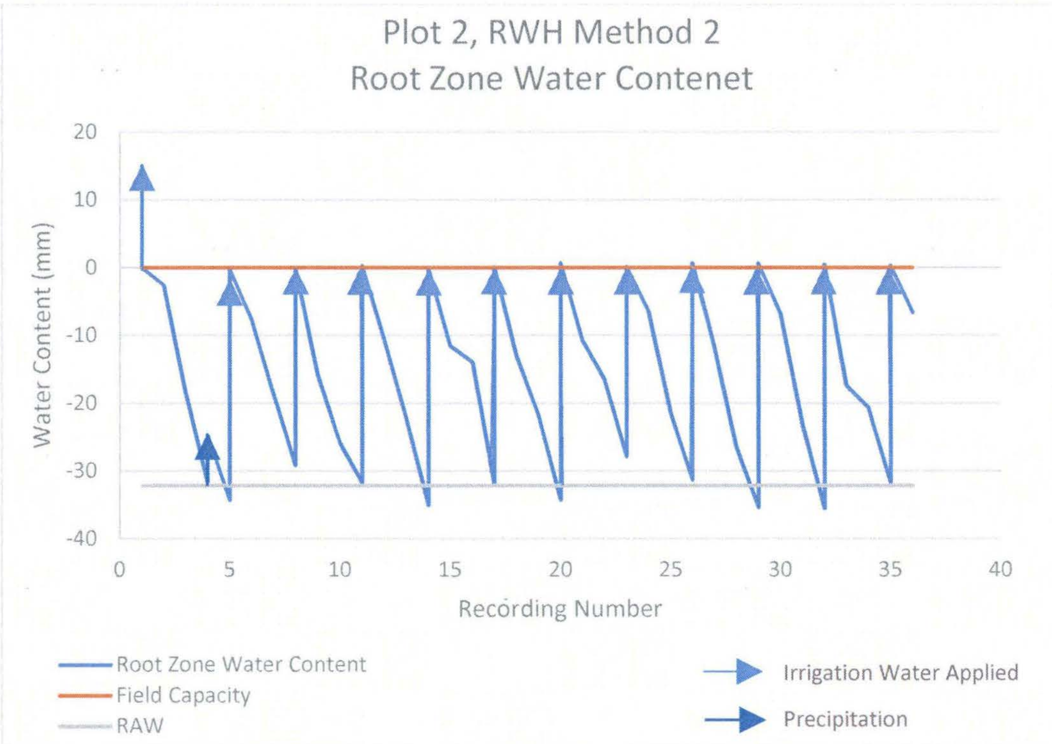


Figure 4-2 - Plot two root zone water content

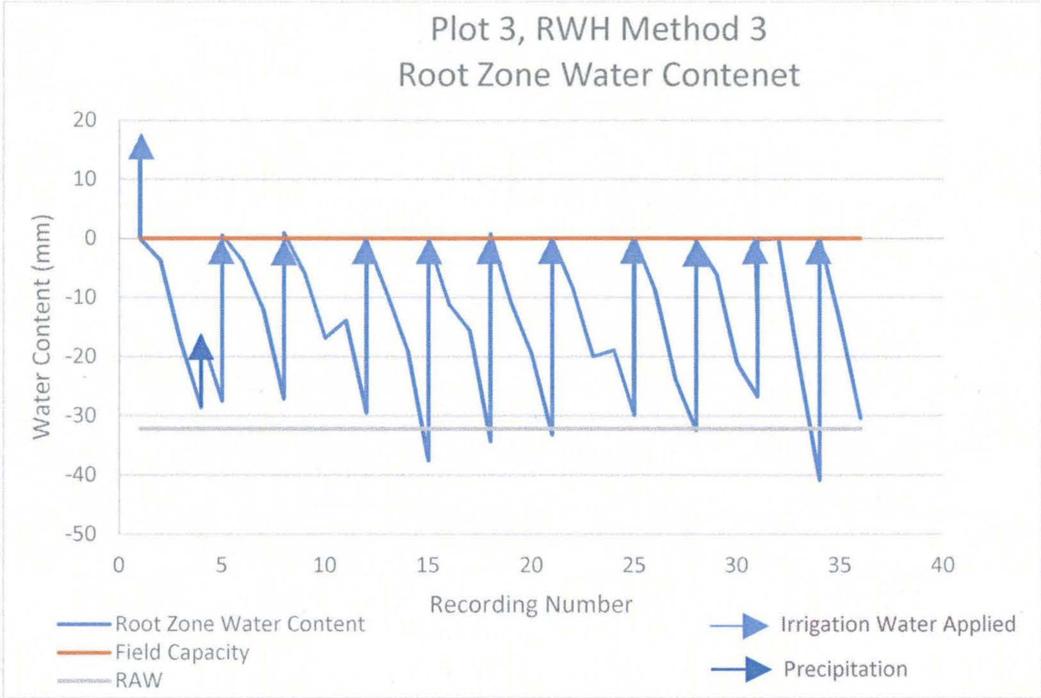


Figure 4-3 - Plot three root zone water content

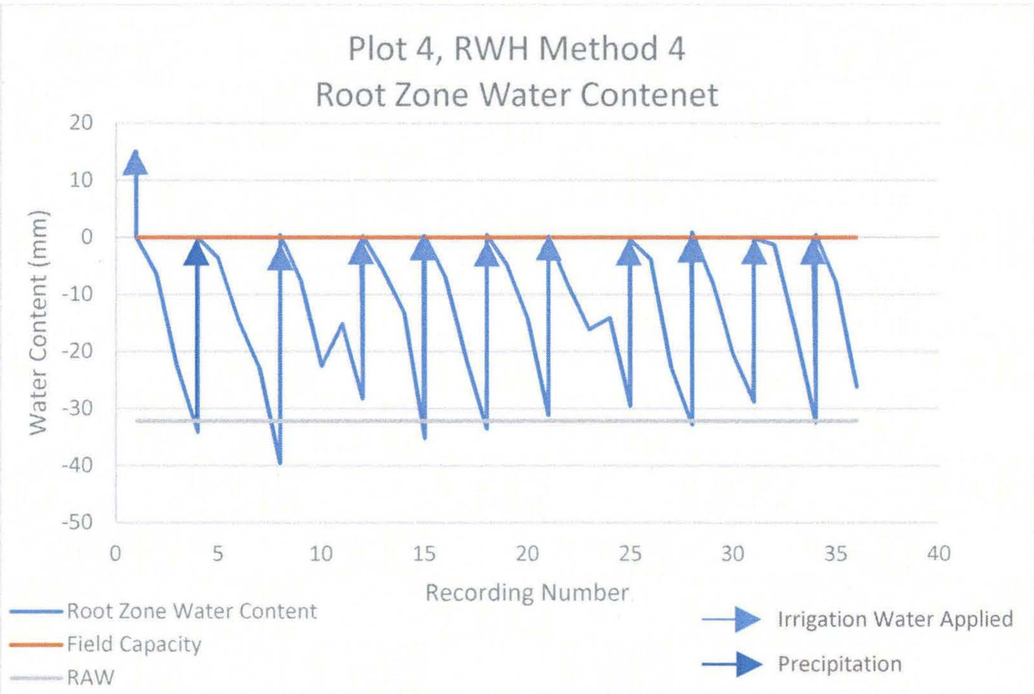


Figure 4-4 - Plot four root zone water content

As illustrated in Figure 4-1 to Figure 4-4, during week 2 (recordings 4 to 5), the experimental site experienced a light rainfall event after which no irrigation was required in plots 1 and 4 because they harvested 27.5 mm and 34.1 mm of water, respectively. It was also noted that during the same rainfall event, irrigation was still required in plots 2 and 3 which only harvested 7 mm and 12 mm of water, respectively. In addition, a gradual increase in the root zone water content was noted in plots 1 and 4, between the recordings of 10 to 11 and 23 to 24. This is noteworthy because no irrigation was applied between the same recordings hence it was presumed that the gradual increase in root zone water content can be attributed to harvesting of dew.

The amount of water harvested by each RWH method was influenced by the degree of permeability and the slope of its catchment area/ridges. It was found that steep slopes and impermeable catchment areas reduced infiltration and thus generated more runoff than shallow slopes and permeable catchment areas. The total irrigation water applied in each plot over the growing season is presented in Figure 4-5 on the following page.

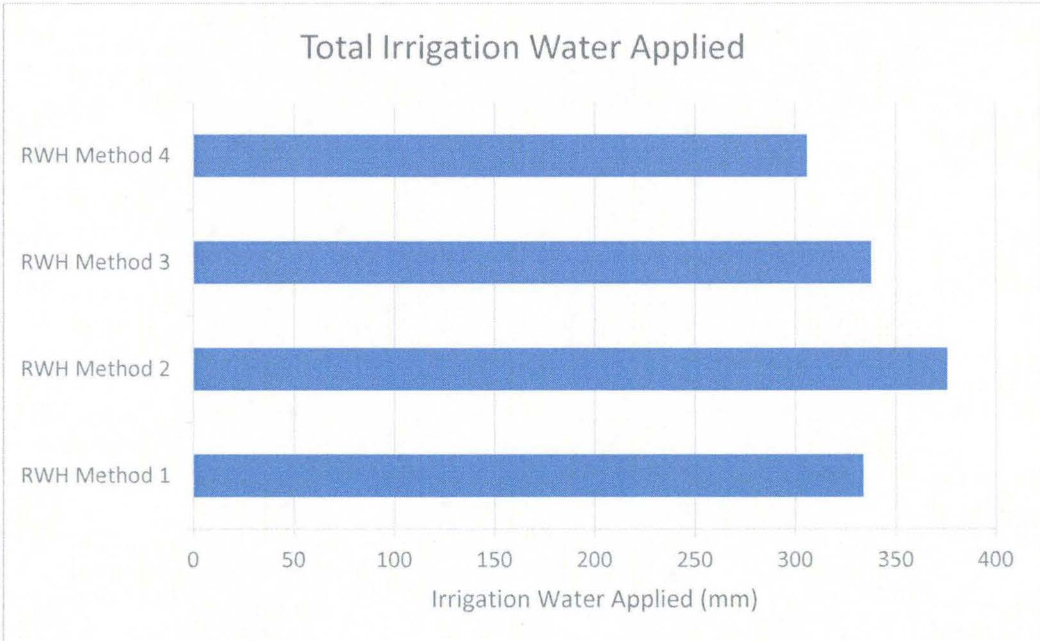


Figure 4-5 - Total irrigation water applied

From Figure 4-5, RWH method 4 used the least amount of irrigation water which required 306 mm, followed by RWH method 1, then 3 and finally 2 which respectively used 328 mm, 338 mm and 376 mm of irrigation water. The different amounts of irrigation water used by these four RWH techniques were influenced by how much of water was harvested by each method, how much of the harvested water was utilized for transpiration and how much was lost through infiltration, deep percolation and evaporation from the soil which is discussed below.

The amount of rainwater harvested for plant growth and consequently the amount of irrigation water was influenced by the surface infiltration and the surface slope of each RWH method. It was found that RWH method 4 which had the least infiltration and had the highest surface slope, generated the most runoff followed by methods 1, then 3 and finally 2. The amount of harvested water lost to evaporation from the soil and deep percolation was assumed to be uniform for all four methods because the site had a uniform soil matrix and no standing water was observed throughout the experiment.

4.3.2 Fresh yield

As alluded in Chapter 3, five plants were randomly selected from each RWH plot for the data recording process. The broccolis were harvested from the selected plants and weighed to measure the fresh yield. The weight of each sample is presented in Appendix B and Figure 4-6 below.

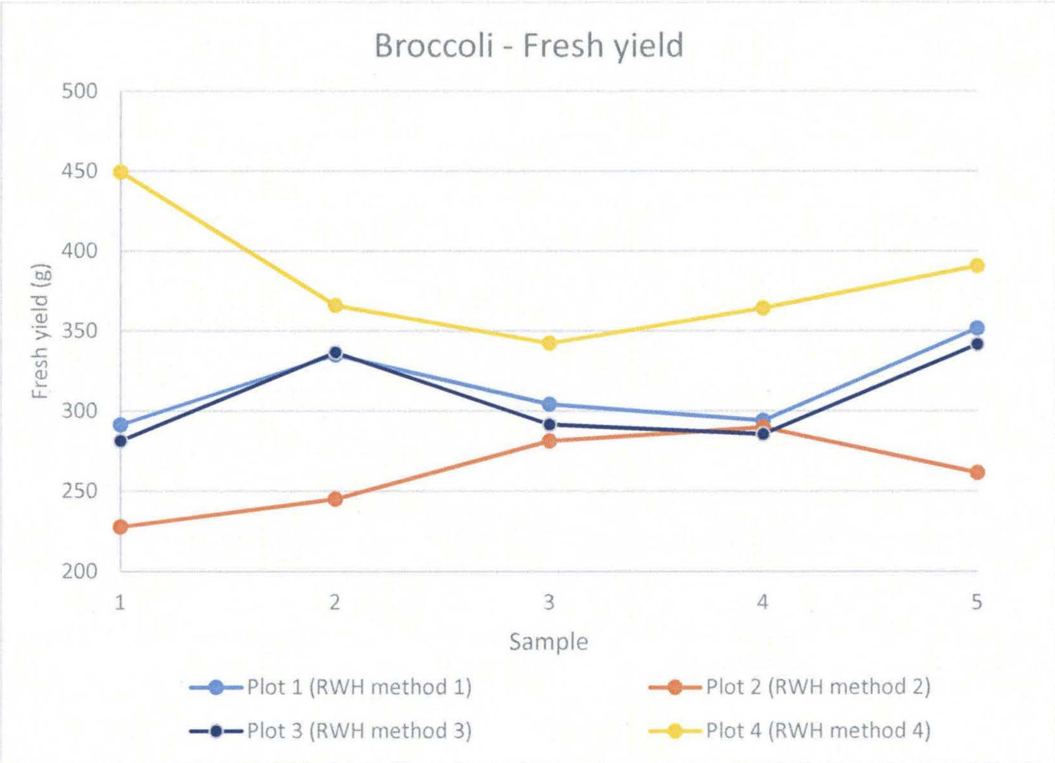


Figure 4-6 - Broccoli fresh yield

The weight of the 5 broccoli samples (as illustrated in Figure 4-6) obtained from plot 1 (RWH method 1) ranged between 291.41 g and 351.63 g, from plot 2 (RWH method 2) varied by 227.74 g to 289.85 g, from plot 3 (RWH method 3) ranged between 281.41 g and 341.56 g and from plot 4 (RWH method 4) varied by 342.31 g to 449.36 g. In addition, the average weight of the broccoli samples per RWH method is presented in Figure 4-7 below.

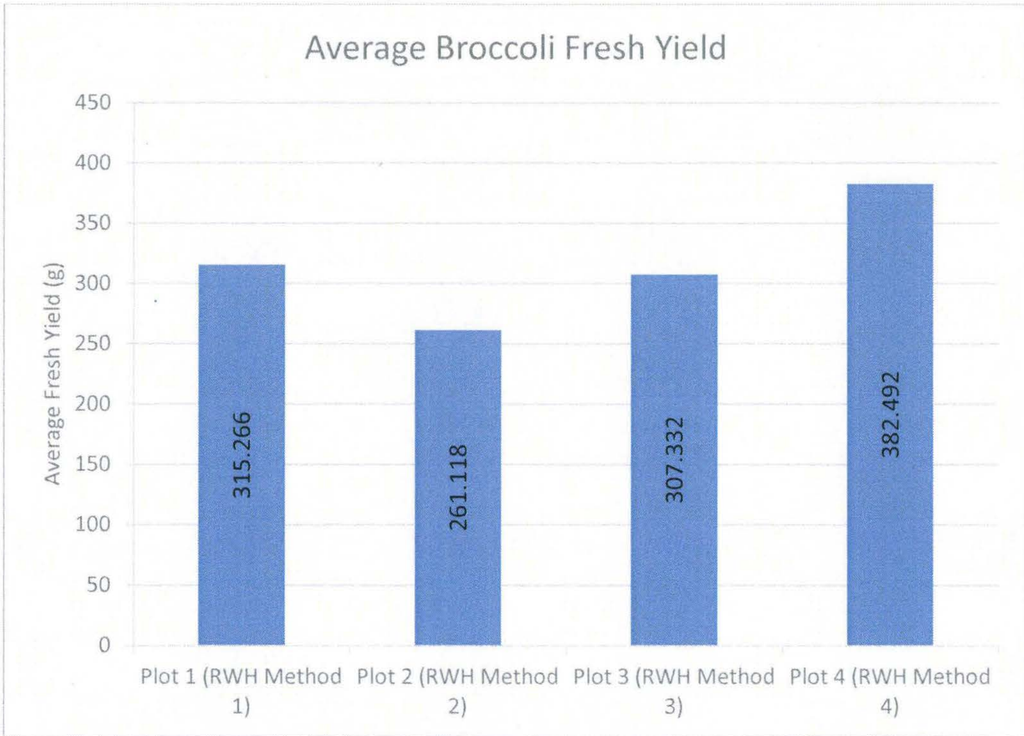


Figure 4-7 - Average broccoli fresh yield per RWH method

As illustrated in Figure 4-7, RWH method 4 produced the highest average fresh yield of 382.49 g. Falling 17.58 % below RWH method 4, is RWH method 1 with an average yield of 315.27 g, followed closely by RWH method 3 with 307.33 g. RWH method 2, with 261.11 g, performed poorly falling 31.73% behind RWH method 4.

4.3.3 Dry yield

As alluded in Chapter 3, the broccolis were oven dried after the fresh yield readings were taken. The dried weight of each sample is presented in Appendix B and Figure 4-8. Oven dried samples obtained from RWH method 4 had the highest dry weight which ranged from 53.11 g to 89.18 g with an average of 73.38 g. Followed by RWH method 1, then closely by RWH method 3 whose oven dried samples had an average dry weight of 67.97 g and 63.54 g, respectively. Oven dried samples obtained from RWH method 2 had the lowest dry weight which ranged from 40.91 g and 74.38 g with an average of 57.16 g.

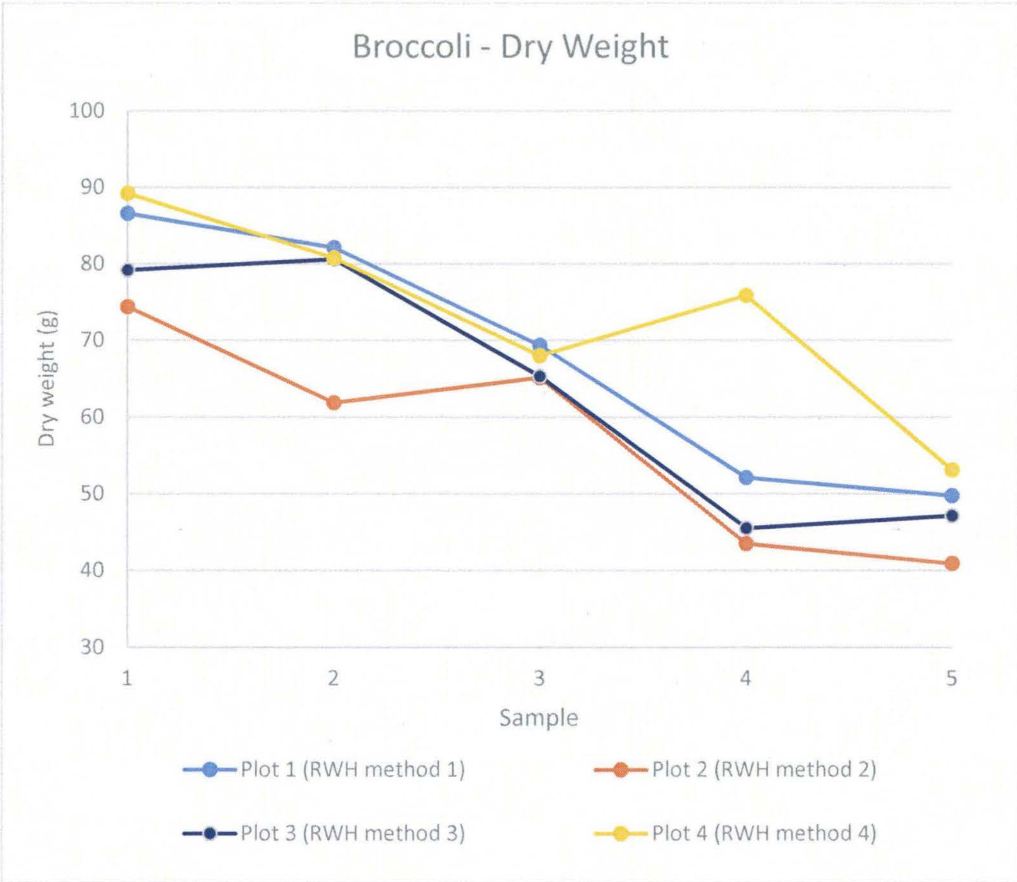


Figure 4-8 - Broccoli dry yield

4.3.4 Plant biomass

As alluded in Chapter 3, the five randomly selected plants were cut at the base of their stems. Thereafter to measure the biomass, the plants (stems and leaves), were washed and weighed. The wet weight of each sample is presented in Appendix B and Figure 4-9.

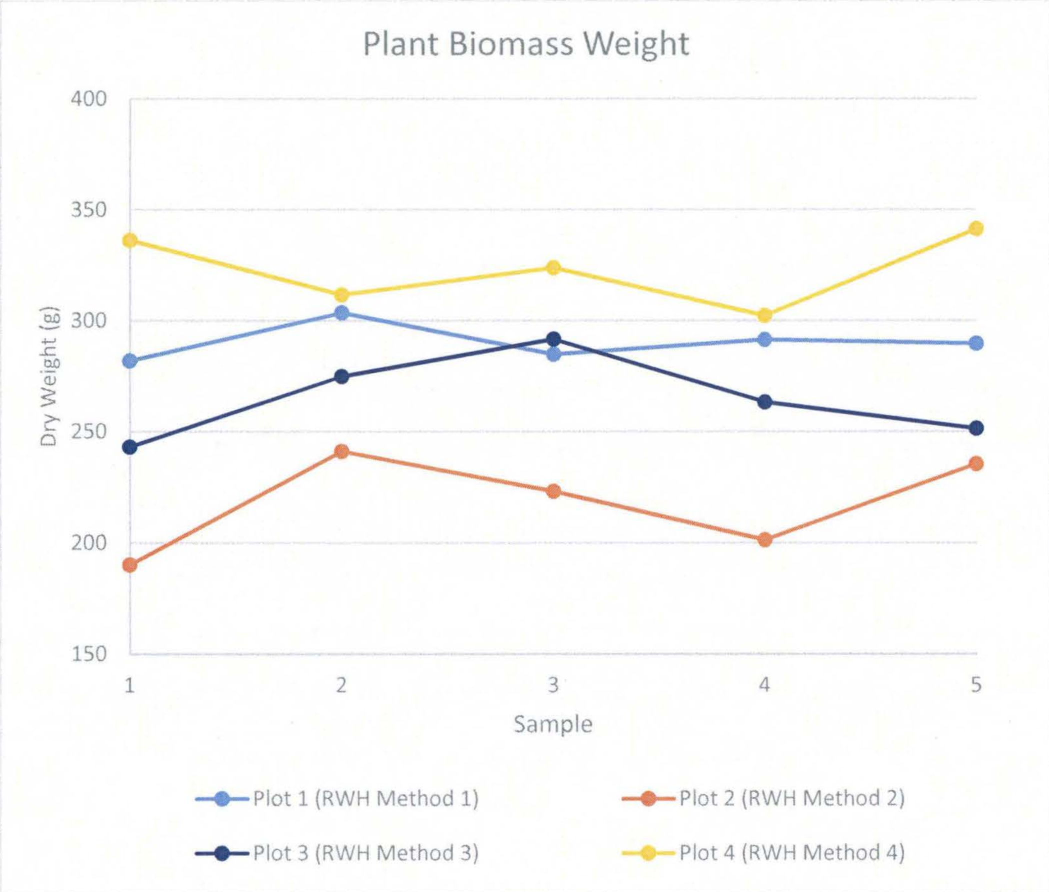


Figure 4-9 - Plant biomass

From Figure 4-9, the weight of the five plant biomass samples attained from plot 1 ranged between 284.85 g and 291.31 g, from plot 2 varied by 190.16 g to 271.56 g, from plot 3 ranged between 243.16 g and 291.56 g and from plot 4 varied by 302.15 g to 341.16 g. In addition, the average sample weight obtained from each plot is presented in Figure 4-10 on the following page.

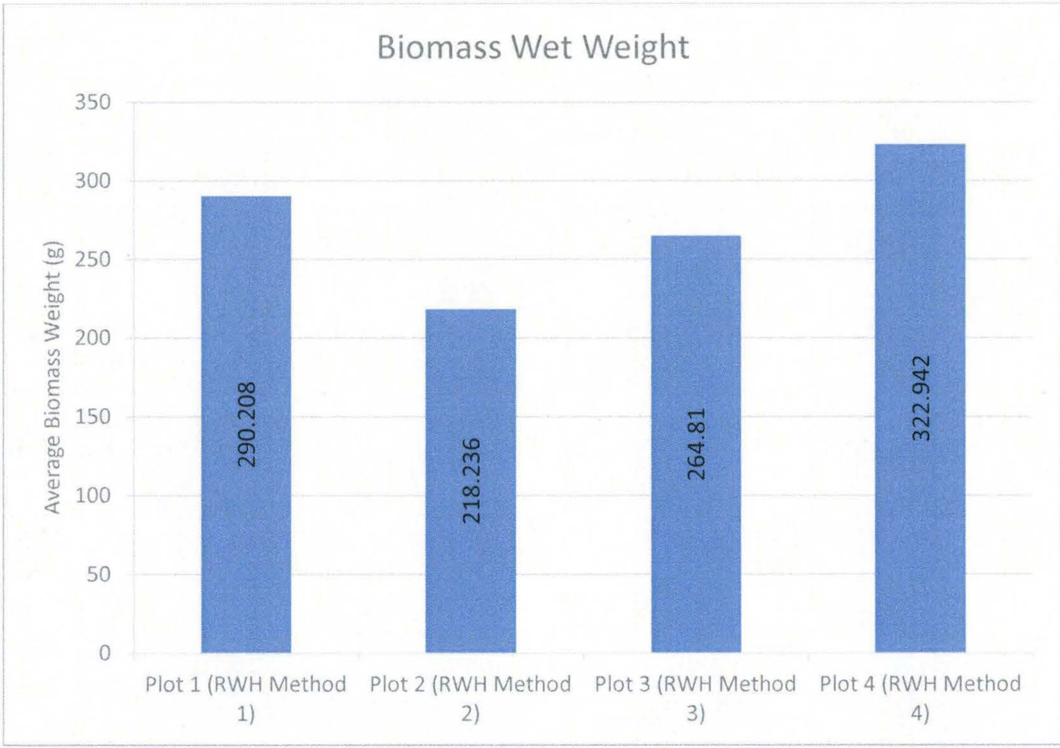


Figure 4-10 - Average plant biomass weight per RWH method

From Figure 4-10, RWH method 4 produced the highest average plant biomass of 308.82 g, followed by RWH method 1, then by RWH method 3 and finally by RWH method 2 which produced respectively 32.73 g, 58.13g and 104.71 g less plant biomass than RWH method 4.

4.3.5 Dry plant biomass

As alluded in Chapter 3, the plants were oven dried after the 'wet' biomass readings were taken. The dry weight of each sample is presented in Appendix B and Figure 4-11. Oven dried samples obtained from RWH method 4 had the highest dry weight which ranged from 84.43 g to 120.15g with an average of 104.51 g. Followed by RWH method 1, then by RWH method 3 whose dried sample weight averaged at 76.83 g and 64.278 g, respectively. Oven dried samples obtained from RWH method 1 had the lowest dry weight which ranged from 25.13 g to 63.51 g with a mean of 55.706 g.

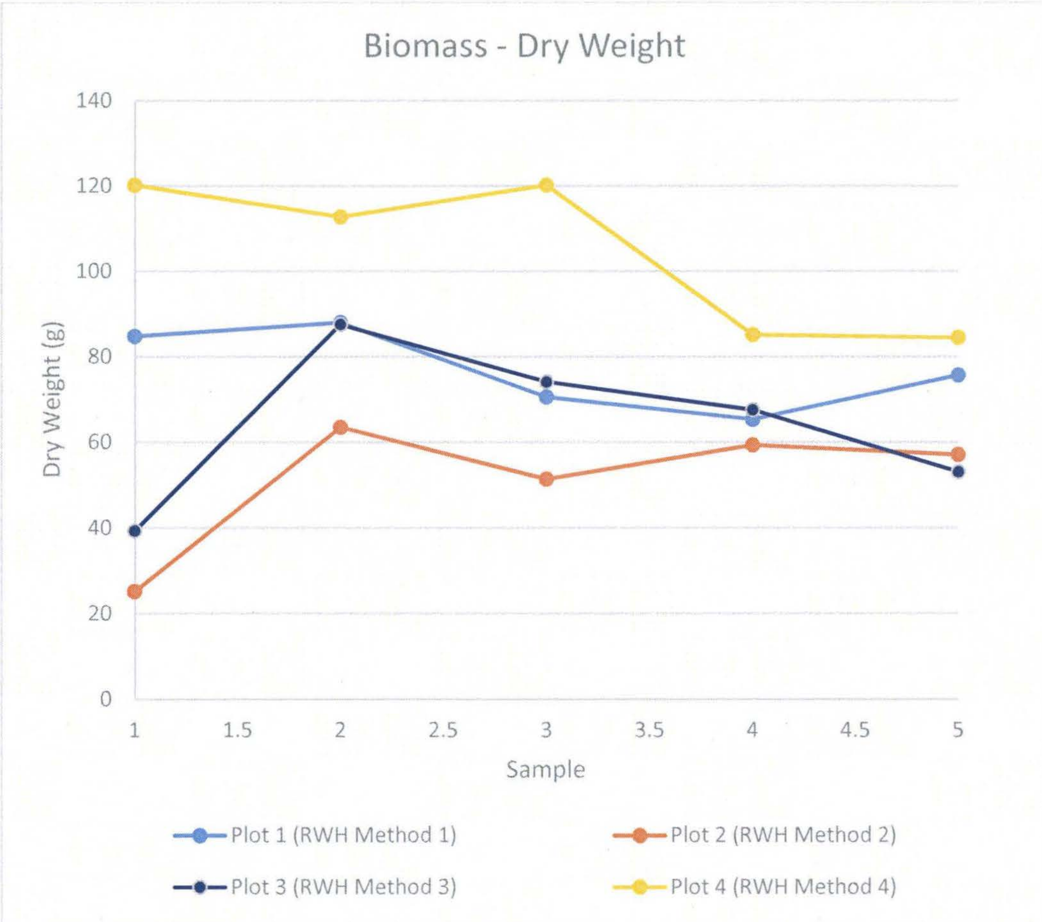


Figure 4-11 - Biomass – dry weight

4.3.6 Water productivity

As alluded in Chapter 3, the total applied irrigation water results and the average dry yield results were used to calculate WP in terms of yield. In addition, WP in terms of biomass was calculated from the total applied irrigation water results and the average dry biomass results. WP in terms of both yield and biomass is presented in Figure 4-12.

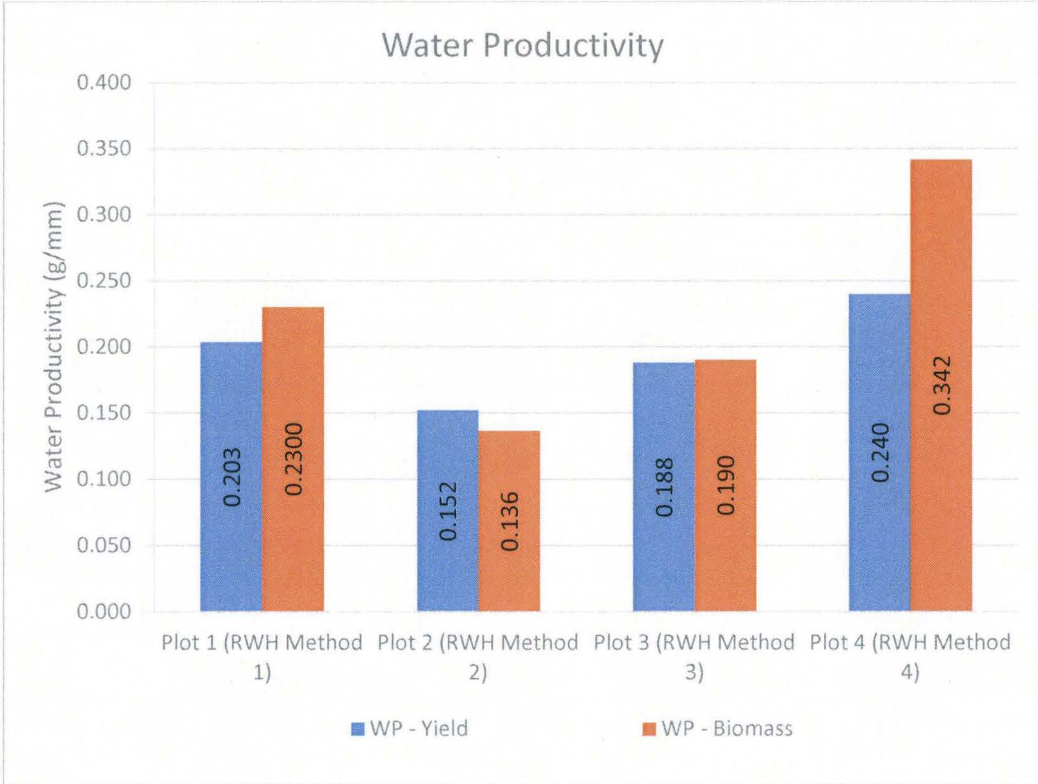


Figure 4-12 - Water productivity – yield and biomass

From Figure 4-12, RWH method 4 was the most water productive in terms of yield with a figure of 0.239 g/mm, followed by RWH method 1, then 3 and finally 2 which was respectively 15.14%, 21.61% and 36.6% less productive than RWH method 4. In addition, in terms of biomass, RWH method 4 was the most water productive with a value of 0.342 g/mm. Falling 32.65% below RWH method 4, is RWH method 1 with an average WP of 0.230 g/mm, followed by RWH method 3 with 0.190 g/mm. RWH method 2, with 0.136 g/mm, performed poorly falling 60.06% behind RWH method 4.

The varying WP figures for both yield and biomass were influenced by the amount of water that was harvested by each RWH method, how much of the harvested water was utilized as transpired water rather than lost to evaporation or deep percolation. The superiority of RWH method 4 was found in its capability to harvest more rainwater than RWH methods 1, 2 and 3.

4.4 Discussion: Objective 2 - Evaluation of the most productive RWH method

Four RWH methods were tested in this experiment to determine which method is the most productive. WP is an overarching term which describes the relationship between inputs and outputs. Inputs are inclusive of irrigation water, mulching, fertilizers and seeds. Outputs are inclusive of yield and biomass. A reduction in inputs such as irrigation water results in an increase in WP which is beneficial to the urban farmer as it would relate to a reduction in costs. An increase in outputs such as yield and biomass also results in an increase in WP which is particularly beneficial to the urban farmer as it would relate to an increase in the access to nutritious vegetables and provide a source of secondary income through the sale of biomass and food products.

RWH method 4 proved to the most productive among all the treatments because the method used the least volume of irrigation water, produced the highest yield and biomass when compared to methods 1, 2 and 3. This is further supported by the WP of each method which showed that RWH method 4 was the most productive in terms of both yield and biomass. It can therefore be deduced that RWH method 4 has the potential to reduce the volume of irrigation water required whilst simultaneously increasing yield and biomass. RWH method 4 thereby, potentially reduces the demand on South Africa's stressed water resources and increases the access to and surety of nutritious food products for the underprivileged community.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Food insecurity is a major problem affecting most developing countries including South Africa. The South African government and numerous scholars believe that UA holds huge promise towards combating food insecurity in poor communities. Successful implementation of UA requires various support mechanisms, one of which is to provide urban residents with a greater access to fit-for-purpose irrigation water. This study therefore identified and evaluated various sources of fit-for-purpose water for irrigated UA whilst exploring methods which can be used to increase water productivity. The Siyakhana Food Garden was used as the case study.

This study identified and investigated wastewater, greywater, and rainwater as possible sources of fit-for-purpose irrigation water for UA. The nutrient properties and reliability of wastewater and greywater make them attractive sources of fit-for-purpose irrigation water for UA. However, wastewater and greywater irrigation can promote soil salinization, soil sodicity and groundwater pollution. In addition, consumption of agricultural products that were irrigated with wastewater or greywater can cause severe public health risks. On the other hand, rainwater has been the primary source of water for agriculture since the beginning of time. Rainwater offers various advantages such as a lower salinity, sodicity and heavy metals concentration over wastewater and greywater. In conclusion and in fulfilment of this study's specific objective 1, rainwater was identified as the most suitable source of fit-for-purpose irrigation water for UA. However, semi-arid countries such as South Africa experience erratic rainfall periods and frequent periods of drought which affects the sustainability of rainwater irrigation. Therefore, to safeguard their grain yields numerous urban farmers have adopted RWH techniques.

RWH techniques are designed at increasing rainwater productivity thus mitigating against water scarcity. Numerous RWH techniques were identified in the literature review, and four of these techniques were evaluated in terms of the highest productivity on the basis of both biomass and yield. The ridge and furrow technique in which the ridges are covered by plastic sheets (RWH method 4) was found to be the most productive for the Siyakhana Food Garden. It produced water productivity figures whose values, for fresh produce yield of Broccoli, ranged from 15.14% to 36.6% greater than the other three methods, and for biomass, ranged from 32.65% to 60.06% greater than the other three methods. It can therefore be concluded that in terms of yield and biomass RWH method 4 proved to be the most productive among all the treatments.

5.2 Limitations

In an ideal world, the experiment which was part of research task 2 would have been carried out over a longer timeframe and it would have had a randomized block design with multiple replications. The experiment would have also considered numerous vegetables as urban farmers grow several different types of vegetables per season. However, due to space, resources, time and monetary limitations, these additional variables could not be incorporated into this research work. The results and conclusions reached in this work should therefore be considered applicable to the Siyakhana Food Garden, but the procedure adopted here can be followed for other field investigations where different vegetables and different environmental conditions are considered.

5.3 Recommendations for further research

This study employed two research tasks to address the specific objectives. Task 1 identified a suitable source of irrigation water for UA and task 2 identified the most productive RWH method in an UA context. Several recommendations for further research were identified for both tasks and are discussed in the paragraphs that follow.

In terms of task 1, rainwater was concluded as a suitable source of fit-for-purpose irrigation water for UA. This conclusion was based solely on a desktop study. The author was unable to identify any literature which compared all three sources of fit-for-purpose irrigation water in an UA context. Conclusions were therefore drawn by evaluating literature which concentrated on a single source of fit-for-purpose irrigation water. To provide empirical evidence and enhance the credibility of the conclusion, an experiment should be carried out which compares wastewater, greywater and rainwater irrigation to determine which source of water is best suited for UA.

In addition, Wastewater and greywater were identified as an easily accessible and reliable source of irrigation water. This statement holds true for the large-scale farmer who has access to municipal wastewater or who can implement large scale greywater recycling schemes. However, the abovementioned statement may not be true for the underprivileged urban farmer. The author was unable to identify any literature which evaluated the accessibility of greywater and wastewater to the underprivileged urban farmer. Therefore, further investigation into the accessibility of greywater and wastewater to the underprivileged urban farmer is required.

In terms of task 2, several limitations were identified in Section 5.2 which limits the application of the conclusion drawn in task 2. Below is a list of further research required to confirm the applicability of the results obtained in task 2:

- To quantify the effects the seasons has on productivity of the RWH methods, the experiment can be carried out over a minimum of two years;
- To identify and eliminate extraneous variables that may influence the results, the experiment should have larger plots, a randomized block design with multiple replications, a greater population and sample size;
- The experiment should also consider numerous vegetables.

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Appendix A

A1 Irrigation Recordings – Plot 1

The soil water content readings, root zone water content results and irrigation recordings for plot 1 (RWH method 1) is presented in Table A1-1 below.

Table A1-1 - Irrigation recordings for plot 1

Recording Number	Date	Soil Water Content (m^3/m^3)				Root Zone Water Content (mm)	Irrigation (mm)	Comment
		Reading Position			Average			
		1	2	3				
1	19/04/2017	0.41	0.474	0.439	0.441	15	15	Site Establishment
2	21/04/2017	0.377	0.369	0.341	0.362	-4.217		
3	24/04/2017	0.343	0.33	0.315	0.329	-22.367		
4	26/04/2017	0.32	0.305	0.3	0.308	-33.917		
5	28/04/2017	0.355	0.355	0.325	0.345	-13.75		light rain observed
6	02/05/2017	0.32	0.33	0.29	0.313	-31.167	32	
7	03/05/2017	0.38	0.37	0.345	0.365	-2.75		
8	05/05/2017	0.355	0.355	0.31	0.34	-16.5		
9	08/05/2017	0.326	0.329	0.301	0.319	-28.233	28	
10	10/05/2017	0.405	0.365	0.31	0.36	-5.5		
11	12/05/2017	0.385	0.37	0.285	0.347	-12.833		
12	15/5/2017	0.365	0.323	0.266	0.318	-28.6	29	
13	17/5/2017	0.4	0.38	0.32	0.367	-1.833		
14	19/5/2017	0.36	0.355	0.295	0.337	-18.333		
15	22/5/2017	0.33	0.325	0.265	0.307	-34.833	35	
16	24/5/2017	0.365	0.375	0.355	0.365	-2.75		
17	26/5/2017	0.351	0.365	0.331	0.349	-11.55		
18	29/5/2017	0.323	0.311	0.305	0.313	-31.35	32	
19	31/5/2017	0.351	0.355	0.367	0.358	-6.783		
20	02/6/2017	0.342	0.3	0.375	0.339	-17.05		
21	05/6/2017	0.309	0.28	0.34	0.31	-33.183	34	
22	07/6/2017	0.377	0.361	0.385	0.374	0		
23	09/6/2017	0.322	0.345	0.361	0.343	-15.033		
24	12/6/2017	0.291	0.311	0.329	0.31	-32.817	34	
25	14/6/2017	0.344	0.359	0.373	0.359	-6.233		
26	16/06/2017	0.323	0.349	0.356	0.343	-15.033		

Recording Number	Date	Soil Water Content (m^3/m^3)				Root Zone Water Content (mm)	Irrigation (mm)	Comment
		Reading Position			Average			
		1	2	3				
27	21/06/2017	0.299	0.315	0.321	0.312	-32.083	32	
28	26/06/2017	0.333	0.376	0.367	0.359	-6.233		
29	28/06/2017	0.335	0.367	0.351	0.351	-10.45		
30	30/06/2017	0.295	0.321	0.321	0.312	-31.717	32	
31	03/07/2017	0.341	0.368	0.367	0.359	-6.233		
32	05/07/2017	0.327	0.356	0.341	0.341	-15.767		
33	07/07/2017	0.301	0.331	0.311	0.314	-30.617	32	
34	10/07/2017	0.349	0.371	0.355	0.358	-6.417		
35	12/07/2017	0.333	0.361	0.33	0.341	-15.767		
36	17/7/2017	0.311	0.341	0.321	0.324	-25.117		
Total Irrigation Water Applied							335.000	mm

A2 Irrigation Recordings – Plot 2

The soil water content readings, root zone water content results and irrigation recordings for plot 2 (RWH method 2) is presented in Table A2-2 below.

Table A2-2 - Irrigation recordings for plot 2

Recording Number	Date	Soil Water Content (m3/m3)				Root Zone Water Content (mm)	Irrigation (mm)	Comment
		Reading Position			Average			
		1	2	3				
1	19/04/2017	0.457	0.417	0.479	0.451	15	15	Site Establishment
2	21/04/2017	0.371	0.366	0.359	0.365	-2.567		
3	24/04/2017	0.339	0.339	0.331	0.336	-18.517		
4	26/04/2017	0.311	0.321	0.305	0.312	-31.717		
5	28/04/2017	0.313	0.305	0.305	0.308	-34.283	34	light rain observed
6	02/05/2017	0.359	0.359	0.351	0.356	-7.517		
7	03/05/2017	0.339	0.341	0.329	0.336	-18.517		
8	05/05/2017	0.315	0.325	0.311	0.317	-29.15	29	
9	08/05/2017	0.351	0.352	0.321	0.341	-15.767		
10	10/05/2017	0.329	0.329	0.311	0.323	-25.85		
11	12/05/2017	0.311	0.315	0.311	0.312	-31.717	32	
12	15/5/2017	0.343	0.351	0.359	0.351	-10.45		
13	17/5/2017	0.321	0.333	0.335	0.33	-22.183		
14	19/5/2017	0.295	0.309	0.315	0.306	-35.017	35	
15	22/5/2017	0.331	0.355	0.361	0.349	-11.55		
16	24/5/2017	0.329	0.36	0.345	0.345	-13.933		
17	26/5/2017	0.298	0.32	0.318	0.312	-31.9	32	
18	29/5/2017	0.333	0.355	0.351	0.346	-13.017		
19	31/5/2017	0.311	0.341	0.339	0.33	-21.817		
20	02/6/2017	0.285	0.317	0.321	0.308	-34.283	35	
21	05/6/2017	0.321	0.361	0.369	0.35	-10.817		
22	07/6/2017	0.323	0.349	0.348	0.34	-16.5		
23	09/6/2017	0.306	0.325	0.327	0.319	-27.867	28	
24	12/6/2017	0.355	0.359	0.361	0.358	-6.417		
25	14/6/2017	0.341	0.321	0.331	0.331	-21.45		
26	16/06/2017	0.326	0.305	0.308	0.313	-31.35	32	
27	19/06/2017	0.361	0.341	0.344	0.349	-11.733		
28	21/06/2017	0.337	0.318	0.311	0.322	-26.4		
29	23/06/2017	0.321	0.295	0.301	0.306	-35.383	36	
30	30/06/2017	0.351	0.371	0.351	0.358	-6.783		
31	03/07/2017	0.321	0.341	0.321	0.328	-23.283		

Recording Number	Date	Soil Water Content (m3/m3)				Root Zone Water Content (mm)	Irrigation (mm)	Comment
		Reading Position			Average			
		1	2	3				
32	05/07/2017	0.298	0.323	0.295	0.305	-35.567	36	
33	07/07/2017	0.355	0.329	0.331	0.338	-17.417		
34	10/07/2017	0.345	0.321	0.331	0.332	-20.717		
35	12/07/2017	0.321	0.305	0.311	0.312	-31.717	32	
36	17/7/2017	0.362	0.351	0.361	0.358	-6.6		
Total Irrigation Water Applied							376	mm

A3 Irrigation Recordings – Plot 3

The soil water content readings, root zone water content results and irrigation recordings for plot 3 (RWH method 3) is presented in Table A2-2 below.

Table A3-3 - Irrigation recordings for plot 3

Recording Number	Date	Soil Water Content (m^3/m^3)				Root Zone Water Content (mm)	Irrigation (mm)	Comment
		Reading Position			Average			
		1	2	3				
1	19/04/2017	0.492	0.419	0.451	0.454	15	15	Site Establishment
2	21/04/2017	0.399	0.356	0.335	0.363	-3.667		
3	24/04/2017	0.369	0.335	0.31	0.338	-17.6		
4	26/04/2017	0.349	0.315	0.29	0.318	-28.6		
5	28/04/2017	0.349	0.312	0.299	0.32	-27.5	28	light rain observed
6	02/05/2017	0.375	0.369	0.345	0.363	-3.85		
7	03/05/2017	0.349	0.351	0.321	0.348	-12.1		
8	05/05/2017	0.326	0.325	0.311	0.321	-27.133	28	
9	08/05/2017	0.362	0.366	0.349	0.359	-6.05		
10	10/05/2017	0.336	0.351	0.331	0.339	-16.867		
11	12/05/2017	0.342	0.353	0.339	0.345	-13.933		
12	15/5/2017	0.309	0.329	0.311	0.316	-29.517	30	
13	17/5/2017	0.345	0.371	0.343	0.353	-9.35		
14	19/5/2017	0.319	0.359	0.328	0.335	-19.067		
15	22/5/2017	0.279	0.331	0.295	0.302	-37.583	38	
16	24/5/2017	0.321	0.389	0.339	0.34967	-11.183		
17	26/5/2017	0.319	0.371	0.335	0.342	-15.583		
18	29/5/2017	0.289	0.339	0.295	0.308	-34.283	35	
19	31/5/2017	0.341	0.369	0.341	0.35033	-10.817		
20	02/6/2017	0.326	0.351	0.326	0.334	-19.617		
21	05/6/2017	0.295	0.323	0.311	0.31	-33.183	33	
22	07/6/2017	0.335	0.361	0.368	0.35467	-8.433		
23	09/6/2017	0.311	0.339	0.351	0.334	-19.983		
24	12/6/2017	0.312	0.342	0.353	0.336	-18.883		
25	14/6/2017	0.292	0.322	0.333	0.316	-29.883	30	
26	16/06/2017	0.335	0.359	0.369	0.354	-8.617		
27	19/06/2017	0.308	0.331	0.341	0.327	-23.833		
28	21/06/2017	0.301	0.311	0.321	0.311	-32.45	33	
29	23/06/2017	0.349	0.362	0.365	0.359	-6.233		
30	30/06/2017	0.321	0.332	0.342	0.332	-21.083		
31	03/07/2017	0.311	0.321	0.332	0.321	-26.767	27	

Recording Number	Date	Soil Water Content (m³/m³)				Root Zone Water Content (mm)	Irrigation (mm)	Comment
		Reading Position			Average			
		1	2	3				
32	05/07/2017	0.361	0.371	0.382	0.371	0		
33	07/07/2017	0.315	0.327	0.352	0.331	-21.267		
34	10/07/2017	0.295	0.295	0.297	0.296	-40.883	41	
35	12/07/2017	0.343	0.348	0.342	0.344	-14.117		
36	17/7/2017	0.319	0.31	0.315	0.315	-30.433		
Total Irrigation Water Applied							338	mm

A4 Irrigation Recordings – Plot 4

The soil water content readings, root zone water content results and irrigation recordings for plot 4 (RWH method 4) is presented in Table A4-4 below.

Table A4-4 - Irrigation recordings for plot 4

Recording Number	Date	Soil Water Content (m^3/m^3)				Root Zone Water Content (mm)	Irrigation (mm)	Comment
		Reading Position			Average			
		1	2	3				
1	19/04/2017	0.492	0.419	0.451	0.454	15	15	Site Establishment
2	21/04/2017	0.38	0.355	0.34	0.358	-6.417		
3	24/04/2017	0.351	0.325	0.311	0.329	-22.55		
4	26/04/2017	0.321	0.322	0.281	0.308	-34.1		
5	28/04/2017	0.366	0.375	0.349	0.363	-3.667		light rain observed
6	02/05/2017	0.37	0.345	0.315	0.343	-14.667		
7	03/05/2017	0.352	0.315	0.309	0.32833	-22.917		
8	05/05/2017	0.329	0.29	0.275	0.298	-39.6	40	
9	08/05/2017	0.38	0.359	0.33	0.356	-7.517		
10	10/05/2017	0.356	0.342	0.289	0.329	-22.55		
11	12/05/2017	0.345	0.349	0.333	0.342	-15.217		dew observed
12	15/5/2017	0.309	0.322	0.325	0.319	-28.233	28	
13	17/5/2017	0.345	0.365	0.368	0.359	-5.867		
14	19/5/2017	0.331	0.352	0.355	0.346	-13.2		
15	22/5/2017	0.285	0.325	0.32	0.306	-35.2	35	
16	24/5/2017	0.339	0.37	0.363	0.35733	-6.967		
17	26/5/2017	0.311	0.341	0.342	0.331	-21.267		
18	29/5/2017	0.29	0.326	0.311	0.309	-33.55	34	
19	31/5/2017	0.348	0.376	0.359	0.361	-4.95		
20	02/6/2017	0.315	0.378	0.339	0.344	-14.3		
21	05/6/2017	0.285	0.347	0.308	0.313	-31.167	31	
22	07/6/2017	0.335	0.361	0.367	354	0		
23	09/6/2017	0.333	0.349	0.34	0.341	-16.133		
24	12/6/2017	0.34	0.352	0.341	0.344	-14.117		dew observed
25	14/6/2017	0.295	0.335	0.319	0.316	-29.517	30	
26	16/06/2017	0.365	0.369	0.355	0.363	-3.85		
27	19/06/2017	0.331	0.325	0.329	0.328	-22.917		
28	21/06/2017	0.309	0.31	0.312	0.31	-32.817	32	
29	23/06/2017	0.351	0.355	0.361	0.356	-7.883		
30	30/06/2017	0.333	0.325	0.341	0.333	-20.35		
31	03/07/2017	0.32	0.311	0.322	0.318	-28.783	29	

Recording Number	Date	Soil Water Content (m³/m³)				Root Zone Water Content (mm)	Irrigation (mm)	Comment
		Reading Position			Average			
		1	2	3				
32	05/07/2017	0.37	0.361	0.372	0.368	-1.283		
33	07/07/2017	0.342	0.335	0.346	0.341	-15.95		
34	10/07/2017	0.311	0.301	0.321	0.311	-32.45	32	
35	12/07/2017	0.361	0.341	0.365	0.356	-7.883		
36	17/7/2017	0.321	0.311	0.335	0.322	-26.217		
Total Irrigation Water Applied							306	mm

Appendix B

B1 Yield and biomass recordings – Plot 1

The fresh and dry yield recordings for plot 1 (RWH method 1) are presented in Table B1-1 below. In addition, the wet and dry biomass recordings for plot 1 (RWH method 1) are presented in Table B1-1 below

Table B1-1 - Yield and biomass recordings for plot 1

Sample	Broccoli Wet Weight (g)	Broccoli Dry Weight (g)	Biomass Wet Weight (g)	Biomass Dry Weight (g)
1	291.41	86.54	281.89	84.75
2	335.04	82.11	303.43	87.97
3	304.3	69.33	284.85	70.51
4	293.95	52.11	291.31	65.3
5	351.63	49.74	289.56	75.63
Average	315.266	67.966	290.208	76.832

B2 Yield and biomass recordings – Plot 2

The fresh and dry yield recordings for plot 2 (RWH method 2) are presented in Table B2-2 below. In addition, the wet and dry biomass recordings for plot 2 (RWH method 2) are presented in Table B2-2 below

Table B2-2 - Yield and biomass recordings for plot 2

Sample	Broccoli Wet Weight (g)	Broccoli Dry Weight (g)	Biomass Wet Weight (g)	Biomass Dry Weight (g)
1	227.74	74.38	190.16	25.13
2	245.05	61.87	241.11	63.51
3	281.42	65.13	223.19	51.35
4	289.85	43.51	201.31	59.31
5	261.53	40.91	235.41	57.12
Average	261.118	57.16	218.236	51.284

B3 Yield and biomass recordings – Plot 3

The fresh and dry yield recordings for plot 3 (RWH method 3) are presented in Table B3-3 below. In addition, the wet and dry biomass recordings for plot 3 (RWH method 3) are presented in Table B3-3 below

Table B3-3 - Yield and biomass recordings for plot 3

Sample	Broccoli Wet Weight (g)	Broccoli Dry Weight (g)	Biomass Wet Weight (g)	Biomass Dry Weight (g)
1	281.41	79.15	243.16	39.3
2	336.5	80.59	274.82	87.51
3	291.56	65.31	291.56	74.06
4	285.63	45.51	263.15	67.51
5	341.56	47.12	251.36	53.01
Average	307.332	63.536	264.81	64.278

B4 Yield and biomass recordings – Plot 4

The fresh and dry yield recordings for plot 4 (RWH method 4) are presented in Table B4-4 below. In addition, the wet and dry biomass recordings for plot 4 (RWH method 4) are presented in Table B4-4 below

Table B4-4 - Yield and biomass recordings for plot 4

Sample	Broccoli Wet Weight (g)	Broccoli Dry Weight (g)	Biomass Wet Weight (g)	Biomass Dry Weight (g)
1	281.41	79.15	243.16	39.3
2	336.5	80.59	274.82	87.51
3	291.56	65.31	291.56	74.06
4	285.63	45.51	263.15	67.51
5	341.56	47.12	251.36	53.01
Average	307.332	63.536	264.81	64.278